HIGHLY EFFICIENT MECHANICALLY V-TEXTURED SILICON SOLAR CELLS APPLYING A NOVEL SHALLOW ANGLE CONTACTING SCHEME

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ABSTRACT: Mechanical surface texturisation leads to reduced cell reflectance, enhanced light trapping and an increase in carrier collection probability. Above all the structuring method opens numerous possibilities of novel solar cell concepts. For an estimate of the potential of these cell concepts investigations of simple, mechanically single side textured silicon solar cells have been carried out. Three different basic cell types, each requiring its own metallisation technique, have been processed. The V-grooved cell which is contacted applying the novel, the SAP&SAFE metallisation scheme, i. e. shallow angle photolihtography and shallow angle finger evaporation. Another V-grooved cell type leaves plateaus for the grid fingers which are defined by an adapted standard photolithography (ASP) step. The third type is a rear side textured cell with a flat front side. The local rear contact is formed by applying local SAP to open the oxide on the rear and use standard photolithography (SP) for the front side oxide. The results of mechanically V-textured cells (on float zone silicon) with the SAP&SAFE metallisation show an efficiency η=19.8% (V_{OC}=675mV, J_{SC}=37.7mA/cm^2, FF=77.7%, cell area=4cm^2) and cells with grid fingers on plateaus an efficiency η=20.1% (V_{OC}=671mV, J_{SC}=37.1mA/cm^2, FF=80.7%, cell area=4cm^2). In comparison, the flat references reached an efficiency η=17.8% (V_{OC}=677mV, J_{SC}=32.2mA/cm^2, FF=81.2%, cell area=4cm^2).

Keywords: - Metallisation Scheme 1: - Mechanical Texturing2: - c-Si 3

1. INTRODUCTION

Mechanical surface texturisation leads to a reduction in cell reflectance, an improvement in light trapping and an increase in carrier collection probability. Most important hoowever, the mechanical structuring method opens numerous possibilities of novel cell concepts like LOPE cells [1], MECOR (MEchanically CORrugated) cells [2], LAMELLA cells [3] (Figure 1), POWER (Polycrystalline Wafer Engineering Result) cells [4] or OECO (Obliquely Evaporated COntacts) cells [5]. All these concepts but the OECO cell are investigated at the University of Konstanz.

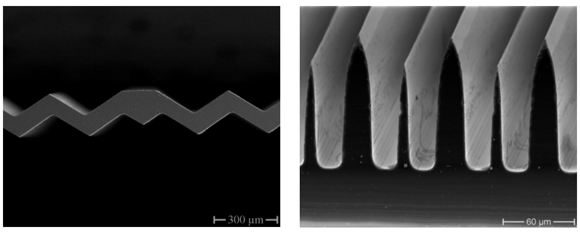

Figure 1: *Novel solar cell concepts relying on mechanical texturisation: MECOR cell concept (left), LAMELLA cell concept (right)*

The MECOR and the POWER cell concepts rely on mechanically texturing both the front and the back side. In the case of the POWER cell the grooves on front and rear side of mostly multi-crystalline wafers are running perpendicular to another while on MECOR cells a parallel orientation of the texture on front and rear side is chosen. For the MECOR cells in contrast to the POWER cells floatzone silicon wafers are deployed in general but the concept is also suitable for silicon wafer with a short carrier lifetime. In that case both concepts making use of the short distances from any place of charge carrier generation to the emitter region.

Single sided textured cells allow the separation of effects related to the front and those originating from the rear side texture. Therefore single sided textured cells of which either the front or the rear side was structured have been processed.

The mechanical V-groove surface texturisation was done using a conventional dicing machine equipped with a bevelled saw blade (35° or 60° tip angle). Two main structures have been examined leading to two different types of front side metallisation. One approach leaves plateaus for the metal grid fingers and the other forms higher V-groove tips for the **s**hallow **a**ngle **f**inger **e**vaporation (SAFE). Because of the self aligning character of this metallisation scheme it offers a simple way to vary the grid finger spacing just by adjusting the cutting parameters.

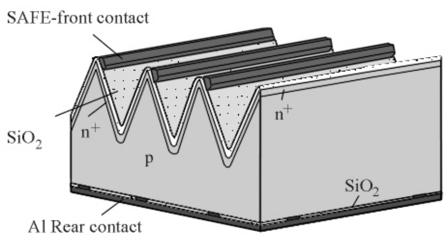

Figure 2: *Schematic representation of a single sided mechanically V-textured solar cell using the SAP&SAFE technique for metallisation.*

The cells' busbars runs perpendicular to the V-grooves. After a shallow emitter diffusion into an oxide defined region the subsequently grown thermal passivation oxide has to be opened by means of photolithography for rear and front contacting. On cells with plateaus this is done using a conventional maskaligner and an adapted standard photolithography. The contact area for cells with SAFE metallisation is defined by the exposure angle. The contact metals are evaporated subsequently. A schematic representation of a cell which is metallised by the SAP&SAFE technique is descibed in Figure 2.

2. SOLAR CELL PROCESSING

For the V-groove formation on front and rear side of a 250µm thick wafer a saw blade with a 35° or a 60° tip angle was used. The cutting depth was around half the wafer thickness for the SAP&SAFE metallised cells but only 80µm for the cells with plateaus. The saw damage of 4µm is etched in an acidic solution (HNO_3, CH_3COOH, HF). After an RCA-cleaning the wafer undergoes a thermal oxidation for masking the wafer for the subsequent shallow emitter diffusion. A second thermal oxide serving as surface passivation and single layer antireflection coating (SL-ARC) is opened locally at the rear side. The front side contact is formed either by means of SAP&SAFE or by standard photolithograpy which is adapted to the special constraints of deeply grooved surfaces (ASP). Subsquently the Ti/PdAg front contact is evaporated either by means of the SAFE technique or conventionally. The Al-rear contact is thermally evaporated. Figure 3 shows a summary of the applied processing sequences.

Front side textured		Rear side textured
Plateaus	SAP&SAFE	local SAP (rear)

Mechanical texturisation
saw damage etch

Thermal oxidation:
Masking oxide

Definition of emitter region
Emitter diffusion: $POCl_3$ 90Ω/sq

Thermal oxidation:
Surface passivation
Single layer antireflection coating

Rear contact area definition	
Standard Photolithography	Local SAP

Front contact formation		
ASP + Ti/Pd/Ag evaporation	SAP&SAFE of Ti/Pd/Ag	SP + Ti/Pd/Ag evaporation

Al-rear contact evaporation and silver electroplating
Contact sintering

Figure 3: *Processing sequences for three different types of single sided textured cells.*

The difficulty of any photolithography on textured surfaces is the complete coverage with photoresist of the whole wafer surface especially at the edges and ridges. Therefore a novel photolithographical processing sequence was established taking into account the demand of completness of coverage. The key result of the optimisation is that the light exposure and development duration have to be very carefully matched with the special drying sequences for the particular multi layer photoresist system which in turn depends on the chosen kind of surface texture, Figure 3. If during light exposure a comb like mask is placed on the exposed wafer with the prongs running perpendicular to the V-grooves also local oxide openings can be achieved. and the oxide can be locally opened through the photoresist mask.

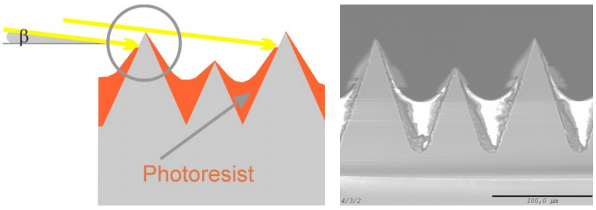

Figure 4: *Schematic representation of the SAP-technique (left) and a SEM-picture of a successfull SAP (right).*

3. REFLECTANCE MEASUREMENTS

For a characterisation of the mechanically textured cells the impact of the particular texturing pattern on the electrical performance is important. Therefore the reflectance curves of different structures are considered. The wafers are mechanically textured using a saw blade with a tip angle of 35° or 60° for front or rear side of the structures.

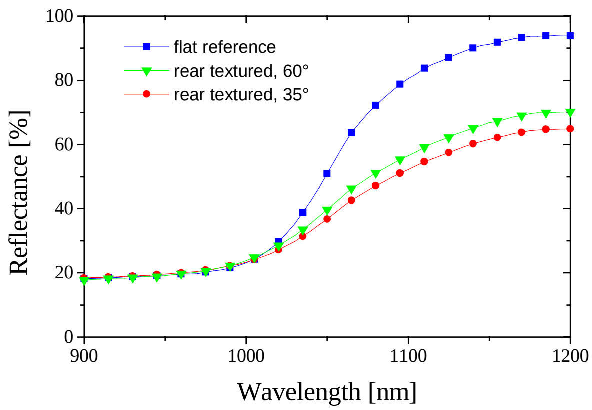

Figure 5: *Comparison of reflectance of rear side textured wafers coated with a SiO_2 SL-ARC. The texturing was done applying saw blades with 35° or 60° tip angles.*

The wafers have a SiO_2 SL-ARC and an aluminium back side reflector. Figure 5 shows the reflectance of two different rear side textures, one is formed using a saw blade with a 35° tip angle and the other is cut by a blade with 60° tip angle. This is compared to a flat reference wafer.

As can be drawn from the graph the wafer with a rear side textured with a saw blade of 35° tip angle shows a slightly lower reflectance for long wavelengths between 1000 and 1200nm. The reflectance of the flat reference wafer is as high as 95% at 1200nm which indicates the very low absorption of the Al-rear side.

Double sided textured wafers have also been investigated. Figure 6 shows the reflectance of wafers with rear grooves running parallel or perpendicular to the front grooves.

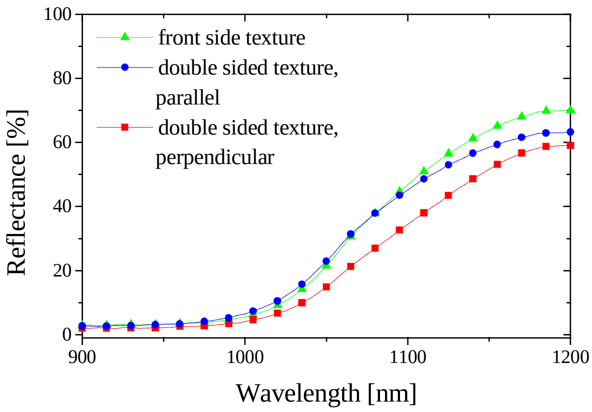

Figure 6: *Comparison of the reflectance of perpendicularly and parallelly mechnically textured wafers with a SL-ARC and a Al rear contact but no front contacts. The texturing was done applying a saw blades with 35° tip angle.*

The enhanced optical pathlength in the perpendicularly textured wafer becomes obvious comparing the shape of the curves of the two double sided structures. While the reflectance of the parallely textured wafer starts to increase at a wavelength of 960nm the reflectance of the perpendicular textured wafer stays almost constant up to λ=1000nm. The comparison of the reflectance curve of the front side and the parallely textured wafer indicates the influence of the light trapping effect of rear side texture even in the case of the parallely textured wafer where the influence is much smaller than in the case of the perpendicularly grooved wafer.

4. SINGLE SIDED TEXTURED SILICON SOLAR CELLS

Different single sided textured solar cells have been processed, more precisely there are rear side textured cells and two different kinds of front side textured ones. The solar cell processing was carried out according to the process sequence outlined in Figure 4. From the illuminated IV-curves the following cell parameters listet in Table 1 have been extracted:

Table 1: *Illuminated IV-parameters of different types of single sided mechanically textured solar cells and a flat reference cell(all cells: floatzone silicon, cell area 4cm^2, 0.5Ωcm).*

Cell type	V_{OC} [mV]	J_{SC} [mA/cm^2]	FF [%]	Efficiency [%]
Front texture/ SAP&SAFE	675	37.7	77.7	19.8
Front texture/ Plateaus	671	37.1	80.7	20.1
Rear texture/ local SAP	667	32.7	80.2	17.5
Flat reference	677	32.2	81.2	17.8

The efficiency of 19.8% of the front textured cell with SAP&SAFE metallisation indicates the high potential of these techniques. Once the fill factor is well above 80% the efficiency will reach 20.5%. Unfortunately the fill factor is quite low due to local shunt resistances caused by contacting the base with the emitter contact. Despite of that the open circuit voltage , V_{OC}, is almost as high as for the flat reference cell. Hence there is no disadvantage due to mechanical texturisation with regards to V_{OC} at this level of efficiencies. But the saturation current I_{02} of the second diode is by a factor of ten higher compared to the flat reference. A factor of two could be explained by the enlarged front surface area, i.e. by a doubled emitter area. Besides that effect there must be another one related to handling of the mechanically textured cells. This is currently under investigation.

The front side textured cell with plateaus for the finger grid features a lower short circuit current. This due to a higher reflectance caused by the flat plateaus (12-14%) and the shallower V-grooves compared to the SAP&SAFE cell.

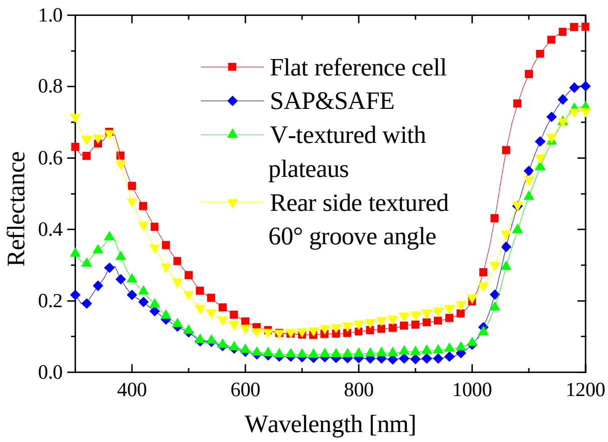

Figure 7: *Reflectance measurements of differently textured cells as indicated. The light trapping effect is clearly visible, especially for the rear side textured cell compared to the flat one.*

With the groove depth the influence of the tip radius of the saw blades becomes more pronounced. Since the saw blades are not exactly sharp but rounded with radii between 20-40µm at the tip the V-grooving also causes almost flat areas.

The rear side textured cell with flat front surface shows a significant loss in V_{OC}. The main reason is an enhanced rear surface recombination. Computer simulations with $DESSIS_{ISE}$, a commercial program for semiconductor devices [6], show that a rear surface velocity smaller than 100cm/s is necessary to maintain the V_{OC} of the flat reference for that kind of cell [7].

Reflectance measurements presented in Figure 7 clearly show the light trapping effect of mechanically textured cells of any kind. Unfortunately the oxide did not get the right thickness.

The external quantum efficiencies (EQE), Figure 8, explain in which wavelength region which contribution to J_{SC} is missing. The two front textured cells show similar curves. The lower reflectance of the cell with plateaus in the wavelength range above 1050nm results in a J_{SC} increase of less than 0.05mA/cm^2. But the contribution to

J_{SC} in this wavelength range of the front side textured cells is with 1.6mA/cm^2 double as high as it is for the flat reference cell. Even the rear side textured cell achieves a very slight increase in J_{SC} compared to the flat reference despite the much lower EQE at wavelengths between 800 and 1050nm.

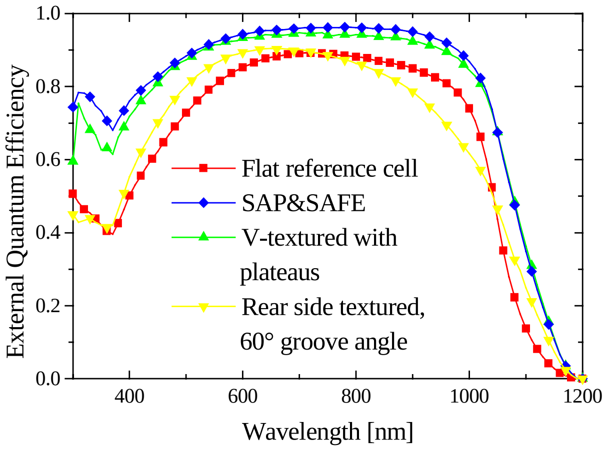

Figure 8: *Measurements of external quantum efficiency of differently textured cells as indicated. The light trapping effect of either front or rear side textured cells is clearly visible.*

5. CONCLUSION

Highly efficient mechanically textured silicon solar cells have been processed using the SAP&SAFE metallisation scheme or a combination of an adapted standard photolithography process with conventional lift off technique. Cell efficiencies of 19.8 % for the first type of cells could be achieved and 20.1% for the latter. Reflectance studies have been carried out investigating the influence of different texturing profiles.

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