Analysis of a Technology for CZ Bifacial Solar Cells

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***Abstract*—A bifacial cell technology for Cz Si and evaporated contacts is presented. A p^+nn^+ structure on high resistivity material gives 17.7% for n^+ side illumination and 15.2% for p^+ side illumination. Cell performance is analyzed by fitting experimental measurements with PC1D. Analysis shows that p^+ layer puts a limit to cell performance, mainly due to a high surface recombination velocity. The boron depleted zone near the surface also enhances recombination, but its effect can be reduced by performing a boron etch-back step in the process. Cells with boron etch-back give higher short-circuit current and a reduction of open-circuit voltage of around 10 mV. These results are consistent with the PC1D model.**

***Index Terms*—Bifacial, Cz silicon, solar cells.**

I. Introduction

Bifacial solar cells were first fabricated by the Instituto de Energía Solar by the end of the 1970s [1]. By using a n-FZ high resistivity substrate, an efficiency of 15.7% when illuminated by the p^+ side, and 12.0% when illuminated by the n^+ side was achieved. The technology was transferred to the company Isofotón, which fabricated the first bifacial modules of the market.

Recently, the interest in bifacial cells has grown due to the experimental realization of higher cell efficiencies. In 1994 a p^+nn^+ structure developed at our laboratory reached 19.1% for n^+ side illumination and 18.1% for p^+ side illumination [2]. Hübner *et al.* [3] developed a cell passivated with silicon nitride and with local Al back surface field (BSF) in the rear side, giving 20.1% for front side illumination and 17.2% for rear side illumination. Glunz *et al.* [4] reported for a rear contact cell with an efficiency of 20.6% when illuminated by the unmetallized side, and 20.2% when illuminated by the metallized one. Also with a rear contact cell, Zhou *et al.* [5] achieve 20.6%–15.2% for a 10% coverage on the side with the contacts, and 21.9%–13.9% for 20% coverage. Ohtsuka *et al.* [6] present a triode structure with p–n junctions on both sides that reaches 21.3%–19.8%. With screen-printed contacts, best results reported are those of Rohatgi *et al.* [7], 16.4% front efficiency and 11.6% rear efficiency.

These results are always on high quality FZ material, while there is an interest in Cz silicon for industrial processes. With this material, Münzer *et al.* [8] report an efficiency of around 16%–9% for thin cells (100 μm) with boron BSF.

In this paper we present a technology for Cz bifacial solar cells. Cell process is described, highlighting the key aspects responsible of good bifacial performance. Results are analyzed with the help of the device simulator PC1D [9], and main limits to cell performance are identified. Finally, ways of improvement are explored.

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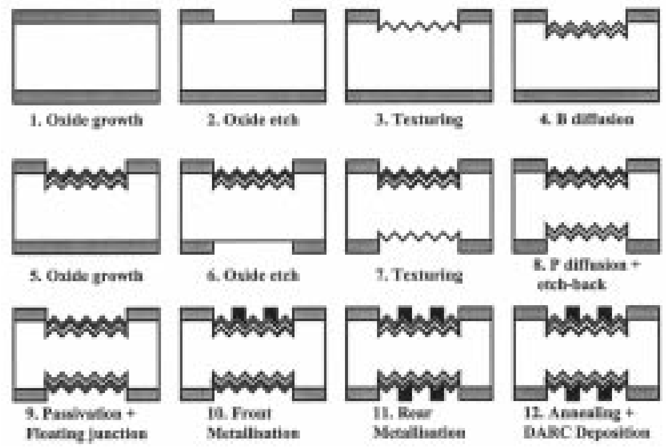

Fig. 1. Bifacial solar cell process for Cz Si.

II. Cz Bifacial Cell Technology

Baseline process for Cz bifacial cells with evaporated contacts has been presented elsewhere [10], and is schematised in Fig. 1. Process is designed to minimize degradation of Cz material due to thermal steps. Lifetime measured in a test sample by transient photoconductive decay technique is of 180 μs [10]. To achieve such value, phosphorus diffusion is performed in supersaturation conditions to produce gettering, and the last passivation step is a short one, that produces a 100 Å oxide and does not degrade lifetime recovered by phosphorus gettering.

On the other hand, passivation of boron-doped surfaces, which is known to be less effective than for phosphorus doped ones, is improved by implementation of a floating junction. It is done by a simple method, consisting of carrying out passivation step in a furnace for phosphorus diffusion, so that the walls work as dopant source during oxidation. A thin n layer forms on p^+ region, and the Aluminum deposited on it during metallization goes through this n layer by spikes, contacting the p^+ layer. Details are given in [11].

A summary of results obtained on 4 cm^2, 20 Ωcm cells is presented in Table I, in the column labeled "Baseline process." Short-circuit currents for n^+ side illumination in the case of n-type bases (that of the high–low junction) confirm that high

TABLE I
SUMMARY OF RESULTS OF BIFACIAL CELLS ON Cz, 20 Ωcm, 4 cm^2, n-TYPE AND p-TYPE Si, MEASURED AT STANDARD CONDITIONS. SHORT-CIRCUIT CURRENT, OPEN-CIRCUIT VOLTAGE, FILL FACTOR AND EFFICIENCY IS GIVEN FOR CELLS FABRICATED BY THE BASELINE PROCESS AND CELLS FABRICATED BY THE PROCESS WITH BORON ETCH-BACK. SEE TEXT FOR DETAILS. 48 CELLS HAVE BEEN PROCESSED IN SEVERAL RUNS, FABRICATED ON 27 WAFERS, AND VALUES OF THE TABLE ARE AVERAGES ON PARAMETERS OF THE CORRESPONDING TYPES OF CELL

	Baseline Process		Process with boron etch-back	
	n-type Si	p-type Si	n-type Si	p-type Si
n^+ side illumination	35.5 mA/cm^2	38.6 mA/cm^2	35.3 mA/cm^2	38.6 mA/cm^2
	607 mV	608 mV	596 mV	596 mV
	0.78	0.73	0.77	0.74
	16.8%	17.0%	16.2%	16.9%
p^+ side illumination	32.0 mA/cm^2	31.5 mA/cm^2	35.1 mA/cm^2	32.7 mA/cm^2
	605 mV	604 mV	595 mV	592 mV
	0.78	0.73	0.77	0.74
	15.0%	13.9%	16.2%	15.0%

TABLE II
PARAMETERS OF THE CELL LABELED CCI, n-TYPE Cz, 20 Ωcm, 4 cm^2, MEASURED AT STANDARD CONDITIONS BY NREL

	n^+ side illumination	p^+ side illumination
Cell CCI	36.3 mA/cm^2	31.6 mA/cm^2
	613 mV	609 mV
	0.796	0.788
	17.7%	15.2%

bulk lifetimes have been obtained. They are always higher than short-circuit currents for p^+ side illumination, although this one is the side of the p–n junction. Cells on p-type Si give similar open-circuit voltages to those on n-type Si, better short-circuit currents for n^+ side illumination (now that of the p–n junction), and worse short-circuit currents for p^+ side illumination. This difference in bifacial cell performance between n-type and p-type bases is the expected one when bulk lifetime is high [12].

TABLE III
PC1D PARAMETERS FOR SIMULATION OF THE CELL LABELED CCI

Phosphorus layer	*Surface concentration*	2×10^{19} cm^{-3}
	Junction depth	0.6 μm
	Surface recombination velocity	15000 cm/s
	Lifetime ($\tau=\tau_n=\tau_p$)	50 μs
	Doping influence in lifetime	$\alpha=-1$ $N_{dop}=2.5\times10^{16}$ cm^{-3}
Bulk	*Width*	250 μm
	Resistivity	20 Ωcm
	Lifetime ($\tau=\tau_n=\tau_p$)	300 μs
Boron layer	*Peak concentration*	2×10^{19} cm^{-3}
	Depth of peak concentration	0.25 μm
	Junction depth	1.5 μm
	Surface recombination velocity	2×10^{6} cm/s
	Lifetime ($\tau=\tau_n=\tau_p$)	50 μs
	Doping influence in lifetime	$\alpha=-1$ $N_{dop}=4\times10^{14}$ cm^{-3}
General	*Series resistance*	480 mΩcm^2
	Shunt resistance	16000 Ωcm^2
	Front reflectivity	Measured
	Total internal reflectivity	0.95
	Rear reflectivity (first bounce – subsequent bounces)	0.65 - 0.95
	Diode J_0 corresponding to metallised region	3×10^{-12} A/cm^2
	Shadow factor	4 %

III. ANALYSIS OF RESULTS

We analyze bifacial cell performance by fitting with PC1D experimental measurements (dark and illuminated current–voltage (I–V) curves, and external quantum efficiency EQE) on the cell labled CCI, whose parameters are given in Table II. The simultaneous fitting of quantum efficiency curves for n^+ side illumination and p^+ side illumination allows obtaining recombination parameters of the cell. Roughly speaking, the performance for high–low junction illumination (n^+ in the case of n-type cells) is determined in the infrared by bulk lifetime, and in the ultraviolet by the recombination at phosphorus layer. Similarly, when illuminating by the p–n junction side, the performance in the ultraviolet depends on boron layer characteristics, and in the infrared on bulk lifetime and phosphorus layer recombination.

The device is divided in three regions, corresponding to phosphorus layer, bulk and boron layer. Phosphorus and boron profiles have been measured by spreading resistance. In addition to Auger recombination, it has been experimentally observed that in highly doped layers there is another contribution to recombination associated to Shockley–Read–Hall mechanism [13], [14]. This is also taken into account in the model, using the value of -1 for the PC1D parameter α, so that inverse SRH lifetime is linearly dependent on doping level. For simplicity, lifetime value for majority and minority carriers is considered to be the same, with a single trap level at the midgap. Cell reflectivity has been measured with an integrating sphere, and front, total internal and rear components of reflectivity have been extracted from it, according to the procedure explained in [15].

Simulation with PC1D to extract parameters tries to reproduce measurement conditions, in particular that of measuring EQE with a bias light, so that the carrier injection level in the cell corresponds to that of illumination at 1 sun. This is relevant in these cells because they work at high injection at this illumination level.

Table III summarizes parameters of the simulation, and Fig. 2 shows curve fitting.

Fitting allows obtaining the following conclusions.

1) Bulk lifetime is high, even higher than the one measured in the test sample. This confirms phosphorus gettering effect, which remains effective even after passivation step. Thanks to the designed fabrication process, bulk is not a limit to the bifacial performance of the cell.
2) Surface recombination velocities are very high, that is to say, passivation properties of the grown oxide are poor. Dif-

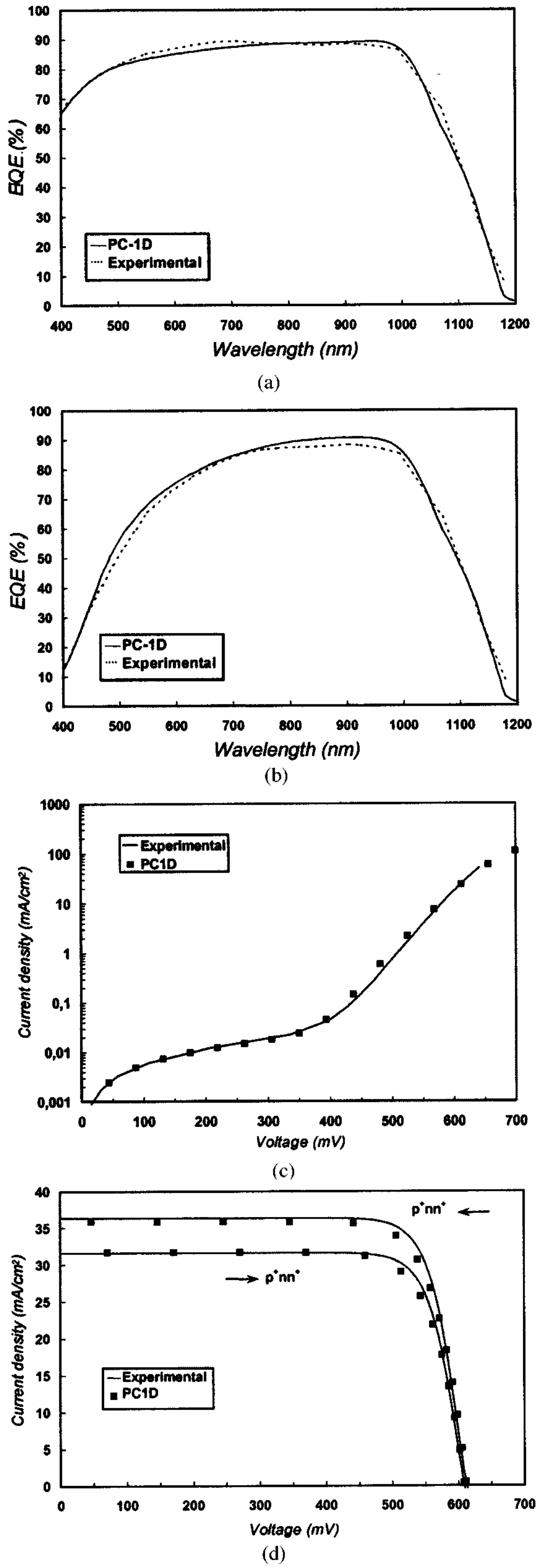

Fig. 2. Curve fitting of the labled cell CCI with PC1D: (a) external quantum efficiency for n^+ side illumination, (b) external quantum efficiency for p^+ side illumination, (c) dark I–V curve, and (d) illuminated I–V curve for both illumination modes.

ferences between these results and those of our FZ bifacial cells, which have a thick passivating oxide [2], can be explained by the fact that a thin oxide of 100 Å passivates worse than a thick one (1000 Å). There are two reasons that support this explanation: First, silicon oxide passivates because when growing, silicon is consumed, and the interface Si–SiO_2 is deepened to cleaner areas inside the wafer; our thick oxide consumes 450 Å of silicon, while the thin one only consumes 45 Å. Second, the surface state density of the interface Si–SiO_2, is lower the higher the process temperature, and the thick oxide is grown at 1000 °C, while the thin one is grown at 850 °C [16].

3) Surface passivation of boron layer is worse than that of the phosphorus layer. It seems that the floating junction does not succeed in reducing surface recombination, as it does in the case of boron emitters with thick oxide [11]. This fact is under research, and no explanation has been found yet.
4) Recombination in the boron layer itself is also big, and that can be attributed to the fact that boron profile is depleted near the surface because segregation to the oxide layer takes place during the three thermal steps after boron deposition.

IV. Modifications to the Baseline Technology

Surface boron-depletion can be reduced by an extra boron etch-back step, eliminating then one of the sources of recombination. This etch-back step is performed before the passivation one, and consists of a chemical bath in $HF : HNO_3 : H_2O$, 1 : 300 : 30. It leaves a boron layer of approximately 130 $\Omega/\square$. Fig. 3 shows the boron profile before etch-back and the final boron profile after oxidation step, measured by spreading resistance. Note that boron depletion is not totally avoided, because there is also some segregation to the passivating oxide. Nevertheless, the thickness of the depleted zone is reduced.

Cells with a boron etch-back have been fabricated on both n and p-type Si wafers, and results are shown in Table I, under the column "Process with boron etch-back." For n-type Si, there is a relevant improvement in short-circuit current, mainly in that corresponding to p^+ side illumination. However, there is a reduction of open-circuit voltage of around 10 mV. Cells on p-type Si present a higher short-circuit current for illumination by the p–n junction, and the same reduction in open-circuit voltage.

Fig. 4 compares quantum efficiency measurements of two cells processed in the same run, one with etched boron layer and the other nonetched, for p^+ side illumination. They are relative measurements to discard small differences in cell shadow factor. The comparison proves that introduction of a boron etch-back in the process succeeds in improving cell response in the ultraviolet for p^+ side illumination.

On the other hand, reduction of open-circuit voltage by 10 mV can be explained because boron emitter is transparent, and surface recombination is dominant. The buffering role of the thicker p^+ layer is lost in the etched cell.

Modifications in the boron profile have been incorporated in our PC1D model, and results are shown in Fig. 5 and Table IV. Both effects of improvement of ultraviolet response and reduction of open-circuit voltage are reproduced, proving the consistency of our assumptions.

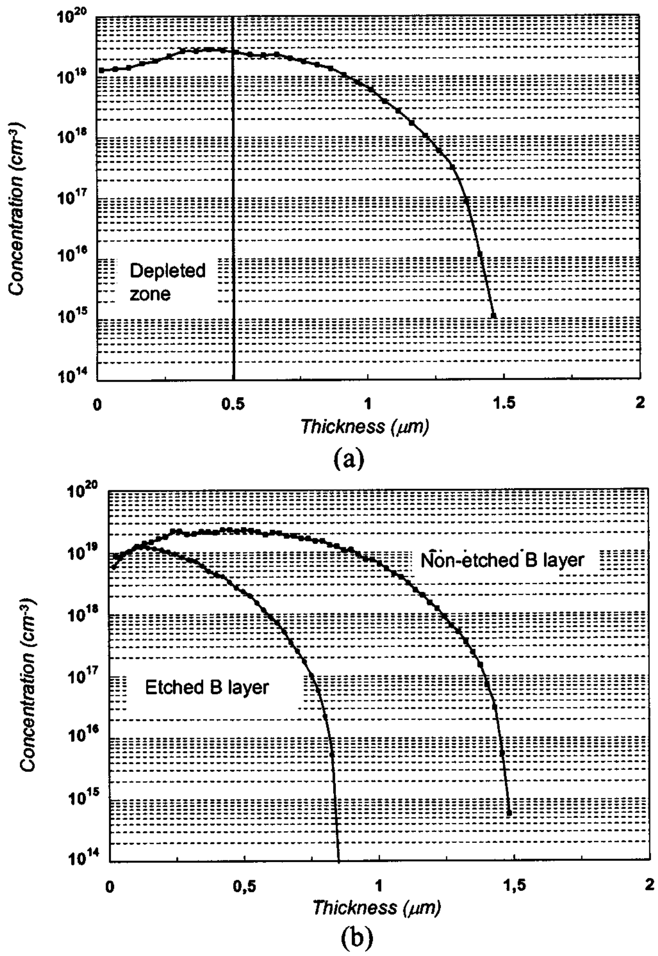

Fig. 3. Boron profiles measured by spreading resistance: (a) before etch-back, showing depleted zone and (b) after passivation step for both cases (with boron etch-back and without boron etch-back).

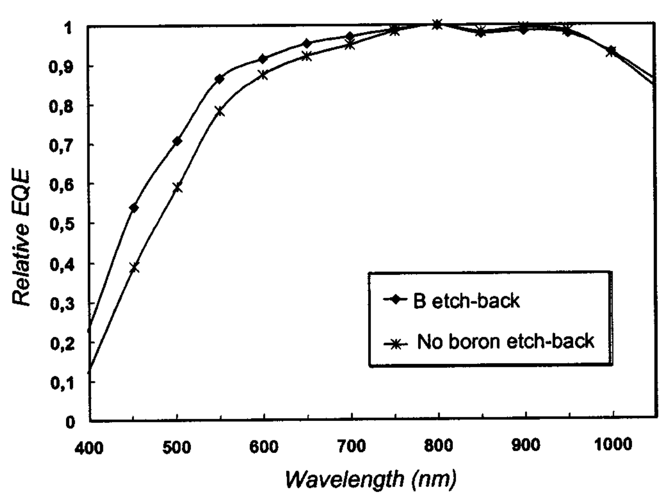

Fig. 4. Relative external quantum efficiency for bifacial cells (P^+ illumination). Comparison of two cells of n-type, one with boron etch-back and the other without it.

V. Conclusions

A technology to fabricate Cz bifacial silicon solar cells with evaporated contacts has been presented. Process has been designed to minimize degradation of Cz material due to thermal

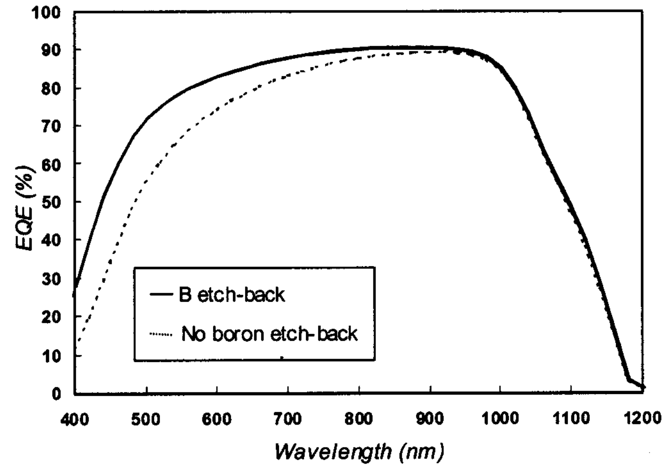

Fig. 5. External quantun efficiency of bifacial cells illuminated by the p^+ side, as simulated with PC1D. Responses of a cell with boron etch-back and another without it are compared.

TABLE IV
Open-Circuit Voltage According to PC1D for a Cell With Boron Etch-Back and a Cell Without it

V_{oc} (mV)	n^+ side illumination	p^+ side illumination
Without boron etch-back	613	609
With boron etch-back	603	601

steps. A result of 17.7% for n^+ side illumination and 15.2% for p^+ side illumination has been obtained.

Cell performance is analyzed by fitting experimental measurements with PC1D. The simultaneous fitting of quantum efficiency curves for n^+ side illumination and p^+ side illumination allows obtaining recombination parameters of the cell. Analysis shows that bulk is not a limit to cell performance. Main limit is due to recombination at the p^+ layer because of a high surface recombination velocity.

Surface boron depletion is also responsible of additional recombination, and can be reduced performing a boron etch-back step in the process. Introduction of this step succeeds in improving cell response in the ultraviolet for p^+ side illumination, but boron surface recombination velocity should be drastically reduced to take more advantage of boron etch-back.

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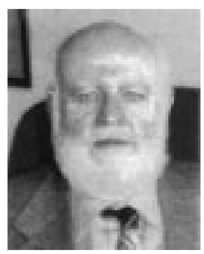

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