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INDUSTRIAL REALIZATION OF DRY PLASMA ETCHING FOR PSG REMOVAL AND REAR SIDE EMITTER ETCHING

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ABSTRACT: Inline production sequences are gaining more and more importance considering improved material flow and decreasing wafer material thickness. With the application of dry phosphorus silicate glass (PSG) etching combined with a subsequent SiN_x deposition a further simplification of the process flow can be reached. Within this work, a new prototype etching and deposition system from Roth&Rau (called MAiA) is presented implementing a dry PSG removal, a single side emitter etch for the rear side as well as a SiN_x deposition without leaving the vacuum line. Each process step itself has been tested and optimized and complete multicrystalline silicon solar cells have been produced implementing the new process sequence.
Keywords: Silicon; Manufacturing and Processing; Etching; PECVD

1 INTRODUCTION

The application of dry processing offers the possibility to simplify the process flow in solar cell production significantly. Wet chemical phosphorus silicate glass (PSG) removal represents a process step with a high degree of automation and wafer handling. Wet chemical in-line etching systems [1] present certain progress in reducing wafer handling steps, but still these processes are characterised by high water and chemical waste disposal [2] as well as a high mechanical impact. Therefore, for complete in-line production of solar cells dry PSG plasma etching may represent the most favourable solution [3]. Major drivers for the demand of integrated solutions for dry process equipment with a minimum of wafer handling are the growing costs for water and chemical waste disposal as well as the further reduction of wafer thickness in cell production [4].

Further on advantages of plasma processing compared to standard wet chemical manufacturing steps are:

- Handling of less hazardous chemicals, e.g. perfluorocompounds (PFCs), avoids massive use of water and HF acid.
- High flexibility concerning different wafer materials, no principal difference in material processing.
- Suitability for high throughput processing even for thin-wafers could save material costs due to less wafer breakage.
- Different treatment for front and rear side processing (e.g. different front/rear side structure, single side emitter removal).

PFCs and sulphur-hexafluoride (SF_6) are commonly used for saw damage removal as well as oxide etching during solar cell processing. Due to their high Global Warming Potential (GWP) these gases are main contributors to the greenhouse effect [4,5]. Therefore and due to the creation of process residuals (e.g. HF, CO, SOF etc.), which are toxic and/or polluting agents, an effective waste treatment is essential and necessary for the application of plasma processing in PV industry. A measure for the environmental impact of the used fluorine etching gases represents the carbon equivalent (CE). In general, the reduction of the CE compared to conventional energy sources marks the largest environmental benefit using photovoltaics, therefore dry solar cell processing has to address matters of waste gas treatment most seriously [6].

For the first time, clustering of plasma processing steps has been technically realized on industrial suitable process equipment. The combination of dry PSG removal and edge isolation by single side emitter etching shows the cost reduction potential of plasma processing for solar cell production.

2 EXPERIMENTAL AND APPROACH

2.1 MAiA prototype system

Etching and deposition experiments have been carried out at Roth&Rau's new MAiA prototype etching and deposition system. This process cluster comprises the removal of the PSG, the removal of the rear side emitter layer, cleaning and SiNx deposition within one single system without leaving vacuum (see Figure 1).

Figure 1: Overview picture of combined MAiA process cluster system from Roth&Rau AG implementing all mentioned process steps (PSG removal, single side emitter removal, cleaning and SiNx deposition).

Preliminary tests of the selective etching process suitable for $POCl_3$ based PSG removal as well as rear emitter etching have been carried out on a similar dynamic plasma in-line etching system at Fraunhofer ISE [3].

For the different etching and cleaning steps two different kinds of plasma sources have been used. For PSG removal the plasma excitation was performed with a simple low frequency (110 kHz) plasma source consisting of two parallel graphite electrodes with a length of approximately 0.9 meter (see Figure 2). For rear side emitter etching as well as cleaning and SiNx deposition the well known microwave linear plasma sources (2.45 GHz) were used.

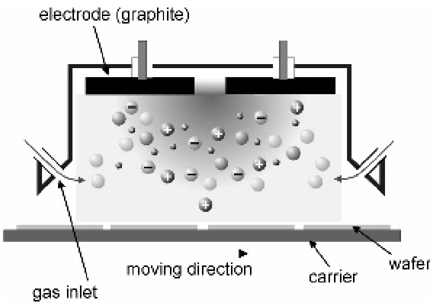

Figure 2: Working principle of the low frequency plasma source used for selective PSG etching

2.2 Approach

As etching gas for PSG removal CF_4 with small quantities of additional hydrogen has been used. Main focus for the experiments has been put on process stability and homogeneity together with a high selectivity between the etch rates of PSG and the underlying silicon emitter [7]. Process optimization for single side etching emphasized on fast and nearly damage free removal of the parasitic emitter at the solar cell rear side. Prior to SiN_x deposition removal of remaining etch residuals was carried out applying O_2 or NH_3 plasma processes. Industrial type multicrystalline (mc) silicon solar cells (cell area 243 cm², resistivity range 0.5 – 2 Ωcm, neighbouring wafers) have been processed using screen printing techniques implementing the new process sequence. The impact of the different dry etching steps on solar cell performance in terms of either etching induced surface or bulk damage has been investigated by lifetime measurements on test structures as well as IQE measurements.

3 RESULTS AND DISCUSSION

3.1 PSG etching

For PSG removal high ion energies are necessary to reach suitable oxide removal rates. With the given set-up of the prototype system, the low frequency plasma source delivers a certain fraction of ion energies around 150 eV enabling PSG removal rates of more than 100 nm/min (see Figure 3).

Although high ion energies are involved during the etching process, the emitter layer can be protected against ion induced damage by the formation of a steady-state fluorocarbon layer. Nevertheless this layer has to be removed prior to further solar cell processing, since it causes problems during contacting and changes the properties of the antireflection coating. The effectiveness of such a layer in terms of securing the underlying emitter from ion bombardment has been successfully demonstrated in the past [7,8].

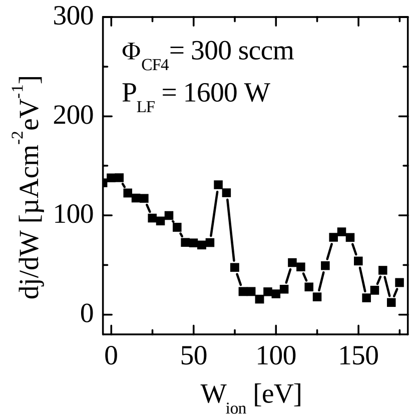

Figure 3: Ion energy distribution of the low frequency source used for PSG removal. Ions with energies around 150 eV are ensuring the fast oxide removal and are promoting the PSG/Si selectivity of the etching process.

For removal of the fluorocarbon layer several cleaning plasmas have been tested including also a wet chemical HF-dip for reference. Lifetime test structures (both sides of the wafer etched and passivated equally) were prepared and characterized after the subsequent etching steps (PSG etch with CF_4/H_2 plasma as well as cleaning). Figure 4 summarizes the results of the QSSPC measurements on the final test structures clearly indicating the impact of the cleaning step. On lifetime test structures best results for dry cleaning, compared to the wet chemically etched reference, could be reached by applying a NH_3 plasma resulting in effective carrier lifetime of around 60 µs.

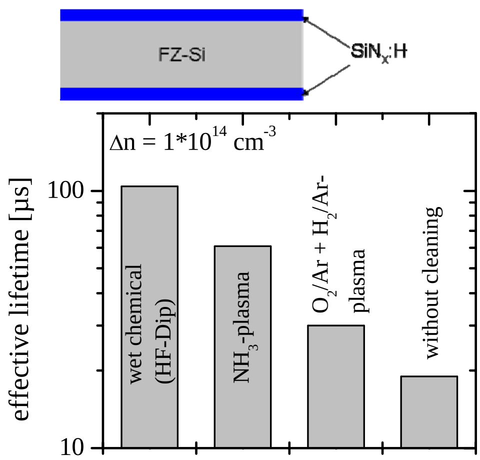

Figure 4: Test sample structure and effective carrier lifetimes τ_{eff} of dry PSG etched (CF_4/H_2) and differently cleaned FZ-Si wafers (test structure preparation: $POCl_3$ emitter diffusion, dry PSG removal, cleaning, SiN_x:H passivation).

3.2 Rear side etching

Edge isolation is performed by rear side emitter removal using a linear antenna microwave plasma source. The homogeneity of the dynamic etch rate ER over the full carrier width is shown in Figure 5 for a SF_6 plasma. Dynamic etch rates of around 0.4 µm*m/min ensure a fast etch process, since 2 µm etch depth should be sufficient for a complete emitter removal, e.g. an effective edge isolation.

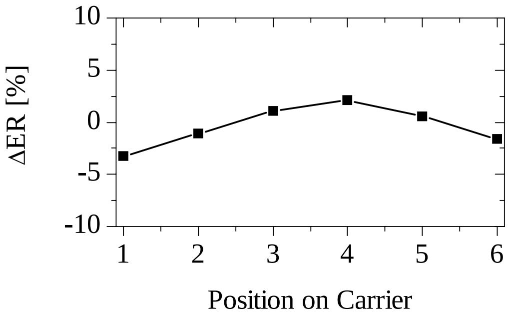

Figure 5: Etch rate homogeneity during single side emitter removal across the transport carrier.

Besides the etch homogeneity, the surface cleanliness after emitter removal has been considered. The process pressure during emitter etching shows a strong influence to measured effective lifetimes on specially prepared test structures (FZ-Si wafers, $POCl_3$ diffused, dry emitter etch on both sides equally, a-Si passivation) as illustrated in Figure 6. The high lifetime level of around 500 µs also shows the potential of the dry etching step for further application in high efficiency processes as surface conditioning prior to rear side passivation schemes.

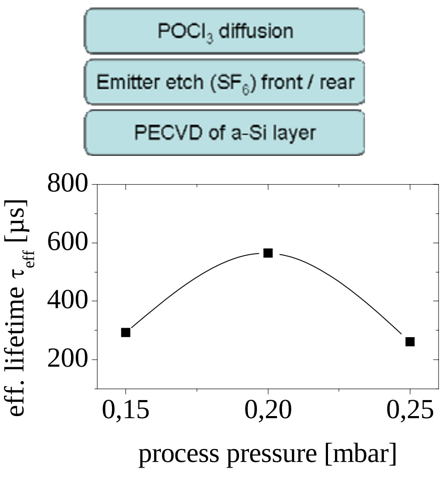

Figure 6: Process sequence for the preparation of the test structures and results of the effective lifetime τ_{eff} of plasma etched and a-Si passivated FZ-Si wafers (ρ=1 Ωcm, N_D=1x10^{14}cm^{-3})

Main issue in rear side emitter etching is the designated transport carrier design, as a plasma wrap around has to be avoided to secure the emitter on the front side from the etch attack. Several carrier design are currently investigated at Roth&Rau addressing the both-sided plasma treatment..

3.3 Solar cells

Table I shows the results of solar cells with dry etching and cleaning of PSG in comparison to wet chemically etched references on mc-silicon material. The front- and back-end processing was carried out at Fraunhofer ISE. Except for the wet chemically etched reference group, dry PSG removal and SiNx deposition have been carried out in the prototype system at Roth&Rau. For polymer removal after PSG etching pure oxygen microwave plasma has been used prior to the SiN_x deposition.

Listed are best cell results as well as mean cell results of 20 solar cells. Best solar cell results have been reached with the dry PSG etch sequence resulting in 14,5 % efficiency. As a result of the implemented plasma etching and cleaning step, open circuit voltages and short circuit currents of the dry etched cells show slightly lower values than the wet chemically etched references.

Table I: Solar cell results for dry PSG etched and SiNx deposited industrial screen printed mc-Si solar cells (cell area 243 cm², thickness 240 µm) as well as wet chemically etched references. Average values are given from batches of 20 cells each.

	V_{oc} [mV]	j_{sc} [mA/cm²]	FF [%]	η [%]
Dry PSG removal + SiNx				
Average	597 ± 2	31,1 ± 0,2	76,1 ± 0,6	14,1 ± 0,2
Best	601	31,4	76,7	14,5
Reference (wet chemical PSG removal)				
Average	604 ± 2	31,6 ± 0,3	76,5 ± 1,4	14,6 ± 0,3
Best	606	32,1	77,0	15,0

Compared to earlier results with low surface damage due to the PSG etching process [7], the current etching process on the prototype system has to be further optimised mainly in terms of the etch selectivity.

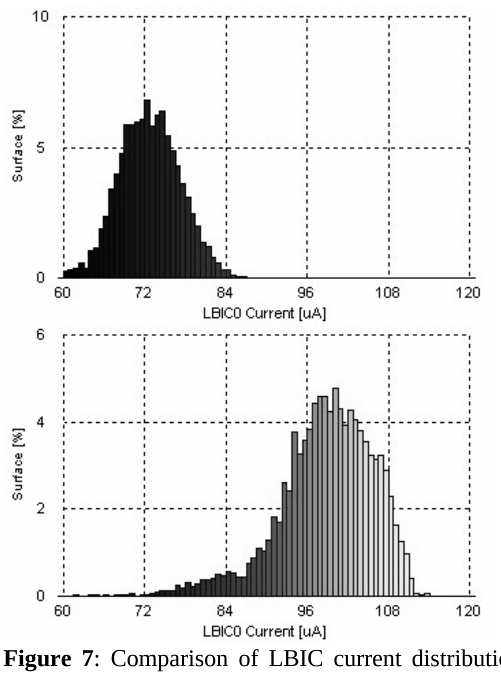

Figure 7: Comparison of LBIC current distribution at 405 nm laser wavelength for dry PSG etched cell (upper diagram) and wet chemically etched reference (lower diagram).

The forming fluorocarbon polymer layer seems to be too thin to completely avoid a certain surface damage by bombarding high energy ions. The damage to the underlying emitter is clearly visible by comparing the LBIC current distributions at 405 nm laser wavelength of the dry etched and the wet chemically reference solar cell.

The ion induced damage of the emitter layer is also documented in the IQE measurements in Figure 8 as decrease of the current for short wavelengths.

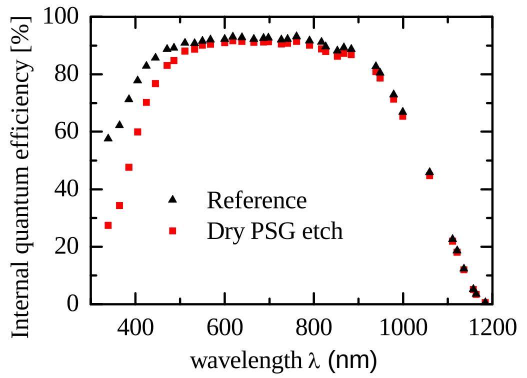

Figure 8: Internal quantum efficiency of dry and wet chemically (Reference) PSG etched solar cell. Clearly, the ion induced damage of the emitter layer is visible in the short wavelength range.

4 SUMMARY

The transfer of a dry PSG and rear side emitter etching processes to an industrial suitable dynamic in-line plasma etching and deposition system could be demonstrated. Main features of the newly developed system are the possibility for both-sided wafer treatment as well as the possibility to directly deposit the SiNx layer on the etched and cleaned surfaces without leaving vacuum. Effective lifetimes of more than 500 µs could be reached on emitter etched and passivated lifetime test structures pointing out the future applicability to rear passivated solar cell approaches. For PSG etching high ion energies above 150 eV are needed for a fast and reliable oxide removal, remaining fluorocarbon layers on the surface can be effectively removed by NH_3 or oxygen plasma processes. By the application of the new process sequence to multicrystalline silicon solar cells still slightly lower V_{oc} and j_{sc} values are reached. SR-LBIC as well as IQE measurements identified a certain emitter damage caused by the not yet optimised PSG etch as main contributor for the losses. Further optimisation will be undertaken in the future mainly to improve the etch selectivity between PSG and silicon, e.g. increasing the buffering fluorocarbon layer, and therefore eliminating the impact of the high ion energy bombardment.

However, the experiments shall be considered as not fully completed. Further experiments are necessary and planned in order to full fill the final goal to reach comparable results between dry and wet chemical etching.

5 ACKNOWLEDGEMENTS

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