Open-rear side H-pattern optimization based on 2D computer simulations

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Abstract

Currently, photovoltaic-cell manufacturers are tending to use thinner wafers in order to reduce material costs. However, thin wafers that have a full aluminum (Al) rear coverage suffer from bowing and therefore have an increased chance of breakage. Another consequence of the thinner wafer is that the surface recombination velocity (SRV) of the rear side is getting more important for the overall cell performance. To overcome these problems one could use an open rear side (i.e. partial metal coverage) and passivate the wafer rear surface. In this paper, we will focus on an Al H-patterned rear metallization with two bus bars. The aim thereby is to attempt a first validation of the solar cell simulation software package Microtec against experiments and to get a better physics understanding of the open rear side cell. We performed a parameter study, where we calculated the standard output parameters like shortcut current (Isc), open-circuit voltage (Voc) and fill factor (FF) for varying cell parameters. The parameter space that has been explored is composed of the finger pitch, the finger width, the back surface field (BSF) depth, the Al doping concentration in the BSF and the surface recombination velocity (SRV) of the SiN_x in between the contacts.

Introduction

To reduce costs of solar electricity, solar-cell manufacturers are aiming for thinner wafers. This has two major consequences. Firstly, for thinner wafers the contribution of the rear side to the cell efficiency becomes more important. Secondly, the difference in thermal expansion coefficient of silicon versus aluminum causes cell bowing, which is accompanied by an increased breakage probability in production.

To overcome these problems a reduction of the rear-side aluminum coverage in combination with an enhanced passivation of the area in between the contacts is necessary. In mass production SiNx deposited by chemical vapor deposition, which is already used for the front side, is the ideal candidate for this.

In this work we restrict ourselves to an aluminum (Al) two-busbars H-patterned design applied on industrial mc-Si wafers. The aim thereby is to validate the model against experiments and to obtain a better physics insight into such an open rear-side cell.

The parameter that is of greatest importance of an open-rear side cell is the metallization fraction. It is evident that an increase of metallization causes an increase in fill factor due to a decrease in series resistance. For rear-side H-patterned cells this can be achieved by an increase of the finger width or by a decrease of the finger pitch, i.e. the heart-to-heart distance between two neighboring fingers. On the other hand, an increase of metallization leads to an increase of the effective (i.e. 'homogenized') surface recombination velocity (SRV). This caused by an increase of the contribution of the effective SRV of the Al contacts compared with that of the SRV of the SiNx. An increase of the effective 'homogenized' SRV causes a decrease of both the Isc and the Voc.

Due to the competition of the increasing FF on the one hand and the decreasing Isc and Voc on the other hand one can expect a metallization fraction between 0 and 1 at which the efficiency is optimal.

However, when the ratio of SRV_{SiNx}-to-SRV_{Al} is relatively high, an increase in metallization will result in a relatively low decrease in Isc and Voc, whereas the decrease in FF remains unchanged. In this case we expect the optimum efficiency to tend to full metallization.

The effective SRV of the Al contacts is determined by the properties of the back surface field (BSF). In general, an increase of the Al concentration and an increase of the BSF depth lead to a lower effective SRV.

Two-dimensional computer simulation

For the computer simulation we used the two-dimensional semiconductor simulation software package Microtec [refMicrrotec].

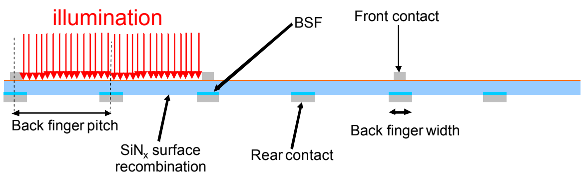

Figure 1 Two dimensional model used in simulation with Microtec.

We performed a parameter study in which computed the Isc, Voc, FF and efficiency. The parameter space that has been explored is composed by:

1. The rear finger pitch
2. The rear finger width
3. The Al concentration in the BSF.
4. The BSF well depth.
5. The SRV of the SiNx.

In Microtec we modeled Ohmic contacts at the front and the rear side, with a p–doped bulk zone, an n-doped emitter and a p+ doped Al BSF on top of the rear contacts. Attempts to model the effective SRV at the rear contacts rather than an explicit model for the BSF were unsuccessful. Due to symmetry we modeled a unit-cell with a length of half the front finger pitch and with front-to-rear finger ratios of 1:1, 1:2, 1:3 etc.. Furthermore, the model was characterized by the following properties: A base resistivity of 1 Ωcm and a life time of 16 μs. The internal reflection coefficients for front and rear were tuned by fitting a simulated IQE curve against an experimental one. This leads to coefficients of 0.93 and 0.94, respectively. These high values can be ascribed to the shortcoming of the model that diffusive scattering of light at the rear surface is not included. A negative side effect of this is, is that we were not able to make the internal rear reflectance dependent on the metallization fraction.

The IV values generated by Microtec were corrected for the series resistance of both the front (5 mΩ) and the rear contacts. The latter was calculated by a formula that was obtained by a fitting the series resistance computed by the program Patopt [[refPatopt] as function of the finger pitch and width. Main input parameters to this program were the resistivity of 7 $\cdot 10^{-5}$ Ωcm for the aluminum and the contact resistance of 5 mΩcm^2. From the IV values, corrected for the series resistance, the maximum power was derived.

Computational results

Below we will assess the cell-performance parameters for several combinations of the input parameters.

BSF effects

Figure 2 shows the cell power at the maximum power point (P_{mpp}) as a function of the rear finger pitch.

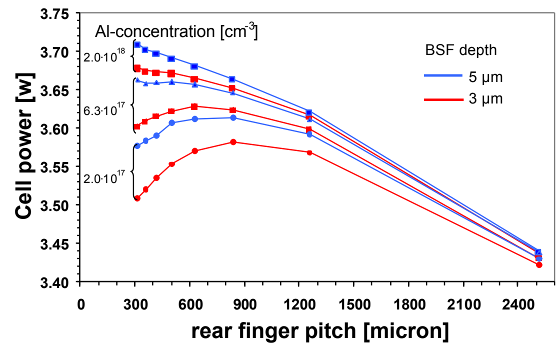

Figure 2 The cell-power (at mpp) as function of the rear finger pitch, with both the BSF depth and the Al-concentration as a parameter. Here the S_{SiNx}= 250 cm/s, the rear finger width = 300 μm and the number of front fingers is 62.

Note that the metallization increases with decreasing finger pitch. Figure 2 shows that both an increase of the BSF depth and an increase of the Al concentration in the BSF result in a higher cell power. Furthermore we note that the optimum shifts to a lower pitch, and hence a higher metallization. For an Al concentration of 6.3 $\cdot 10^{17}$ cm^{-3} and a BSF depth of 3 μm the optimum lies at a finger pitch of 630 μm. This corresponds with a front-to-rear finger ratio of 1:4 and metallization fraction of about 50%. For an Al concentration of 2 $\cdot 10^{18}$ cm^{-3} we can observe that optimum disappears. This concentration and a BSF depth of 3 μm correspond with an effective SRV for the Al contacts of about 700 cm/s [refLolgen]. Since the SRV for the SiNx in this calculation is about 250 cm/s the SRV_{SiNx}-to-SRV_{Al} ratio is relatively high, namely 0.35. For a BSF depth of 5 μm, this ratio even tends to 0.6 [refLolgen]. It is evident that the closer the SRV_{SiNx}-to-SRV_{Al} gets to unity, the more the optimum will shift to full metallization, for the effect of a deteriorating Isc an Voc with increasing metallization is dominated by the much stronger enhancement of the fill factor.

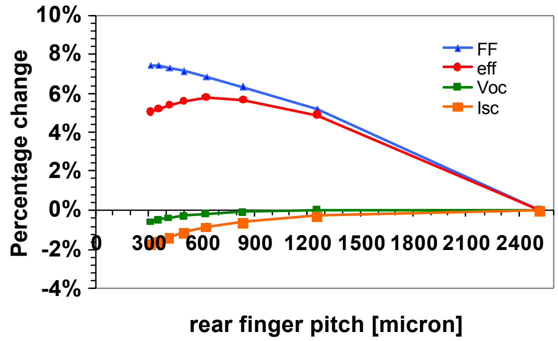

Figure 3 The percentage change of the cell parameters as a function of the rear finger pitch. Here, the Al BSF doping concentration is 6.3 $\cdot 10^{17}$ cm^{-3} and the BSF well depth is 3 μm. This case belongs to the power curve in Figure 2 with the corresponding parameters.

Figure 3 shows the percentage change of the cell parameters, for the case of a BSF depth of 3 μm and an Al concentration of 6.3 $\cdot 10^{17}$ cm^{-3}. Here, the reference point is defined at the front-to-rear finger ratio of unity. From this figure we see that the competition of an increasing Voc and Isc with increasing pitch is counteracted by a decrease in fill factor, which in total leads to the occurrence of an optimum in efficiency that lies at a rear finger pitch of 630 μm.

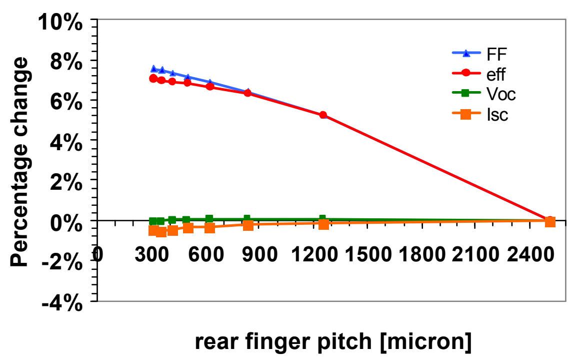

Figure 4 The percentage change of the cell parameters as a function of the rear finger pitch. Here, the Al BSF doping concentration is 2 $\cdot 10^{18}$ cm^{-3} and the BSF well depth is 3 μm. This case belongs to the power curve in Figure 2 with the corresponding BSF parameters.

Figure 4 shows the competition between Voc and Isc on the one hand and the FF on the other, where the FF is the dominant factor and is therefore setting the trend of a decreasing efficiency with increasing rear finger pitch. This implies that in this case full metallization yields the maximum efficiency.

Here we seem to have arrived at a paradox. Our aim is to achieve less metallization coverage to prevent cell bowing. To this end we need a good quality rear surface. The latter can be achieved by having a good BSF. However a good BSF makes the SRV_{SiNx}-to-SRV_{Al} ratio tend to unity. Then the relative decrease in Voc and Isc is small with increasing metallization and is over-shadowed by the increasing FF. This on its turn causes the maximum efficiency to shift to full metallization.

However, one should note that the P_{mpp} at a rear finger pitch of 630 μm is higher for the Al concentration of 2 $\cdot 10^{18}$ cm^{-3} than for the 6.3 $\cdot 10^{17}$ cm^{-3} concentration, although the former is off-optimum and the latter is on the optimum.

There seems to be two approaches to attain an efficiency optimum at lower optimization. Thinking in terms of the relatives changes depicted in Figure 3 and Figure 4, one should either make the Voc and Isc more tilted or make the FF curve more flat. We expect that the former can be achieved by decreasing the SRV_{SiNx}-to-SRV_{Al} ratio. Put differently, for a given BSF with a corresponding effective SRV_{Al}, the SRV_{SiNx} should be lowered, which can be achieved by further improving the passivation of SiNx. A curve for the percentage change of the fill factor that is more flat can be obtained by reducing the series-resistance dependence of the metallization. Note that this is different from simply reducing the series resistance. E.g. reducing the series resistance of the front fingers will act adversely in terms of finding an optimum at low metallization, since then the series-resistance dependence of the rear metallization fraction becomes more pronounced and therefore the curve more tilted. A lower series-resistance dependence of the rear metallization fraction might be obtained by a lower resistivity of the aluminum in the fingers, or shorter fingers and thus more busbars.

Below we will first focus on the effect of a varying SRV for the SiNx and thereafter on the series resistance.

SINX SURFACE RECOMBINATION EFFECT.

Figure 5 shows the eefficiency as function of the rear finger pitch, with the SRV for SiNx as parameter. For 10 < SRV_{SiNx} < 250 cm/s the position of the optimum remain at a rear finger pitch of 672 µm. This corresponds with a front-to-rear finger ratio of 1:4 and metallization fraction of about 50%.

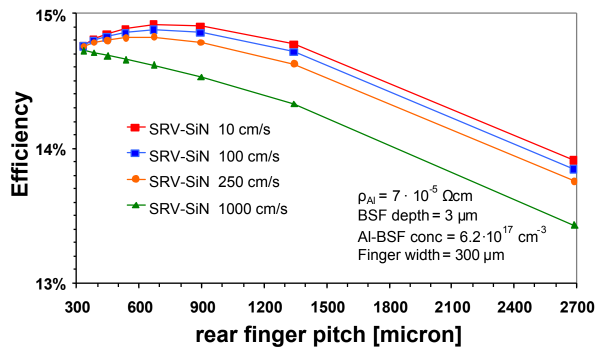

Figure 5 Efficiency as function of the rear finger pitch, with the SRV for SiNx as parameter. Number of front fingers is 58.

So, a reduction of the SRV_{SiNx} from to 250 to 10 cm/s obviously leads to a higher efficiency but not to a shift of the optimum to higher pitches (lower metallization). However, the same value of the efficiency corresponding to the optimum of the 250 cm/s can be obtained for a SRV_{SiNx} from of 10 cm/s at a pitch of 1345 µm. This corresponds with a front-to-rear finger ratio of 1:2 and metallization fraction of 30%.

For a SRV_{SiNx} of 1000 cm/s, the SRV_{SiNx}-to-SRV_{Al} ratio has become so high that the Voc and Isc hardly change by varying the rear finger pitch so that the increasing fill factor with decreasing pitch (increasing metallization) dominates and therefore the optimum lies at full metallization.

SERIES RESISTANCE EFFECT.

FIGURE 6 shows the efficiency as a function of the rear metallization fraction. For one curve the series resistance of the H-patterned Al back contact is included, whereas for the other it is omitted. As we showed before the optimum for the former case occurs at about 50% metallization (front-to-rear finger ratio of 1:4). The omission of the series resistance of the rear contact obviously leads to an increase in efficiency and moreover to a shift of the optimum towards 25% metallization (front-to-rear finger ratio of 1:2) or lower. Apparently a competition between the increasing FF on the one hand and a decreasing Voc and Isc with increasing metallization is still present.

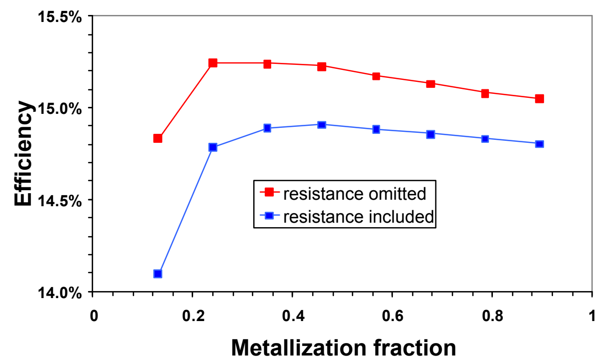

Figure 6 Efficiency as a function of the metallization where the series resistance of the rear H-patterned contact has been included and omitted. (62 front fingers, ρ_{Al}= 7 10^{-5} Ω cm, finger width=300µm, BSF-depth 3µm, BSF Al-conc.=6.3 10^{17} cm^{-3}.)

In order to verify that, we have plotted the cell percentage change of the parameters again against the metallization fraction.

Figure 7 reveals that the fill factor still increases with 4% if the metallization fraction increases from 14% to 95%. Here, the fill factor does not include the series resistance of the Al H-patterned rear contact. This implies that the change in FF comes from inside the cell. By comparing the FF-curve of Figure 3 and the FF0-curve of Figure 7 we can observe that contribution of the latter is about half of the total FF change. It seems likely that the FF0 increase with increasing metallization can be ascribed to Ohmic losses that the majority carriers in the p-layer (holes) suffer. In order to verify that, we have repeated the computation, but now with a mobility of the holes that is twice as high. Figure 8 shows that then the FF0-curve is indeed increasing only by 2% rather than by 4%, whereas the Voc and Isc curve remain unchanged.

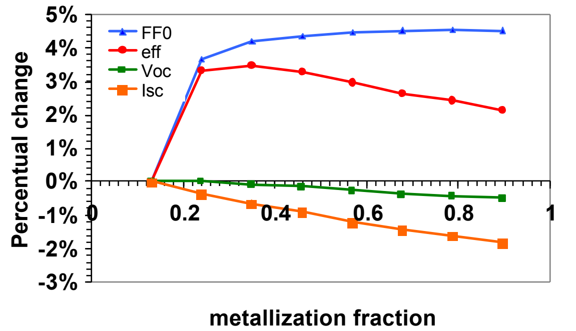

Figure 7 Percentage change of the cell parameters as a function of the metallization. Here, FF0 is the fill factor that excludes the series resistance of the Al H-patterned rear contact. (58 front fingers, ρ_{Al}= 0 Ω cm, finger width=300μm, BSF-depth 3μm, BSF Al-conc.=6.3 10^{17} cm^{-3}.)

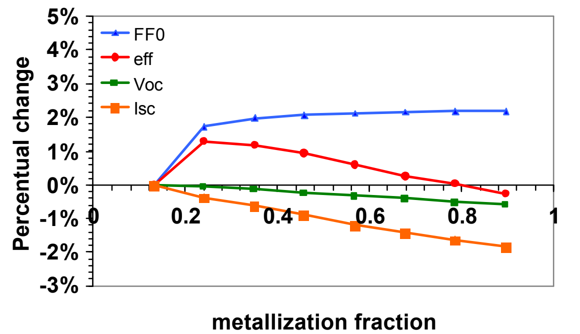

Figure 8 Percentage change of the cell parameters as a function of the metallization. Here, FF0 is the fill factor that excludes the series resistance of the Al H-patterned rear contact. In this calculation the mobility of the holes is set to twice its normal value. (58 front fingers, ρ_{Al}= 0 Ω cm, finger width=300μm, BSF-depth 3μm, BSF Al-conc.=6.3 10^{17} cm^{-3}.) Compare the relatively low FF0 with that of Figure 7 (normal hole mobility).

A natural choice to reduce the Ohmic losses from which the majority carriers in the base suffer is to enhance the conductivity by increasing the bulk p-doping. To this end we carried out a new computation where we increased the p-doping with a factor of four, for the case where we have a BSF-depth of 3μm and BSF Al-conc. of 2 $\cdot 10^{18}$ cm^{-3}.

Figure 9 shows that the slope of the FF-curve is less steep compared with that of Figure 4, which represents its counterpart with the initial doping concentration. Whereas the latter case does not show an optimum in efficiency, the highly doped case does at a pitch of 500 μm (i.e. a front-to-rear finger ratio of 1:5 which corresponds with a metallization of 60%).

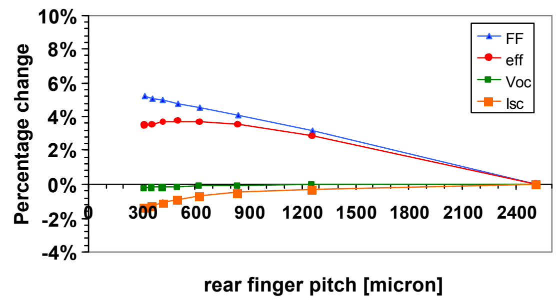

Figure 9 The percentage change of the cell parameters as a function of the rear finger pitch. Here, the Al BSF doping concentration is 2 $\cdot 10^{18}$ cm^{-3} and the BSF well depth is 3 μm. In this case de bulk p-doping was augmented by a factor of four.

COMPARISON WITH EXPERIMENT

At ECN new PASHA-cells (Passivated on All Sides H-patterned cells) were produced where a single silicon-nitride (SiN_x:H) layer for rear surface passivation in combination with an open, firing-through, Al metallization have been applied [refRomijn]. These Pasha cells were processed with front-to-rear finger ratios of 1:1, 1:2, 1:3 and 1:4, corresponding with metallization fractions ranging from 16% to 60-70%.

Figure 10 shows the efficiency as a function of rear-finger pitch both for the simulation and the experiment. The simulation shows some deviation from the experimental data, although both show the same trend, namely an increase of the efficiency with decreasing finger pitch. The deviation can be ascribed to the fact that, at the time of writing of this paper, not all input parameters for the model were clear. We therefore assumed values that are close to what has been observed before.

Figure 11 reveals that for both experiment and simulation the fill factor is setting the trend for the increasing efficiency with decreasing finger pitch (increasing metallization).

Furthermore, the experimental data show a stronger decrease of the Isc with decreasing finger pitch, which might be attributed to the deteriorating overall reflectance, due to an increasing contribution of the relatively poor reflecting aluminum. As mentioned before, this effect could not be included in the simulations.

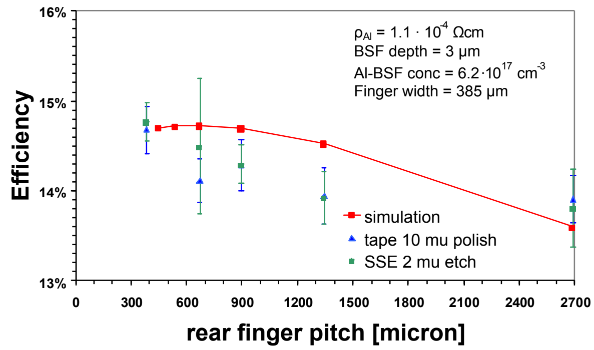

Figure 10 Comparison of experiment (symbols) and simulation (line). The mentioned BSF parameters have been assumed, whereas the others were measured.

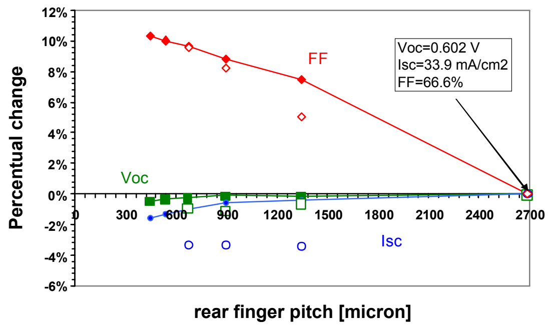

Figure 11 Cell parameters as a function of rear-finger pitch, for simulation (lines) and experiments (open symbols).

Conclusions and recommendations

Simulations of open-rear side PV cells with aluminum H-patterned rear contacts, with a 1 Ωcm base resistivity and a BSF with an Al-doping of 2 $\cdot 10^{18}$ cm^{-3} and a depth of 3 µm show an increasing efficiency with increasing metallization (decreasing finger pitch). This can be attributed to the much stronger percentage increase of the fill factor (+10%) than the percentage decrease of both Isc(-1%) and Voc(<1 % negative), with increasing metallization.

About half of the increase of the fill factor can be attributed to the series resistance of the H-patterned rear contact. The remainder stems from the resistivity that the majority carriers are experiencing in the base of the device.

The trends of the cell parameters are corroborated in experiments with PASHA cells although the experimental percentage decrease in the Isc is higher (-4%).

In order to achieve the industry objective to use thinner wafers, a partial metallization at the rear side is required. To do this without loss of efficiency, or preferably with a gain in efficiency, some measures are to be taken. These might include:

- Lowering the rear series resistance, by reducing the finger length, by introducing more bus bars.
- Tapering of fingers
- Enhancing the conductivity in the base.
- More but smaller fingers.

Acknowledgements

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