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Shading Effects in Back-Junction Back-Contacted Silicon Solar Cells

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ABSTRACT

One of the most often mentioned advantages of back-junction back-contacted silicon solar cells is that this cell structure has no shading losses, because metallization fingers and busbars are both located on the rear side of the solar cell. However, this is only true if only *optical* shading losses are regarded. In this work *electrical* shading losses due to recombination in the region of base busbar and fingers are analyzed using two-dimensional numerical device and network simulations. The base doping dependence of these effects is investigated as well as the influence of the rear side passivation. The results of the simulations are compared with EQE maps of back-junction solar cells. The influence of the busbars is quantified and the influence on the overall cell performance is discussed.

INTRODUCTION

Silicon back-junction solar cells are one of the most promising cell structures to achieve high efficiencies. They already achieve efficiencies above 22 % in production line [1] and are part of current research activities [2],[3],[4]. One of the most often mentioned advantages of such a cell structure is that this cell structure has no shading losses, because both metallization fingers are on the rear side of the solar cell. However, this is only true regarding optical shading losses. In back-junction solar cells with interdigitated fingers, not the whole rear side is covered with an collecting emitter. Figure 1 shows a two dimensional symmetry element of a typical back-junction solar cell with interdigitated fingers.

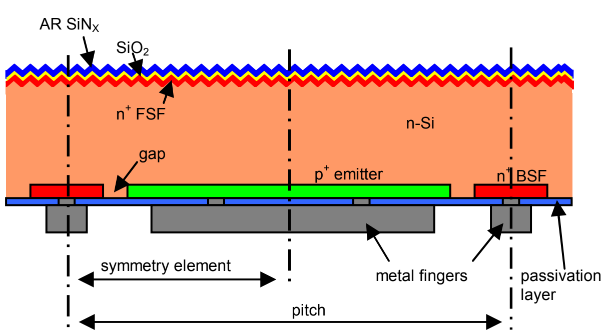

Figure 1: Symmetry element of a back-junction silicon solar cell with interdigitated fingers.

Recombination at the rear side, in the regions without emitter, locally reduces the short-circuit current of the back-junction cell and can be regarded as *electrical* shading. In contrast to optical shading losses, these losses depend not only on the geometry of the base finger, but also on the base doping and the passivation quality of the rear side. Further on, they influence not only the short-circuit current, but also the fill-factor and V_{oc} of a back-junction solar cell.

CELL STRUCTURE AND SIMULATION APPROACH

We have investigated back-junction silicon solar cells on n-type FZ-silicon. The front side is textured with inverted pyramids and passivated with a front surface field (FSF) and a passivation layer stack of a thin layer of silicon oxide and an additional SiN antireflection layer. For a more detailed description of the cell structure see [4]. Figure 2 shows a Light Beam Induced Current (LBIC) map of the investigated 2x2 cm² back-junction solar cell. The reduced signals above the base fingers (a) and the base busbar (b) are clearly visible.

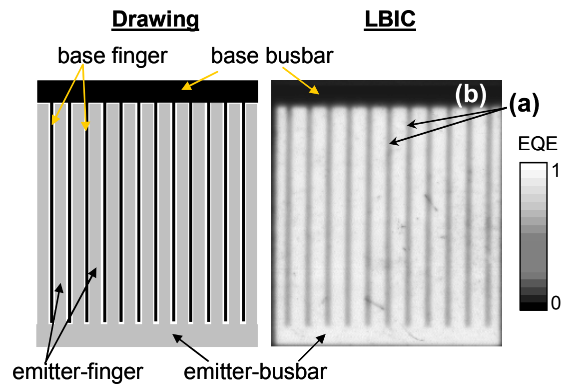

Figure 2: Drawing of the rear side and LBIC map of the 2x2 cm² back-junction silicon solar cell. The reduced signals above the base fingers and the base busbar are clearly visible.

Above the base busbar, the EQE drops down to nearly zero as if this area was totally shaded. Above the base fingers the EQE is only reduced to about 0.7 and thus it is more like a semi-transparent shading. For a more detailed investigation of the reduced signals above the base fingers, we have extracted line scans perpendicular to the fingers and compared them with numerical *Sentaurus Device (SDevice)* [5] simulations. Figure 3 shows the comparison between measurement and simulation for cells with different finger pitches and base resistivity of 1 Ω cm and 10 Ω cm. The width of the base area (BSF and gap) is the same for both finger pitches. The signal for the solar cell with 10 Ω cm base resistivity is always above the cell with 1 Ω cm base resistivity. One reason is the improved surface passivation of the front side, due to the high-low junction of the FSF [6]. Along the n-base finger, the LBIC signal is clearly reduced. This can be associated with a kind of *electrical* shading loss, due to the recombination at the base region rear side [7].

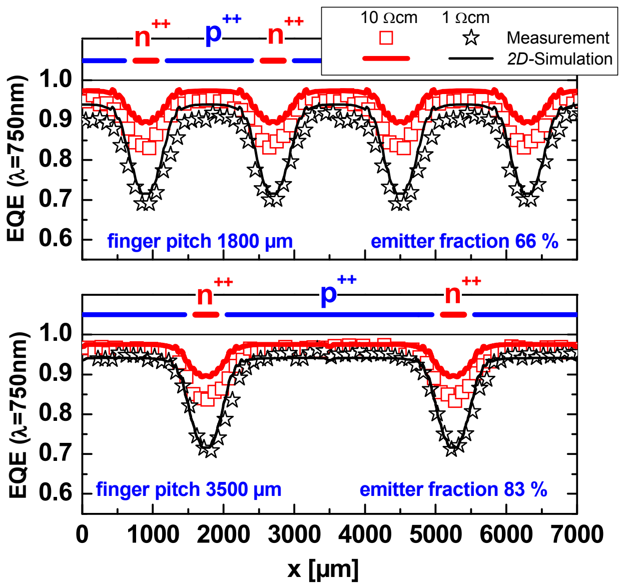

Figure 3: Simulated and measured EQE (λ=750 nm) line scan from cells with 1 and 10 Ω cm base resistivity and a finger pitch of 1800 µm and 3500 µm. The width of the base area (BSF and gap) is the same for both finger pitches.

In contrast to standard "*optical*" shading for cells with the metallization on the front side, this *electrical* shading is base-doping dependent as can be seen in the higher EQE for the cells with 10 Ω cm base resistivity in Figure 3. This is no lifetime effect, because the used SRH-lifetime in the simulated LBIC line scans is 1 ms for both doping concentrations. This increase of the EQE results mainly from an increased effective surface passivation of the rear side, due to the high-low junction of the BSF. The comparison of the two finger pitches show, that an increased emitter fraction leads to a higher medium EQE signal and thus to a higher short-circuit current density. Thus the *electrical* shading loss due to the base fingers are affected by the base doping, the passivation quality of the gap region (see Figure 1) and by the emitter fraction. This will be investigated in the next section.

ELECTRICAL SHADING DUE TO THE BASE FINGER

To investigate the influence of the rear side base region a two dimensional symmetry element of a back-junction solar cell (see Figure 1) was simulated. The results of these simulations for 10 Ω cm base resistivity (left column) and 1 Ω cm base resistivity (right column) are shown in Figure 4.

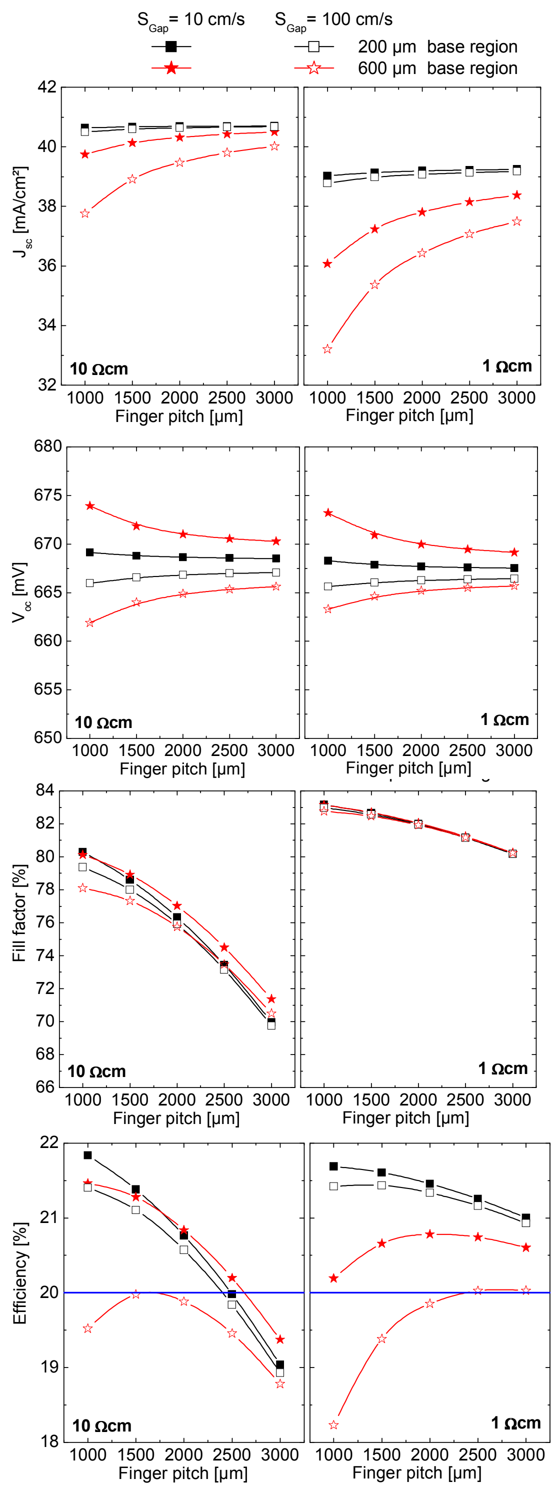

Figure 4: Simulated IV-parameter of the symmetry element in dependence of the finger pitch. The width of the base region is 200 µm (boxes) and 600 µm (stars) and the recombination velocity of the passivated gap region at the rear side 100 cm/s (open symbols) and 10 cm/s (filled symbols).

The passivation quality of the gap region, the finger pitch and the width of the base region were varied. An increase of the finger pitch or a decrease of the base region width leads to a higher emitter fraction of the rear side. The width of the BSF (50 µm) and the contact openings (30 µm) are fixed during all variations, since the dimension of the contact openings is limited by the used technology and cannot be reduced.

Regarding shading losses, the short-circuit current density is of major interest. It is obvious that increasing the emitter fraction increases the short-circuit current density. Further on, the passivation quality of the gap is more important for cells with broader base regions. Comparing the 1 Ω cm and 10 Ω cm base resistivity, there is on the one hand a difference for the cells with a high emitter fraction, which results from the differences in the effective passivation quality of the FSF. On the other hand, for the cells with broader base regions, the cells with higher base resistivity show a weaker dependence on the finger pitch than the cells with lower base resistivity. This correlates with the LBIC line scans in Figure 3. This is a result of an increased effective surface passivation of the rear side, due to the high-low junction of the BSF and high-injection effects, because the cell with 10 Ω cm base resistivity is already in high-injection at J_{sc}.

Regarding the open-circuit voltage the variations lead only to changes in V_{oc} smaller than 2 %. Depending on the passivation quality of the gap region, the dependence of the emitter fraction shows different behavior. For a very well passivated gap region, an increase of the finger pitch decreases V_{oc}, since $J_{0e} > J_{0,base}$. For higher recombination velocities at the gap surface V_{oc} increases with increasing finger pitches, since $J_{0e} > J_{0,base}$.

The fill-factor is mainly influenced by the finger pitch and the base resistivity due to the lateral conductivity in the base [4]. For the 1 Ω cm base resistivity there is nearly no influence of base width and passivation quality of the gap region. For the 10 Ω cm, the fill-factor is affected by the base width and the passivation quality of the gap. For larger finger pitches and a smaller base width, the carriers have a longer way in the emitter, and thus a higher series resistance loss occurs. In addition to the series resistance losses, higher recombination currents near V_{mpp}. reduces the fill-factor of the cells with the higher S_{gap}-values.

The efficiency comprises the above discussed effects and the following statements can be made:

- The efficiency increases with decreasing pitch width.
- Broader base regions decrease the efficiency, especially for lower base resistivity.
- The optimal finger pitch depends strongly of all investigated parameters.

An extrapolation of the results show, for very small finger pitches (< 100 µm) and an excellent surface passivation (< 10 cm/s), a reduction of the finger pitch would not decrease the current density, but increase V_{oc} and the fill-factor. This corresponds with the result of earlier calculations of Swanson [8] concerning the point contact back-junction solar cell, which reached highest efficiencies for a very low emitter fraction.

In this investigation additional series resistance losses due to the finger metallization are not regarded. If the width of the base finger is restricted to the width of the base region (to avoid shunts between base finger and the emitter), a high emitter fraction, and thus a small base region, leads to higher series resistance losses due to the narrow base finger. Thus in industrial-type back-junction solar cells, where series resistance losses due to longer fingers have been considered, broader finger pitches and thus smaller emitter fractions are necessary.

ELECTRICAL SHADING DUE TO THE BUSBARS

As can be seen in Figure 2, not only the base fingers show a reduced EQE. Above the base busbar the EQE is nearly zero. Thus, this area reduces also the current of the solar cell. In contrast to the base busbar the emitter busbar shows a very high EQE and thus did not reduce the current of the solar cell. To investigate the influence of the busbar regions we have simulated border-elements for the emitter and base busbar. Figure 5 shows the short-circuit current density of the base busbar border-element. An increasing base busbar width is accompanied by an increasing BSF. The emitter and the gap between the emitter and BSF are fixed. With increasing busbar width, the current density of the busbar border-element decreases, due to the fact, that more minority carriers have a longer distance to the pn-junction and recombine at the rear side or in the volume. The differences between the 10 Ω cm and the 1 Ω cm cell results again from the higher collection efficiency of the lower doped material.

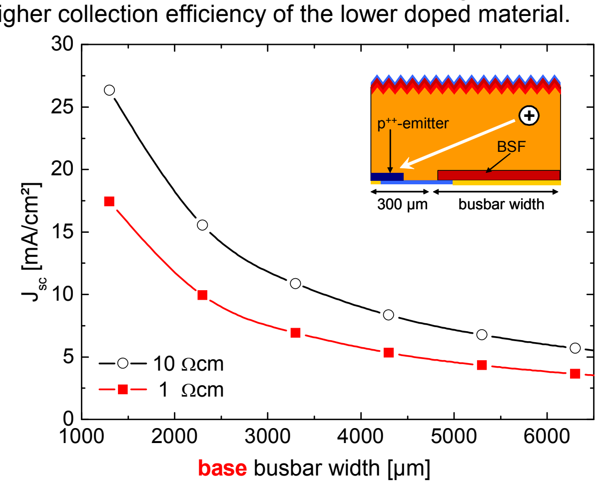

Figure 5: Simulated short-circuit current of the n^{++} - base busbar border-element in dependence of the busbar width.

As stated above, the emitter busbar didn't show a reduced current signal in the LBIC map, as the distance for the minority carriers to the pn-junction is at most the cell thickness. However, the majority carriers have to be extracted as well, and the distance to the base contact increases with increasing emitter busbar. This leads to a series resistance loss and thus to a reduction of the fill-factor. This fill-factor loss can be seen in Figure 6. The cell with 10 Ω cm base resistivity shows a stronger decrease of the fill-factor due to the higher series resistance losses. For a busbar width above 5000 µm, the fill-factor saturates to a value of 37 %. At this point, the short-circuit current density decreases and prevents a further decrease of the fill-factor.

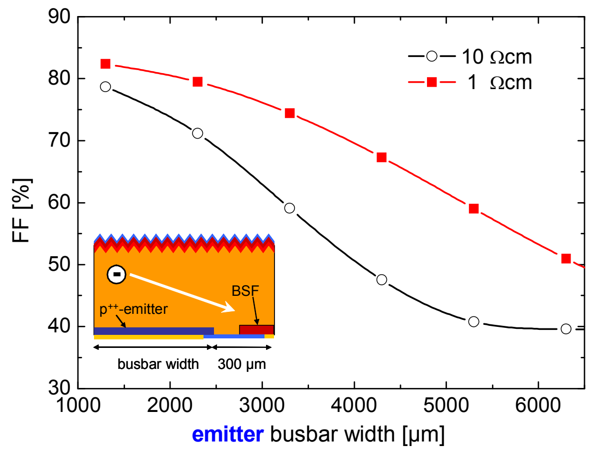

Figure 6: Simulated fill-factor of the p++ - emitter busbar symmetry element in dependence of the busbar width.

The curves shown in Figure 5 and Figure 6 reflect only behavior of the investigated symmetry element. To determine the influence of the busbars to the whole solar cell, we have performed a network-simulation based on *LTSpice* [9] including the ohmic losses and the non-generation losses [10] due to the metallization fingers and the losses due to the busbar regions. The investigated solar cell has an edge length of 125 mm and a metallization scheme which leads to an analytically calculated series resistance of 0.275 Ωcm² for 120 mm long fingers. The resulting efficiency as a function of the busbar width is shown in Figure 7. Plotted are the efficiencies of the elementary diodes (lines), which represent the area in between the busbars, the efficiency regarding only the series resistance losses do to the finger metallization (boxes) and the efficiency regarding finger metallization and the losses due to the busbars (stars).

The series resistance losses due to the metallization finger reduce the efficiency about 0.4 $\%_{,abs}$. With increasing busbar width, the series resistance losses decrease due to decreasing finger length. Taking the busbars into account, Figure 7 shows the decreasing efficiency with increasing busbar width. For a busbar fraction of 5 % the busbars decreases the efficiency of the cell due to the losses in current and fill-factor about 0.8 $\%_{,abs}$. Thus the *electrical* shading of the busbar regions leads to a strong reduction of the efficiency of the back junction solar cell, due to the reduction of the short-circuit current density and the fill-factor. Thus both busbar regions are responsible for the efficiency losses.

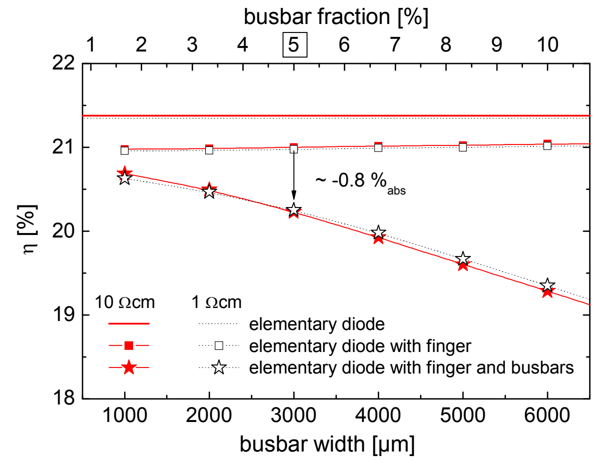

Figure 7: Simulated efficiency of a back-junction solar cell with an edge length of 125 mm depending on the busbar width.

SUMMARY

In this work, the electrical shading losses due to the base regions below the base fingers and due to the busbar regions were investigated. It could be shown, that a higher emitter fraction leads to higher efficiencies, especially for larger finger pitches. The simulations of the busbar regions have shown, that the base busbar leads to a reduction of the short-circuit current density, while the emitter busbar results in a reduction of the fill-factor. Thus both busbars reduces the efficiency of the back junction solar cells and should be designed as small as possible.

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