

PECVD PSG AS A DOPANT SOURCE FOR INDUSTRIAL SOLAR CELLS

J. Benick, J. Rentsch, Ch. Schetter, C. Voyer, D. Biro, R. Preu

Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstrasse 2, D-79110 Freiburg, Germany
Phone +49-761-4588-5287; Fax +49-761-4588-9250; email: jan.benick@ise.fraunhofer.de

ABSTRACT: Emitter formation by in-line deposition of a PECVD PSG and subsequent diffusion in an in-line belt furnace is suggested as an alternative to quartz tube diffusion. The PSG deposition process reached excellent layer homogeneities, both across a single wafer and across the whole carrier, resulting in very uniform sheet resistance distributions. Relative standard deviations of 2,5 % have been achieved.

Solar cells with the developed emitter reached efficiencies of up to 17,5 % and 16,8 % on textured and untextured Cz-Si respectively.

Keywords: Deposition, Doping, c-Si,

1 INTRODUCTION

The standard method for forming the solar cell emitter which used by the majority of solar cell manufacturers, is the diffusion in a batch-like tube diffusion furnace. To reduce mechanical stress during processing and handling and to obtain high mechanical yields, the use of in-line PECVD systems for phosphorus deposition with an horizontal transport of wafers is favourable. Due to the low impact of forces on wafer edges and surfaces, in-line processing is well suited for the production of large and very thin wafers [1].

Besides the PECVD process presented in this paper emitter forming has been done by deposition of an APCVD PSG and adjacent rapid thermal annealing (RTA) [2,3]. Another alternative is the emitter formation by a spray-on process [4,5] which is also promising for industrial realisation.

One advantage of PECVD is its flexibility. Single-sided and double-sided deposition are possible in one process step. Furthermore, the deposition of PSG can directly follow an in-line plasma texturing process, also in development at Fraunhofer ISE, further reducing necessary wafer handling steps [6].

This paper presents some features of PECVD-deposition of PSG as well as solar cell results.

2 DEPOSITION OF DOPANT SOURCE

2.1 Deposition homogeneity

A large-scale in-line PECVD reactor from Roth & Rau AG [6] has been used to deposit PSG as a dopant source for forming the emitter of industrial solar cells. The plasma excitation was performed by a microwave linear plasma source operating at a frequency of 2,45 GHz. As process gases for the PSG deposition, TMCTS (Tetramethylcyclotetrasiloxane), TMPi (Trimethylphosphite) and O₂ have been used.

Ellipsometric measurements have been performed in order to characterise layer thickness homogeneity. The measurements were done on a single wafer positioned in the middle of the carrier as well as on wafers occupying the whole carrier width.

A capping layer is deposited on top of the PSG for moisture protection because of the strong hygroscopic nature of PSG.

Various deposition parameters such as pressure, temperature, microwave power, gas flow and composition of gases have been examined. As an example, Fig. 1 -3 show the parameters that influence

layer uniformity the most: microwave power and process pressure.

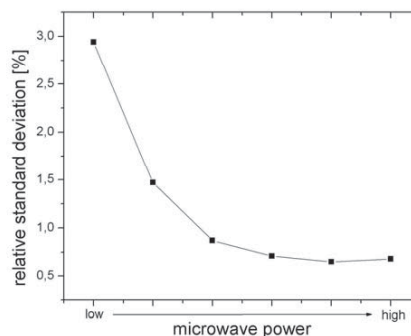


Fig. 1 Deposition homogeneity across a 50x50 mm² FZ Si wafer varying with the microwave power.

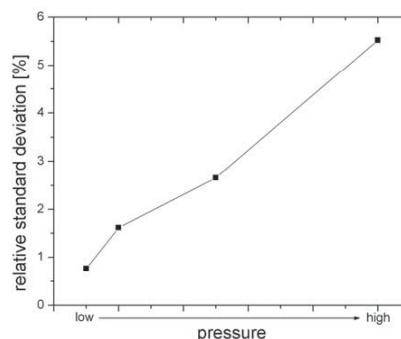


Fig. 2 Deposition homogeneity across a 50x50 mm² FZ Si wafer varying with the process pressure.

As can be seen, deposition homogeneity increases with increasing microwave power as well as with decreasing process pressure. Because of the linear decrease of microwave power along the microwave antenna, high powers are needed to form a uniform plasma along the whole length of the microwave antenna.

Decreasing process pressure enhances the diffusive transport of reactive species, thus improving layer homogeneity. Moreover, both an increase in microwave power and a decrease in process pressure result in an enhanced deposition speed. Other parameters such as

deposition temperature or O₂ content show an opposite effect. Increasing deposition temperature as well as increasing the O₂ content improve deposition uniformity, but reduce deposition speed. Deposition speed for processes with highest homogeneities is in the range of about 2 nm/s. As can be seen, very homogeneous layers have been deposited, not only across a single wafer (relative standard deviation below 1 %) but also across the whole deposition carrier (relative standard deviation of about 3 %) whose width is approximately 90 cm.

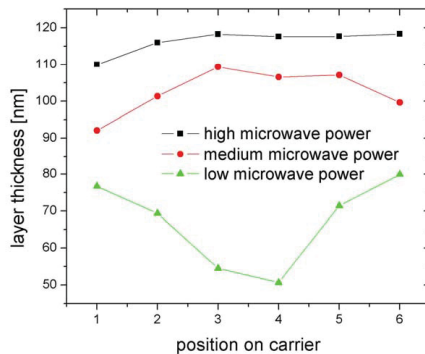


Fig. 3 Layer thickness across the whole deposition carrier at varying microwave power.

2.2 Layer composition

Layer composition has been determined with Energy Dispersive X-ray Analysis (EDX) and X-ray Photoelectron Spectroscopy (XPS) measurements. Because of the organic nature of deposition precursors TMCTS and TMP, a significant carbon content in the deposited PSG layer could not be excluded, therefore the phosphorus as well as the carbon content have been determined.

Since PSG is an electrical insulator, it has to be covered with a thin carbon layer before EDX measurement to avoid surface charging. The carbon content can therefore not be determined by EDX. XPS measurements have been used instead. By sputtering the surface, organic contamination can be removed from the sample surface prior to measurement. Measurements before and after surface sputtering have been performed.

Table I Composition of PSG layer measured by EDX technique.

layer	C [at%]	O [at%]	Si [at%]	P [at%]
PSG	6,5	66,3	18,5	8,7

As expected, EDX measurements show a high carbon fraction. The proportion of phosphorus in the PSG is about 9 %. As can be seen on the XPS spectrum the carbon peak (labeled with C_{1s}) vanishes after sputtering, indicating insignificant carbon content of the deposited layers.

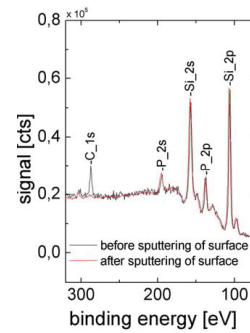


Fig. 4 XPS spectrum of a PSG layer before and after sputtering of the surface.

3 EMITTER FORMATION

The diffusion step, subsequent to the PSG coating, has been carried out in an in-line walking string furnace [7]. Two processes, one with high temperature and high conveyor speed i.e. a short diffusion time (process 1), the other with low temperature and low conveyor speed (process 2), both yielding sheet resistances of about 45 Ω/sq, have been used.

For emitter characterisation, four point probe measurements of sheet resistance and SIMS doping profile measurements have been carried out.

Sheet resistance shows a strong decrease with increasing layer thickness up to 60 nm, proving that beyond this thickness, the deposited PSG acts as an inexhaustible dopant source (see Fig. 5). The resulting lateral sheet resistance distribution is very homogeneous (see Fig. 6). With a relative standard deviation over the full wafer (125 x 125 mm²) of 2,5 % for a polished Cz wafer, the developed process shows results even superior to the POCl₃ reference process (relative standard deviation 3,8 %).

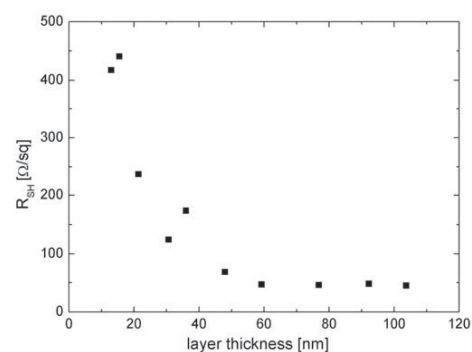


Fig. 5 Dependence of sheet resistance on layer thickness. The diffusion has been performed at low temperature and long diffusion time (process 2).

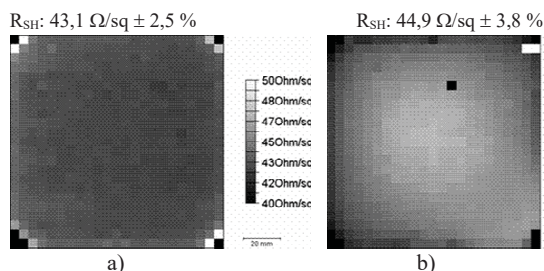


Fig. 6 Four point probe measurements of sheet resistance topography. Compared are the homogeneities of a) a wafer processed with the developed plasma process, b) a POCl_3 reference wafer.

Although all emitters characterised with SIMS have similar sheet resistances in the range of $45 \Omega/\text{sq}$, their doping profiles are significantly different. The POCl_3 emitter, which serves as a reference, has the deepest emitter profile of about $0,5 \mu\text{m}$. The developed in-line emitters have shallower diffusion profiles with $0,3 \mu\text{m}$ for process 1 and $0,4 \mu\text{m}$ for process 2. This could easily be changed by varying the diffusion parameters of the walking string furnace, e.g. conveyor speed (time) and temperature.

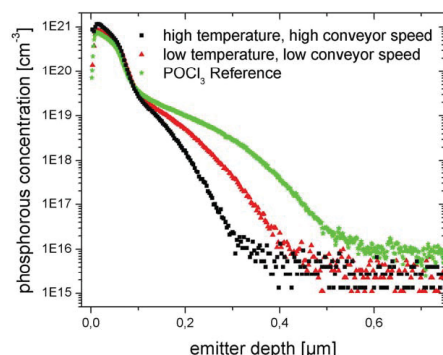


Fig. 7 SIMS profiles of FZ Si material. The line displayed with green stars represents the diffusion profile of the POCl_3 reference emitter, the one depicted in red triangles emitter 2 and the last one (black squares) emitter 1.

4 SOLAR CELL PROCESSING AND RESULTS

Industrial-type solar cells were fabricated on textured and untextured 3-6 Ωcm Cz-Si wafers ($125 \times 125 \text{ mm}^2$). They have been processed using the PSG PECVD deposition process, screen printing metallisation and fast firing through a passivating SiN_x -ACR layer. The solar cell process scheme is shown in Fig. 8.

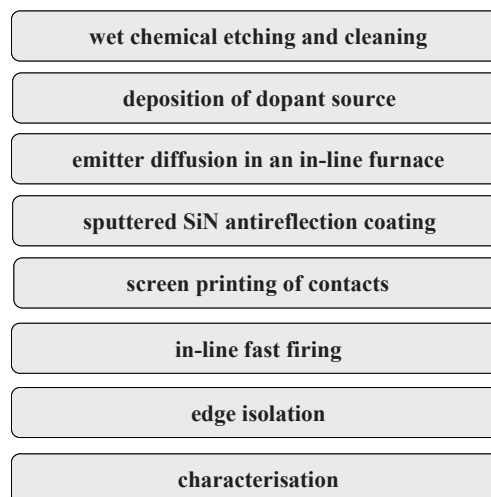


Fig. 8 Used industrial solar cell process scheme.

The two previously described emitter profiles (relatively shallow emitter 1 and the deeper emitter 2), both yielding sheet resistances of about $45 \Omega/\text{sq}$, have been tested. Firing temperatures have been varied from 840°C to 900°C .

For all cells, the best results have been reached at the firing temperature of 860°C .

Very good cell results (Table 1) have been achieved with this in-line process, leading to efficiencies up to 17,5 % for alkaline textured and 16,8 % for untextured Cz-Si material respectively.

Table II Solar cell results on alkaline textured and planar Cz-Si material (thickness $270 \mu\text{m}$). Two diffusion processes are compared which differ in process time and temperature.

		V_{OC} [V]	J_{SC} [mA/cm ²]	FF [%]	ETA [%]
textured					
emitter 2	best cell	619,1	35,4	80,1	17,5
	average	617,3 $\pm 1,0$	35,4 $\pm 0,2$	80,0 $\pm 0,5$	17,3 $\pm 0,1$
emitter 1	best cell	613,4	35,2	78,9	17,0
	average	611,6 $\pm 1,6$	35,1 $\pm 0,1$	78,8 $\pm 0,1$	16,9 $\pm 0,1$
untextured					
emitter 2	best cell	625,4	33,3	80,6	16,8
	average	624,4 $\pm 0,9$	33,1 $\pm 0,2$	80,0 $\pm 0,3$	16,6 $\pm 0,2$
emitter 1	best cell	624,3	33,4	79,8	16,6
	average	623,1 $\pm 1,4$	33,2 $\pm 0,2$	79,9 $\pm 0,2$	16,5 $\pm 0,1$

Uniform FF values of about 80 % have been reached, proving the ability of the emitter to form very good contact with the used screen printing metallisation technique. In the case of untextured cells, both emitters show almost identical results, while there is a significant difference for textured cells. For the shallower emitter 1, a drop in fill factor of about 1 % absolute down to approximately 79 % can be observed. The same drop can be observed in V_{OC} where the voltage decreases from an average value of 617 V for emitter 2 down to 611 V for emitter 1. So obviously there are difficulties in contacting the relatively shallow emitter on textured surfaces.

IQE measurements of the best cells for both textured and untextured surfaces processed with emitter process 1 and 2 are displayed in Fig. 9.

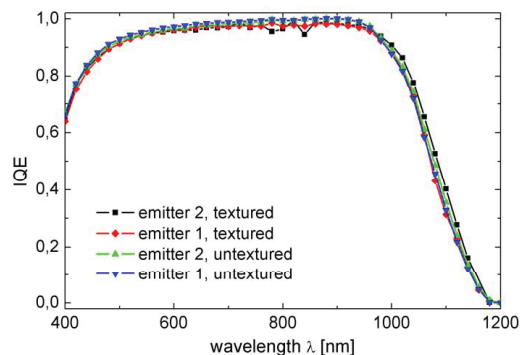


Fig. 9 IQE of best solar cells for both textured and untextured surfaces processed with emitter processes 1 and 2.

4 CONCLUSIONS

The developed process for emitter formation, in-line deposition of a PECVD PSG as a dopant source with subsequent high-temperature treatment in an in-line diffusion furnace, is a promising alternative to diffusion in a quartz tube diffusion furnace particularly when combined with an inline plasma texturing process.

Deposition of PSG has proven to be very homogenous across the single wafer as well as across the whole deposition carrier. Relative standard deviations of about 1 % for single wafer and about 3 % for the whole deposition carrier respectively have been reached. Analysis of layer composition showed a phosphorus content of approximately 9 % and insignificant carbon content.

Resulting sheet resistances have been shown to be independent of layer thickness for a PSG thickness above approximately 60 nm. Uniformity of sheet resistance across a single wafer shows very low relative standard deviation of about 2,5 %.

First results in solar cell production are very promising yielding efficiencies up to 17,5 % for textured and 16,8 % for untextured Cz-Si material.

5 ACKNOWLEDGEMENTS

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