Improved Performance of Uncapped Al_2O_3 and Local Firing-Through Al-BSF in Bi-facial Solar Cells

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***Abstract* — Silicon solar cells that dominate today's market are H-pattern cells based on p-type silicon wafer material with a full Al Back Surface Field (BSF) as rear contact. ECN's rear passivated bi-facial PASHA (Passivated on all sides H- pattern) and ASPIRe (All Sides Passivated and Interconnected at the Rear, MWT) concepts answer the market pressure to decrease the euro/watt price and increase the efficiency. For optimized cells we estimate 0.5-0.8% absolute higher cell efficiencies compared to the industrial standard due to better rear passivation and reflection, while thinner wafers <150um) can be processed with limited yield loss. In addition, Al paste consumption can be reduced by 50-70% owing to the open rear metallization. Here we report on the improved performance of PASHA cells passivated by an uncapped Al_2O_3 layer on the rear, through which Al paste is fired for contact and local aluminum BSF formation. The Al_2O_3 dielectric layer is deposited in the Levitrack, an industrial-type system for high-throughput Atomic Layer Deposition (ALD) developed by Levitech. On Cz and mc material, a gain in $J_{sc}xV_{oc}$ of 1% and 2.5% respectively is obtained compared to the reference, at a rear metal fraction of 30%. Localized IQE mapping shows that the passivation quality of the Al_2O_3 passivation layer is maintained after firing which is a major improvement as compared to our previous report. Furthermore, reliability tests on single cell laminates (Cz cells) suggest that the passivation layer remains stable during the lifetime of a module.**

***Index Terms* — Bi-facial, P-type, Al_2O_3, ALD, firing-through, Al-BSF, mono, multi, reliability testing.**

I. INTRODUCTION

In order to process thinner wafers at an increased cell efficiency, 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. This cell concept is referred to as the PASHA cell (Passivated on all sides H- pattern) and is illustrated in fig 1. For this rear passivated multi-crystalline solar cell with local contacts, we estimate that the bi-facial cell could result in a gain of 0.5-0.8% in absolute efficiency [1,2]. This gain can be achieved when the bi-facial cell is placed on an effective rear reflector such as a (module) back-sheet foil, 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 $J_{sc}*V_{oc}$ are improved effective 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 in combination with SRV values below 10cm/s for the dielectric layer. Additional advantages of the bi-facial cell are reduced consumable costs, as the Al-paste use per cell will be reduced by 50-70% while reduced cell bowing after firing will increase production yield due to less cell breakage. In addition to the extra dielectric layer deposition step for rear passivation, it is our approach to limit the extra processing steps for the bi-facial cell and apply the most simple processing sequence. Ideally, this is done by an improved wet chemical edge isolation step and combining it with rear side polishing and cleaning. No extra step is used to the open the dielectric layer as the contacts are fired-through the dielectric layer forming an effective BSF.

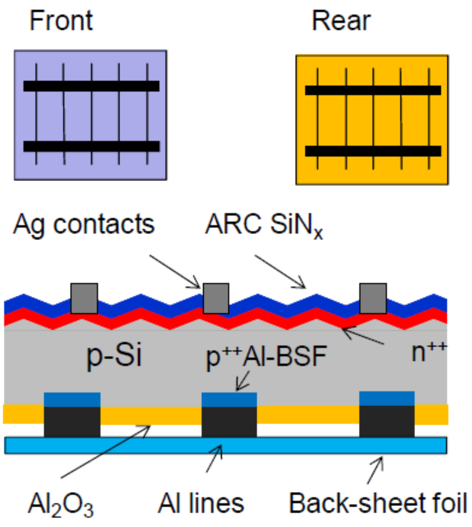

Figure 1, bi-facial cell concept with metal print on front and rear consisting of parallel fingers connected to busbars. The metal fraction on the rear is about 30-50%. The back-sheet foil as well as the rear metallization, reflect photons at wavelengths between 1000-1300 nm back into the solar cell.

II. THE CELL CONCEPT EVOLUTION

One of the new concepts that is currently investigated at ECN is the ASPIRe (All Sides Passivated and Interconnected at the Rear) cell, which combines our MWT and rear surface passivation (PASHA) technologies [1, 2]. With our MWT cell (full area Al BSF) and module technology we have reached 17.9% cell, and 17% module efficiency (aperture area) on multi-crystalline material, published as a new World Record in December 2009 [3]. ASPIRe has the potential to increase this efficiency further by an improved rear-side passivation and an enhanced reflection. The evolution of the cell concept is shown in Figure 2.

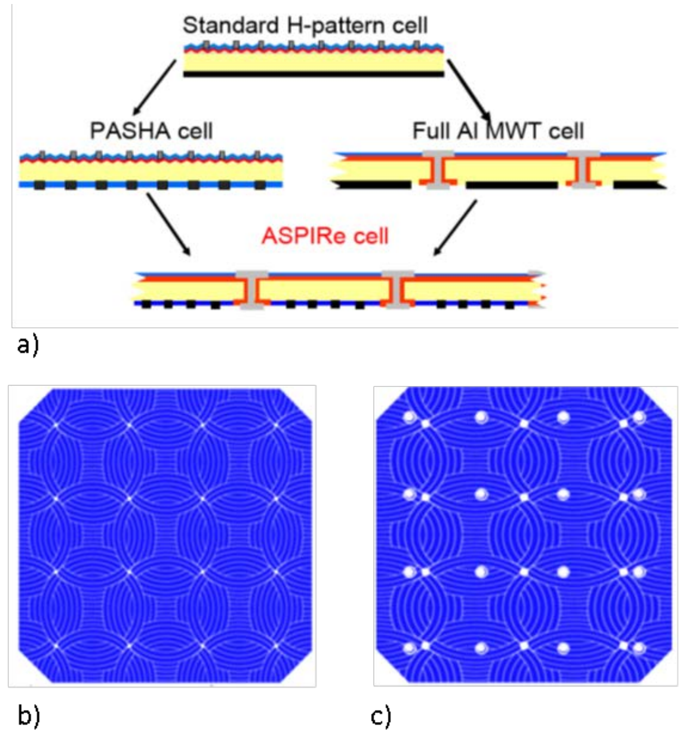

Figure 2 a) Evolution of ECN open rear cell concepts. Metallization design on b) front and c) rear side ASPIRe metal wrap-through cell with open rear side pattern consisting of fingers, rear and wrapped-through front contacts.

III. AL$_2$O$_3$ PASSIVATION AND LOCAL BSF FORMATION

As a passivating dielectric, aluminum oxide has received much attention in recent years because of its potential surface passivation performance in silicon solar cells and an excellent review is reported by Dingemans et al [4]. It is known to passivate boron emitters [5] and can be applied as rear dielectric in rear passivated solar cells based on p-type wafers, like the PERC [6] and the PASHA cell [7]. High surface passivation levels of 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 charge density (10^{12} - 10^{13} cm^{-2}) [8,9] that repels 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 SiN_x [10;11]. Although Al_2O_3 has proven its potential as effective rear dielectric in high-efficiency solar cells (> 20%) [6], 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 the surface recombination velocity of 27 nm thick Al_2O_3 layers deposited on p-Fz (1 ohm.cm) by Plasma Enhanced ALD [5]. 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.

Screen printable Al pastes can enable the formation of a localized BSF when firing through Al_2O_3 passivation layers. The peak firing temperature is known to be an important factor for both the BSF dopant density and thickness [12]. Therefore, higher peak temperatures are expected to yield a thicker localized BSF under the Al grid lines. Thus, the main challenge for the industrialization of the Al_2O_3 passivating layer 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 uncapped Al_2O_3 films in rear passivated bi-facial solar cells of the PASHA type using a firing-through Al-paste. Additionally, we report on the long term stability of the surface passivation quality after firing of these Al_2O_3 films.

IV. PROCESS FLOW

The potential for industrial rear side passivation of uncapped Al_2O_3 layers was assessed on 6 inch p-type multi and mono (Cz) crystalline wafers. The wafers were textured on the front side and polished on the rear for better light entrapment and rear passivation. They received a 75 ohm/sq emitter (tube furnace using $POCl_3$), followed by an isolation step. Before the ARC layer deposition (SiN_x PECVD), all groups received the same thorough clean steps to ensure the same blue response. The wafers were shipped to Levitech for the deposition of an Al_2O_3 coating on the rear using the Levitrack. The deposition condition compared to our previous report have been further optimized for the PASHA cell. Subsequently they were printed and fired using a newly developed Al firing-through paste. These cells had a rear metal fraction of 30%. The fired wafers were shipped back to ECN for optoelectrical characterization (IV and LBIC). The complete process flow is shown in figure 3. Eight PASHA and 7 reference mono crystalline cells were processed further into single cell laminates with standard back-sheet foil and EVA to test the long-term stability of the cell concept. Interconnection tabs were soldered on the Ag pads that connect to the Al-rear metallization on both tested cell concepts. The laminates were submitted to climate chamber tests which are part of the IEC testing procedure: 1000 hr of damp heat or 100 thermal cycles (200 cycles is full test). The laminates were prepared in 2 batches and the second batch was added into the damp heat chamber together with the first batch of laminates after the latter had been tested for 500hr. Part of the second batch was used for thermal cycling under maximum power current load (above 25°C). The laminates were measured before and after climate testing. The first batch was also measured after 500h of damp heat. IV measurements on cells and laminates were conducted in a Class "AAA" simulator. The cells were measured on a brass chuck for temperature control. This chuck reflects the majority of IR light that passes through the bi-facial solar cell back into the cell. In case of the laminates this reflection is brought about by the laminated white back-sheet foil.

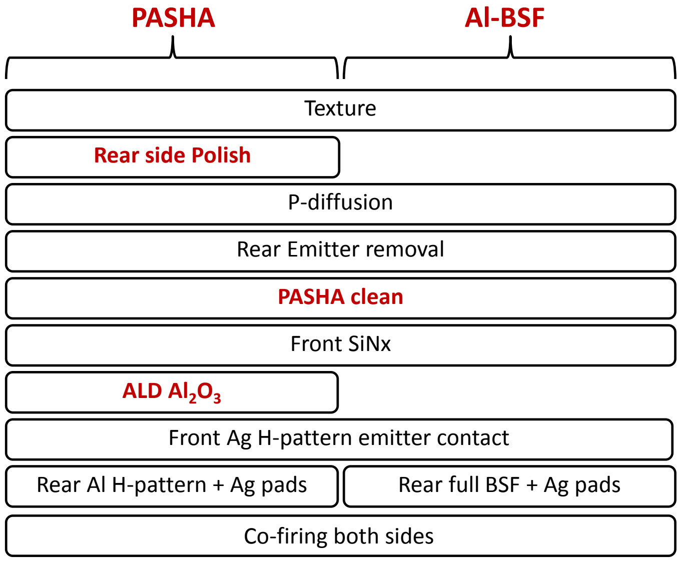

Figure 3, Process flow of Al-BSF reference (black) with in red the additional steps that are specifically used for the Al_2O_3 passivated PASHA cells. The PASHA clean is used as a thorough clean procedure that affects both the front and rear side [13,14].

V. LEVITRACK: HIGH THROUGHPUT ALD OF AL_2O_3

In conventional ALD of Al_2O_3 the precursors TMA and H_2O are sequentially injected into a low-pressure reaction chamber, separated (in time) by inert gas (N_2) purges. In a complete ALD cycle (TMA, N_2, H_2O, N_2), the layer thickness increases with ~ 0.09-0.12 nm/cycle, depending on the process temperature. Films are grown at low temperatures (150-300ºC) with excellent step coverage and almost ideal morphology. Unfortunately, one of the drawbacks of the conventional ALD method is the low throughput, typically 50 wafers/hr. This is far too low to be of interest for the PV industry where throughputs in the range of 2400 wafers/hr are required.

In the Levitrack, sketched in Figure 4, wafers are transported in a linear track. During the process, the wafers are floating on a gas bearing. The gas bearing ensures that during the entire process there is no physical contact with the track walls. The combination of a gravitational force and viscous drag ensures a constant transport velocity of the wafers through the track. During transport the wafers pass several segments in which they are sequentially, single-sidedly exposed to TMA, N_2, H_2O and N_2; a so-called ALD cell. The system contains many of such ALD cells, each of which has a typical length of 12 cm and can be switched on and off for Al_2O_3 layer thickness tuning; in each of these cells 0.12 nm aluminum oxide is deposited. With the Levitrack system, single sided Al_2O_3 layers can be deposited at a throughput of up to 3600 wafers/hr. The non-uniformity is in the range of 3% 1sigma% with a non-reproducibility <1%.

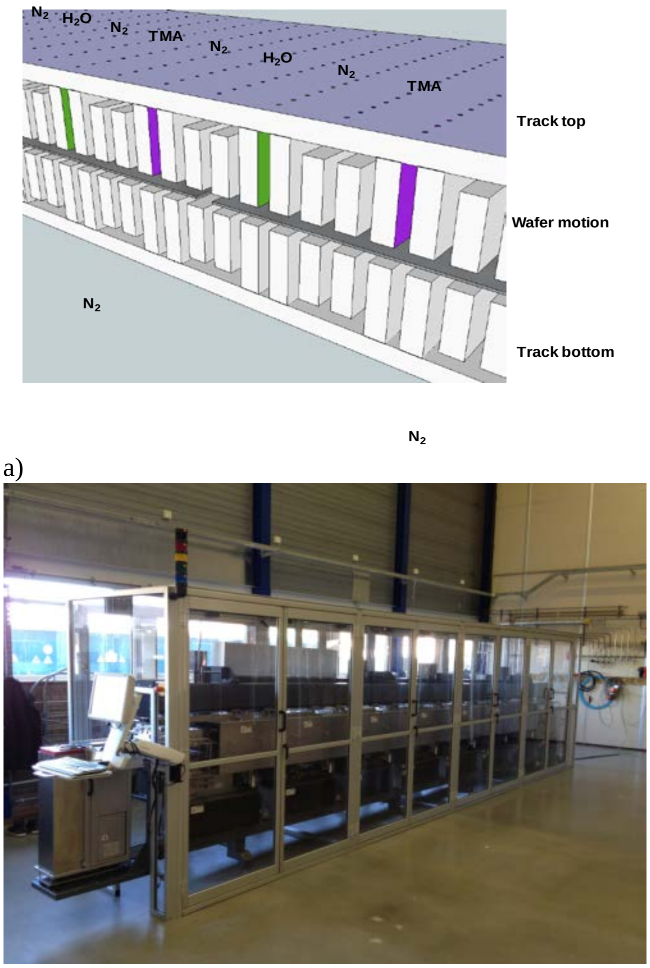

Figure 4, Layout of the Levitrack ALD system for Al_2O_3 layers. Figure a) shows a schematic cross section of the Levitrack. b) Photograph of the Levitrack ALD system.

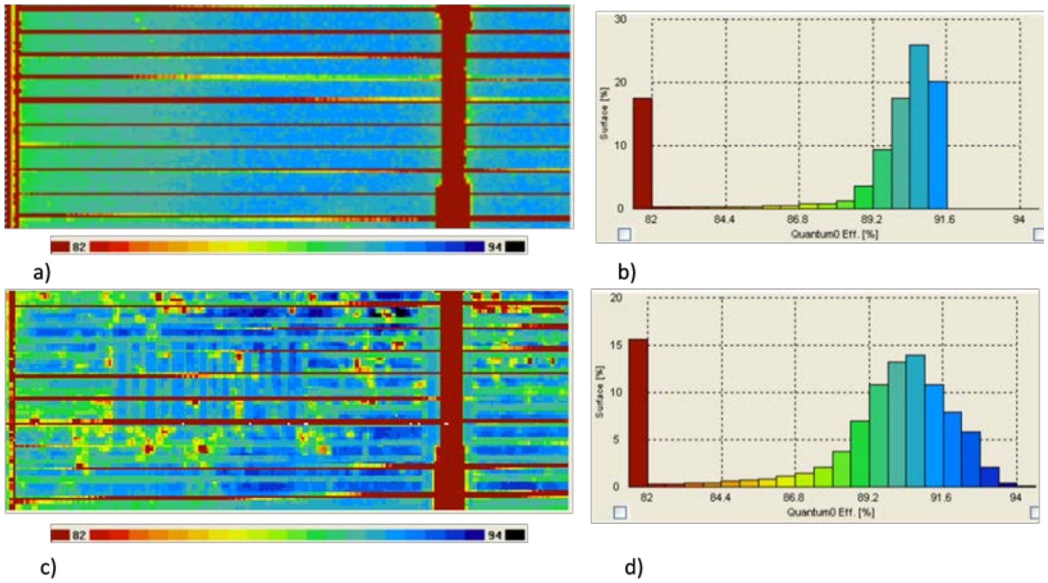

Figure 5**,** (a-d) Laser beam induced current IQE mapping (range 82 to 94%) at a wavelength of 976 nm. Illumination is done through the emitter; silver fingers appear in red. (a) side of a full area Al-BSF reference cell with corresponding histogram (b).(c) P-PASHA cell passivated by Al-BSF fingers and Al_2O_3 with corresponding histogram (d).

VI. LBIC MAPPING STUDY PASHA WITH AL$_2$O$_3$ AND FIRING-THROUGH FINGER WITH AL-BSF

Surface passivation on the rear of standard H-pattern cells is achieved by the back surface field induced by Al surface doping during firing. The major improvement of this work compared to our previous report [2] is that the passivation quality of the Al_2O_3 is maintained after firing while a BSF is formed at the aluminum rear fingers. The passivation quality at the rear fingers is compared to the dielectric layer by LBIC measurement at 976 nm as illustrated in Figure 5 and 6. It is clear that in parts of the rear surface the passivation layer with IQE values up to 94% performs better than the metal fingers with a maximum IQE of 92% as illustrated by the histograms of Figure 5 b and d. The difference in passivation is presented in more detail in a high-resolution LBIC mapping of a test structure, consisting of Al lines of different width, separated by Al_2O_3 passivated areas, as shown in Figure 6. A horizontal line scan through the different areas clearly illustrates the superior passivation of the Al_2O_3 over the local Al-BSF, which is maintained after firing. It also becomes clear that the passivation of the Al fingers is limited by a decreased passivation at the edge. On cell level the gain in $J_{sc}xV_{oc}$ of Cz and mc based bi-facial solar cells was 1% and 2.5% respectively compared to the corresponding Cz and mc full Al-BSF reference. The gain in Jsc is clearly related to a gain in rear reflection as the IQE of the Pasha cell between 1000 and 1200 nm was several tens of percent points higher than the reference.

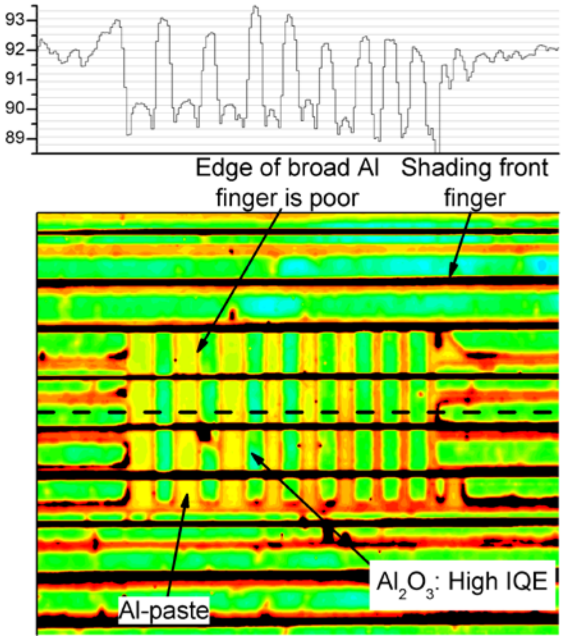

Figure 6**,** Laser beam induced current IQE mapping at a wavelength of 976nm on a test structure at the rear of a PASHA cell. Dashed line marks path 2D profile. Illumination is done through the emitter.

Interestingly, the gain in $J_{sc}xV_{oc}$ was maintained on laminate level for the investigated Cz samples. For the laminates of the second batch the gain in $J_{sc}xV_{oc}$ on laminate level vs. the Al-BSF was 1.2% while on cell level this was 0.8%. The difference was due to a slightly increased J_{sc} and V_{oc} vs. the reference on laminate level. Changes in V_{oc} could be related to redistribution of hydrogen enabled by the elevated temperature of the lamination process as suggested by L. Hennen et al [15]. This could result in more effective passivation of dangling bonds at the Si surface.

From the LBIC mapping it becomes apparent that the recombination in the PASHA cell would benefit from a smaller finger edge area. Increasing the finger width at constant contact area, results in a larger spacing between the fingers. This in turn results in a larger resistance loss in the base causing the FF to decrease. We expect that optimization of the pitch and finger width will improve the cell efficiency of the PASHA cell.

VII. CLIMATE TEST RESULTS

As little information is available on the long term stability of uncapped Al_2O_3 layers, a preliminary test was conducted to study the effect of damp heat and thermal cycling which is part of the IEC testing procedure. In fig. 7 is shown that for the damp heat exposure the average loss in J_{sc} is well below 1% and that the V_{oc} even slightly increases while the FF remained constant. For the thermal cycling the J_{sc} increases slightly while the V_{oc} remains constant which indicates that the passivation of the Al_2O_3 is stable under test conditions. These results are within the 5% performance decrease limit of the complete IEC 61215 ed2 test [16]. Although a complete IEC test includes exposure to 1000 hours of damp-heat and 200 temperature cycles (we report 100 cycles) on separate modules, these results are a strong indication that a module consisting of Al_2O_3 passivated PASHA cells would pass the full IEC 61215 test which is an important milestone for the further industrialization of the concept.

Figure 7, Relative change in J_{sc} and V_{oc} of the single-cell laminates after damp-heat (500 and 1000 hr) and thermal cycle (100 cycles) treatment.

VIII. CONCLUSION

The PASHA concept is an attractive concept to improve the cell efficiency of standard full area Al-BSF solar cells by replacing the rear side with a passivated surface and an open aluminum grid. The rear contacts are fired-through and in an ideal process flow, the only additional process step is the ultra-fast spatial Al_2O_3 ALD tool such as the Levitrack. Improved firing stability of the Al_2O_3 could be demonstrated and the results appear to be limited to the edge of the Al-BSF fingers. Optimization of the metal pattern should limit this problem. Climate testing results suggest that the that a module consisting of Al_2O_3 passivated PASHA cells would pass the full IEC 61215 test which is an important milestone for future industrialization.

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