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Rear passivated mc-Si solar cells textured by atmospheric pressure dry etching

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Abstract

In this contribution, atmospheric pressure dry etching (ADE) texture is integrated into a passivated emitter and rear cell (PERC) process. In order to make the texture suitable for the solar cell processing, two post-etching processes (inverted pyramid, spherical cap) are implemented and compared. The passivation of the front surface could be improved substantially by the introduction of an Al_2O_3 layer deposited via atomic layer deposition under the classical antireflection coating SiN_X. The impact of the addition of the Al_2O_3 layer on the contact resistance cannot be neglected and becomes significant for thicknesses higher than 4 nm. Multicrystalline silicon (mc-Si) PERC solar cells are fabricated and measured, leading to a maximum efficiency of about 18.6% for the acidic texture, and for both posts-processed dry chemical etching (ADE) textures. No current gain for the ADE textured wafer compared to the acidic texture could be observed on cell level due to an inhomogeneous etching. However, a gain of 0.4 mA/cm^2 for the ADE texture was calculated from local EQE measurements. ADE texture presents therefore 2 advantages: compatibility to diamond wire sawing and a potential current gain for PERC solar cell structure.

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Keywords: Multicrystalline; PERC; Texture

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1. Introduction

In the last years, the price of monocrystalline wafers has significantly decreased due to the introduction of diamond wire sawing instead of the slurry-based sawing to slice the bricks into wafers. This led to a significant increase in the production of monocrystalline solar cells relative to multi-crystalline cells. However, this wafering technology is currently not significantly applied for multi-crystalline material as the state-of-the-art acidic texturing process requires the surface roughness resulting from the slurry cut. Therefore, an alternative texturing approach for mc wafers could have a major impact in decreasing the wafering cost by allowing the use of diamond wire sawing, and by increasing the efficiency due to a decrease in the surface reflection. Atmospheric pressure dry chemical etching (ADE) is one of the alternative texturing approaches with such a potential [1].

The gain in short-circuit current density (j_{SC}) of the ADE texture compared to the acidic texture was already shown on Al back surface field solar cells [2], whereas the potential of ADE texture for high-efficiency mc-Si PERC-type solar cells was discussed in [3]. In this contribution, the integration of ADE texture in a PERC solar cell process is presented.

2. Texture process and post treatment

The texture process presented in this paper is based on the thermally driven etching of Si by F_2/N_2 gas mixture. This process is carried out under atmospheric pressure conditions in an inline reactor. The reaction takes place spontaneously when the hot wafer (about 200°C) comes in contact with the reactant gas. The details of the etching tool can be read elsewhere [1].

Before the etching process diamond sawed Cz-Si wafer (diamond sawed mc-Si wafer been not available) undergoes a surface wet preparation process, which consist in saw damage etching process and a cleaning process, the wafer are then etched applying the ADE processes. Directly after a deep etching process, the wafer surface is too porous (Fig. 1a) and it is very challenging to use it directly in the solar cell process, especially for the emitter formation [3] and surface passivation [6]. Therefore, the wafer undergoes a smoothing process, which decreases the porosity whereas still maintains a low reflectivity. In this study, two different wet chemical based processes were used, both leading to the formation of completely different surface texture. The first post processing etching leads to inverted pyramid formation (Fig. 1b) and the second leads to spherical cap-like structures (Fig. 1c).

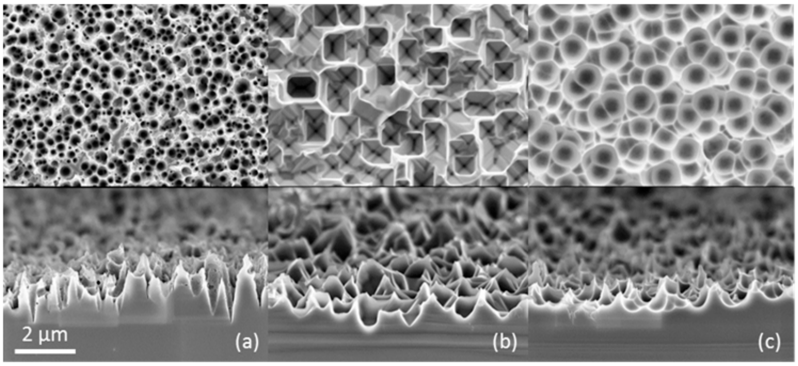


Fig. 1. Scanning electron microscope images of the ADE textured wafer (a), of the inverted pyramid (ADE 1) post processed wafer (b), of the spherical cap (ADE 2) post processed wafer (c)

The initial weighted surface reflectivity (R_w) in 300 - 1200 nm, calculated using the equation by Sparber [7] directly after ADE texturing, is below 5%. After applying any of the two post-etching processes, the reflectance increases to about 8-10%, and the porosity almost completely disappears. A diffusion process is applied to the post treated surfaces (ADE1, ADE2) and to the acidic textured surfaces, leading to an emitter sheet resistance of 85 Ω/☐ regardless of the surface texture.

3. Compromise between passivation and contact resistance

One of the most effective techniques for the passivation of rough surface is the use of atomic layer deposited (ALD) Al_2O_3 layer [4]. In this section, we are studying the influence of the Al_2O_3 layer thickness on the passivation quality and the contact resistance.

This experiment is performed on *n*-type Cz wafers. The ADE texture process is followed by the post-processing step to form the inverted pyramid-like structures (ADE1). Two surface reflectance groups are formed by varying the duration of the post-processing etch: the low-reflectance group ($R_w = 12\%$), and the high-reflectance group ($R_w = 20\%$). After a chemical cleaning is carried out, the wafers are coated with Al_2O_3 using the fast ALD deposition technique from Solaytec, followed by an outgassing process carried out at 550°C for 10 min. Then, the wafers are coated with a PECVD SiN_X layer, with the thickness adapted to reach a reflection minimum at 600 nm. Finally, the wafers are fired and characterized (method for j_{0e} calculation: see [5]).

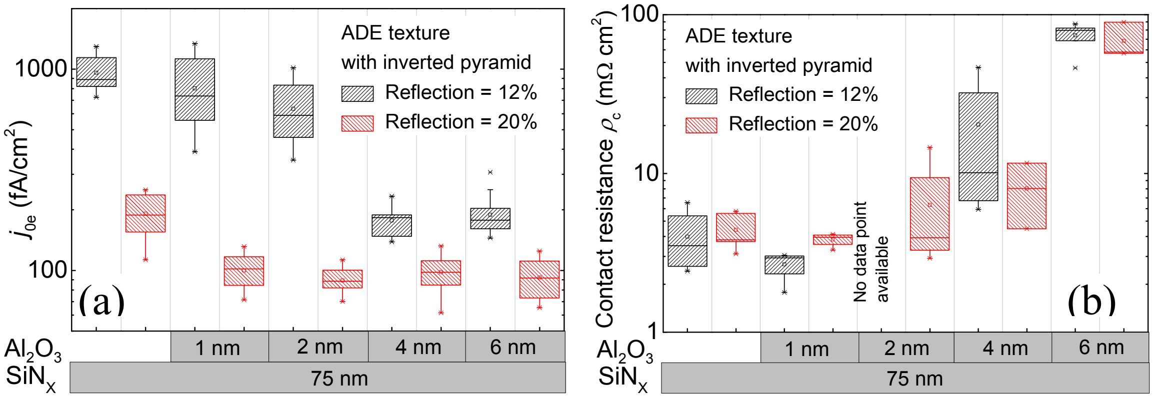


Fig. 2. (a) Emitter saturation current density as a function of the Al_2O_3 layer thickness (b) Specific contact resistivity as a function of the Al_2O_3 layer thickness

In Fig. 2 (a) the j_{0e} value is plotted as a function of Al_2O_3 thickness. For the high reflectance group, the passivation quality is independent of the Al_2O_3 layer thickness. In contrast, a minimum Al_2O_3 layer thickness of 4 nm is required to reach j_{0e} below 300 fA/cm^2 for the low reflectance group. It should be noted that despite the high negative charge density in the Al_2O_3 layer, which might cause a depletion region at the emitter surface, the passivation quality reached with Al_2O_3/SiN_X passivation stack is higher than the one reached by using a single layer of SiN_X. In Fig. 2 (b), the contact resistance is plotted as a function of the Al_2O_3 layer thickness. Here, it is clear that Al_2O_3 layer thickness of more than 2 nm leads to a significant increase in the contact resistance. Therefore a trade-off between the passivation quality and the contact resistance needs to be considered. Hence, a good compromise between reflectance and passivation quality is required.

4. PERC solar cell batch

The ADE texture process is integrated in a PERC solar cell batch. *p*-type, mc-Si material with a resistivity ranging 1-2 Ω cm is used. Three texture morphologies are applied: acidic texture as a reference, ADE texture with inverted pyramid post processing (ADE 1), and ADE texture with spherical cap post processing (ADE 2) and doped by using an identical $POCl_3$-based emitter diffusion process. The ADE textures only are applied to the front sides of the solar cells. For each texture group, half of the wafers are coated with 2 nm ALD Al_2O_3 on the front surface, and for all wafers 6 nm ALD Al_2O_3 is deposited on the rear. Both sides are then coated with SiN_X using the PECVD technique. For the contacting, lines are opened in the rear passivation using a laser. The rear and front contacts are formed using screen printing (including rear pads). Finally, the wafers are fired. The process sequence is presented in Fig 3 and the illuminated cell characteristics are given in Fig 4.

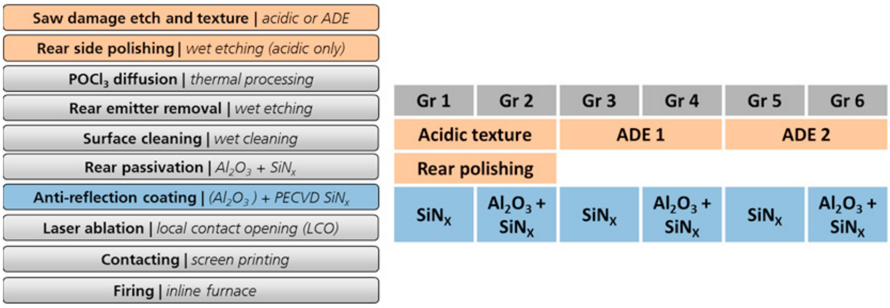


Fig. 3. Schematics of the process sequence and variation groups

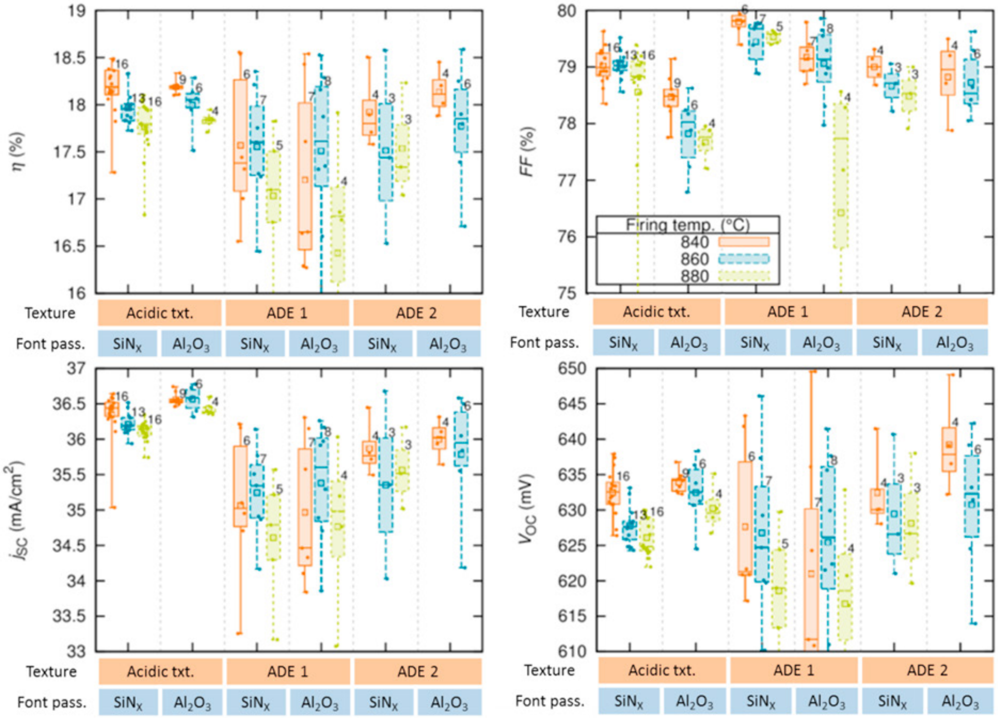


Fig. 4. Illuminated current voltage parameters (η, FF, j_{SC}, V_{OC}) for all cell groups

The peak efficiencies, which are almost the same for all groups, equal $\eta = 18.4\%$-18.6%. The ADE textured wafers present a much higher spreading of the efficiency, which might be related to the inhomogeneity of the ADE process used for the texture. The fill factor (FF) seems to vary slightly mainly due to pseudo fill factor (pFF) variation, the series resistance (R_S) is very low ($R_S = 0.3$-$0.4\ \Omega\ \mathrm{cm}^2$) for all groups. The open circuit voltage (V_{OC}) of the acidic textured cells is about 630 mV, which is unusually low. The ADE textured wafers present a strong V_{OC} distribution from 610 mV up to 650 mV. The introduction of Al_2O_3 passivation in the front does not have a significant impact on the V_{OC}. It is surprising that the acidic textured group has higher j_{SC} than the ADE textured group, and this observation contradicts the current gain observed for Al-BSF (aluminium back surface field) solar cells in previous works [2].

A strong correlation between short-circuit current and open-circuit voltage is observed (see Fig. 5). In contrast to the result presented in section 3, where the recombination (based on j_{0e} measurements) increased for low reflectance wafers, it is observed that a higher j_{SC} coincides with a higher V_{OC} for both acidic and ADE texture. This strongly suggests that the current is not limited by the reflection but rather by the recombination. If we extrapolate the curve we notice that they should cross at around 650 mV and 37.5 mA cm^{-2}. This suggests that if V_{OC} above 650 mV are reached, the ADE cells would show also a higher current than the acidic textured cells.

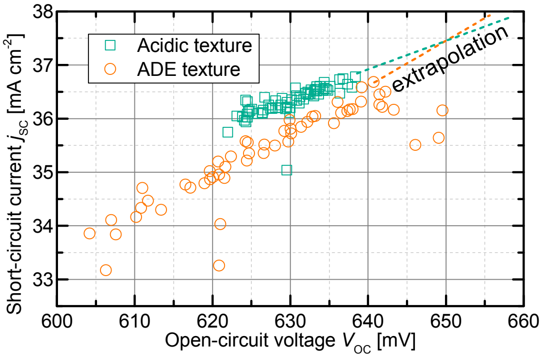
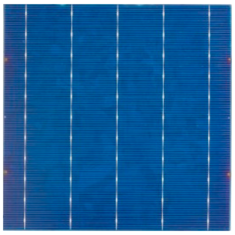
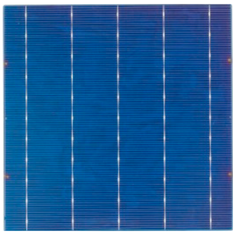
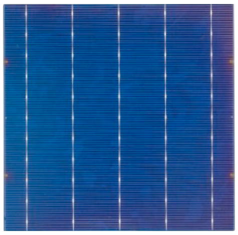
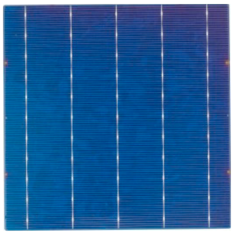
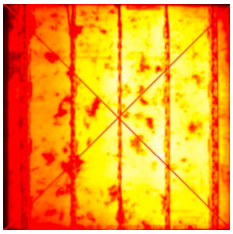
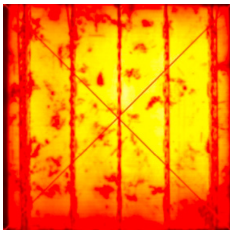
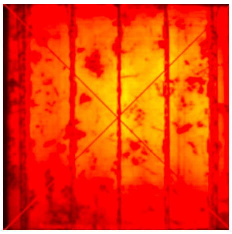
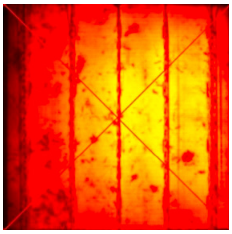
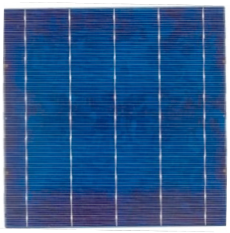
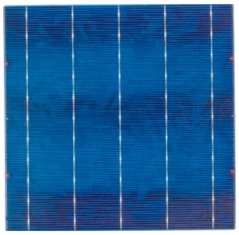
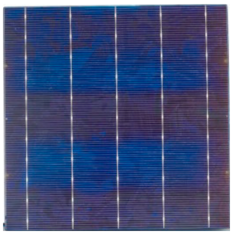
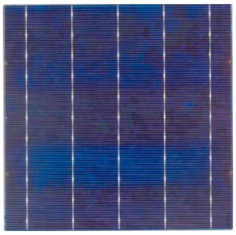
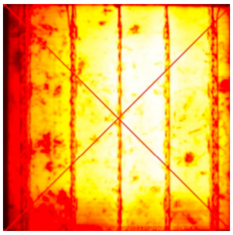
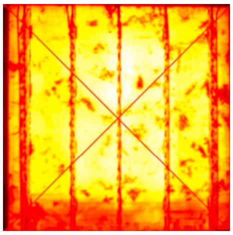
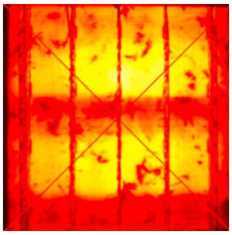
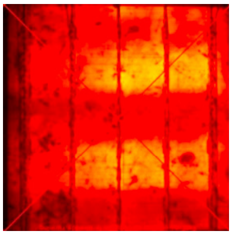


Fig. 5. Correlation between short-circuit current and open-circuit voltage

Table 1. Comparison of exemplary “good” cells and “bad” cells: scan and electroluminescence measurement for group 2 and 6.

Group	Measurement	“Good” cells		“Bad” cell examples	
Group 2 Texture: Acidic Front passivation: Al$_2$O$_3$ SiN$_X$	Scan				
	Electroluminescence (a. u., same scaling)				
Group 6 Texture: ADE 2 Front passivation: Al$_2$O$_3$ SiN$_X$	Scan				
	Electroluminescence (a. u. same scaling)				

In Table I. the scan and the electroluminescence (EL) images of two “good” cells (2 highest efficiencies of the group) and two “bad” cells (2 lowest efficiencies of the group) of the group 2 with acidic texture and aluminium oxide front surface passivation and group 6 with ADE 2 texture and aluminium oxide front surface passivation are shown. For the acidic textured cells the optical aspect of the cells is not correlated with the efficiency; the bad cells however have significantly lower EL signals, probably due to a non-radiative higher recombination rate. For the ADE textured cells the optical aspect is more inhomogeneous than for the acidic cells. The cells with a rather dark aspect are the “bad” cells and the ones with higher reflection are the “good” cells. This also correlates with the EL image of the cells: the low reflection areas are also dark on the EL image, whereas the high reflection areas are bright on the EL image. It is important to consider this observation as qualitative for the moment. In fact, as the EL signal depends on both the optical and the electrical properties of the wafer, we have not been able to separate the influence of both factors for these EL images. We have just postulated that the electrical properties made the main impact on the EL signal.

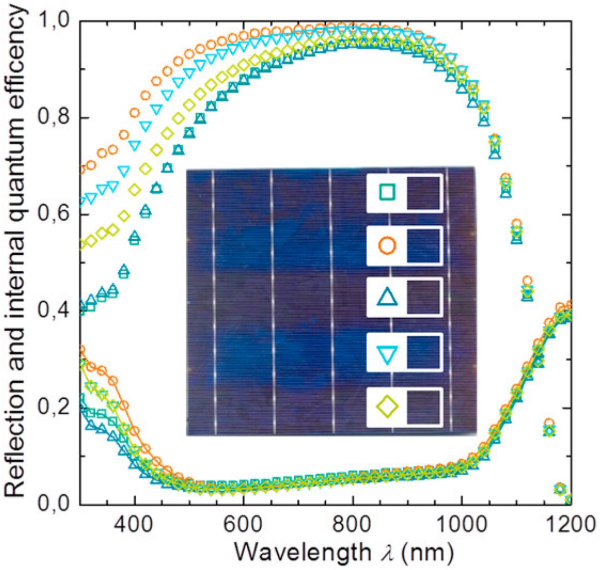


Fig. 6 Local reflection and internal quantum efficiency on five points of 2x2 cm^2 each

Local IQE measurements where performed on 5 points of an inhomogeneous cell from group 6 (one of the “bad” cell). The measurement spots are 2 × 2 cm² large. The reflection and the spectral response are measured for the wavelengths ranging from 280 nm until 1200 nm. The measurements were performed in the LOANA instrument from pv-tools GmbH. It is clear from this measurement that the blue response of the dark areas of the cell is much lower than on bright areas. On the dark areas, the decrease in IQE is more important than the decrease in reflection, and explains the current losses. This shows that the recombination on the front surface of heavily textured areas (with very low reflection) is too high and induces recombination, which decreases both current and voltage of the solar cell. The integration of the EQE allows a calculation of the local j_{SC}. For this low performance cell from group 6 the local j_{SC} varies from 35.0 mA/cm^2 to 38.1 mA/cm^2. For the most efficient acidic textured solar cells of this batch the local j_{SC} is homogeneous around 37.7 mA/cm^2. These means that by achieving an homogeneous ADE texture with a well-controlled post-processing step (see section 2) the ADE texture would enable to increase the j_{SC} value by 0.4 mA/cm^2 with a diamond wire sawing-compatible process.

Summary

This study focused on the development of an atmospheric dry etching texture and its integration in a PERC solar cell. The rough and porous surface obtained directly after processing is smoothened before further processing. The smoothening is obtained using two different etching solutions leading to either inverted pyramid (ADE1) or spherical cap-like structures (ADE2).

Another important point of this paper is the front surface passivation, which could be improved by using a thin Al_2O_3 layer deposited by atomic layer deposition. However, this layer also impacts the contact resistance and its thickness needs to be therefore reduced to 2 nm for optimum contacting.

PERC solar cells were fabricated varying the texture (acidic, ADE 1 - with inverted pyramid post-etching, ADE 2 - with spherical cap post-etching), and the front passivation layer (PECVD SiN_X layer or ALD Al_2O_3 / PECVD SiN_X layer stack). All the groups resulted in a maximum efficiency of about 18.4%-18.6%, however the results from the dry chemical etching (ADE) texture groups were more spread. Surprisingly, the ADE textured cells showed a lower j_{SC} than the acidic textured cells. As observed from locally measured IQE curves, the lower reflection led to lower current, which is due to an increased front recombination rate for an increased surface roughness. The comparison of the local j_{SC} calculated from the EQE measurement shows a potential gain of 0.4 mA/cm^2 for ADE texture in comparison to acidic texture on the solar cell level, the related gain in the module still needs to be evaluated. In addition to this potential current gain ADE texture is also compatible with diamond wire-sawn mc-Si. This gain in current can only be achieved on the cell level with a homogenous ADE texture process.

As a homogeneous ADE process has been achieved lately, we are confident of future contribution with an improved short-circuit current for the ADE textured solar cells.

Acknowledgements

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