

Industrial Application of Uncapped Al_2O_3 and Firing-Through Al-BSF In Open Rear Passivated Solar Cells

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ABSTRACT

Current bottlenecks for industrial application of Al_2O_3 deposited by Atomic Layer Deposition (ALD) on open rear passivated solar cells are low growth rate, firing stability of thin and uncapped layers, and Firing-through BSF formation during co-firing. Long term stability results on the performance of a high throughput ALD proto-type, the Levitrack, are presented. Excellent passivation properties have been obtained after firing: for 12 nm thick films deposited on p-Fz (1.8 $\Omega\cdot\text{cm}$) a τ_{eff} of 2.2 ms ($\Delta n=3\times 10^{15} \text{cm}^{-3}$) was obtained that remained constant over a period of 20 weeks. Furthermore, we report on the passivation quality of the firing-through BSF and Al_2O_3 coating as function of wafer peak temperatures between 790 and 845°C. Bifacial cells covered for 50% Al contacts resulted in local BSF thicknesses of 5 to 7 μm and FF of 78% and 77% for the best mc and mono crystalline cell respectively. For this study 12 nm uncapped aluminum oxide layers are deposited on the rear of p-type mc and mono bifacial cells. LBIC measurements confirm literature reports that uncapped Al_2O_3 passivation in general is heavily dependent on the wafer peak temperatures during firing in the investigated range.

INTRODUCTION

In search of solar cell concepts that allow processing of thinner wafers (<150 μm), the conventional full Al rear side of p-type solar cells can be replaced by an open rear metallization combined with a dielectric passivation layer as illustrated in figure 1. We estimate that the bifacial cell could result in a gain of 0.3-0.4% in absolute efficiency for a rear passivated multi-crystalline solar cell with local contacts [1,2]. This gain can be achieved when the bifacial cell is placed on an effective rear reflector such as a back-sheet foil (or an additional full area metallization on so-called PERC cells for which a gain of 0.5% is estimated due to lower resistive losses), optimized for reflections between 1000 and 1300 nm as the transmittance in this range increases as the wafer thickness decreases. The principle gain factors in terms of the product of $J_{\text{sc}}\cdot V_{\text{oc}}$ are improved internal rear reflection and improved passivation of the dielectric layer as compared to a standard full Al-BSF. This efficiency gain is a balance of the superior passivation and reflection quality of the dielectric layer compared to the metal contacts and extra resistive losses in the base and the metal grid that are induced by the openings in the rear metal design. The efficiency gain can

be obtained if the local BSF quality of the contacts matches the quality of the full area BSF and SRV values below 100 cm^2/s are achieved for the dielectric layer. Additional advantages of the bifacial cell are reduced consumable costs, as the Al-paste use per cell will be reduced by 50-75% while reduced cell bowing after firing will increase production yield due to less cell breakage. In addition of the extra dielectric layer deposition step for rear passivation it is our approach to limit the extra processing steps for the bifacial cell. Ideally, this is done by improving on the wet chemical edge isolation step by combining it with rear side polishing and cleaning. No extra step is used to open the dielectric layer as the contacts are fired-through the dielectric layer forming an effective BSF.

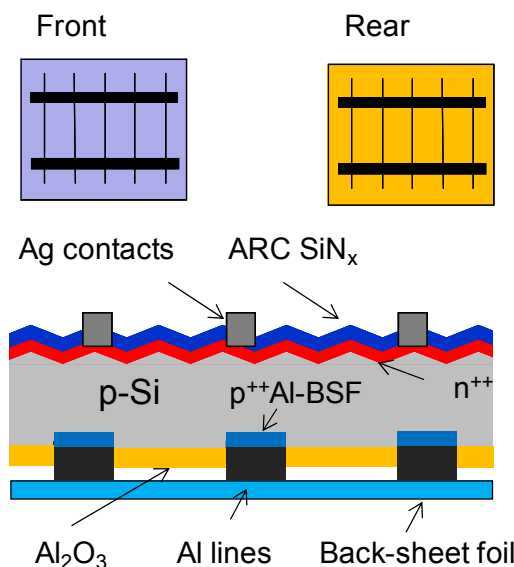


Figure 1, open cell concept with metal print on front and rear consisting of parallel fingers connected to busbars. The metal fraction the rear is about 30-35%. Back-sheet foil reflects photons at wavelengths between 1000-1300 nm back into solar cell.

Firing-through BSF formation and firing temperature

Ferro has developed screen printable Al pastes that enable the formation of a localized BSF when firing through Al_2O_3 passivation layers. The challenge is to obtain the optimal paste composition that results in sufficient BSF thickness under the rear side grid lines in a typical co-firing process. In order to

form a good BSF the glass frit is required to wet and etch the Al_2O_3 layer. Secondly, at higher temperatures (above 577 C) the aluminum in the paste needs to react with the silicon surface and form a liquid eutectic alloy that results in a BSF upon cooling. The peak firing temperature is known to be an important factor for both the etching rate and BSF thickness. Therefore, higher peak temperatures are expected to yield a thicker localized BSF under the grid lines.

AL2O3 passivation and firing stability

As passivating dielectric, aluminum oxide has received much attention in recent years because of its potential surface passivation performance in silicon solar cells. It is known to passivate boron emitters [3] and can be applied as rear dielectric in rear passivated solar cells based on p-type wafers, like the PERC [4] and the PASHA cell [5]. Surface passivation levels at Al_2O_3 layers expressed by values below 10 cm/s for the effective surface recombination velocity, S_{eff} , are commonly reported. The reduced recombination at the surface is caused by field effect as well as chemical passivation. This dielectric is characterized by very high negative surface density (10^{12} - 10^{13} cm⁻²) [6,7] that repel electrons from the surface, reducing the chance for recombination with holes. A major advantage of the negatively charged Al_2O_3 on p-type surfaces is that it does not cause inversion layer shunting. This phenomenon severely reduces the J_{sc} of rear passivated solar cells and is commonly observed for positively charged dielectrics such as SiNx [8;9]. Although Al_2O_3 has proven its potential as effective rear dielectric in high efficiency solar cells (> 20%) [4], its application in industry is impeded by several factors: 1) low wafer throughput rates related to the deposition method and lengthy anneals, 2) firing stability and 3) contact formation through the dielectric. These issues are addressed in this work. Benick et al studied that the surface recombination velocity of 27 nm thick Al_2O_3 layers deposited on p-Fz (1 ohm.cm) by Plasma Enhanced ALD [3]. It is reported that the SRV increased from below 10 cm/s at a peak temperature of 700°C to values well above 1000 cm/s at 850°C. On the other end, the BSF formation after firing-through a dielectric layer generally improves at high wafer temperatures. Thus, the main challenge for the industrialization of this dielectric and the firing-through paste is to optimize the BSF formation to match the firing condition at which the Al_2O_3 retains its passivation quality. Measures to improve the firing stability by capping the Al_2O_3 layer, as well as the application of long forming gas anneals steps, are unfavorable for industrialization. Here we show preliminary results on the integration of 12nm thick and uncapped Al_2O_3 films in rear passivated bifacial solar cells of the PASHA (Passivated on all sides H-pattern) type using new firing-through Al-pastes. Additionally, we report on the long term stability of the surface passivation quality after firing of these Al_2O_3 films.

EXPERIMENTAL SECTION

In order to assess the potential for industrial rear side passivation of uncapped Al_2O_3 layers, cells were fabricated on 6 inch p-type multi (neighboring) and mono (Cz) crystalline wafers. The wafers were textured on the front side (multi: iso-texture; mono: random pyramid) and polished on the rear for better light entrapment and rear passivation. They received a 70 ohm/sq POCl emitter, followed by an isolation step using wet chemical etching and a SiNx coating on the front side at ECN after which they were shipped to Levitech for the deposition of an Al_2O_3 coating on the rear using the Levitrack. Subsequently they were shipped to Ferro where they were printed and fired using a newly developed Al firing-through paste. The firing was done using a DOE with various peak temperature settings which resulted in wafer temperature between 790 and 845°C. The wafer temperature was measured using a e-Clipse profiling unit with K-type thermocouples that measure the temperature at four locations on the wafer [14]. The fired wafers were shipped back to ECN for optoelectrical characterization (IV and LBIC). The fill factors reported are obtained by contacting only the front and rear busbars without electrically shorting the rear fingers. A small selection of wafers was kept at ECN and processed with a full Al-BSF as a reference. The complete process flow is shown in figure 2..

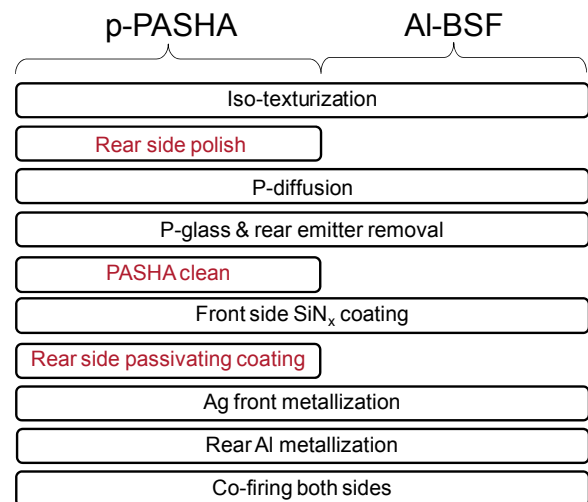
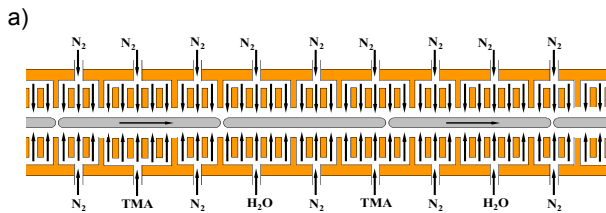
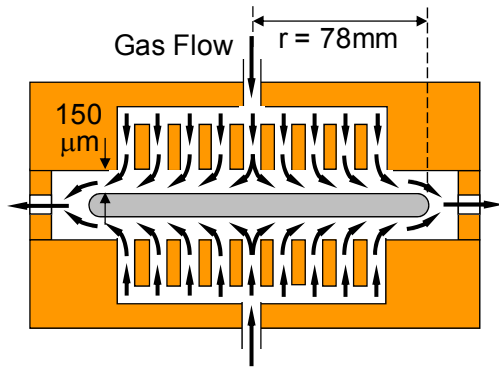


Figure 2, process flow of Al-BSF reference (black) with in red the additional steps that are only used for the Al_2O_3 passivated PASHA cells. The PASHA clean used is a thorough clean procedure that affects both the front and rear side [10;11].

Levitrack: industrial deposition of ALD Al_2O_3 films

The basic principle of the system is shown in figure 3. The wafers are floating in a linear gas track; N_2 and N_2 /precursor mixtures are injected from the bottom wall upwards onto the wafers, while at the top only N_2 is introduced. The combination of a narrow gap (0.15 mm) and a relatively large gas flow of a

few slm above and below each of the wafers results in a robust transport of wafers in the track. This arrangement ensures that the wafers do not touch the top and bottom walls of the reaction chamber. Special precautions are taken to guarantee that the wafers also do not collide with the side walls of the track.



a) and b) cross sections in directions perpendicular and parallel to the wafer transport direction, respectively.

Figure 3, Levitrack system, a high-throughput ALD system (developed by Levitech, patents pending). The wafers float in gas injected into the transport chamber through holes in the top and bottom walls. Each sequence of TMA-N₂-H₂O-N₂ results in the deposition of a saturated (mono-) layer of Al₂O₃ on one side of the wafer.

Each time a wafer passes a cell containing a TMA-N₂-H₂O-N₂ gas injection sequence, a saturated ALD Al₂O₃ layer is deposited. The total number of cells in the track determines the final Al₂O₃ film thickness on all wafers. For the first systems a film thickness of 10-12 nm is targeted (~100 cells). The system is designed to operate in a temperature window of 150-300°C and to process wafers with a throughput up to 1 wafer/s (3600 wafers/hr).

The characteristics of the Levitrack approach are the following: as the TMA and H₂O precursor flows are strictly separated in space (in case of a fully loaded track as well as in case of an empty track), there is no parasitic deposition of Al₂O₃ films on the walls of the track. This will have a very positive impact on the maintenance aspects of the system. Further, when precursors are injected from one wall only (top or bottom), deposition will take place on only one side of the wafer. In addition to that, as the gap between wafer and walls is only 0.15mm, heating of the wafer is very fast; the wafer will be heated to process temperature in a matter of seconds. Finally, as the process is at atmospheric pressure, no vacuum pumps are

present; the Levitrack system is made entirely from aluminum, and does not have any moving parts.

A series of layer thicknesses was deposited on p-Si FZ wafers (100 mm, 1.8 Ω.cm) in the 2 m long gas track of the Levitech proto-type. A single run at a deposition temperature of 200°C resulted in an Al₂O₃ layer thickness of about 2 nm. As the Levitrack currently operates in single side deposition mode (precursors only flow from bottom), double side depositions of the layer thicknesses 5, 12, 18 and 24 nm were achieved by multiple deposition runs through the gas track while flipping the wafer after each run. As a consequence, one unpassivated side of each wafer was exposed to the handling and thermal treatment of its first run. This might have a negative effect on the final surface passivation quality for the symmetric test-structures. However, this does not pose a problem for future cell processing as the front side can be coated by SiNx prior to the rear side deposition or the Levitrack can be modified to operate in double side deposition mode.

We evaluated the performance of the Al₂O₃ layer obtained from the levitrack system as rear dielectric in a PASHA cell at three firing temperatures. It is important to mention that no forming gas anneal was performed in this experiment to activate the Al₂O₃ passivation and that a typical firing step was performed. The rear metallization designs consist of an H-pattern. In each corner of the cell a pattern of lines of varying width is printed to study the passivation of the AL-BSF and the dielectric by means of laser beam induced current mapping (LBIC). For research reasons, the lines are printed perpendicular to the front fingers as illustrated in figure 5 Front and rear contacts are prepared by screen printing firing through silver and aluminum based pastes respectively.

The details of the performed experiments such as the ALD system and deposition temperature, wafer resistivity and deposited Al₂O₃ layer thickness are summarized in Table 1.

Table 1, Overview experiments: Deposition parameters, Al₂O₃ layer thickness, sample structure and material.

Deposition parameters	Lifetime test structure (double side deposition)	PASHA Cell (Rear side deposition)
Levitrack ALD T _{dep} =200°C Continuous process	100 mm p-Si Fz 1.8 Ω.cm 5-24 nm Al ₂ O ₃	156 mm, p-Si mc, p-Si Cz, 1-1.5 Ω.cm 12 nm Al ₂ O ₃

RESULTS AND DISCUSSION

Lifetime performance

Depositions of Al₂O₃ on p-type Fz-Si (1.8 Ωcm) obtained from the Levitrack system yielded excellent passivation quality after firing. The wafers were cut in quarters after deposition and as

deposited, these layers had lifetimes in the order of 0.1 ms while firing step activated the surface passivation quality to excellent levels as illustrated in figure 4. For films with layer thicknesses of 5, 12, 18 and 24 nm τ_{eff} of 0.28, 2.3, 1.1 1.2 ms were measured at $\Delta n=3e15 \text{ cm}^{-3}$, after firing and 20 weeks of storage. The dependence of the τ_{eff} on the film thickness suggests an optimum between 5 and 18 nm. The best lifetime for the 12 nm thick layer corresponds to a surface recombination velocity of 2 cm/s assuming a 4 ms bulk lifetime. The actual peak wafer temperature lies below 750°C.

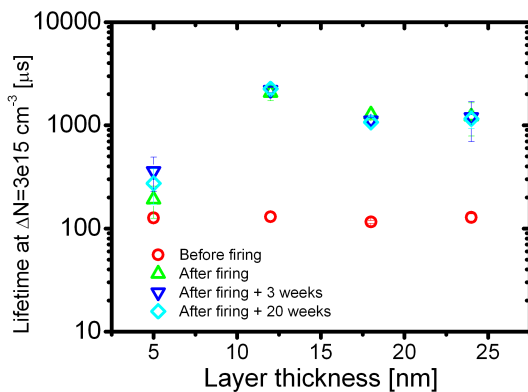


Figure 2. The effect of moderate firing (<750°C), layer thickness and storage time (in dark) of Al₂O₃ layers on the surface passivation as measured by the effective lifetime at $\Delta n=3e15 \text{ cm}^{-3}$ using QSSPC setup (Sinton). The layers were deposited in the Levitrack in multiple runs on both sides of p-Fz wafers (1.8 ohm.cm).

Rear passivation quality vs. firing temperature

The PASHA type solar cells prepared with the Al₂O₃, are fired at three firing temperatures and compared to a full Al-BSF cell fired at optimal conditions. The peak temperatures of the PASHA cells range from 790 to 845°C. As part of a first scan on the influence of the firing profile three neighboring multi-crystalline cells and three mono crystalline cells were fired, one of each cell type at each furnace setting. The performance of these cells is summarized in the table 2 with the IQE at 976 nm of the integral cell and of localized LBIC measurements (figure 5).

In contrast to the excellent rear passivation quality obtained for Al₂O₃ in similar PASHA cells in our previous work [5] which was obtained at much lower peak temperatures (<750°C), the rear passivation performance in the current cell experiment is limited by poor passivation at the dielectric surface. Whereas the IQE at the dielectric was superior to that of the local BSF in the previous report, shifting to higher firing temperatures in this study to aid BSF formation caused the IQE at the dielectric (64 to 73%) to drop significantly below that of the BSF (79 to 81%). Based on a simple PC1D calculation [13], the low

IQE values for Al₂O₃ correspond to SRV values well above 1000cm/s which is much higher than the 2cm/s that is calculated from the best lifetimes presented in figure 4. Also these excellent lifetimes are obtained at more gentle firing conditions (<750°C). The strong dependency on the firing temperature of the IQE measured at the Al₂O₃ passivated surface, confirms similar trends obtained for films deposited by plasma ALD [3].

Table 2. Influence of cell peak temperature on the IQE at 980nm of mc and Cz p-PASHA cells when illuminating the full cell, the Al₂O₃ passivated area (LBIC) and the FT-BSF area (LBIC).

Peak temperature [°C]		790	812	845
Mc (Sister wafers) 1-1.5 Ω.cm	Cell	74%	73%	71%
	BSF	81%	80%	79%
	AlOx	73%	69%	64%
Cz	Cell	84%	83%	79%
	BSF	86%	86%	85%
	AlOx	81%	80%	78%

On a more positive note, the firing through BSF at the rear contacts of the multi wafers passivate as well as the full area BSF reference (near sister wafer), which has an IQE of 81% at 980nm (not shown). This is a major improvement compared to our previous work [5] and a key requisite to obtain the efficiency gain for the PASHA cell as compared to the conventional cell. Inspection of the BSF cross-section presented in figure 6 reveals a BSF thickness in the order of 5 to 7 micron for peak temperature of 790°C and 845°C respectively, which is comparable to the state of the art for full Al-BSF cells. Furthermore, to our knowledge this is the first report on a BSF that forms a continuous band below the contacts of such thickness obtained by a firing-through process at typical firing temperatures.

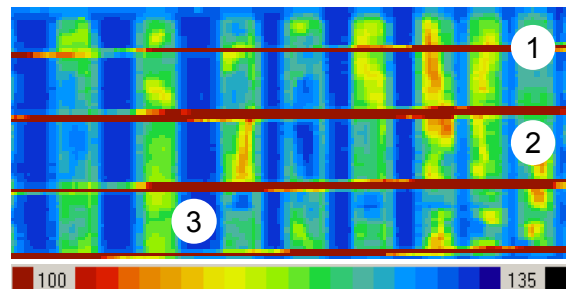


Figure 5, laser beam induced current mapping of bifacial solar cell passivated on the rear by 12 nm Al₂O₃ and fired at a peak wafer temperature of 790°C. Horizontal red line (1) is caused by shading of front Ag lines, (2) Al₂O₃ passivated area, (3) BSF passivated area. The scale shows the LBIC current in μA.

Finally, for the multi-crystalline cell we also improved on the fill-factor as compared to the previous report [5] for it increased from around 70% at a metal fraction of around 22% (5 inch

cells), to 78.0% where half of the rear was contacted (on 6 inch cells) and fired at 790°C. For the Cz cells fired at the same temperature the best FF was 76.9%. As the rear line resistance does not limit the FF in current experiment, lower metal fractions are considered feasible.

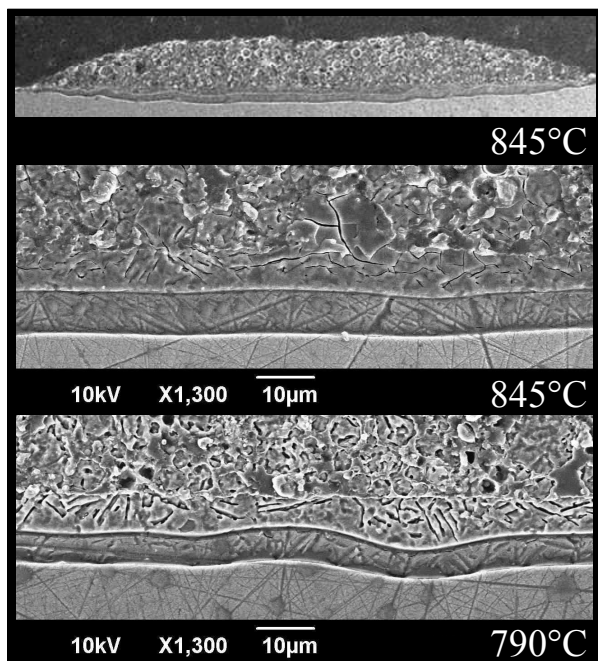


Figure 6, Top, SEM cross-section of a rear finger depicting Al paste, Al alloy and BSF formed on silicon by Ferro's newly developed firing-through paste at peak firing temperature of 845°C. Mid and bottom image show close-up of 7 and 5 micron thick BSF formed at peak firing temperatures of 845 and 790°C respectively.

FUTURE WORK

It will be interesting to perform an integral optimization to achieve excellent Al_2O_3 passivation combined with good BSF formation.

CONCLUSION

We have shown that an aluminum based firing-through paste newly developed by Ferro is able to form 5 and 7 µm thick local BSF when fired through 12 nm thick Al_2O_3 film deposited by the Levitrack at a peak temperature range of 790 to 845°C respectively. To our knowledge this is the first report on a BSF that forms a continuous band below the contacts of such thickness obtained by a firing-through process at typical firing temperatures. Furthermore, our study confirms literature reports that the passivation quality of uncapped Al_2O_3 layers heavily depend on the peak firing temperature used in this study. The average rear passivation in completed silicon solar cells of the PASHA type must be improved by enhancing the Al_2O_3 passivation between the rear metal contacts,

which currently limit the cell results. If the firing through BSF can be sufficiently formed at moderate firing temperatures, the process flow based on uncapped thin Al_2O_3 opens the path towards industrial application of ALD and a concept for high-throughput ALD is demonstrated for >3600 wafer/hr. The long term stability of the passivation quality after firing has been established as the excellent passivation quality of 2cm/s was maintained over a period of at least 20 weeks.

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