Erschienen in: 25th European Photovoltaic Solar Energy Conference and Exhibition / de Santi, G.F.; Ossenbrink, H.; Helm, P. (Hrsg.). - Munich, Germany : WIP-Renewable Energies, 2010. - S. 1770-1773
https://dx.doi.org/10.4229/25thEUPVSEC2010-2CV.2.16

EMITTER OPTIMIZATION FOR MONO- AND MULTICRYSTALLINE SILICON: A STUDY OF EMITTER SATURATION CURRENTS

S. Graf, J. Junge, S. Seren, G. Hahn
University of Konstanz, Department of Physics
P.O. Box X916, 78457 Konstanz, Germany
Author for correspondence: Sabine.Graf@uni-konstanz.de, Tel.: +49 7531 884995, Fax: +49 7531 883895

ABSTRACT: In this work the influence of varied diffusion parameters for an industrial open tube $POCl_3$ diffusion furnace upon the emitter saturation current density on monocrystalline silicon is investigated. Further on, the effect of phosphorus gettering on multicrystalline silicon and on the sheet resistance on both mono- and multicrystalline silicon is under investigation. In addition, diffusion profiles are determined using the ECV (Electrochemical Capacitance Voltage) technique. Aim of this work is to enhance the performance of lowly doped emitters (80-140 Ω/sq) applied in a photolithography based high efficiency solar cell process with special respect to defect-rich block cast multicrystalline silicon material. Understanding the influence of temperature, time and gas flow variations during the diffusion process is very important to enhance solar cell performance especially for mc silicon. For such materials the $POCl_3$ gettering effect and the defect kinetics during the diffusion and the cool down phase after the diffusion are of major interest besides the reliable contact formation and low emitter saturation currents resulting in a good blue response of solar cells. The experiments performed in this work demonstrate that different mono- and multicrystalline silicon materials can benefit from adapted diffusion recipes in terms of significantly reduced emitter saturation currents and increased bulk lifetimes resulting in enhanced solar cell efficiencies.

Keywords: c-Si, Diffusion, multicrystalline Silicon

1 INTRODUCTION

The phosphorus diffusion is one of the most important steps in the manufacturing process of solar cells. During diffusion, the temperature load should be as low as possible to prevent clustered impurities from diffusing in defect-rich materials like multicrystalline silicon and thus lowering the minority charge carrier lifetime. On the other side, the temperature should be high enough to enable an in-diffusion of phosphorous in the boron doped silicon wafers within a reasonable time scale. Further on, the temperature should be high enough to enable an effective phosphorous gettering, i.e. the activation energy for trapped impurities should be high enough to release these species from their sites. Released impurities can then diffuse in direction of the gettering site, i.e. the phosphorous glass or the highly doped surface layer of the emitter (dead layer) where the solubility for the element is higher and thus the impurity is trapped resulting in an enhanced bulk lifetime due to a purification of the bulk. The resulting emitter profile should have a moderate surface dopant concentration to keep Auger recombination as low as possible and the emitter should have a low emitter saturation current density j_{0e} to enable high short circuit current densities of processed solar cells. To meet these requirements, an optimized diffusion sequence is necessary in terms of a reliable control of process parameters such as stability of temperature and gas flow. $POCl_3$ emitter diffusions under investigation in this work were carried out in a conventional batch-type open tube diffusion furnace.

2 EXPERIMENTAL

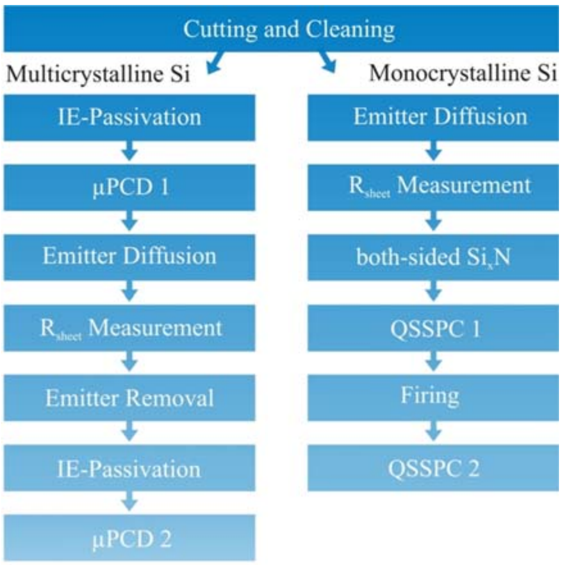

Figure 1: Processing sequence applied to mono- and multicrystalline samples for lifetime and emitter saturation current density measurements.

Figure 1 shows the several processing and measurement steps for multicrystalline and monocrystalline silicon, respectively. After cutting the wafers to a size of 5x5 cm² they were chemically polish etched (HNO_3, HF, CH_3COOH) to remove the surface damage. For each $POCl_3$ emitter diffusion Cz (Czochralski) and FZ (Floatzone) as well as standard block cast multicrystalline silicon wafers were examined.

By varying the diffusion time between 10-25 minutes, the diffusion temperature between 790-850°C or the gas-flows during the diffusion, sheet resistances of 80-140 Ω/☐ and different emitter profiles were achieved.

The sheet resistances were measured using the 4-point technique after removing the phosphorous glass.

For spatially resolved lifetime measurements the surface of the wafers was passivated using an IE (Iodine-Ethanol) solution after a chemically oxidation and HF etching for cleaning.

For the determination of the emitter saturation current density the samples were passivated with a PECVD (Plasma Enhanced Chemical Vapour Deposition) silicon nitride layer of about 75 nm thickness on both sides (symmetrical samples).

3 RESULTS

3.1 Sheet Resistance

The first aim of the $POCl_3$ emitter diffusion is to form a homogeneous sheet resistance over the wafer surface and over all wafers in the quartz boat.

Figure 2 shows the sheet resistance versus the position in the quartz boat for a representative diffusion. A deviation of less than 3% over the boat and less than 2% on the wafer surface was reached (measured with a conventional four point probe setup).

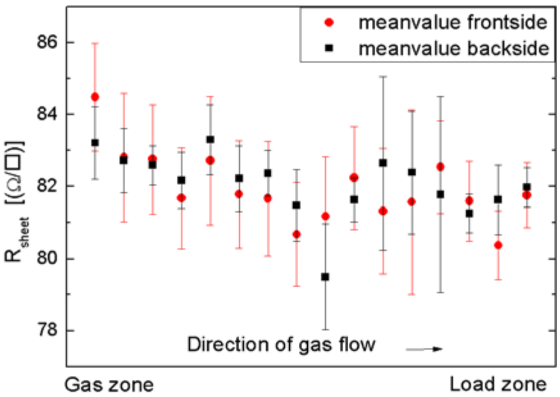

Figure 2: Sheet resistance distribution for a representative emitter diffusion over the quartz boat for monocrystalline (Cz) silicon.

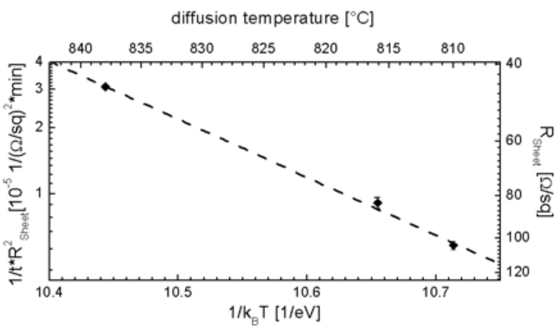

Figure 3: Sheet resistance of Cz-Si wafer versus inverse diffusion temperature including linear regression.

Figure 3 illustrates the effect of the temperature on the sheet resistance. With increasing temperature the sheet resistance decreases and shows Arrhenius-type behaviour.

3.2 Minority charge carrier lifetime

To investigate the influence of the phosphorus gettering the minority charge carrier lifetime was determined before and after the emitter diffusion with spatially resolved µPCD measurements according to the processing sequence shown in Figure 1.

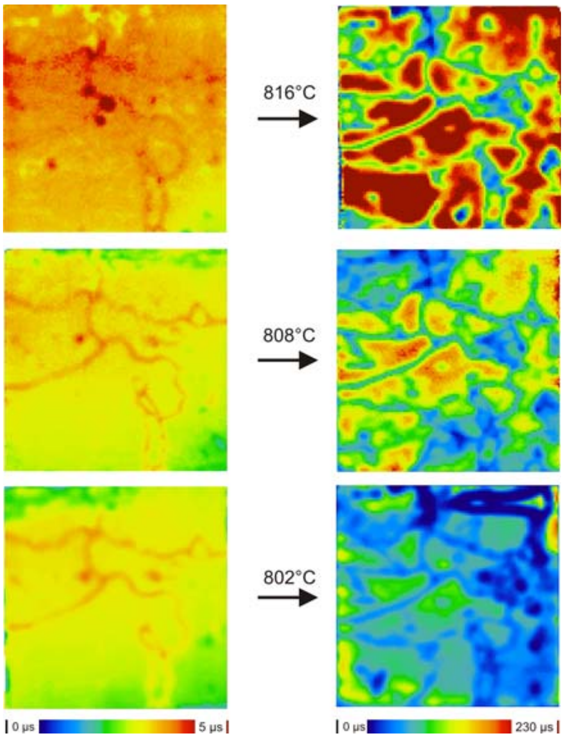

Figure 4: Minority charge carrier lifetime maps of neighbouring mc Si wafer before (left) and after (right) different $POCl_3$ emitter diffusions at different temperatures. Surface passivation was enabled using an IE solution.

Figure 4 shows the spatially resolved lifetime distribution for multicrystalline silicon wafers (resistivity 0.7 Ωcm). It is clearly visible, that a higher diffusion temperature results in a higher minority charge carrier lifetime due to the fact that the mobility of impurities is enhanced and the diffusion to the phosphosilicate glass is favored resulting in an effective gettering of the material.

Figure 4 allows an assessment of the gettering effect in the bulk of the wafers. It is evident that a temperature variation of only a few degrees has a significant influence on the mean lifetime values of the entire wafer as the right hand side graphs of Figure 4 clearly demonstrate. Subject of ongoing experiments is an expansion of the diffusion temperature range using a higher amount of samples providing a larger statistics in order to find the optimum diffusion temperature in terms of gettering effectiveness and thus lifetime maximization.

3.3 Emitter saturation current density

The emitter saturation current density is affected by the diffusion temperature as well. QSSPC [1] measurements revealed emitter saturation current densities well below 100 fA/cm² for FZ-Si passivated by PECVD SiN_x:H on both sides. Figure 5 illustrates the j_{0e} and the calculated implied V_{OC} values from the QSSPC measurements. It is evident that with decreasing diffusion temperature an enhancement in V_{OC} and an improvement in J_{0e} is achieved.

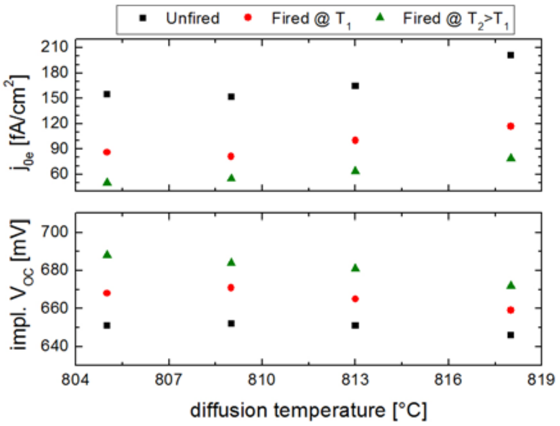

Figure 5: Resulting emitter saturation current densities and implied open circuit voltages of FZ-Si-wafer for $POCl_3$ emitter diffusions at different temperatures (same diffusion time).

The same correlation is found for other diffusions with different gas flows, diffusion- and drive-in times as well. However, for clarity reasons only selected results are presented in this paper as a plot of emitter saturation current density values versus the sheet resistance is less meaningful, if the diffusion profiles are different [2].

3.4 Diffusion profiles

For particular diffusions the depth depending doping profiles are presented in the following measured with the ECV technique.

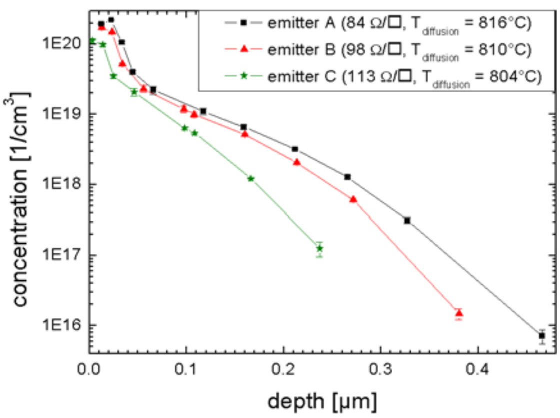

Figure 6: Depth dependant phosphorus diffusion profiles of FZ-Si samples measured by ECV for different diffusion temperatures.

It can be seen that for lower diffusion temperatures the surface concentration decreases which is important in order to avoid a highly doped layer at the wafer surface as the Auger recombination rate depends quadratically on the doping concentration.

3.5 Solar cells results

In Table I the IV data of a representative FZ solar cell is shown. For this solar cell the emitter diffusion temperature was 825°C resulting in a sheet resistance of 80 Ω/□ (lower diffusion time compared to Figure 6). Only a single layer antireflection coating was applied. In this photolithography based cell process [3] the Al-BSF was formed by a fully covering screen printing of Al paste followed by a firing step.

Table I: IV data of a representative FZ solar cell (2x2 cm^2) processed according to the UKN standard photolithography based cell process [3]. Diffusion temperature 825°C, R_{sheet}=80 Ω/□.

Material	FF [%]	J_{sc} [mA/cm²]	V_{oc} [mV]	η [%]
FZ	79.9	34.8	641	17.8

In comparison to the implied V_{OC} (Figure 5) the V_{OC} of the solar cell (Table 1) is decreased by 6% due to the missing metallization during the measurement of the implied V_{OC} and the different illumination intensities and spectra of the two measurements. By replacing the Al-BSF with an atomic layer deposited Al_2O_3 layer an achievement in V_{OC} of 660 mV was reached [4].

4 SUMMARY AND CONCLUSION

In this work the influence of variations in process parameters such as temperature and gas flow for a batch type open tube $POCl_3$ emitter diffusion furnace was investigated in terms of sheet resistivity, homogeneity of the sheet resistivity on the single wafers and the wafer position in the quartz boat. Further on, the gettering effectiveness for multicrystalline wafers as well as the emitter saturation current density for monocrystalline silicon wafers was determined in dependence of the diffusion parameters.

It could be demonstrated that the diffusion temperature has a significant influence on the sheet resistance and the gettering effect as spatially resolved lifetime measurements before and after diffusions at different temperatures clearly revealed. The gettering is herby more effective at higher diffusion temperatures as the mobility of the defect species is enhanced.

Emitter saturation current densities, measured on monocrystalline samples, showed an improvement for decreasing diffusion temperatures. The same trend was found for the implied open circuit voltage.

Depth dependent ECV emitter profiles showed a decrease in the surface dopant concentration with decreasing diffusion temperature resulting in reduced Auger recombination in the surface emitter layer.

More diffusion experiments will be performed in order to further optimize the temperature ramps, gas flow and diffusion time. It is expected that different mono- and multicrystalline silicon materials can benefit from adapted diffusion recipes in terms of significantly reduced emitter saturation currents and increased bulk lifetimes and thus in enhanced solar cell efficiencies.

5 ACKNOWLEDGEMENTS

The authors would like to thank T. Wolff for ECV measurements.

The underlying project of this work was supported with funding by the BMU project (0327650H) SolarFocus. The financial support from the BMU project FKZ 0325079 is also gratefully acknowledged in particular for the processing equipment. The content of this publication is the responsibility of the authors.

6 REFERENCES

[1] R. A. Sinton, A. Cuevas, Appl. Phys. Lett. 69, 2510-2512, 1996.

[2] B. Lenkeit, *Elektronische und strukturelle Eigenschaften von Plasma-Silizium-Nitrid zur Oberflächenpassivierung von siebgedruckten bifazialen Silizium-Solarzellen,* PhD, University of Hamburg, 2002.

[3] J. Junge, C. Strümpel, S. Seren, M. Käs, A. Metz, G. Hahn, *Laser Fired Contacts for High Efficiency Solar Cells based on EFG Material,* Proc. of the 23rd EU PVSEC, 2008.

[4] J. Junge, J. Ebser, S. Graf, B. Terheiden, S. Seren, G. Hahn, *Evaluating the efficiency limits of low cost mc Si materials using advanced solar cell processes,* in print, EU PVSEC Valencia, 2010.