PLASMA SINGLE-SIDED ETCHING FOR REAR EMITTER ETCH-BACK AND FLATTENING OF INDUSTRIAL CRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT: In this paper, we present investigations on single-sided plasma etching for silicon wafers with work aimed for the development, characterization and application of single-sided plasma etching processes for industrial silicon solar cells. Tests were conducted using a popular industrial inline plasma system from Roth&Rau (modified SiNA). For high-efficiency cell structures with passivated and locally contacted rear side; it is beneficial to prepare a polished/flat rear surface to achieve a very good quality of passivation. During this work different dry etching approaches (using SF_6- and O_2-based plasma chemistry) for the solar cells rear, have been investigated in terms of resulting surface topography and optical performance. Solar cells processed with the developed plasma etching steps (for front and rear surface) exceeding 17% efficiency are reported in this study. The investigated process can be adapted to fit in the workflow for PERC-type (passivated emitter and rear cell) high-efficiency solar cell structures.

Keywords: silicon, etching, manufacturing and processing

1 INTRODUCTION

Truly single-sided processing makes fabrication of high-efficiency silicon solar cells simple and representing a cost-effective production as it avoids the need for complicated laboratory-type steps like the use of lacquers (or thick oxides) for solar cell processing. One example of direct application and process simplification is the case of passivated emitter and rear cells (PERC structures) [1]. Here, a parasitic emitter at the back surface has to be removed prior to surface passivation. The textured rear surface should be flattened or even polished in order to achieve a very good quality of surface passivation [2]. The aim of this work is to develop a successful single-sided plasma etching process after the diffusion step. Moreover, the rear-surface parasitic emitter removal is beneficial for the decrease in solar cell manufacturing steps (as no junction edge isolation required) and results therefore in lower processing costs.

Etching the emitter (wet chemically) after phosphorus diffusion and PSG etch faces a hydrophilic surface which may lead to an undesired wrap around [3]. The plasma-based treatment offers single-sided processing which is highly advantageous for high-efficiency solar cell fabrication processes [4] and satisfies the requirements of processing only on the targeted side.

An industrially applicable etching process for emitter removal prior to surface passivation therefore has to fulfill several requirements [4]:

- homogeneous etch back of emitter layer,
- flattening of existing surface structures or even polishing,
- completely single sided and robust process.

The process ensures the electrical separation of the emitter by etching away the doped layer on the complete back side of the wafer. This way, no Al-BSF is any more required to compensate the parasitic doping on the back side of the cell.

Within this paper different dry etching approaches for the solar cell's rear have been investigated in terms of resulting surface topography and optical performance.

2 EXPERIMENTAL DETAILS

2.1 The semi-inline plasma etching system

All plasma etching experiments have been performed at a modified SiNA system by Roth&Rau, which provides etching and deposition sources within one vacuum chamber (see figure 1). For etching a pulsed microwave linear plasma source (2.45 GHz) with peak power values up to 3.5 kW has been used.

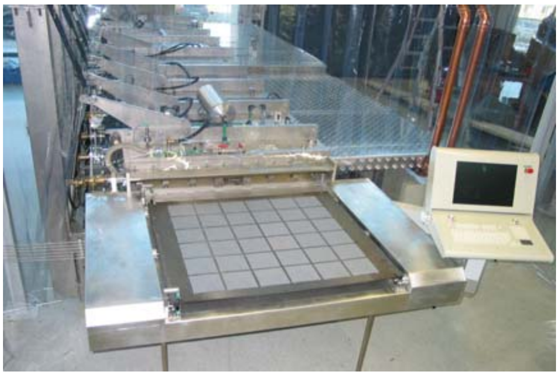

Figure 1: A photograph of Roth&Rau's semi inline plasma system at Fraunhofer ISE, Freiburg. It combines deposition and etching zones within one process chamber.

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A microwave linear antenna consists of conducting rods into which from both ends the MW power is coupled. The plasma builds up around the rod and along its entire length (effective width of plasma zone is approx. 0.2 m and length approx. 0.9 m). By adjusting the speed of the carrier, the time the wafers are subjected to the plasma can be adapted. Process gases can be introduced either near the substrate or from top of the source.

2.2 Sample preparation

The removal of random pyramids at the rear side involves the removal of a great quantity of silicon from the silicon substrate, almost 6 µm in depth, which requires samples to stay in plasma for a sufficient time. For this purpose undiffused wet chemically (alkaline solution) textured samples were used throughout the whole investigation.

All experiments were performed using (100)-oriented, p-type (boron-doped) pseudo square (edge length of 125 mm) CZ silicon wafers with a diameter of 150 mm, a thickness of 210 µm, a resistivity of 1-3 Ω cm and as-cut surface. The samples were textured in alkaline (KOH) solution. The typical measured weighted reflection (R_w) on such textured surface is approximately $R_w \approx 12\%$. The weighted reflection is calculated according to the method described elsewhere [5].

3 FLATTENING OF RANDOM PYRAMIDS

Several attempts have been performed to flatten the pyramids and polish the rough surface by passing the samples multiple times through the plasma zone (see figure 2). The samples were lying on silicon dummy wafers during etching and the carrier speed was kept constant. Initially, the etching was done only using constant SF_6 gas flow and peak power of 3.5 kW.

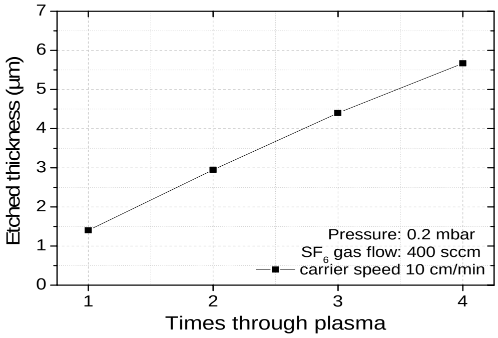


Figure 2: Etched thickness vs. etching time. Here, one time through plasma corresponds two minutes of etching time at one spot. Linear behavior can be extracted from the analysis.

This experimental run brought to evidence a recipe which removes silicon with a relatively fast etching rate of approx. 0.65 µm/min. In this work, plasma etching was performed with maximum 4 runs through plasma zone which shows approx. 6 µm silicon can be etched with this process. It is important to note that all plasma etching experiments were performed at room temperature.

3.1 Reflection measurements

The carrier was individually passed 1, 2, 3 and 4 times through plasma zone to evaluate the reflection and to check the surface topography of the samples. Etching at high pressure seemed to be slightly beneficial to achieve higher reflection value in a quicker way (see figure 3). Very low deviation in measured reflection values (measured at 4 points for each sample) can be the first step to confirm the homogeneity over the surface. The samples etched at high pressure (0.15 mbar) and etched 4 times in plasma (~32 minutes) measures $R_w \approx 32\%$ which represents a relatively flat surface since a shiny etched FZ silicon surface measures $R_w \approx 37\%$.

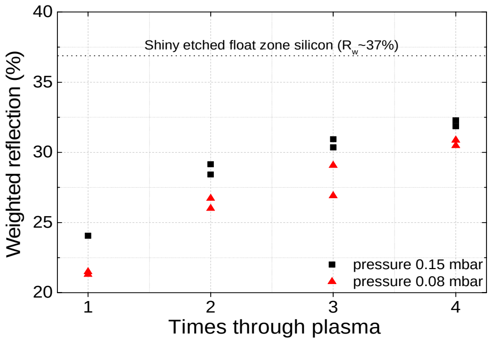


Figure 3: Weighted reflection vs. the time the samples went through plasma zone for rear flattening as a function of process pressure.

The next experiment was mainly focused to investigate the effect of an increased gas flow as well as chamber pressure on the etching process and corresponding reflection from the etched surfaces. Therefore, several variations in chamber pressure in combination with increase in gas flow and etching time have been performed (see figure 4).

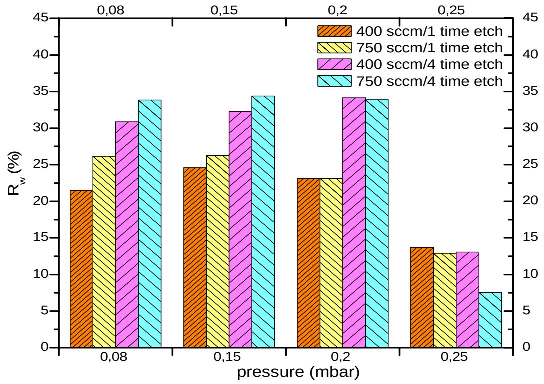
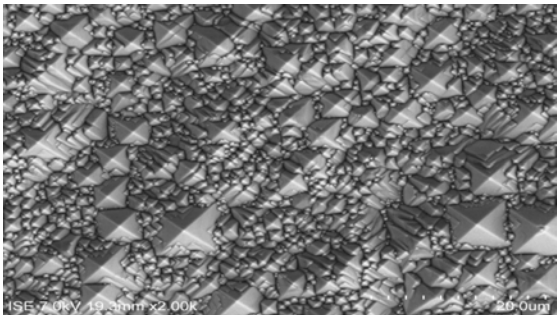


Figure 4: Comparison of the weighted reflection measurements for the samples etched at different chamber pressures as a function of total gas flow (and etching time). Sample etched (4 times) at 0.2 mbar pressure and low gas flow (400 sccm) shows the best results suitable for a flattening process with the lowest gas utilization.

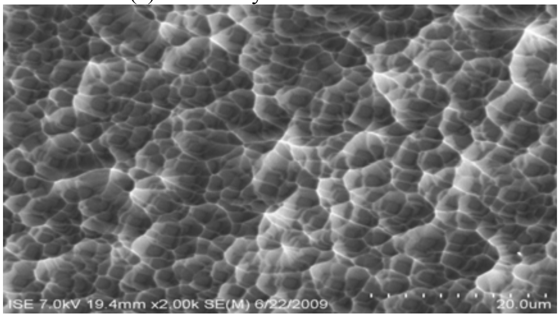
A small increase in the R_w with increased gas flow at lower pressure was observed, while on the other hand the reflection decreases strongly at high chamber pressure (0.25 mbar). The measured values of R_w for samples etched at 0.2 mbar/ 4 times were good at both the gas flow variation. An average $R_w \approx 34\%$ was measured for both cases. The reason for the strong decline in the reflection values measured at 0.25 mbar can be attributed to the decrease in ion current density with increase in pressure [6]. Additionally, the high gas flow results in a faster gas exchange in the chamber and therefore in a lower amount of reactive species that reach the substrate's surface; a reduction of ion current density is the result.

3.2 Surface analysis using SEM

Figures 5 (a) and (b) give an overview of the initial textured surface and the resulting flattened surface after plasma etching, respectively. After plasma etching the surface topography looks strongly changed as the flattening of original pyramid structures can be observed. It was possible to remove the pyramids and create a surface with smooth hollows. This surface has a large scale structure and no sharp edges. However, although the surface still does not appear completely flat, significant gain in R_w was measured. The increase in reflection from such surface can be correlated with the smoothening of the surface.



(a) Alkalinely textured surface.



(b) Flattened surface after plasma etching.

Figure 5: Random pyramids which are shown in fig (a) are the initial surface ($R_w \approx 12\%$) for mono crystalline silicon wafers. The smooth surface ($R_w \approx 34\%$) shown on the right side is achieved after flattening process. See fig (b). A gas flow of solely SF_6 was used for the etching process.

3.3 Results

Figure 6 shows an overview of the spectrally resolved reflection values measured at different surfaces. The developed processes afterwards successfully applied in solar cell fabrication, results of which are discussed in following sections.

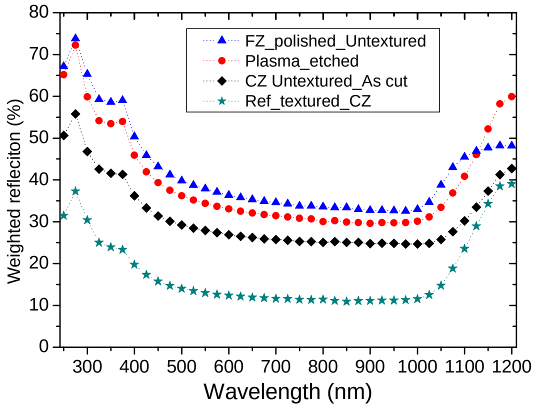


Figure 6: Overview of the reflections measured on different surfaces. The reflection values measured on plasma-etched (flattened) surface ($R_w \approx 34\%$) is on a very good level and in the same range as FZ shiny etched surface ($R_w \approx 37\%$) and CZ untextured surface ($R_w \approx 28\%$).

4 SINGLE-SIDEDNESS EVALUATION OF PLASMA ETCHING

Because of the high material removal, it is paramount to have single sided etching to avoid corruption of structures on the surface not targeted; hence an important aspect was to test the single sidedness of the etching process. Saw-damage etched CZ-Si and shiny etched FZ-Si samples (for ellipsometry investigation) were prepared for the test having silicon nitride (SiNx) coating at one side. The process sequence is depicted in figure 7. The etching was performed on the side without silicon nitride coating. To prevent plasma wrap around from the bottom side, the carrier was fully covered with silicon dummy wafers. The samples were placed on a) silicon dummy wafers, b) aluminum hooks and c) a holder made of CFC (carbon fiber reinforced carbon) material (same material used for the carrier) and these holders were placed on the dummy wafers.

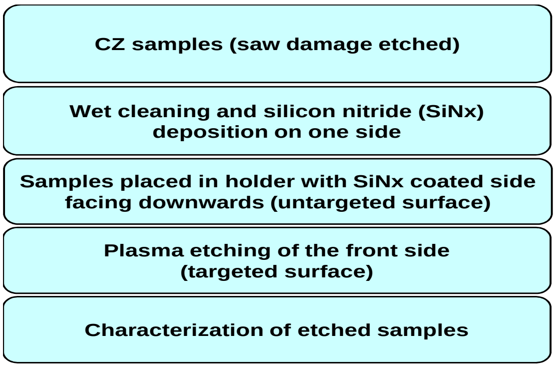


Figure 7: Process plan for single-sidedness test conducted at inline plasma-etching tool. Samples were etched on one targeted side and were coated with SiNx on the other one.

Several variations in plasma-etching parameters were performed such as process pressure, etching time (keeping peak power and total gas flow constant) to check the behavior of plasma on the side not targeted. The best approach was then used for subsequent experiments.

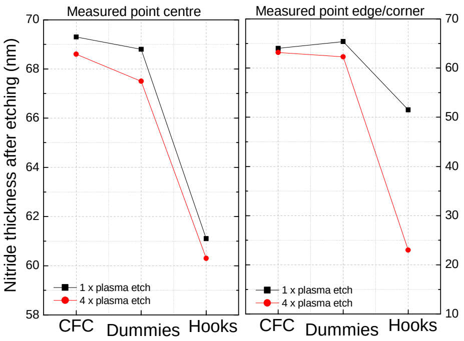


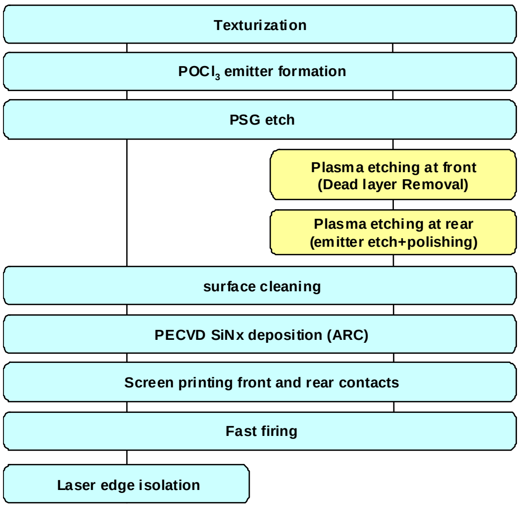
Figure 8: After plasma etching thickness of Silicon nitride layer (which was not targeted during etching) was measured using Ellipsometry technique. Starting thickness of nitride was approx. 70 nm. The measurements were done at several positions over the wafer. The measurement position edge/corner was located approx. 3 mm away from the wafer edge. Direct comparison clearly reveals that hooks are not suitable from single sidedness point of view as the untargeted side was strongly attacked during etching. Samples placed on dummies and CFC plates seem to be feasible.

5 SOLAR CELL FABRICATION

5.1 Approach

The solar cells of this investigation were prepared on large-area monocrystalline CZ-silicon wafers (side = 125 mm, diameter = 150 mm, pseudo square, thickness ~ 200 µm, ρ = 1-3 Ωcm) from Deutsche Solar. Process sequence is shown in figure 9; two different cell processes have been implemented to compare the performance of the plasma etched solar cells to a standard Al-BSF reference cell.

The wafers were texturized in an alkaline solution and the emitter was realized by a batch diffusion process in a tube furnace using $POCl_3$ as phosphorous source. Phosphorous silicate glass (PSG) was removed by dipping the samples in diluted hydrofluoric acid (HF) bath. The measured sheet resistance (R_{sh}) values of these samples were approx. 60 Ω/□. Since the phosphorous diffusion led to an emitter formation at both wafer surfaces, the rear emitter was etched using developed plasma flattening process. Additionally, the dead layer was etched from the front emitter just by removing few nanometers (approx. 50 nm) from the surface which changed the R_{sh} value up to 70±5 Ω/□. The details of plasma dead layer etching process can be found elsewhere [7]. After plasma etching step the wafers were cleaned (SC1/SC2) and passivated with a PECVD silicon nitride (SiNx:H) anti-reflection coating on front surface.



(a) (b)

Figure 9: Process sequence used for the solar cells fabricated with different approaches; (a) standard Al-BSF reference process and (b) rear-flattening process combined with dead-layer etching.

It could also be possible to flatten the rear side after deposition of anti-reflection coating but for the process simplicity (as one needs to protect untargeted side if the process is not single sided) it is better to do this step before deposition so that the cleaning can be performed on both the surfaces together. Silver and aluminum pastes commercially available for solar cell metallization have been screen printed onto the front and back, respectively. The solar cell contacts have been fired using an inline furnace. As the emitter at the back was removed; the junction edge isolation step is not required.

It is to be noted that all processes have been carried out using high-throughput equipment that is also used in industry or is also capable of industrial production throughput. For rear flattening the number of plasma sources would have to be increased for sufficient throughput.

5.2 Results and discussion

An overview of the best cell results is given in table 1. Combination of dead layer etching with rear flattening process, following (b) solar cell fabrication sequence confirms potential of developed processes; up to (on average) η ≈ 16.9 % was achieved as compared to η ≈ 16.6 % measured for cells following reference Al-BSF sequence (a).

Table 1: Overview of the cell parameters measured under one-sun illumination (AM 1.5g). Average values are measured for 5 solar cells of same type.

	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]
(a) Al-BSF reference cell				
Best cell	615	35.2	78.4	16.9
Average cell	610	34.8	78.3	16.6
(b) Plasma-etched front and rear				
Best cell	617	35.8	77.4	17.1
Average cell	616	35.6	76.8	16.9

Comparing the results of open-circuit voltage V_{oc} and the short-circuit current density J_{sc} show that higher values can be found for the plasma etched (front and rear) solar cells. An absolute 0.8 mA/cm² gain in J_{sc} was observed for the cells involving flattening process. The fill factor FF was found to be slightly lower than the reference cells.

To understand the difference between plasma-etched sample and the Al-BSF reference in V_{oc} and J_{sc} in illuminated measurements, measurement of the external quantum efficiency (EQE) and the reflection (R) were performed. The latter and the calculated internal quantum efficiency (IQE) are plotted in figure 10. The performance in short wavelength regime (blue response) of plasma (dead layer) etched sample is slightly increased due to improved emitter.

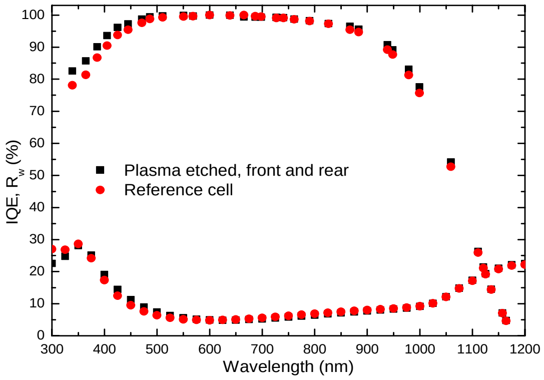


Figure 10: Internal quantum efficiency and weighted reflection, normalized to 100%. Comparison between plasma-etched cell and Al-BSF reference.

The reflections measured on both the cells are almost similar throughout the whole wavelength range. Since the rear side was not passivated, no significant difference in internal reflection can be observed from the plasma flattened sample. This leads to the conclusion that flattening of the surface can not alone substantially increase the internal trapping of light, a coating at the rear surface which can have mirror like properties and also serves the purpose of passivation to further decrease surface recombination velocity (SRV) would be necessary.

6 SUMMARY

In this study it was possible to reach a silicon removal of about 6 µm in one step (four times passing through the plasma zone at a low speed) which gives a weighted reflection of about 34%. For comparison, a shiny etched float zone wafer has a weighted reflection of about 37%. It was possible to remove the pyramids and create a surface with smooth hollows. The developed single sided flattening process was successfully applied in solar cell fabrication and confirms the potential as the plasma etched cells outperforms conventional Al-BSF references.

We observed that the plasma flattened cells (combining dead layer etching at front surface) performs better in terms of J_{sc} and V_{oc}, the first indicating a better harvesting of the light and the second a lower amount of recombination. No significant difference in the internal reflection observed, as the rear surface was not passivated. The best solar cells from this approach (without back side passivation) using standard CZ material and a close-to-industry process reached an efficiency of 17.1%.

ACKNOWLEDGEMENTS

The authors would like to thank the whole PVTEC production team for cell processing, Jutta Zielonka for SEM analyses; Alexander Krieg and Benedikt Köpfer for IV and EQE measurements.

The financial support of the German Federal Ministry of Education and Research (BMBF) under contract no. AZ 03SF0335D is gratefully acknowledged.

REFERENCES

[1] A. W. Blakers, A. Wang, A. M. Milne, J. Zhao and M. A. Green, Appl.Phys. Lett., 55, p 1363 (1989).

[2] G. Beaucarne, Etching, texturing and surface decoupling for the next generation of Si solar cells, in Photovoltaic's international 2008, pg 66-71.

[3] G. Kästner et.al, Single side polish etching for the rear side of crystalline silicon wafers, this conference.

[4] J. Rentsch et.al, Single side etching - key technology for industrial high efficiency processing, Proceedings of the 23rd European Photovoltaic Solar Energy Conference. 2008. Valencia, Spain.

[5] W. Sparber, Diploma thesis (in German), Technische Universität Graz/ Fraunhofer ISE, 2003.

[6] F. Walter, M. Hofmann, and J. Rentsch. In-situ plasma cleaning and deposition of a-Si:H for surface passivation of crystalline silicon wafers using an industrial type inline plasma system, Proceedings of the 23rd European Photovoltaic Solar Energy Conference. 2008. Valencia, Spain.

[7] J. Seiffe et.al, Improved emitters by dry etching, this conference.