ANALYSIS OF EDGE RECOMBINATION FOR HIGH-EFFICIENCY SOLAR CELLS AT LOW ILLUMINATION DENSITIES

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ABSTRACT

Indoor applications of high-efficiency silicon solar cells implicate illumination densities that are significantly below 1 sun. Our investigations show that at low illumination densities, solar cells are very sensitive to the recombination at the cell edges.

We have analyzed the different recombination channels at the perimeter by means of two-dimensional device simulation and experiments. The modeling shows, that at low illumination densities the main recombination channel at the perimeter is due to the surface recombination in the space charge region. The surface recombination velocity at the cell perimeter could be extracted by comparison of the simulated and measured open-circuit voltages. Our investigation shows that the perimeter loss can be reduced drastically by an optimized passivation scheme.

1. INTRODUCTION

The final step of many cell processes is to detach the cell out of the wafer. If the emitter extends across the whole wafer, cleaving the wafer results in the intersection of the pn-junction with a surface with high recombination velocity at the edge of the cell.

Several authors have described the detrimental effect of pn-junctions bordering unpassivated cell surfaces. A strong increase of the space charge region dark saturation current J_{02} was reported.

Kuehn et al. [1] investigated the effect by means of two dimensional simulation of a simple small simulation domain (5x4 µm²), in which the recombination of the pn-junction bordering on the surface is completely dominating the device characteristics.

Catchpole et al. [2] used a combination of device and circuit simulation to investigate the impact of the perimeter losses on the whole solar cell for different cell parameters. Edge recombination is important for small cells, such as concentrator cells, so they investigated among other things the effect for illumination levels above one sun.

The aim of this work is to investigate the impact of pn-junctions bordering unpassivated cell surfaces on the whole solar cell for illumination densities significantly below 1 sun.

2. EXPERIMENTAL RESULTS

Fig. 1 shows the scheme of a high-efficiency cell. We investigated a RP-PERC structure which incorporates random pyramids, a one-step emitter, a dielectrically passivated front and rear surfaces and no boron BSF [3]. A special feature of a high-efficiency cell is that the emitter diffusion is limited to an area smaller than the total cell area. This guarantees an optimal passivation of the pn-junction which borders the thermally oxidized front surface.

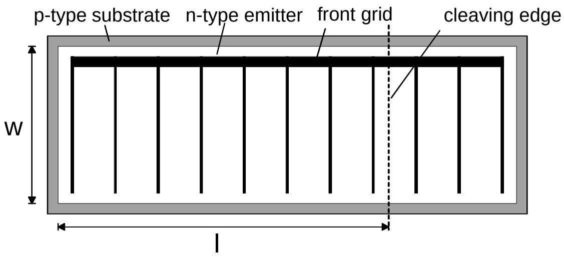


Fig: 1 Cell scheme

In order to experimentally investigate the detrimental effect of unpassivated cell edges on the cell parameters, we have scribed cells on the rear side with a diamond scriber and cleaved along these lines. Now the pn-junction at this edge is bordering an unpassivated surface, increasing the space charge recombination current dramatically.

By subsequent cutting we have prepared cell fractions with decreasing lenght l and thus increasing border-to-area aspect ratios.

$$\text{Aspect Ratio} = \frac{\text{Bad Edge Length}}{\text{Area}} = \frac{W}{W \times l} = \frac{1}{l} \qquad (1)$$

In the case of two cleaved edges the expression changes to 2/l. For increasing aspect ratio (for decreasing cell length) the influence of the unpassivated edge increases. After each cleavage the illuminated IV-characteristic of the remaining cell fraction was measured at four different illumination densities. The results of this investigations are already published in Ref. [3].

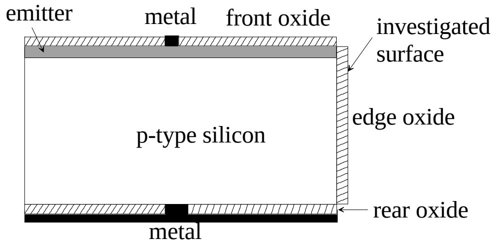
New measurements a few days after cleaving have shown, that there is a slight edge passivation probably due to the formation of a native oxide. The influence of the native oxide will be investigated in section 3.3.

3. SIMULATION

3.1. Approach and used models

As a theoretical approach, we have analyzed the different recombination channels at the perimeter by means of two-dimensional device simulation using DESSIS [5] and circuit simulation.

The PERC cell with a dot rear contact structure was modeled in Cartesians coordinates. So the dot rear contacts was modeled as a line structure in 2D. The width of the back contacts was adjusted so that they formed the same fraction of the surface (0.5 %) as in the real structure. For the circuit simulation we used to types of symmetry elements: the perimeter diode and the elementary diode. The scheme of the simulated perimeter diode is shown in Fig. 2. The edge oxide is used to define the boundary conditions at the cleaved edge. The symmetry element of the elementary diode is the same as of the perimeter diode, but with Neumann boundary conditions instead of the edge oxide. The use of elementary and perimeter diodes for a circuit simulation is based on the assumption of negligible current flow in the semiconductor between two neighbouring sections [4]. In order to check the validity of this assumption we compared the simulated current pattern of our symmetry elements with one using a perimeter diode that expands into the cell by one elementary diode. Furthermore, we compared the IV-curves of the expanded perimeter diode and our standard symmetry elements. Both tests showed, that our chosen symmetry elements fulfill the assumption.



Property	Parameters/Model
Emitter	125 Ω/sqr, junction @ 1.2µm, Gauß-profile
Base	3.2 10^{16} cm^{-3}, 0.5 Ωcm
Recombination	Shockley-Read-Hall, τ = 1ms Auger
Surface recombination	Shockley-Read-Hall, $S_{n0} = S_{p0}$ =S, midgap trap
$S_{front\text{-}oxide}$	1800 cm/s
$S_{rear\text{-}oxide}$	20 cm/s

Fig. 2: Symmetry element for device simulation with the investigated surface on the right and parameters and models used in the simulation study.

3.2. Effect of illumination density in the perimeter region

First of all we determined the main recombination channel in the perimeter region at V_{mpp} of the whole cell. We extracted the surface recombination rate R_{border} at the cell edge for a surface recombination velocity $S = 10^7$ cm/s and different illumination densities from the simulations. In order to determine the main recombination channel at the cell edge, we integrated the surface recombination rate over the cell depth for three regions: emitter, space charge and bulk region:

$$J_{0surf} = q\int_a^b R_{surf}\,dz \qquad (2)$$

The boundary values of the integration a, b are the front and rear surfaces and the boundaries of the space charge region (scr), respectively.

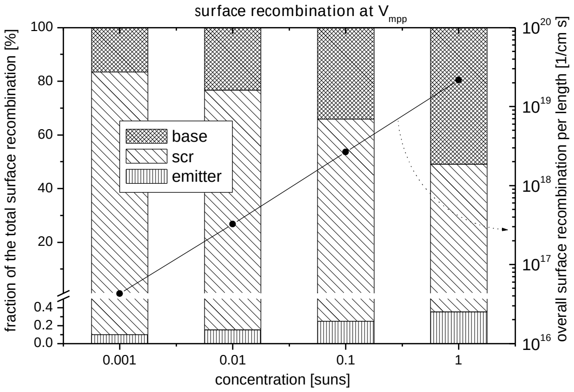


Fig. 3: Fraction of the surface recombination of the three regions for different illumination densities at V_{mpp} and $S_{border} = 10^7$ cm/s. The line shows the overall surface recombination (right axis)

As can be seen in Fig. 3 the recombination fraction of the surface recombination (left axis) in the space charge region increases from 40 % at one sun to over 80 % at 1/1000 sun. This shows, that for lower illumination densities the main recombination channel at the perimeter is due to the surface recombination in the space charge region.

The overall surface recombination rate (right axis) is also shown in Fig. 3. Due to the decreasing excess carrier density with decreasing illumination density, the overall surface recombination also decreases with decreasing illumination density.

The increase of the recombination fraction of the surface recombination in the space charge region can be explained by the decrease of the carrier density in the base and the space charge region. In Fig. 4 the carrier density and the surface recombination rate are plotted over the cell depth for two different illumination densities. In the base, the minority carrier densities and the surface recombination rate decreases with the illumination density. In the space charge region, there is no clear distinction of minority and majority carrier densities, so the surface recombination rate does not decrease proportional to the illumination density. The decrease of the surface recombination rate R_{border} in the space charge region is an order of magnitude smaller compared to the base region for a decrease of the illumination densities from 1 to 1/1000 sun. Thus, the surface recombination in the base decreases stronger than in the space charge region, and the fraction of the surface recombination in the space charge region increases.

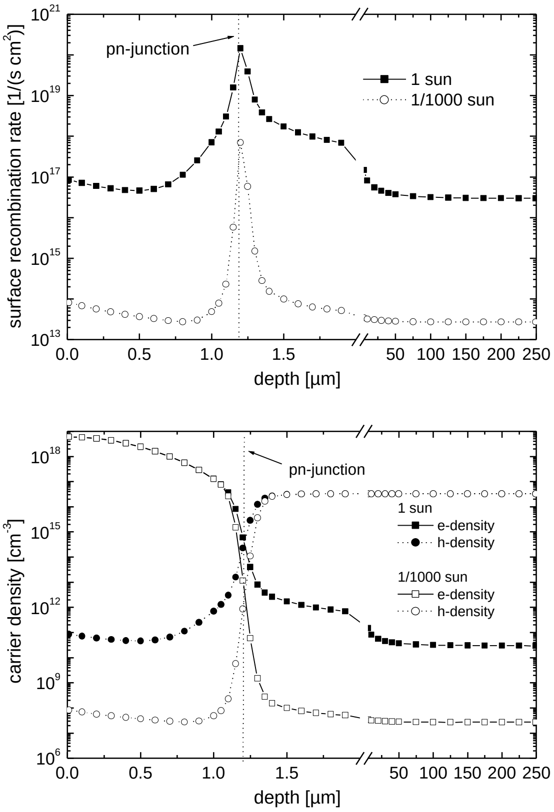


Fig. 4: Carrier densities and surface recombination rate R_{border} for two different illumination densities, extracted at the cell edge from the simulation at V_{mpp} and $S_{border} = 10^7$ cm/s.

3.3. Effect of the edge surface recombination on the overall cell performance

To compare the simulation and the experiments we simulated also an elementary diode without an edge oxide, and interconnected the IV-curves for the perimeter diodes and the elementary diodes using a simple resistance circuit. An elaborate resistance analysis has shown, that the main contribution of the series resistance is due to the contact resistance by the contacting of the p-type base (see Table I).

Table I: Result of the series resistance analysis of the investigated PERC structure.

$R_{s,\text{ contact p}}$	0.2 ± 0.1 Ωcm²
$R_{s,\text{ contact n}}$	0.02 ± 0.01 Ωcm²
$R_{s,\text{ bus}}$	0.013 Ωcm²
$R_{s,\text{ finger}}$	0.011 Ωcm²
$R_{s,\text{ analytical}}$	Σ = 0.24 Ωcm²

Furthermore, it turned out that because of the short fingers, there is only a negligible non generation loss [6]. So the simple resistance circuit shown in Fig. 5 is an accurate model for the investigated solar cell.

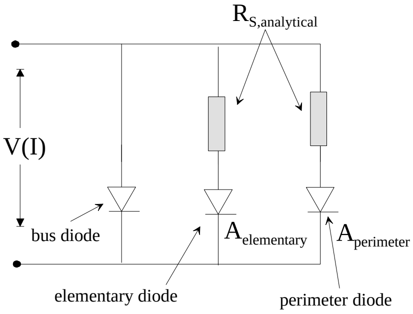


Fig. 5: Scheme of the simple resistance circuit used for the circuit simulation

We weighted the individual IV-curves with their area fraction and compared the simulated and measured open-circuit voltages. In order to emphasize the influence of the edge surface recombination velocity S_{border} on the whole cell, we simulated the open-circuit voltages for an aspect ratio 1/l = 5 cm^{-1}. The results of the circuit simulation are shown in Fig. 6.

For the illumination density of one sun, there is only a small difference between the simulated open-circuit voltages for different edge surface recombination velocities S_{border} whereas for an illumination density of 1/1000 sun there is a large difference. This shows that the cell is much more sensitive to edge surface recombination at low illumination densities.

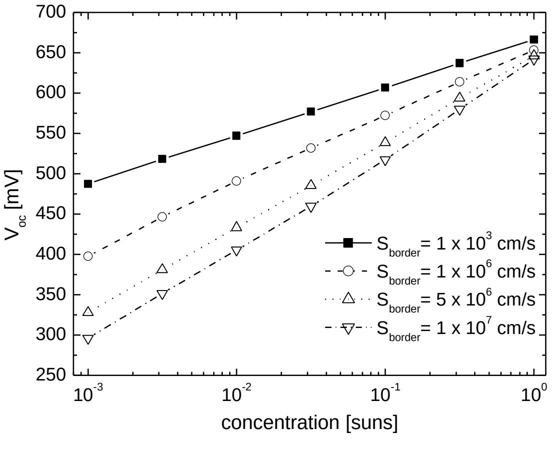


Fig. 6: Effect of edge surface recombination velocity for the whole cell with a large Aspect Ratio 1/l

The comparison between the measurements and the simulations in Fig. 7 shows that the cell fraction directly after cleaving has a surface recombination velocity of about 10^7 cm/s. The measurements in Fig. 7 shows that the native oxide has no influence on the open-circuit voltage at one sun, whereas for an illumination density of 1/1000 sun the improvement of the open-circuit voltage is about 10 %!

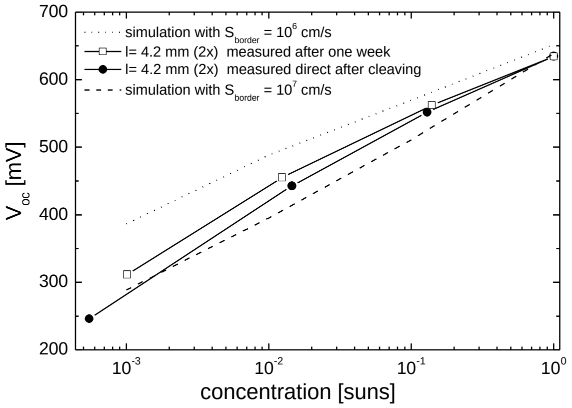


Fig. 7: Simulated and measured open-circuit voltage as a function of concentration for cell fractions with different lengths. The indication (2x) means, that the cell fractions have two cleaved cell edges

In order to elaborate the impact of the unpassivated pn-junction, we split the edge oxide in the simulation into two regions: the emitter + space charge region and the base region. In these two regions, we can specify different surface recombination velocities (SRV). We simulated two passivation schemes: In the first case the SRV of the space charge region was taken to be 10^6 cm/s and in the second case 0 cm/s. In both cases the SRV of the base region was set to 10^6 cm/s.

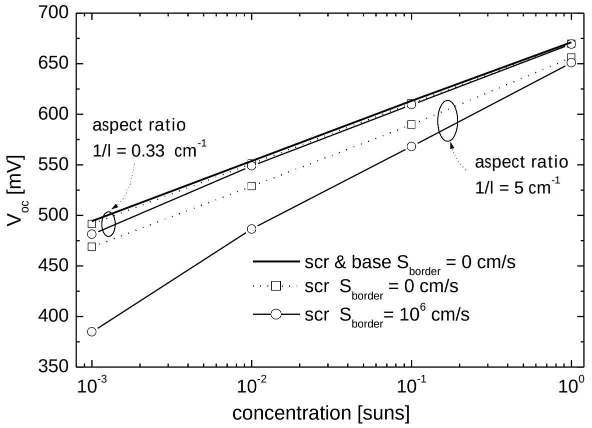


Fig. 8: Simulated open-circuit voltage as a function of concentration for cell fractions with different aspect ratios and different passivation schemes. The solid line is the result of the simulation with a perfect surface passivation $S_{border,scr} = S_{border,base} = 0$ *cm/s.*

It can be seen in Fig. 8, that for small aspect ratios (1/l = 0.33 cm^{-1}) there is only a small influence of the unpassivated junction. The comparison with the ideal passivated edge ($S_{border,scr} = S_{border,base} = 0$ cm/s, solid line in Fig. 8) and the simulations with the passivated junction shows, that the influence of the border recombination at the base region is nearly negligible.

For large aspect ratios (1/l = 5 cm^{-1}), the influence of the cell with the unpassivated junction decreases whereas for the cell with the passivated junction, the impact is still smaller.

This shows, that for low illumination densities and large aspect ratios a passivated pn-junction is necessary to prevent a strong decrease in V_{oc} to low illumination densities.

4. CONCLUSIONS

In this work we investigated the effect of edge recombination, especially for low illumination densities. The main recombination channel at the cell edge for low illumination densities is due to the surface recombination in the space charge region. Circuit simulations showed that at low illumination densities, solar cells are very sensitive to the recombination at the cell edge especially when the pn-junction is bordering an unpassivated surface.

The comparison of measurements and simulations show, that the cleaved edge of the cell fraction directly after cleaving has a surface recombination velocity of about 10^7 cm/s. The formation of a native oxide results in an improvement of the open-circuit voltage of about 10 % at an illumination density of 1/1000 suns.

Simulations with different passivation schemes showed, that for low illumination densities and large aspect ratios a passivated pn-junction is necessary in order to prevent a strong decrease in V_{oc}. On the other hand, the simulations revealed that it is sufficient to passivate only the small region of the pn-junction (ca. 2 µm depth) for achieving higher open-circuit voltages at low illumination densities. The influence of the border recombination at the base region (ca. 248 µm depth) on the open-circuit voltage is comparatively small.

REFERENCES

[1] P. Kühn, P. Fath and E. Bucher,"Effects of pn-junctions bordering on surfaces investigated by means of 2D-modeling" Proceedings of the 28th IEEE Photovoltaics Specialists Conference, Anchorage, USA (2000) p116-119

[2] K. R. Catchpole, A. W. Blakers and M. J. McCann, "Perimeter losses where the emitter reaches the edge of the Cell" Proceedings of the 17th European Photovoltaic Solar Energy Conferences, Munich (2001) p1869-1872

[3] S. W. Glunz et al, "High-efficiency silicon solar cells for low-illumination applications" Proceedings of the 29th IEEE Photovoltaics Specialists Conference New Orleans, USA (2002) p450-453

[4] P. P. Altermatt, G. Heiser and M. A. Green, "Numerical quantification and minimization of perimeter losses in high-efficiency silicon solar cells" *Progr. Photovolt.* **4** (1996) p355-367.

[5] ISE Integrated System Engineering AG, Zürich, DESSIS Manual 7.0 (2001)

[6] J. E. Mahan, G. M. Smirnov, "A new perspective of distributed series resistance effects in photovoltaic devices" Proceedings of the 14th IEEE Photovoltaics Specialists Conference, San Diego (1980), p612