

## QUANTUM EFFICIENCY SIMULATION AND ANALYSIS OF CRYSTALLINE SILICON SOLAR CELLS BY TWO DIMENSIONAL DEVICE MODELING

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**ABSTRACT:** Complete two-dimensional simulations of internal quantum efficiency (IQE) have been carried out for planar and macroscopically V-grooved Si solar cells. The results have been compared with experimental data as well as one-dimensional calculations which were performed with PC1D and IQE1D. The impact of macroscopic textures on IQE has been investigated by simulation studies on bulk diffusion length and back surface recombination velocity for a V-structured and a corresponding planar cell. It is shown that the larger collection surface of V-grooved cells causes a strongly enhanced carrier collection efficiency. The IQE in the near infrared wavelength range is increased with a resulting gain in short circuit current of up to  $1.5\text{mA}/\text{cm}^2$  for medium carrier diffusion lengths.

**Keywords:** Simulation - 1: Characterization - 2: Texturization - 3

### 1 INTRODUCTION

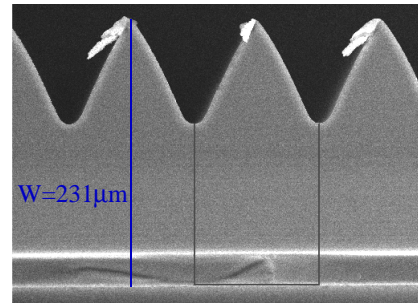
Mechanical texturization has demonstrated to be a valuable technique for improving the short circuit current of solar cells [1]. For a complete cell characterization and optimization a profound understanding of the multi-dimensional effects in macroscopic surface structures is an absolute prerequisite. The device simulation package DESSIS [2] provides a powerful tool for investigating the internal operation of mechanically textured solar cells. The present work concentrates on the impact of V-grooves on the internal quantum efficiency (IQE).

Sections 2 and 3 describe and verify the method used. Section 4 presents a comparison of calculated IQE data for a V-grooved and a corresponding planar cell.

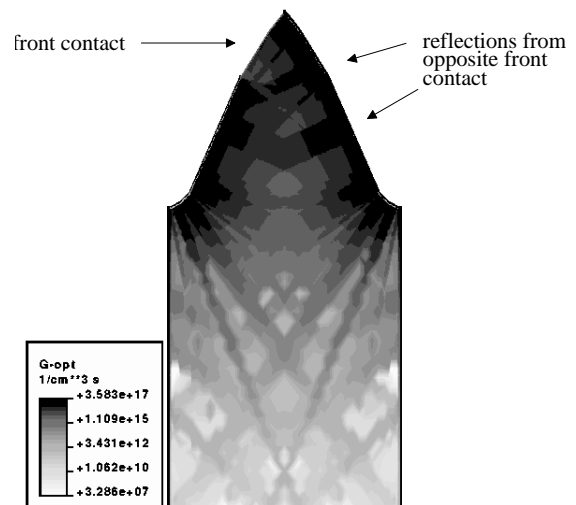
### 2 METHOD

Calculations of cell reflectance  $R(\lambda)$  and spectrally resolved optical generation profiles  $G(\mathbf{r},\lambda)$  have been performed with the program SONNE developed at the University of Konstanz [3]. The fraction of incident photons absorbed in the Si bulk as well as the cell reflectance are calculated by a combination of ray tracing and a Monte Carlo algorithm. Carrier generation is based on an analytical model using classes of possible photon paths through a periodic unit cell of the photovoltaic device. A generation profile for every desired light wavelength  $\lambda$  is created and implemented in DESSIS which is used to calculate the spectral response.

Figs. 1 and 2 exemplify the definition of the unit cell and the obtained generation profiles for a mechanically V-grooved solar cell of thickness  $W = 231\ \mu\text{m}$ . The shape of a V-groove has to be approximated by polyhedrons leading to a somewhat simplified generation distribution. A further simplification is the omission of diffusive reflections by SONNE. In the case of macroscopic textures



**Figure 1:** Cross-section SEM view of a mechanically V-grooved solar cell with thickness  $W = 231\ \mu\text{m}$ . The unit cell used for simulations is outlined. At the cell edges the grid fingers have become partially deformed by dicing the wafer into cells.



**Figure 2:** Calculated generation profile for vertically incident light of wavelength  $\lambda = 800\text{nm}$  and an intensity of  $100\text{mW}/\text{cm}^2$ . The unit cell was taken from Fig. 1.

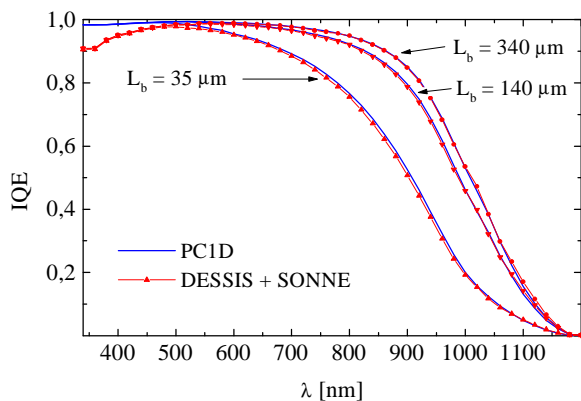
these are of minor importance [4] and should cause only little error. Taking diffusive reflections into account will be part of an update of SONNE.

### 3 COMPARISON OF DESSIS+SONNE WITH PC1D, IQE1D AND EXPERIMENTAL DATA

In order to investigate deviations in the calculations performed with PC1D [5,6], IQE1D [7] and DESSIS+SONNE due to different numerical algorithms and internal physical models three cell types have been simulated: a planar cell with fully Al metallised back contact (one-dimensional problem), a planar cell with local Al back contacts (quasi one-dimensional problem) and a one-sided macroscopically V-grooved solar cell (two-dimensional problem). The results of the different programs are compared in this section.

#### 3.1 Planar cells

The following identical input parameters were used in the simulations with DESSIS+SONNE and PC1D:  $W = 230\mu\text{m}$ ,  $0.5\Omega\text{cm}$  p-type material,  $90\Omega/\text{sqr}$ . emitter, passivated front surface with recombination velocity  $S_{e,\text{SiO}_2} = 100\text{cm/s}$  at the Si-SiO<sub>2</sub> interface, Al back, no BSF, back surface recombination velocity  $S_b = 10^7\text{cm/s}$ , internal back surface reflectance  $R_b = 0.71$ .



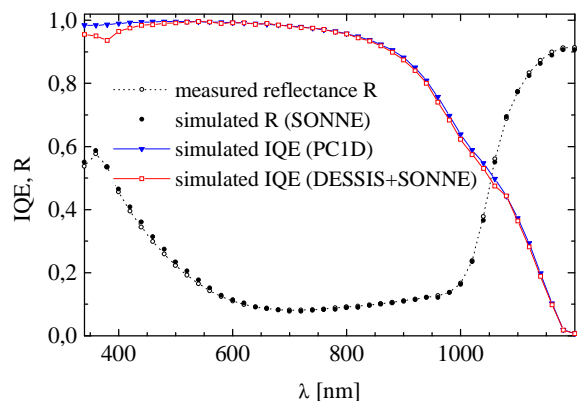
**Figure 3:** Comparison of simulated IQEs obtained by PC1D and DESSIS+SONNE using identical input parameters.

Fig. 3 shows a good agreement between the different methods for wavelengths larger than 500 nm. In order to quantify the introduced uncertainty in  $L_b$  each simulation has been fitted by IQE1D (not shown in Fig.3 for clarity reasons). Whereas the relative differences of IQE1D and PC1D in  $L_b$  are below 2%, DESSIS+SONNE exhibits deviations from IQE1D of about 8% for small diffusion lengths and 3% for the largest investigated  $L_b$ .

The varying results for  $\lambda < 500\text{nm}$  (Fig. 1) are mainly due to the two-dimensional geometry of the front surface respectively the finger grid. The high surface recombination velocity (SRV) under the front contacts is accounted for in DESSIS but neglected in the PC1D simulations when using  $S_{e,\text{SiO}_2}$  as the spatially averaged surface recombination velocity  $S_{e,\text{av}}$ . Additionally we used in the DESSIS simulations a doping independent SRH-recombination model [2], because the doping dependent

model led to an unexpected erratic influence of  $L_b$  on the IQE for  $\lambda < 600\text{nm}$ .

A planar solar cell ( $W = 250\mu\text{m}$ ,  $1\Omega\text{cm}$  p-type material,  $85\Omega/\text{sqr}$ . emitter doping profile, passivated front surface) with local back contacts and passivated surfaces between the contacts has been used to test DESSIS+SONNE in the case of a two-dimensional back surface design with low  $S_b$ . The bulk diffusion length and the spatially averaged back surface recombination velocity  $S_{b,\text{av}}$  were taken from a fit of the experimental data performed with IQ1D. As there is no option in DESSIS to define an averaged SRV, the value of  $S_{b,\text{av}}$  obtained by IQE1D was taken as the SRV at the passivated surfaces  $S_{b,\text{SiO}_2}$  between the back contacts. In order to quantify the resulting  $S_{b,\text{av}}$  of the DESSIS calculation and to compare PC1D with IQE1D, again each simulation (Fig. 4) was fitted by IQE1D.



**Figure 4:** Comparison of PC1D and DESSIS+SONNE for a planar cell with local line-shaped back contacts. Deviations between the results are mainly due to different spatially averaged SRVs when using identical input parameters in the one- and two-dimensional simulations.

**Table I:** DESSIS and PC1D input parameters (input) for a planar cell with local back contacts and resulting values from IQE1D fits to the calculated data (IQE1D fit to).

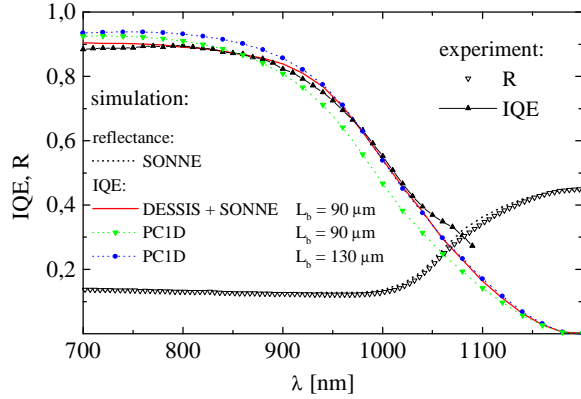
input DESSIS	IQE1D fit to DESSIS	input PC1D	IQE1D fit to PC1D
$S_{b,\text{SiO}_2} = 3500$ [cm/s]	$S_{b,\text{av}} = 4000$	$S_{b,\text{av}} = 3500$	$S_{b,\text{av}} = 3300$
$L_b = 296$ [μm]	$L_b = 280$	$L_b = 296$	$L_b = 299$

As in the previous example only small differences between the one-dimensional models of PC1D and IQE1D were found (see Table I). Deviations between PC1D and DESSIS+SONNE for  $\lambda > 800\text{nm}$  (Fig. 4) are mainly due to the local back contacts causing a higher  $S_{b,\text{av}}$  in the DESSIS simulation although again a difference in  $L_b$  of about 5% is included.

#### 3.2 Mechanically V-grooved Cell

In order to verify the performed two-dimensional IQE calculations the measured IQE of the cell shown in Fig. 1 ( $W = 231\mu\text{m}$ , groove depth  $d = 91\mu\text{m}$ , Al back, no BSF,  $0.5\Omega\text{cm}$  p-type wafer,  $90\Omega/\text{sqr}$ . emitter, shallow

angle evaporated front grid) has been fitted by simulated data with  $L_b$  as a fit parameter. In the case of oblique cell structures numerical errors for incident light with penetration depths smaller than  $5\mu\text{m}$  arise due to a limited resolution of the discretization mesh close to the surface (17000 grid points were used). Therefore wavelengths below  $700\text{nm}$  were omitted in the fit. A very good agreement of simulation and experiment was achieved for  $L_b = 90\pm 7\mu\text{m}$  (Fig. 5). The structure in the experimental IQE for  $\lambda > 1040\text{nm}$  is the result of an error in the used reference detector and has no physical meaning.



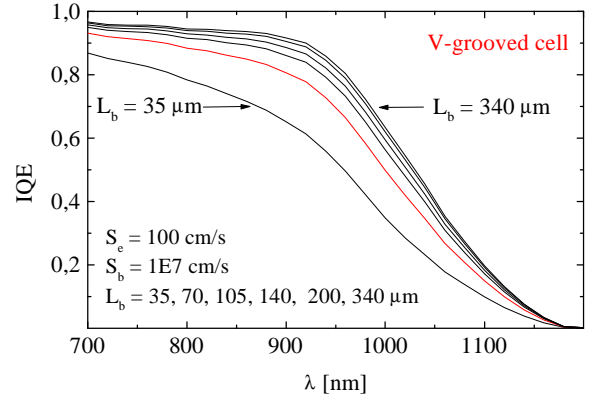
**Figure 5:** Measured IQE and total reflectance of the V-grooved cell shown in Fig. 1. The corresponding DESSIS+SONNE and PCID simulation results using similar input parameters are also shown. PCID's quasi one-dimensional model for surface textures is not sufficient to fit the experiment accurately. The structure in the experimental IQE for  $\lambda > 1040\text{nm}$  is due to an error in the used reference detector.

An attempt to fit the experimental data with PCID using a facet angle [5] of  $60^\circ$  was - as expected - not successful no matter what combination of  $S_e$  and  $L_b$  was tried. The conditions for the quasi one-dimensional model to hold are not satisfied by a V-groove depth of  $91\mu\text{m}$ , which makes a two-dimensional treatment necessary.

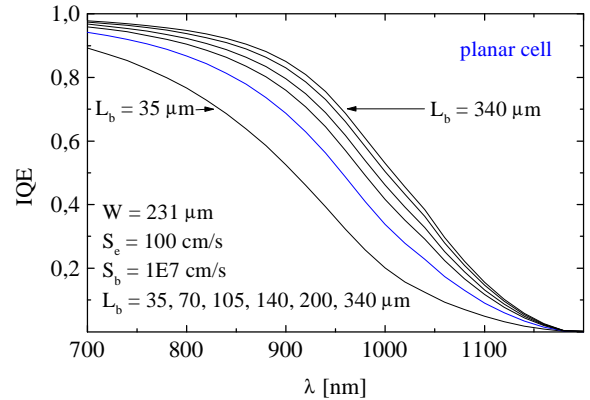
The good agreement between simulation and experiment makes - in principle - a determination of  $L_b$  and  $S_b$  possible by fitting two-dimensional simulations to measured IQEs. If both  $L_b$  and  $S_b$  are unknown, a separation of these parameters is complicated by a measurement uncertainty of about 3% relative and only upper and lower limits for  $L_b$  and  $S_b$  can be obtained from simulations [7].

#### 4 SIMULATIONS

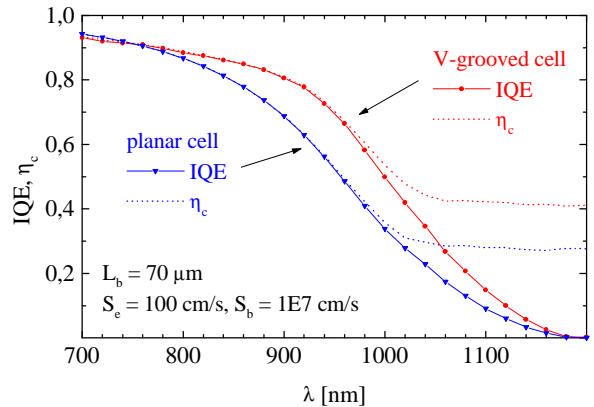
In order to quantify the expected impact of the enhanced carrier collection efficiency  $\eta_c$  in macroscopic V-structures on the IQE and the short circuit current density  $J_{sc}$  for  $\lambda > 700\text{nm}$ , a numerical comparison between the V-grooved cell of section 3 (cell A) and a corresponding planar cell (cell B,  $W = 231\mu\text{m}$ , reflectance simulated with SONNE, all other parameters identical to cell A) was carried out with DESSIS. Figs. 6 and 7 give the dependence of the IQE of cell A and cell B on  $L_b$  in the case of a fully metallized back contact without BSF.



**Figure 6:** Simulated IQE of cell A (V-grooved) for several bulk diffusion lengths.



**Figure 7:** Simulated IQE of cell B (planar) for several bulk diffusion lengths.

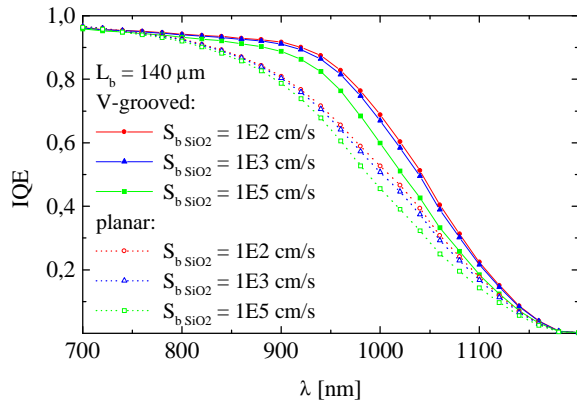


**Figure 8:** IQE and fraction of the photogenerated carriers that are collected under short circuit conditions  $\eta_c$  for both cells in the case of  $L_b = 70\mu\text{m}$ . The enhanced  $\eta_c$  (12% - 16% absolute for  $900\text{nm} < \lambda < 1200\text{nm}$ ) causes a gain of approximately  $1.5\text{mA}/\text{cm}^2$  in the short circuit current density.

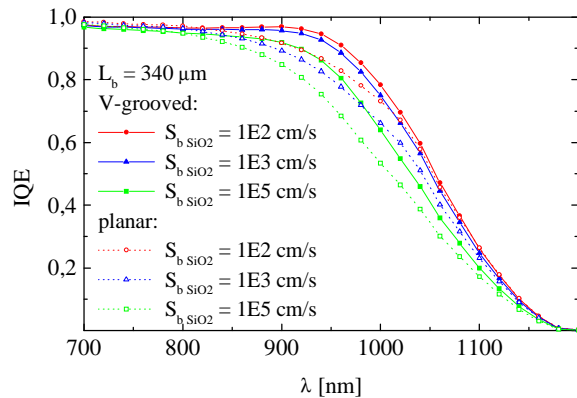
In the near infrared wavelength range ( $\lambda > 800\text{nm}$ ) the IQE of cell A is considerably higher than that of cell B for all  $L_b$ . To estimate the improvement in  $J_{sc}$  due to the raised  $\eta_c$  of V-grooved cells (Fig. 8) an averaged cell reflectance of 10% for both cells was assumed when integrating the data shown. Double layer antireflection

coatings led to a reflectance of about 5% for wavelengths below 1000nm for both cell types. A maximum current density gain  $\Delta J_{sc} \approx 1.5\text{mA/cm}^2$  of cell A with respect to cell B is obtained for  $L_b = 70\mu\text{m}$  (Fig. 8). But even for  $L_b = 340\mu\text{m}$  ( $S_b = 10^7\text{cm/s}$ ) there is still an expected improvement in  $J_{sc}$  of about  $0.85\text{mA/cm}^2$ . Using the real cell reflectances, the lower  $R(\lambda)$  of the V-grooved cell adds an additional current gain.

In order to study the influence of  $S_b$  on the IQE both cells were simulated with local back contacts (5% metallization) and a Si-SiO<sub>2</sub> passivated surface between them (Figs. 9 + 10). For both cell types the IQE showed to be sensitive to variations in  $S_{b,\text{SiO}_2}$  only between  $100\text{cm/s}$  and  $10^5\text{cm/s}$ . Fitting the IQEs of the planar cell in the case of  $L_b = 340\mu\text{m}$  with IQE1D,  $S_{b,\text{av}}$  could be estimated to 600, 1700 and  $10^5\text{cm/s}$  for  $S_{b,\text{SiO}_2} = 100, 1000, 10^5\text{cm/s}$  respectively.



**Figure 9:** Simulated IQE of cell A (V-grooved) and cell B (planar) for several back surface recombination velocities in the case of  $L_b = 140\mu\text{m}$ .



**Figure 10:** Simulated IQE of cell A (V-grooved) and cell B (planar) for several back surface recombination velocities in the case of  $L_b = 340\mu\text{m}$ .

Two conclusions can be drawn from the calculated data. 1) For  $L_b < 140\mu\text{m}$  ( $L_b < 3/5 W$ ) cell A exhibits even in the case of  $S_{b,\text{SiO}_2} = 10^7\text{cm/s}$  a higher IQE than cell B with  $S_{b,\text{SiO}_2} = 0\text{cm/s}$  (Fig. 9). 2) For  $L_b > W$  the IQE of cell A is less sensitive to variations in  $S_{b,\text{SiO}_2}$  than cell B, which might be due to the altered optical generation close to the cell back in the case of macroscopic V-grooves.

Also the apparent development of a local maximum in the IQE around 900nm in some of the curves is not yet understood. In any case further detailed studies have to be carried out to clarify these effects. An experimental comparison of V-grooved and planar cells will be given in [8].

## 5 CONCLUSIONS

Complete two-dimensional calculations of internal quantum efficiencies have been carried out for planar and mechanically V-grooved solar cells. The method could be verified by comparison with the programs PC1D and IQE1D in the case of planar cells and with measurements in the case of V-grooved cells.

PC1D's quasi one-dimensional model was found to be insufficient to fit the experimental IQE of the investigated macroscopically structured cell.

Numerical studies investigating the impact of  $L_b$  and  $S_b$  on the IQE for a V-grooved and a corresponding planar cell show a strong enhancement of the quantum efficiency in the near infrared wavelength range. Assuming a 10% reflectance for both cells, the short circuit current density improvement of  $1.5\text{mA/cm}^2$  for  $L_b = 70\mu\text{m}$  is due to the enhanced carrier collection efficiency in the macroscopic V-structure. For  $L_b < 140\mu\text{m}$  ( $L_b < 3/5 W$ ) the investigated V-grooved cell type exhibits even in the case of maximum back surface recombination velocity a higher IQE than the planar cell without any back surface recombination

## Acknowledgements

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