

## MULTICRYSTALLINE SILICON SOLAR CELL IMPROVEMENT BY ATMOSPHERIC PRESSURE DRY ETCHING PROCESS

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### ABSTRACT:

In this paper, a plasma-less atmospheric pressure dry texture process that is capable of forming nanostructures in the c-Si surface, has been investigated. The texture process uses diluted molecular fluorine ( $F_2$ ) as the process gas. Thermal activation of fluorine occurs on Si wafer surface in a dissociative chemisorption process leading to removal of Si in the form of volatile  $SiF_x$  species. The etching process can be controlled to form nanostructures with different aspect ratios and surface reflection values. Nanotexturing of mc wafers was performed by removing very low amount of Si substrate during the texturing process ( $\sim 0.6 \mu m$ ). These nanotextured wafers were further processed into p-type Al-BSF solar cells. The nanostructured cells show excellent  $V_{oc}$  and  $FF$  that are comparable to the reference cells. Significant gain in short circuit current ( $J_{sc}$ ) was achieved by the virtue of an enhanced light coupling in nanotextured solar cells. The best conversion efficiency of 17.3% was achieved for the mc Al-BSF cell. Adaptation of the emitter on nanotextured surface has potential to further increase the conversion efficiency.

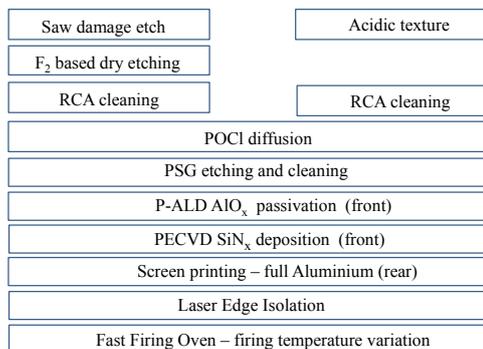
Keywords: etching, multicrystalline, solar cells

### 1 INTRODUCTION

Although maintaining a big share of photovoltaic market, acidic textured mc solar cells traditionally suffer from relatively high reflection losses. Nanotexturing of c-Si surface has been widely reported to reduce the surface reflection losses by introducing a graded refractive index from air to Si [1]. Despite possessing tremendous light trapping ability, nanotextured solar cells have not yet been used for large scale industrial production due to their inferior electrical behaviour. This originates primarily from the high surface and emitter recombination losses as well as from grave contacting issues. In the recent time, solar cells with improved efficiencies have been reported for n-type and p-type nanotextured solar cells [2, 3]. The existing nanostructuring methods are however difficult to apply in large scale fabrication either due to technological prospects or due to economic concerns. In this paper, we report texturing of multicrystalline (mc) wafers using an alternative dry texturing method that operates under atmospheric pressure conditions and uses molecular fluorine  $F_2$  as the process gas. Plasma-less dry texturing process that uses only process gases as the major consumables is an economically competitive process to the existing dry and wet-texturing techniques. Use of the global warming potential (GWP) -free  $F_2$  gas in the etching process also fits with the long term roadmap of a sustainable PV sector. We summarize the results of mc nanotextured Al-BSF solar cells and discuss the ways to further improve the electrical performances of solar cells.

### 2 MULTICRYSTALLINE AL-BSF SOLAR CELLS

p-type, 2-3  $\Omega cm$  mc Si wafers were used to prepare Al-BSF solar cells. Figure 1 summarizes the process plan followed for the test and the reference wafers.



**Figure 1:** Process plan followed for test and reference mc-Si Al-BSF solar cells.

The reference wafers were textured using HF/HNO<sub>3</sub> solution to produce micro-scale ridges reaching weighted reflection ( $R_w$ )  $\sim 24\%$ . The test wafers were first saw-damage etched and then textured using atmospheric pressure dry texturing process by removing  $\sim 0.6 \mu m$  of Si in average. The details of the texture process are described elsewhere [4, 5]. After the texturing process, all of the wafers received standard RCA cleaning followed by POCl<sub>3</sub> diffusion. The acidic textured wafers were diffused leading to a 75  $\Omega/\square$  emitter. The emitter diffusion process was modified for test wafers aiming similar

emitter sheet resistances to the reference wafers. After the etching of phosphosilicate glass (PSG) layer and a cleaning step, 10 nm plasma-based atomic layer-deposited (p-ALD)  $\text{AlO}_x$  was deposited on the textured side of all wafers, followed by the deposition of 65 nm of PECVD  $\text{SiN}_x$ . Screen printing was used to form front and rear metal grids. The ohmic contacts between metal and Si base were formed by industrial fast firing process and the edges were isolated by using a UV Laser.

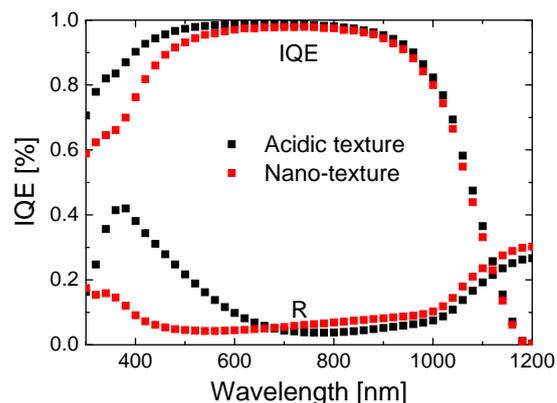
Table 1 summarizes the IV characteristics of the 5cm\*5cm Al-BSF solar cells. IV results show that the nanotextured solar cells show an improvement in  $J_{sc} \sim 0.5 \text{ mA/cm}^2$  and an absolute efficiency gain of 0.1%. This is, however, much less improvement in  $J_{sc}$ , than what is expected from the surface reflection measurements of the nanotextured surface. From the reflection measurements, it seems clear that nanotexture can facilitate much better optical confinement than acidic textured surface, especially in the short wavelength range of the spectrum. The weighted reflection ( $R_w$ ) calculated for nanotexture surface was  $\sim 3.6\%$  in comparison to  $\sim 8.3\%$  for acidic texture surface.

**Table 1:** IV characteristics of solar cells

	$V_{oc}$ (mV)	$J_{sc}$ (mA/cm <sup>2</sup> )	$\eta$ (%)	FF (%)	$R_s$ ( $\Omega \text{ cm}^2$ )	$R_p$ ( $\Omega \text{ cm}^2$ )
Dry Tex.	621	35.6	17.3	78.0	0.25	1.1E4
Wet Tex.	626	35.1	17.2	78.2	0.29	1.9E4

The internal quantum efficiency (IQE) measurement, however, suggests that the charge carriers generated in the near-surface emitter region predominantly due to the short-wavelengths, are not collected in p-n junction due to the fast recombination before they can reach the junction. In other words, the minority charge carriers have a very high recombination velocity that does not allow it to travel to the p-n junction in order to get collected. The recombination is supposed to be caused partly by the high concentration of inactive phosphorous near the surface region, aided by higher active doping in the emitter region (Auger recombination). A deeper p-n junction could also have resulted in the increased recombination of the charge carriers that are generated in the near-surface emitter region as their diffusion length might be insufficient to reach the depletion layer. In order to get the maximum advantage of the nanotextured surface by achieving better blue response, it is evident that one of the most important steps is to further optimize the emitter formation process considering both surface concentration as well as the depth of the diffused emitter in the nanotextured solar cell.

Good  $V_{oc}$  values achieved for nanotextured solar cell are due to the conformal  $\text{AlO}_x$  layers that were deposited by ALD technique. A comparable FF and low series resistance ( $R_s$ ) suggest that screen-printing method can be very well adapted for the nanotextured surfaces. Transmission line measurements (TLM) performed on the solar cell revealed low contact resistances for both nanotextured ( $\rho_c \sim 2.9 \Omega \text{ cm}^2$ ) and acidic textured surfaces ( $\rho_c \sim 2.34 \Omega \text{ cm}^2$ ).



**Figure 2:** Internal quantum efficiency (IQE) and surface reflection (R) plotted for the wavelength spectrum of 250 nm – 1200 nm. The PECVD  $\text{SiN}_x$  deposited was slightly thinner for nanotexture and slightly thicker for the acidic texture surfaces.

#### 4 SUMMARY

We have applied plasma-less dry texturing technique that uses molecular fluorine to etch c-Si. The texturing conditions can be controlled to create nanostructures of different graded depths by removing relatively low amounts of Si from the wafer. The dry textured structures with 200-600 nm depth and 50-200 nm width are found extremely well suited for the light confinement. We dry textured mc wafers by removing only 0.6  $\mu\text{m}$  of Si and applied an ALD- $\text{Al}_2\text{O}_3$ /PECVD- $\text{SiN}_x$  stack for the surface passivation. Despite a high surface enlargement due to formation of nanostructures, excellent passivation of the nanostructured surface was achieved by ALD  $\text{Al}_2\text{O}_3$  layer. This has resulted in good open circuit voltages  $V_{oc} \sim 620 \text{ mV}$ . The dry textured solar cells showed good FF and low contact resistance values that indicates their compatibility with the industrially viable screen-printing process. After the application of PECVD  $\text{SiN}_x$  layer, the nanotextured surface showed lower surface reflection values in comparison to the reference acidic textured surface. The actual improvement in  $J_{sc}$  is, however, much lower than expected from the reflection values. This indicates that the formation of a highly doped near-surface emitter region is responsible for the parasitic absorption of incident light coupled into the solar cell, which could otherwise be used for the photogeneration. This near-surface emitter thus acts

like an electrically inactive region. Additionally, a higher doping level expected in the emitter bulk and formation of a deeper p-n junction is also expected to enhance the minority charge carrier recombination. The formation of the highly doped emitter can however be avoided by careful optimization of the emitter diffusion process to the nanotextured surface.

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#### 6 REFERENCES

- [1] R. B. Stephens, and G. D. Cody, *Thin Solid Films* **45**, 19 (1977).
- [2] P. Repo *et al.*, in *Silicon PV* (Hamelin, 2013).
- [3] J. Oh, H.-C. Yuan, and H. M. Branz, *Nature nanotechnol.* **7**, 743 (2012).
- [4] B. Kafle *et al.*, in *Proc. 28th EUPVSEC (WIP Munich, ETA-Florence, Paris, 2013)*.
- [5] B. Kafle *et al.*, *physica status solidi (a)* (2014).