THE MECOR (MECHANICALLY CORRUGATED) SILICON SOLAR CELL CONCEPT

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ABSTRACT

The novel MECOR solar cell concept relies on double sided mechanically V-textured surface with V-groove running parallel on both sides. The cell thickness can be freely chosen by adjusting the cutting depth. After shallow emitter diffusion and thermal oxidation the oxide is opened either by standard photolithography adapted to the V-textured surface or by shallow angle photolithography. The selection depends on the chosen cell structure. The local back surface field is formed by evaporating aluminum through a silicon mask with point like openings. Different kinds of MECOR cells have been processed varying the angle of the V-grooves on front and rear side. Efficiencies of up to 16.4% (4cm^2, mono-Si) have been demonstrated. Two-dimensional device simulations investigating the influence of surface recombination and diffusion length on the cell parameters have been carried out.

INTRODUCTION

Especially solar cells for space application should have low weight and short distances between the place of optical carrier generation and the emitter, because the hard radiation in space destroys the diffusion length of the minority carriers.

The distance for the carriers to reach the space charge region is shortened using thin silicon wafers for solar cell fabrication as it is the overall trend for industrial production of terrestrial cells.

An effective light trapping scheme must be applied because of the poor light absorption of silicon. This is given by the corrugated cell structure. Both sides of the wafer are V-textured with the V-groove directions running parallel.

At the University of Konstanz a novel solar cell concept was investigated which relies on a corrugated wafer structure. The V-grooves are made mechanically using a conventional dicing saw equipped with bevelled saw blade of different tip angles. The mechanical way of defining the surface structure in contrast to anisotropic etching [1] gives the choice of different V-groove tip angles on front and rear side of the same wafer. It is also suitable for multicrystaline wafer.

The wafer are still mechanically stable despite of the reduced cell thickness of down to 50 µm measured from the top of the front side to the bottom of the rear side. More over the wafer are highly flexible perpendicular to the V-grooves and therefore suitable to be mounted on bent surfaces.

Furthermore, there is a potential for high efficiencies if the enhancement of the open circuit voltage can be exploited. This is only possible if the surface passivation is excellent [1].

Figure 1 shows a scanning electron micrograph (SEM picture) of a MECOR wafer with a V-groove angle of 90° at front and rear side.

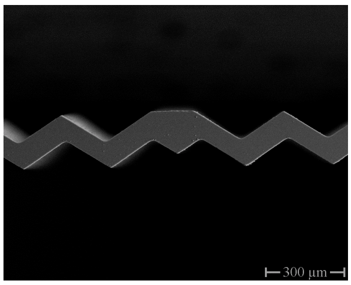

Figure 1: SEM picture of a MECOR wafer structured with a bevelled saw blade having a tip angle of 90°.

After mechanically texturing the wafer receive a shallow emitter diffusion onto the front side and a thermal oxide on both sides. This oxide is opened at the front side by shallow angle photolithography or to the V-texture adapted standard photolithography. On the rear side the local back surface field is formed by evaporating aluminum through a point mask. The cells have a full area Al layer as back surface reflector at the rear side.

MECOR CELL PROCESSING

For the V-groove formation on front and rear side of the 250 µm thick wafer a saw blade with a 35°and 60° tip angle was used. The cutting depth from the particular side depends on the desired cell structure. The deeper the cuts from front and rear side the thinner are the wafer. The investigated cells have cutting depths of 120 µm to 140 µm that means an effective cell thickness of less than 100 µm. The saw damage is etched in an acidic solution (HNO_3, HF, CH_3COOH). After a RCA cleaning the wafer undergoes a thermal oxidation. The oxide has to be removed from the front side for the following shallow emitter diffusion. A second thermal oxide serving as surface passivation and antireflection coating is opened at the front side by two different photolithographical techniques depending on the chosen kind of MECOR cell after the Al-BSF formation.

The Al is evaporated through a two or six percent dot-like opened mask, avoiding an additional photolithographical step and sintered at around 800°C.

The difficulty of any photolithography on structured surfaces is the complete coverage with photoresist of the whole wafer surface including edges and ridges. Therefore, a new photolithographical process sequence was established taking this feature into account. Figure 2 illustrates the two different types of MECOR cells.

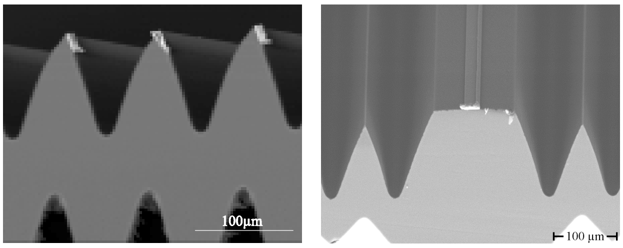

Figure 2: The left SEM picture shows a MECOR cell with contact fingers (10 µm wide) on the right flank. On the right photograph one contact finger (15 µm wide) can be seen on a plateau of 100 µm width.

MECOR cells with contact fingers on plateaus have been fabricated by using a conventional maskaligner equipped with a mask optimised for flat solar cells with homogeneous emitter. Despite a loss in sharpness of the illuminated photoresist edges contact fingers of around 15 µm could be obtained. Because of the texture the busbars has to be thickened by an additional busbar evaporation step.

The oxide of MECOR cells without any plateaus is opened by using shallow angle photolithography (SAP) [2]. This technique relies on the exposition of one particular flank under a shallow angles to the light. One V-groove top serves the following as a shadowing mask. The photoresist at the top of the V-grooves is removed during resist development. The metalisation is done again under a shallow angle by evaporating Ti/Pd/Ag. The shallow angle finger evaporation (SAFE) technique [3] relies on the same principle as the SAP. In this case one V-groove tip allows the following just a 15-20 µm wide and one micron thick metal stripe at one particular flank. Finally the Al rear contact is evaporated onto the whole rear side. Figure 3 shows a summary of the processing sequence.

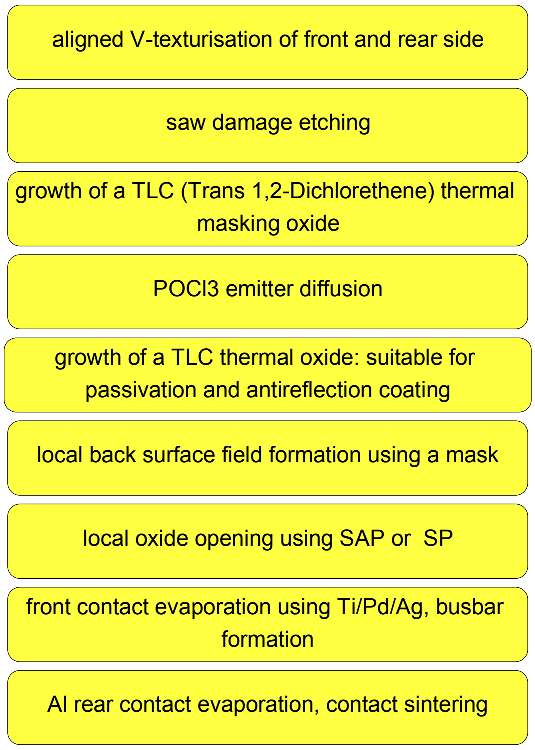

Figure 3: MECOR cell processing sequence (SP means 'standard photolithography')

Al rear contact optimization

First MECOR cells had a very low efficiency mostly due to a very poor surface passivation, a lifetime degradation during cell processing and a big problem with the rear contacting. Because of the large surface on front and rear side of the MECOR solar cell the influence of the surface recombination on the cell parameters is high (Figure 5). After optimization of the diffusion and oxidation process bulk and surface lifetimes significantly improved.

The local Al-BSF is formed without opening the oxide prior to the Al evaporation. Therefore, the Al easily forms spikes into the Si at the places where the Al first penetrates through the oxide. Different rear contact scenarios have been compared to overcome this problem.

Before starting this investigation it was known already that 3 µm thick Al is not enough to go through the oxide (110 nm) and to form a good contact. As a consequence 6 µm Al have been evaporated and the sintering process was slightly changed. Table 1 shows that the fill factor achieved with the 6 % Al coverage using the Si-mask is quite good. If the oxide is opened beneath the Al no problems with the spiking occured. The high series resistance of the untextured reference solar cell with a 2.5 % metal coverage on the rear side oxide might be due to the Al spiking which leads to a very much smaller contact area than the 2.5 %. In addition to that the 2.5 % dot pattern had very much smaller holes than those of the 6 % mask. According to this study the local BSF for MECOR cells was formed by using a 6 % Si mask.

Table 1: Illuminated IV-parameters of flat mono-Si cells (4 cm^2) with different types of BSF formations.

BSF type	V_{OC} [mV]	J_{SC} [mA/cm^2]	FF [%]	η [%]	R_{serie} [Ω/cm^2]
SP 5 %, 6µm Al	651	31.6	77.0	15.8	0.7
mask 6 %, 6 µm Al	650	31.5	79.2	16.1	0.6
SP oxide opened, 3 µm Al	650	31.3	78.7	16.0	0.5
mask 2.5 %, 6 µm Al	647	31.7	75.0	15.4	1.2

MECOR SOLAR CELL CHARACTERIZATION

MECOR cells (mono-Si, 4cm^2) with two different V-groove angles, 35° and 60°, have been processed. Front and rear side have been textured with the same angle. The contact fingers with a thickness of 3 µm are on plateaus in all cases. From the illuminated IV-curves the following cell parameters have been extracted.

Table 2: Illuminated IV-parameters of two different types of MECOR cells.

MECOR cell type	V_{OC} [mV]	J_{SC} [mA/cm^2]	FF [%]	η [%]
35°/35°	628	36.1	72.2	16.4
60°/60°	623	34.4	72.3	15.5

As it can be seen from Table 2 the short circuit currents J_{SC} are quite high. Keeping in mind that the cell thickness is only 50-100 µm, the light trapping must be very effective. The difference in J_{SC} between the two structures can be explained by the difference in the weighted reflection.

The fill factors are both very low which is due to the large I_{02} caused by the V-texturisation and the mechanical pn-junction isolation.

From the dark IV-curve a quite high series resistance can be extracted, Table 3. This is related to the strong drift in sheet resistance over the diffusion furnace quartz boat due to a technical problem. The sheet resistance lies around 200 Ω/sq. Another reason could be the rear side point contacting. For the V-textured rear side the same mask as for the flat cells was used. Evaporated on textured surfaces the Al contact points tend to be wider and less than 6 µm thick. The decreased thickness supports the spiking.

Table 3: Dark IV-parameters of the two different MECOR cells shown in Table 2.

MECOR cell type	I_{02} [A/cm^2]	I_{01} [A/cm^2]	R_{Series} [Ωcm^2]	R_{Shunt} [Ωcm^2]
35°/35°	$6.3*10^{-8}$	$7*10^{-13}$	1.1	$5.5*10^{5}$
60°/60°	$8.8*10^{-8}$	$8*10^{-13}$	0.8	$7.9*10^{5}$

The internal quantum efficiency (IQE) of the MECOR-cells shows the excellent light trapping, since even at wavelengths longer than 1100 nm there is still a non negligible contribution to the J_{SC}.

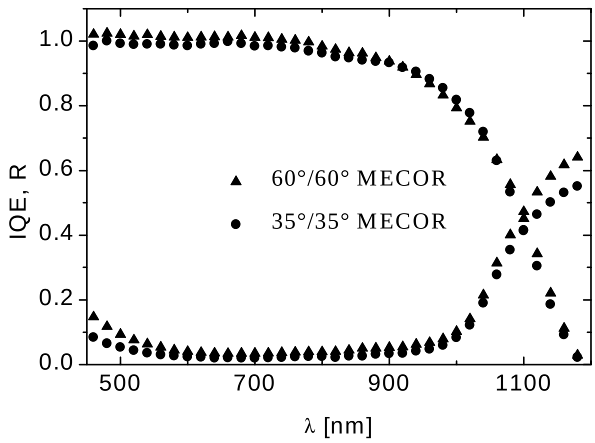

Figure 4: Internal quantum efficiency and hemispherical reflectance of the two different MECOR cells.

2 DIMENSIONAL DEVICE SIMULATIONS

Because of the importance of the surface recombination two dimensional MECOR cell simulations have been undertaken using the software package $DESSIS_{ISE}$ [4].

Two different cell designs have been investigated, first a MECOR cell with 35° V-grooves on both sides and second a cell with front side 35° and rear side 60° V-grooves. The contacts are not on plateaus but on the flanks. An oxide region on the front and on the rear side is used to define the surface passivation conditions.

The optical generation is done with the program 'Sonne' [5] which relies mainly on ray tracing applying geometrical optics. For the optical simulation the rear side is covered with an oxide and an Al-layer as back reflector. The front side just got a 110 nm thick SiO_2 as an antireflection coating.

The results of the simulation of the MECOR cell (35° on both sides) are shown in Figure 5. Different surface recombination velocities (SRV) and their influence on the short circuit current have been investigated. The influence of the front SRV is quite small compared to the increase in J_{SC} of 0.8 mA/cm^2 while decreasing the rear SRV from just 500 cm/s to 100 cm/s in the case of a diffusion length of 300 µm.

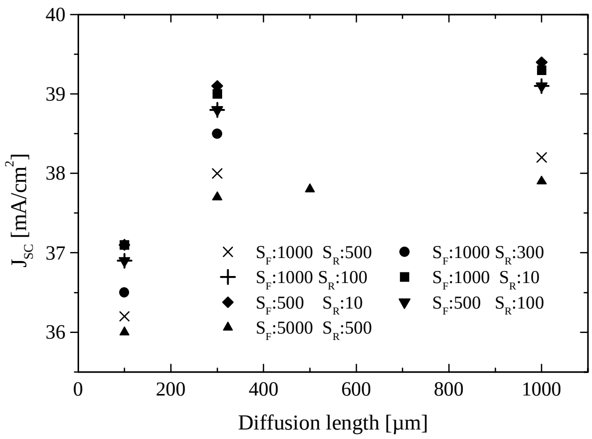

Figure 5: J_{SC} in dependence of the diffusion length for different surface recombination velocities.

A comparison of two different texture angles at the rear side, 35° and 60° regarding their illuminated IV-parameters shows the following Table 4:

Table 4: Simulated illuminated IV-parameters of two kinds of MECOR cell with different angles of the rear side V-texturisation, 35° and 60°.

angle/ diffusion length	V_{OC} [mV]	J_{SC} [mA/cm2]	FF [%]	η [%]
35°/100µm	585	36.9	81.9	17.7
35°/300µm	627	38.8	82.4	20.0
35°/1000µm	642	39.1	82.5	20.7
60°/100µm	587	38.3	82.1	18.5
60°/300µm	631	40.3	83.1	21.1
60°/1000µm	651	40.5	83.7	22.1

From the illuminated MECOR cell parameters the benefit of the reduced surface of the 60° cells becomes obvious. MECOR cells with 100 µm diffusion length (L_D) have a very much smaller V_{OC} and J_{SC} than cells with L_D=300 µm which is due to the special cell geometry. Since the cells are 110 µm thick for rays entering the wafer at the tips, it makes no difference for the L_D = 100 µm cell if the rear surface area is decreased. Despite of this the J_{SC} of the L_D = 100 µm MECOR cell increases similar to the other J_{SC}. The reason for the increase in J_{SC} of all cells with an angle of 60° on the rear side is besides the reduced surface recombination, the larger remaining silicon bulk.

FUTURE PLANS

Further activities will include an improvement of the processing sequence to obtain higher fill factors. Therefore I_{02} has to be reduced as well as the series resistance. I_{02} will be mainly reduced by avoiding the mechanical pn-junction isolation. In addition to that the SAP&SAFE metalisation concept will be further optimised. This will also help to improve the FF, since the contact fingers can be very narrow while the reflectance stays low.

CONCLUSIONS

The novel MECOR solar cell concept has been introduced. Cell process development leads to efficiencies of 16.4%. Two dimensional device simulations have been carried out and show the importance of an excellent surface passivation as well as the great benefit of a larger angle for the rear side V-texturing.

ACKNOWLEDGEMENTS

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