Industrial η=15.5% mc-Si solar cells with boron BSF and open rear contact

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ABSTRACT: In this work a standard screen printed mc-Si solar cell with boron Back Surface Field (BSF) is demonstrated on 200 μm thin wafers. The boron BSF formation is done by BBr_3 diffusion in a tube furnace; the rear contacts are only locally alloyed, therefore this process avoids wafer bowing. The best solar cell processed so far with a boron BSF (100 x 100 mm² p-type mc-Si wafer with a thickness of ~200 μm) had an efficiency of η=15.6 % with J_{SC}=33.3 mA/cm², V_{OC}=613 mV and FF=76.1 %. The open rear contact has an additional advantage as the boron BSF solar cell works under backside illumination (η=10.3 %, J_{SC}=22.2 mA/cm², V_{OC}=602 mV, FF=76.9 %).
Keywords: Boron Back Surface Field, Multicrystalline Silicon, Bifacial

INTRODUCTION

The standard industrial process for manufacturing p-type multi-crystalline silicon solar cells includes screen printed aluminium BSF, achieving an average efficiency of more than 15% in industrial production. One key issue for reducing costs of photovoltaic devices is the use of thinner and larger wafers. In existing production lines the wafer thickness is about 250-300 μm and wafer size about 150 x 150 mm², but with advances in wafer technology thinner and larger wafers are available. Thinner wafers with a standard thick film aluminium paste for rear side metallization cause bowing of the wafer, leading to problems and breakage during later processing [1].

The easiest way to avoid wafer bowing when thin wafers are used, is the replacement of the full rear side metallization by a finger grid on the back side. Unfortunately the benefit of the Al-BSF is lost in this case, which would lead to a decrease in cell performance, particularly when thin wafers are used. For this reason the Al-BSF was replaced by a B-BSF in an industrial relevant process. 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 aluminium, higher carrier concentrations are achieved. Similar processes are already done on FZ material [2].

Simulations using PC1D suggested that an industrial solar cell with a B-BSF using thin substrates could achieve similar cell result compared to standard industrial solar cell.

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 phosphorous. 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 done 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. Therefore the benefits of the double sided phosphorous gettering will be lost. However it was shown that boron diffusion is possible at moderate temperatures (around 950°C) in an open tube furnace using a BBr3 source while maintaining the lifetime of mc-Si material [3]. For various diffusion temperatures different sheet resistances have been obtained (diffusion time 60 minutes) on n-type mc-Si. The doping profiles were measured using electrochemical capacitance voltage (ECV) method and are depicted in Figure 1.
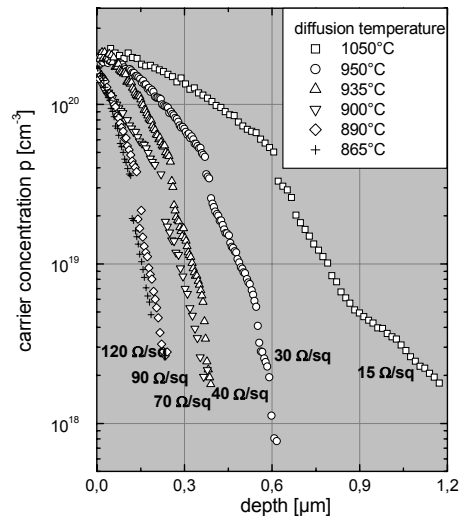

Figure 1 Profiles after boron diffusion for different diffusion temperatures measured by ECV [3]

In the experiments described below we used 125x125 mm² p-type mc Si wafers with a standard thickness of ~300 μm (Group A) and ~200 (Group B). Two different solar cell processes were used; Group A with an etch back of the boron diffused silicon layer on the front side and group B with isotextured wafers and back to back diffusion. Both process flow charts are shown schematically in Table I.

SOLAR CELL PROCESS

Solar cell process for untextured wafers (Process A)

For the solar cell process BBr_3 diffusion at a moderate temperature around 950°C was used in an open tube furnace leading to a BSF sheet resistances of around 30 Ω/□. The wafers in the quartz boat were diffused on both sides. After the boron diffusion the boron rich layer (BRL) that is created during the diffusion has to be removed from the wafer. This is done by a thermal oxidation and deglazing step. The backside with the BSF was then passivated by a silicon oxide/ PECVD silicon

nitride stack system. The boron on the front side was etched of with NaOH, with the back side already protected by the SiN$_x$ layer.

The Emitter was formed by phosphorous diffusion (POCl$_3$), than a PECVD SiN$_x$ ARC was deposited. The contact metallization was done by screen printing and cofiring. On the reference cells Al paste was printed on the entire back side, on the B-BSF cells a AgAl fingergrid with a coverage of approximately 8 % was printed on the back side.

Process A	Process B
saw damage etch	isotexture
double sided BBr$_3$ diffusion (BSF), in-situ oxidation and deglaze	single sided BBr$_3$ diffusion (back to back), in-situ oxidation and deglaze
SiO$_2$/SiN$_x$ stack on rear side	SiO$_2$/SiN$_x$ stack on rear side
front side etch of p+ (NaOH)	
POCl$_3$ emitter diffusion	single sided POCl$_3$ emitter diffusion (back to back)
PECVD SiN$_x$ ARC front side	PECVD SiN$_x$ ARC front side
	"edge isolation"
screen printing (open rear contact)	screen printing (open rear contact)
co firing	co firing
edge isolation	

Table I Comparison of the solar cell processes for untextured and isotextured wafers

Solar cell process for isotextured wafers (Process B)

To improve the cell performance the surfaces of the wafers were isotextured. This requires some changes in the B-BSF process. For the solar cell process BBr$_3$ diffusion at a temperature of 935°C was processed in an open tube furnace leading to a BSF with sheet resistance of around 60 Ω/□ after removal of the BRL. The wafers were diffused back to back, followed by an in-situ thermal oxidation and deglazing step for the removal of the BRL. The BSF is passivated and protected by a silicon oxide (~10 nm) and an additional PECVD SiN$_x$ (~74nm) layer.
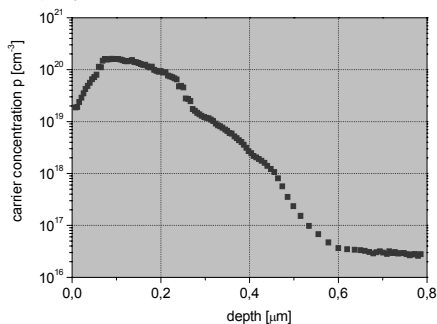
Figure 2 Profile of the boron BSF after BRL removal and oxidation measured by ECV

The BSF profile is shown in Figure 2. The depletion of the carrier concentration at the surface due to the oxidation is clearly visible. The emitter was formed by phosphorous diffusion, with a following PECVD SiN$_x$

ARC deposition. The contact metallization was done by screen printing and cofiring. To contact the B-BSF an AgAl finger grid was printed on the back side which leads to a coverage of approximately 8%.
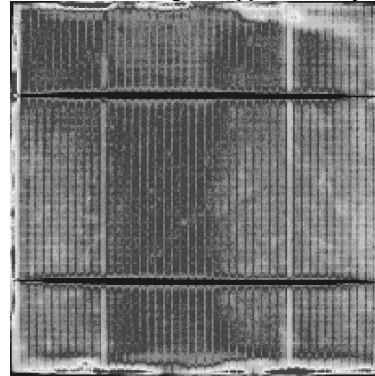
Figure 3: Lock-in thermograph measurement. The length of the edge is 123 mm

Even though the wafers were diffused back to back, some boron atoms diffuse around the wafer edges to the front side into the wafer. These boron diffused region at the edge of the front side leads to shunting of the solar cell. This can be seen in the Lock-in thermograph measurement in Figure 3. At least around seven millimetres on each side have to be cut away from the wafer to get rid of the shunting edges. For convenience in the further processing 100 x 100 mm² solar cells were diced out of the wafers.
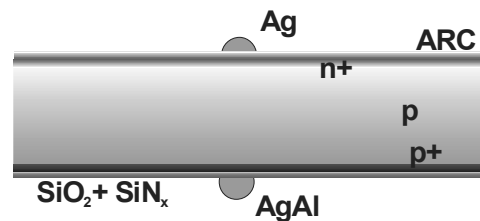
Figure 4 Schematic sketch of the boron BSF solar cell

The cross-section of the solar cell is shown schematically in Figure 4.

The advantage of process A is that the edge isolation could be done by plasma etching or with a dicing saw and therefore the lost wafer area is zero or small. But the process is not suitable for textured wafers as the surface is etched back. Further alternatives will be discussed later.

RESULTS AND DISCUSSION

Solar cell results

The measurement of the IV curve was not trivial for the cells with open rear contact as the chuck for the cells is constructed for contacting the whole area and no optical control was possible, whether all the contact needles were in contact to the busbar. This could lead to an error in the FF due to a higher series resistance In addition to this there exists no standard for measuring bifacial solar cells. One way for example is to examine the performance of bifacial solar cells in modules in field tests [4].

To measure the processed solar cells without encapsulation the IV curve was measured with the cell

illuminated on only one side at a time with one sun. Estimations of the bifacial performance were done later theoretical using PC1D. The cell measurement chuck is made of brass. Therefore the light will be reflected back into the wafer on the back side. This could be seen nicely in the spectral response (SR) measurement. The PC1D simulation calculates the light transmitted through the wafer. In the SR measurement this light is partly reflected back into the wafer, which was seen in a higher IQE than calculated for wavelength greater than 1000 nm (Figure 5).
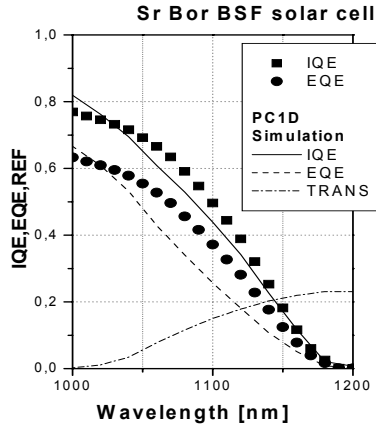

Figure 5: SR measurement

Therefore we have to assume that the J_{sc} measured in the IV measurement is also higher, due to reflections of the chuck surface. However for conventional module fabrication, if the module is intended to be illuminated from only one side, modules with a highly reflecting back side could be used to increase the module performance.

Process A	FF [%]	J_{SC} [mA/cm^2]	V_{OC} [mV]	ETA [%]
Reference cell	78.5	31.3	612	15
Boron BSF only	78.7	30.4	601	14.4
Boron BSF + SiN$_x$	73	31.3	606	13.8
Boron BSF + SiO$_2$ + SiN$_x$				
front side illumination	76.4	31.7	610	14.8
back side illumination	72.9	19.2	595	8.3

Table II: Best cell results of 300 μm thick solar cells, sized 125 x 125 mm²

The solar cell results of the untextured wafers (125 x 125 mm² p-type mc-Si wafer with a thickness of ~300 μm) are summarized in Table II. The performance of our reference cell is typical for a screen printed industrial solar cell. The high FF (> 78%) of the cell with no rear side passivation could be explained by the high carrier concentration on the back side which leads to good contact. However the open circuit voltage is reduced by 11 mV compared to the reference cell due to missing passivation. Rear side passivation with PECVD SiN$_x$ showed only little improvement, in most cases even a change to the worse. The passivation property of SiN$_x$ layers on p$^+$ surfaces is discussed in more detail in [3].

With an additional SiO$_2$ and PECVD SiN$_x$ passivation a V$_{oc}$ of 610 mV was reached on the best cell. . The cells with passivation on the back side have lower fill factors which could be explained by the not optimised firing through process.

For further improvement of the cell performance for the following investigations the wafers were isotextured. In process B only a SiO$_2$/SiN$_x$ stack was applied for the rear side passivation. Also thinner wafers with a thickness of 200 μm were used, as the process should be applicable for thin wafers. The solar cell results of the isotextured (100 x 100 mm² p-type mc-Si) wafers are summarized in Table III. The best solar cell processed so far with a boron BSF have an efficiency of η=15.6 % with J$_{SC}$=33.3 mA/cm², V$_{OC}$=613 mV and FF=76.1 %.

Process B	FF [%]	J_{SC} [mA/cm^2]	V_{OC} [mV]	ETA [%]
Boron BSF solar cell 100x100mm², 200 μm thick				
front side illumination	73.3	34.3	614	15.4
back side illumination	72.2	23.1	603	10.1
After additional Ag platting				
front side illumination	76.1	33.3	613	15.6
back side illumination	76.9	22.2	602	10.3

Table III: Solar cell results on 100 x 100 mm² wafers, 200 μm thick, best cells

The performance of the cell is limited by the low fill factor, which are due, among other reasons, to a high series resistance. Additional silver plating of the finished solar cells leads to higher FF and higher performance. However J$_{SC}$ is reduced after the plating because of the higher shading of the finger grid. After the Ag plating the fingers are not only higher, but also the width is increased.
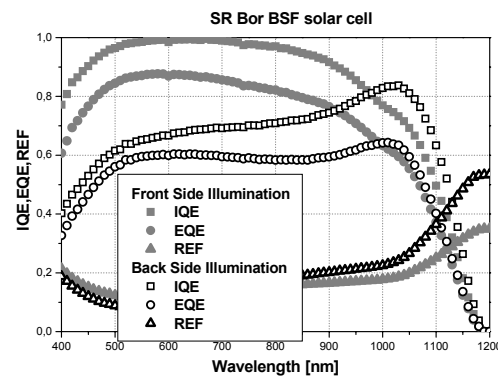

Figure 6: SR measurements under front and backside illumination.

Under back side illumination the performance (η=10.3 %, J$_{SC}$=22.2 mA/cm², V$_{OC}$=602 mV, FF=76.9 %) decreased as expected, due to the unfavourable ratio between wafer thickness and bulk lifetime (compared to FZ silicon) and a higher absorption for low wavelengths in the B-BSF. This can also be seen in the IQE (and EQE) 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 pairs generated from those photons are generated closer to the emitter, therefore the IQE is higher (Figure 6). However the intention of the B-BSF solar cell concept isn't to reach nearly the same performance on both sides, as the main purpose of the work were the replacement of the Al-BSF and the prevention of wafer bowing.

Simulation of cells illuminated on both sides

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 those parameters we simulated the cell performance with one sun illumination on the front side and different albedos on the back side. The simulated results are summarized in Table IV.

Rear side albedo [%]	Performance [Watt]	Gain [%]
0	1.54	0
10	1.65	7.1
20	1.74	13
30	1.85	20.1

Table IV: Simulation of the boron BSF solar cell performance under double sided illumination.

The simulation showed that the increase in wafer performance is expected to be even higher if thinner wafers are used (Figure 7).
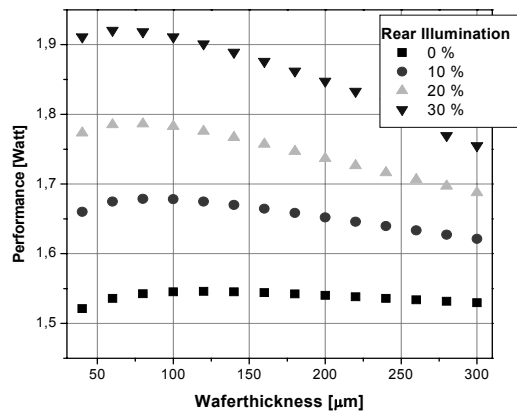

Figure 7: Simulation of the influence of the wafer thickness under varying rear side illumination on the cell performance

CONCLUSION AND OUTLOOK

We have demonstrated that solar cells with boron BSF could be realized on mc-Si. The solar cell results were comparable to industrial mc-Si solar cells, especially as the whole process was further improved. The boron diffusion has still to be optimized to get a more homogeneous boron BSF. The cell performance is mainly limited by the poor fill factors around 74 %. A better conductivity of the base grid would be favorable. This could be either done by additional plating or AgAl pastes with a higher conductivity have to be found or developed. Also the parameters for the co-firing process after screen printing are not yet optimized.

The simulation showed that the process has a potential for thinner and larger wafer as it avoids bowing. The main challenge for the isotextured process is to avoid the diffusion around the edges to the front side during the back to back diffusion. One idea to solve this is to etch off and isotexture only the front surface single sided. Maybe this problem could be avoided if spray on dopants would be used and diffusion around the edges could be avoided completely. Except for this, all the other process steps could be realized in most of the existing solar cell production lines.

In future we plan to verify the process on a larger number of wafers. These wafers should then be encapsulated into mini modules for field testing. For cells used in modules which are illuminated from only one side, it is planned to add a back surface reflector.

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