HIGHLY EFFICIENT DOUBLE SIDE MECHANICALLY TEXTURED NOVEL SILICON SOLAR CELL CONCEPTS

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ABSTRACT

Silicon solar cell concepts based on double side mechanical V-texturing were developed and investigated. In the case of the MECOR (MEchanically CORrugated) solar cell concept, the V-grooves run parallel on the front and rear sides while the BOSS (BOth Sides perpendicularly Structured) solar cell concept is based on perpendicular V-grooves on the front and rear sides. The solar cell contacting was mainly done using the SAP&SAFE (Shallow Angle Photolithography & Shallow Angle Finger Evaporation) concept which was specifically developed for V-textured surfaces. The highest efficiency achieved for MECOR solar cells was 18.5%. For BOSS solar cells an efficiency of 19.3% was demonstrated. Optical simulations of different geometric cell structures were done.

1. INTRODUCTION

The mechanical structuring technique based on the fast rotating profiled sawing blades mounted on a dicing machine opens numerous possibilities of novel solar cell concepts such as MECOR [1], BOSS [2], POWER [3], LOPE [4], LAMELLA [5] or OECO [6] cells. These cell concepts can be divided into two categories: front sided and double sided textured. In this paper the MECOR and the BOSS cell concept are investigated, different surface structures and metallization concepts are compared. The surface structuring was done according to the chosen metallisation concept. One approach is characterised by untextured plateaus for the contact fingers and the other by higher V-tips for the application of the SAFE-metallization. The SAFE-metallisation requires an appropriate technique to define the contact area on the flank of a V-groove. This was done by utilizing the **S**hallow **A**ngle **P**hotolithography, SAP. For both techniques the surface structure is used as a shadowing mask [7].

The calculations done by Green and Campbell [8] show the excellent light trapping properties of the BOSS structure. Figure 1 demonstrates the differences in absorption of the MECOR and the BOSS structure in comparison to a front side textured cell. The absorption, A, was calculated from transmission, T, and reflectance, R, measurements according to: $A = 1 - R - T$.

For an evaluation of the BOSS solar cell concept, additional parameters must be taken into consideration e.g. surface roughness, combination of groove angles on the front and the rear.

The MECOR concept which allows cells to be mounted on curved surfaces was investigated and the influence of the cell thickness, the surface passivation and the contacting scheme on the IV-curve were determined.

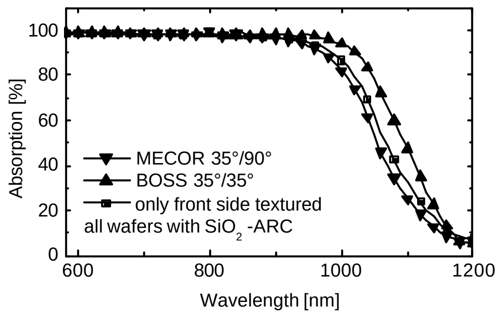

Fig. 1 Comparison of the absorption of cell structures underlying MECOR and BOSS cells. The groove angle on the front side of all three wafers is 35°. While the MECOR structure was obtained by implementing a 90° groove angle, the BOSS structure shows 35° grooves on the rear.

2. MECOR SOLAR CELL CONCEPT

In the following, various MECOR solar cell types are characterised. They have a differing structure, processing sequence and applied contacting scheme. Figure 2 shows a schematic drawing of a MECOR solar cell with SAFE-metallisation.

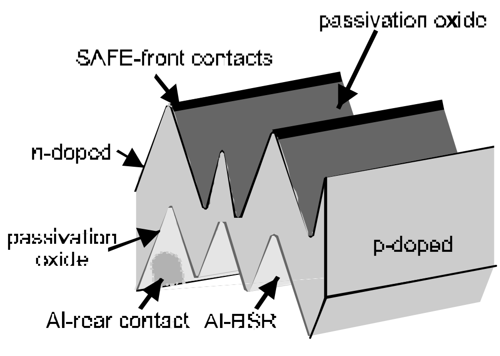

Fig. 2 Schematic drawing of a MECOR solar cell with SAFE front contacts.

2.1 Simulations of different MECOR geometries

side and surface passivati

For an estimate of the short circuit current potential of different MECOR structures, three dimensional simulations of the absorbance with the program SUNRAYS [8] were done. Groove angles of 35°, 60° and 90° for the rear side and 35°,60° for the front side were assumed. The front and rear surfaces were covered with 110nm thick SiO_2 and the rear side reflectance was considered to be 97% for all cells. Additionally, the surface roughness was considered by assigning a fraction of Lambertian reflectance to the silicon surface.

In Table I the calculated short circuit current densities assuming an internal quantum efficiency of one, corresponding to the optical absorptance, are displayed. The absorbed short circuit current densities show the large influence of the surface roughness. These results show that for an optimal exploitation of the incoming light, a polished front surface and a Lambertian rear surface are required.

Table I. Absorbed short circuit current densities of different MECOR structures simulated with SUNRAYS [8].

Texture FS/RS [°]	$J_{SC, absorbed}$ [mA/cm^2] FS+RS pol.	$J_{SC, absorbed}$ [mA/cm^2] FS pol.+ RS Lam.	$J_{SC, absorbed}$ [mA/cm^2] FS+RS Lam.
35/35	41.4	42.4	40.0
35/60	40.8	42.6	40.2
35/90	41.1	42.9	40.3
60/60	41.5	42.4	38.7
35/flat	41.4	43.2	40.2

Figure 3 shows the dependence of absorbed J_{SC} on rear side reflectance for the 35/90MECOR structure and the 35/flat structure. The MECOR structure was assumed to behave like a Lambertian reflector on the front and rear side and the 35/flat structure was assumed to behave like a Lambertian reflector on the front side and to have a polished rear side. These results show that the absorbance of the 35/flat structure obviously decreases with lower rear side reflectances.

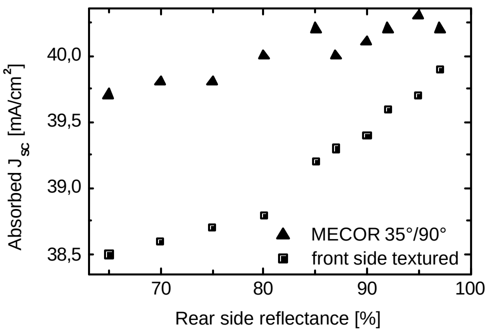

Fig. 3 Dependence of the simulated absorbed short circuit current of a MECOR structure and a front side textured wafer on the rear side reflectance.

2.2 MECOR solar cells

A series of MECOR solar cells with differing geometries were produced applying the processing sequence displayed in figure 4 using float zone silicon. This general process description was realised for MECOR cells with contact fingers running on untextured plateaus and those applying the SAP&SAFE scheme. The different contacting schemes require different texturing patterns. For this investigation the texture depth on the rear side was also varied to apply the two different contacting schemes.

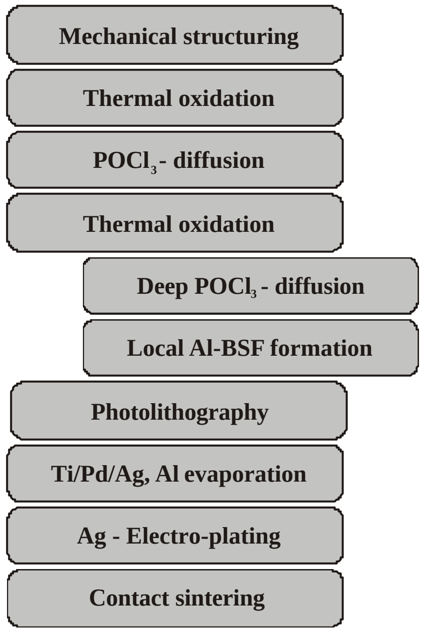

Fig. 4 Processing sequence for MECOR and BOSS cells with (process P2) / without (process P1) deep diffusion and Al-BSF.

The rear side texture was only 40µm deep to allow the application of an adapted photolithography in combination with a 2% local point contact mask as it was used for the untextured rear side.

Table II Cell parameters of MECOR cells with a SAP&SAFE front contact or one using an adapted standard photolithography forming the contacts on untextured plateaus in comparison with an only front side textured cell measured under illumination.

Texture FS/RS [°] Contacting FS/RS	V_{OC} [mV]	J_{SC} [mA/cm^2]	FF [%]	η [%]
M1: 35/90, SAP&SAFE / 2% mask	652	36.5	77.8	18.5
M2: 35/90, Plateaus / 2% mask	651	35.6	78.6	18.2
VPB1: 35/polished, Plateaus / 2% mask	665	37.8	77.4	19.4

In Table II the best MECOR cells for each front side contact scheme are shown in comparison to a cell textured only on the front side. While the MECOR cells had a selective emitter design and an Al-back surface field (Al-BSF), the front side textured cell only has got a homogeneous emitter and no BSF. The V_{OC} and the J_{SC} values show that the recombination at the rear side dominates the efficiency of MECOR cells. This effect becomes more obvious in the internal quantum efficiency, IQE as displayed in figure 5. This limits the MECOR cell efficiencies to 18.5% compared to 19.4 % for the cell textured only on the front side.

For very flexible MECOR cells, the rear side texture was deeper. This led to thinner MECOR cells. In this case, the SAP was applied defining the rear contact area. The cell results of differently front contacted MECOR cells are depicted in Table III.

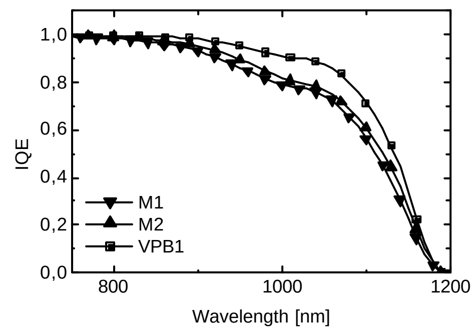

Fig. 5 IQE, of two MECOR solar cells, M1, M2 and an front side only textured cell, VPB1.

Table III Cell parameters of MECOR cells with a SAP&SAFE front contact or those with the contact fingers on untextured plateaus using an adapted standard photolithography and a local SAP&SAFE rear contact measured under illumination.

Texture FS/RS [°] Contacting FS/RS	V_{OC} [mV]	J_{SC} [mA/cm^2]	FF [%]	η [%]
M3: 35/90, FS, RS SAP&SAFE	627	35.4	73.1	16.2
M4: 35/90, Plateaus / SAP&SAFE	617	36	74	16.4

A comparison of MECOR cells M1 and M2 with M3 and M4 demonstrates the losses in V_{OC} due to the larger influence of the non optimal passivated rear side because of the light trapping in the rear side texture.

3. BOSS SOLAR CELL CONCEPT

The BOSS solar cell concept relies on one of the best light trapping structures as calculated by e.g. Green and Campbell [7], Campbell and Green [10] and Brendel [9]. Extended simulations also have been done by Zechner *et al.* [11]. The excellent light trapping properties of the BOSS structure assuming polished surfaces degrades significantly when considering diffuse reflectances as they occur at mechanically grooved surfaces.

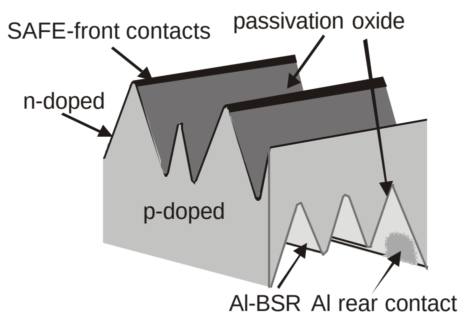

Fig. 6 Schematic drawing of a BOSS solar cell with SAFE front contacts.

3.1 Simulations of different BOSS geometries

Comparing BOSS structures with polished and rough surfaces, the diffuse reflecting surfaces lead to an enhanced transmittance whereas the reflectance stays roughly the same. Especially for a MECOR cell with 35°/90° structure, there is no transmittance for polished surfaces.

Considering BOSS structures and only front side textured wafers with an Al-BSR, there is no difference in the absorbed short circuit current density regardless of the surface properties, as shown in Table IV.

Table IV Absorbed short circuit current densities of a typical BOSS structure in comparison to a front side only textured wafer simulated with SUNRAYS [8].

Texture FS/RS [°]	$J_{SC,\ absorbed}$ [mA/cm^2] FS + RS pol.	$J_{SC,\ absorbed}$ [mA/cm^2] FS pol. + RS Lam.	$J_{SC,\ absorbed}$ [mA/cm^2] FS Lam. + RS pol.	$J_{SC,\ absorbed}$ [mA/cm^2] FS + RS Lam.
35/35	41.4	43.2	40	40.3
35/flat	41.4	43.2	39.9	40.2

Although the absorbed short circuit current densities in the simulations shown in Table IV are the same for both structures independent of the rear side configuration, they start to differ with reduced rear side reflectance because of the higher transmittance of the front side textured wafer compared to the BOSS structure. Considering quite realistic surface properties, for example for the front side textured wafer, a Lambertian front side and a polished rear side and for the BOSS cell both sides Lambertian than there is a small difference in J_{SC} as shown in Table IV. If the front side textured wafer is compared to another BOSS structure, the difference will even be smaller, because only the 35°/90° structure allows zero transmittance in the case of no BSR.

Figure 7 show absorption as a function of wavelength as calculated from measured transmittance and reflectance curves. The simulation program SUNRAYS [8] was used to fit the absorption curves for wavelengths larger than 1050nm varying the silicon thickness of an untextured wafer. The BOSS structure corresponds to a 2mm thick silicon wafer.

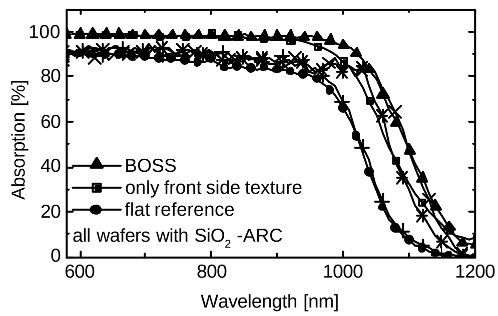

Fig. 7 Comparison of the absorption of different geometric structures with an untextured wafer of corresponding thickness fitting the absorption curves for wavelengths larger than 1050nm.

3.2 BOSS silicon solar cells

Series of BOSS cells on FZ-Si were processed with different front contact design: SAFE contacts or untextured plateaus for the contact fingers. The comparison of the BOSS cells with front side textured cells aimed at balancing the increase in J_{SC} of the BOSS cells against the increase in rear side recombination.

J_{SC} and V_{OC} of a BOSS solar cell and a front side textured cell can be compared using the two cells, B2 and

VPB1, which have the same front contact design. Despite the selective emitter and the Al-BSF of the BOSS cell, the open circuit voltage is about 14mV reduced (Table V). Hence BOSS cells show the same V_{OC} as MECOR cells with corresponding geometry.

Table V Cell parameters of BOSS cells with a SAP&SAFE front contact or those with the contact fingers on untextured plateaus using an adapted standard photolithography and a local SAP&SAFE rear contact measured under illumination.

Texture FS/RS [°] Contacting FS	V_{OC} [mV]	J_{SC} [mA/cm^2]	FF [%]	η [%]
B1: 35/90, SAP&SAFE, P2	650	38.0	78.1	19.3
B2: 35/90, plateaus, P2	651	38.1	77	19.1
VPB1: 35/flat, plateaus, P1	617	36	77.4	19.4

Considering the IQE of the BOSS cell B2 and the front side textured cell VPB1 the difference in rear side recombination becomes obvious.

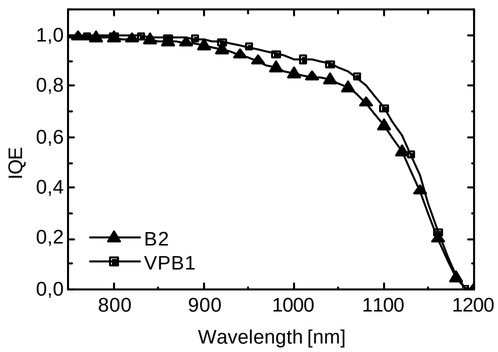

Fig. 8 IQE of the BOSS cell B2 in comparison to that of the front side textured cell VPB1.

The BOSS cell B1 with a SAP&SAFE front contact shows the highest efficiency of 19.3% but due to technical problems independent of the cell concept the fill factor of 78.1% besides the V_{OC} is too low to come over the 20% efficiency mark.

4. CONCLUSION

The MECOR and the BOSS silicon solar cell concept were analysed by experiments and by simulating the optics in particular the light trapping. Different contacting schemes, the SAP&SAFE and an adapted standard technique, were applied to MECOR and BOSS cells.

Only with an improved rear surface passivation the full potential of these concepts can be exploited. While the highest MECOR cell efficiency was 18.5% the BOSS cells show efficiencies of up to 19.3% due to a significantly higher short circuit current density of 38.1mA/cm^2.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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