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Formation of High Efficiency Epitaxial Emitters by APCVD

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Abstract

Improvements in emitter passivation as well as back contact passivation lead to several high efficiency solar cell concepts. PERC (Passivated Emitter Rear Contact) solar cells on monocrystalline wafers above 21 % [1] have been achieved, but the diffusion processes with POCl_3 and BBr_3 have emerged as one of the limiting factors. The formation of high efficiency emitters by APCVD (Atmospheric Pressure Chemical Vapour Deposition) has several advantages compared to the standard diffusion. Epitaxial emitters can be optimised to match the passivation and metallisation of high efficiency concepts as well as industrial approaches like nickel plating. Simulations by PC1D show the potential of epitaxial emitters by featuring low contact resistance in combination with high shunt resistance, a good blue response and low emitter saturation current (J_{0e}) [2,3]. The emitter profiles can be designed in depth and in doping in the range from $1 \times 10^{17} \text{ cm}^{-3}$ up to $1 \times 10^{20} \text{ cm}^{-3}$ for p-type and n-type emitters. Simple reference solar cells with $J_{0e} = 46 \text{ fA/cm}^2$ and efficiencies of $\eta = 17.5 \%$ on float zone (FZ) and $\eta = 16.1 \%$ on multicrystalline (mc) wafers have been processed. Furthermore an epitaxial selective emitter has been developed. The deposition process itself has been enhanced to improve the emitter profiles as well as material quality.

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1. Introduction

The standard emitter is produced by diffusion of phosphorus with POCl_3 or boron using BBr_3 as precursor. The diffusion process takes about 45 and 60 minutes respectively and requires additional steps to produce a deep high efficiency emitter. Epitaxial emitters by APCVD can lift some of those challenging limitations and offer additional advantages:

- The emitter deposition by APCVD takes only a few minutes (deposition rates of 0,25-2.0 $\mu\text{m}/\text{min}$)
- The doping profile can be adjusted and offers new possibilities for the improvement of emitter properties to match high efficiency concepts
- The epitaxial emitter process needs no wet chemical etching after the deposition
- Shunt formation due to firing can be solved by increasing the emitter depth
- The contact resistance can be optimised depending on metallisation scheme and passivation

Furthermore it will be possible to grow cost effective high efficiency emitters as well as epitaxial BSF (Back Surface Field) for industrial applications by APCVD using TCS (Trichlorosilane) in an in-line reactor with very high throughput [4].

2. Formation of epitaxial emitter

The concept of the epitaxial emitter has already been proven on wafer cells by Schmich et al. [5] and as cSiTF (Crystalline Silicon Thin Film) solar cells with voltages of 621 mV and efficiencies of 16.9 % by Van Nieuwenhuysen et al. [6]. The potential of epitaxial emitters has been shown by S. Reber [2] using PC1D simulations. The main task reported in this paper is to transfer improved epitaxial emitters onto wafer substrates, to optimise these emitters for monocrystalline and multicrystalline materials and to design emitter profiles which work perfectly in our existing high efficiency, high throughput concepts.

2.1. Solar cell results

Based on experiments and detailed simulations using PC1D [3] the emitter profiles (see Fig.1a) and the front surface field (FSF) have been adjusted for different thicknesses and doping concentrations. The following solar cell batch has been done to evaluate the improvement of epitaxial emitters and to have a valid base for the simulation of high efficiency concepts and for further optimisation.

Table 1. Comparison of IV-Characteristics between epitaxial n-type and POCl₃ emitters on mono and mc material

Cell type (20x20mm ²)	V _{oc} [mV]	J _{sc} [mA/cm ²]	FF [%]	η [%]
Epitaxial emitter (FZ; 1 Ωcm) ^{*)}	621	35.9	78.3	17.5
Reference with POCl ₃ (FZ; 0,5 Ωcm) ^{*)}	638	35.9	79.8	18.3
Epitaxial emitter (mc; 1 Ωcm) ^{*)}	608	33.1	80.2	16.1
Reference with POCl ₃ (mc; 1 Ωcm) ^{*)}	611	35.3	79.6	17.1

*) Best cell of the batch, internally measured

This simple reference solar cell concept as seen in Fig.1b does not include texturing, back side passivation, local epitaxial BSF or a selective emitter. However this batch shows that epitaxial emitters are able to compete with the standard diffusion. Solar cell results in Table 1. show a similar short circuit current (J_{SC}) and fill factors (FF) for the epitaxial emitter on monocrystalline wafers.

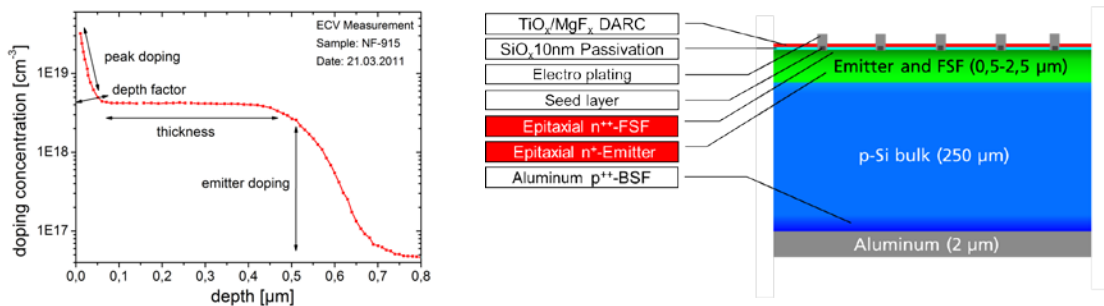


Fig. 1. (a) Profile of an epitaxial emitter processed at standard conditions and measured by ECV. (b) Solar cell concept for the work described in this chapter without texture and rear side passivation and full area aluminium BSF.

Furthermore the dark characteristic curves show that epitaxial emitters have lower saturation currents due to the space charge region (J_{02}) than POCl_3 diffused emitters. On FZ material diffused emitters show a J_{02} of 3.0×10^{-5} mA/cm² and epitaxial emitters only 3.3×10^{-6} mA/cm² (both values are averaged over 10 cells 20x20 mm²). This proves that the stress at the growth interface shown by μRaman measurements [3] has no significant influence on J_{02} because due to high doping concentrations and diffusion the space-charge region is smeared and moved into the bulk material. However further characterisation had to be done because the open circuit voltage of epitaxial emitters in this batch is about 18 mV lower (mainly due to different bulk doping) on FZ material compare to the POCl_3 diffusion.

2.2. Material and solar cell characterisation

As a start, we investigated how the effective lifetime of wafers depends on temperature and process duration. In Fig. 2a the importance of reducing the deposition temperature even for FZ material is shown. The lifetime of 1 Ωcm n-Type FZ material improved from 39 μs to 253 μs by decreasing the deposition temperature about 100 K. A possible reason for this temperature dependence could be thermal stress in the crystal after high temperature treatments. Additional QSSPC measurements show that this effect is even more pronounced for p-type material and multicrystalline substrates.

Table 2. SunsVoc measurements of epitaxial emitters to determine V_{oc} , pseudo FF, and pseudo η

Cell type (20x20mm ² , FZ; 1 Ωcm , p-type)	V_{oc} [mV]	pFF [%]	$p\eta$ [%] ^{2*)}
Epitaxial emitter at 950°C ^{1*)}	612,2	81,9	18,06
Epitaxial emitter at 1000°C ^{1*)}	625,8	81,9	18,46
Epitaxial emitter at 1050°C ^{1*)}	617,2	81,5	18,11

^{1*)} Average of two cells ^{2*)} pseudo η for a short circuit current of 36 mA/cm²

The SunsVoc measurements in Table 2 underline the influence of the deposition temperature and the effective lifetime on V_{oc} values for cells with epitaxial emitters. However due to lower layer quality of the emitter does the V_{oc} decrease again for temperatures below 1000 °C. Additional QSSPC, LBIC and MWPCD measurements support these findings. Further process optimisations to find specific deposition temperatures and process conditions for different bulk materials have been done.

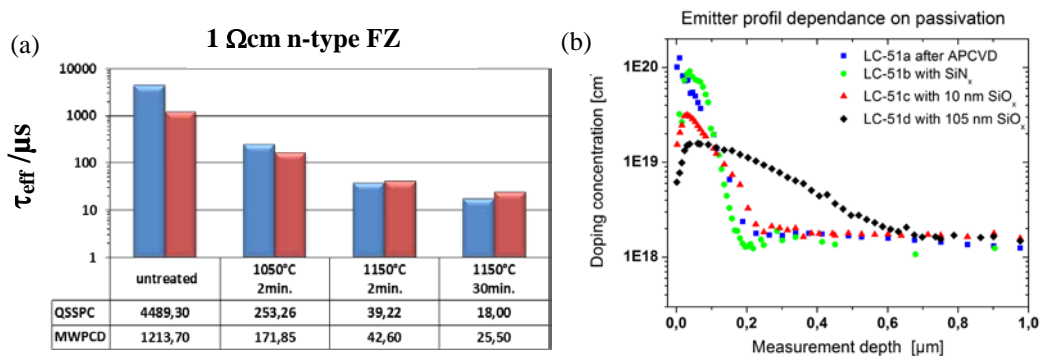


Fig. 2. (a) Effective bulk lifetime determined by QSSPC (Quasi Steady State Photo Conductance) and MWPCD (Microwave Photo Conductance Decay) measurements.; (b) Emitter FSF measured by ECV (Electrochemical Capacitance Voltage) is heavily depending on following high temperature processing steps.

2.3. Process development and optimisation

The APCVD process with TCS currently uses high temperatures of about 1150 °C and deposition rates of up to 2 μm/min. The reduction of the deposition rate for better control of the emitter profile without reducing the homogeneity can be achieved by adding HCl to the precursor gas mixture (see Table 3.) Furthermore this improvement makes it possible to deposit epitaxial emitters of the same quality at lower temperatures [7]. Depositions with 45% HCl at 1050 °C show a similar average defect density of $9.7 \times 10^3 \text{ cm}^{-2}$ compared to depositions at 1150 °C without HCl. However the change in doping incorporation by reducing the temperature and the deposition rate has to be considered (see Fig.3. left). While the boron incorporation displays a dominant correlation to the deposition temperature does the phosphorous incorporation show an inverse dependence on temperature and deposition rate.

Table 3. Deposition rates for the high conversion efficiency deposition depending on HCl concentration in the gas flow and temperature. Values determined by SRP, ECV, REM and weight. Some values have been determined on a single sample

% of max. HCl Flow	Deposition rate [$\mu\text{m}/\text{min}$] at different deposition temperatures				
	950°C	975°C	1000°C	1050°C	1150°C
0%	NE	1,1	1,5	2,4	2,0
15%	ND	0,5	1,1	ND	1,8
30%	0,3	0,4	0,8	1,0	1,5
45%	ND	0,1	0,5	0,8	1
70%	etching	etching	~ 0	0,6	0,5
90%	etching	etching	etching	etching	0,1

(ND = not determined; NE= no epitaxial growth)

When complex emitter profiles are deposited the subsequent process steps have to be taken into account as well. As an example Fig. 2b shows how the FSF (Front Surface Field) of a two layer emitter (deposited at 1150 °C) is changing by the following high temperature passivation. The decreasing deposition rates and diffusion coefficients by reducing the temperature make it possible to deposit sharp emitter profiles with defined shallow FSF in the range of 40-80 nm.

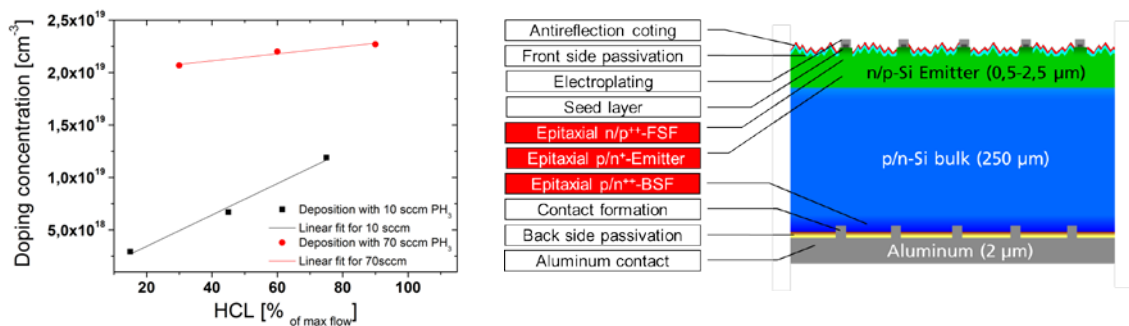


Fig. 3. (left) Increase of the doping incorporation by increasing the HCl flow.; (right) concept for high efficiency p-type solar cells with epitaxial selective emitter by plasma texturing, rear side passivation and local epitaxial BSF.

3. High efficiency solar cell concepts

Based on the presented solar cell result and the improvement in material quality (diffusion length L_{eff} of 840 μm) by reducing the thermal degradation it was reasonable to adapt a high-eta concept including epitaxial emitters. Epitaxial emitters offer unique advantages for the implementation of a selective emitter and texturing. The optimisation of a back side passivation as well as the back contact formation can be improved by using epitaxial BSF. In Fig. 3. (right) the high efficiency front side process using plasma texturing in combination with a simultaneous formation of a selective emitter is shown.

3.1. Optimisation of the epitaxial FSF

For high efficiency concepts it is necessary to improve and adjust the epitaxial FSF depending on passivation and metallisation. A FSF thinner than 10 nm results in lower V_{OC} because of insufficient field effect passivation by the FSF. Above 80 nm the solar cells deteriorate because of auger recombination [8]. However the optimal FSF layer thickness of about 20 nm can only be realised in combination with SiN_x by PECVD. The influence of a thermal oxide processed at about 850 $^{\circ}\text{C}$ can be seen in Fig. 2b.

3.2. Standard selective emitter and local BSF formation

The formation of a selective emitter with a potential of 0.5-0.6 %abs [9] can be achieved using various technologies. An overview including advantages and disadvantages is given by Hahn [9]. A standard selective etch back process using 40% KOH at 85 $^{\circ}\text{C}$ has been optimised for epitaxial emitters (see Fig. 4a). The process features etch rates of 900-1300 nm/min and results in emitters with selective FSF (see Fig. 4c). Further improvements can be achieved by developing a local BSF by diffusion, by epitaxial growth or by using doped passivation layer stacks like *PassDop* [10].

3.3. Plasma texturing and selective emitter formation

The plasma texture has certain advantages over the wet chemical texture by KOH [11] and offers interesting possibilities in combination with epitaxial emitter. The plasma texturing can be done after the deposition of an epitaxial emitter including a FSF (see Fig. 4b). An etch rate of 0.2 $\mu\text{m}/\text{min}$ and weighted reflection of about $\sim 12\%$ have been determined. In this case simply by masking the FSF of the epitaxial emitter the plasma texturing includes the formation of a selective emitter (see Fig. 5.).

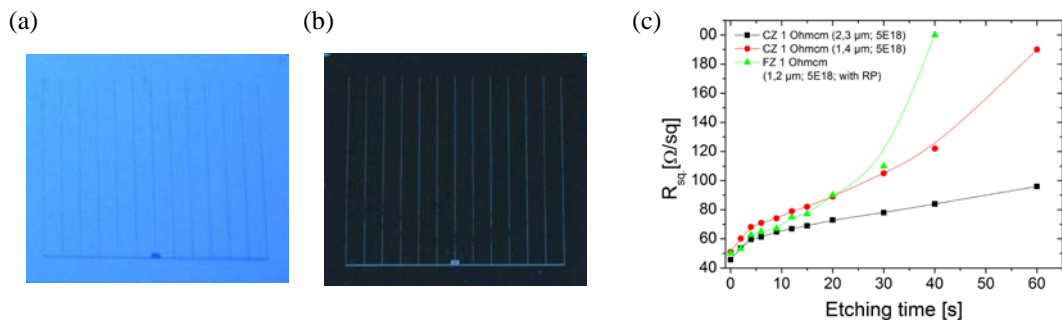


Fig. 4. Solar cells 20x20 mm^2 on FZ 1 Ωcm (a) with SiN_x masking after etching a selective emitter by KOH; (b) after plasma texturing; (c) Four-point probe resistivity measurements on different substrates with varying emitter thicknesses show the behaviour of the epitaxial selective emitter formation by KOH.

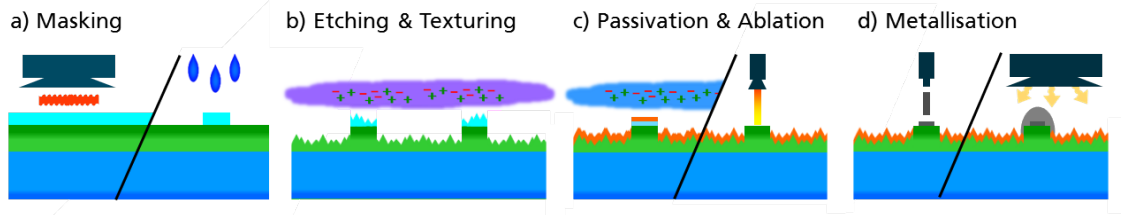


Fig. 5. Process for a) masking of the front side and chemical opening of the etch mask b) plasma texturing and selective removal of the highly doped FSF c) front side passivation and contact opening using laser ablation d) contact formation in this case by seed layer and electroplating

4. Conclusion

This paper shows that epitaxial emitters with efficiencies of $\eta = 17.5\%$ are able to compete with standard diffusion and have the potential for high efficiency and industrial application. The deposition process has been improved ($L_{\text{eff}} = 750 \mu\text{m}$) by reducing the temperature and introducing the use of HCl. Furthermore technologies for the formation of selective emitters, texturing and the deposition of an epitaxial BSF have been successfully established for epitaxial emitters. Further optimisation, simulations and solar cell batches are ongoing.

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