

CHARACTERISATION OF LPE THIN FILM SILICON ON LOW COST SILICON SUBSTRATES

J. Hötzel, K. Peter, R. Kopecek, P. Fath, E. Bucher, C Zahedi*

University of Konstanz, Department of Physics, P.O. Box X916, D-78457 Konstanz, Germany
*Elkem ASA, Silicon Division, N-0303 Oslo

ABSTRACT

Thin Si layers of 8-30 μm were grown by LPE on upgraded metallurgical (UMG) multicrystalline Si substrates. A melt back step just before the growth process circumvented the additional supply of Si to the melt. Solar cells, realized by using a simple screenprinting process, reached efficiencies up to $\eta = 6\%$ ($\text{FF} = 74.1\%$, $J_{\text{SC}} = 14.7 \text{ mA/cm}^2$, $V_{\text{OC}} = 551 \text{ mV}$) without antireflection coating. The influence of impurity diffusion from the substrate into the active layer and the impurity incorporation from the In solution during the growth process have been studied (e.g. by SIMS). Using Secco etching, LBIC and spectral response measurements it could be shown that the local I_{sc} is not limited by impurities and further increases in I_{sc} could be achieved by growing thicker epilayers. The results of the investigations underline the good crystal quality of the epilayers on UMG Si substrates and enables the further increase of the efficiency.

INTRODUCTION

At the present time nearly 45% of the costs for the energy out of silicon solar cells is related to the solar cell manufacturing process and the preparation of the silicon wafers [1]. Due to this fact, there is a great potential for cost reduction in decreasing dramatically the consumption of high quality silicon. This goal could be achieved by successful establishment and commercialisation of a thin film technology. Up to now, thin films based on polycrystalline silicon appear to be a long term solution [2]. With the possibility to use cheap silicon substrates, to precipitate thin silicon layers of high quality on them and to enable the implementation of this technique in an industrial process, the Liquid Phase Epitaxy (LPE) combines several favourable advantages. Therefore LPE is a very promising method to reach the goal of cheaper silicon solar cells.

With the use of upgraded metallurgical grade Si substrates, containing impurities like Fe, Ca, Cr, Ni, the quality and finally the efficiency of the cells strongly depended on the growth rate, temperature and time. During the growth process the impurities can diffuse into the active layer. Because increasing growth time correlates with decreasing lifetime and increasing collection probability due to increasing layer thickness there has to be an optimal layer thickness.

Our investigations were therefore focused on the thickness of the active layer and its effect on the cell parameters especially on the local short circuit current I_{sc} . I_{sc} was locally measured by LBIC measurements. Combining this results with the corresponding spectral response (SR) data and delineation of the epilayer the influence of the layer thickness to the cell parameters could be demonstrated.

LPE GROWTH

Thin p-type LPE layers, grown from an In solution in a hydrogen ambience were deposited on upgraded metallurgical multicrystalline Si substrates. The growth temperatures ranged between 950-990°C. To achieve a doping level of $5 \times 10^{16} \text{ cm}^{-3}$, Ga was added to the In solution. Initially the Indium was saturated with silicon but the further supply of Si within the melt was maintained by a meltback step just before each growth process. This meltback shows two other favourable features: 1) The removal of surface oxides and 2) the smoothening of the wafer surface 3) no need of electronic grade Si.

The variation of the growth time, the temperature and the temperature ramp, resulted in different surface morphologies and epilayer thickness.

Generally two different growth methods were used: 1) The "steady state" and 2) the "ramping temperature" method [3]. The key parameter for the applied growth method is the growth rate desired.

Applying a steady state method the growth rate is lower than 0.5 $\mu\text{m}/\text{min}$ and the surface of the epilayer is flat and smooth showing no difference in the crystal orientation.

Higher growth rates of 2-4 μm can be achieved by ramping down the temperature. In this case the surface morphology varies from flat layers, on grains with (111) crystal orientation, to pyramidal growth on (100) oriented grains [4]. This phenomenon exists because of the difference in the corresponding growth velocity for the crystal orientations [3]. The quality of the crystal structure and the electronic quality of the Si film strongly depend on the growth rate. The higher the growth rate the higher is the incorporation of In in the epilayer and the lower is the mobility of the electrons [5].

The segregation coefficients of other impurities like Fe, Ca or Cr, released from the meltback of the substrate, are very small so they rather remain in the melt. The small amount of impurities detected in the layer is below the critical concentration of lifetime degradation.

CELL PREPARATION

The solar cells were processed with low cost methods [9]. Emitter diffusion was realised by screenprinting of a phosphorous containing paste on the wafers which were fired in a belt furnace under air. Contact formation was done by both, screenprinting and evaporation of Ti/Pd/Ag as front and Al as back contact. Metal masks were used for the front contact. Finally a hydrogen passivation step by MIRHP (Microwave Induced Remote Hydrogen Plasma) [6] was carried out. The parameters of the best cell without antireflection coating (ARC) are listed in the following table:

Cell	FF [%]	I_{SC} [mA/cm ²]	V_{OC} [mV]	ETA [%]
10d	74.1	14.7	551	6.0

Table 1: Solar cell parameters of the best cell

LBIC/SR MEASUREMENTS

Local information about the short circuit current I_{SC} was obtained from LBIC measurements. The surface of the solar cells was scanned with laser light of 833 nm. wavelength or 905 nm respectively and I_{SC} was measured with a resolution of 1-100 μ m.

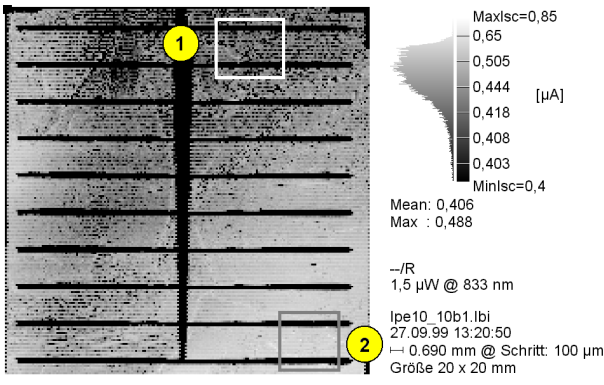


Fig. 1: LBIC signal of a LPE solar cell with strong variations. The change of the signal is very smooth. The squares 1 and 2 define the analysed regions.

Fig.1 shows the LBIC map of a LPE solar cell. There are strong variations in I_{SC} across the whole cell but the transitions are very smooth. With measurements on reference cells it could be excluded that the variations are due to inhomogeneous emitter formation. The differences in the signal depends on the difference in the epilayer thickness.

The thicker the epilayer, the higher the current I_{SC} . This is in good agreement with the theory of charge carrier generation. This assertion was also confirmed by the results of spectral response (SR) measurements where corresponding regions with high and low LBIC signals were measured.

The two curves in Fig. 2 represent the local spectral response of the high and the low current (LBIC signal) region on one cell. Curve 1 (circles) and the curve 2

(triangles) show the IQE in the high and the low LBIC signal area respectively. The better response of curve 2 in the long wavelength region is due to a thicker epilayer.

Diffusion lengths were obtained from spectral response data by Basore fits and by PC1D simulations. The values of cells with $J_{SC} < 15$ mA/cm² range from $L_{eff} = 16$ μ m to $L_{eff} = 33$ μ m. $L_{eff} > 30$ μ m for the cells with $J_{SC} > 15$ mA/cm²

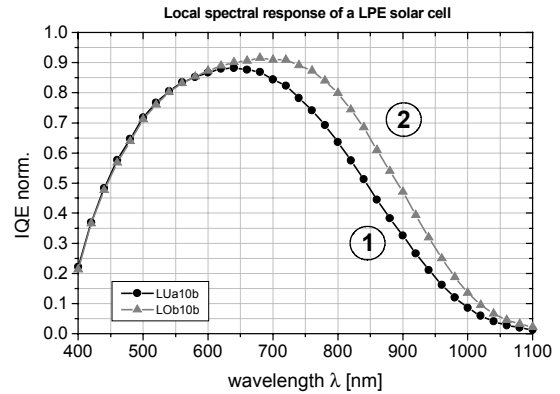


Fig. 2: Spectral response of the two extreme regions on a LPE solar cell. The low and high LBIC signal area is represented by curve 1 (circles) and curve 2 (triangles) respectively.

DELINATION AND STAINING

Secco [7] etching and delimitation were carried out to determine the epilayer thickness in the LBIC/SR measured regions to confirm the correlation.

Since the substrate was p^{++} and the epilayer was p-type doped a few possibilities to separate the layers optically and to delineate the transition by etching were offered. Runayan [8] describes different recipes to realise the etching. Two solutions were used. The etch time and sequence were varied and adapted to the materials to get optimal results.

The sample preparation was done by the following steps: 1. metal/ contact etching in aqua regia, 2. cutting the wafer into strips, 3. etching/delimitation, 4. microscope analysis.

1-3-6	Secco
1ml HF	$K_2Cr_2O_7$
3ml HNO_3	HF
6 ml acetic acid	H_2O

Table 2: Ingredients and composition of the etch solutions [7],[8]

The combined use of a LEICA microscope, a digital camera as well as the software package allowed the

analysis and determination of the layer thickness on the substrate optically.

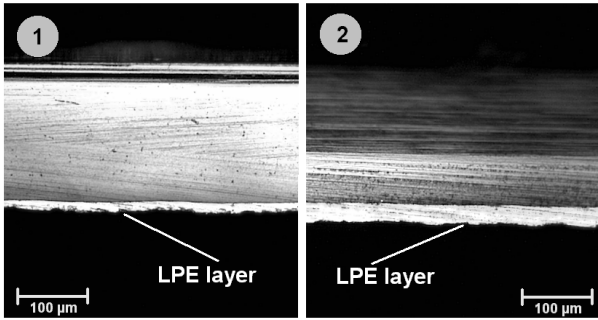


Fig. 3: Cross sections of two extreme regions (1 and 2) on one wafer. The average thickness d of the epilayer on the right is $d = 14.3 \mu\text{m}$ and on the left it is $d = 28.1 \mu\text{m}$.

In the cross section of the etched samples in Fig.3 two different coloured regions are visible. The darker stained region represents the substrate and the brighter one the LPE layer. Therefore the differences in layer thickness can clearly be shown with this method. The thicker layer is related to the region with the higher LBIC signal and the better spectral response in the long wavelength region.

RESULTS

The LBIC linescan parallel to the busbar of a solar cell and the values of the average layer thickness d along this line are in direct correlation. Fig.4 shows the linescan and the corresponding epilayer thickness. The periodical drop down of the LBIC signal is due to the fingers of the front contact. The analysis proves the correlation between thickness d and local I_{SC} on one single solar cell.

The comparison of different solar cells shows the same behaviour: A linear relationship between layer thickness and the resulting LBIC current. By taking into account the measurement error, the different cells can be represented by the linear fitting curve in Fig.5.

Fig. 4: LBIC linescan parallel to the busbar of a LPE solar cell. The periodically collapsed signal is caused by the fingers of the metallisation. The squares show the corresponding epilayer thickness.

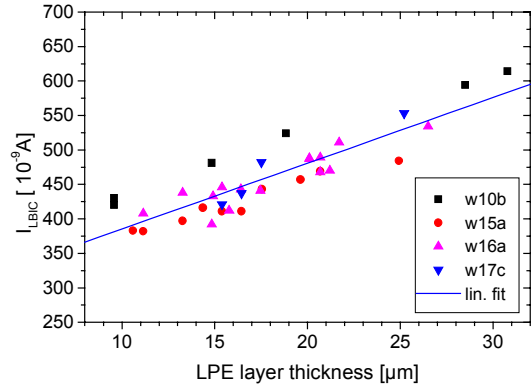


Fig. 5: LBIC signals and the linear fit curve of different LPE solar cells.

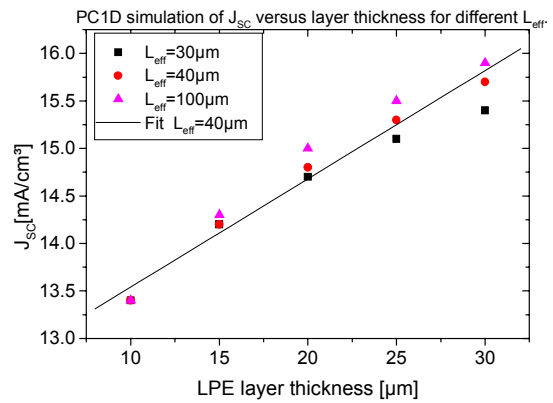
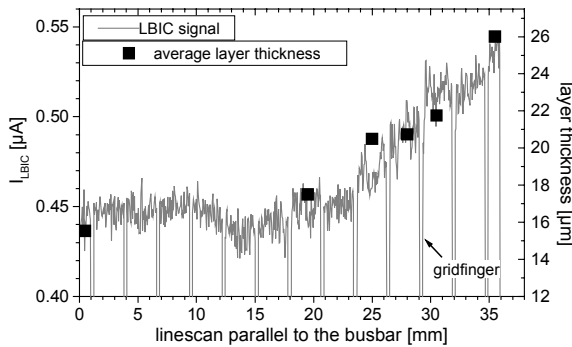


Fig. 6: Simulation (PC1D) of J_{SC} versus Layer thickness for different values of L_{eff} . The straight line is the fit curve for $L_{eff} = 40 \mu\text{m}$.



The linear behaviour of I_{SC} in this range of the layer thickness is in good agreement with PC1D simulations in Fig. 6.

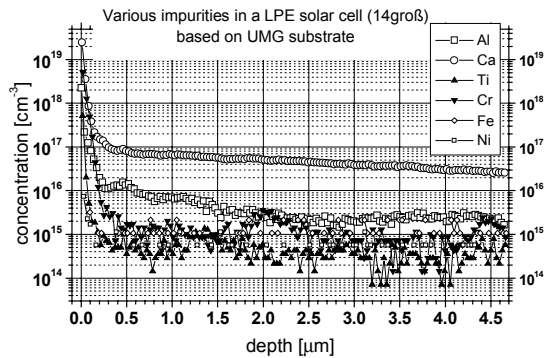


Fig. 7: SIMS profile measurement of the impurities Fe, Ca, Al, Ti, Cr, and Ni in a LPE solar cell.

SIMS measurements in the surface of the epilayer to the depth of 4.5 μm in Fig. 7 show, that the impurities Fe, Al, Ti, Cr, and Ni are below the level of significant degradation

Fig.5 demonstrates additionally that the intervals of the layer thickness on one wafer vary very strong. They range from 10 μm to 20 μm . But no correlation between the width of the interval and solar cell parameters could be found.

DISCUSSION

Solar cells with a layer thickness in the range of $d = 8\text{--}30\ \mu\text{m}$ were characterised with optical and electronic methods. A linear relationship between the local I_{SC} and the layer thickness have been found. All measurements showed the same behaviour: thicker layers are correlated with higher currents in the LBIC signal.

The diffusion lengths determined by Basore fits and PC1D simulations exceed the layer thickness for cells with $J_{\text{SC}} > 15\ \text{mA}/\text{cm}^2$. However for cells with $J_{\text{SC}} < 15\ \text{mA}/\text{cm}^2$ L_{eff} is in the range of the layer thickness d and the local I_{SC} is not limited by d .

This shows that the diffusion of impurities from the substrate and their incorporation from the melt in the active layer during the growth process is below the level of a significant degradation of crystal quality of the LPE layer. This fact is supported by SIMS depth profile measurements ($d \leq 4.5\ \mu\text{m}$) in the epilayer (Fig.7). All kinds of impurities with the exception of Ca are below the critical level of degradation. The influence of Ca has to be proven in further investigations.

With epilayers of 30 μm thickness we are not yet at the point where the current is limited by the diffusion length. This presents several opportunities to continue the investigations. One way of improvement is to increase the layer thickness. However unlimited increase of the epilayer thickness does not make sense because LPE is in fact a thin film technique. Another way is to use light trapping schemes to enhance the effective layer

thickness. This could be reached by structured LPE layer growth which is already part of actual investigations.

The strong variations in the LPE layer thickness are related to the use of a quartz boat. Small temperature variations caused by the heating elements and the apparatus were transferred to the temperature distribution of the melt because of the small thermal capacity of quartz. Using a graphite crucible a homogeneous temperature distribution could be achieved and therefore the variations could be minimised.

The linear dependency between the LBIC current and the LPE layer thickness offers a simple method to control the homogeneity of the LPE layers by LBIC measurements.

These results show that UMG Si is suitable as a substrate for LPE and demonstrate that the concept: High quality LPE Si layer on a cheap Si substrate might be suitable for solar cell production.

ACKNOWLEDGEMENTS

This work was supported by the Ministerium für Wissenschaft, Forschung und Kunst, Baden-Württemberg within the COSOLAR project.

REFERENCES

- [1] A. Goetzberger, B. Voß, J. Knobloch: *Sonnenenergie: Photovoltaik*, Teubner, Stuttgart (1997)
- [2] M. A. Green, *Silicon Solar Cells, Advanced Principles and Practice*, Bridge Printery, Rosebery (1995)
- [3] K. Peter, *Schnell wachsende kristalline Silizium-Dünnschichten*, Ufo Verlag, Allensbach (1997)
- [4] J. Hötzel, K. Peter, G. Willeke, E. Bucher: *14th EC PVSEC*, Barcelona, 1997, 1421
- [5] R. Kopecek, K. Peter, J. Hötzel, E. Bucher: *Journal of Crystal Growth*, **208** (2000) 289
- [6] M. Spiegel, P. Fath, K. Peter, B. Buck, G. Willeke, E. Bucher: *13th EC PVSEC*, Nizza, 1995, 421
- [7] F. Secco d'Aragona: *J. Electrochem. Soc.*, July (1972) 948
- [8] W.R. Runyan: *Semiconductor Measurement and Instrumentation*, Mc Graw-Hill, Koga Kushu
- [9] J. Hötzel, R. Kopecek, S. Volz, K. Peter, P. Fath, E. Bucher, C. Zahedi*, F. Ferraza*: *16th EC PVSEC*, Glasgow, 2000