LARGE AREA SCREEN PRINTED N-TYPE SILICON SOLAR CELLS WITH REAR ALUMINIUM EMITTER: EFFICIENCIES EXCEEDING 16%

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ABSTRACT

We present low cost, screen printed industrial solar cells with a rear Al-emitter for n-type mono- and mc-Si large area thin wafers showing efficiencies of 16.4% and 14.4% respectively. The gap of 2% absolute between the cell efficiencies for mono- and mc-Si is not material related but is largely due to the non-textured surface of the mc-Si substrate. Applying a surface texture by acidic wet chemical etching could lead to efficiencies above 15% on the mc-Si material. The process is based on the standard industrial p-type firing through solar cell concept with slight modifications in individual processing steps similar to the Phostop cell presented by Ebara Solar. There is still need for further optimisation before industrialisation for instance in the fields of wafer bowing reduction and the implementation of AgAl pads for wafer interconnection. We propose two different ways of pad printing - one directly to the Al-emitter, the other on top of the Al rear contact.

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 additional source of mono- and multi-crystalline (mc) form. In addition n-type Si tolerates prominent impurities (e.g. Fe, O) much better than p-type Si, and consequently, higher diffusion lengths and reduced degradation (lack of B-O complexes) result from n-type, compared to p-type material of the same quality [1, 2, 3]. Thus, the focus of our studies is on the development of industrially relevant n^+np^+-type solar cells in order to benefit from the availability and higher quality of n-type Si.

One of the solar cell concepts we are developing is similar to the Phostop solar cell on n-type dendritic web presented by the former Ebara Solar in co-operation with Georgia Institute of Technology [4]. With this concept efficiencies on small areas (4 cm^2) of 15% on mc-Si [5] and recently 18.3% on Cz-Si [6] were reported using photolithographic steps and evaporated front contacts. We show that on large areas (12.5x12.5cm^2) an efficiency above 16% is feasible using a simple firing through process on mono- and after some optimisation on mc-Si substrates as well.

LOW COST N-TYPE SI SOLAR CELL CONCEPTS

The solar cell market presently suffers from the lack of p-type Si feedstock. There are, however, other sources of Si such as n-type mono c-Si substrates from the electronic industry or waste from the production of such substrates. In addition some metallurgical purification techniques more easily produce n-type mc-Si material. We have developed two solar cell concepts that are suitable for these two types of n-type Si materials and can be processed at low cost.

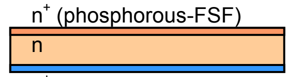
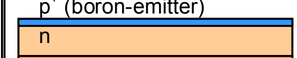
rear Al emitter solar cell	front B emitter solar cell
n^+ (phosphorous-FSF)  p^+ (Al-emitter)	p^+ (boron-emitter)  n^+ (phosphorous-BSF)
FZ-Si: 16.4% mc-Si: 14.4% on areas of about 150cm^2	Cz-Si: 17.1% mc-Si: 14.7% on areas of about 150cm^2
☺ similar to p-type screen printed solar cell process ☺ easy implementation into existing process lines ☹ higher quality, lowly doped material needed	☺ low quality material acceptable ☺ bifacial character ☹ B-diffusion with mc-Si? ☹ passivation of p^+-Si?

Table 1. Rear- and front emitter n-type solar cell concepts.

Table 1 depicts their cross-sections and summarises the solar cell results and properties of both cell structures. The left hand side shows the rear aluminium (Al) emitter solar cell and the right hand side the front boron (B) emitter solar cell. The rear Al emitter concept will be discussed in this paper. Details on the front B emitter device are summarised in another paper in these proceedings by T. Buck.

The rear Al emitter solar cell process is almost identical to the standard screen printing process for p-type Si (firing through PECVD SiN_x) one and can be therefore fabricated within the existing production lines. One drawback is that higher quality material is needed. The ratio between diffusion length and substrate thickness L_d/d has to be higher than 2.5 to guarantee that the device performance is not limited by the substrate quality. For material of lower quality the front B emitter concept can be used. One additional advantage of the latter device is that it is bifacial which increases the total power output. Central steps of development are the B-diffusion on mc-Si substrates and low temperature passivation of p^+-Si surfaces. The first point is discussed in the paper of T. Buck, the second in the paper of R. Petres in these proceedings. With both solar cell concepts high efficiencies have been reached: between 16% and 17% for mono c-Si and between 14% and 15% for mc-Si substrates.

N-TYPE SI SOLAR CELL WITH AL REAR EMITTER

As mentioned before this solar cell concept can be applied for high quality material for example, the off-spec mono c-Si from the electronic industry.

Device geometry: main differences from p-type

Figure 1b) shows n-type device in comparison with a standard p-type solar cell (Figure 1a).

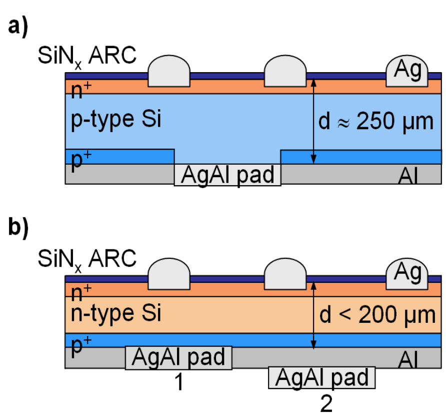


Figure 1. a) Standard p-type solar cell in comparison with b) n-type rear Al emitter solar cell.

Both solar cells have a PECVD SiN_x on top of a phosphorous diffused region that serves as the emitter in the case of the p-type cell and as a front surface field (FSF) in the n-type solar cell. This n^+ diffused layer is contacted via Ag-paste, which is fired through the SiN_x in a co-firing process in a belt furnace. The rear p^+-region is formed in the belt furnace during the same process in a recrystallisation of the screen printed Al-paste. As the n-type solar cell has the emitter on the rear, it has to be preferably thinner because of the $L_d/d > 2.5$ requirement.

The main difference is the AgAl pad at the rear side. While the pad is printed directly on the p-type substrate this would cause a shunt on the n-type device. Therefore the AgAl pad has to be printed either on the p^+ region or on top of the Al-rear contact. This will be discussed in more detail later.

Solar cell process and requirements for substrate

Figure 2 shows the applied solar cell process in a flow chart.

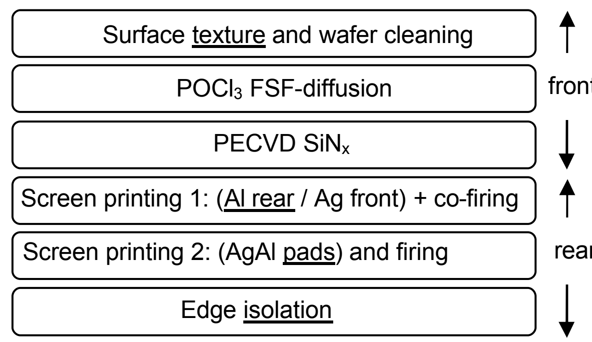


Figure 2. Process flow chart of the n-type solar cell.

In the first step, the substrate is textured and industrially cleaned (HCl and HF-dip) before entering the tube furnace for $POCl_3$ diffusion where a 50 Ω/sq FSF is formed at about 900°C. After removal of the P-glass a 70 nm PECVD SiN_x is deposited on the front side. Then Ag front and Al rear contacts are screen-printed and co-fired in a belt furnace. In the last step the pn-junction is isolated with a dicing saw, by cutting of the edges. The underlined steps, which represent the most critical processes, are discussed in more detail in the next paragraphs focussing on the front and rear side of the device.

An important prerequisite for the fabrication of solar cells with high efficiency with the given process is the substrate property. From simulations (shown in Figure 3), it can be seen that, in order to exploit the full potential of the cell concept, thin substrates of about 150 µm with high specific resistivity of higher than 10 Ωcm are required. The starting point of these simulations was a real cell with 16.4% efficiency depicted in the plot.

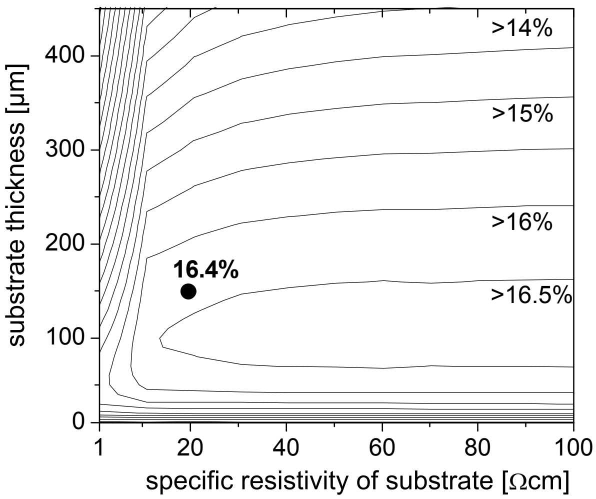


Figure 3. Contour plot of solar cell efficiency as a function of substrate thickness and substrate resistivity.

Front side of the device

An important process is the front surface texture of the substrate. A better front surface texture increases the current output of the device.

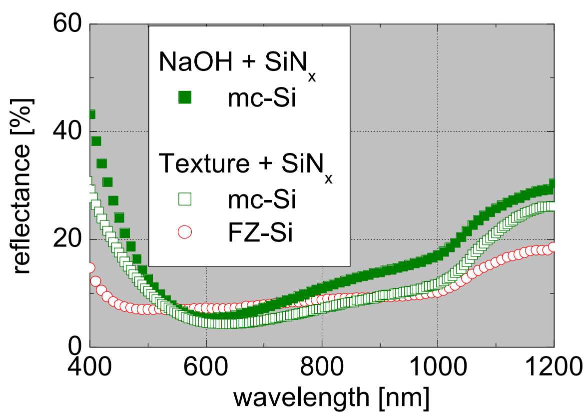


Figure 4. Reflectance of untextured and isotextured mc-Si and alkaline textured FZ-Si surface covered with SiN_x.

For mono c-Si substrates we used an alkaline solution consisting of KOH and isopropanol (IPA), which is used in the PV industry. Texturing of mc-Si substrates using the isotexturing solution (HF and HNO_3) we use for standard p-type mc-Si substrates is not successful because the texture quality is dependent on the substrate resistivity. Initially, we overcame this problem by pre-treating the substrate surface with an additional $POCl_3$-diffusion. On one hand the substrate quality is improved by an additional P-gettering step and on the other the isotexture can start on a highly doped surface. Since an additional high temperature step would lead to an increase in the thermal budget we have subsequently optimised our texture for high resistivity substrates with success, as can be seen in Figure 4. Figure 4 shows the reflectance curves for 3 different surfaces with a PECVD SiN_x layer - untextured (NaOH etched) mc-Si, an isotextured mc-Si and an alkaline textured FZ-Si surface. The texturing resulted in an increase in the short circuit current density, J_{sc}, of about 1 mA/cm^2.

Rear side of the device

Many optimisations and changes in the process had to be done at the rear side of the device.

Al-emitter

In order to guarantee a homogeneous and interruption free Al-emitter, the firing parameters were optimised using the fill factor. The n-type cells are fired at higher temperatures, which leads to a deeper recrystallised layer; about 10 µm, compared to 7 µm for a standard Al-BSF as used at the University of Konstanz. With our firing parameters, fill factors of up to 80% were reached.

Edge isolation

Such fill factors are of course only possible if sufficient edge isolation is accomplished. Without sufficient edge isolation, n-type cells may suffer from a tunnelling diode, formed by the co-existing p^+ (Al-emitter) and n^+ (P-diffusion) regions at the rear, which leads to an edge shunt. The pn-junction must therefore be isolated by cutting directly through the Al-contact. This can be optimised by a closer Al-print to the edges or even avoided by a one-sided P-diffusion which is already used in the solar cell industry.

Pad-geometry

A crucial process step for our device is the printing of the AgAl pads as depicted in Figure 1b). If the pads are printed directly on the n-type substrate we end up with a completely shunted cell. Therefore we have proposed and fabricated two different assemblies of the pads. In case 1 a standard AgAl paste is printed on the p^+-region. This works of course well but an additional step has to be added to the process, namely an prior screen-printing and firing step of a Al-paste followed by HCl etch of the rear contact. This can be avoided (case 2) by the use of a new Ag-based paste which can be fired at 400°C and therefore printed at the top of the Al-contact at the end of the process as depicted in Figure 1b). This geometry is also interesting for standard p-type solar cells as it would lead to an increased performance. First experiments showed a good printability of the paste without pealing off the Al-contact, good line resistance, good contact resistance and good solderability. One property that still has to be studied and optimised is the stability of the Si-Al interface as the tabbings can be easily removed from the cell.

SOLAR CELL RESULTS

Mono c-Si solar cell

The efficiencies for n-type FZ-Si solar cells with a substrate resistivity of 20 Ωcm were all above 16% with the highest efficiency 16.4% (Table 2).

Multi c-Si solar cell

Untextured solar cell (mc1)

The untextured mc-Si solar cells have efficiencies above 14% with the highest efficiency 14.4%. The lower performance in *FF* and V_{oc} can be explained by higher substrate resistivity (50 Ωcm) and the lower J_{sc} by the texture as the IQEs for the FZ and mc-Si cell are almost identical as shown in Figure 5.

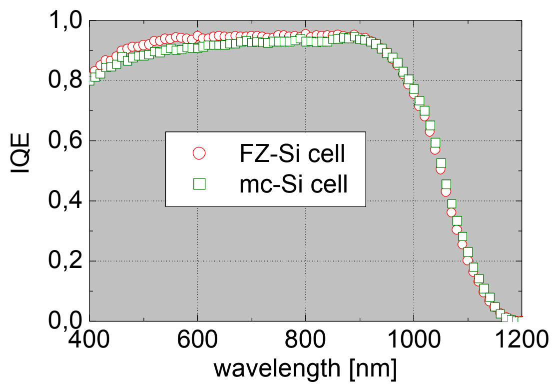


Figure 5. IQEs of FZ and mc-Si solar cell.

Textured solar cell (mc2)

In order to increase the current of the mc-Si solar cell a lot of effort was put into the isotexturing of the front surface. After optimisation a homogeneous surface texture was achieved resulting in a dark surface with no grain structure visible after SiN_x deposition. The gain in J_{sc} was higher than 1mA/cm^2 as can be seen in Table 2. As the firing conditions were not optimised for this cell type the overall cell performance is lower. With a realistic FF of 77% an efficiency of 15% would be reached.

cell	***rho*** [Ωcm]	***d*** [µm]	***FF*** [%]	J_{sc} [mA/cm^2]	V_{oc} [mV]	*η* [%]
FZ	20	150	77.9	34.0	618	16.4
mc1	50	180	76.6	31.7	604	14.4
mc2	50	150	71.3	33.1	589	13.9

Table 2. Parameters of best solar cells on FZ and mc-Si.

Substrate properties

As can be seen from Figure 6 the n-type mc-Si has very good quality which does not limit the cell performance. Important to note is that if 15% are reached with our n-type cell no light induced degradation is expected, which is not necessarily the case for p-type devices as can be seen in Figure 6. We have measured a loss in V_{oc} for p-type mc-Si solar cells of about 5 mV and up to 0.3% absolute in efficiency, whereas the performance of the n-type solar cell remains stable.

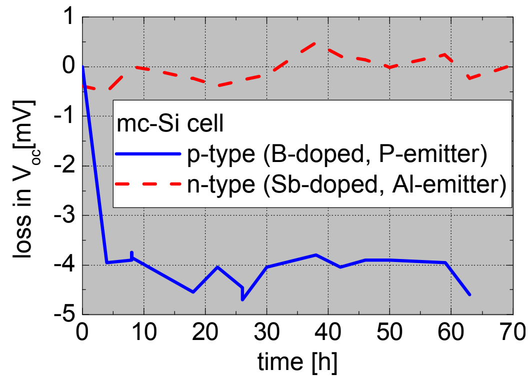


Figure 6. Loss in V_{oc} after illumination for different solar cell types.

CONCLUSION AND OUTLOOK

We have demonstrated that our n-type solar cell concept leads to efficiencies of more than 16% on FZ- and close to 15% for mc-Si substrates with a low cost solar cell process. As it is almost identical to the p-type process, our process can be easily implemented into existing production lines. In addition, we do not observe any long term light-induced degradation of the n-type mc-Si material we used, which leads to stable efficiencies.

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