COMPREHENSIVE COMPARISON OF DIFFERENT REAR SIDE CONTACTING METHODS FOR HIGH-EFFICIENCY SOLAR CELLS

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ABSTRACT: High-efficiency solar cells have to be designed carefully in order to minimize all possible losses. One of the critical parameters to obtain good performance, is the rear side recombination velocity. There are many approaches to passivate the rear side. They differ not only in their passivation quality and their optical properties but also in the complexity of the process steps. We have investigated the six most common methods for rear side contacting and their potential to achieve high efficiencies: dielectric passivation with local back surface field (LBSF/PERL), dielectric passivation with ohmic contacts (PERC), dielectric passivation with laser-fired-contact (LFC), full area Boron-Back Surface Field (BSF), screen-printed Aluminium-BSF and evaporated Aluminium (ohmic contact).
Keywords: Recombination, Modelling, High-Efficiency

1 INTRODUCTION

Two important tasks in crystalline silicon solar cell research are to lower the module cost and to overcome the silicon wafer shortage. One way to solve these tasks is the use of thinner high efficient cells. A crucial point for thinner silicon solar cells is a very good light confinement and a high quality rear side passivation. We investigated different techniques for rear side contacting and their optical and electrical potential to achieve high efficiencies. In this work we have investigated the six most utilized techniques: dielectric passivation with local back surface field (LBSF/PERL), dielectric passivation with ohmic contacts (PERC), dielectric passivation with laser-fired-contacts (LFC), full area Boron-Back Surface Field (BSF), evaporated Aluminium (ohmic contact) and at last the present state-of-the-art rear side structure for industrial silicon solar cells, screen-printed Aluminum BSF rear side.

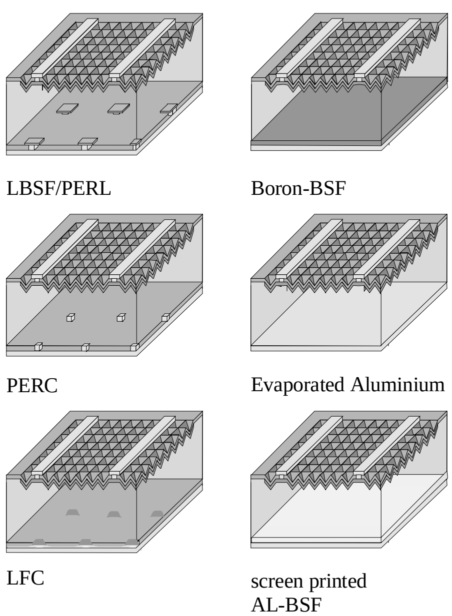

Figure 1: Schemes of the investigated cell structures. All cells have a dielectrically passivated front surface and are textured with inverted pyramids.

Figure 1 shows a sketch of the investigated cell structures. They can be divided into two groups: cells with dielectrically passivated rear side and local point contacts and cells where the whole rear side is contacted. We processed cells on 250 µm thick monocrystalline float-zone p-type silicon in the resistivity range between 0.5 Ωcm and 10 Ωcm. All cells exhibit a front surface with inverted pyramids, evaporated front contacts and a phosphorus diffusion (ρ_{sheet}=120 Ω/sq.) passivated by a 105 nm thermal oxide. Thus, the quality of the material and the front side of all cells are sufficient to achieve high efficiencies and identical for all the different rear surface structures. The screen-printed Al-BSF was formed in a rapid thermal processing (RTP) unit [1].

2 EXPERIMENTAL RESULTS

Figure 2 shows the efficiency and the open-circuit voltage of the different cell structures as a function of the doping concentration. The cells without a high-low junction (BSF), i.e. the PERC and the evaporated Al cells show a strong decrease of the open-circuit voltage with decreasing doping concentration. This behavior results from the direct influence of the doping concentration N_A on the dark saturation current J_{0b} (1) and thus to the open-circuit voltage:

$$J_{0b} = \frac{n_{i,eff}^2}{N_A}\frac{D}{L_b}G\left(W, L_b, D, S_{back}\right) \qquad (1)$$

This trend can only be compensated by an efficient high-low junction at the rear surface (LBSF, Bor-BSF and LFC in Figure 2), which decrease the rear side recombination velocity S_{back}.

Even though the rear side of the PERC structure is significantly better passivated than the evaporated Al structure, the efficiency decreases much stronger with decreasing doping concentration. This is caused by a strong reduction of the fill factor. The 1 mm contact pitch of the PERC cells result in high spreading resistance on high-resistivity material [2]. These fill factor losses can also be observed at the LFC structure with the 1 mm contact pitch. The LFC cells with the adapted rear contact pattern ("best pitch") did not show these fill factor losses.

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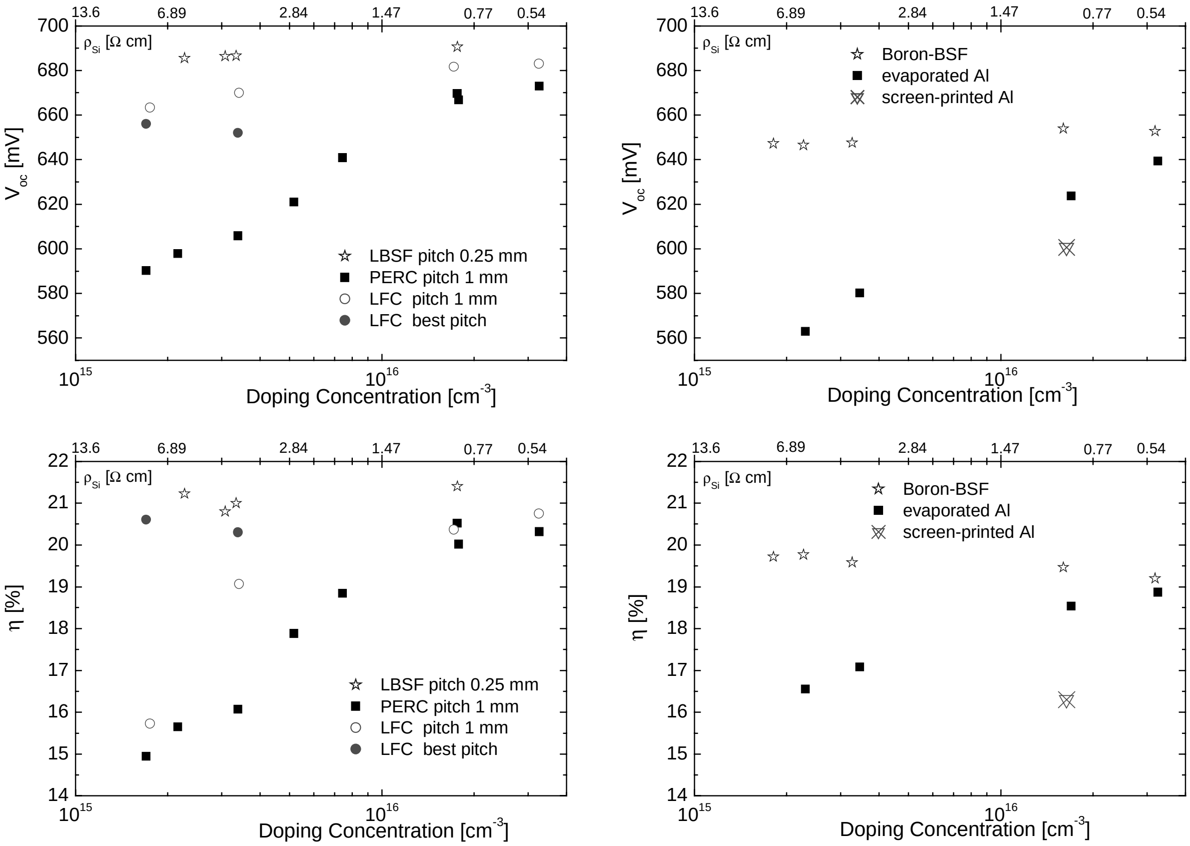

Figure 2: Measured efficiency and open-circuit voltage of the different cell structures in dependance of the doping concentration. The cells with point contacts are in the left column, the cells with the whole rear side contacted are in the right column. The cells without high-low-junction show a strong voltage decrease with decreasing doping concentration. The efficiency decrease of the point contact cells with 1 mm contact pitch is caused by the spreading resistance losses in the high resistivity material. The spreading resistance losses can be reduced by a reduction of the contact pitch (LFC best pitch and LBSF 0.25 mm pitch). The low open-circuit voltage of the screen-printed Al-BSF is caused by a strong degradation of the front surface passivation (see Figure 4), and thus the open-circuit voltage is not comparable.

Although the reduction of the contact pitch degrades the passivation of the rear side and thus decreases the open-circuit voltage, the efficiency of the "best pitch" LFC cells are clearly above 20 % for the whole range of the investigated doping concentration.
If we have a look at the cells with a high-low junction, the absolute level of the open-circuit voltage depends on the passivation quality of the rear side and the quality of the junction.

The results of the screen-printed Al-BSF cells (the crossed triangle in Figure 2) differ strongly from the results of all other cells. The very low open-circuit voltage of these cells is not caused by a poor rear side passivation or a increased bulk recombination, but is due to a detrimental degradation of the surface passivation on the front side of the cell. The reduced passivation quality can be seen in a strong reduction of the internal quantum efficiency in the blue wavelength range (see Figure 4). Investigations have shown that the used RTP process is not appropriate for the used front side, however the BSF shows a good passivation quality and is comparable to industrially processed screen-printed Al-BSF.

3 EVALUATION OF CELL-DIFFERENCES

For a detailed investigation of the differences in the optical and the recombination behaviour, we have analyzed the reflection and the internal quantum efficiency.

3.1 Optical differences

Figure 3 shows the measured und simulated reflection of the different cells. All cells have a thickness of 250 µm.

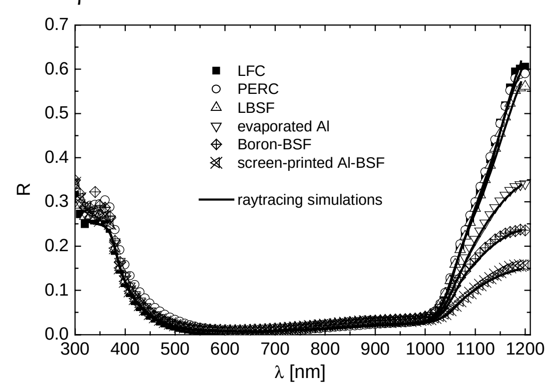

Figure 3: Measured and simulated reflection of the different solar cells. Due to the same front side, they differ only in the wavelength range above 1000 nm.

We have evaluated the different reflections with our

3-dim. raytracing program RAYN [3]. RAYN uses for the modelling of the rear side the reflectivity R_{back} and to describe the diffusivity the model of Phong [4], which modelled the scattering of an initial intensity I_0 with a symmetrical scattering pattern about the direction of the direct reflection.

$$I(\alpha) = I_0 \cos^w(\alpha) \tag{2}$$

A small "Phong exponent" w means a high diffusivity, (w =1 describes a perfect Lambertian reflection) whereas a large w means a more specular reflection. The results of the raytracing simulations are listed in Table I.

Cell	R_{back} [%]	w	J_{gen} [mA/cm²]
LFC	95.5	800	42.23
PERC	95.0	900	42.18
LBSF	94.5	800	42.16
evaporated Al	83.0	170	41.61
Boron-BSF	71.0	110	41.14
screen-printed Al-BSF	65.0	10	41.08

Table I: Results of the raytracing simulations of the investigated solar cell. J_{gen} is the corresponding maximal generation current for the 250 µm thick cells.

Figure 3 and Table I reveal that cells with dielectrically passivated rear side and local point contacts have very similar optical behaviour. They have a very specular high reflective rear side with a reflection R_{back} above 94 %. This high reflection, together with the inverted pyramids on the front side, leads to a very good light confinement. The Bor-BSF and the screen-printed Al-BSF have much lower reflectivites, still lower than the evaporated Al rear side. These lower reflectivities result from higher absorption of the metallization and free-carrier absorption (FCA) in the BSF. However, the reflection of the rear side of these cells is much more diffuse, which is reflected in the lower Phong exponent. Also listed in Table I is the generation current J_{gen}, which is the cumulative generation rate times the elementary charge, for the 250 µm thick cells. It can be seen, that the maximum achievable J_{sc}, of the cells with dielectrically passivated rear side is more than 2.5 % higher than the J_{sc} of cells with back surface fields.

These differences in the internal reflection are a critical aspect if we go to thinner cells where a good light trapping is crucial for the performance.

3.2 Internal Quantum Efficiency

In Figure 4 the measured IQEs of the different solar cells are plotted. We have evaluated the IQE of cells with a resistivity of about 1 Ωcm. In this doping range, the cell is mainly limited by surface recombination at the rear side, because Auger-recombination reduces the bulk lifetime only for higher doping concentrations. Also bandgap narrowing effects in the base can be neglected and the doping concentration is high enough, that we have no losses due to differences in the chemical potential, which would arises from different majority carrier concentration at the rear and the edge of the pn-junction. Due to the fact, that the cells are well passivated on the front side, we would expect an excellent IQE in the blue wavelength range. However the cell with the screen-printed Al-BSF rear side has a strongly reduced IQE in the blue wavelength range.

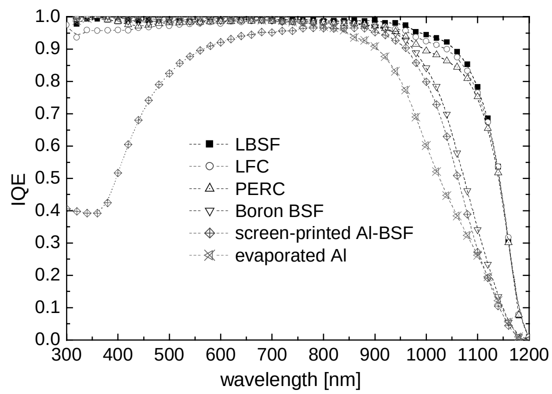

Figure 4: Measured IQE of the different solar cells. All cells expect the screen-printed Al-BSF have an excellent IQE in the blue wavelength range. Above 900 nm the different passivation qualities of the rear side can be observed.

This strongly reduced IQE is an indication of a strong increased surface recombination at the front side. The screen-printed Al-BSF was produced in a RTP unit with a peak temperature of 810°C. We believe, that this fast and high-temperature step has heavily damaged the SiO_2 passivation on the front side, especially at the tips of the inverted pyramids. This increased surface recombination leads to the reduced IQE and the low open-circuit voltage (see Figure 2).

To investigate the electrical differences of the several rear side structures, we have modelled the IQEs with *PC1D* [5] to extract the effective rear side recombination velocity S_{back}. For all simulations the Shockley Read Hall (SRH) bulk lifetime τ_{bulk} was set to 1000 µs, thus the fitted values are upper limits of S_{back}. The results of the simulations are listed in Table II.

Cell	S_{back} [cm/s]	V_{oc} meas. [mV]	V_{oc} PC1D [mV]
LFC	**110**	681	680
PERC	**200**	671	676
LBSF	**60**	691	685
evaporated Al	**10^7**	623	626
Boron-BSF	**430**	654	657
screen-printed Al-BSF	**750**	*600**	650

Table II: With *PC1D* determined S_{back}-values of the different solar cells with a resestivity of 1 Ωcm by means of adaption to the measured EQE. Also listed are the measured and simulated V_{oc}. The measured V_{oc}* of the screen-printed Al-BSF is not comparable to the other results, because of the degraded front surface passivation.

With the extracted S_{back}-values, also the simulated V_{oc} agree very good with the measured V_{oc} (Table II).
The replacement of the damaged front side in the *PC1D*-model of the screen-printed Al-BSF with the standard front side, which we use for all other simulations, leads to

an open-circuit voltage of 650 mV. This shows, that the cell is limited by the recombination at the front side.

3.3 Loss Analysis

The losses at the rear side can be divided into recombination losses and optical losses. To quantify these losses we used the *PC1D*-model and the results of the previous simulations. We started from a perfect rear side, which means S_{back} = 0 cm/s and a totally diffuse internal rear reflection with R_{back} =100%, which leads to a maximum efficiency of 23.3 %. For the different cell structures we "switched on" the individual loss mechanism by setting S_{back} or the rear reflection to the previous extracted values and calculated the losses in the efficiency. The results of this loss analysis for the 250 µm cell with high bulk lifetime is shown in Figure 5. The diagram shows that the surface recombination losses exceed the optical losses clearly for all cell structures. This is obvious because of the very high bulk lifetime, the diffusion length is only limited by the surface recombination at the rear side. However, the optical losses for the Bor-BSF and the screen-printed Al-BSF cell are above 1 % absolute.

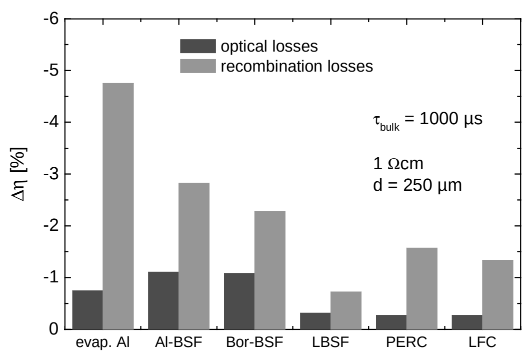

Figure 5: With *PC1D* calculated efficiency losses from the rear side, divided in optical losses and recombination losses.

The ratio between these two loss channels changes drastically if the material quality is the limiting factor of the diffusion length. For a bulk lifetime of 20 µs, which is in the magnitude of a degraded boron-doped 1 Ωcm Czochralski-material, the optical losses exceed the surface recombination losses.

4. OUTLOOK TO THINNER SOLAR CELLS

To show the influence of the internal reflection for thinner solar cells, we compared the LFC-optics (which is similar to the PERC and LBSF-optics) with the screen-printed Al-BSF optics. In Figure 6, the calculated efficiencies for a 50 µm thin solar cell for different bulk lifetimes and recombination velocities of the rear side are plotted. The upper diagram show the results with the LFC-optics and the lower with the screen-printed Al-BSF optics. The shape of the contour lines are very similar, but the absolute level is shifted at about 1 % absolute. This means that independent from the recombination properties of the bulk-material and the rear side, the reduced internal reflection of the BSF cells reduces the achievable efficiency about 1 % absolute. For 250 µm thick cells, the efficiency difference is still about 0.5 % absolute. To achieve efficiencies above 20 % with a 50 µm thin silicon solar cell with the internal reflection of an Al-BSF, the recombination velocity of the rear side has to be significantly lower than 100 cm/s.

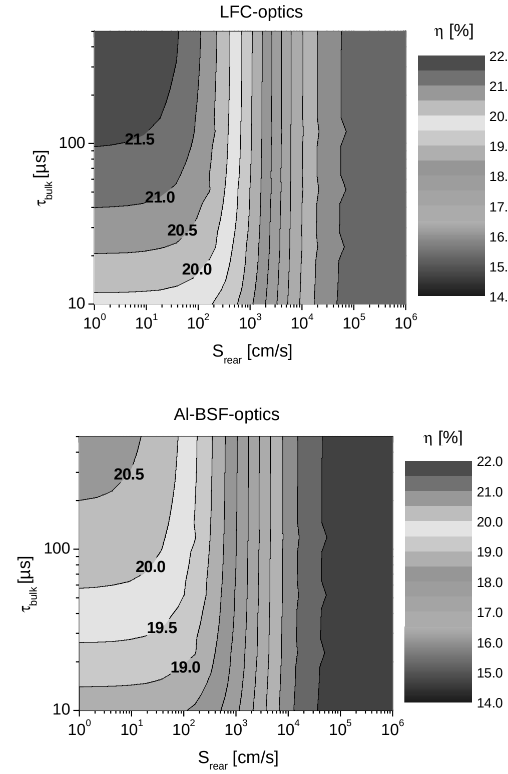

Figure 6: With *PC1D* calculated efficiency for a 50 µm thin solar cell with the LFC-optics and the Al-BSF optics for different bulk lifetimes and recombination velocities of the rear side.

Thus to achieve high cell efficiencies with medium or low quality material, a high reflective rear side is imperative [6].

5. CONCLUSION

The optical and electrical differences of the different cell structures were determined. We extracted optical differences and the effective recombination velocity S_{back} of the different rear side structures for 1 Ωcm material.
For thinner silicon solar cells, it is necessary to optimise the internal reflection to achieve an efficiency above 20 %.

6. ACKNOWLEDGEMENTS

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