

COMPARISON OF HIGH EFFICIENCY SOLAR CELLS ON LARGE AREA N-TYPE AND P-TYPE SILICON WAFERS WITH SCREEN-PRINTED ALUMINUM-ALLOYED REAR JUNCTION

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ABSTRACT

Low-cost, high-efficiency, and large area n-type silicon cells can be processed based on the screen printed Aluminum-alloyed rear junction concept. This process uses fabrication techniques which are very close to the current industry-standard screen printed mc-Si cell process. We compare, by experimental tests and modeling, the differences of using n-type wafers and p-type wafers with this process. An independently confirmed record-high efficiency of 17.4% is achieved on n-type floatzone (FZ) silicon wafers (area 140 cm²). On p-type FZ wafers, with the same process 17.6% is obtained, and 16.8% on p-type Cz wafers. Model calculations allow us to identify the potential for further enhancement of the n-type cell efficiency to slightly above 18.0% by improving front surface passivation. We also discuss experimental characteristics of cells produced by this process from n-type multicrystalline wafers.

INTRODUCTION

The vast majority of today's commercial silicon solar cells are made from p-type doped material. More than 80% of the produced solar cells have a homogeneous emitter, a PECVD-SiN layer as antireflective coating, and screen printed contacts on both sides. For the backside, an aluminum paste is used to create a back surface field during the contact co-firing. Recently, n-type silicon materials have received much interest as they are considered promising candidates for future generations of high-efficiency solar cells.

However, in spite of these advantages, the n-type solar cells are not yet abundantly produced in industry. In order to realize this, n-type silicon solar cells must have stable efficiencies of at least the same level as for p-type.

A few solar cell concepts based on n-type Si materials are currently under investigation. One of these concepts, investigated in this paper, is the Al-alloyed back-junction cell [3-10]. This concept was introduced for the first time by EBARA Solar Inc. in 2000 [9]. Cell efficiencies up to 17.0% were reported [7]. It represents a fast way, for industry, to move from p-type to n-type substrates because of the possibility of maintaining the same process sequence. The only difference, compared with the conventional p-type (n⁺pp⁺) process used in industry for p-type wafers, is that during the phosphorus diffusion a front surface field is created instead of an emitter, and during the contact co-firing the aluminum back junction is formed.

Aluminum rear-junction cells are also an interesting

and simple approach to study and identify the material limitations for all back-contacted solar cells, in particular, for multicrystalline n-type substrates.

In this paper we present results on our n-type cell development based on the Al back-junction. We compare by experimental tests and modeling the differences of using n-type wafers versus p-type wafers, applying the same processing sequence. We present an independently confirmed record-high efficiency of 17.4% based on n-type float zone (FZ) wafers, which demonstrates the potential for high efficiency of this n-type process. On p-type FZ wafers with the same process 17.6% was obtained, whereas 16.8% was obtained on p-type Cz wafers.

EXPERIMENTAL PROCEDURE

The cell process was mainly focussed on 148.5 cm² n-type and p-type monocrystalline silicon wafers, but results on 156.25 cm² industrial n-type multicrystalline silicon (mc-Si) wafers are also presented in this paper. The cell process we used is based on in-line processing for diffusion, co-firing, and on process steps which can be industrialized. It starts by a texture etch (industrial isotexture, or random pyramids) of the surface. Then the front-surface field (n-type wafer) or front emitter (p-type wafer) is formed by phosphorus diffusion in an infrared conveyor belt furnace from a spin-on source. To improve the accuracy of our modeling, and investigate the potential improvements in cell efficiency by improvement of the front properties, two front diffusions were tested: one standard diffusion (≈ 60 Ohm/sq) and one diffusion for improved front surface properties. Subsequently, a rear side polishing etch is carried out followed by the phosphorus glass removal and the PECVD SiN_x anti-reflection coating deposition on the front side. This process sequence does not further require wafer dicing or other methods for junction isolation, and thus the entire initial wafer area is used. The silver grid is then screen-printed on the SiN_x front side, followed by screen-printing of Al on the whole rear side of the cell. Both contacts are co-fired in an infrared conveyor belt furnace, thus forming also the p⁺ emitter (n-type wafer) or BSF (p-type wafer) at the rear. The process flow chart and a schematic cross section of the Al back junction solar cell are shown in Fig. 1.

CELL PROCESS AND RESULTS

Effect of base resistivity and front diffusion

Table 1 summarizes solar cell parameters obtained for

n-type mc-Si and FZ substrates of different base resistivities, and for the two different front diffusions. It is observed that the highest n-type cell efficiency is obtained for high substrate resistivity. This is in agreement with model calculations [4,8], which show that, in order to benefit from the full potential of this type of solar cell, the wafer resistivity should typically be higher than 10 Ωcm .

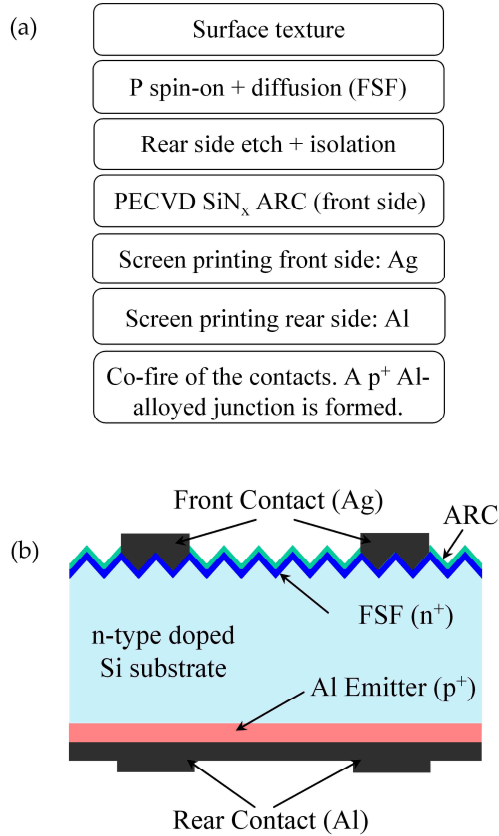


Fig. 1. Process flow chart (a) and the schematic cross section (b) of the resulting n-type back junction cell.

To understand the effect of base resistivity, we investigated the internal quantum efficiency (IQE) of cells with base resistivity of 3.8 and 30 Ωcm . The standard phosphorus diffusion was used. Fig. 2 shows the experimental IQE (symbols) together with the PC1D fit (lines) using a measured front doping profile and surface reflection, and assuming a constant Al doping profile for the rear junction. The relevant fit parameters for the modelling are the bulk lifetime and the front surface recombination velocity (SRV). The IQE at lower wavelengths is completely determined by the SRV. The bulk lifetime is very high (>1 ms), and does not limit the IQE. The fit to experimental data reveals a SRV of $6.0(\pm 1) \times 10^5$ cm/s independent of the base resistivity.

The bulk lifetime must be taken into account, however, for multicrystalline wafers. The IQE fit of the multicrystalline cell with base resistivity 0.8 Ωcm from Table 1 reveals the same SRV value as that obtained for

the monocrystalline cells above (6.0×10^5 cm/s), but with a considerable lower bulk lifetime of only 28 μs (as obtained from PC1D fit). The ratio of diffusion length and substrate thickness (L_d/W) must be higher than 2.5 for good cell performance [11]. To meet these conditions, the effective lifetime of the multicrystalline substrates must be higher than 130 μs . Fortunately, resistivity and bulk lifetime usually go together: increasing bulk resistivity also increases the bulk lifetime.

wafer	ρ [Ωcm]	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	η [%]
mc	0.8	19.77	589	73.7	8.6
mc	12	29.7	580	72.1	12.4
FZ	3.8	30.74	620	77.9	14.9
FZ best	30	34.41	627	74.8	16.1
FZ	30	34.34	627	74.1	15.9
average		± 0.1	± 1	± 0.6	± 0.1

mc	25	31.4	582	74.5	13.6
FZ best	31	34.75	626	77.2	16.8
FZ	31	34.72	623	76.8	16.6
average	31	± 0.06	± 3	± 0.4	± 0.2

Table 1. Effect of base resistivity (ρ) and front diffusion on n-type FZ and mc-Si cell properties. All cell surfaces are isotextured. Above dashed line: standard front diffusion. Below dashed line: optimised front diffusion. The area of the solar cells is 156.25 cm^2 for mc-Si cells and 148.5 cm^2 for monocrystalline cells.

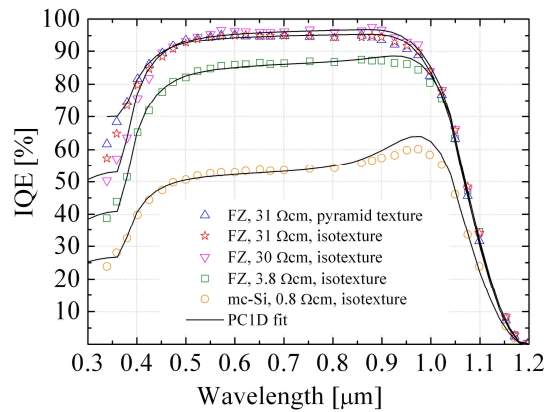


Fig. 2. Internal quantum efficiency data (symbols) of the n-type solar cells with different base resistivity and PC1D fit (lines), taking into account the measured front doping profile, surface reflection, wafer resistivity, and wafer thickness.

Lowering the front surface recombination velocity

Currently we are investigating ways to reduce the SRV of these types of cells and, thus, to further improve their efficiency. In the lower part of Table 1 (below dashed line) the results for an improved phosphorus diffusion are shown. It is observed that a higher J_{sc} is achieved by engineering the FSF diffusion and improving the cell

process. In other experiments we also observed improvements in V_{oc} up to 12 mV due to the improved front diffusion [12]. However, the V_{oc} results show more scatter.

As a result of the new process, the SRV was further reduced to $8.5(\pm 1.5) \times 10^4$ cm/s (determined by fitting the IQE data). Model calculations [12] indicate that the gain in J_{sc} and V_{oc} of the cells is indeed due to a lower SRV.

Best cell efficiencies for p-type and n-type substrates

The best cell results are obtained using a random pyramids texture etched surface and the optimized diffusion. The conversion efficiencies that we reached on n-type FZ wafers are 17.3% on 148.5 cm², and 17.4% on 140 cm² (after dicing away the unprinted Al area on the rear side), independently confirmed at Fraunhofer ISE CalLab, Freiburg, Germany. To our knowledge, this is the highest efficiency obtained for n-type silicon solar cells featuring a screen-printed aluminum rear-emitter.

Table 2 shows best results for n-type cells, as well as for p-type cells processed in the same way. Clearly, for the diffusion parameters used, the results on the two types of FZ wafers do not differ much. Fig. 3 shows that the internal quantum efficiencies are indeed comparable. However, compared to p-type Cz wafers the n-type process performs better. It is expected that n-type Cz wafers will perform as well as the n-type FZ wafers (n-type Cz wafers of appropriate resistivity were not available for tests).

The V_{oc} of 633 mV for the n-type FZ cells is among the highest measured on large area (148.5 cm²) solar cells featuring screen printed contacts and is already close to the V_{oc} limit (about 642 mV) of an Al-alloyed rear full area emitter cell [10, 13].

It is clear that for n-type mc-Si wafers, it is difficult to obtain sufficient performance. In the comparison of the mc-Si cells in Table 2 it should also be noted that the p-mc-Si cells were processed on wafers from the upper part of an ingot, which results in some reduction of cell efficiency due to increased crystal defect density.

Si	ST	ρ [Ω cm]	J_{sc} [mA/cm ²]	V_{oc} [mV]	FF [%]	η [%]
n-mc	IS	25	31.4	582	74.5	13.6
p-mc	IS	1.5	33.5	603	76.6	15.5
n-FZ	IS	31	33.27	633	78.8	16.6
n-FZ	RP	31	35.53	632	77.4	17.4
p-FZ	RP	2.4	35.52	626	79.0	17.6
p-Cz	RP	1.1	35.76	617	76.0	16.8

Table 2. Parameters of the best fabricated solar cells on FZ and mc-Si substrates. The area of the solar cells is as in Table 1. ST - surface texture.

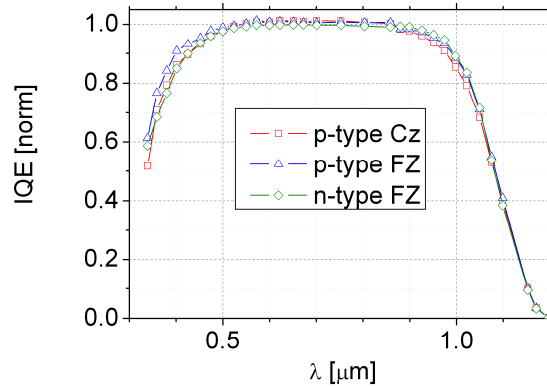


Fig. 3. Internal quantum efficiency (IQE) data of the best monocrystalline p-type and n-type solar cells.

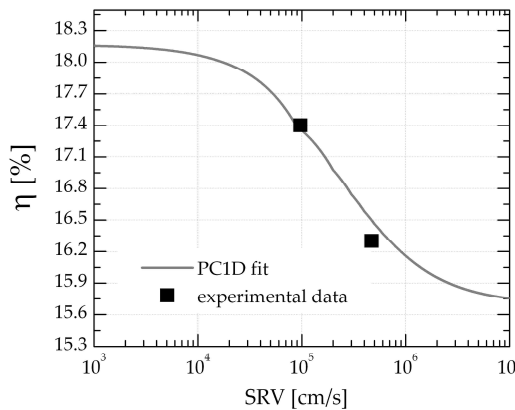


Fig. 4. Calculated solar cell efficiency as a function of surface recombination velocity for an n-type FZ with a resistivity of 30 Ω cm. The calculation is done considering a FF of 78.8% and a random pyramid texture surface. The parameters used in the calculation are those found by fitting the experimental data of Figure 2.

Potential of n-type FSF cell process

In Fig. 4 a model calculation for the conversion efficiency versus SRV is shown. The starting point of this calculation was the experimental data of the 17.4% efficiency cell. It is clear from the figure that efficiencies only slightly over 18% can be obtained even after fully minimizing SRV. With the FF reaching 79% there are two major factors left that limit the efficiency of this industrial screen-printed aluminium rear-emitter cell: Firstly, the metallization shading of the front surface (which amounts to 7.5% in our cells), and, secondly, the fundamental limitation imposed on V_{oc} (and J_{sc}), of approximately 642 mV, due to recombination that occurs in the Al-alloyed emitter.

Cuevas et al. [10] have reported that the recombination current density in the p^+ region formed by screen printed aluminium and alloying cannot be lower

than approximately 5×10^{-10} mA/cm². Such recombination can drastically limit the J_{sc} and V_{oc} of a cell even if front SRV is minimized and high quality wafers are used [10, 13]. Recently Bock et al. [14] reached 250 fA/cm² using low temperature annealed a-Si as surface passivation layer on the rear aluminum-doped emitter, after etching away the metallic aluminum layer. Preliminary modeling shows this could increase the cell efficiency by about 0.2%.

n-type mc-Si substrates

As Fig. 5 shows, the n-type mc-Si cells are strongly limited by the poor performance at crystal defects for short and middle wavelengths, which the slightly better performance at long wavelengths (compared to p-type wafers) cannot compensate for. From the cell results in Table 2, it seems that in n-type mc-Si cells especially the V_{oc} is suppressed. In addition, the n-type mc-Si wafers that we have used originate from the edge of an ingot (top edge in Fig. 5) which also reduces performance.

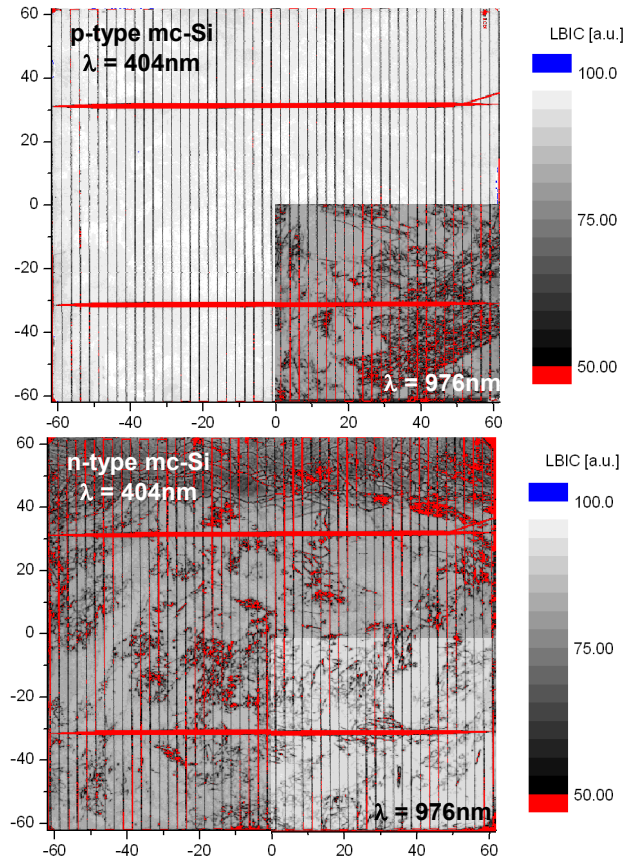


Fig. 5. Local light beam induced current data of the p-type (top) and n-type (bottom) mc-Si solar cells from Table 2. Light is 404nm wavelength. Bottom right insets in both images: light of 976nm. Same scale in both figures.

The best efficiency we obtained so far is 13.6%, while Kopecek et al [8] have reported 14.4% for a wafer from

the center of an ingot. It is known that 130 μ s lifetime, which is good enough to reach high efficiencies on homogeneous substrates, can be obtained quite well in n-type mc-Si. The main issue is, however, to produce sufficiently homogeneous mc-Si.

CONCLUSIONS

We have demonstrated that a low cost process of fabricating n-type solar cells based on the Aluminum rear-emitter concept leads to a new record efficiency of 17.4% for large area monocrystalline FZ substrates. The same process on p-type monocrystalline substrates resulted in 17.6% (FZ) and 16.8% (Cz) efficiency. By improving the front surface passivation somewhat higher efficiencies can still be realized on n-type wafers with this process, but the results are already quite close to fundamental limitations due to the rear Al emitter. High efficiencies may also be conceivable on n-type multicrystalline substrates if those can be produced with high lifetime and, especially, high homogeneity.

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