LARGE AREA BURIED CONTACT SOLAR CELLS ON MULTICRYSTALLINE SILICON WITH MECHANICAL SURFACE TEXTURISATION AND BULK PASSIVATION

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ABSTRACT: The purpose of this study was the development of a processing sequence for Buried Contact Solar Cells (BCSC) especially suitable for multicrystalline silicon (mc-Si). The proposed processing sequence includes features which are essential for high efficiencies on mc-Si solar cells: selective emitter, front surface texturisation (mechanical V-texturing), surface passivation on front (SiN_x) and rear (Al-BSF) as well as bulk passivation (gettering, hydrogen passivation). Mechanical V-texturing for the reduction of reflection losses was done with a structuring tool mounted on an automatic dicing machine. This process step enhanced the efficiency by 0.6 to 0.7% abs. Different temperatures for the P-Al co-diffusion step were investigated in order to increase the bulk diffusion length during solar cell processing due to a co-gettering action. It was shown that hydrogen passivation of bulk defects and grain boundaries leads to an improvement in cell efficiency of 0.7 to 1.7% abs., depending on the initial material quality. With the optimised processing sequence efficiencies of η=15.9% on a cell area of 23 cm^2 and η=15.6% on a cell area of 144 cm^2 on Baysix material were obtained.
Keywords: Buried Contacts – 1: texturisation – 2: gettering - 3

1. INTRODUCTION

Besides screenprinting metal containing pastes the Buried Contact Solar Cell (BCSC) concept is one of the most important metallisation techniques used for commercially fabricated crystalline Si solar cells. The BCSC was invented and patented in the late eighties at the University of New South Wales [1].

In this concept the selective emitter structure can easily be realised in a production environment. Additionally contact and series resistance as well as shadowing losses of the finger grid are low. Due to these positive attributes efficiencies between 16 and 17 % are obtained in production line by BP Solarex on Cz-Si (cell area 143 cm^2). For multicrystalline Si (mc-Si) efficiencies of 16.7 % (cell area 10.5 cm^2) [2] and 15.8 % (cell area 130 cm^2) [3] were demonstrated.

Mc-Si is a very attractive material since it can reduce the cost of Si wafers, resulting in a cost reduction of PV modules. Due to the lower material quality as compared to mono-Si caused by defects and metallic impurities the lifetime of minority charge carriers is lower in these materials. Also alkaline texturing is not as effective as for mono-Si. In order to reach a good cell performance modifications in the processing sequence are necessary. Therefore we introduced processing steps which are necessary for high efficiencies on mc-Si: Macroscopic V-texturing of the front surface for the reduction of reflection losses and process steps for bulk passivation to enhance the bulk diffusion length of minority charge carriers during solar cell processing. Bulk passivation was done by P/Al co-diffusion/gettering and hydrogen passivation. The resulting solar cell structure of a V-textured solar cell is given in Figure 1. It includes a selective emitter, LPCVD SiN_x as anti-reflection coating and surface passivation, and an Al-alloyed Back Surface Field (BSF).

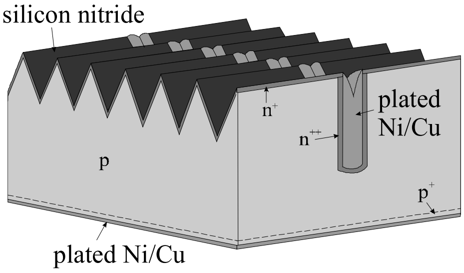

Figure 1: *Schematic diagram of an mc-Si BC solar cell with a V-groove texture. The contact grooves are perpendicular to the V-grooves. The front surface is passivated by silicon nitride, the back surface by an alloyed Al-BSF. The silicon nitride also serves as anti-reflection coating.*

2. CELL PROCESSING

The investigated process sequence is given in Figure 2. The benefit of each processing step was investigated, especially mechanical V-texturing, hydrogen passivation and P-Al co-diffusion/gettering. For hydrogen passivation and co-diffusion different process parameters were investigated.

Cast mc-Si wafers from Eurosolare (Eurosil, bulk resistivity of $\rho \approx 1.8\ \Omega$cm) and Bayer (Baysix, bulk resistivity of $\rho \approx 1\ \Omega$cm) have been investigated in this study. Cell processing started with a wafer size of 12.5x12.5 cm^2 on neighbouring wafers of each material. Two different types of front surface texturisation were used and compared to each other: Alkaline texturing (done at the production line of BP Solar España in Spain) and mechanical V-texturing. Mechanical V-texturisation was carried out with a structuring tool mounted on an automatic dicing machine (for further details see next section and [4]). The saw damage of the V-textured wafers was removed in a solution of hot NaOH. Processing was

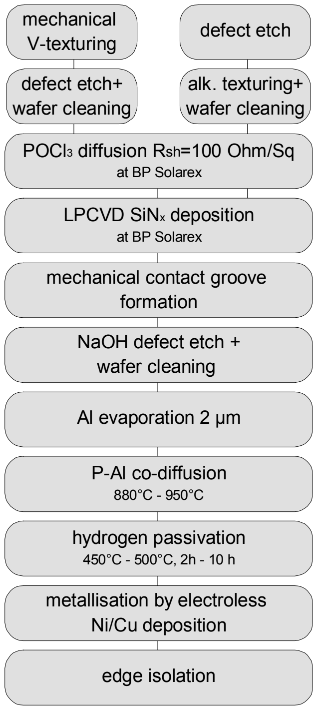

Figure 2: *Applied processing sequences for mechanically V-textured (left) and alkaline textured (right) BCSC. For co-diffusion and hydrogen passivation different parameters were used as indicated in the flow chart.*

continued at the production line of BP Solar España with a P-diffusion from a liquid $POCl_3$ source (sheet resistance R_{sh}≈100 Ω/sq) to form the lightly doped emitter. In the BCSC concept a dielectric is deposited which has to fulfil various requirements: masking during second heavy groove diffusion and during electroless metal deposition, anti-reflection coating and front surface passivation. LPCVD-(Low Pressure Chemical Vapour Deposition) SiN_x is a candidate that can fulfil these requirements also for V-textured wafers which was shown in previous experiments [5]. The wafers were cut into a size of 5x5 cm^2. The contact grooves were formed by mechanical abrasion using 15 µm thick dicing blades (further details are given in [5]). A finger spacing of 1.5 mm was chosen, the busbar consisted of several cuts with a spacing of 0.1 mm. The saw damage was removed in a solution of hot NaOH leading to a total width of the contact grooves of around 25 µm and a depth of around 35 to 45 µm. For the V-textured wafers the groove depth was measured from the bottom of the V-grooves. Then the wafers were subjected to an IMEC-clean [6]. A 2 µm thick layer of Al was deposited on the back of the wafers by electron beam evaporation. For the following P-Al co-diffusion/co-gettering step the wafers were loaded into a conventional furnace and the front grooves were heavily P-diffused from a liquid $POCl_3$ source (R_{sh}<12 Ω/sq at a diffusion temperature of 950 °C). Simultaneously the Al-BSF was formed on the rear side. As a further step for the enhancement of the minority charge carrier diffusion length L_B hydrogen passivation of bulk defects and grain boundaries was implemented into the processing sequence. In our lab, a MIRHP (Microwave Induced Remote Hydrogen Plasma)- system was set up by Spiegel et al. [7]. Cells were metallised by electroless deposition of Ni and Cu using commercial plating baths. The metals are deposited in the front grooves as well as on the Al-alloyed rear side. Processing was finished by mechanical edge isolation using a conventional dicing machine.

In the following, the processing steps which seem to be essential for high efficiency BCSCs on mc-Si are discussed in more detail and the benefits are investigated.

3. RESULTS

3.1. V-texturing

In this section V-textured cells are compared to alkaline textured ones. V-texturing is supposed to lead to an efficiency improvement due to a reduction of reflection losses and an enhancement of charge carrier collection probability [8].

Mechanical V-texturisation was carried out with a structuring tool mounted on a DISCO DAD 320 dicing machine. The length of the texturing wheel in this experiment was 25 mm and therefore five cuts were necessary to texture the whole wafer. Recently, a new fully automatic texturing machine was installed at the University of Konstanz. This machine is capable to use longer structuring tools up to a length of 75 mm and hence texturisation can be done in two cutting steps. Additionally this machine is equipped with a fully automatic handling system. The angle at the V-grooved tips was 80°. This angle is more effective for encapsulated cells but for non encapsulated cells a smaller angle would be better due to lower reflection losses.

In Figure 3 typical reflection data of an alkaline and V-textured cell with LPCVD SiN_x anti-reflection coating are shown. Both curves include finger metallisation without busbar.

In Table I the illuminated IV-parameters of a V-textured and an alkaline textured cell of Baysix material is given. Both cells were subjected to a hydrogen passivation at 450 °C for 2 h. An efficiency of η=15.9 % was measured for the V-textured Baysix cell compared to an efficiency of

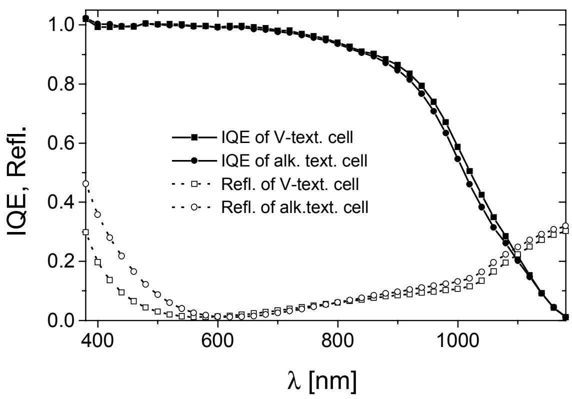

Figure 3: *Internal Quantum Efficiency IQE and reflectivity of mechanically V-textured and alkaline textured cells of neighbouring Baysix material. The minimum of the reflectivity is at about 575 nm for the V-textured cell and at about 625 nm for the alkaline textured cell.*

Table I: *Cell parameters of cells with different processing sequences on neighbouring Baysix material. Cell area 23 cm^2.*

V-text	MIR HP	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
no	no	606	32.1	76.4	14.9
no	yes	611	32.5	76.3	15.2
yes	**yes**	**608**	**34.0**	**76.7**	**15.9**

15.2 % for the alkaline textured one. This efficiency gain was mainly due to an increase in J_{sc} by 1.5 mA/cm^2 (4.4 % relative). To distinguish between the effect of reduced reflectivity and enhanced minority charge carrier collection probability measurements of the reflectivity and spectral response were performed. The spectral response was measured with bias light (intensity about 0.5 sun) and the illuminated cell area was about 9 cm^2. The measurement was performed on neighbouring wafers with the same crystal grain structure. The obtained curves of reflectivity and Internal Quantum Efficiency IQE are given in Figure 3. The higher charge carrier collection probability of the V-textured cell enhances the IQE in the long wavelength range. Since the measured IQE is only slightly higher in the long wavelength range this effect can only account for a small enhancement of the measured J_{sc}. Therefore most of the benefit in J_{sc} is due to the reduced reflectivity. The high IQE in the short wavelength range for both cells also indicate the high quality of the lightly diffused emitter and surface passivation.

3.2 Co-processing

The advantage of the P-Al co-diffusion/gettering step is twofold: first of all it reduces the number of high temperature furnace steps and therefore manufacturing costs. Additionally it can lead to an improvement of the diffusion length due to a gettering action. The benefit of co-gettering was already investigated in our lab for Eurosil material for cells with a photolithographically defined front metallisation [9]. Gettering refers to a high temperature annealing step in which lifetime reducing metallic impurities are removed from active regions of the device (i.e. the bulk) and are captured in regions with a higher solubility, where they are less harmful (i.e. emitter, Al-alloyed rear). Processing temperatures exceeding 880°C have been chosen to ensure a sufficient P-diffusion in a reasonable time. A heavy P-diffusion in the contact grooves is necessary to realise a low contact resistance and hence a good semiconductor-metal contact. Three temperatures of 880°C (R_{sh}<25 Ω/sq), 920°C (R_{sh}<15 Ω/sq) and 950°C (R_{sh}<12 Ω/sq) were investigated. Before electroless plating, the wafers were subjected to a hydrogen passivation at 450 °C for 2 h.

The main focus of this study was to obtain high bulk diffusion lengths after this final high temperature step, since they strongly affect cell efficiency. The IQE, obtained from spectral response and reflectivity measurements, as well as illuminated IV-parameters were determined for Eurosil and Baysix for the three co-diffusion temperatures. The bulk diffusion length was extracted from the IQE in the long wavelength range using the programme IQE1D [10]. The IQE in this wavelength range is mainly determined by the bulk diffusion length L_B and the back surface recombination velocity S_B, which is not known. Hence the IQE was fitted by keeping S_B at a constant value of S_B=4000 cm/s, which seems to be a reasonable value for an Al-BSF of the obtained thickness. For both materials the co-diffusion temperature of 950 °C led to the highest bulk diffusion lengths, which were determined to L_B=195 µm for Eurosil and to L_B=180 µm for Baysix. This temperature was found in previous investigations to be the optimum Al-gettering temperature for Eurosil [11]. The higher value of L_B is correlated with an improvement in J_{sc} (see Table II) for both materials. Due to a non-optimum ARC for the solar cells of Eurosil material, the higher value of L_B did not lead to a higher J_{sc} as compared to Baysix.

Table II: *Bulk diffusion lengths L_B and short circuit current density J_{sc} for Baysix and Eurosil at different co-diffusion temperatures. The best values of J_{sc} and L_B were obtained at 950°C. Due to non-optimum ARC, the higher value of L_B for Eurosil did not lead to a higher J_{sc}. Cell area 23 cm^2.*

Co-diff. Temp.	Baysix		Eurosil	
	L_B [µm]	J_{sc} [mA/cm^2]	L_B [µm]	J_{sc} [mA/cm^2]
880°C	165	32.4	165	32.2
920°C	170	32.7	175	32.3
950°C	180	33.0	195	32.5

3.3 Hydrogen passivation

In the proposed processing sequence hydrogen passivation of bulk defects and grain boundaries was carried out after all high temperature furnace steps. This was done, since hydrogen is highly mobile at elevated temperatures and an out-diffusion of hydrogen during high temperature furnace steps is very likely. In-diffusion of hydrogen takes place most probably either through the Al-BSF at the rear or through the front grooves since the LPCVD-SiN_x on the front will act as H-diffusion barrier. In this initial experiment rather high temperatures of 450°C and 500°C and a long duration (up to 10 h) were chosen since we expected that the in-diffusion of hydrogen would be difficult through the Al-alloyed BSF or front grooves.

Hydrogen passivation was investigated for Baysix with different material quality from different positions of the ingot (initial average lifetime of 500 ns and 2.7 µs, respectively, as measured with µW-PCD without surface passivation). IV-parameters of hydrogen passivated cells and unpassivated reference cells are given in Table III for the material with lower initial lifetime. For all temperatures and times an enhancement in all cell parameters was observed leading to an average gain in efficiency of about 1.7% abs. A temperature of 450°C and a duration of 2 h was sufficient, which was used in the following experiments. The results on MIRHP for Baysix with higher initial lifetime is given in Table I. In this case an enhancement in efficiency of 0.3% abs. was observed which was not as pronounced, probably due to the already higher quality of the initial material.

Table III: *Illuminated IV-parameters of cells (area 23 cm^2) with different temperatures and duration of the MIRHP process. Parameters of unpassivated cells are also given. Cells are processed according to Figure 1 with alkaline texturing. The values in italics are average values of eight solar cells .*

V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]	MIRHP
576	*29.0*	*73.8*	*12.3*	*No (av. 8 cells)*
578	29.5	75.0	12.8	No (best cell)
589	*31.7*	*74.9*	*14.0*	*450°C, 2h*
591	32.1	75.6	14.3	450°C, 2h
589	*31.9*	*73.0*	*13.7*	*450°C, 10h*
590	32.7	74.7	14.4	450°C, 10h
591	*31.7*	*74.8*	*14.0*	*500°C, 2h*
596	32.1	74.9	14.3	500°C, 2h

4. PROCESSING OF LARGE AREA SOLAR CELLS

After process optimisation on 5x5 cm^2 wafers, 12.5x12.5 cm^2 solar cells were processed. The materials used for this study were again Baysix and Eurosil, but from different deliveries. Differences in the applied processing sequence were made for the finger spacing, which was reduced to 1.4 mm to account for the longer finger lengths to the busbar. Also the IMEC-clean of the previous section after contact groove etching was replaced by an HF-dip before co-diffusion (co-diffusion 950°C, 30 min). The total cell area after edge isolation was 12x12 cm^2.

Results of illuminated IV-measurements for Baysix and Eurosil are given in Table IV for the best solar cells. Again the benefit of V-texturing is clearly visible for the Baysix material with an efficiency improvement of 0.6 %abs. as compared to an alkaline textured cell. Hydrogen passivation increased the efficiency by 0.8% abs,. with improvements in all cell parameters. Therefore the gain of hydrogen passivation and V-texturing added up to 1.4% abs. The resulting efficiency of 15.6% (independently confirmed by FhG-ISE, Freiburg, Germany) is one of the highest for BCSC on mc-Si of this area. The average efficiency of V-textured and hydrogen passivated Baysix cells in a batch of fifteen wafers was 15.4%, including several wafers with an efficiency of 15.6%. Also an efficiency of 15% was obtained for an alkaline textured cell of Eurosil material. Unfortunately, problems occurred during the processing of the V-textured Eurosil cells.

Table IV: R*esults of cells processed out of 12.5x12.5 cm^2 wafers (cell area after edge isolation 144 cm^2) for Baysix (BS) and Eurosil (ES) with different processing sequences. The result of the V-textured Baysix cell was independently confirmed by FhG-ISE, Freiburg.*

mc-Si	text.	MIR HP	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
BS	**V**	**yes**	**604**	**34.0**	**76.0**	**15.6**
BS	alk	yes	602	32.1	77.4	15.0
BS	alk	no	593	31.0	77.2	14.2
ES	alk	yes	606	32.3	76.7	15.0

5. CONCLUSION

It was shown that optimisation of a potentially low-cost process, which includes V-texturing of the front surface and bulk passivation, led to high efficiencies for large area buried contact solar cells on mc-Si. The results indicate that J_{sc} benefits from the mechanical V-texturing improving the cell efficiency by about 0.6 to 0.7% abs. P-Al co-diffusion led to a process simplification and additionally to a co-gettering action. The highest bulk diffusion length was obtained at a temperature of 950°C for Baysix (L_B=180 µm) and Eurosil (L_B=195 µm). Hydrogen passivation in a MIRHP-reactor enhanced the cell efficiency by 0.6 to 1.7% abs., depending on the initial material quality. The best efficiencies obtained in this work are 15.9% (cell area 23 cm^2) and 15.6% (cell area 144 cm^2) on Baysix material.

6. ACKNOWLEDGEMENTS

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