

BIFACIAL SOLAR CELLS ON MULTI-CRYSTALLINE SILICON WITH BORON BSF AND OPEN REAR CONTACT

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ABSTRACT

The standard industrial multi-crystalline silicon (mc-Si) solar cell is monofacial and includes screen printed aluminum back surface field (BSF). A simple approach to increase performance and reduce costs per W_{peak} is to collect the albedo on the rear side. In this work a bifacial, screen printed mc-Si solar cell with boron BSF is demonstrated. Rear to front efficiency ratios of up to 0.83 have been reached on 100x100mm² mc-Si wafers with a thickness of about 200 μm . The best solar cell processed so far with a boron BSF had an efficiency under front side illumination of $\eta=16.1\%$ and a back to front efficiency ratio of 0.77. The possible gain in performance in later operation was estimated using PC1D simulation and depends on the albedo that is the amount of light that penetrates into the solar cell from the rear side. The simulation was confirmed by outside module tests, leading to an average gain of 19.5% over one day.

INTRODUCTION

The standard industrial process for manufacturing monofacial p-type mc-Si solar cells includes screen printed aluminum BSF, achieving an average efficiency of more than 15% in industrial production. Key issues for reducing costs of photovoltaic devices per W_{peak} are to increase performance as well as to reduce wafer thickness. An easy way to achieve the first task is to collect the albedo on the rear side of the cell. Therefore the replacement of the full rear side metallization by an open rear contact (finger grid) is necessary to get a bifacial cell (Figure 1). By doing this the second task is solved as well as the most crucial step in processing of thin wafers is the fully Al metallised rear side leading to high rear recombination velocity and wafer bowing. Most of the common bifacial solar cells are made from silicon with very high charge carrier lifetimes, such as FZ silicon. An overview of different bifacial solar cells is given in [1].

Compared to the Al-BSF alloying, the B-BSF is diffused into the wafer and causes no measurable bowing. As the solubility of boron in silicon is higher than that of aluminum, higher carrier concentrations are achieved. Similar processes are already demonstrated on FZ material [2].



Figure 1. The boron BSF bifacial solar cell. The back side can be seen in the mirror and looks similar to front side

Boron diffusion is considered to be the main difficulty in processing mc-Si solar cells. The diffusivity of boron is much lower than that of phosphorus. Higher diffusion temperatures (or longer processing times) have to be applied for the boron diffusion. Therefore the BBr_3 diffusion has to take place before the emitter diffusion, to avoid further diffusion of the phosphorus atoms. As both diffusions were carried out in an open tube furnace, the opposite side of the wafer has to be protected to secure single sided diffusion or the diffused layer of silicon has to be etched off on one side afterwards. It was shown that boron diffusion is possible at moderate temperatures (around 930°C) in an open tube furnace using a BBr_3 source while maintaining the minority charge carrier lifetime in mc-Si material [3].

SOLAR CELL PROCESS

In the experiments described below we used 100x100 mm² p-type mc-Si wafers with a standard thickness of about 200 μm . The cross-section of the bifacial boron BSF solar cell is shown schematically in Figure 2.

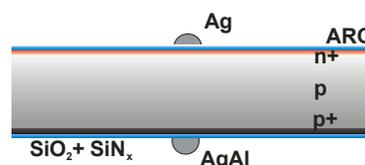


Figure 2. Cross-section of the boron BSF solar cell.

For the solar cell process BBr_3 diffusion at a moderate temperature around $930^\circ C$ was used in an open tube furnace leading to BSF sheet resistances of around $60 \Omega/sq$ with the silicon wafers face to face. To avoid the boron rich layer (BRL), that is created during the diffusion, an in-situ thermal oxidation and deglazing step took place. The emitter was formed by phosphorous diffusion ($POCl_3$) afterwards in back to back configuration. The doping profiles of the boron BSF and the phosphorus emitter were measured using electrochemical capacitance voltage (ECV) method and are depicted in Figure 3. Surface passivation on the front side was done by PECVD SiN_x deposition and thermal $SiO_2/PECVD SiN_x$ stack on the back side.

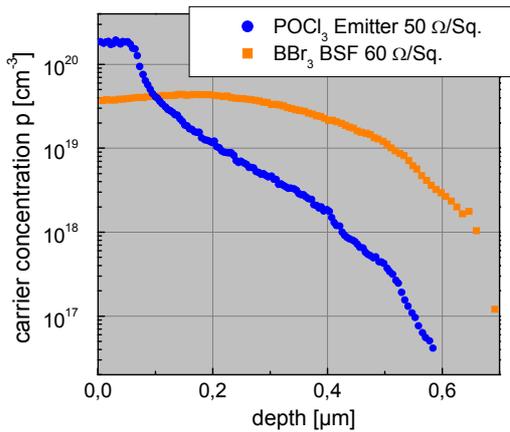


Figure 3. Carrier concentration profiles of the boron BSF and the phosphorus emitter measured by ECV technique.

Even though the wafers were diffused back to back, boron atoms diffuse around the wafer edges to the front side into the wafer. This boron diffused region at the edge of the front side leads to shunting of the solar cell. Therefore the edge isolation using a dicing saw is essential. The untextured cells get an additional etch off of the front surface prior to the emitter diffusion, which makes the process more reliable. The contact metallization was carried out by screen printing using an Ag paste on the front side and an AgAl paste on the back side. The co-firing of the contacts was done in a belt furnace.

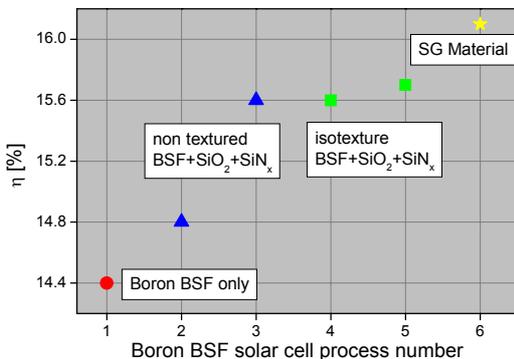


Figure 4. Increase of front side efficiency during process development.

Various variations in the solar cell process have been made to increase the front side efficiency (Figure 4) as well as the back to front efficiency ratio (Figure 5). The first cell generation featured only boron BSF and no additional surface passivation on the back side. Therefore the first generation shows only a very marginal performance under back side illumination. With a SiO_2/SiN_x stack system on the rear side a gain in performance is obtained, due to the better rear side passivation which leads to a higher V_{OC} and also better rear performances due to the ARC.

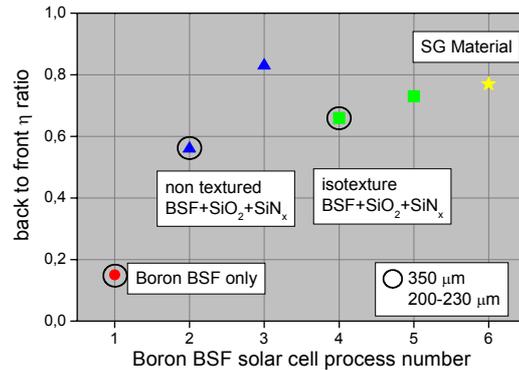


Figure 5. Increase of the back to front efficiency ratio during process development

Starting with the fourth generation the solar cells feature an isotextured surfaces on both sides. Due to the better reflection more light get into the cell, which leads to a higher J_{SC} and therefore a better performance. Thinner wafer with a thicknesses of 200-230 μm were used in process # 3, 5, and 6 (compared to 350 μm in #1, 2, 4) to increase the rear side performance due to the better ratio between bulk lifetime and wafer thickness ($L_d/d > 2.5$ requirement). In # 6 wafers from Elkem's solar grade silicon were processed. The process for both, textured and untextured solar cells is summarized in Figure 6.

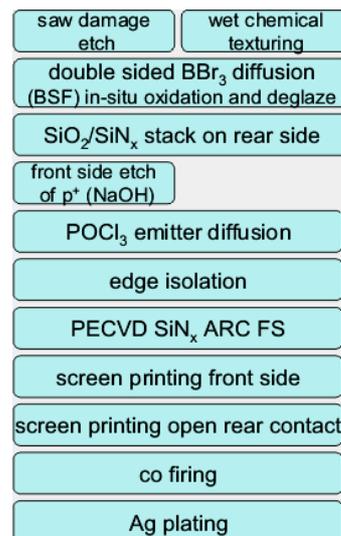


Figure 6. Process sequence of the bifacial boron BSF solar cell

RESULTS AND DISCUSSION

The solar cell results (100 x 100 mm² p-type mc-Si wafer with a thickness of about 200 μm) for the best cells are summarized in Table 1.

Table 1. Solar cell results on 100 x 100 mm² wafers, 200 μm thick, best cells

	FF [%]	J _{SC} [mA/cm ²]	V _{OC} [mV]	ETA [%]	ratio [%]
isotextured, 200 μm thick					
front side illumination	76.0	33.4	617	15.7	0.73
back side illumination	77.0	24.3	609	11.4	
75% SoG & 25% EG Si, 230 μm thick					
front side illumination	75.6	34.3	620	16.1	0.77
back side illumination	74.8	26.9	615	12.4	

An average efficiency of $\eta = 15.1\%$ was reached for a group of eight isotextured cells. For comparison, solar cells were processed on wafers made from a newly developed solar grade silicon feedstock [4]. This solar grade silicon (Elkem-Si) comes from a metallurgical purification process of MG-Si, with cost effective refining steps. For the group (4 cells) with the SG-Si material (Table 1) the average efficiency was $\eta = 15.5\%$. Why the SG material is more beneficial for this process has to be resolved in future experiments.

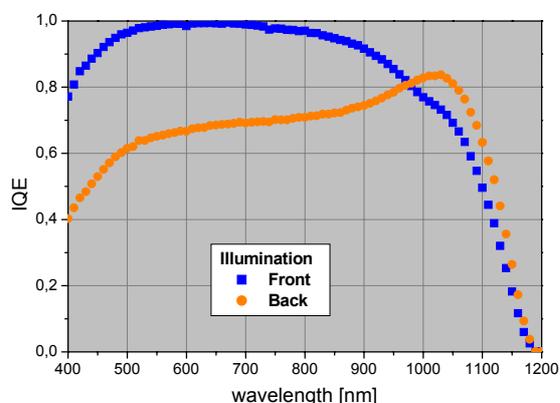


Figure 7. Spectral response measurement

Under back side illumination the performance decreased as expected, due to the unfavorable ratio between wafer thickness and bulk lifetime (compared to FZ silicon). This can be also seen in the IQE curve, as the IQE increases only slowly for wavelengths greater than 500 nm and reaches its maximum at a wavelength at around 1000 nm. Photons with higher wavelengths penetrate deeper into the silicon; electron holes generated from those photons are generated closer to the emitter, therefore the IQE is higher (Figure 7).

PC1D SIMULATION

To make further estimations of the cell performance under double sided illumination, the boron BSF solar cell was simulated using PC1D. First the PC1D parameters were fitted to the cell results for illumination from each side separately. With these parameters we simulated the cell performance with one sun illumination on the front side and different albedos on the back side for different wafer thicknesses. The simulated results are summarized in Figure 8.

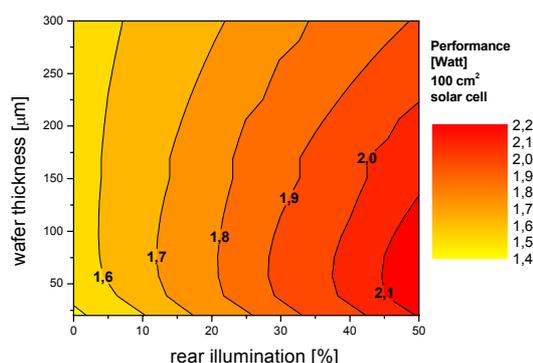


Figure 8. Contour plot: performance as a function of wafer thickness and intensity of rear illumination

The simulation showed that the increase in wafer performance is expected to be even higher if wafers thinner than 100 μm are considered.

MODULE DESIGN AND MOUNTING

For a bifacial module both sides have to be transparent, which was realized by a glass-glass module. A one cell mini-module was made for field testing.

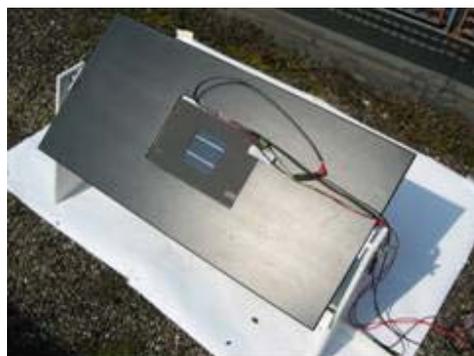


Figure 9. Module test setup

For the output performance the orientation of the bifacial module to the sun is important. There are many possibilities to do this which are discussed in [5] and [6], especially for cells made of FZ or Cz which back to front efficiency ratio is close to one. One possibility is to maximize the irradiation on both sides, as for example in vertical free standing structure. But we have to take in consideration that our bifacial cells are made of mc-Si and

have a lower back to front efficiency ratio due to their lower bulk quality. Therefore we prefer a setup with a fully illuminated front side and only a partly illuminated back side.

In a preliminary experiment our module was mounted south with an angle of 30°, approx. 50cm above the ground, similar to conventional rack system (Figure 9). The cell was surrounded with a 0.5x1m² black, wooden plate to simulate the shadowing produced by a commercial size panel and a 1.6x1.2 m² white board was placed on the ground to simulate a high reflecting surface as proposed by [7].

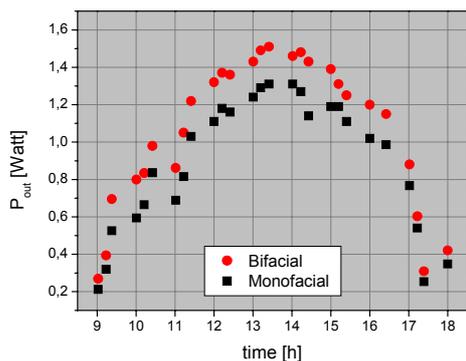


Figure 10. Output power measured over one day in mid April

A complete IV curve was measured every 20 minutes on a sunny day in mid April with little clouds in the sky. Due to the thin wispy cirrus clouds the irradiation varies. The output power is plotted for monofacial and bifacial illumination in Figure 10. As expected there is a peak during mid day. The gain due to collecting the albedo on the back side is plotted in Figure 11. It is highest in the morning hours and decreased at mid day. In the afternoon the sky was bit cloudier, also the temperatures of the module increased up to 32° C. Over the day the average gain in performance of the bifacial cell was 19.5 % due to collecting the albedo.

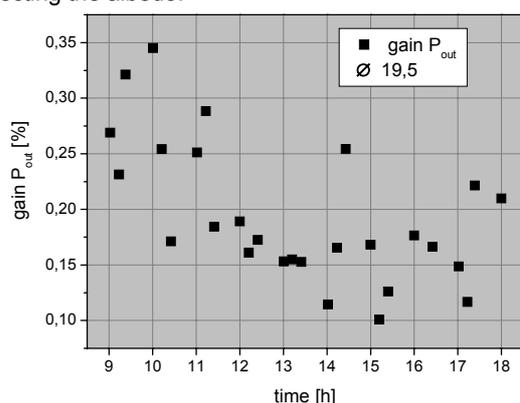


Figure 11. Gain in performance over one day in mid April

The albedo could be further increased by using a larger surface with a higher reflection behind the module, for example mirrors could be mounted or small parabolic

concentrators. Or small spaces could be left between the solar cells within the module as suggested by [6].

CONCLUSION AND OUTLOOK

We have demonstrated that solar cells with boron BSF could be realized on mc-Si and is also applicable on solar grade feedstock material. The best solar cell processed so far on SG Si wafers had an efficiency under front side illumination of $\eta=16.1\%$ ($J_{SC}=34.3\text{mA}/\text{cm}^2$, $V_{OC}=620\text{mV}$ and $FF=75.6\%$) and under rear side illumination of $\eta=12.4\%$ ($J_{SC}=26.9\text{mA}/\text{cm}^2$, $V_{OC}=615\text{mV}$, $FF=74.8\%$) with a back to front efficiency ratio of 0.77. The solar cell results in front illumination were comparable to industrial mc-Si solar cells and the PC1D simulation as well as the preliminary module experiments showed that there is an additional gain in performance due to the bifacial cell concept. Wafer bowing is completely avoided with the process and it could be realized in near future in most of the existing solar cell production lines. When introduced to the industry it could contribute to maintain the rapid growth of the PV sector as less Si per W_{peak} is needed.

In a module test under realistic conditions an average gain in performance of 19.5% was reached over one day. The test showed that bifacial solar cell concepts are promising, not only for Cz or FZ material but also for industrial mc silicon solar cells. More detailed studies of different types of bifacial modules made with cells from multi-crystalline silicon have to be made.

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