LARGE AREA MULTICRYSTALLINE SILICON BURIED CONTACT SOLAR CELLS WITH BULK PASSIVATION AND AN EFFICIENCY OF 17.5%

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ABSTRACT

The purpose of this study was the development of a processing sequence for buried contact solar cells on multicrystalline silicon (mc-Si). The applied process includes mechanical V-texturing for the reduction of reflection losses as well as bulk passivation by a remote hydrogen plasma source. Record high efficiencies of 17.5% (V_{oc}=628 mV, J_{sc}=36.3 mA/cm^2, FF=76.8%, independently confirmed at FhG-ISE) have been obtained on Polix mc-Si on a solar cell area of 144 cm^2. The high J_{sc} results from low shadowing and reflection losses, high bulk diffusion lengths and from a selective emitter structure. Hydrogenation was investigated for Baysix mc-Si and led to an increase in V_{oc} of 5-11 mV and in J_{sc} of 0.3-0.6 mA/cm^2, which were caused by an increase in the effective diffusion length of 40-50 µm. It has been demonstrated, that hydrogenation from a PECVD SiN_x layer applied to screen printed solar cells could be more effective than remote plasma hydrogenation in BCSCs.

INTRODUCTION

Crystalline silicon is still the major material contributing to about 85% of the annual PV shipments. In the last years multicrystalline silicon (mc-Si) has replaced mono-Si as the dominant material for silicon solar cell processing. Several investigations were made to manufacture highly efficient solar cells on mc-Si. The highest efficiency was demonstrated by Zhao et al. [1] at the University of New South Wales (UNSW) with an efficiency of 19.8% (cell area 1 cm^2). On larger substrate sizes, an efficiency of 17.2% on a cell area of 100 cm^2 was demonstrated in [2] and 17.1% on 225 cm^2 in [3].

The Buried Contact Solar Cell (BCSC) technology was invented and patented at the UNSW in the late eighties [4] as a low cost approach for high efficiency solar cells. Currently, BCSCs are fabricated by BP Solar with an annual output of 11 MWp in 2001 using Cz-Si. Efficiencies in production range between 16 and 17%, whereas efficiencies up to 18% have been demonstrated in pilot-line production recently [5].

The objective of this work was to combine the advantages of the BCSC technology with the lower cost material of mc-Si to manufacture highly efficient solar

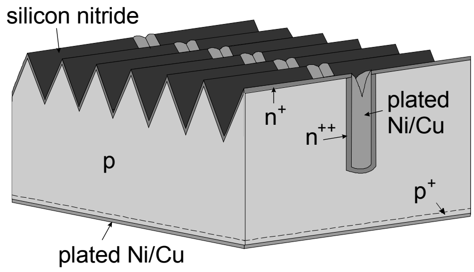

Fig. 1: Schematic illustration of a mechanically V-textured BCSC with selective emitter. The front surface is coated by SiN_x as single layer ARC, the contact grooves are perpendicular to the V-texture and metallisation is performed by electroless plating of Ni/Cu.

cells. Due to the presence of defects, the material quality of mc-Si is lower than for mono-Si. Therefore bulk passivation by hydrogenation was investigated by remote hydrogen plasma passivation. For the reduction of reflection losses, macroscopic mechanical V-texturing was included in the processing sequence.

DEVICE DESIGN

The device design of a mechanically V-textured BCSC is illustrated in Fig. 1. The V-grooves in this study have an angle at the V-tips of about 60 ° and the depth of the V-grooves is around 70-80 µm. The front surface is coated by Low Pressure CVD silicon nitride, which serves as single layer ARC and for surface passivation. The contact grooves are perpendicular to the V-texture leading to a reduced series resistance in the emitter. Rear surface passivation is accomplished by a screen printed Al-BSF. The BCSCs are metallized by electroless plating of Ni and Cu.

PROCESS DESCRIPTION

Processing started with mechanical V-texturing followed by saw damage removal. Emitter diffusion (R_{sheet}=100 Ω/sqr) was carried out in an open-tube quartz furnace using a liquid $POCl_3$ source followed by the deposition of SiN_x in a Low Pressure CVD system. The emitter saturation current density J_{01e} is about

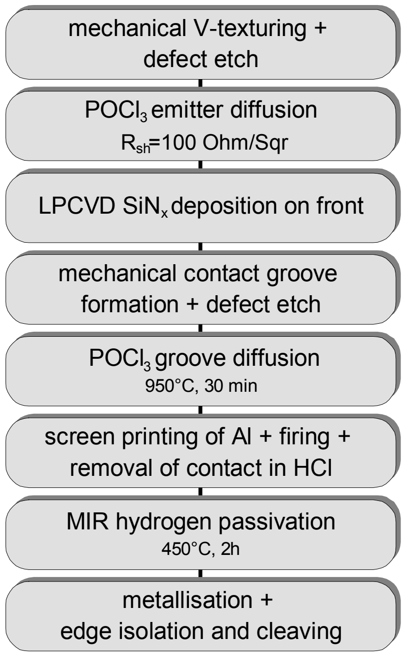

Fig. 2: Process flow for the fabrication of mechanically V-textured buried contact solar cells including remote hydrogen plasma passivation in a MIRHP-reactor.

$1.5x10^{-13}$ A/cm^2 after groove diffusion as determined by QSSPC-measurements on test samples. The contact grooves were formed by mechanical abrasion using 15 µm wide dicing blades mounted on a conventional dicing machine. The groove depth was 40 µm measured from the bottom of the V-grooves. The saw damage was removed in a hot solution of NaOH. Heavy $POCl_3$-diffusion within the contact grooves was performed at 950 °C for 30 min (R_{sheet}≈10 Ω/sqr). In the next step Al is screen printed on the rear and fired for the formation of the Al-BSF. The Al rear contact was removed in HCl exposing the p^+-doped BSF. Hydrogen passivation was carried out by remote hydrogen plasma passivation using a Microwave Induced Remote Hydrogen Plasma (MIRHP)-reactor. The passivation was carried out at 450 °C for 120 min, which was determined as optimum process temperature in a previous investigation [6].

In BCSC processing, metallization is carried out by electroless plating of Ni and Cu. Ni-plating on the p^+-layer on the rear could be initiated with the commercial plating baths used in this study. However, the adhesion of the Ni-layer was very poor without Ni-sintering. Currently, Ni-sintering cannot be performed for large substrate sizes at the University of Konstanz. Therefore a thin layer of Al was deposited by electron beam evaporation prior to plating, which led to improved adhesion. Edge isolation was performed by mechanical abrasion and cleaving.

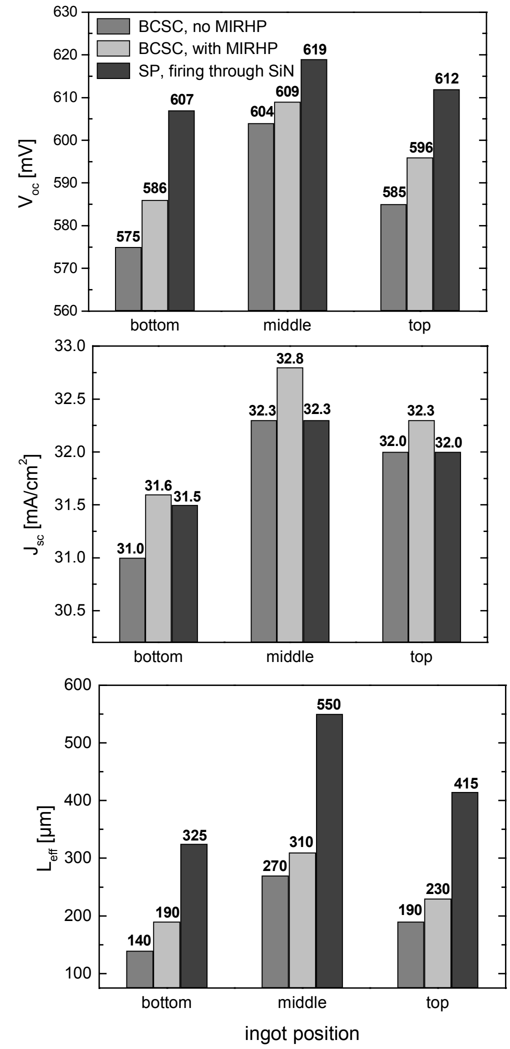

Fig. 3: V_{oc}, J_{sc} and effective diffusion length L_{eff} for BCSCs with and without MIR hydrogen passivation as well as screen printed solar cells with hydrogenation by "firing-through" PECVD SiN_x. The wafers were selected from different positions within the same brick.

HYDROGEN PASSIVATION

We have already applied MIR hydrogen passivation for bulk passivation in BCSC processing in a previous investigation. Efficiency gains up to 1.7 % abs. were obtained on Baysix mc-Si with a low initial lifetime [7] demonstrating the effectiveness of this technique. The experiment in this work was conducted to compare MIR hydrogen passivation with hydrogenation from PECVD SiN_x layers. Since rather lengthy high temperature process steps are required subsequent to the dielectric layer deposition in the applied BCSC process, an effective hydrogenation from SiN_x layers is rather doubtful due to the release of hydrogen from the wafer. Therefore hydrogen passivation from PECVD SiN_x layers was performed within the "firing-through" process of screen printed solar cells.

In the experiment Baysix mc-Si wafers with a size of 12.5x12.5 cm^2 (specific resistivity ρ=1.0-1.4 Ωcm, wafer thickness w=310 µm) were processed from the bottom, middle and top region from the same brick. Three different processes were applied without mechanical V-texturing. The first one was BCSC fabricated according to Fig. 2 without MIR hydrogen passivation, the second one was BCSC with MIR hydrogen passivation and the third screen printed solar cells with hydrogenation by the firing-through PECVD SiN_x process (homogenous emitter R_{sheet}=35 Ω/sqr, co-firing of contacts).

V_{oc} and J_{sc} of the three processes are illustrated in Fig. 4. From the same cells, the spectral response and reflectivity was measured scanning the complete solar cell with the set-up described in [8]. From the IQE, the effective diffusion length L_{eff} was extracted [8], which is also illustrated in Fig. 4. The following can be concluded:

In the processing of BCSCs MIR hydrogen passivation leads to improvements in the V_{oc} in the range of 5-11 mV and J_{sc} in the range of 0.3-0.6 mA/cm^2 depending on the wafer position within the brick. The highest gains were achieved for wafers from the top region of the brick which had the lowest J_{sc} and V_{oc} without passivation. Hence, hydrogen passivation will lead to a narrowing of the efficiency distribution. L_{eff} increased by 40-50 µm due to MIR hydrogenation. For the BCSCs from the middle of the brick, L_{eff} reached a good value of 310 µm which corresponds to the wafer thickness.

However, hydrogen passivation within the firing-through process in screen printed solar cells was more effective, giving an additional gain in V_{oc} in the range of 10-21 mV. The corresponding L_{eff} was larger than the cell thickness, independent of the wafer position within the brick. For a comparison of J_{sc} one has to consider the differences in the shading losses (2.2 mA/cm^2 for BCSC as compared to 3.9 mA/cm^2 for screen printed solar cells) and in the emitter losses [8] (0.5 mA/cm^2 for BCSCs and 1.3 mA/cm^2 for screen printed cells).

For a further analysis local LBIC and reflectivity measurements were performed from solar cells of the three different processes taking the wafers from the bottom region. The results are illustrated as a histogram of the IQE at λ=980 nm in Fig. 4. MIR hydrogen passivation led to a reduction of the "poor" grains with an IQE below 0.5. However, by hydrogenation with the "firing-through" process almost all "poor" grains were well passivated with regions of an IQE below 0.5 almost completely disappearing. Hence, the regions with a higher defect density are well passivated in the "firing-through" process but only to a smaller extent by MIR hydrogen passivation as compared to cells without hydrogen passivation.

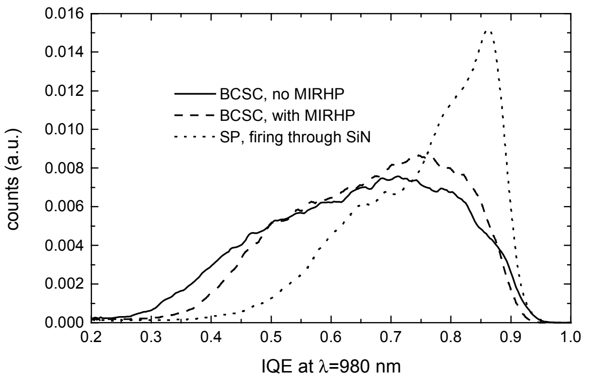

Fig. 4: Histogram of the IQE at λ=980 nm as determined from spatially resolved LBIC and reflectivity measurements for three different processes.

The main difference between the MIR hydrogen passivation and the firing through process is the region from which hydrogen diffuses into the wafer. In the firing-through process hydrogen is released from the SiN_x layer on the front side. If the MIRHP-technique is applied to BCSCs the front surface is covered by LPCVD-SiN_x which will act as a diffusion barrier at the applied process temperatures. Therefore most of the hydrogen will be incorporated from the rear. In this case, hydrogen has to diffuse through the complete wafer in order to passivate defects close to the front surface. This could explain the fact that MIR hydrogen plasma passivation was not as effective as hydrogenation from PECVD SiN_x in screen printed solar cells. Further investigation will be performed concerning the optimisation of the MIRHP process for BCSC processing and the implementation of hydrogenation from PECVD SiN_x layers in a modified process.

HIGH EFFICIENCY SOLAR CELLS

High efficiency solar cell processing was performed on Baysix and Polix (ρ=0.5 Ωcm, w=350, 12.5x12.5 cm^2) mc-Si. For Baysix, the same material was taken as in the previous section from the middle of the ingot. Processing started with mechanical V-texturing of the front surface using the single blade technique followed by saw damage removal. Further processing was performed according to the processing sequence given in Fig. 2 including MIR hydrogen passivation at 450 °C for 120 min. The solar cell area after edge isolation was 144 cm^2 for Polix and only 119 cm^2 for Baysix due to wafer breakage. The results of the illuminated IV-measurements are given in Tab. I.

Tab. I: Illuminated IV-parameters of mechanically V-textured solar cells on Polix (144 cm^2) and Baysix (119 cm^2) mc-Si. The cells are coated with a single layer ARC of LPCVD SiN_x. The results of Polix 1 was indepently confirmed at FhG-ISE callab, Germany.

	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
Polix 1	628	36.3	76.8	17.5
Polix 2	626	36.2	76.9	17.4
Baysix 1	603	36.0	76.1	16.5

For Polix 1, an independently confirmed efficiency of 17.5% was attained. The corresponding illuminated IV-characteristic is shown in Fig. 5. This is, to the knowledge of the authors, the highest efficiency reported to date for mc-Si solar cells with cell areas exceeding

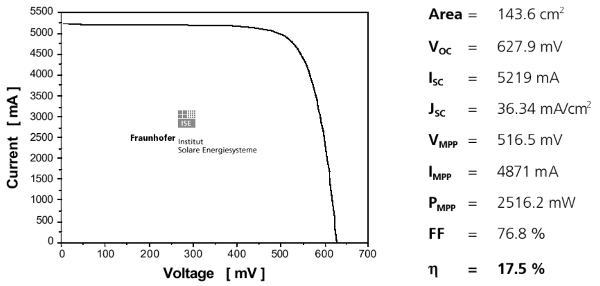

Fig. 5.: Illuminated IV-characteristics of Polix 1 as measured at FhG-ISE callab.

100 cm^2. The second best solar cell on Polix also led to a remarkable efficiency of 17.4%. For Baysix, an efficiency of 16.5% was obtained. The high V_{oc} close to 630 mV follows from the high base doping in conjunction with high effective diffusion lengths. The FFs for all three cells were in the range between 76 and 77%. These rather moderate values were due to a low shunt resistance for Polix and due to a high J_{02} for Baysix. A detailed discussion will be published elsewhere.

For Polix 1, spectral response and reflectivity measurements were performed and the results are illustrated in Fig. 6. The shadowing losses of the front metallization are about 4%, the weighted average reflectivity on the unmetallized part about 3.9%. L_{eff} determined on planar reference cells exceeds the cell thickness leading to a good red response. The IQE-mapping at λ=980 nm obtained from spatially resolved LBIC and reflectivity measurements in Fig. 7 shows a reasonable homogeneity of the material with only a small amount of regions with low IQE.

CONCLUSIONS

In this work, high efficiencies have been obtained on mechanically V-textured BCSCs on mc-Si. A record efficiency of 17.5% on a cell area of 144 cm^2 has been achieved on Polix with a high V_{oc} of 628 mV and very good J_{sc} exceeding 36 mA/cm^2. The good J_{sc} follows from low shadowing losses due to the buried contact metallization, low reflection losses due to mechanical V-texturing and from the selective emitter structure.

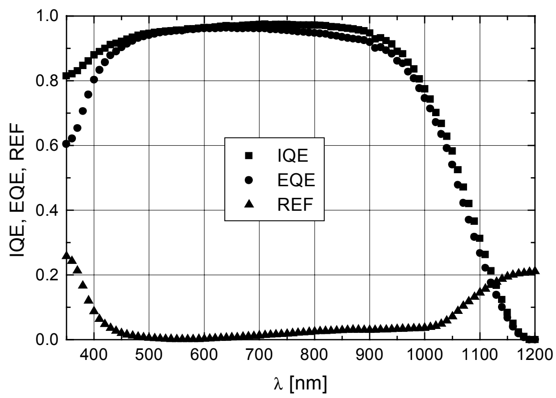

Fig. 6: Internal Quantum Efficiency IQE, External Quantum Efficiency EQE and reflectivity of Polix 1.

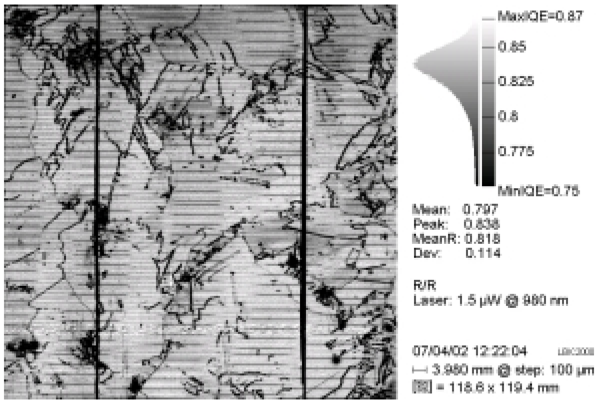

Fig. 7: IQE-mapping of Polix 1 at λ=980 nm as determined from local LBIC and reflectivity measurements.

Remote hydrogen plasma passivation in a MIRHP-reactor improved the bulk diffusion length in the range of 40-50 µm on Baysix mc-Si leading to an increase in V_{oc} of 5-11 mV and J_{sc} of 0.3-0.6 mA/cm^2. However, the hydrogenation from PECVD SiN_x layers in the "firing-through" process of screen printed solar cells led to superior bulk passivation.

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