

DRY PLASMA TEXTURING - AN ALTERNATIVE TECHNIQUE FOR INDUSTRIAL PRODUCTION OF THIN MC-SI SOLAR CELLS.

N. Le Quang¹, F. Madon¹, O. Nichiporuk¹, A. Esson¹, S. Mermet¹, A.M. Messant¹, M. Gauthier¹, G. Goaer¹
Gerd Walther², BT Chan², Gustav Otto²

¹Photowatt International S.A.S 33, Rue Saint Honoré 38300 Bourgoin Jallieu, France

²Secon Semiconductor Equipment GmbH Laxenburger Str.17, Guntramsdorf A-2353 Vienna, Austria

ABSTRACT: The rapid growth of the PV production today and in the upcoming years necessitates a more environmentally friendly and more suitable for thin cell surface treatment technique. Dry texturing using plasma processing represents one possible alternative way to meet the above requirements.

Within this work the multicrystalline silicon solar cells textured by dry plasma process with an industrial solar cell process sequence consisting of gas phase diffusion, front side silicon nitride PECVD deposition and screen-printing technology for metallisation have been carried out. The comparison between alkaline and plasma texturing processes for multicrystalline silicon solar cells and modules produced in the industrial environment has been realised. Different technical problems concerning surface homogeneity, modules performance...etc have been considered. The high Global Warming Potential (GWP) of the plasma etching gases has been analysed and some solutions have been suggested.

Keywords: plasma texturisation, shallow emitter, multicrystalline silicon

1 INTRODUCTION

In order to realise an isotropic texturing - an approach to improve the conversion efficiency of multicrystalline silicon solar cells, numerous techniques have been studied and developed. One of the most transferable into industrial production techniques is acidic texturing which was presented for the first time in 1995 [1]. Although this technique is already used now in the production of several PV manufactures, different problems concerning environmental impacts of a wide application of acidic texturing have to be solved. The most pressing problems are: a) the expensive chemical waste treatment, b) stocking and manipulation with large volume dangerous acids; c) increase of DI water consumption [2], [3]. The other problem is the fragility of acidic textured wafers that could increase material cost due to higher breakage rate. The dependence of acidic texturing quality on pre-treated surface state is also a technical problem. Replacement of the wet acidic texturing with a dry process based on plasma technology, would present notable advantages for PV industries.

Plasma texturing is a stress free, low temperature process with a reduced environmental impact in regard to acidic texturing. This technique allows to process only one side of the wafer. From an industrial point of view, plasma texture process is suited for large size and thin solar cell production and is well compatible with current trends in PV: shallow emitter, dry inline processing, isotropic texturing and cost reduction.

Within this work, a dry plasma texturing process based on the Secon technological concepts has been chosen and investigated on multicrystalline silicon solar cells.

2 EQUIPEMENT DESCRIPTION

The development of the plasma texturing technique was done based on the Secon XCD-724 etcher (Fig.1). This is a laboratory system, which is capable to process 4 wafers of 125 x 125 mm² in batch. Two Microwave high rate plasma generators, XRG-900 are used for the dissociation of the Fluorine-radical plasma.



Figure 1: Secon XCD-724 etcher.

Fig. 2 shows the XRG-900 plasma source, which consists of horizontal ceramic rods coupled to a microwave cavity. These rods acts as an antenna for guiding waves with coaxial shielding from the microwave cavity to the active area inside the reaction chamber. Thus the plasma region is localized around the ceramic rods and no ion-impact damage is observable at the solar substrates which are placed 60-120mm beneath the ceramic rods.

The Secon microwave (MW) plasma technology offers the Chemical Dry Etching (CDE), which ensures low ion impact rates to the substrate. No RF bias was used to generate additional (kinetic) energy to accelerate the F-radicals to the silicon surface and react with the silicon atoms. The chemical reaction of the etching produces volatile reaction gases such as SiF₄ (Silicon Tetra fluoride), which can be pumped away.

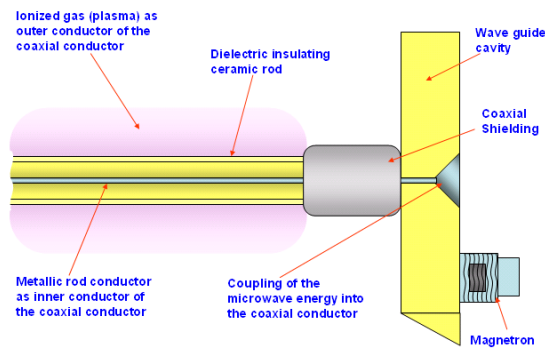
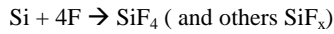


Figure 2: XRG-900 plasma source.

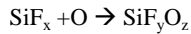
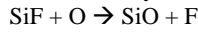
3 MECHANISMS OF PLASMA TEXTURISATION

The texturing process operates in the following steps:

- Fluorine radicals (SF_6 is the source of active fluorine) react with all the bonds of Si atoms.



- Oxygen radicals (coming from N_2O) passivate the surface of the etched silicon surface. It is useful to equilibrate two mechanisms: etching and redeposition of a thin layer of silicoxyfluoride (micromasking)[4].



- Chlorine radicals (from Cl_2) which are bigger atoms react only with front bonds (no additional energy with this type of microwave plasma.) and lead to an increase of the surface roughness.

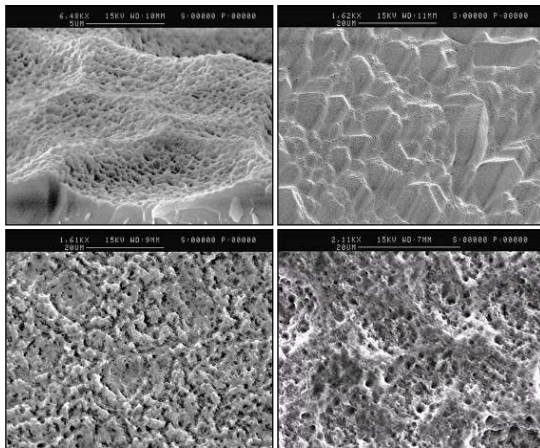


Figure 3: Different SEM pictures of plasma textured surfaces (20 μm scale)

Depending from the ratio of gases N_2O , SF_6 and Cl_2 , a lot of different shapes and sizes can be created (Fig. 3). Surfaces with the lower reflectivity are not necessarily the best for final solar cells (impact on emitter quality).

4 ENVIRONMENT-SECURITY

Sulfur hexafluoride SF_6 has a high global warming potential and contributes to the greenhouse effect. Moreover, some process residuals (SO_x , HF, etc...) can be toxic or not environmentally friendly. Consequently, it must be treated by gas abatement. In the frame of our study, although microwave plasma have a high power of

dissociation of gas molecules, we used the **Centrotherm gas burner "Flawamatt"** (also used for our Silicon Nitride PECVD furnaces) which is well adapted for our small quantities of used gases.



Figure 4: Centrotherm Gas Burner

New solutions of gas abatement for an industrial scale production with a better efficiency have been studied during the last years. [5]

Chlorine is a hazardous and corrosive gas and it is also an "ozone killer". Chlorine atoms react with ozone and convert it back into plain oxygen. A single chlorine atom involved in a chain reaction can destroy many ozone molecules. All precautions of security have been considered at Photowatt, despite the small quantities of used gases and the associated risks: double gas pipe lines, gas detectors, alarms, nitrogen purges, etc...have been installed for this work.

5 EXPERIMENTAL

For the investigations, p-type multicrystalline silicon wafers (125.5mm x 125.5mm) were used. The following process sequence has been used (Fig. 5):

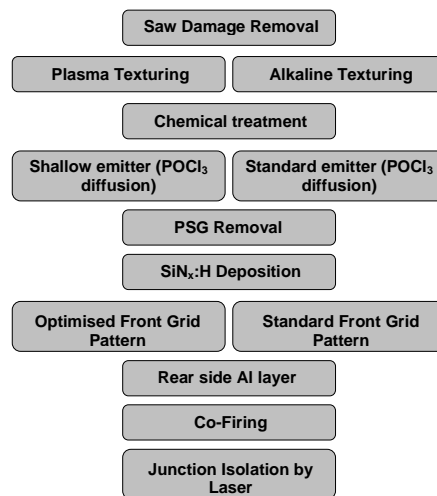


Figure 5: Process sequence used for plasma texturing.

Chemical treatment has been necessary after the plasma texturing step to improve the cell performances. The substitution of these wet cleaning treatments by a post internal cleaning plasma (SF_6 et H_2) should be

investigated and used for the future works.

6 CELL PROCESS OPTIMISATION

To optimise the emitter formation step for plasma textured cells, a wide range of emitter sheet resistances has been tested (from 35 to 75 Ohms/sq). The diffusions were carried out in an industrial quartz furnace tube with a low pressure (LYDOP® technology). In this experiment the same front contact grid pattern and the same firing profile was applied for all studied solar cells.

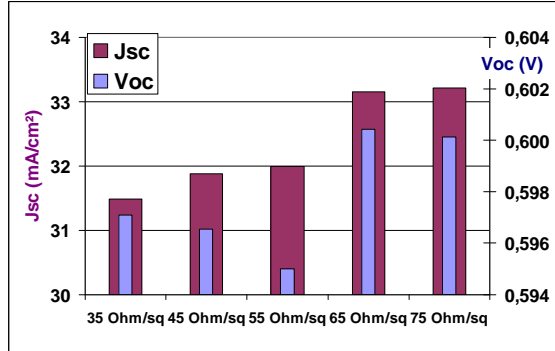


Figure 6: Impact of emitter sheet resistance on Voc and Jsc of plasma textured cells

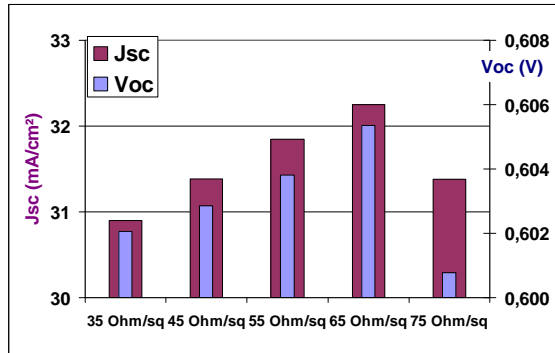


Figure 7: Impact of emitter sheet resistance on Voc and Jsc of alkaline textured cells

The influence of emitter sheet resistance on Voc and Jsc of plasma textured cells is shown on figure 6. We can conclude, that shallow and lightly doped emitters are well suited for plasma textured cells: the increase of emitter sheet resistance from 45 ohms/sq to 65 ohms/sq improves the Jsc of the cells by 4% (+1.3mA/cm²). Such Jsc improvement on plasma textured cells is remarkably more important compared to alkaline textured cells (Fig. 7): The same increase of emitter sheet resistance on NaOH textured cells leads to Jsc improvement by only 2.7% (+0.9 mA/cm²). Meanwhile the further increase of emitter sheet resistance on plasma textured cells (from 65 Ohms/sq to 75 Ohms/sq) does not lead to significant improvement of Jsc (Fig. 7).

For NaOH textured cells the increase of emitter sheet resistance to 75 Ohms/sq leads to significant degradation of Jsc and Voc degradation mainly due to shunting. To explain the more significant improvement of Jsc on plasma textured cells with light and shallow emitter, the

Internal Quantum Efficiency (IQE) of the cells was measured and analysed (Fig. 8).

As expected, for lightly diffused emitters, the improvement in the blue part of spectra was observed. However, this improvement is much more pronounced for plasma textured cells. This phenomenon can be explained by the difference of shapes for heavy and shallow emitters profiles on plasma textured surface (Fig. 9). The very small size of pits (~100 nm) on plasma textured surface leads to local over-doping of such structures (Fig 9, left image) and formation a relatively thick “dead layer”. At the same time, for the shallow and lightly doped emitter the effect of over-doping can be much less pronounced (Fig 9, right image).

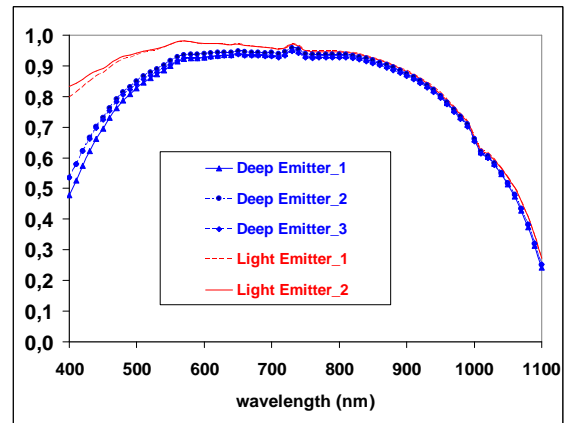


Figure 8: Internal Quantum Efficiency of solar cells with two types of emitters.

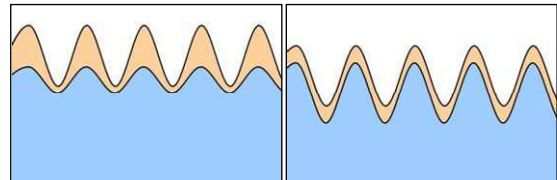


Figure 9: shallow and deep emitter shape on plasma textured solar cells.

Another important result concerns the Fill Factor evolution for different emitter sheet resistances (Fig. 10).

For NaOH textured solar cells, a strong decrease of FF was observed for shallow and lightly doped emitters with sheet resistances 65 Ohms/sq and 75 Ohms/sq. This degradation of FF is mainly due to a strong increase of contacts resistance (confirmed with CorreScan mapping). Moreover for 75 Ohms/sq emitter some shunting problems have been observed.

For plasma textured cells the FF degradation with increase of emitter sheet resistance is much less pronounced (Fig 10). The CorreScan mapping does not reveal significant contact resistance problem even for 75 Ohms/sq emitter. After front contact grid optimisation Fill Factor FF up to 77% were obtained on 65 Ohms/sq emitters.

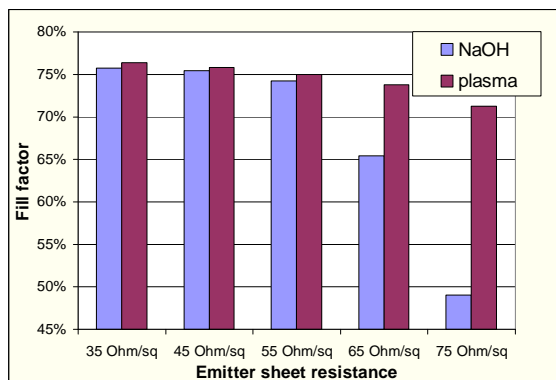


Figure 10: Fill Factor vs emitter Sheet Resistance for Plasma and Alkaline textured solar cells.

An important point is the homogeneity of texturing. The benefits of this homogeneity can be seen on figure 11, where Laser Beam Induced Current (LBIC) cartography is shown for alkaline (left) and plasma (right) textured solar cells fabricated from two sister mc-Si wafers. We can see, that the photocurrent distribution difference between the grains is clearly visible for alkaline textured cell due to the difference of texturing effect versus different crystalline orientations. This difference is totally eliminated for plasma textured cell however some variation on photocurrent distribution is still observed on different regions of this cell due to inhomogeneity of plasma texturing.

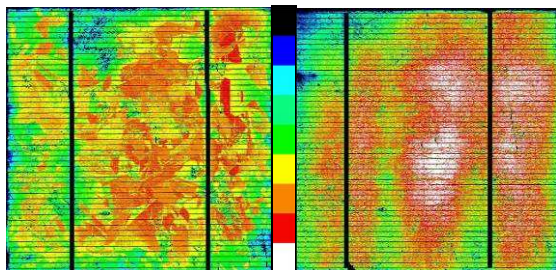


Figure 11: LBIC images of alkaline (left) and plasma (right) textured solar cells fabricated from sister mc-Si wafers.

The comparison between alkaline and plasma textured solar cells parameters after process optimisation is shown on figure 12. The plasma textured cells demonstrate improved short-circuit current (+1.3% relative) and improved Fill Factor (+1.3% relative). The gain in Fill Factor is explained by modified front contact grid pattern where the number of fingers was increased to compensate the increase of emitter sheet resistance. For the same reason the gain in Jsc is less important compared to previous experiments. The final absolute efficiency gain of about +0,4 % was obtained for plasma texturing process.

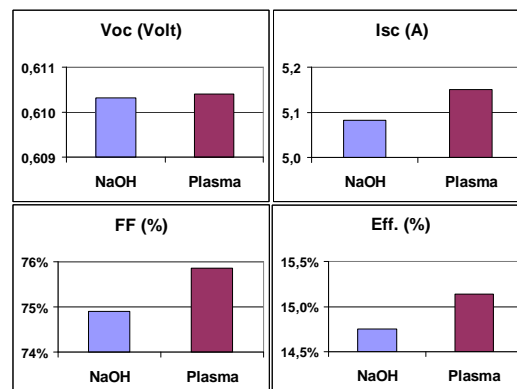


Figure 12: Electric parameters for plasma textured solar cells.

Plasma textured solar modules and encapsulated cells have been made. Module reliability tests give satisfying results.

However some problems have been noticed: “plasma modules” give lower output power than “alkaline modules”, which were both prepared from solar cells with identical performances. This power loss is approximately 1 to 2% (relative value). Some solutions have been suggested as modifications of Silicon Nitride thickness, refractive index and using alternative encapsulants.... We’re still working to find a definitive solution.

7 CONCLUSION AND OUTLOOK

Developed plasma process is able to create a dry and isotropic texturisation on multicrystalline silicon wafers with relatively low surface damages. An exhaust abatement system for plasma process gases has been tested.

The surface reflectance can be reduced significantly in regard to alkaline textured surface (~2%). Our study shows, that plasma texturing process is well compatible with current trends in PV: shallow emitter, dry inline processing, isotropic texturing. After cell process optimisation (diffusion profile, SiNx:H ARC, front contact grid pattern), an improvement on conversion efficiency up to 0.4% (absolute value) has been reached. The chemical treatment after plasma processing is still needed. The loss on output power of the modules produced from plasma textured cells in regard to alkaline modules has been observed. These problems have to be solved by further process optimisations.

Acknowledgements

The French agency ADEME and the European Commission are gratefully acknowledged for their financial participation in the frame of the French National REDUCOP project and in the frame of CRYSTALCLEAR Project under Contract number SES6-CT_2003-502583.

We would like to thank H.F.W. Dekkers, from IMEC in Belgium for all useful technical discussions.

References

[1] D. Sarti, Q.N.Le, S. Bastide, G. Goer, D. Ferry, "Thin Industrial Multicrystalline Silicon Solar Cells and improved Optical Absorption, Proc. 13th EUPVSEC (1995), pp.25 – 29.

[2] G. Agostinelli, H.F.W.Dekkers, S.de Wolf, and G. Beaucarne, "Dry Etching and Texturing Processes for Crystalline Silicon Solar Cells: Sustainability for Mass Production", 19th EUPVSEC, (2004) 423-426

[3] H.F.W. Dekkers, G. Agostinelli, D. Dehertoghe and G. Beaucarne, "Improved performance of mc-Si solar cells by isotropic plasma texturing", 19th EUPVSEC, (2004)

[4] H.F.W. Dekkers, F. Duerinckx, L. Carnel, G. Agostinelli and G. beaucarne, "Plasma texturing processes for the next generations of crystalline Si solar cells", 21st EUPVSEC (2006)

[5] M.J. de Wild-Scholten, E.A. Alsema, V.M. Fthenakis, G. Agostinelli, H. Dekkers, V. Kinzig "Fluorinated greenhouse gases in photovoltaic module manufacturing: potential emissions and abatement strategies", 22nd EUPVSEC, (2007) to be published.