SCREEN PRINTED c-Si THIN FILM SOLAR CELLS ON INSULATING SUBSTRATES

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ABSTRACT

A simple industrially feasible process scheme, the screen printed Buried Base Contact (BBC) concept, was applied to Cz-Si wafers as well as to c-Si thin films (CSiTF) on insulating substrates. Cells with interdigitated front grid design on untextured Cz-Si wafers show fill factors up to 73 % and a maximum efficiency of 11.5 %. The application of the process to CSiTF on insulating substrates yields in an V_{oc} of 509 mV. Despite series resistance values below 1 Ωcm^2 the cells are severely limited by a low fill factor as well as an inactive cell area of 27 % including grid shading and unpassivated base area. In particular, rough surfaces of the CSiTF's prevent good printing alignment, resulting in shunt resistances below 50 Ωcm^2. These first results lead to a 3 % efficiency of CSiTF cells. Thus, the challenge for future oneside contacting schemes will be the modification of the BBC concept regarding reduced alignment requirements.

1. INTRODUCTION

The need for cost reduction in production forces the PV industry to develop more cost effective solar cell and production schemes. One promising concept to reduce material costs is the crystalline silicon thin film (CSiTF) solar cell [1]. In contrast to conventional solar cells, the base of a CSiTF solar cell can be contacted from the rear side only if the substrate is conducting. Otherwise, both contact grids have to be applied on the front side. Best cells processed so far on CSiTF cells on ceramic substrates reached maximum efficiencies of 10.8 % on insulating substrates and 11.0 % on conducting substrates [2] with a laboratory-type solar cell process on small areas. Besides material development, current R&D work has a focus on implementation of industrial process schemes, as the BBC concept [3].

The aim of this work is the application of the screen printed BBC concept, an industrially feasible process scheme for front side contacted crystalline silicon thin film solar cells on insulating substrates, which is suitable for series interconnection. The concept bases on an interdigitated emitter and base grid and has been developed in our previous works [3], [4] and further adapted within this work. BBC cells made on Cz wafers are compared with BBC solar cells on CSiTF on insulating substrates as well as reference cells on the same CSiTF material. With additional characterization the potential of this approach is evaluated.

2. EXPERIMENTAL

2.1 Cell fabrication steps

Reference cells were fabricated on *p*-type Cz-Si wafers with a bulk resistivity of ~ 1 Ωcm. Wafer thickness before damage etching was about 330 µm. The main process steps are shown in Fig. 1. After saw damage removal and cleaning the formation of the *n*-type emitter lead to a sheet resistance of ~ 35 Ω/sq. The diffusion was carried out in an infrared heated conveyor belt furnace. As an etching mask for RIE a screen printable etch resist has been used. The width of the designated base regions was fixed at 350 µm, bearing in mind the limitations of the screen printed contact fingers. Approximately 3 µm of the silicon surface including the emitter layer were removed by low-damage RIE in a SF_6-plasma. Afterwards the etch resist was stripped off using acetone.

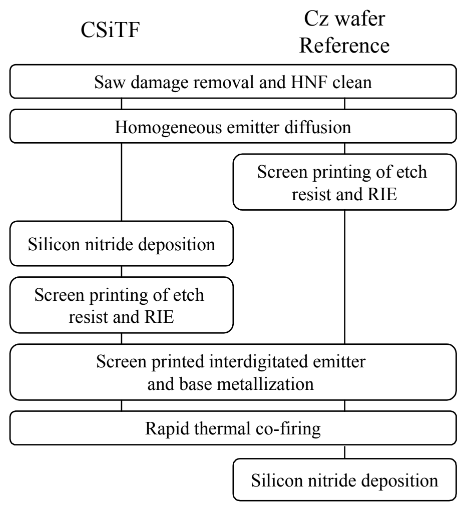

Fig. 1 Process scheme of the BBC concept applied within this work to CSiTF substrates and Cz wafer, as reference.

The passivating SiN_x layer was deposited by PECVD in a conventional parallel plate direct plasma reactor [5] either prior to metallization allowing a firing through process or after contact formation. The base contacts were screen printed prior to the emitter grid due to enhanced alignment requirements for base regions and base contact grid. For the base contacts we used a commercially available aluminium paste in case of the non-fired through cells and an aluminium-silver paste in case of the cells facing the firing through process. Screen printing of the interdigitated grid has been performed using a screen printer with an optical alignment system. The alignment was carried out by adjustment marks or edge detection, respectively. For the CSiTF solar cells a thermally grown SiO_2 layer on *p*-type Cz silicon (bulk resistivity ~ 1 Ωcm) has been used as insulating substrate. Thereon a *p*-type seeding layer has been deposited. After recrystallization by Zone-Melting Recrystallization (ZMR) the active silicon layer was grown by epitaxy (p^+-BSF 10 µm, N_A~1×10^{17} cm^{-3} and *p*-type layer 20 µm). The process scheme of Fig. 1 remained unchanged unless the silicon nitride deposition. An image of a processed solar cell is shown in Fig. 2.

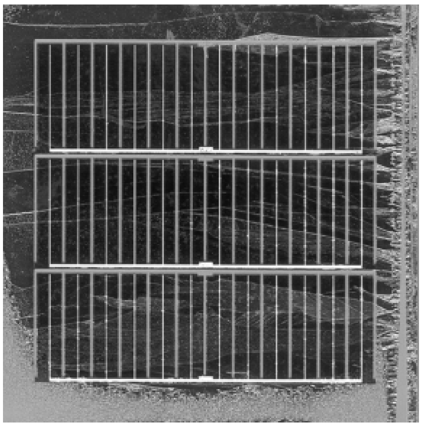

Fig. 2 Processed solar cell on a CSiTF substrate. Subcells have a size of 1.3 x 4 cm².

3. Results and discussion

3.1 Definition of base regions on CSiTF

As a result of the rough CSiTF surfaces, severe problems in the exact lateral definition of the emitter structure occur. As the most critical surface structures regarding aligned screen printing, we identified the steps at grain boundaries. They are caused by the different growth rates in Si epitaxy, which depend on the crystallographic orientation of neighbouring grains.

In addition, trench etching for the base grid by means of reactive ion etching (RIE) is noticeably inhomogeneous on CSiTF substrates as shown in Fig. 3. A dependence of the etching rate on the grain structure of the epitaxially grown silicon layer has been observed, which enhances the surface roughness in the designated base areas.

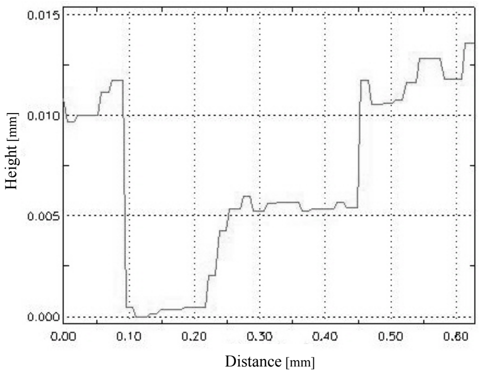

Fig. 3 Base groove etched by RIE on a CSiTF substrate.

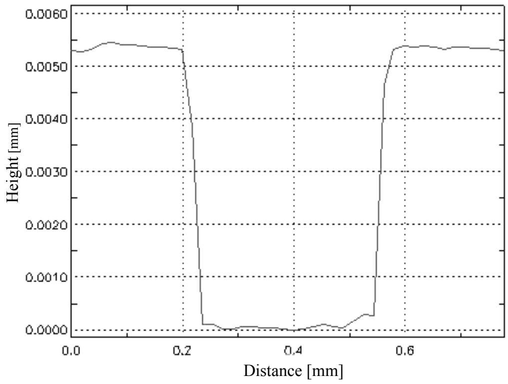

Fig. 4 Base groove etched by RIE on Cz-Si.

In comparison, trenches etched on Cz silicon wafers are remarkable reproducible and homogeneous in terms of the trench width and depth (see Fig. 4). As a result of these negative effects on CSiTF substrates, the BBC cells suffer from increasing leakage currents due to slumping of the aluminium paste as well as the etch resist. Furthermore, screen printing of the emitter grid leads also to broadened contact fingers especially at grain boundaries of the epitaxially grown silicon layer (see Fig. 5).

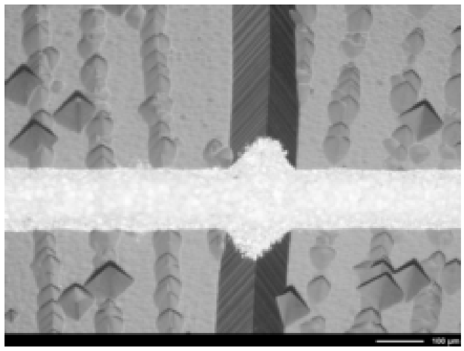

Fig. 5 Emitter grid finger screen printed across a grain boundary on a CSiTF substrate.

In consequence, the base grooves had to be further broadened to 400 µm in case of CSiTF substrates. As a result of these difficulties, the application of the BBC concept to CSiTF substrates still requires larger efforts regarding a larger tolerance to alignment variations.

3.2 Solar cell results

Results of the best cells made with and without firing through process are shown in Table 1 for the different materials used. A double layer antireflection coating has been applied after the metallization for the BBC cell on Cz wafer silicon with non-firing through process. Concerning V_{oc} values of the cells on Cz wafer silicon, the gap between a cell with interdigitated grid and a standard cell can be decreased by applying a firing through process using a well passivating SiN_x layer, as shown in Table 1. However, V_{oc} is still lowered by ~ 10mV.

Without firing through, a fill factor of 73.2 % is obtained, resulting in a cell efficiency of 11.5 %. By comparing the dark with the light IV-characteristics series resistance values of 1.6 Ωcm^2 results. The shunt resistance values increase up to values of $2 \cdot 10^4$ Ωcm^2 for a base region width of 360 µm. Short circuit current densities of 26.5 mA/cm² have been measured for these interdigitated grid cells. This value reflects the inactive cell area of 20 % due to surface recombination in the base regions surrounding the base contacts as well as shadowing of the base grid. LBIC-mappings confirm the very low current collection in this region (see Fig. 6, left).

Table 1. Results of best solar cells with and without firing through (FT) process.

	Area [cm^2]	V_{oc} [mV]	j_{sc} [mA/cm²]	FF [%]	η [%]
BBC, Cz no FT	5.3	596	26.5	73.2	11.5
BBC, Cz FT	5.3	603	28.9	53.5	9.3
BBC, CSiTF	5.3	509	15.3	39.1	3.0
CSiTF Ref.	1.0	595	22.6	76.0	10.2
Standard, Cz, FT	23.04	613	30.2	77.5	14.3

Results are different implementing a firing through process for the base metallization with an AgAl paste. The used paste is characterized by a higher glass frit content to punch through the SiN_x layer. However, the cells reveal a R_s of 6 Ωcm². This value can be explained by an increased contact resistance of the base contact to the underlying Si material for firing through the passivating SiN_x layer, and indicates a limited firing through ability of the paste. The short circuit current increases significantly compared to the non-firing through process, also confirmed by the LBIC mapping of such a cell (see Fig. 6, right), where the unpassivated open base area is obviously reduced. However, the cells performance is limited by a very low fill factor. These values cannot be explained by shunting problems due to a bad printing alignment or series resistance problems, only. The fill factor is badly influenced by humps of the dark IV characteristic in the region of the maximum power point (0.4-0.55 V) due to the formation of inversion channels beneath the SiN_x layer (see Fig. 7) [6].

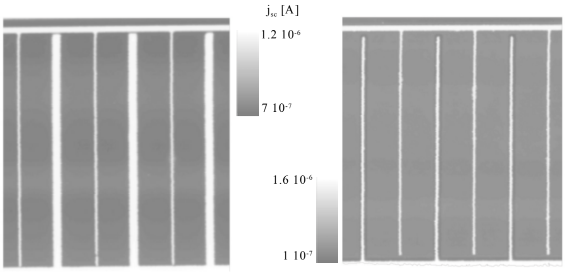

Fig. 6 LBIC mappings of cells without firing through (left) and with firing through (right) process (measured at wavelength of 790 nm).

This shows that the conventional firing through process cannot be transferred to front side contacted interdigitated grid cells without modifications of the concept. On approach is to exchange the SiN_x deposition step with the RIE etching of the designated base regions.

In case of the CSiTF substrates, as reference a solar cell was prepared using photolithography for the definition of the base grooves and the metallization. An efficiency of 10.2 % could be reached showing the potential of the prepared crystalline silicon thin films.

The BBC CSiTF solar cell reaches an efficiency of 3 % and is also dominated by a low fill factor caused by severe shunts as shown in Fig. 7. The j_{sc} values of the BBC cell on Cz material reflect the furthermore increased inactive cell area due to grid shading and open base region. The enlarged base region on CSiTF substrates led to a further decrease of j_{sc} and consequently $V_{oc.}$ The total inactive cell area for this cells is 27%, including 17 % grid shading and 10 % open, unpassivated base area. An LBIC-mapping confirms the very low current collection in the base region (Fig. 9). Also the dispersed grain structure of the CSiTF substrate leads to a significant current distribution over the cell area (Fig. 9). Therefore the overall current density of the BBC CSiTF solar cell is lowered compared to the much smaller CSiTF reference cell.

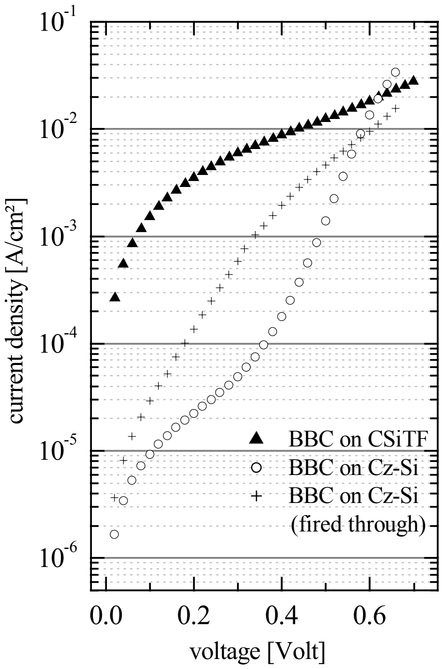

Fig. 7 Comparison of Dark current characteristics of solar cells on Cz wafer silicon and CSiTF.

Fig. 8 shows the internal quantum efficiencies for BBC cells on CSiTF substrate and Cz wafer silicon as well as for the CSiTF reference. The higher photon yield of the CSiTF reference cell (laboratory type solar cell process with photo-lithographical front grid) for small wavelength originates from a higher emitter sheet resistance (~ 70 Ω/sq.) compared to the BBC solar cells with R_{sh} of 35 Ω/sq. (see Fig. 8).

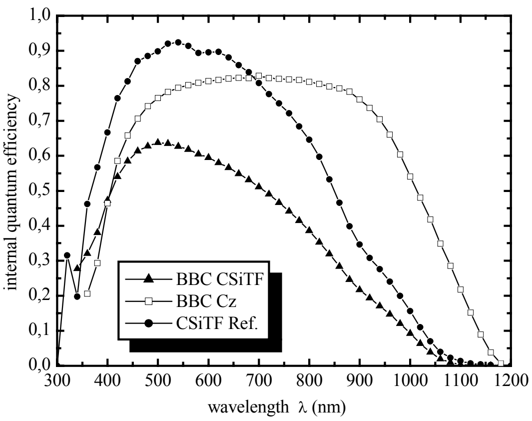

Fig. 8 Comparison of internal quantum efficiency data of BBC cells on CSiTF and Cz material.

Responsible for the overall lower level of the IQE of both BBC cells are the bulk as well as surface properties. In comparison with the BBC cell on Cz material, the base regions of the BBC CSiTF solar cell are fully unpassivated, and surface recombination lowers the IQE for all wavelengths considerably. In addition, the thin Si layer leads to the typically reduced response in the infrared. For small wavelength below 450 nm the BBC CSiTF cell has a slightly higher IQE than the BBC cell on Cz wafer silicon. This is a result of the SiN_x passivated emitter regions and the firing through of the emitter contact grid leading to a significant reduction of recombination currents at the front surface.

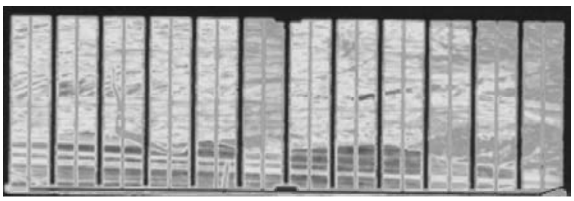

Fig. 9 LBIC of BBC cell on a CSiTF substrate (measured at a wavelength of 790 nm).

4. CONCLUSION

An industrially feasible interdigitated emitter and base front side metallization scheme for CSiTF cells with series interconnection based on the BBC concept is presented. On Cz silicon wafers efficiencies up to 11.5 % could be achieved, without firing through a SiN_x layer, and applying a double layer antireflection coating after the metallization step. Transferring this concept to crystalline silicon thin film substrates results in a cell efficiency of 3 %. The efficiency is badly limited by overall shading losses of more than 25 % due to the two contact grids and the wide open base region. More significantly, problems arise due to steps at the surface of the epitaxially grown thin silicon layer resulting in shunts due to slumping of the aluminium paste and etch resist.

Implementing a firing through process leads to significant fill factor losses due to the inability of the screen printed paste to punch through the passivating SiN_x layer. For this reason a passivation of the base regions on the solar cells front side could not be achieved yet.

For process stability self aligned process schemes or processes with significantly reduced alignment requirements have to be considered to overcome the difficulties linked to screen-printed interdigitated base contact grids in one side contacted solar cell process schemes.

5. ACKNOWLEDGEMENTS

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