THE RANGE OF HIGH-EFFICIENCY SILICON SOLAR CELLS FABRICATED AT FRAUNHOFER ISE

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ABSTRACT

An overview of the high-efficiency solar cell development with crystalline silicon at Fraunhofer ISE is given. Seven types of cells are discussed: (1) LBSF cells (local back surface field), (2) RP-PERL cells (random pyramids, passivated emitter rear locally-diffused); (3) RP-PERC (random pyramids, passivated emitter and rear cell); (4) MESC (mesh-structured emitter cell); (5) cells with interdigitated contacts; (6) high-efficiency thin film cell based on SOI (silicon on insulator); and (7) mini modules integrated on one 4" SOI-wafer. All these cells show very good efficiencies close to or well above 20 %, respectively. The goal of all activities is to develop technologies for efficiencies as high as possible but at the same time as simple as possible. Many of the developments are performed in close cooperation with German PV companies and/or with European research teams in the framework of projects of the European Commission.

LBSF SOLAR CELLS

Our „base" technology is the LBSF processing scheme [1] which is similar to the PERL cell of UNSW [2]. The main features of this technology are: front texture by inverted pyramids, two-step emitter, boron-diffused local BSF under the rear point contacts and passivation of the front and rear side by SiO_2.

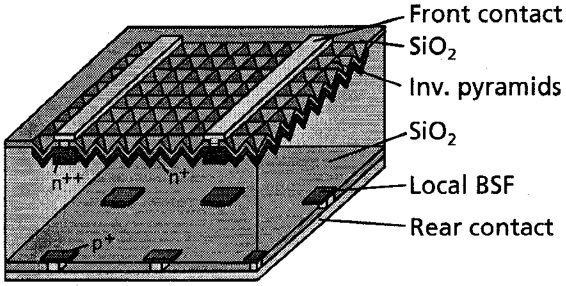

Fig. 1. LBSF solar cell.

This processing scheme requires five oxidations, two phosphorus and one boron diffusion and a minimum of six photomasking steps with high accuracy of alignment. The highest efficiency we could obtain was 23.3 % on a 250 µm thick 1 Ω cm p-type FZ-wafer and a cell size of 4 cm^2. Using a photoresist definition for the front contacts during electroplating in combination with a double layer antireflective coating resulted in a record high short circuit current of 42.0 mA/cm^2. Applying a single layer SiO_2-AR coating of 105 nm we obtained a slightly higher value of V_{OC} = 700 mV, however a somewhat smaller J_{SC} = 41.3 mA/cm^2 thus also leading to the same efficiency of 23.3 % [3]. For a cell area of 21 cm^2 an efficiency of 21.4 % was obtained. The lower value is mainly due to a not yet very well optimized front grid (table 1).

Tab. 1. Confirmed results for LBSF-cells from Fz-Si.

Area [cm^2]	4	4	21
V_{OC} [mV]	685	700	692.4
J_{SC} [mA/cm^2]	42.0	41.3	38.6
FF	0.81	0.806	0.802
η [%]	23.3	23.3	21.4

Making use of the LBSF process scheme to Czochralski (Cz) grown silicon the best efficiency so far was 22.0 % which is an international record value for this material. The used silicon was in the resistivity range 5-10 Ω cm. Cells from such high-resisistivity material show practically no degradation [4]. Results are given in table 2.

Tab. 2. Confirmed results for LBSF-cells from Cz-Si.

Area [cm^2]	4	21	42
V_{OC} [mV]	680.5	674.3	678.5
J_{SC} [mA/cm^2]	41.8	38.7	38.9
FF	0.772	0.790	0.786
η [%]	22.0	20.6	20.8

RP-PERL SOLAR CELLS

The RP-PERL cell is a simplified version of the LBSF cell, showing texturization with random pyramids and a one-step emitter only. This cuts down the processes to three oxidations, one phosphorus and one boron diffusion and four photomasking steps. The obtained values using 1 Ω cm FZ-silicon are given in table 3. There is only a minor reduction in efficiencies.

Tab. 3. Confirmed results for RP-PERL cells.

Area [cm^2]	4	21	42
V_{OC} [mV]	688.1	674.8	677.5
J_{SC} [mA/cm^2]	40.5	38.5	39.1
FF	0.811	0.819	0.808
η [%]	22.6	21.3	21.4

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RP-PERC SOLAR CELLS

A much more simple solar cell is the RP-PERC cell, based on the PERC scheme [5]. The cell incorporates random pyramids, one-step emitter and no boron BSF. The production requires only two oxidations, one phosphorus diffusion two or three photomasking steps with relaxed alignment. The two necessary photomasking steps (pm) are the definition of the front grid and of the rear contact points. A third optional pm is the definition of the emitter area for a planar diffusion. Cells without this pm step receive a phosphorus diffusion on the complete front surface and are cut by laser from the rear side to avoid shunting problems. The results are given in table 4.

Tab. 4. Confirmed results for RP-PERC cells (FZ-silicon).

Area [cm^2]	4	21	4
V_{OC} [mV]	676.4	675.4	672.0
J_{SC} [mA/cm^2]	39.6	38.7	39.3
FF	0.807	0.799	0.797
η [%]	21.6	20.9	21.0
pm steps	3	3	2

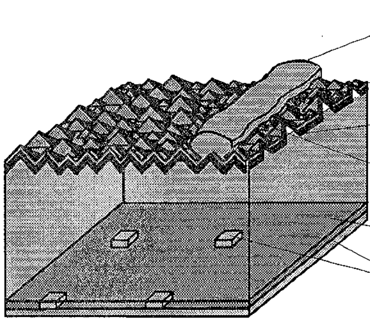

Fig. 2. RP-PERC solar cell.

In spite of the strong process simplifications we could reach efficiencies of up to 21.6% with three pm steps (to our knowledge the highest value for such a simple cell), and 21.0% with two pm steps. The "missing" 1.7% compared to 23.3% of a LBSF cell have to be "paid" for with three oxidations, one boron and one phosphorus diffusion and a minimum of three pm steps. Table 5 gives the solar cells parameters, when p-type Cz-silicon of about 1 Ω cm is used. Higher resistivities would decrease the fill factor because of the high transition resistance between semiconductor and aluminum at the rear contact points.

Tab. 5. Confirmed results for RP-PERC cells (Cz-Si).

Area [cm^2]	V_{OC} [mV]	J_{SC} [$mAcm^{-2}$]	FF	η[%]
4	656.3	37.7	0.795	19.7

CELLS WITH A MESH-STRUCTURED EMITTER

The mesh-structured emitter (ME) is a new processing scheme consisting in principal of a laterally homogeneous heavy phosphorus diffusion followed by a texturization with inverted pyramids or microgrooves [6]. The resulting structure, a mesh of highly doped emitter lines, has some versatile features:

- The emitter conductivity is not isotropic, but can be controlled by the texturization pattern, e.g. a higher conductivity orthogonal to the front grid can be achieved by microgrooves aligned orthogonal to the grid fingers.
- The high phosphorus concentration in the ridge tops of the pyramids reduces the contact resistance to the front grid, which is very important for screen printed contacts.
- With an additional lateral shallow emitter, a two-step emitter is formed without any additional photolithographical process step.
- The emitter conductivity can be increased without increasing the recombination losses too much, because the highly recombining volume is reduced to the emitter lines.

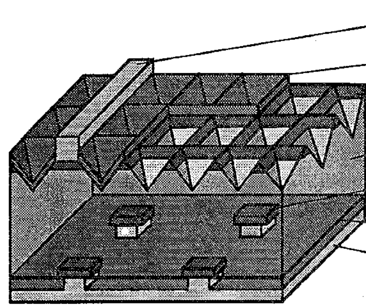

Fig. 3. Solar cell with a mesh-structured emitter (MESC).

Table 6 shows results of solar cells fabricated with the conventional mask set for high-efficiency solar cells (inverted pyramids with 20 μm base length) on 1 Ω cm FZ-silicon. Two types of mesh-structured emitters were used: one without any additional diffusion (abbr. as ME) and the other one with an additional very shallow phosphorus diffusion (ρ_{sheet}> 250 Ω/sq) after the pyramid texturization (abbr. as MEW). Using these both emitter types, rear passivated cells without (Al) and with (Bor) local boron back surface fields were fabricated.

Efficiencies of well above 20% were reached for the structures with additional shallow emitter diffusion (MEW). However, the efficiency of the cells without shallow emitter is clearly decreased. This is mainly due to the decreased open circuit voltage, which is caused by the relatively high recombination velocity at the textured silicon-oxide interface [7].

Tab. 6. Confirmed results of cells with mesh-structured emitter.

	ME-Al	MEW-Al	ME-Bor	MEW-Bor
V_{oc} [mV]	657.8	677.0	656.9	696.1
J_{sc} [mA/cm^2]	39.5	39.8	39.1	40.53
FF	0.739	0.783	0.777	0.803
η [%]	19.2	21.1	20.0	22.7

CELLS WITH INTERDIGITATED CONTACTS

A set of masks for cells with interdigitated grids was used on 250 µm thick low-resistivity (1 Ω cm) p-type FZ-silicon. Two types of cells were fabricated: the first for a bifacial application (BFC), the second for a monofacial illumination from the unmetallized side (RCC).

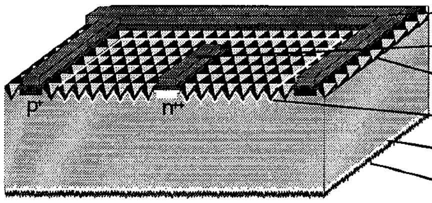

Fig. 4. Solar cell with interdigitated contacts.

The bifacial cell (BFC) is textured on both sides for optimal optical characteristics. An oxide passivated floating emitter is applied on the unmetallized side (bottom side in Fig. 4) in order to decrease the surface recombination velocity. A thermal oxide alone on a textured surface is known to have a non-optimal surface recombination velocity of more than 1000 cm/s and leads to a decrease of 30 mV in V_{oc} for this cell type [7]. Since the floating emitter on the unmetallized side is processed in the same step as the one on the metallized side, the process is not becoming more complex with this additional feature. On the metallized side of the cell nearly the whole surface is covered by phosphorus diffusion. Only a fraction of around 2% is left undiffused for the base contacts. Local deep diffusions underneath both, emitter and base contacts were used. Due to the resulting high surface doping concentration it is possible to use Ti/Pd/Ag not only for the emitter but also for the base contacts. The distance between the finger lines of one grid type is between 1000 to 1430 µm. The results in table 7 show that efficiencies of more than 20% for the illumination from both sides have been achieved on the same cell, an international record value [8].

Tab. 7. Confirmed results of cells with interdigitated contacts

	BFC illum. from top (see Fig.4)	BFC illum. from bottom	RCC illum. from bottom
V_{oc} [mV]	689	688	688
J_{sc} [mA/cm^2]	38.8	40.4	40.1
FF	0.755	0.741	0.778
η [%]	20.2	20.6	21.4

For the cell acting as a rear contact cell (RCC, illumination from the bottom side in Fig. 4) the texturization on the metallized side is obsolete. Thus, this surface was kept flat, resulting in better recombination characteristics. With this cell type efficiencies of up to 21.4 % have been achieved up to now. A detailed analysis of the RCC structure is given in another publication at this conference [9].

HIGH-EFFICIENCY THIN-FILM CELLS BASED ON SOI

In order to study the influence of different cell parameters on crystalline silicon thin-film cells, we have processed a high-efficiency cell on a thin epitaxially grown silicon layer. [10],[11]. This layer was grown epitaxially by CVD on a SOI (Silicon-On-Insulator) structure, and resulted in a 46 µm thick mono-crystalline Si layer (N_A = 8x10^{16} cm^{-3}) on an ion implanted insulating SiO_2 layer.

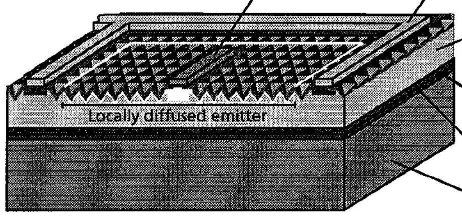

Fig. 5. Thin-film solar cell based on SOI.

To study the influence of the effective back surface recombination velocity, some of these wafers were prepared with an additional highly doped 5 µm thick p^+-layer (N_A = 6x10^{18} cm^{-3}) between the SiO_2 layer and the active Si-film which acts as a back surface field. Fig. 5 shows the structure of the cell. All contacts are on the front side, beside that all the features of the LBSF-structure are given. Some cells have been processed without any texturization but with a double layer AR coating, therefore showing no light confinement. The results are summarized in table 8.

19.2% (confirmed by ISE) is up to now the highest efficiency for a epitaxially grown thin film silicon solar cell. The difference in efficiency was absolute about 5% between the application of electrical and optical confinement (19.2 %) and no confinement measures (14 %), underlining the important influence of this parameters on the cell performance.

Tab. 8. Thin-film silicon cells on SOI.

	Inverted Pyramids		Flat with ARC	
	BSF	no BSF	BSF	no BSF
V_{OC} [mV]	668	634	658	623
J_{SC} [mA/cm^2]	37.1	33.9	33.0	29.4
FF	0.775	0.781	0.735	0.764
η [%]	19.2	16.8	15.9	14.0

MINI MODULES INTEGRATED ON ONE SOI WAFER

Thin-film cells on insulating substrates with interdigitated front contacts allow a series interconnection of cells on one wafer or substrate, respectively. Such a "mini module" is realized on a 4" SOI wafer with a similar cell type as described in the previous section.

The active Si-layer consists of a 40 µm thick p-type base on top of 5 µm thick p^+-BSF. The cells have an active area of 1x1 and 2x1 cm^2 and are arranged in strings with 6 and 8 cells, respectively. Within one string the base bus bar of one cell is located opposite to the emitter bus bar of the next. Subsequently, grooves are lasered around the active cell areas down to the insulating SiO_2 layer. Thus, the base of each cell is separated from the other cells. In a final step the cells are series interconnected using a bond technique.

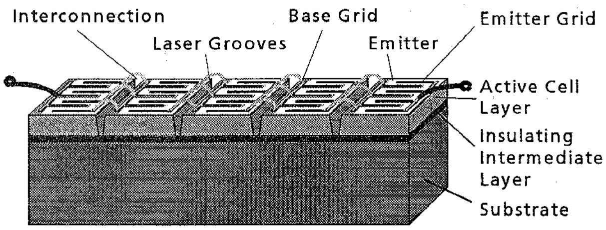

Fig. 6. Simplified scheme of a mini module integrated on one SOI wafer.

Since 4 strings with each 6 1x1 cm^2 cells and one string with 8 2x1 cm^2 are available on one 4" wafer, it is possible to achieve different voltages and currents.

Tab. 9. Results of various configurations of mini modules integrated on one SOI wafer

Configuration	I_{sc} [mA]	V_{oc} [V]
6 x 1 cm^2 cells	35.3	3.87
12 x 1 cm^2 cells	35.3	7.77
18 x 1 cm^2 cells	34.1	11.54
24 x 1 cm^2 cells	33.96	15.23
8 x 2 cm^2 cells	70.7	5.2

The efficiency of a mini module can not be determined very accurately because the cell area is defined only by the laser groove around the cells. Approximating the cell area with 1.02 cm^2, the efficiency of the mini module with 12 cells (see row no.2 in table 9) would be 17.1 %. Even in comparison with the maximum efficiency of 19.2 % for a single thin film cell with interdigitated front contact (see previous section) this output is excellent, since the layout of the cells used for the mini module was chosen less complicated in order to achieve a very high reliability of all cells.

CONCLUSION

Six different cell types all fabricated in the ISE cleanroom are discussed: Additionally to the LBSF cell for highest efficiencies (23.3 % on FZ-Si, 22.0% on Cz-Si), a strongly simplified high-efficiency cell process scheme, RP-PERC, with efficiencies up to 21.6 % is described. Cells incorporating the new mesh-structured emitter have reached efficiencies of 22.7 %. A set of masks for cells with interdigitated grids was designed. This mask set was used for bifacial cells on 250 µm thick FZ-Si, which have shown efficiencies higher than 20 % from both sides. Using this set of masks for thin Si-layers (46 µm) which were epitaxially grown on an insulating intermediate SiO_2-layer (SOI-structure) an efficiency of 19.2% has been obtained. With the same cell concept a mini module was integrated on such a SOI wafer and voltages of more than 15 V have been obtained with 24 1x1 cm^2 cells interconnected on one 4" wafer.

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