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BENCHMARK OF OPEN REAR SIDE SOLAR CELL WITH IMPROVED AL-BSF PROCESS AT ECN

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ABSTRACT: In search of methods that allow processing of thinner multi-crystalline silicon solar cells (<<200µm) without bowing, an open rear side concept, the PASHA cell (Passivated on All Sides H-patterned cell), was developed in our laboratories based on an H-patterned rear metallization design combined with a industrial silicon nitride rear side passivation layer. We report on the performance of this method compared to an improved full Al-BSF reference process on thin 6 inch mc-Si wafers (<210µm, 156x156 mm). Evaluating the average performance of both processes, the product of Jsc and Voc for the PASHA cell with opened silicon nitride is 20.3 mW/cm2, which is 2% lower than for the reference. When the rear side fingers of the PASHA cell are short-circuited, equal fill factors of 77% are obtained as for the reference. The maximum efficiency obtained for the short-circuited PASHA cell and the reference is 15.8% and 16.1% respectively. The key factors that explain these results are: an improved front side passivation of the reference due to an additional PASHA clean step that precedes the SiNx deposition; poor passivation under and high series resistance in the rear fingers of the PASHA cell; an internal rear reflection gain that does not sufficiently compensate these effects. Further, a strong bias illumination dependence of spectral response for the PASHA cell is found which is attributed to the recombination behavior of the SiNx layer on the rear side of the cell.
Keywords: Bifacial, Silicon-Nitride, Back-Surface-Field

1 INTRODUCTION

A general trend is to reduce costs for PV by reaching high efficiencies on thin solar cells. However, processing of thin (<<200µm) and fragile wafers using today's technology with full rear surface Al Back Surface Fields (BSF) will reduce the cell efficiency due to non-optimal back-surface passivation and lower internal reflection at the rear side [1-7]. Furthermore, the use of such wafers will cause problems for processing and module assembly due to the increased bowing and breakage. In the past couple of years, several solutions to overcome these bottlenecks are put forward: the usage of bifacial rear side passivated solar cells [1,2], passivating the rear side with dielectric layers and using laser fired contacts (LFC) at the rear [3,4], or selective alloying of a local BSF at the rear in combination with a dielectic layer (i-PERC) [5,6]. While in the case of bifacial cells only part of the rear surface is covered with metallization, in the case of the LFCs or i-PERC a full Al layer is deposited on top of the passivating layer(s) rendering it unsuitable for bifacial use. An additional advantage of a bifacial cell with an open rear side is the lower material cost in Al consumption compared to full Al-BSF

To increase the efficiency and reduce the bow for thin cells, an open rear side concept, the PASHA cell (Passivated on All Sides H-patterned cell), was developed in our laboratories based on an H-patterned rear metallization design combined with a single silicon nitride rear side passivation layer. Open rear metallization of the bifacial cells has shown to reduce cell warping to zero [1,2]. The fact that the single SiNx layer of a PASHA can be fired through with dedicated Al-pastes, simplifies the process relative to that of LFC and i-PERC which will reflect on lower production cost. The main challenge for optimizing the efficiency of the PASHA cells lies in achieving reasonable surface passivation on the rear wilts minimizing series resistance losses. This trade-off needs to be found by improving the metallization properties and pattern. We report on the performance of this method compared to an improved full Al-BSF reference process on thin 6 inch wafers (<210 µm, 156x156 mm). The PASHA cells prepared in this work are prepared in identical manner as previously reported [11].

2 EXPERIMENTAL SECTION

The processing sequence of the PASHA cells, as it is carried out in the ECN laboratory, is shown in figure 1. P-type mc-Si wafers are iso-textured by a wet chemical acid etch, after which a 65 Ω /□ emitter is diffused using an inline belt furnace. To prepare the rear surface for optimal passivation, the rear side emitter is removed using a wet chemical etch that simultaneously smoothens the rear surface. Subsequently the phosphor glass is removed and an additional clean step is applied, referred to as the PASHA clean, to improve surface passivation. The standard ECN remote MW PECVD SiNx coating [8] is used as a front side anti-reflection layer and for bulk and surface passivation [9]. On the rear side, a single SiNx layer for surface passivation is applied, using the same remote MW PECVD system. The metallization is applied by screen printing, Ag on the front side and an H-pattern Al metallization for rear side contacting and local BSF formation. The Aluminum paste used was adjusted to enable firing through the SiNx on the rear side. Both the Ag front and Al rear contacts were fired through the SiNx layers in a single co-firing step. As the emitter removal in step 3 (figure 1) acts also as junction isolation, no edge isolation (e.g. laser) is required. Thus, effectively only one extra process step, the additional SiNx layer at the rear, is needed with respect to the conventional mc-Si processing. This means that the process can be easily implemented into industry. In this work full Al-BSF cells (group 1) are processed with the same chemical cleaning steps as the PASHA cells. The Al-BSF process is compared to two types of PASHA contacting processes: the standard firing thought process as defined above (group 2) and opened SiNx below the Al-rear metallization (group3). The front metallization consisted of 2 bus bars and 58 fingers covering 7.4% (Standard deviation (Sd)=0.4%) of the cell. For the rear this was 2 bus bars and 62 fingers covering 14.0 % (Sd=0.5%) of the surface. In addition to these groups the influence of the PASHA clean on the reference process is evaluated on two additional Al-BSF groups (100% rear coverage) that are processed on similar wafer material as used for group 1 to 3. An overview of the investigated groups is given in table 1. In order to investigate the efficiency of the PASHA cells in absence of rear finger resistance losses, measurements were conducted before and after the rear side metallization was short-circuited

The current voltage measurements were performed on a class A solar simulator at ECN according to ASTM-E948 standard norm. The obtained data is statistically analyzed using Statgraphics Centurion XV v.15.2.00. Observed trends in IQE data are analyzed with PC1D.

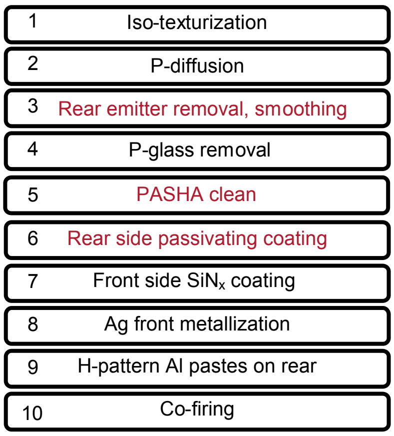


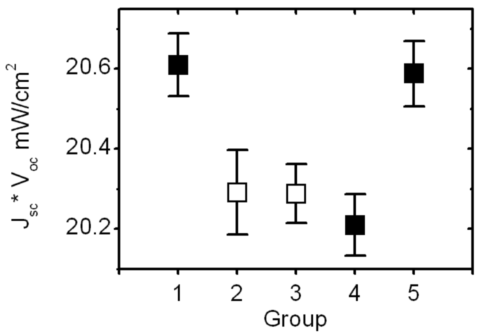
Figure 1: Process flow of Al-BSF and PASHA cells. In black: Process step shared between PASHA and standard ECN Al-BSF process. In red: additional PASHA process steps (step 3,5 and 6).

Table 1, Experimental groups

Group & Process	Rear metallization fraction
1 Al-BSF + PASHACLEAN	100%
2 PASHA firing though	14%
3 PASHA Opened SiNx	14%
4 Al-BSF without PASHA clean	100%
5 Al-BSF + PASHA CLEAN	100%

3 PASSIVATION AND SERIES RESISTANCE

The results in terms of the least significant differences of the product Jsc and Voc of all investigated groups, are illustrated in figure 2a. This comparison is obtained after the rear metallization grid was short-circuited. The product of Jsc and Voc enables benchmarking the PASHA cells independently of its FF. It becomes apparent that no significant influence on Jsc*Voc is observed by opening the silicon nitride as group 2 and 3 have matching averages of 20.3 mW/cm2. These PASHA groups perform as well as the AL-BSF cells without the PASHA clean with an average of 20.2 mW/.cm2. When the PASHA clean is applied on the full Al-BSF reference group a clear improvement of 1.9% (relative) on average to 20.6 mW/cm2 is observed (group 1 and 5 vs. group 4). Results of group 1 and 5 also show the reproducibility of the clean step.



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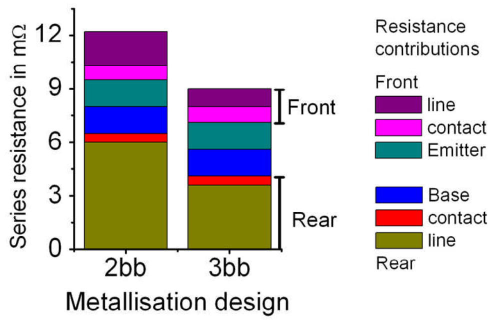


b)

Figure 2 a), Least significant differences plot of the product of Jsc*Voc obtained under 1 sun front side illumination of full Al-BSF reference (1), PASHA cell with firing though (2) and opened SiNx (3) and additionally two Al-BSF groups without (4) and with PASHA clean (5 equal processing as (1)). **b)** Calculated series resistance composition of typical PASHA cell with 2 and 3 bus bar design.

The cell performance as measured after short-circuiting the rear metallization and without further statistical analysis is summarized in table 2. The standard deviation in these results is larger compared to figure 2a as it contains the process and the material variability while figure 2a excludes the material contribution. When the rear side fingers of the PASHA cell are short-circuited, the average fill factor is 75.8 (Sd=0.6%) for the pasha cell which is 0.9% (ABS) less than the average for the full aluminum reference of 76.7 (Sd=0.6%) (group 1). This slight drop of 0.9% could be attributed to ohmic losses between the fingers (base resistance). The maximum efficiency obtained for the short-circuited PASHA cell and the reference are 15.8% and 16.1% respectively. In order to estimate the modular losses of the PASHA cell, IV measurements were conducted before the rear metallization was short-circuited, contacting only the front and rear bus bars. The obtained fill factors ranged between 70 and 72%, which is 5 to 7% lower than the Al-BSF reference (group 1). The difference in fill factor after short-circuiting the rear metallization grid, illustrates the important role of the rear finger resistance. This becomes more apparent when comparing the front and rear bus bar to bus bar resistance of the PASHA cells prepared in this experiment of 29

(Sd=1) and 134 (Sd=21) mΩ respectively. The high resistance value for the rear is explained by the low finger aspect ratio that was obtained with line widths that ranged between 310 and 360 microns with finger height between 17 and 20 microns. Line heights of 45 microns are normally achieved in our laboratory when using other pastes.

Table 2, Cell performance of group 1 to 5 as measured after short-circuiting the rear metallization.

Group	Jsc Max	Jsc Avg	Jsc Sd	Voc Max	Voc Avg	Voc Sd
	mA/cm^2			mV		
1 AL-BSF	33.9	33.7	0.1	618	614	3
2 PASHA Firing through	33.6	33.4	0.2	615	608	4
3 PASHA Opened SiNx	33.9	33.5	0.3	615	609	4
4 Al-BSF no clean	33.8	33.3	0.3	614	607	6
5 Al-BSF + PASHA clean	34.0	33.7	0.3	619	611	7

Group	FF Max	FF Avg	FF Sd	η Max	η Avg	η Sd
	[%]			[%}		
1 AL-BSF	77.3	76.9	0.2	16.1	15.9	0.2
2 PASHA Firing through	76.6	76.1	0.6	15.7	15.5	0.2
3 PASHA Opened SiNx	76.6	75.3	0.1	15.8	15.3	0.3
4 Al-BSF no clean	77.7	76.8	0.8	15.8	15.5	0.3
5 Al-BSF + PASHA clean	77.3	76.3	0.4	16.0	15.7	0.3

The composition of the series resistance of a PASHA cell with a symmetric front and rear side metallization design that comprises of 2 and 3 busbar with nde
bedne58 finger is presented in figure 2b. The input parameters that give rise to this series resistance are: equal Al/Si (p-type) and Ag/Si (n-type) contact resistance of 10mΩ.cm2, emitter and base resistance of 65 and 62 Ω/□, aluminum and silver line resistance of 0.78 and 0.28 Ω/cm respectively. The compounded series resistance is 12.3 and 9.0 m Ω for the 2bb and 3bb case respectively which illustrates the possible gain that can be achieved by changing the metallization grid.

4 FIT RESULTS SPECTRAL RESPONSE

In order to understand which part of the PASHA cell should be improved further, spectral response and reflection measurements are conducted on all groups after which the internal quantum efficiency (IQE) is determined. From group 1, 2 and 3, one cell each is selected on the basis of neighboring wafer material. The IQE spectra of these samples are fitted with PC1D [12] to extract key parameters such as the front and rear surface recombination velocity, the internal reflection coefficient and the bulk life time. The IQE spectra and the fit results are illustrated in figure 3 and table 3 respectively.

The IQE spectra obtained from all cells under front side illumination largely overlap below 700nm but show differences at longer wavelengths. At these longer wavelengths the IQE spectrum is sensitive to the rear side quality of the cell which is mainly characterized by fit parameters such as the surface recombination velocity (SRV) and the internal reflection coefficient on the rear. The latter coefficient is most strongly represented by IQE's at wavelengths between 1100nm and the band gap (1200nm). In this region the PASHA cells out perform the Al-BSF reference cells, explaining the higher rear reflection coefficient of 86 to 88% compared to 75% for the reference. On the basis of a PC1D calculation, this difference in internal rear reflection is estimated to improve the Jsc by 1.1%. The fact that the IQE at 1000nm of the Al-BSF sample is higher than for the fired through PASHA cell is reflected in a higher rear recombination velocity fit value for the PASHA cell. This value is 350 cm/s for the Al-BSF sample while it is 1000 and 550cm/s for the PASHA cells with firing through contacts and Opened SiNx respectively. It is calculated with PC1D that a difference between 1000 and 350cm/s results in a Jsc and Voc improvement of 2.8% and 0.75% respectively.

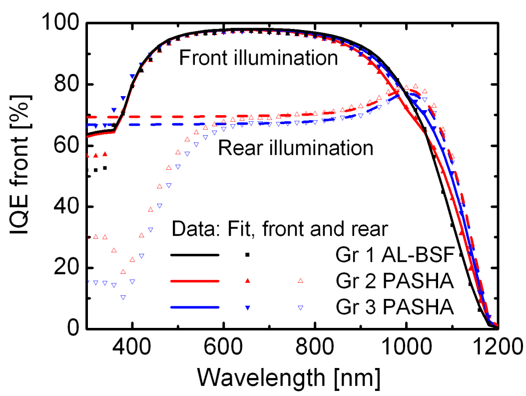


Figure 3, Internal quantum efficiency spectra of 3 neighboring wafers obtained under front and rear side illumination. The bias illumination intensity used resulted in a bias current of 10 and 6 mA/cm^2 for the front and rear side respectively which is 30% of the Jsc under 1 sun.

These fit results point to a surface passivation problem on the rear of the PASHA cells relative to the Al-BSF. For comparison, typical recombination velocities for our passivating SiNx layers deposited on mono material, range between 10 and 20 cm/s [10]. If this value can be transferred onto multicrystalline wafers it can be inferred that the poor passivation of the PASHA cells are to be attributed to the poor quality of the BSF below the aluminum metallization on the rear of the pasha cells. A consequence of this logic would also be that the quality of the BSF improves when the SiNx is opened as the SRV is lower after opening the SiNx (group 3). This is expected as it would be easier for the aluminum to form a BSF without having to work its way though the SiNx layer. In order to verify that the passivation problem is dominated by the aluminum fingers it is essential to determine the IQE under bias illumination locally between the fingers, several diffusion lengths away from the finger edge.

Table 3, PC1D Fit results based on IQE spectra of neighboring wafers from group 1 to 3.

		Group 1 Al-BSF +clean	Group2 PASHA Firing though		Group 3 PASHA Open SiNx	
Parameter		Front	Front	Rear	Front	Rear
Base resistance	Ω.cm	0.8	0.8	0.8	0.8	0.8
Emitter resistance	Ω/□	66	66	66	66	66
Bulk lifetime	□s	30	30	30	30	30
SRV S_{front}	cm/s	2.5e5	2.6e5	2.6e5	2.5e5	2.5e5
SRV S_{rear}	cm/s	350	1000	300	550	375
R Front	[-]	85%	90%	90%	90%	90%
R Rear	[-]	75%	86%	86%	88%	88%
Isc calculated	mA/cm^2	8.35	8.33		8.35	
Voc calculated	mV	618	615		617	

SRV: surface recombination velocity, R= Internal recombination velocity

To increase the efficiency of the PASHA cell relative to the Al-BSF reference with the extra clean it is necessary to improve the rear surface passivation and reflection as well as the fill factor. The current level of passivation below the aluminum rear metallization requires decreasing the metallization fraction even further in order to benefit from the superior reflection and passivation property of the SiNx. This will result in a higher Jsc*Voc and come at the expense of a lower fill factor as the series resistance will increase. Depending on the gain in Jsc*Voc obtained at a low metallization fraction (below 10%) it would be possible to design a metallization that would result in a higher efficiency. A first attempt to model this trade-off is reported by E. Bende et al. [15]

5 INFLUENCE OF CLEAN

In order to understand in influence of the PASHA clean on the Al-BSF cells, IQE spectra are determined of neighboring material of all investigated groups. These spectra as well as the relative change of each group compared to the baseline groups are presented in figure 4. The blue response at 400nm of all PASHA cells and the Al-BSF cell prepared with the PASHA clean are 10 to 15 % (relative) higher than the Al-BSF without the clean which points to an improved SRV at the front side. The PASHA cells show a 2 to 5% (relative) lower red response at 1000nm which indicates a lower rear side recombination velocity than the Al-BSF cell without clean. The Al-BSF with PASHA clean shows a 3% improvement at 1100nm probably mainly caused by a higher rear reflection coefficient. Based on the analysis of the integral of the product of the EQE with the solar spectrum, it is estimated that the PASHA cell looses up to 2.1% in Jsc due to the lower red response while it gains 1.8% in Jsc due to the improved reflection.

6 BSF QUALITY NEAR SINX

As the analysis of the rear side passivation of PASHA cells points to a higher recombination velocity in the region below the fingers on the rear we speculate on the origin of this effect. The passivation depends of course on the average BSF thickness that is formed below the Al-fingers. The thicker the BSF the lower the SRV observed. However, an additional edge effect could prove to be important as well. As the aluminum finger height decreases towards the fingers edge it is likely that the BSF decreases with it up to a point that no BSF is formed. Further it is likely that the SiNx below the paste is removed up to the finger edge resulting in a region where nor a well formed BSF nor an effective SiNx layer is formed. This could give rise to a significant rear surface area with an extremely high SRV (>10e5 cm/s)

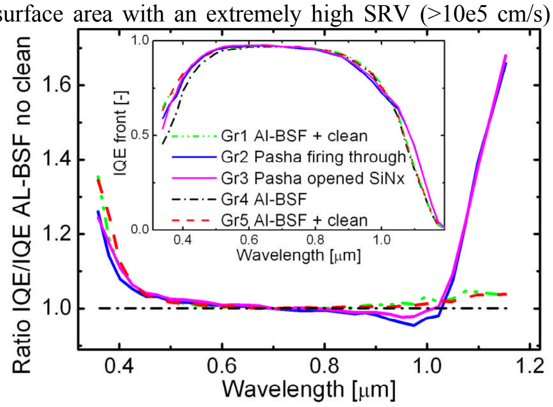


Figure 4, Effect of PASHA-clean on Al-BSF cell performance illustrated in terms of IQE ratios of group 1,2,3 and 5 over group 4 (Al-BSF without PASHA clean). The inset shows the original IQE spectra of the investigated cells. The bias illumination intensity used resulted in a bias current of 10 mA/cm^2 which is 30% of the Jsc under 1 sun.

adding to the poor performance of the PASHA cell in this experiment.

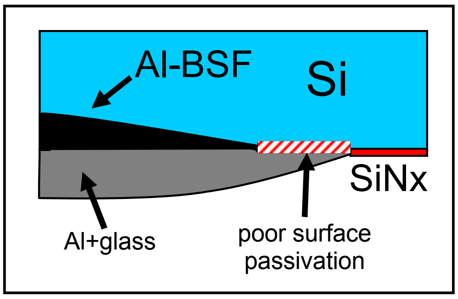
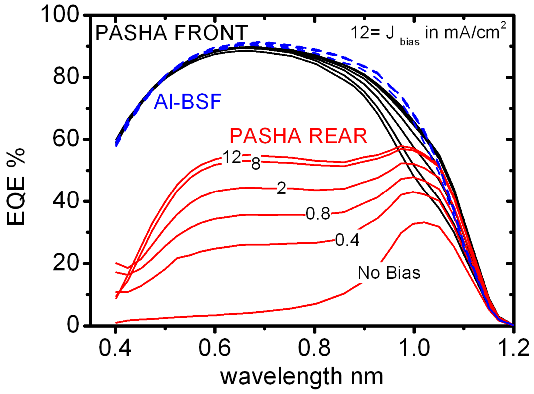


Figure 5, Illustration of the Al-BSF formation under the fingers pointing towards the location of the passivation problem

7 BIAS DEPENDENCE OF SPECTRAL RESPONSE

It is found that the SiNx surface passivation behavior, observed in the spectral response of PASHA cells, depends heavily on the bias illumination intensity used during the measurement. This type of cell response could lead to problems when comparing IQE spectra in literature if the bias current is not reported. The typical influence of the bias illumination intensity on the EQE of a PASHA (group 3) and a full AL-BSF (group 1) cell is shown in figure 6 a and b. The cells are prepared on neighboring wafers. The EQE spectrum of the Al-BSF cell is hardly affected by the bias illumination expressed in the DC cell current density, J_{bias} in mA/cm^2, . The EQE value of this cell increases merely by 0.7% (relative) at 1000nm between 2.05 and 12.3 mA/cm^2 and saturates at 8.2 mA/cm^2. When the front side of the PASHA cell is illuminated in this bias range at the same wavelength, this increase is 14% and saturates at 10 mA/cm^2, while the rear shows an even larger increase of 24% without reaching saturation at this intensity. This effect is also found for fired though samples.



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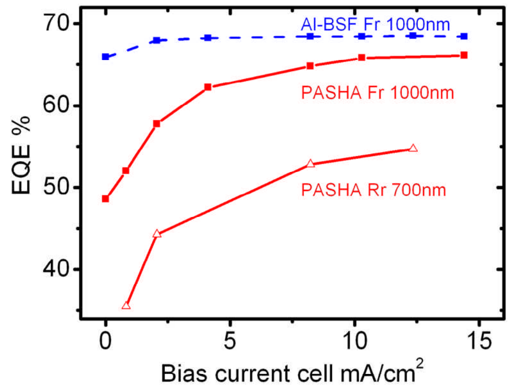

b)

Figure 6 a), Study on the influence of bias illumination intensity on the EQE spectra of PASHA and full Al-BSF cells under front and rear. The SiNx of the PASHA cell is opened (group 4). The used bias current density levels marked in figure A are of units mA/cm^2. **b)** The EQE at wavelengths most affected by the bias illumination are plotted vs. the bias current density.

This strong bias dependence of the EQE at wavelengths most dominated by the rear side recombination velocity, points towards a strong relation between the excess minority carrier concentration and the passivation behavior of the rear side of the PASHA cell. It is frequently reported [13,14] that the SRV of the SiNx depends on the excess minority carrier concentration which suggests that the bias effect measured in the PASHA cell is caused by the recombination behavior of the SiNx. Preliminary photocurrent linearity tests under white light were conducted on a series of PASHA cells with increasing rear metallization fractions. This series showed that the photocurrent response became more linear at higher metallization fractions. Also PASHA cells were prepared with passivating SiNx on the rear on which aluminum paste is printed that covered the complete rear area. These samples showed a bias dependency of the red response that changed less than 0.5% for J_{bias} between 2 and 12 mA/cm^2. These findings are in support of the hypothesis that the bias dependency of the EQE of the PASHA cell is caused by the SiNx layer and not by the firing-through aluminum metallization. This is independent from the fact if the SiNx was opened or not. Further it can be concluded that the SRV of SiNx decreases with excess minority carrier concentration as the red response increases with bias illumination intensity in the range between 0 and 12 mA/cm^2. Based on this carrier concentration dependence of the SiNx recombination behavior, it is expected to obtain a higher SRV for front illumination as compared to rear side illumination as in the latter condition most photons are absorbed at the SiNx/Si interface. This is in line with the results presented in table 3 were the fit results of both pasha cells show a higher SRV of for front than for rear side illumination.

8 ANNUAL YIELD

To estimate the effect that the observed non-linearity of the PASHA cell has on the annual yield, the efficiency of a PASHA (group 3) and an Al-BSF cell is measured between 0.1 and 1 sun. Based on these efficiency dependencies the annual yield is calculated for the location of Amsterdam. The program PVSYST v3.41 was used to simulate the yearly irradiance at this location and to calculate the annual yield in kWh/kWpeak. For the PASHA cell this is 1059.4 and for the Al-BSF this is 1072.5 kWh/kWpeak which is only 1.2 % higher. It can be concluded that strong the effect observed in the EQE spectra has relatively small consequences for the commercial use of the cell. The reason being of course that only a small part of the EQE spectrum is affected and that lower current levels have a positive effect the FF.

9 FUTURE WORK

Future work will include a demonstration of the potential of a lab scale PASHA cell at a metallization fraction below 10%. A gain in Jsc*Voc relative to the Al-BSF cell with PASHA clean is expected as the internal reflection and the rear SRV will improve by decreasing the metallization fraction.. In addition research effort will be directed to determine the SRV contribution of the aluminum metallization independent from that of the SiNx coating on multicrystalline material. This allows optimizing this part of the cell more independently from the rest of the cell.

10 CONCLUSION

We report on the performance of the PASHA cell compared to an improved full Al-BSF reference process on thin 6 inch mc-Si wafers (<210micron, 156x156 mm). Evaluating the average performance of both processes, the product of Jsc and Voc for the PASHA cell with opened silicon nitride is 20.3 mW/cm2, which is 2% lower than for the reference. The same trend was observed for un-opened SiNx (fired-through). The best obtained commercially applicable fill factor is 72%, which is 5% lower than the reference. The key factors that explain these results are: an improved front side passivation of the reference due to an additional PASHA clean step that precedes the SiNx deposition; poor passivation under and high series resistance in the rear fingers of the PASHA cell; an internal rear reflection gain that does not sufficiently compensate these effects. It is found that the SiNx surface passivation behavior, observed in the spectral response of PASHA cells, depends heavily on the bias illumination intensity used during the measurement.

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REFERENCES

[1] L. Janssen et al., Progress in Photovoltaic's: Res and Appl 15, 2007, 469-475
[2] I. G. Romijn et al., Proceedings 21st EPVSEC, Dresden, September 2006, 717; Proceedings 22nd EPVSEC, Milano, September 2007
[3] M. Hofmann et al., Proceedings 21st EPVSEC, Dresden, September 2006
[4] M. Hofmann et al., Proceedings 22nd EPVSEC, Milano, September 2007
[5] G. Agostinelli et al., Proceedings 21st EPVSEC, Dresden, September 2006;
[6] P. Choulat et al., Proceedings 22nd EPVSEC, Milano, September 2007
[7] C. J. J. Tool et al., Solar Energy Mat. and Solar Cells 90, 2006, 3165-3173
[8] C. J. J. Tool et al., Proc. 20th EPVSEC, Barcelona, June 2005
[9] I. Romijn et al., 15th Workshop on crystalline silicon solar cells & modules: Materials and Processes, Vail, Colorado, 2005, 82-85
[10] R. A. Sinton and A. Cuevas, Appl, Phys. Lett 96, 1996, 2510
[11] I.G. Romijn et al., m07090, Proceedings 22nd EPVSEC, Milano, September 2007
[12] P.A. Basore, D.A. Clugston, PC-1D v5.5, University New South Wales 2000
[13] J. Schmidt et al., 33rd IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE, San Diego, May 2008
[14] A.G Aberle, "Crystalline Silicon Solar cells,,, 0-7334-0645-9
[15] E. Bende et al., 33rd IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE, San Diego, May 2008