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METAL FINGERS ON GRAIN BOUNDARIES IN MULTICRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT:
We have developed a method of applying a net-like finger grid to the front side of multicrystalline (mc) silicon solar cells, which lies mainly on the grain boundaries (Grain Boundary Oriented Finger grid, GBOF grid). This net has no busbars. It is drawn by a plotter using screen printing paste.
The efficiency of cells contacted in this manner has been tested in a comparative study of pairs and triplets of cells of size 100x100mm^2 (Bayer) and 103x103mm^2 (Eurosolare). In the pairs-study pairs of neighbouring wafers of the original ingot were processed into solar cells. One wafer received a GBOF-grid, the other got the same grid rotated by 90 degrees and so had little coverage of grain boundaries. In the triplets study a third neighbouring wafer was added and equipped with a standard H-pattern of the same shading as the GBOF-grid. Many pairs and triplets were made. The pairs study showed that the GBOF-grid gives solar cells with 3.7% more output, on average, under approximately standard conditions. The triplets study shows that the GBOF-grid increases power output by 2.5%, on average, over the standard H-pattern.

Keywords: 1, multi-crystalline - 2, grain - 3, contact

1. Introduction

In multicrystalline silicon solar cells the grain boundaries and the higher concentraion of in-grain defects are the main reason for lower conversion efficiency. The usual way of improving the efficiency is to passivate the grain boundaries with hydrogen atoms, often in combination with surface passivation, and to getter impurities during the cell production. In the present work another method has been investigated, which may also be applied in addition to the existing methods: The front metal grid of the solar cell has been designed such that it mainly follows the grain boundaries. Theoretically, this entails some beneficial effects:

- The shading due to the metal lines is over areas of short lifetime, thereby exposing more long lifetime area to sun light. This should increase the short circuit current.
- Since the metal lines run over 'dead' area, they can be thicker, which reduces the series resistance.
- The electrons in the n-doped emitter drifting to the metal lines do not have to cross the potential barriers at the grain boundaries. This, too, reduces the series resistance.

A theoretical simulation tends to support this [1] as well as earlier work by us [2, 3] and by another group [4]. Here we report for the first time on the largest statistical sample done so far on cells of industrial size.

2. Experiments

2.1 Layout of the study

The study was done on a series of pairs of solar cells made from adjacent wafers of the original ingot, and then on a series of triplets, similarly obtained from neighbouring wafers.

The pairs study was done on Baysix 100x100mm^2 wafers of about 270µm thickness and on Eurosolare 103x103mm^2 wafers of about 340µm thickness, both boron doped between 0.5 and 2.0 Ω.cm. The triplets study was done only on Baysix wafers. In the pairs study one wafer of each pair received the GBOF-grid (from now on called an 'ON-cell') and the other got the same grid but rotated by 90° before application (from now on called an 'OFF-cell').

Since the two wafers had almost identical grain structure, any difference in performance of the solar cells would be largely due to the way the front metal grid was placed relative to the grain boundaries. In the triplets study the additional solar cell was equipped with a standard H-grid consisting of parallel fingers and two busbars (we shall call these cells 'STD-cells'). But care was taken that the shading of this grid was the same as that of the GBOF grid. The purpose of the triplets study was to see whether the GBOF-grid, when rotated by 90°, so that it would not follow the grain boundaries, showed any difference in its electrical parameters compared to the standard H-grid, which seems to be optimal with respect to minimizing optical and electrical losses. Since in both cases grain boundaries would be covered only accidentally, the difference should be mainly attributable to different series resistance losses.

2.2 Solar cell preparation and characterisation

2.2.1 Laboratory process

The solar cells were made in batches of typically 20 pieces because the quartz boat of the diffusion furnace was limited to 25 pieces and 2 to 3 wafers served as buffers against the gas draft at either end. The following process and characterisations were used:

- Saw damage removal.
- Determination of minority carrier lifetime.
- pn-junction formation in $POCl_3$ atmosphere.
- Measurement of n-emitter sheet resistance.
- backside metalization with screen printed Al/Ag paste.
- scanning of front side of wafer in flat bed scanner.
- Calculation of optimal number of fingers for standard H-grid.
- Calculation of the layout of the GBOF-grid.
- Drawing of front grid with Ag screen printing paste.
- Mechanical abrasion of parasitic junction at the edges.
- Current-voltage characterisation of cell, in the dark and under illumination.

The cells received no anti-reflection coating and no passivation of the grain boundaries.

The sheet resistance of the emitter ranged between 25 and 35Ω/sq, going as high as 45Ω/sq at the first and last wafer of a batch.

The paste used for the back side was Ferro FX33-130, and the one for the front side was Ferro 3347 Ag Conductrox. All three kinds of patterns on the front were written with a dispensing tube of 250µm. After sintering the typical line thickness was 350µm. The specific line resistance, determined on separate wafers without n-doping, was approximately 30mΩ/cm. The contact resistances were also established on separate wafers having an n-emitter just as the actual solar cells. Typical values were 11 to 12mΩcm^2. A triplet of wafers is shown in Fig.1.

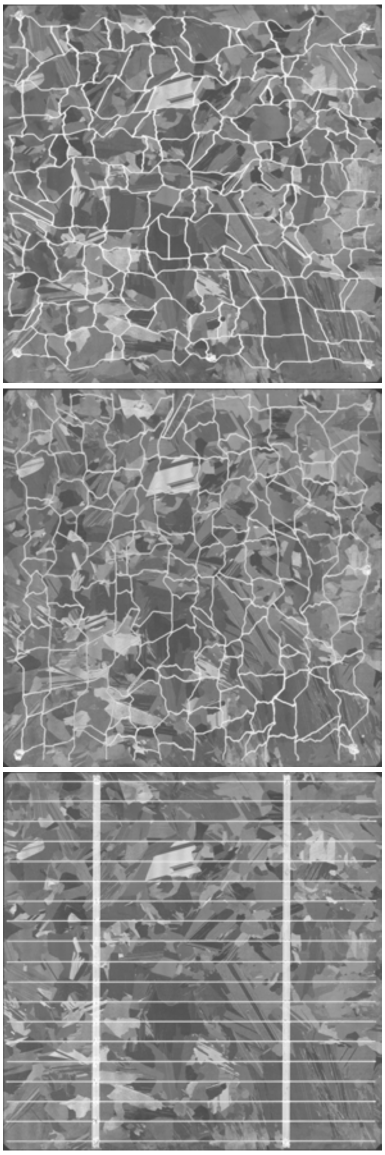

Fig. 1: Top: ON-cell, Middle: OFF-cell, Bottom: STD-cell

2.2.2 The GBOF grid

Some details on the automated calculation of the layout of the GBOF-grid have already been given elsewhere [3]. A numerical grid, whose number of horizontal and vertical lines depends on the emitter sheet resistance, the finger line and contact resistivities and total shading, as well as the current per unit area, is put over the grey scale image of the wafer. The lines are bent and twisted within adjustable limits, so that they come to lie over grain boundaries as much as possible. The image is obtained at 50µm resolution but plotted with 25µm positioning accuracy. The writing speed of the lines was between 0.5 and 1mm/s. The whole process was automated.

The percentage of the wafer front surface which is shaded is determined by optical scanning. The theoretically expected shading and the actual shading were in very good agreement. An important experimental information was the fraction of the total line length of the GBOF grid, that really lay over grain boundaries. Since the grid had to be constrained to a certain mesh density in order to avoid undue losses in the emitter sheet, the GBOF grid could not always follow grain boundaries. The fraction of grid length on grain boundaries was typically 64-75% for ON-cells, whereas it was only 17-31% for OFF-cells.

2.3.3 Current-voltage-measurements

Current-voltage measurements were taken in the dark and under illumination. The current of ON-cells and of OFF-cells was tapped at four points close to the corners, and at the busbars in STD-cells. The voltage was taken at a fifth point. The whole back area was contacted for current, except for a small region in the middle which served as contact point for voltage measurement. The illumination was provided by two 500 watts quartz lamps whose distance to the wafer was set such that a known reference cell gave the same short circuit current as under a sunlight simulator of AM1.5 spectrum. In some cases the intensity was reduced to 75%, 50% and 25%, respectively. The cells were kept at room temperature (19 – 22°C).

3. Results

3.1 Overall results

The results from 119 cells are shown in Table 1. (More cells were made but had FF below 50%.)

Gr.	Grid	Nr.	U_{oc} [mV]	I_{sc} [mA/cm^2]	P_m [mW/cm^2]	P_r [%]	$FF_{>50}$ [%]	GB [%]
A	ON	14	566.7	19.15	7.065	**102.60**	65.0	67.7
	OFF	15	565.5	19.15	6.886	100.00	63.3	21.9
B	ON	10	569.1	20.23	7.902	**104.72**	68.7	69.9
	OFF	10	567.9	20.03	7.545	100.00	66.3	30.5
C	ON	14	550.9	18.42	6.689	**102.29**	66.0	64.9
	OFF	13	548.8	18.01	6.539	100.00	66.1	16.9
	STD	15	548.2	18.46	6.661	101.87	65.8	-
D	ON	6	554.3	19.03	6.848	**106.12**	64.9	70.4
	OFF	4	551.4	18.61	6.453	100.00	62.7	24.7
	STD	6	533.1	18.80	6.527	101.15	65.0	-
E	ON	7	554.7	19.66	7.299	**100.84**	66.9	75.0
	OFF	8	555.2	19.43	7.238	100.00	67.1	26.6
	STD	7	552.5	19.52	6.988	96.55	64.8	-

Table I: characteristic parameters of the different types of cells of the pairs study (groups A and B) and of the triplets study (groups C, D and E)

ON: cells with GBOF grid, OFF: cells with GBOF grid rotated by 90°, STD: cells with standard H-pattern grid; Nr...number of cells; U_{oc}...open circuit voltage; I_{sc}...short circuit current density; P_m...maximum output power density; P_r...maximum output power density relative to maximum power density of OFF-cells; FF...fill factor (cells with FF below 50% were not included); GB...percentage of the total line length of the front grid that lies over grain boundaries; More complete numbers with mean deviations will be published elsewhere.

Group B were Eurosolare wafers, all others were Baysix wafers. Wafers of groups A, B, C, D were damage etched and surface structured in NaOH. Wafers of group E were only damage etched in HF/HNO_3. For groups A, B, C the optimal coverage of the front grid was calculated from the mean value of the sheet resistance of the emitters of the whole group. For groups D and E it was calculated from the mean value of the sheet resistance of the emitters of each triplet separately.

The shading caused by the front grid was about 11.0% for cells of groups A, B and C. For group D it was mostly 8.9%. For group E it was between 7.6% and 8.1%. The difference in front grid shading between ON- or OFF-cells and STD-cells for any triplet in groups C, D and E was usually no more than 0.2% of the cell's area.

The results of the maximum output power measurements are displayed in Figure 2, where the value of the respetive quantity of each individual cell is shown as a horizontal bar. Mean values of the group are highlighted as wider horizontal bars.

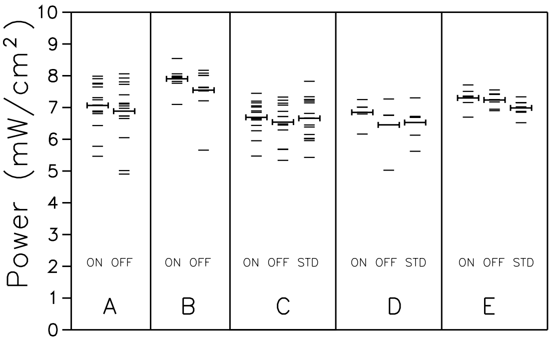

Fig. 2: Maximum power of all cells and average values.

Table I reveals that the ON-cells are superior in various aspects. They exhibit the higher mean values of open circuit voltages (except in group E), a higher mean value in short circuit current (except in group C), and a *higher mean value of the maximum power output (true for all groups)*. This is emphasized in the column 'P_r' in table I, which gives the values of maximum power as a percentage of maximum power of OFF-cells: For the ON-cells this value *is always* above 100%.

In order to see the effect of the grain boundary contacting as such, one can compare the ON-cells to the OFF-cells. We obtain an increase of short circuit current density of ON-cells versus OFF-cells of 0.97%. It seems to confirm our original motivation that ON-cells expose more high-lifetime area to the incident light and have lower series resistance losses. This is also reflected in the mean of the maximum power of ON-cells and OFF-cells from all five groups. The ON-cells give 2.63% more power than the OFF-cells at approximately standard conditions. To obtain a measure of credibility of this number it is instructive to look at the pairs study and at the triplets study separately. Taking only groups A and B, the ON-cells give 3.71% more power than the OFF-cells. When taking the groups C, D and E, the ON-cells give 1.98% more power than the OFF-cells. However, for a specific batch of cells the ON-cells were more than 8% better in power output over OFF-cells under $1000 W/m^2$ illumination (see VC1.17, this conference).

The relative merits of the grain boundary contacting scheme over the standard scheme can be assessed by comparing the ON-cells and the STD-cells of the triplets study. We obtained an increase of power output density of 2.50% of ON-cells over the STD-cells and of 0.52% of OFF-cells over the STD-cells. This latter difference shows that, when going from the standard H-grid of the STD-cells to the net-like grid of the OFF-cells, while aiming at having the same shading for both, the power output of the cells changes very little.

3.2 Different illumination levels

For the cells of group A the current-voltage curves were also recorded for lower illumination levels. The ON-cells produced higher average power than the OFF-cells at all illumination levels, but the relative difference between them decreases as the illumination goes down. At an illumination intensity of 25% of our approximate standard conditions, the ON-cells produced 0.14% more power than the OFF-cells, at an intensity of 50% it was 1.51% more and at 100% it was 2.60% more.

3.3 Series resistance

The indication for lower series resistance losses in ON-cells cannot be easily extracted from the dark and bright I-V-curves. It has been emphasized in [5] that the simple one-diode model, even when extended to a two-diode model, is not a physically correct description for large area cells and is often manifested in bad curve fits between model and data. However, data analysis by means of the more complex model of [5] requires current and voltage data at the maximum power point under many different illumination levels, which are not available.

Two different contributions to the series resistance at the front side of the cells must be distinguished: An effective resistance R_e of the emitter sheet including its contact to the metal grid, and an effective resistance R_m of the metal grid up to the points of extraction of power. R_m should be the same for the ON-cells and the OFF-cells, while R_e should be different. On the other hand, the STD-cells should differ both in R_e and in R_m with respect to the ON-cells and to the OFF-cells.

In order to gain an understanding, two quantities were extracted from the dark and the bright I-V-curve of each cell:

- The 'series' resistance R_s as it appears in the current-voltage relation of the single diode model, using a method proposed in [6]. It takes the voltage U_d of the dark curve under forward bias, when the absolute value of the current is the same as the short circuit current under illumination, I_{sc}. Because of the series resistance, U_d is smaller than the open circuit voltage U_{oc} (except when the shunt resistance is very low), so that $R_s = (U_d - U_{oc})/I_{sc}$.
- The 'flank' resistance R_F, here defined as $R_F = (U_{oc} - U_{mp})/I_{mp}$,

where U_{mp} and I_{mp} are voltage and current density, respectively, at the maximum power point. R_F is an artificial quantity, which reflects the slope of the bright I-V-curve at voltages higher than U_{mp}. It can be an effective indicator for series resistance, because series resistance affects predominantly that part of the I-V-curve. But R_F does not vanish at zero series resistance. Therefore, noticeably different values for R_F for the different kinds of cells should be an even stronger indication of differences in series resistance.

Evaluation shows that R_S is lower for the STD-cells than for both the ON-cells and the OFF-cells, but a distinction between ON-cells and OFF-cells cannot be drawn. The lower value for the STD-cells is understandable, because the dark I-V-curve of the STD-cells has a stronger exponential rise, presumably because the busbars permit to distribute current efficiently to the whole metal grid. But since this happens under forward bias, there is little current flow in the emitter sheet. Most of the current flows from the n- to the p-side directly under the front metal grid. Therefore, R_S is a good indicator only for the metal grid component R_m of the total series resistance. The results suggest that this component is lower in the STD-cells than in the other cells.

	R_s [Ωcm^2]		
Group	ON-cells	OFF-cells	STD-cells
A	7.624 (0.849)	7.976 (0.536)	-
B	7.922 (0.197)	7.912 (0.282)	-
C	9.032 (0.612)	8.894 (0.819)	7.420 (0.885)
D	7.612 (0.601)	7.805 (0.933)	6.707 (1.030)
E	7.090 (0.272)	7.544 (0.505)	7.012 (0.560)

Table II: R_s values for each kind of cell for all five groups. (Mean deviations in brackets.)

Evaluation of R_F shows in *all five groups* a lower value for the ON-cells than for the OFF-cells, while the STD-cells exhibit no clear tendency. Since R_F is based only on bright I-V-data, and since the metal grid component R_m should be the same for the ON-cells and the OFF-cells, it seems to represent a difference in the emitter sheet component R_e.

	R_F [Ωcm^2]		
Group	ON-cells	OFF-cells	STD-cells
A	8.281 (1.149)	8.934 (1.607)	-
B	6.916 (0.571)	7.593 (1.229)	-
C	8.242 (1.242)	8.292 (1.368)	8.256 (1.424)
D	8.111 (0.385)	9.094 (2.058)	7.804 (0.622)
E	7.279 (0.470)	7.371 (0.282)	8.082 (0.487)

Table III: R_F values for the five groups.

Comparing the values of R_F for the ON-cells and the OFF-cells, one may conclude that the expected difference in series resistance of the emitter, and possibly of the contact between metal and emitter, does indeed exist. This strengthens our original motivation that the GBOF-grid in which a significant fraction of the total metal line length follows and covers grain boundaries, lowers the average ohmic resistance from any point in the emitter to the metal grid.

4. Conclusion

We have investigated the effect of applying the metal grid for current collection on the front side of multicrystalline silicon solar cells as a kind of net, whose lines follow grain boundaries wherever possible. Cells with this kind of front contacts yield approximately 2.5% more power under approximately standard conditions than cells equipped with the standard H-pattern (two busbars and perpendicular fingers), when both patterns have the same shading and when the standard H-pattern is optimized for the given sheet resistance. It should be pointed out, however, that for individual batches and for illumination with somewhat different 1000W/m^2 spectrum the on-grain boundaries contacted cells showed significantly higher gains over cells with the standard H-grid (VC1.17, this conference). The pure effect of having the current collecting lines follow the grain boundaries could be established by comparing these cells to those made from the immediate neighbours in the ingot, to which the same grid was applied as to the first cell, but rotated by 90 degrees, so that it covered grain boundaries only accidentally. Here, different batches showed that the on-grain-boundary contacted cells are superior in power output by between 2.0% and 3.7%. As the main cause for this difference the lower series resistance losses in the emitter sheet and possibly between emitter and metal of the new contacting scheme could be established, because the difference in power output became smaller with lower illumination levels.

Future investigations will focus on identifying the electronically relevant grain boundaries by position resolved lifetime measurements, and on replacing the plotting of the contacts with screen printing paste by a galvanic process.

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