p-Si BASED BIFACIAL SOLAR CELL WITH IMPROVED PERT STRUCTURE

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ABSTRACT: Photovoltaic and recombination characteristics of new generation bifacial solar cells are demonstrated. The cells were fabricated using 6" pseudo square wafers of 5 to 6 Ω.cm single crystalline Cz p-Si. Their front efficiency is exceeding 20 % with back to front short circuit current ratio 89 - 92%. The design is characterized by high bulk minority carrier lifetime above 0.5 ms, not degraded during the fabrication process. Rear p^+ layer was prepared by controllable doping process using preliminary deposited thin B contained solid layer. Effective back surface recombination is below 10 cm/s. Measured implied V_{oc} values of the PERT structure exceeding 700 mV are evidencing the intrinsic potential of the structure to provide the cell efficiency far exceeding 22 %. Textured front surface in combination with smoothly etched back provides effective light trapping. The equivalent efficiency of a bifacial solar cell, which characterizes its energy generation capability, will achieve values in the range 23 – 27 % as a function of use conditions.
Keywords: Silicon Solar Cell, Bifacial Cell, PERT structure, p-type, Boron, High-Efficiency.

1. INTRODUCTION

Solar cell structure n^+-p-p^+ or p^+-n-n^+ with passivated emitter and rear totally diffused (PERT) is very promising for achieving high conversion efficiency and extraordinary bifaciality (ratio of short circuit currents at back and front illumination). High photovoltaic parameters were demonstrated for laboratory and industrially produced n-Si based cells [1], [2]. Some laboratory experiments validated as well chance to prepare p-Si based PERT cells [3]. Co-diffusion of boron and phosphorous with CVD deposited BSG and $POCl_3$ as respective doping sources was used. The parameters of I-V characteristics of the PERT cells were lower than PERC (local BSF cells), and the best efficiency was measured for structure with complete back Al contact. Authors of [4] published outstanding efficiency (24.5 %) of p-Si based PERT cell. However, not regular, but magnetically confined Czochralski grown silicon was used as starting material.

The main factors, which determine success or failure in achieving high cell efficiency and bifaciality, are low bulk and rear surface recombination losses. The importance of high lifetime for achieving front and back high efficiencies have been shown theoretically [5] and experimentally (for example, [6] and [7]).

The Cz p-Si based PERT cells dominating in PV industry are fabricated using aluminum alloying on the rear side, and therefore not optimal for achieving uppermost efficiency due to relatively high back surface recombination. Moreover, this kind of cell obviously does not have back light response and does not have bifacial properties.

Boron diffusion in the rear cell side should provide effective p-p^+ barrier needed for the best front efficiency and bifacial properties of the cell. The main problem of applying boron doping process to p-Si wafers is the degradation of bulk lifetime τ_b during the high temperature treatment (in contrary to n-Si, which is more resistant to thermally induced defects). Degradation of τ_b during the cell fabrication process or use of low τ_b starting Si leads to decreased solar cell efficiencies [8].

Authors of [9] proved the possibility of τ_b retaining during industrially fabrication of p-Si based bifacial PERT cells with B doped p^+ back layer. No degradation of high starting τ_b (in the 0.5 - 1 ms range) during the cell processing was found. Bifaciality of described cells was limited in the range 74 – 79 % mainly due to not controllable heavy boron doping of the rear p^+-layer. Effective back surface recombination, S_{eff}, was of one order of magnitude lower than in Al alloyed back cell structure, and was kept at values of 55 – 95 cm/s. The optical cell design, providing effective light trapping, was used in the mentioned research: front cell surface was texturized and rear one was chemically planar etched.

To avoid the limitations of over-doping at p^+ layer formation, as it happened in [9], a fine controllable B doping procedure was developed. Higher quality of p^+ layer prepared without negative effect on the bulk lifetime was achieved. Some results of such processing focused on improvement of recombination parameters of bifacial solar cell with p-PERT structure are presented in the paper.

2 EXPERIMENTAL

2.1 Solar cell structure and fabrication.

The bifacial n^+-p-p^+ solar cells under discussion were fabricated using 6" pseudo square wafers, with resistivity 3 to 6 Ω.cm, single crystalline Cz Si as starting material. The wafer front was textured, and the back was smoothly etched. $POCl_3$ gas phase diffusion process was used for uniform n^+ layer doping by P. The rear p^+ layers with different sheet resistance, R_{sh}, in the range 50 -150 Ω/□ were doped by high temperature diffusion using preliminary deposited B containing thin layer. Combined thermally grown or CVD deposited thin SiO_2 layers and CVD deposited SiN films were applied to both sides as passivating/antireflective coatings. Contact grids with floating four bus bars were screen printed on both sides.

2.2 Measurements.

I-V curves at one sun illumination (irradiance 1000 W/m^2, light spectrum equivalent to solar spectrum under air mass AM 1.5) and in the dark were measured using h.a.l.m. tracker PV-CTL1 of h.a.l.m. electronics. During the measurements under illumination, the receiving of scattered or reflected light by opposite cell side was prevented.

LOANA IQE-SCAN (pv-tools) was used for front and back spectral response determination. Influence of chuck reflectance on spectral response measurement was evaluated experimentally. Comparative measurements using reflective golden and black chucks demonstrated some difference in long wavelength spectral response (above ~980 nm).

The lifetime measurements by Quasi Steady State Photoconductivity Decay (QSSPCD) technique were undertaken for determination of light injected carriers in plain wafers before and after cell fabrication processing. The measurement tool was WCT-120 Silicon Wafer Lifetime Tester (Sinton Consulting Inc.). The same technique was used for evaluation of recombination in complete structure (before metallic contacts deposition). Implied open circuit voltage at one sun illumination, iV_{oc}, and reverse saturation current density, J_o, are distinguishing the recombination quality of the semiconductor structure of a cell.

Properties of doped layers were evaluated using sheet resistance, R_{sh}, determined by four-probe measurement tool. At least nine points per wafer were checked for characterizing the doping uniformity over the wafer area. Depth distribution of doping impurity was analyzed based on the data of Secondary Ion Mass Spectroscopy, SIMS, and the data of Electrochemical Capacitance-Voltage, ECV, characterization using wafer profiler CVP21 (WEP). Witness n-Si samples were used for more correct determination of B doped layer parameters.

3 MEASUREMENT RESULTS

3.1 Structural properties of bifacial cells.

Examples of the B doping profile are shown in Fig. 1. The profiles are characterizing the p^+ layers with sheet resistances 65 and 140 Ω/□ indicating practically whole doping range studied. Maximal B concentrations are relatively low, and are below B solubility limit in Si. The doping is properly deep, mainly when sheet resistance is going down.

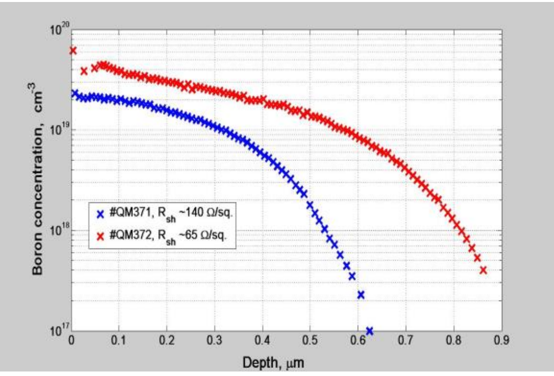

Figure 1: Boron distribution profiles showing the range of doping levels used in the experiments

Important data describing the recombination quality of the fabricated cell diode structures is given in Fig. 2. The implied V_{oc} as a function of the p^+ layer doping level (characterized by R_{sh}) was measured for the structures with R_{sh} of the front n^+ layer ~ 120 Ω/□. Over 10 structures of each shown nominal R_{sh} value was measured. Even with some decrease of iV_{oc} with higher doping values the measurements indicates high cell open circuit voltage expectation.

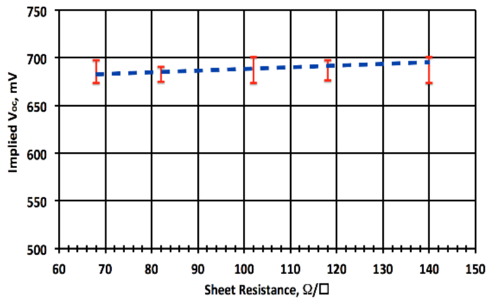

Figure 2: Implied open circuit voltage of n^+-p-p^+ structures vs. doping level of a p^+ layer.

The other illustration of recombination quality of the structure (excluding the edge losses) is the minimal reverse saturation current measured for the structures with each given back R_{sh}. It can be seen in the Table 1.

Table 1. Minimal reverse saturation current densities, J_o, corresponding to iV_{oc} of the n^+-p-p^+ cell structures with different R_{sh} of p^+ layer.

p^+ layer sheet resistance, R_{sh}, Ω/□	68	82	102	118	140
Reverse saturation current density, J_o, fA/cm^2	42	58	36	42	34

3.2 Solar cell internal quantum efficiencies.

Spectral response and IQE data are effective means for illustration and analysis of the physical properties of solar cells. Fig. 3 represents the front IQE of a bifacial cell. The measurements were made using reflective golden chuck (with long wavelength reflectivity ~0.9) and "black" low reflecting chuck (with reflectivity ≤ 0.06). Front spectral reflectance of the cell installed on each chuck is shown in the same Figure 3. Some difference of the two IQE curves due to chuck reflection can be seen at the wavelength longer than ~1000 nm. The impact of the chuck reflectance on the correct determination of energetic cell parameters at solar illumination can be evaluated by integration of the cell spectral response over standard solar radiation spectrum and comparison of the results for the cases of using reflective and black chucks.

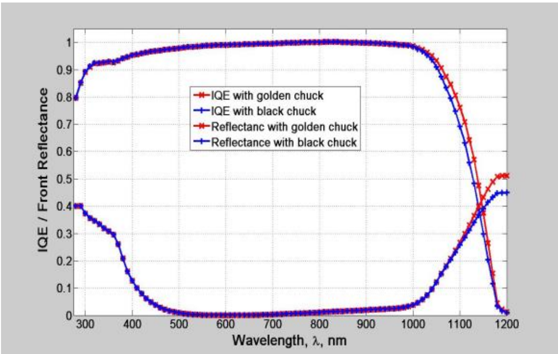

Figure 3: Front internal quantum efficiency, IQE, of the bifacial cell placed on reflective and black chucks.

Such kind of calculations based on the spectral response data for the cell, IQE-s of which are shown in Fig. 3, results in short circuit current densities, J_{sc}, of 39.47 and 39.28 mA/cm^2 for the cases of reflective and black chucks use. Therefore, the relative difference in determination of solar cell current when measured using two type of a chuck is ~ 0.5 %. The relatively small effect of the chuck reflection is the result of effective trapping of the light beams entering through the cell front surface [9]. The same small difference will be resulted in the determination of cell efficiency values.

Fairly high cell spectral response can be seen in the short wavelength range, proving the high n^+ emitter quality.

IQE data for the back illuminated solar cell are presented in Fig. 4. Short wavelength IQE at back illumination is only slightly lower than the front IQE. The depth and profile of doping are explaining this difference. Like in previous figure, spectral reflectance of the cell is shown. Since the rear illuminated surface is not textured the reflectance of the cell is remarkably higher. A little lower short wavelength IQE, higher reflectance and ~ 1 % greater contact shading result in lower back short circuit current, $J_{sc\ b}$. The $J_{sc\ b}$ values calculated as above by integration of spectral response over standard solar spectrum for reflective and black chuck data are: 36.60 and 36.41 mA/cm^2, respectively. These values are ~92.7 % of the respective front J_{sc}. It means, that bifacial factor for the given cell is above 92 %.

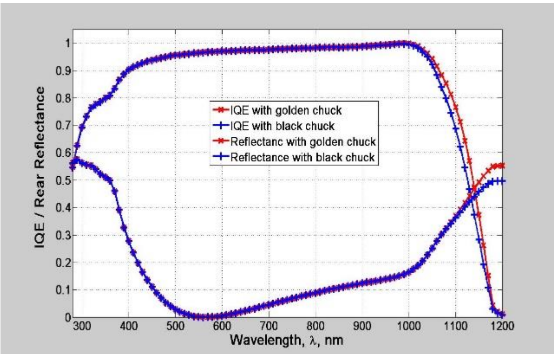

Figure 4: Back internal quantum efficiency, IQE, of the bifacial cell placed on reflective and black chucks.

3. 3 The I-V curves.

The front and back I-V curves of a bifacial cell of ~20.2 % front efficiency at simulated 1 sun illumination are shown in Fig 5. The V_{oc} value of the cell is significantly lower than iV_{oc} measured for the plain structures (see Fig. 1). The obvious explanation is the influence of the contacts.

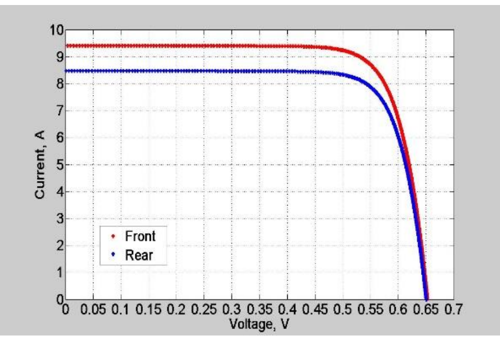

Figure 5: The I-V characteristics of a bifacial cell at front and back 1 sun illumination

A more comprehensive analysis of fabricated bifacial cells can be done based on Table 2. This Table contains the approximate statistical data for the batch (excluding breakage and samples made using mistake operations).

Table 2: Approximate statistical data for a ~ 40 bifacial cell lot

Parameter	Range	Expected
I_{sc}, mA/cm^2	39.2 – 39.6	>40
V_{oc}, V	650 - 658	>660
FF, %	78 - 79	>80
Eff. (front), %	19.9 - 20.3	>21
(I_{scb}/I_{scf})x100, %	89 - 92	>92

Despite a relatively wide range of cell parameters, due to some technological variations in the fabrication process, efficiencies of the cells are quite high and bifacial symmetry exceeding 89 % is good. The data demonstrate an intrinsic superiority of the bifacial n^+-p-p^+ design and fabrication technology used not only in comparison with regular p-PERT cells with Al alloyed back, but as well with p-PERT cells of the first generation [9]. The shown in Table 2 expected parameters of bifacial solar cells are evaluated using the values, which can be improved without any significant change in fabrication processing.

4 DISCUSSION

The described experimental fabrication, quite close to industrial one, demonstrates that the fabrication technology of bifacial n^+-p-p^+ Si solar cells provides the main requirements for high efficiency cells.

The most imperative factor for attaining the highest cell efficiency is a high τ_b. The fabrication technology retains very high τ_b in Cz wafers. The measured τ_b values are in the range 0.5 – 1.2 ms, i.e. in the range typical for the tested starting wafers before thermal processing.

Properties of high-low back barrier are of the first order of significance in influence on the front and back cell efficiencies. Controllable B doping of the p^+ layer forms a very effective BSF resulting after proper passivation in low S_{eff}. The S_{eff} values below 10 cm/s were measured on symmetrically B doped passivated n-Si wafers (as it was described in [10]). Both above factors in combination with high quality emitter with sheet resistance of ~ 120 Ω/□ are responsible for low recombination losses of solar cell structure and due to this for high implied voltages, as can be seen in Fig. 1. iV_{oc} is varying in the range 680 - 702 mV depending on B doping level. Large iV_{oc} values and low reverse saturation currents (Table 1) are proving the intrinsic potential of the structure to provide cell efficiency far exceeding 22 %.

Effective light trapping due to high back internal reflectance for the light rays refracted on the front textured surface ($R_{in\ b} \approx 0.76$) [9] leads to a significant contribution in I_{sc} improvement compared to a regular mono-facial cell with an Al alloyed back.

Low S_{eff} in combination with large τ_b are responsible for good back spectral response. Small losses in short wavelength response are explained by relatively deep B doping. High back spectral response results in a high bifaciality factor. The back IQE-s similar to curve shown in Fig. 3 in combination with optimal SiN antireflective layer result in $I_{sc\,b}/I_{sc\,f}$ exceeding 92 %.

The above data on high cell efficiency and on retaining during the fabrication procedure of high carrier lifetime leads to conclusion that Cz p-Si used for fabrication of n^+-p-p^+ bifacial cells can be competitive with n-Si as a material for high efficiency cell production.

The quality of bifacial cells cannot be evaluated only by front efficiency as far as regular mono facial cell. The adequate quality criteria may be given by evaluation of energy generated by a solar cell. This can be described by "equivalent efficiency". (See Table 3). Equivalent efficiency is determined as the efficiency of a mono-facial cell needed for generating the same energy as a bifacial cell under the given conditions. The data in the Table are based on the outdoor monitoring of bifacial modules under different working conditions [11], [12], [13]. The table demonstrates how high the values of equivalent efficiency are for a bifacial cell described here with front efficiency of 21 %. It can be seen that the equivalent efficiency of these bifacial cells is always higher than 23 % and for most typical applications exceeds 25 – 27 %.

Table 3: Equivalent efficiency as quality criteria of bifacial cell.

Front efficiency, %	Back contribution (energy gain), %	Equivalent efficiency, %
21	10 (field installation with low albedo)	23.1
21	20 (roof installation with intermediate albedo)	25.2
21	30 (roof installation with high albedo)	27.3

5 CONCLUSIONS

- n^+-p-p^+ with uniformly B doped p^+-layer is a promising structure for industrially produced terrestrial bifacial cells.
- B diffusion using preliminary deposited B containing solid layer allows controllable doping of p^+ layer.
- Retained high bulk lifetime, low back S_{eff} and high quality emitter provide implied V_{oc} of the PERT structure exceeding 700 mV.
- Back to front short circuit current ratio (bifaciality factor) is in the range **89 - 92 %.**
- Equivalent efficiency as quality criteria of PERT bifacial cell reaches **23 - 27 %** in the most typical applications.
- High quality starting Cz p-Si can compete with n-Si as a material for cell production with front efficiency above **22 %**.

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