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SUBJECT 2.2 Silicon Solar Cell Improvements

IMPLEMENTATION OF AN ALD-AL_2O_3 PERC-TECHNOLOGY INTO A MULTI- AND MONOCRYSTALLINE INDUSTRIAL PILOT PRODUCTION

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ABSTRACT: In this paper, we present the InPERC technology implemented into a multi- and monocrystalline silicon (mc- and Cz-Si) solar cell production of major Asian cell manufacturers. Stable average efficiencies over 18% and 20 % were demonstrated, respectively. Best average efficiencies of 18.4% were achieved on mc-Si solar cells with a best cell efficiency of 18.8%. To reduce the cost of ownership (CoO) of the InPERC upgrade, the annealing step after ALD of Al_2O_3 was successfully skipped by integrating it into the direct tube PECVD without increase of PECVD process time. Furthermore, the Al_2O_3 thickness was reduced to 4 nm and the etch removal for rear side smoothening to 2 µm without loss in efficiency. An InPERC module passed all applied accelerated ageing tests (five times humidity freeze, damp heat, PID-test). In a CoO-comparison of different PERC routes, the InPERC technology showed the lowest total CoO and the lowest payback period of all investigated PERC candidates.
Keywords: ALD, Al_2O_3, PERC, i-PERC, Aluminum Oxide, Atomic Layer Deposition, CoO, stability

1 INTRODUCTION

The PERC technology is expected to be the next step in the evolution of industrial crystalline silicon solar cells production. On monocrystalline Czochralski silicon (Cz-Si) wafers many companies have achieved efficiencies of more than 20% by implementing a PERC technology into their pilot or mass production. However, 78% of today's mainstream solar cell production is using multicrystalline silicon (mc-Si) wafers, while only 22% is using Cz-Si wafers [1]. Thus, a profitable PERC upgrade for mc-Si solar cells is of great interest to the majority of solar cell manufacturers. Within this work, we present results of the implementation of a mc- and Cz-Si PERC-technology – the InPERC technology – into an industrial pilot production of major Asian cell manufacturers.

The InPERC technology has been developed for Cz-Si and mc-Si solar cells and has been described in detail previously [2]. In this publication, we report the results of the technology integration with focus on improvement that significantly reduces the cost of ownership (CoO) of the InPERC technology. Then an analysis is presented that shows even further efficiency potential in the near future. Furthermore, we show results of an accelerated ageing test on an InPERC module. Finally, a CoO-comparison of different PERC technologies is presented.

2 EXPERIMENTAL

The process sequence (Figure 1) utilizes all the production equipment of the standard production line for screen printed full area Al-BSF solar cells. Wafer material (mc- and Cz-Si) with a base resistivity of ρ_{base}= 1-3 Ohm cm was used to process both PERC and full-Al-BSF solar cells. For each experiment the wafers were randomized at the beginning of the process chain. In the following sections, deviations from the process flow in Figure 1 will be highlighted where applicable.

	Reference	InPERC ALD technology for mc-Si	
1	Inline acidic texture		
2	$POCl_3$ diffusion		
3	Wet chemical edge isolation	Wet chemical edge isolation with integrated smoothing of the rear surface	upgrade
4		Spatial atomic layer deposition of Al_2O_3	tool 1
5		PECVD rear SiN_x with integrated PDA	tool 2
6	PECVD front SiN_x		
7		Laser contact opening	tool 3
8	Screen printing of metallization and fast firing		

Figure 1: The InPERC technology for mc-Si solar cells adds 3 tools and one equipment upgrade to the standard production line.

Texturing was performed in an Inline acidic texture for mc-Si and by alkanie-based batch texture for Cz-wafers. In the case of mc-PERC integration a standard industrial back-to-back loading was compared to a single loading of the quartz boat during the $POCl_2$ diffusion (see sec. 3).

It is well known that PERC solar cells profit from a fine adapted rear side smoothing during the wet-chemical edge isolation. For this purpose, the hardware of one existing standard RENA InOxSide® for wet chemical edge isolation is upgraded to InOxSide®+ without additional footprint. The rear side is passivated using SoLayTec's InPassion® ALD mass production machine for ultrafast spatial atomic layer deposition (ALD) of Al_2O_3. The thickness of the layer was varied from 4-10 nm.

In a first mc-PERC integration phase an external PDA (post deposition annealing step) was performed in a furnace tube. In the second phase the external PDA step was skipped and integrated into SiN_x tube PECVD rear side process (PDA integration, see sec. 4.1). The SiN_x at the rear side acts as an isolating barrier layer to Al during local BSF alloying, hydrogen source, and as a reflector. The dielectric stack at the rear side is locally ablated by a commercially available laser system. For screen printing and firing the same production equipment have been applied for the standard full Al-BSF baseline cells and the InPERC technology cells. For the formation of a local BSF a special PERC aluminum paste was used.

3 AVERAGE EFFICIENCY EXCEEDING 18% IN INDUSTRIAL PILOT PRODUCTION

In Q3 2013 the mc-InPERC technology integration into the industrial pilot production of a major Asian cell manufacturer started. A large number of process adaptations were carried out in order to find the optimum conditions for the customer’s production line and wafer material. The evolution of average electrical parameters are shown in Figure 2 for the complete technology integration period of about 8 months, divided into 2 phases.

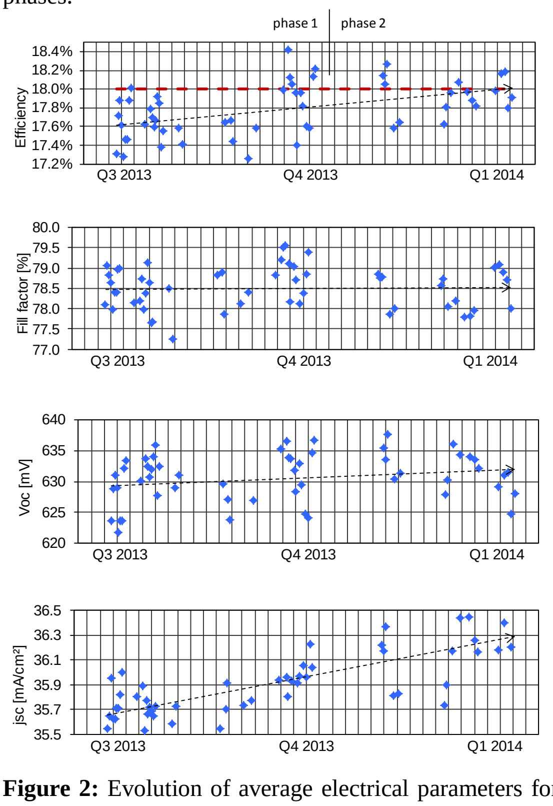

Figure 2: Evolution of average electrical parameters for the technology integration phase of about 8 months, divided into 2 phases.

In phase 1, the main contribution to the improvement of average efficiency can be attributed to a stabilization of the process for wet chemical smoothening of the rear side and an adjustment of the laser process to the customer’s precursors. In this first phase the best results were obtained using a post deposition anneal (PDA) in a tube furnace directly after the ALD process.

At the end of phase 1, stable average efficiencies over 18% were achieved. Using $POCl_3$ diffusion gettering from both wafer surfaces by single wafer loading (instead of loading 2 wafers back-to-back in one slot) an average efficiencies of 18.4% and a best efficiency of 18.8% were demonstrated as shown in Table 1. This observation shows that with further improvements in wafer quality (reduced need for gettering) the efficiency advantage of the PERC technology will increase on mc-Si wafers.

Table 1: Using $POCl_3$ diffusion by single wafer loading and thus gettering from both sides, best average efficiencies of 18.4% were demonstrated.

Group	Voc [mV]	jsc [mA/cm²]	FF [%]	Efficiency [%]	*number of cells*
Full Al-BSF Baseline back-to-back loading in diffusion	628.8 ±3.2	34.7 ±0.2	80.4 ±0.5	17.53 ±0.35	*94*
InPERC back-to-back loading in diffusion	633.8 ±4.6	35.8 ±0.3	79.6 ±0.4	18.05 ±0.24	*96*
InPERC single wafer loading in diffusion	636.6 ±5.2	36.5 ±0.2	79.2 ±0.5	**18.42** ±0.33	*67*

4 REDUCTION OF COST OF OWNERSHIP FOR THE InPERC TECHNOLOGY

4.1 Passivation stack layers related optimizations

After reaching stable average efficiencies over 18% in phase 1, the focus of phase 2 was to further reduce the cost of ownership (CoO) of the InPERC technology. In particular, three main contributors were addressed:

(1) Skipping the PDA step
(2) Reducing the Al_2O_3 thickness
(3) Reducing the chemical consumption in wet chemical rear side smoothening

Skipping the PDA step has the largest effect on the CoO, since equipment process step can be omitted. It was demonstrated that the PDA step can be integrated into the subsequent PECVD process [3]. A direct tube PECVD was used to apply the SiNx capping layer. This recipe was successfully adjusted to integrate the PDA under the precondition that the process time for front and rear PECVD did not increase.

Reducing the Al_2O_3 thickness from 10 nm to 4 nm also has a relevant effect on the CoO. In addition to reducing the consumption of gases, this modification increases the throughput of the InPassion® ALD considerably. It was shown on lifetime samples that the passivation quality can be fully attained with an Al_2O_3 thickness of 4 nm [2]. Furthermore, the need and time for outgassing (one mechanism of the PDA) decreases with a lower Al_2O_3 thickness.

Table 2 shows results that demonstrate the successful integration of the PDA step with a simultaneous reduction of Al_2O_3 thickness to 4 nm. The full Al-BSF baseline shows the level of the standard production at that time.

Table 2: Average electrical parameters that show the successful integration of the PDA step in the PECVD SiNx process and a simultaneous reduction of Al_2O_3 thickness to 4 nm.

Group	Voc [mV]	jsc [mA/cm²]	FF [%]	Efficiency [%]	*number of cells*
Full Al-BSF Baseline	626.2 ±4.1	35.0 ±0.2	79.8 ±0.4	17.48 ±0.23	*2418*
InPERC external tube PDA 4 nm Al_2O_3	636.7 ±4.5	36.0 ±0.3	79.4 ±0.6	18.22 ±0.33	*70*
InPERC PDA integrated in tube PECVD 4 nm Al_2O_3	635.4 ±3.2	36.2 ±0.2	78.8 ±0.5	18.15 ±0.26	*192*

All results shown in phase 2 in Figure 2 are from solar cells processed with the PDA integrated in the tube PECVD and with an Al_2O_3 thickness of 4 nm. In phase 2, always two wafers were loaded per slot (back-to-back loading $POCl_3$ diffusion process.

In case the SiNx capping layer is applied with a remote PECVD (instead of a direct tube PECVD) the PDA step can be integrated in SoLayTec's InPassion® ALD as an upgrade. Figure 3 shows a low-cost annealing furnace located directly after the deposition modules.

Figure 3: SoLayTec's InPassion® ALD can be upgraded to integrate the post deposition anneal (PDA). The low-cost annealing furnace is located directly after the deposition modules.

4.2 Rear side smoothing related optimizations

Reducing the chemical consumption in the rear side smoothing/polishing process was addressed as the next step in lowering the CoO of the InPERC technology. Previous studies showed that smoothing of the rear surface is necessary to obtain high efficiencies, but best results can already be achieved with relatively low etch removal [4]. Therefore, the process of RENA's InOxSide®+ was optimized further. Table 3 shows results with an optimized InOxSide®+ process. On solar cell level, best InPERC results are already obtained with an etch removal of 2 µm, resulting in a lower chemical consumption.

Table 3: Results with an optimized InOxSide®+ process are shown. Best InPERC results are already obtained with a rear side etch removal of 2 µm, resulting in lower chemical consumptions.

Group	Voc [mV]	jsc [mA/cm²]	FF [%]	Efficiency [%]	*number of cells*
Full Al-BSF Baseline	623,9 ± 2,0	35,3 ± 0,1	79,9 ± 1,1	17,61 ± 0,28	*73*
InPERC 2 µm rear smoothing	631,5 ± 2,7	36,5 ± 0,2	78,9 ± 0,8	18,19 ± 0,27	*61*
InPERC 3 µm rear smoothing	629,6 ± 3,4	36,4 ± 0,3	79,2 ± 0,6	18,18 ± 0,28	*56*
InPERC 4 µm rear smoothing	629,6 ± 3,8	36,2 ± 0,3	79,2 ± 0,8	18,07 ± 0,35	*66*

5 FURTHER EFFICIENCY POTENTIAL OF THE InPERC TECHNOLOGY

A comparison of the electrical parameters of the InPERC cells and full Al-BSF cells quickly shows, that the InPERC cells show a higher Voc (~10 mV) and a higher jsc (~1 mA/cm²), but suffer from a lower FF. Experiments to reduce the series resistance were performed, but did not result in a significantly higher FF. Therefore, we believe that the origin of the lower FF is not mainly caused by series resistance losses. The root cause lies in a lower pseudo fill factor (PFF), as is explained by the following analysis.

Figure 4 shows the fill factor (FF) and pseudo fill factor (PFF) plotted over the corresponding V_{oc} of mc-Si full Al-BSF and mc-Si InPERC solar cells. The theoretical fill factor limit FF_0 is also shown. The difference *PFF-FF* is a good measure for fill factor losses due to series resistance, whereas FF_0*-PFF* quantifies the FF loss due to different j_0 recombination current densities and shunt resistance.

The fill factor loss due to series resistance (*PFF-FF*) is almost equal for standard and InPERC cells. But the difference FF_0*-PFF* is much higher for all InPERC solar cells compared to the standard cells. This observation is unexpected, but several mechanisms have been identified that might lead to a lower PFF for the InPERC cells.

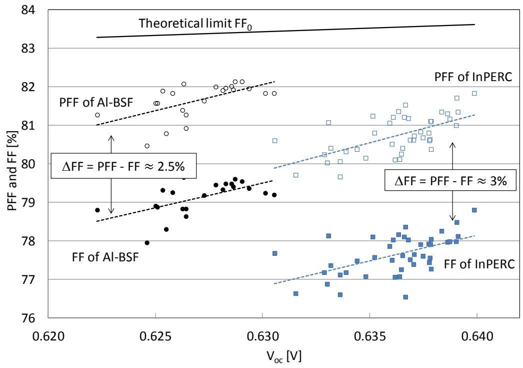

Figure 4: Fill factor (FF) and pseudo fill factor (PFF) plotted over the V_{oc} of mc-Si full Al-BSF and mc-Si InPERC solar cells.

One mechanism, that can lower the PFF are scratches on rear and/or front side (shunts) that occur before SiN_x coating. Great improvement is expected by applying automated wafer loading at the PECVD process. Another possible mechanism is parasitic laser damage. Such damage occurs, when the passivation layer is opened, but the local Al-BSF is not formed completely to heal the laser damage.

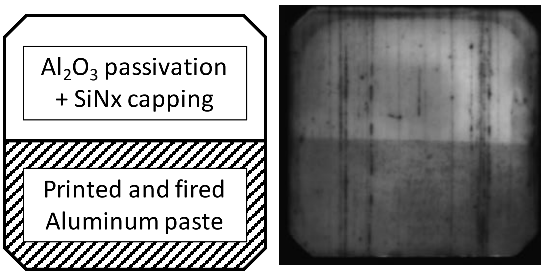

Figure 5: Lifetime sample printed with PERC Aluminum paste on the lower part and fired. The area covered by Aluminum shows a reduced PL, suggesting a non-optimum capping property of the SiNx capping layer.

A third possible mechanism is an imperfect barrier performance of the SiN_x capping layer against Aluminum in the fast firing process. This effect is demonstrated in Figure 5. An InPERC cell without metallization and without laser openings (lifetime sample) was printed with PERC Aluminum paste on the lower part of the wafer and fired. In the Photoluminescence (PL) picture, the area covered by Aluminum shows a reduced PL signal compared to the not-covered area on the same wafer.

In total, we see a potential for FF improvement for InPERC cells in the range of 1-2% (absolute) in the near future. Furthermore, an additional pre-clean before the ALD process might result in further efficiency increase of 0.2 to 0.4%$_{absolute}$.

6 INTEGRATION OF InPERC TECHNOLOGY INTO A CZ-PRODUCTION LINE

The same hardware upgrade as applied to the mc-production line (sec. 3 & 4) was integrated into a Cz-production line at a different Asian customer.

In Table 4 an overview of the results of a PERC Al-paste variation is shown. The full Al-BSF baseline group showed an average efficiency about 19%. Applying the developed best known method from the mc-PERC integration (presented in sec. 3 & 4) to Cz-wafers results in an average efficiency gain of 0.8%. A comparison of a new generation of PERC Al-pastes to the standard Al paste (used for mc-InPERC experiment presented in this publication), resulted in a further efficiency increase of up to 0.2% (see Tab. 4).

Table 4: Results of PERC Al paste variation (Cz-wafer). The full Al-BSF group serves as a reference and a measure for the efficiency gain.

Group	Voc [mV]	Jsc [mA/cm²]	FF [%]	Efficiency [%]	No. of cells
Full Al-BSF baseline	637,1 ±1	38,4 ±0,1	77,4 ±0,9	18,96 ±0,21	46
InPERC Standard PERC Al paste	644,7 ±1,6	40 ±0,1	76,9 ±0,9	19,82 ±0,24	58
InPERC New Al Paste A	647,2 ±1,5	40,2 ±0,1	77 ±1,1	20,03 ±0,3	65
InPERC New Al paste B	647,3 ±1,5	40,2 ±0,1	76,6 ±1	19,94 ±0,27	66
InPERC New Al paste C	647 ±1,7	40,2 ±0,1	76,3 ±1,3	19,85 ±0,36	65

The upgraded Cz-production line shows stable efficiencies above 20%. The amount of produced wafer per day is increasing steady. Up to 12000 PERC cells per day were processed at this early stage of technology integration.

7 LONG TERM STABILITY OF InPERC MODULES

To investigate the long term stability of InPERC cells and modules, several tests have been performed. Obviously, a possible failure mechanism could be the solder adhesion of the rear side solder pads. The results of a 180° peel test for 4 different pastes for rear side pads are shown in Table 5. Adequate adhesion values were measured compared to the reference. The solar cell efficiencies did not vary significantly.

Table 5: Results of a 180° peel test for 4 different pastes for rear side pads are shown. Adequate adhesion values were measured compared to the reference.

Group	Full Al-BSF Baseline	InPERC			
	Standard Pad Paste	Standard Pad Paste	PERC Pad Paste A	PERC Pad Paste B	PERC Pad Paste C
Average peel off force [N]	2.9	2.4	1.8	2.9	2.0

A module of 60 InPERC cells was manufactured. In this case, the module consisted of Cz-Si InPERC cells. First, the module was subjected to light soaking in order to stabilize any light induced degradation (LID) due to the well-known Boron-Oxygen complex. This initial LID is not part of this investigation, since it occurs at both InPERC and standard Cz-Si solar cells.

After that, the module was subjected to a number of accelerated ageing tests. After LID stabilization the module remained stable under outdoor weathering. Then 5 subsequent humidity freeze tests were carried out. Each humidity freeze test consisted of 10 cycles of -40°C to 85°C at 85% humidity during 10 days of testing time. One such test is part of the IEC 61215 test conditions. After the 5 humidity freeze tests, the module entered a potential induced degradation test (PID test). After the PID test, a power loss of -1.0 % was measured. According to the requirements of IEC 61215, the module passed the damp heat test after it passed the humidity freeze test five times in a row. During the whole testing procedure, electroluminescence pictures were taken, but showed no noticeable problems.

This leads to the conclusion that the InPERC process, especially the Al_2O_3 layer and the new metallization pastes for the rear side, enable long term stable modules.

8 COMPARISON OF COST OF OWNERSHIP OF DIFFERENT PERC TECHNOLOGIES

The passivation of the rear side is undoubtedly being pursued by many solar cell manufacturers today. For a successful establishment of this new technology, a profitable cost of ownership (CoO) is obviously a requirement. In CoO calculations, the absolute values in €/Wp or €/wafer are highly dependent on up-to-date market prices and production data. The solar cell manufacturers have exact data to calculate their CoO for new technologies and most have decided to pursue the PERC technology.

However, many different PERC routes exist, each using different processes, equipment and material for the passivation layer. Therefore, we performed a very detailed CoO calculation, in order to compare our InPERC technology to the other published PERC technologies. Our focus is not on absolute values, but rather a correct comparison. By using the same assumptions for each of the different PERC technologies, a direct comparison is possible.

The results of the CoO calculation are shown in Table 6 and Figure 6. All values have been normalized to the values of the InPERC route. The calculation mostly (but not only) uses data from [5]. It has been assumed that the efficiency gain of all PERC technologies is equal (1.0% on Cz-Si). All configurations are assumed to have a wet chemical rear side smoothening/polishing.

The detailed configurations and number of machines were chosen to match the throughput of all equipment in the most favorable manner. The capital expenditure (CAPEX) per wafer includes depreciation of the investment over 5 years, but no interest and insurance. The consumables per wafer include personnel and maintenance. The total CoO per wafer also includes a yield loss due to the additional equipment.

Table 6: Comparison of the CoO of different PERC routes. All results are normalized relative to the InPERC technology (configuration 7).

#	Name	Wet Chemistry	Passivation	Capping	Laser
1	**ICP PECVD**		ICP PECVD (Al_2O_3 + SiNx + automation)		
2	**HPP PECVD**		HPP PECVD (Al_2O_3 + SiNx + automation)		
3	**InLine APCVD**		InLine APCVD Al_2O_3	Direct tube PECVD SiNx	
4	**Remote PECVD**	RENA InOxSide®+ upgrade	Remote PECVD (Al_2O_3 + SiNx + automation)		
5	**Batch ALD**		Thermal batch ALD Al_2O_3	Direct tube PECVD SiNx	
6	**Spatial ALD (B)**		Spatial ALD (B)	Direct tube PECVD SiNx	
7	**InPERC**		SoLayTec InPassion® ALD (5 nm Al_2O_3 + automation)	Direct tube PECVD SiNx	

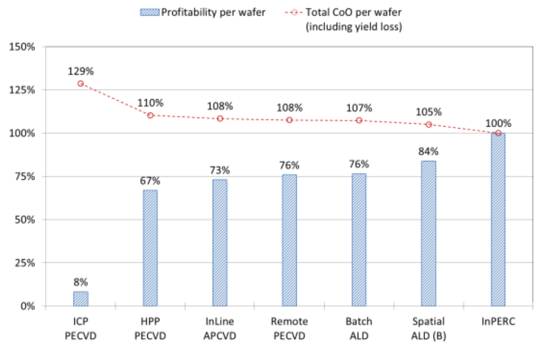

Figure 6: Comparison of the CoO of different PERC technologies. All results are relative to the InPERC technology.

It can be seen from Figure 6 that the total CoO per wafer of all technologies is very similar.However, even slight variations in the total CoO mean a large variation in the profitability per wafer. The InPERC technology has the lowest total CoO per wafer, mostly due to the low amount of required consumables. As a consequence, the profitability per wafer is the highest and the payback period of the InPERC route is the lowest. In summary, this comparison makes us confident, that the InPERC technology is a very competitive PERC solution, with lowest total CoO and an attractive payback period.

9 CONCLUSION

The InPERC technology has been implemented into a mc- and Cz-Si solar cell pilot production. Stable average efficiencies over 18% and 20 % were demonstrated, respectively. Best average efficiencies of 18.4% were achieved with a best cell efficiency of 18.8% on mc-Si industrial solar cells without selective emitter.

To reduce the CoO of the InPERC upgrade, the PDA step after ALD was successfully skipped, by integrating it into the direct plasma PECVD tube deposition process without increase of PECVD process time. Furthermore, the Al_2O_3 thickness was reduced to 4 nm and the etch removal for rear side smoothing to 2 µm without loss in efficiency.

An InPERC module passed successful all applied accelerated ageing tests, leading to the conclusion that the InPERC technology does not add any stability issues to the solar cell.

In a CoO-comparison of different PERC technologies, the InPERC technology showed the lowest total CoO and the lowest payback period of all investigated PERC candidates.

We would like to thank all our industrial partners for the cooperation in reaching the presented results.

10 REFERENCES

[1] Coleville,F.http://www.pv-ech.org/guest_blog/can_pv_technology_change_before_2015

[2] Sastrawan, R. et. al. In proceedings of the 28th EU PVSEC 2013, Paris, France

[3] Gay, X. et al. In proceedings of the 28th EU PVSEC 2013, Paris, France

[4] Cornagliotti, E. et al. How much rear side polishing is required? In proceedings of the 27th EU PVSEC 2012, Frankfurt, Germany

[5] Chunduri, S. K. Evolutionary revolution. Photon International March 2014