GALVANIC GRAIN BOUNDARY CONTACTS ON MULTICRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT:
We present new results of putting the metallic front contact pattern of multicrystalline silicon solar cells over and along grain boundaries (Grain Boundary Oriented Finger grid – GBOF-grid). In a previous study the contacts were formed by automated grain boundary detection and writing of the contact pattern with ordinary screen printing paste. Now we used a galvanic method with nickel as a diffusion barrier and silver as the conductor, in view of a possible application in laser grooved buried contact cells. This gave very low contact and series resistances. Using Baysix® 100x100-wafers, we compared so called ON-cells, which received the GBOF-grid so that the front contacts ran mostly along grain boundaries, OFF-cells, where the same pattern was used but was rotated by 90° to give only little coverage of grain boundaries, STD-cells with the H-pattern of most commercial silicon solar cells, and GRD-cells with a geometric rectangular grid pattern. With the same total shading on all four kinds of patterns, a clear advantage for the grain boundary contacted ON-cells is found, exceeding the results of the previous study. Under approximately standard conditions, ON-cells gave at least 5% more power than the STD-cells and in some batches over 10% more. Their performance improvement over the OFF- and the GRD-cells shows similar values.

Keywords: 1, multi-crystalline - 2, grain - 3, galvanic contacting

1. Introduction

Judging from the recent market development, multicrystalline silicon solar cells will be the dominant cell type for the next 10 to 15 years. It is with cells of this material, that photovoltaic energy will start to make an impact on the future electricity supply. Therefore, it is important to develop these cells to their maximum capability.

In multicrystalline silicon solar cells the grain boundaries and the higher concentration of in-grain defects are the main reason for lower conversion efficiency relative to monocrystalline cells. 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 our recent work we have investigated an additional possibility of improving the cell performance: Instead of using the customary H-pattern front metal grid, which is in fact optimal only for cells with homogeneous emitter sheet resistivity, we have placed the current collecting grid over and along grain boundaries, wherever possible. 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.

Our earlier work showed that it is mainly the last point, the reduction of the effective series resistance in the emitter sheet, which causes an increase of fill factor and power output, with some small improvement also coming from less shading of good area [1,2,3,4]. In these studies the front metal lines were fabricated by automated writing of commercial screen printing paste along the desired lines. This resulted in an average increase of power output of ON-cells (metal grid on grain boundaries) over STD cells (metal grid in the usual fashion of two busbars and many fine fingers) of 2.5% under standard conditions. In the present study the front metal lines were applied galvanically with the aid of a photoresist mask. Due to lower contact and series resistances the advantages of ON-cells over the other contact patterns were even more pronounced.

2. Experiments

2.1 Layout of the study

The study was done on Baysix® 100x100mm^2 wafers of about 270µm thickness, which were boron doped between 0.5 and 2.0 Ω.cm. Several batches of up to 80 wafers each were processed. The batch size was limited by the quartz boat for $POCl_3$-diffusion, which could carry 90 wafers. Four different types of front grid were produced, as shown in Fig.1: ON, OFF, STD and GRD. There were four different studies, all conducted in a comparative manner:

- <u>Pairs study ON-OFF:</u> The two wafers of a pair were immediate neighbours in the original ingot and thus had almost identical grain structure. One was made into an ON-cell, thus receiving a GBOF-grid on the front, and the other was made into an OFF-cell, where it got exactly the same grid as the ON-cell, but the grid was rotated by 90° before it was applied. The purpose was to extract the pure effect of grain boundary contacting, because the other properties of the front grid were identical. Number of evaluated cells: 69.
- <u>Pairs study STD-GRD:</u> The two wafers of a pair were also immediate neighbours in the original ingot. One was made into an STD-cell, thus receiving two busbars and many thin fingers, as in most cemmercial cells, and the other was made into a GRD-cell, where it got a rectangular grid of thin lines, without busbars. Care was taken that both had the same shading. The purpose was to see whether a rectangular grid as such has

advantages over the industrial standard scheme, as one would expect for small series resistance of the metal lines, and that this would be part of the explanation of the high performance of ON-cells, as they also have a grid-like contact pattern. Number of evaluated cells: 49.

- <u>Triplets study ON-OFF-STD:</u> The three wafers of a triplet were immediate neighbours in the original ingot and thus had almost identical grain structure. One was made into an ON-cell, the next into an OFF-cell, and the third into an STD cell. Care was taken that the shading was the same for all three of them. The purpose was to be able to compare the performance of ON-cells and STD-cells on the one hand, and of OFF-cells and STD-cells on the other. The latter comparison should show the advantages or disadvantages of an irregular grid-like contact pattern relative to the industrial standard pattern of same shading. Number of evaluated cells: 56.
- <u>Quartets study ON-OFF-STD-GRD:</u> The four wafers of a quartet were again immediate neighbours in the original ingot and thus had almost identical grain structure. The first was made into an ON-cell, the second into an OFF-cell, the third into an STD-cell and the fourth into a GRD-cell. The shading was the same for all four cells of a quartet. The purpose was to have a direct comparison of all four types of cells, with all wafers coming from the same lot, being processed in the same phosphorous diffusion, and all other process steps also being virtually identical. Number of evaluated cells: 19.

2.2 Solar cell preparation and characterisation

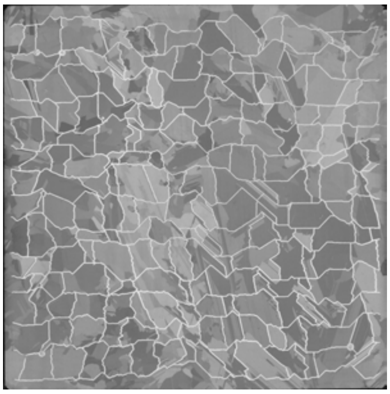
2.2.1 Laboratory process

The solar cells were made in batches with 25 to 80 pieces in a quartz boat accepting up to 90 pieces for phosphorous diffusion. The following process was used:

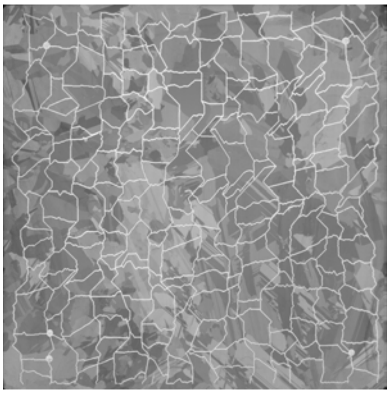
- Saw damage removal in buffered HF-HNO_3.
- pn-junction formation in $POCl_3$ atmosphere.
- Backside screen printing with Al/Ag paste; firing.
- Calculation of optimal number of fingers for standard H-grid from measured front side sheet resistivity.
- Photographic scanning of front side of wafer.
- Calculation of the layout of the GBOF-grid.
- Development of film masks.
- Spin on of photoresist, exposure through mask, development.
- Dip in buffered HF-HNO_3.
- Galvanic deposition of 3-5µm of nickel on desired lines on front.
- Galvanic thickening of lines with silver (10-15µm).
- Removal of photoresist.
- Mechanical abrasion of parasitic junction at the edges.

The cells received no passivation of surfaces and grain boundaries, and no antireflection coating.

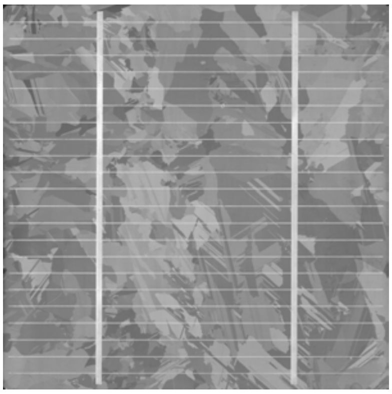
The sheet resistance of the emitter ranged between 20 and 60Ω/sq. But care was taken that it was very similar for any pair, triplet or quartet to be compared. The contact pattern was always calculated such that the average sheet resistance of the pair, triplet or quartet in question was



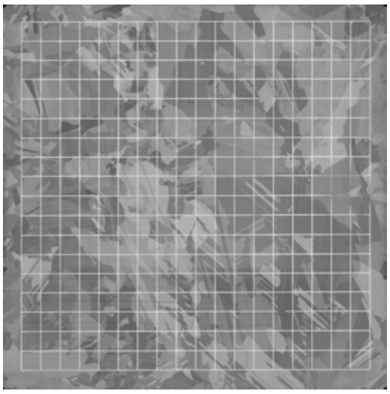
ON-cell



OFF-cell



STD-cell



GRD-cell

Fig.1: The four types of front contact patterns investigated.

taken as the basis to calculate the optimal layout of the STD-pattern and the other patterns were calculated with the restraint of giving the same shading as that pattern. The line width of fingers, respectively grid lines, was designed as 200µm. After the galvanic process it was around 210µm. The busbars in the STD-pattern were 2mm wide. The contact resistance of the front contact patterns was established on separate wafers having an n-emitter just as the actual solar cells. Average values were 1.5mΩcm^2. The line resistance of fingers and grid lines was typically 100mΩ/cm. The shading due to the front contact patterns was between 6.0 and 7.9%.

The back surface was covered with Ag/Al screen printing paste, except for a 2mm wide margin on all four sides. After sintering in air for two minutes at 710°C a back surface field and good ohmic contact was obtained.

2.2.2 The GBOF grid

Some details on the automated calculation of the layout of the GBOF-grid have already been given elsewhere [1,4]. First, a theoretical rectangular grid is put over the grey scale image of the wafer. The number of horizontal and vertical lines depends on the desired total shading, as determined from the optimal STD-grid for a cell with the given emitter sheet resistivity. The lines are bent and twisted within adjustable limits, so that in the end they follow the grain boundaries as much as possible. The image is obtained at 50µm resolution. The resulting bitmap file is then processed into a lithographic mask.

An important experimental information was the fraction of the total line length of the GBOF grid, that really covered grain boundaries. Its average value, obtained form all ON-cells, was about 77%. Of course, the metal lines in the other contact patterns ran partially over grain boundaries, too. The typical fraction for the OFF-cells and the GRD-cells was between 25 and 30%. (The image processing software counts a perpendicular crossing of a grain boundary by a metal line as a grain boundary coverage length equivalent to the apparent width of the grain boundary.) For the STD cells it was around 25%.

2.2.3 Current-voltage-measurements

Current-voltage measurements were taken in the dark and under illumination. The current of ON-cells, of OFF-cells and of GRD-cells was tapped at four points close to the corners. For STD-cells it was tapped at the four ends of the two busbars. The voltage was taken at a fifth point right beside one current extraction 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. The cells were kept at room temperature (19 – 22°C).

3. Results

The results presented below were obtained from a total of 193 cells. A total of 232 cells had been processed, but 11 broke during mechanical abrasion of the edges, 20 had a fill factor below 50% due to bad adhesion of the galvanically deposited nickel and were not included in the final data analysis. And 8 cells received only a set of unconnected parallel straight lines on the front for measurement of contact and series resistances of the front metalization.

Batch	Grid	Cells	I_{sc} [mA/cm^2]	P_m [mW/cm^2]	P_r [%]	FF [%]
Pairs (W241-W325)	ON	33	18.89	7.510	**105.12**	72.1
	OFF	36	18.77	7.144	*100.00*	69.0
Pairs (W326-W385)	GRD	24	18.31	6.838	97.19	68.0
	STD	25	18.52	7.036	*100.00*	69.0
Triplets (W141-W165)	ON	5	19.71	8.443	**117.28**	74.1
	OFF	5	18.84	6.885	95.64	63.8
	STD	4	18.92	7.199	*100.00*	66.4
Triplets (W166-W190)	ON	8	20.30	8.473	**125.73**	77.3
	OFF	6	19.78	7.297	108.28	69.1
	STD	8	19.78	6.739	*100.00*	63.9
Triplets (W191-W215)	ON	7	19.28	7.132	**105.19**	67.6
	OFF	7	19.12	6.848	101.00	65.5
	STD	6	19.32	6.780	*100.00*	63.7
Quartets (W216-W240)	ON	5	17.65	6.804	**114.24**	68.2
	OFF	5	17.46	5.666	95.13	60.6
	STD	5	17.47	5.956	*100.00*	63.1
	GRD	4	17.40	6.593	110.70	69.1

Table I: Average values of short circuit current, maximum power, and fill factor, of the different types of cells, grouped by processed batches. A batch was always devoted to a specific study (pairs, triplets, or quartets of cells).
I_{sc}...short circuit current density.
P_m...maximum output power density.
P_r...maximum output power density relative to maximum power density of STD-cells of that batch, except in the first pairs study, where it is relative to the power density of the OFF-cells. (The percentage values "*100.00*" in column P_r indicate which type is defined as reference.)

Despite considerable statistical fluctuations, Table I shows quite clearly that ON-cells outperform the other types in terms of power output and fill factor, and mostly also in the short circuit current. The quality of the starting material was not always the same, and it seems that especially in bad material (with low minority carrier lifetime in the base, as has been determined by means of the photo conductance decay method on two wafers of each batch before processing) the GBOF-grid can extract considerably more power from the cells than the other front contact grids. Values of the open circuit voltage are not displayed here. Depending on the batch, they ranged from 540 to 570 mV, with no clear tendency, except that in those batches with higher mean values of open circuit voltage, the ON-cells seemed to be slightly above the others (1 to 2 mV). This agrees with the findings of our earlier study [4].

The results of the maximum output power measurements of column P_m of Table I are also displayed in Figure 2. They have not been normalized to an area of 1 cm², but show the actual average values of the respective type of cell of the given batch.

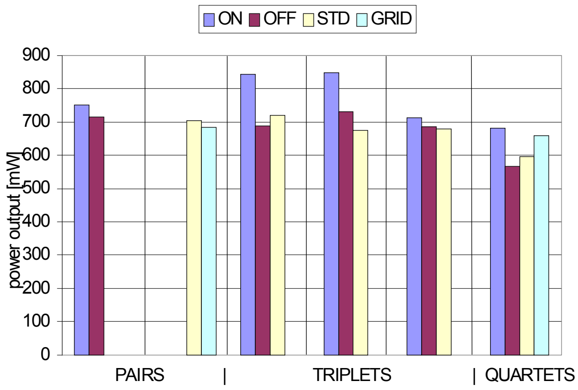


Figure 2: Average values of maximum power output of the different types of cells of the different batches as listed in Table I.

4. Discussion

The pure effect of the grain boundary contacting can be seen by comparing the power output of ON-cells and of OFF-cells. The difference can range from about 4% in the third triplets batch (wafers W191-W215) to as much as almost 23% in the first triplets batch (W141-W165). But these batches did not consist of many wafers. The most probable difference between ON-cells and OFF-cells seems to be the one established in the first pairs study (W241-W325), where it amounts to over 5%.

The difference between ON-cells and STD-cells can be obtained from the triplets batches and the quartets batch. As one can see in column P_r in Table I, the increase in power output of ON-cells over STD-cells ranges from about 5% (W191-W215) to over 25% (W166-W190). However, the latter value should be treated with some statistical caution. But an average increase of at least 5% seems to be a trustworthy conclusion from these data.

The difference between the OFF-cells and the STD-cells can also be obtained from the triplets batches and the quartets batch. In two cases the OFF-cells give about 5% *less* power than the STD cells, in the other two cases they give *more* power, by about 1% and 8%, respectively. Therefore, one cannot make a clear statement, which of the two grids is better. This agrees with the results of our earlier study where contact patterns were written with screen printing paste [4]. It showed that the OFF-cells and the STD-cells yield about the same power, the OFF-cells tending to be slightly lower by about 1%. This is not really surprising, because both patterns have the same shading (by design), and both cover grain boundaries only accidentally, so that with sufficiently low losses in the metal lines themselves, they should perform very similarly.

A comparison of the GRD-cells and the STD-cells is possible by looking at the second pairs batch (W326-W385) and at the quartets batch. In the former case the GRD-cells yield about 3% *less* power than the STD-cells and in the latter (which has much lower statistics) the GRD-cells yield over 10% *more* power than the STD-cells. One can interpret this as both patterns probably being very similar in power output. Again, this is not so surprising, as both patterns have the same shading, and both ignore the grain boundary structure of the cells.

Some additional information on these studies can be found in [5]. More details will be published elsewhere and on our homepage: http://www.ati.ac.at/~summweb

5. Conclusion

We have investigated four different kinds of front contact patterns on multicrystalline silicon solar cells, which were applied galvanically using nickel and silver through a photoresist mask. One of these patterns was a so called grain boundary oriented finger grid (GBOF-grid), whose metal lines formed a kind of net, which followed the grain boundaries wherever possible. The detection of the grain boundaries was done by optical contour tracing methods. Under approximately standard conditions the cells with the GBOF-grid showed a higher power output over the cells with any of the other patterns, because they had a higher fill factor, and in most cases also a higher short circuit current. Despite some statistical variation it can safely be concluded that the cells with the GBOF-grid give at least 5% more power than cells equipped with the standard industrial grid of two busbars and many thin fingers. Since the cells had no antireflection coating and an earlier study [4] had shown that the difference increases with increasing amount of incident light, the cells with GBOF-grid will outperform cells with standard contact scheme even more, once an ARC is applied.

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REFERENCES

[1] Radike M, Summhammer J, Novel process of grain boundary metallisation on mc Si solar cells, *Solar Energy Materials and Solar Cells* 2001: **65**, 303-309.

[2] Ebner R, Radike M, Schlosser V, Summhammer J, Metal fingers on grain boundaries in multicrystalline silicon solar cells, *Conference proceedings, 17th EPVSEC,* Munich, 2001: paper OC9.1

[3] Schlosser V, Ebner R, Markowitsch W, Bajons P, Klinger G, El-Amin A.A., Summhammer J, Investigations of evaporated front contacts along the grain boundaries of multicrystalline silicon solar cells, *Conference proceedings, 17th EPVSEC,* Munich, 2001: paper VC1.17

[4] Ebner R, Radike M, Schlosser V, Summhammer J, Metal fingers on grain boundaries in multicrystalline silicon solar cells, *Prog. Photovolt: Res. Appl.* 2002; **10:** 1-13.

[5] Schlosser V, Markowitsch W, Klinger G, Bajons P, Chancy S, Ebner R, Summhammer J, Investigations of the electro-optical properties of multicrystalline silicon during solar cell processing, *Conference proceedings, PV in Europe,* Rome, Oct. 2002. [This conference.]