HIGH-EFFICIENCY DIAMOND WIRE-SAWN MC-SI-BASED PERC SOLAR CELLS TEXTURED BY ATMOSPHERIC PRESSURE DRY ETCHING

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ABSTRACT

In this paper, we present further results on the integration of a “black-silicon” texturing process on diamond-wire sawn multicrystalline silicon wafer, using atmospheric pressure dry texturing (ADE) in a passivated emitter and rear cell (PERC) solar cell architecture. Following on from our previous work on high-efficiency nanotextured solar cells, we present further optimization of our texturing process, resulting in the uniform formation of spherical caps-like surface morphology with low reflectivity and comparable reflection distribution to the wet-chemical acidic texture based on additives. First cell results show up to 19.8% conversion efficiency. Characterisation and analysis of the cells highlight current limitations and identify potential for improvement: optimization of the firing process and minimization the inherent bulk-related recombination losses in the mc-Si material, which is expected to lead to further gain in conversion efficiencies.

Keywords: black silicon, nanotexture, atmospheric pressure process, dry etching, chemical etching, PERC solar cells

1. INTRODUCTION

1.1 Context:

A significant cost reduction in wafering is possible by the adoption of diamond-wire-sawing (DWS). For mc-Si wafers, it also requires a change in the texturing process as the incumbent wet acidic process is not suitable. The use of additives allows the adoption of the DWS mc-Si but results in a high reflectivity texture. In order to stay competitive against mono-Si cells, mc-Si based cells also need to further improve their efficiency and industries are looking at introducing advanced texturing processes into solar cell production, which promises J_{SC} improvement in comparison to the state-of-the-art techniques. Introduction of such novel textures, however, demands successive optimizations of the cell-processing steps in order to deliver improved electrical performance at cell and module levels.

In this study, a dry chemical etching process (atmospheric dry etching, ADE) is used to form low reflectivity surface texture, as it provides economical, technological and ecological advantages compared to the competing wet-chemical technologies such as metal-assisted chemical etching (MCCE) and other dry-etching alternatives (reactive ion etching - RIE). The advantages of using ADE are summarized as: a) high etching rate and inline modular nature of the etching tool allowing high volume production, b) low cost of ownership (COO) due to no vacuum nor plasma, c) easy abatement of waste gases through standard wet scrubber systems, d) use of environmental friendly F_2 gas with zero global warming potential (GWP), and e) chemical etching without any ion-induced damage in Si.

Formation of nano-scale structures on mc-Si surfaces by using ADE process and their successful integration in a standard Al-BSF mc-Si solar cells [1,2] and on PERC mc-Si solar cells [3] has already been demonstrated, achieving > 20.0% conversion efficiency when using HP grade mc-Si wafers. PERC solar cell is now set to become the standard cell architecture in industrial production [4].

1.2 Approach:

Each etching process step induces a degree of crystal orientation dependency on the mc-Si wafer. The result is a grain dependant texture, with difference in aspect ratio of nanostructures formed in different grains. This non-uniformity makes it more difficult to optimize the emitter formation as well as the PECVD deposition processes, which eventually can limit the internal quantum efficiency (*IQE*) of the solar cell. Meanwhile, a large distribution of reflection limits the external quantum efficiency (*EQE*) and therefore the short circuit current density (J_{SC}) of the solar cell.

In order to further improve our PERC cell results; this work is focussing on narrowing the distribution of reflection within the wafer surface by optimizing the sequence of etching steps toward a more isotropic process. Narrowing this distribution will also improve the overall appearance of the cell. In this study, we present our first results of optimization using ADE-texture on industrial standard diamond-wire sawn *p*-type mc-Si wafer-based PERC solar cells.

2. EXPERIMENTAL

2.1 Sample preparation

The wafers used in this process are large area (156 mm edge length) *p*-type mc-Si. First generation (Gen.1) PERC solar cells were fabricated on high performance (HP) slurry-cut mc-Si wafers, whereas third generation (Gen.3) are fabricated on DW-sawn industrial type mc-Si wafers. The process plan for both groups is shown in Figure 1.

Both group of wafers are first saw-damage etched and then textured using the ADE process, during which the wafers are dynamically transported in an inline mode through the reaction chamber of the ADE tool (Nines ADE-100) with the process described elsewhere in detail [2], followed by a short post-etching step to enlarge the surface structures and facilitate conformal deposition of SiN_x by PECVD. Gen.1 received an alkaline post-treatment step after ADE black silicon texturing. In case of Gen.3, the ADE-texture and the post-etching steps are collectively optimized to achieve a more isotropic result. Afterwards, Q.ANTUM process [5] of Hanwha Q-Cells is applied to prepare PERC solar cells.

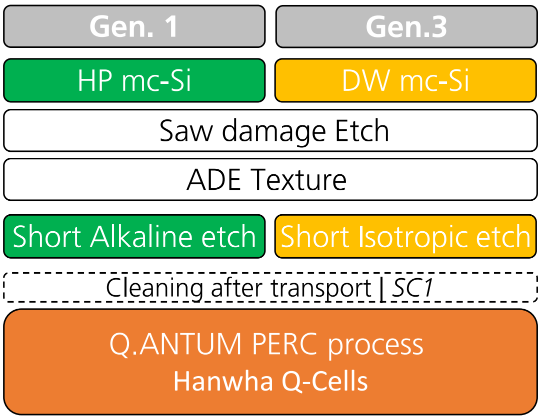

Figure 1: Process plan for ADE-textured mc-Si PERC solar cells of first (Gen.1) and third (Gen.3) generations.

2.2 Characterisation

Illuminated *I-V* measurements are performed under the standard test conditions using an in-house solar simulator that is calibrated with the Fraunhofer ISE CalLab reference. Spatial mapping of quantum efficiency and reflectivity of solar cells is performed at 406 and 960 nm wavelength using light beam induced current (LBIC) method using a PV Tools Loana system with a resolution of 200 µm.

3. RESULTS

3.1 Texturing homogeneity

A more isotropic post-ADE process is used for this work and compared to the results obtain previously [3] with an anisotropic (alkaline) post-etching process. Further increase of the J_{SC} should focus both on lowering of the overall reflection as well as narrowing the spatial distribution of reflectivity. Collective optimization of ADE and post-etching processes is performed on DW-sawn mc-Si wafers in order to achieve best optical and electrical performances in the cell-level. Figure 2 a) shows the scan image of Gen.1 ADE-texture after post-treatment in the alkaline solution, showing a large distribution of reflection in the full-wafer area. SEM images of the darkest and the lightest grains of the mc-Si wafer, respectively Figure 2 b) and c), show the formation of pseudo-pyramid like structures with substantial differences in the aspect ratios, and hence the surface reflection values.

In contrast, Gen.3 ADE-textured DW-sawn mc-Si wafer (scan image shown in Figure 2 d)), has a narrow distribution of reflection in the whole wafer-area. The etching process developed results in spherical cap-like structures with dimensions of 1 µm (see Figure 2 e) and f)) homogeneously in all crystal orientations of the mc-Si wafer. Such characteristic dimensions are expected to cause high scattering of the middle and long wavelengths of visible light, leading to an improved light trapping in comparison to sub-micron wavelength structures. In this particular wafer, the weighted surface reflection measured along the full-wafer area is in the range of 14-17% after the texturing process.

Figure 3 compares the distribution of reflection values at 405 nm from the mapping of the full wafer area of ADE-textured samples after PECVD SiN_x anti-reflective coating. For comparison, reflection data of additive-based texture after SiN_x coating is also included. One should note a significantly smaller reflection distribution for Gen.3 ADE texture. In comparison to the additive-based wet-chemical texture on DW-sawn wafers, Gen.3 ADE texture shows both lower average reflection values as well as a comparable reflection distribution in the full wafer area. Using Gen.3 texture on industrial standard diamond wire mc-Si wafers, PERC solar cells were fabricated.

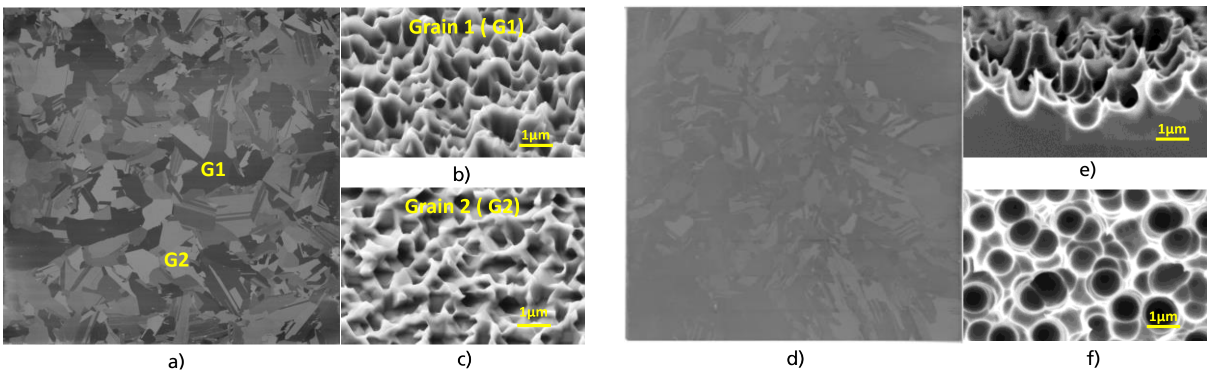

Figure 2: a) Scanned image of Gen.1 ADE-textured DW-sawn wafer and corresponding SEM images of pseudo-pyramid like structures formed in two grains – b) Grain 1 (G1) with lowest reflection and c) Grain 2 (G2) with highest reflection properties; d) Scanned image of Gen.3 ADE-textured DW-sawn wafer and corresponding SEM images showing e) cross-section view and f) top-view of the etched surface. In case of Gen.1 ADE texture, pseudo-pyramid structures with difference in aspect ratios are formed in various mc-Si grains. The etching process developed for Gen.3 ADE texture leads to the formation of spherical cap-like structures homogeneously distributed in all crystal orientations of the mc-Si wafer.

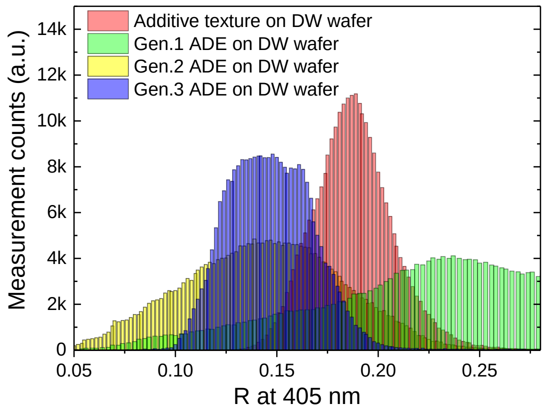

Figure 3: Histograms showing distribution of reflection at 405 nm in the full wafer area for different generations of ADE texture, in comparison to the additive-based acidic texture on DW-sawn wafer.

3.2 *I-V* results

Table 1 lists the *I-V* characteristics of Gen.3 ADE-textured solar cells on industrially used DWS mc-Si wafers. For comparison with our previous results in [3], *I-V* characteristics of Gen.1 ADE textured solar cells on HP mc-Si substrates are also listed.

Table 1: *I-V* characteristics of Gen.1 and Gen.3 ADE textured large area mc-Si wafer-based PERC cells. Please note that Gen.1 ADE texture is fabricated previously on high performance (HP) mc-Si substrates [3]. Gen.3 optimized ADE texture, featuring spherical caps-like surface topography, is used to fabricate PERC-solar cells on industrial type DWS mc-Si wafers.

Texture	Avg./ Best	V_{OC} (mV)	J_{SC} (mA/cm^2)	*FF* (%)	η (%)
Gen.1	Avg. (12)	659	38.2	79.5	20.0
Gen.1	Best [3]	660	38.4	79.4	20.1
Gen.3	Avg. (12)	650	38.1	78.8	19.5
Gen.3	Best	655	38.2	79.7	19.8

ADE-based solar cells of Gen.3 reached an average efficiency of 19.5%, with the best cell achieving 19.8%. The major loss in conversion efficiency is coming from *FF*, which is mainly due to a high series resistance caused by an un-optimized firing process for this batch as no firing variation was performed. Improved *FF* that is comparable to Gen.1 ADE texture would allow an immediate gain of 0.2% absolute in η of Gen.3 ADE-based PERC solar cells.

The short circuit current density (J_{SC}) of this batch is identical to the Gen.1 ADE-textured solar cells. Comparing to the Gen. 1 solar cells with ADE-texture, Gen.3 solar cells have lower V_{OC} values, which is expected to be linked to: a) higher internal quantum efficiency (*IQE*)-related losses in short wavelengths, b) difference in bulk quality of the HP mc-Si and standard mc-Si substrates. These *IQE* maps are compared to Gen.1 solar cells at short wavelength (405 nm) and at long wavelength (940 nm) in Figure 4.

Comparing the short wavelength spectral response in Figure 4 a) and b), Gen.3 texture exhibits slightly more *IQE* losses and would suggest recombination losses at the front surface/emitter. Meanwhile, a much more homogeneous distribution of *IQE* is observed for Gen.3 as a result of improved uniformity of the texturing process.

The *IQE* mapping at 940 nm provides mostly the information coming from the bulk material and the rear-side passivation. Since the rear-side passivation is unchanged, the differences are expected to be mostly due to the bulk. It can be observed that, in comparison to the HP mc-Si used in Gen.1, standard mc-Si wafer used in Gen.3 consists of higher percentage of wafer area exhibiting low bulk lifetime possibly associated to higher percentage of dislocations/impurities. This suggests that a fraction of V_{OC} and J_{SC} is lost due to the inherent lower bulk quality of the standard mc-Si wafer in comparison to HP mc-Si wafer.

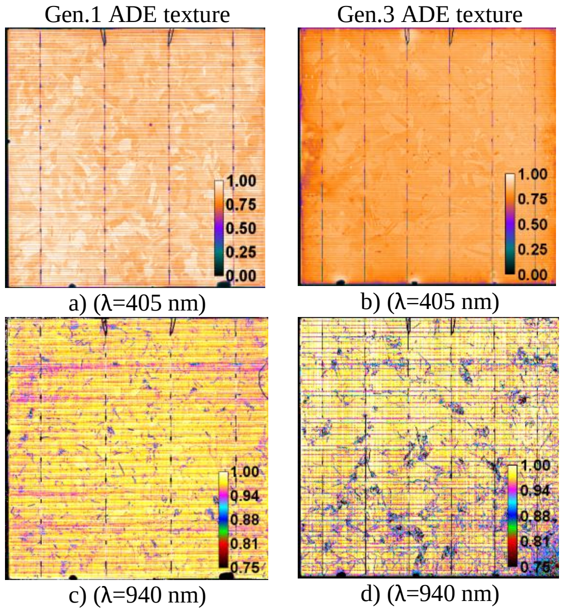

Figure 4: *IQE* mapping at 405 nm for representative ADE-textured solar cells of a) Gen.1 on HP mc-Si and b) Gen.3 on standard DWS mc-Si substrates respectively. In c) and d), *IQE* mapping at 940 nm is plotted for Gen.1 and Gen.3 respectively.

Hence, in order to further increase the conversion efficiency of Gen.3 texture and fully take advantage of the more uniform texture process, further work should focus on the combined optimization of texture and emitter diffusion to further improve the blue response. Using mc-Si of better bulk quality or further improving the inherent bulk quality of mc-Si material during the cell processing steps would also lead to higher efficiency values, directly comparable to previous results [3].

4. SUMMARY

ADE method of black silicon texturing on DW-sawn mc-Si is an alternative to MCCE and RIE due to its technological and ecological advantages. Based on high efficiencies of >20.0% on Gen.1 ADE-texture using high performance mc-Si, we presented a process showing improved spatial homogeneity of the texture in order to increase the J_{SC} gain and enhances the aesthetic appearance of the solar cell. This process is applied to industrial-type DWS mc-Si wafer-based PERC solar cells and reach mean efficiency η_{mean} = 19.5%, with champion efficiency η_{max} = 19.8%. The major loss in conversion efficiency is coming from *FF* and a firing variation is expected to increase the η by +0.2% absolute. We expect to further improve the electrical performance by boosting both V_{OC} and J_{SC} values by: a) minimizing *IQE*-losses in short wavelengths by co-optimization of texture and emitter diffusion processes, and b) avoiding the recombination associated with the material quality of standard DWS mc-Si substrates.

5. ACKNOWLEDGEMENTS

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