Large Area N-Type Multicrystalline Silicon Solar Cells with B-Emitter: Efficiencies Exceeding 14%

R. Kopecek[1], T. Buck[1], J. Libal[1], R. Petres[1], I. Röver[2], K. Wambach[2], R. Kinderman[3], L. J. Geerligs[3], P. Fath[1]

[1]University of Konstanz, Faculty of Sciences, Department of Physics, Jakob-Burckhardt-Str. 27, 78464 Konstanz, Germany
Phone (+49) 7531/88-2074; Fax (+49) 7531/88-3895; e-mail: Radovan.Kopecek@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: We present n-type Si solar cells on large area mc-Si wafers processed with industrially relevant techniques such as open-tube furnace diffusions, PECVD SiN_x deposition and screen printed contacts. The resulting solar cells have efficiencies exceeding 14%. This is the first time, to our knowledge, that solar cells with such high efficiencies were obtained on large areas using this type of material. We show that with slight modifications and improvement of the solar cell process efficiencies above 15% are feasible with our simple processing sequence as first results on large area Cz-Si material led to an efficiency of 16.6%.

Key Words: n-Type Si, mc-Si Solar Cells, Boron-Emitter

1 Introduction

The PV market needs new sources of Si to satisfy the demand for solar cell production in the future. N-type Si is a promising candidate for an additional source as it tolerates prominent impurities (e.g. Fe, O) much better than p-type Si and therefore higher diffusion lengths and reduced degradation (lack of B-O complexes) result from n-type, compared to p-type material of the same quality. The focus of our studies is on the development of industrially relevant p^+nn^+-type solar cells in order to benefit from the higher quality of n-type Si.

2 Processing Techniques

2.1 Boron Diffusion

The temperatures used for boron diffusion in the electronic industry are usually above 1000°C, due to the lower diffusivity of boron compared to phosphorous. In addition, boron diffusions were thought not to have a gettering effect, unlike phosphorous diffusions, which have been shown to have a beneficial effect. It was therefore generally expected that boron diffusions may degrade mc-Si.

In our case, for an industrial solar cell process, a temperature for B-diffusion of 930°C (emitter formation) is sufficient. We measured the bulk lifetime initially and after BBr_3-diffusion in an open-tube furnace and removal of the doped region. The average lifetime remained nearly unchanged and some areas showed even higher lifetimes after diffusion. Since such high temperatures without any gettering will certainly cause some degradation of the mc-Si material, this is a strong indication of gettering [1, 2]. This possible boron gettering of the n-type Si material will be studied in detail. (In addition, it may play a role that the release of interstitial Fe from precipitates, during a high-temperature process step, will have much less effect on the lifetime in n-type silicon than in p-type).

Figure 1 shows the diffusion profiles of the P-BSF and B-emitters measured by Electrochemical Capacitance Voltage (ECV) measurement. The solid line shows the B-profile with a so called “Boron Rich Layer” (BRL) which is why the measured carrier concentration is above the boron solubility limit in Si. The other profiles show the B-emitter with 1) a two step diffusion (dashed line) and 2) a diffusion with in-situ oxidation (stars). Removal of the BRL (which is a highly conductive thin layer) in both cases resulted in an increase in the sheet resistance from 40 to 60 Ohm/sq. As the B-glass is present during the in-situ oxidation almost no depletion on the surface is visible. Because the B-diffusion with in-situ oxidation is faster, easier, results in a more suitable emitter profile for contacting and has long time stability [3], it was chosen for the emitter formation.

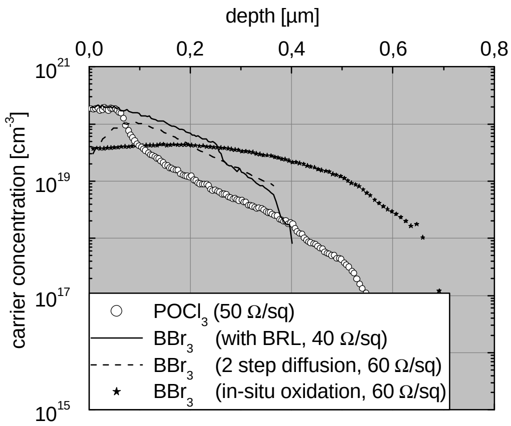

Figure 1 Diffusion profiles of P-BSF and B-emitters with and without BRL measured by ECV method.

2.2 Front Side Metallisation

In order to achieve a good front side contact, different pastes were tested on various emitters. Table I summarises the results.

paste / sheet res.	Ag	Ag/Al	Al
	Contact resistance rho_c [$mOhmcm^2$]		
60 Ohm/sq	155 ± 25	**7.5 ± 3**	9.5 ± 2
80 Ohm/sq	-	30-40	-
30 Ohm/sq	-	6	-

Table I Contact resistance to various B-emitters (BBr_3-diffusion) using different metal pastes.

The only candidate from the industrially available pastes trialled that gives a sharp print, has an acceptable line resistance and results in a good contact resistance to the p^+-emitter was Ag/Al paste. It is not easy to understand why pure Ag paste did not create a similar contact to the highly p-doped surface especially considering that the Ag/Al has only a small amount of Al added. Experiments are underway to understand this phenomenon.

2.3 Front Surface Passivation

The passivation of p^+ Si surfaces is of course an important issue which is also interesting for p-type solar cells and has been investigated by many groups. SiN_x does not work on highly p-doped surfaces as shown by Cuevas [4]; therefore alternative layers have to be studied. A detailed description of results on this topic can be found in an additional paper at this conference [5].

3 Solar Cell Process and Results

Using the processing techniques described above, solar cells have been made on large area Cz and mc-Si substrates. The mc-material was directionally solidified by Deutsche Solar. The material shows a very good quality; the average bulk lifetime of the minority charge carriers is close to 200 µs on as-grown 156 cm^2 wafers.

3.1 Solar Cell Process

The process is shown in Figure 2. It is a simplified flow chart without all cleaning steps.

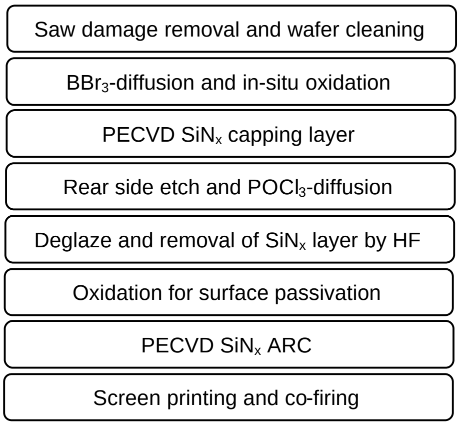

Figure 2 Flow chart of the industrial n-type solar cell process.

3.2 Solar Cell Results

Table II summarises the best results obtained on Cz- and mc-Si material.

material	**area** [cm^2]	**res.** [Ocm]	**FF** [%]	J_{sc} [mA/cm^2]	V_{oc} [mV]	h [%]
Cz-Si	146	2	72.8	33.3	610	**14.8**
1. mc-Si	154	1	73.3	31.7	595	**13.8**
2. mc-Si	154	1	72.8	31.5	596	**13.7**
2. plated	154	1	74.5	31.5	599	**14.1**

Table II Parameters of best solar cells obtained by the process described in Figure 2.

The poor fill factor is mainly due to a low line resistance of the Ag/Al paste and can be partly improved by Ag-plating as shown in the last row. This means that the metallisation of the front side still has to be optimised. The low V_{oc} is a cause of the recombination on both the front and rear side as can be seen in Figure 3.

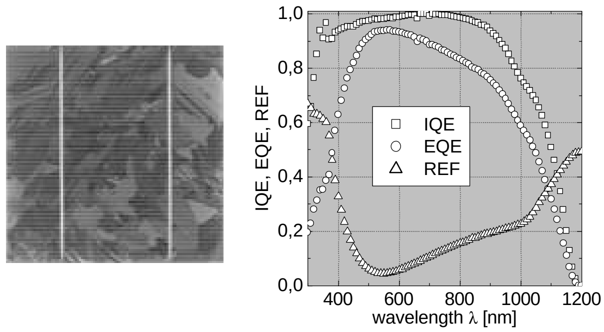

Figure 3 (left) 12.5x12.5 cm^2 n-type mc-Si solar cell and (right) spectral response measurement of this cell.

3.3 Simplified and Improved Cell Process

Future experiments will focus on solar cell improvement including also simplifications of the process to the following steps:

- Texturing and cleaning
- Front to front BBr_3-diffusion and in-situ oxidation
- Back to back $POCl_3$-diffusion
- SiC_x front passivation and ARC
- SiN_x rear passivation (n=2.4)
- Screen printing of open front and rear contact and co-firing

With this solar cell process we believe we can obtain cell efficiencies far above 15% since the quality of our mc-Si material is very homogeneous and first solar cells including already some steps listed above on Cz-Si material led to a high efficiency of 16.6%.

4 Conclusions and Outlook

We have presented a low cost solar cell process for n-type mc-Si wafers which has resulted in an efficiency of 14.1% for a cell area of 154 cm^2. With the improvement of the cell concept, efficiencies above 15% are feasible and an additional simplification would make this process very attractive for industrial applications. The introduction of this cell concept into the PV market would help to reduce the Si feedstock shortage since additional n-type sources could be used.

5 Acknowledgements

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6 References

[1] J. Libal et al., 19th EPSEC, Paris, France, 2004, 1013
[2] J. Libal et al., 20th EPSEC, Barcelona, Spain, 2005, in press
[3] J. Zhao et al., 3rd PVSEC world conf., Osaka, 2003, 923
[4] A. Cuevas et al., 3rd PVSEC world conf., Osaka, 2003, 913
[5] Petres et al., paper at this conference