INDUSTRIAL SCREEN PRINTED n-TYPE SILICON SOLAR CELLS WITH FRONT BORON EMITTER AND EFFICIENCIES EXCEEDING 17%

T. Buck[1], R. Kopecek[1], J. Libal[1], A. Herguth[1], K. Peter[1], I. Röver[2], K. Wambach[2], B. Geerligs[3]

[1] University of Konstanz, Faculty of Sciences, Department of Physics, Jakob-Burckhardt-Str. 29, 78464 Konstanz, Germany
Tel: (+49)07531-88-3048, e-mail: **Thomas.Buck@uni-konstanz.de**
[2] Deutsche Solar AG, Alfred-Lange Str. 18, D-09599 Freiberg/Sachsen, Germany
[3] Energy research Centre of the Netherlands–ECN, Westerduinweg 3, NL-1755 ZG Petten, The Netherlands

ABSTRACT: In this article we present large area solar cells on n-type silicon. The emitter of the solar cells is formed by a boron doped layer at the front side of the solar cells and was established by tube furnace BBr_3-diffusion. A transparent phosphorous doped back surface field leads to a bifacial structure of the solar cells. With respect to the higher thermal sensitivity of mc-Si all relevant process steps were optimized at moderate temperatures leading to solar cells with efficiencies of 14.7% on mc-Si, 15.9% on FZ-Si and 17.1% on Cz-Si substrates. As a result of the bifacial topology new features of the solar cells arise and a significant increase of the power output can be reported. Based on these solar cells an innovative way of module interconnection is possible, discussed in a separate paper at this conference by Kopecek et al. [1].
Keywords: n-type, boron emitter, bifacial

1 INTRODUCTION

There is a rising interest in n-type silicon for solar cell applications: besides being an additional silicon feedstock source for the PV production it attracted attention by a higher tolerance to common impurities as Fe or O. The resulting higher diffusion lengths compared to p-type combined with the reduced degradation due to the lack of B-O complexes qualifies the n-type material [2].

During the last years several successful n-type solar cell concepts (HIT, Sunpower, Phostop) for industrial application have been reported but except for the Phostop approach they are rather applicable to mono-crystalline material. In this paper we present a developed process suitable for both multi- and monocrystalline n-type Si substrates. The solar cells have a boron emitter and are manufactured on base of industrial relevant techniques such as open tube furnace diffusion and screen printed thick film metallization.

2 SOLAR CELL PROCESS

Related to the choice for a front side emitter geometry most of the preliminary development work had to be done at the face of the solar cell: while the structure at the rear side follows the style of the current industrial dominant composition of p-type solar cell front surfaces, there is no such correspondence for the front side of our n-type solar cell. Passivation and metallization of the boron doped p^+ layer had to be investigated as well as the most favorable progression of the two different diffusions and their screening of one side respectively during the high temperature steps.

2.1 Passivation

A good passivation of p^+ Si surfaces is one of the central issues to be dealt with for a good performance of n-type solar cells with a B-emitter on the front side. Passivation experiments showed that SiN_x does not work on highly p-doped surfaces and even shows a slight depassivating behaviour [3]. However, SiO_2 is known for its excellent passivating properties on both p^+ and n^+. If the oxide layer is thick enough, it even screens the
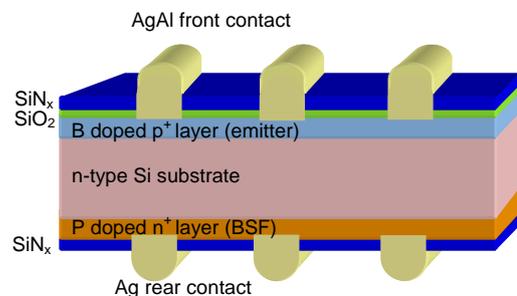

Figure 1: Cross-section of the front B emitter n-type Si solar cell.

negative effect of SiN_x and offers the possibility of a SiO_2/SiN_x stack system that additionally benefits from good hydrogen passivation. First results with SiC_x as surface passivating layer are very promising and are discussed by Petres et al. [4].

2.2 High temperature steps

At the moment, a thermal oxide is indispensable for a sufficient passivation of the boron front emitter, there is a third high temperature step necessary during the processing in addition to open tube furnace diffusions of the emitter and the BSF.

Effective lifetime measurements of the minority charge carriers after different process sequels have shown that it is advantageous to start the process sequence with the boron diffusion. Because of its lower diffusivity boron diffusion requires longer times or higher temperatures than phosphorous to yield the same sheet resistance. Both possibilities mean a higher thermal impact and especially the second is detrimental to mc-Si. To avoid this problem, our boron emitter diffusion was done at moderate temperature of about 930°C. Effective lifetime measurements of the bulk before and after the BBr_3 open-tube furnace diffusion confirmed constant values averaged over the entire wafer and thus suggest no thermal degradation of the mc-Si.

Due to its excellent gettering effect the process was finalized with the $POCl_3$ diffusion and the oxidation with its detrimental effect on the bulk lifetime was performed as the second high temperature step.
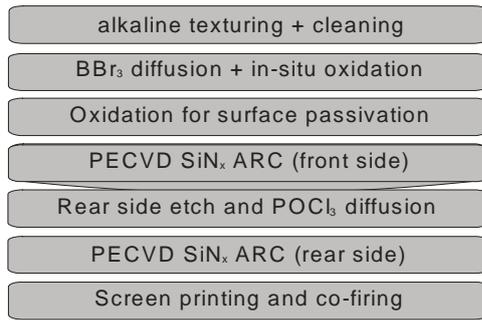
Figure 2: Flowchart of the FZ solar cell process

2.3 Metallisation

The most suitable solution for the front side metallisation was the screen printing of commercial available Ag/Al paste. Though its good contact resistance and print handling it suffers from a more than doubled line resistivity compared to Ag paste. Silver plating or double print of an Ag/Al and Ag stack reduced the series resistance but stayed still above the value for pure Ag paste.

3   RESULTS

As shown in Figure 2, the chosen process sequence started with an alkaline texturing and wafer cleaning. Followed by the boron diffusion with a sheet resistance of 60 Ω/sq , a thermal oxide of 20 nm is grown on the emitter and gets screened by 70nm PECVD SiN$_x$ before the rear side phosphorous tube furnace diffusion (45 Ω/sq). The process steps are completed by the rear surface SiN$_x$ (70 nm) passivation, Ag metallization of the rear and an Ag/Al screen printing of the front side. The cofiring of the metals was done in a belt furnace. The process was applied to different substrates leading to a 17.1% Cz-Si, 15.9% Fz and 14.7% mc-Si device respectively (Table I).

Table I: Parameters of best n-type solar cells with front B-emitter on Cz-, FZ and mc-Si substrate (all with an area of about 144cm^2)

material	d [μm]	res. [Ωcm]	FF [%]	J$_{sc}$ [mA/cm^2]	V$_{oc}$ [mV]	η [%]
Cz-Si	150	2	76	36.3	620	**17.1**
FZ-Si	200	4	72.7	36.1	605	**15.9**
mc-Si	230	1	74	32.8	602	**14.7**

As all materials differ in thickness and resistivity, a real comparison of the cells is difficult. They all have in common a weak FF originating from the high line resistivity of the Ag/Al paste front metallisation. Ag plating of the Cz and mc-Si samples improved their fill factors of about 2% to the quoted values in table I. The rather poor V$_{oc}$ is a matter of the weak back surface field. Compared to a 8 μm closed Al BSF, the phosphorous doped 45 Ω/sq BSF reflects charge carriers much less effective. In the next section it will be shown, that this disadvantage can be easily compensated by the gain due to the bifacial characteristic of the solar cells.
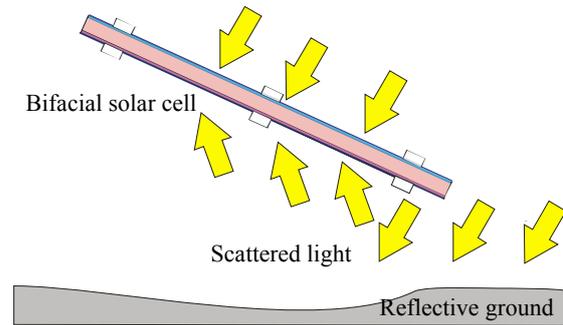
3.1 Bifacial solar cells

Figure 3: Bifacial solar cell principle: Light scattered from a reflective ground invades the solar cell from the rear side and improves the power output

The solar cell shown in figure 1 with an open rear contact and transparent BSF has a bifacial structure. That means, as depicted in figure 3, light injection is possible from both, front and rear side of the device. Although the efficiency of the solar cell is not improved, scattered and reflected light enters additionally the solar cell from the rear and enhances the power. Outdoor tests with bifacial glass / glass modules have shown, that a growth of up to 30% averaged over a whole day is feasible [1, 4]. To characterize bifacial solar cells, IV measurements are done from both sides of the cell. Table II shows the best result on a FZ-Si wafer.

Table II: Parameters of best bifacial n-type FZ solar cell (A=144cm^2) for front and rear illumination

illumination	d [μm]	FF [%]	J$_{sc}$ [mA/cm^2]	V$_{oc}$ [mV]	η [%]
front	200	72.7	36.1	605	**15.9**
rear	200	74.4	30	601	**13.4**

The solar cell features an excellent rear side performance. For the rear side injected light, the junction of the solar cell is situated on the opposite side of the wafer. The holes generated in the short
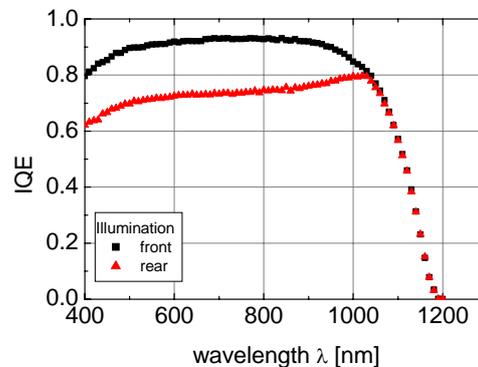

Figure 4: IQE of the best FZ-Si solar cell for front and rear side illumination measured by Spectral Response.

wavelength region therefore have to cross almost the whole wafer thickness to reach the emitter. For that reason the ratio of effective diffusion length to wafer thickness (L_d/d) is a good parameter for the quality of a bifacial solar cell and should be in the range of 2.5. The internal quantum efficiency of the device for the front illumination is a quite balanced plateau in the range of 1100 to 500 nm while the rear IQE drops in the same intermittent from 80% to 50%.

Another advantage of the bifacial cell structure is the elimination of wafer bowing for thin wafers which can be observed for solar cells with a closed Al back contact. Since there is no recrystallisation but a diffusion process used to establish the n^+ region, we do not have the problem of two materials with different coefficients of expansion causing a bow. The trend towards wafers below 200 µm intensifies the necessity of new back surface concepts and as demonstrated by A. Kränzl, [5], the boron doping can also be an option for the back surface field of p-type solar cells. Actually a nearly identical process had been applied to p-type silicon leading to comparable cell results [6]. Another important point related to progressive wafer thinning is the higher surface to bulk ratio. As a matter of fact the contribution of the surface recombination is going to dominate the solar cell performance and improved surface passivation will enter the centre of interest. Bifacial solar cells on both, p- and n-type have a good chance to play an important role in that field.
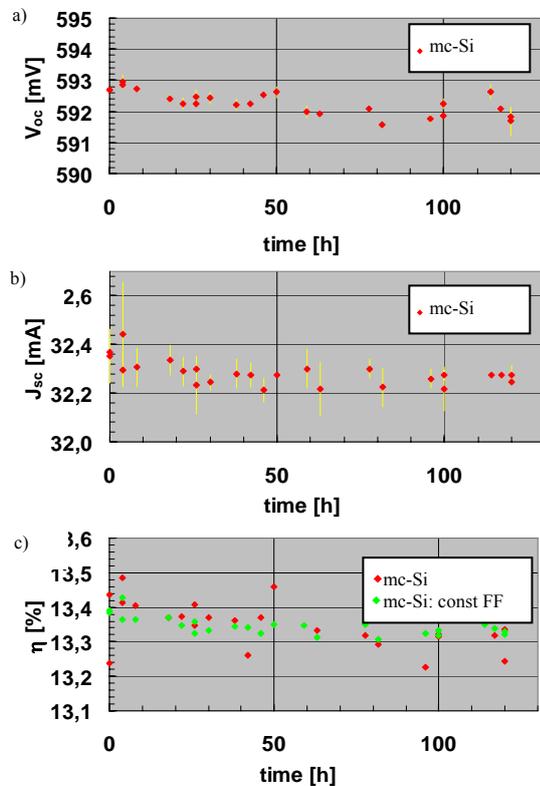
3.2 Long term stability

Figure 5: Time resolved development of a)V_{oc}, b) J_{sc}, and c) η for a mc-Si solar cell under constant illumination. A slight degradation effect can be observed.

During a period of 120 h a mc-Si bifacial solar cell was exposed to permanent illumination. In irregular intervals the IV data was logged.

As can be seen in figure 5, there is a slight drop in V_{oc} of about 1mV within that short term. While the current density J_{sc} stayed nearly constant, the measurement of fill factor was affected by fluctuations and had a strong influence on the efficiency. To get a more realistic and stable value for the efficiency, an averaged constant fill factor was assumed and revealed a drop of the efficiency of 0.04%. The observed data is a first hint on long term stability or at least just slight degradation of the n-type solar cells but for reliable conclusions an analysis of more data is necessary. Of special interest could be a comparative study to the behaviour of encapsulated n type solar cells.

3.3 Module interconnection

In section 3.1 we pointed out that the introduced solar cell process also works well on p-type substrates. A combination of these n^+pp^+-solar cells with the p^+nn^+-solar cells presented in this work leads to a new possibility of module interconnection. If p- and n-type solar cells are alternatingly placed on the module array, the interconnection between the solar cells is simplified. Instead of laborious tabbing of each backside with the neighbouring front side just a front to front and back to back stringing is necessary (Figure 6). A flipping of the solar cells is no longer necessary and the solar cells can be packed closer. Several test modules have been fabricated and will be presented in a separate paper at this conference by Kopecek et al. [1] including more detailed information about this new device.
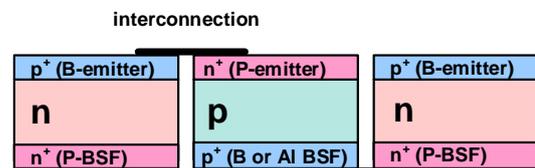

Figure 6: Alternating placement of bifacial p-type and n-type solar cells with front emitter leads to a simplified module interconnection (front to front / back to back)

4   SUMMARY AND OUTLOOK

In this work we presented p^+nn^+-Si solar cells with a boron diffused emitter at the front side on different substrates. The best sample so far was a 17.1% Cz solar cell with an area exceeding 140 cm^2.
On the basis of their bifacial characteristic the solar cells have shown in an appropriate ambient a benefit in power of up to 30%. First long term tests showed a slight degradation of the solar cells, which has to be analyzed in more detail. The cell design of our solar cells approves a new way of module interconnection that has been presented in an additional work at this conference [1].

Future work will concentrate in solar cell optimization for an industrial implementation with a focus on simplified front side passivation e.g. by PECVD SiC$_x$. and a reduction of R_{series} of the front side metallization.

5 ACKNOWLEDGEMENTS

6 REFERENCES

[1] R. Kopecek et al., Module interconnection with alternate p- and n-type Si solar cells, this conference

[2] L.J. Geerligs and D. Macdonald, Base doping and recombination activity of impurities in crystalline silicon solar cells, Progress in Photovoltaics **12**, 309 (2004);

[3] J. Libal et al., n-type multicrystalline silicon solar cells, BBr$_3$ diffusion and passivation of p$^+$ diffused silicon surfaces, 20th EU-PVSEC, Barcelona 2005, pp. 793-796

[4] R. Petres et al., "Passivation of surfaces by PECVD silicon carbide films" *Proc. 15th PVSEC*, Shanghai, 2005, pp. 128-129

[5] T. Buck et al.,Large area screen printed n-type mc-Si solar cells with B-emitter: efficiencies close to 15% and innovative module interconnection, Proc. 4th WCPEC, Waikoloa, (2006)

[6] A. Kränzl et al., Bifacial solar cells on multi-crystalline silicon with boron BSF and open rear contact, Proc. 4th WCPEC, Waikoloa, (2006)