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POTENTIAL AND LIMITATIONS OF EPITAXIAL EMITTERS

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ABSTRACT: Reducing the total costs of modules by increasing the efficiency of solar cells is one of the major challenges in today's photovoltaic research. The emitter epitaxy by atmospheric pressure chemical vapour deposition (APCVD) offers a cost-efficient and faster alternative to the standard furnace diffusion process. The epitaxial emitter formation at 1050 °C only takes 1-2 min whereas the diffusion process using $POCl_3$ takes up to 60 min. The purpose of this work is to show the potential of epitaxial grown emitters compared to diffused emitters. PC1D simulations show an increase in voltage of ΔV_{OC} = + 10 mV and a reduction in saturation current J_{0e} of 30% for the epitaxial emitter. These advantages are due to lower surface recombination velocity and reduction of Auger recombination of the optimised emitter profile. The lifetime experiments including an epitaxial emitter show a diffusion length L_{eff} of 750 µm and an emitter saturation current of J_{0e} = 46 fA/cm² on a planar 10 Ωcm p-type FZ wafer. Another important aim of this work is to determine the limitations of epitaxial emitters due to thermal degradation of the base material, interface recombination and the change of reflective properties on textured wafers due the deposition process. In a first batch, solar cell efficiencies up to 18.4 % underline that emitter epitaxy by APCVD is a competitive process for the emitter formation.

Keywords: Emitter Formation, Epitaxy, CVD Based Deposition

1 INTRODUCTION

The industrial standard emitter is produced by tube furnace diffusion using $POCl_3$ or BBr_3 as precursor. The diffusion process takes about 60 minutes, is limited in the doping profile and requires additional steps to produce a deep high efficiency emitter. Compared to the diffusion the epitaxial emitter formation by APCVD [1] (atmospheric pressure chemical vapour deposition) can lift some of those challenging limitations and has several advantages:

- The emitter deposition by APCVD requires only 1-2 min (deposition rate of 0.2-2.0 µm/min)
- The doping profile can be adjusted to improve the emitter properties
- The epitaxial emitter process does not require wet chemical etching after the deposition
- Shunt formation due to firing can be reduced by increasing the emitter depth
- The contact resistance can be optimised depending on metallisation process

Apart from a time and cost effective formation process, the epitaxial emitter also offers the possibility to adjust the emitter profile. This results in an optimised emitter thickness, emitter doping and surface doping concentration which matches the metallisation and passivation process of high efficiency concepts.
Furthermore it is possible to grow cost effective high efficiency emitters for industrial applications by APCVD using an in-line reactor with very high throughput [2]. Knowing the limitations and the theoretical potential of an epitaxial emitter is of great importance for further investigations and for showing the feasibility for industrial applications. Therefore PC1D simulations as well as crystallographic and electrical characterization have been done and will be presented. Additionally, solar cell results including spectral response measurements will be shown to evaluate the epitaxial emitters.

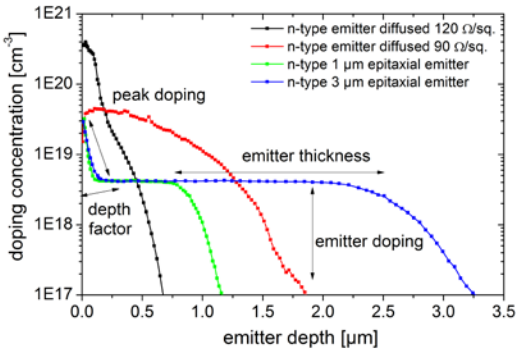

Figure 1: Epitaxial and diffused emitter profiles of various n-type emitters.

2 EXPERIMENTAL PROCEDURE

The emitter formation by APCVD [3, 4] offers an interesting alternative to the state of the art diffusion. The optimised two layer epitaxial emitters with a moderately doped bulk and a highly doped surface region offer a low contact resistance in combination with a high shunt resistance and a good blue response. The epitaxy process itself was modified towards a lower process temperature of 1025 °C for mono- and 1000°C for multicrystalline due to the degradation of the base material by the high thermal budget. After this optimisation emitter saturation currents of J_{0e} < 100 fA/cm² and effective lifetimes of τ_{eff} > 200 µs have been measured. Based on previous experiments and simulations using PC1D [5, 6] the emitter profiles and the contact layer have been adjusted for different thicknesses and doping concentrations depending on the metallisation and passivation process. The solar cell batch presented in this paper uses polished, (100) oriented, 0.5 Ωcm, p-type

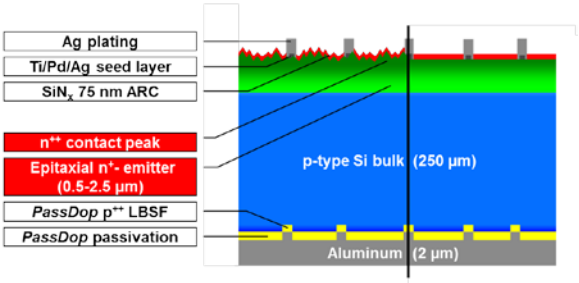

Figure 2: p-type solar cell concept for epitaxial n-type emitters including a front side texture and a passivated back side structure.

FZ wafers. The reference emitter was diffused at 790 °C with a 30 min $POCl_3$ inlet and a 30 min drive in step using a Centrotherm tube furnace. In Figure 2 an example for a solar cell concept including an epitaxial emitter is shown. The front side features either a KOH- or a plasma-texture [7, 8] and a 70 nm firing stable ARC SiN_x deposited by an inline Roth & Rau SiNA reactor. For the back side passivation in this concept a doped passivation layer stack like *PassDop* [9] was used. The front side metallisation was realised by seed layer (50 nm Ti, 50 nm Pd, 100 nm) thickened by silver plating. The backside metallisation is done by evaporation of 2 µm aluminium and subsequent *PassDop* laser process to form the rear side contacts.
Additional samples have been processed to investigate the limitations of solar cells including an epitaxial emitter by using effective lifetime, µRaman and spectral response measurements.

3 SIMULATION

PC1D simulations are a fast and suitable way to compare epitaxial and diffused emitter profiles and determine the potential of an epitaxial emitter. In this case two state of the art diffused 120 Ω/sq and 90 Ω/sq emitter profiles are compared with two optimised two-layer epitaxial emitters with 1 µm and 3 µm in thickness (see Figure 1).

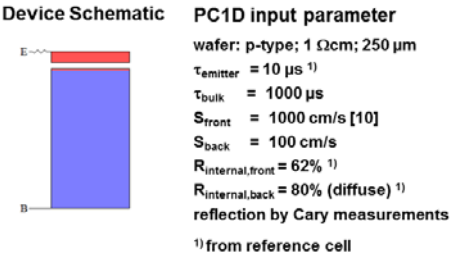

Figure 3: PC1D Simulation parameters of an ideal solar cell with a 1 µm thick epitaxial n-type emitter.

The simulation parameters shown in Figure 3 have been determined based on a reference cell process. The surface recombination velocity on the backside S_{back} has been set to 100 cm/s and the bulk lifetime τ_{bulk} to 1 ms. These parameters were chosen to focus on the influence of the emitter properties and the front side by minimising the effect of bulk recombination. The front surface recombination has been adjusted for every emitter depending on the surface doping concentration [10]. In Table 1 the resulting IV curve parameters for the four

Table 1: PC1D Simulation to evaluate the potential of epitaxial emitters.

Cell type (FZ; 1 Ωcm, p-type)	V_{oc} [mV]	J_{SC} [mA/cm²]	J_0 [fA/cm²]
1 µm epitaxial	688	38.8	110
3 µm epitaxial	683	38.0	132
120 Ohm/sq diffused	677	38.8	166
90 Ohm/sq diffused	676	38.8	176

different emitters are shown. The 1 µm epitaxial emitter shows an increase in voltage of ΔV_{OC} = + 10 mV and a similar short circuit current compared to the 120 Ω/sq. diffused emitter. In contrast to previous simulations [3] the 3 µm epitaxial emitter shows losses in V_{OC} of 5 mV and J_{SC} of 0.8 mA/cm².Equation 3-1, including the Boltzmann constant k_B and the temperature T, is used to determine the saturation current $J_0 = J_{0b} + J_{0e}$ for the simulated cells with different emitters.

$$V_{OC} = \frac{k_B T}{q} \ln\left(\frac{J_{SC}}{J_{0b} + J_{0e}} + 1\right) \qquad 3\text{-}1$$

For all simulated results the contribution of the base saturation current is the same. Hence, the reduction in J_0 of 30% for cells with an epitaxial emitter results from a lower surface recombination velocity and a reduction of auger recombination of the 1 µm epitaxial emitter profile.

4 RESULTS AND DISCUSSION

µRaman measurements [11] were carried out to investigate the interface quality between substrate and epitaxial layer and its influence on the electrical performance of the structure. Figure 4 shows the shift of the Raman scattered light (left row) which is correlated to the stress and the peak width (right row) at high laser injection which is correlated to the carrier lifetime and doping density.

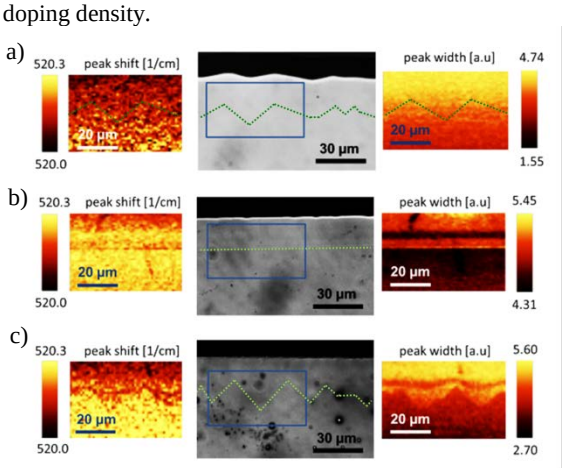

Figure 4: Peak shift (left row) and peak width analysis (right row) as well as SEM pictures (middle row) of µRaman measurements of a 20 µm epitaxial layer with high (b, c) and low doping concentration (a) on a substrate with and without texture. (lines are guide to the eye)

In this experiment a 20 µm epitaxial layer is deposited to reduce the influence of the surface and to investigate how the structural surface properties are changing. These measurements have been done on textured (Figure 4 a, c) as well as planar samples (Figure 4 b). The doping concentration is high in the case of Figure 4 b, c and low for the sample Figure 4 a. These variations are necessary to determine the impact of either variation on the material properties and the measurements. In all cases the surface structure has been smoothed out after the deposition. The dark area in the epitaxial layer in Figure 4 b and c is a drop in doping concentration at 5 µm to visualise the impact of the doping concentration. The stress measurement (peak shift) in Figure 4 (left row) shows no significant increased values at the interface between emitter and substrate. The contrast can be seen in the peak shift due to the higher doping concentration. The peak width shows a similar behaviour and suggests that the emitter-bulk-interface is not a limiting factor for the epitaxial emitter. Further µRaman and µPL measurements and a set of calibration measurements are ongoing to determine the doping density, defect luminescence and Shockley-Read-Hall-lifetime in the epitaxial layer. Details for the applied methods can be found in [12].

For lifetime investigations Quasi-Steady-State Photo Conductance (QSSPC) measurements were used to fit the emitter saturation current J_{0e} and evaluate implied V_{OC} values according to equation 3-1 and 4-1 by [13].

$$\frac{1}{\tau_{eff}} - \frac{1}{\tau_{auger}} = \frac{1}{\tau_{SRH}} + \frac{S}{W} + \frac{J_{0e}}{qn_i^2 W}\Delta n \qquad 4\text{-}1$$

The lifetime measurements with QSSPC on a set of samples with epitaxial emitters show that processes below 1050 °C are beneficial for the conservation of bulk lifetime and therefore for the cell performance. By decreasing the process temperature, the measured lifetimes of approximately 200 µs for 10 Ωcm, p-type, FZ wafers are almost 10 times higher than the ones resulting from the standard process at 1150 °C. The lowest determined value for the emitter saturation current on 10 Ωcm was J_{0e} < 50 fA/cm^2 on planar p-type silicon and J_{0e} < 30 fA/cm^2 on planar n-type silicon.

4.1 Solar cell results and IV-measurements

The reference cells show a V_{OC} of 655 mV, J_{SC} of 38.4 mA/cm² and a *FF* of 79.8 % (see Table 2) which is resulting in a total conversion efficiency of 20.1 % on textured wafers.

Table 2: IV measurements of textured solar cells with epitaxial emitters and diffused emitters.

1.0 Ωcm, p-type FZ	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
diffused emitter	654.8 ± 1.4	38.4 ± 0.2	79.8 ± 2.6	20.1 ± 0.6
epitaxial emitter	652.0 ± 1.3	35.0 ± 0.4	79.0 ± 2.3	18.0 ± 0.5
(best cell)	653.1	34.7	81.1	18.4

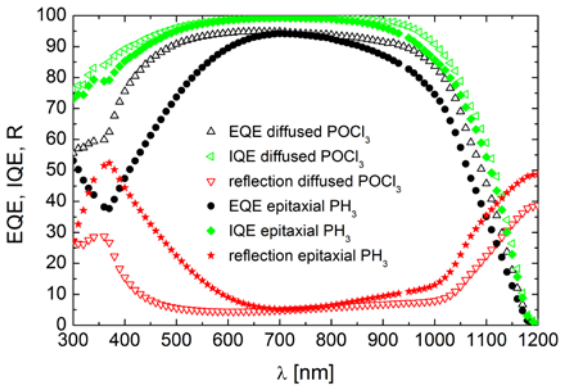

Figure 5: Spectral response measurements of diffused and epitaxial emitters on FZ 1 Ωcm p-type wafers.

Despite a similar V_{OC} and FF the solar cells with epitaxial emitter only show an average efficiency of 18.0 %. Nevertheless, the V_{OC} of 652 mV of epitaxial emitters in combination with fired SiN_x ARC as front side passivation layer is a promising result and shows that the overall material quality is good for a p-type solar cell concept. The best solar cell with an epitaxial n-type emitter shows an efficiency of 18.4 % which is an increase of 2%$_{abs}$ over the last three years and a new record.

In Figure 5 a comparison of the external quantum efficiency (EQE), the internal quantum efficiency (IQE) and reflectance measurements for epitaxial and diffused emitters on p-type FZ material with texturisation is shown. These measurements show a difference in emitter passivation quality, the overall emitter quality and a difference in reflection. The major difference in external quantum efficiency (EQE) and the losses in J_{SC} for the epitaxial emitter can be explained by the reflective properties which can be optimised.

5 CONCLUSION

This paper discusses the advantages and limitations of epitaxial emitters formed by APCVD. Lifetime measurements show a diffusion length above 750 µm and very good emitter saturation currents below 50 fA/cm^2 on planar silicon surfaces. µRaman measurements show no significant stress or material degradation at the growth interface. The solar cell batches show an efficiency of 18.4 % on 1 Ωcm, p-type FZ. The spectral response measurements and the good IQE values underline the quality and the potential of the epitaxial emitter. The p-type emitters using B_2H_6 as dopant gas deposited by APCVD offer the same advantages, while the typically used diffusion process with BBr_3 is even more difficult.

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