Quantum Efficiency Analysis of Highly Doped Areas for Selective Emitter Solar Cells

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Abstract

The increase of solar cell efficiency via the implementation of a selective emitter in crystalline silicon solar cells is currently under research and partly in transition into production. The choice of the doping profile underneath the contacts can have significant impact on cell efficiency. In this work, the quantum efficiency of highly doped areas and its impact on the short circuit current are investigated. The aim of this work is to assess the influence of highly doped illuminated areas, which can possibly diminish the gain of the selective emitter structure regarding $J_{SC}$. Areas of high doping are created by the technique of laser induced diffusion. The doping profile is varied by adjusting the laser pulse energy. The IV characteristics and spectral response of finished solar cells are measured. The internal quantum efficiency is analyzed using a model proposed by Fischer. Deeper diffused profiles are found to have larger dead layers and a linear correlation between the dead layer thickness and the resultant short circuit current is observed. The impact on solar cells with selective emitter is discussed.

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Selective Emitter; Laser Processing; Quantum Efficiency

1. Introduction

Selective emitter solar cells enable the improvement of the solar cell efficiency by decoupling the requirements of the emitter for contact formation at the metal-semiconductor interface and conversion of photons into free charge carriers. Lowly doped emitters feature a potential for higher open circuit voltages and also lower losses of converted charge carriers both due to reduced recombination in the emitter. This results in a higher short circuit current density $J_{SC}$ and a higher open circuit voltage $V_{OC}$. However, the commonly used technology for metallization is screen printing which poses certain restrictions for the doping in order to ensure the formation of an ohmic contact on the front side of the device. Thus, in a

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selective emitter solar cell, a different level doping underneath the contacts is implemented.

Different technologies for the formation of selective emitters have been proposed, well summarized in [1]. Most of these technologies are not “self-aligned”; therefore the metallization needs to be aligned to the prior formed areas of high doping. Thus the inclusion of certain tolerances is required and the high doping underneath the metal fingers is chosen broader than the latter metallization. This results in illuminated regions of high doping, which is around 2-10% of the total cell area, depending on the precision of the alignment. As these areas are highly doped and exhibit high losses, they diminish the intended gain in efficiency of the selective emitter solar cell. The choice of the doping profile underneath the contacts can have significant impact on open circuit voltage as well [2, 3].

In this paper we investigate the losses caused by the highly doped illuminated areas. This work focuses on the impact of the quantum efficiency, thus short circuit current, of the highly doped areas on cell level. In our experiments, we apply the technology of selective laser doping as presented in [4-6] for the selective emitter formation. The layer of PSG after thermal diffusion serves as a doping precursor and additional phosphorous is driven into the substrate during the laser induced diffusion.

2. Experimental details

2.1. Sample preparation

Solar cells with a size of 50x50 mm² were fabricated on 180 μm thick, 2 Ωcm Cz-Si alkaline textured base material. After a shallow thermal POCl₃ diffusion (R_sheet = 120 Ω/sq), laser overdoping was performed on the entire cell area to allow for a latter investigation of the properties of the highly doped areas. The level of doping was altered for the different solar cells by modifying the doping profile by adjusting the laser pulse energy (figure 1). This resulted in sheet resistances between 26 Ω/sq for the lowest applied pulse energy and 17 Ω/sq for the highest. After laser processing the remaining PSG was etched off and subsequently SiNₓ anti-reflection coating was applied to the front side by means of PECVD. The solar cells received an aluminium back surface field and screen printed front contacts. The cells were submitted to a contact firing step and were cut out to 50x50 mm². Finally, after 36h of light induced degradation, the IV characteristics and the spectral response of the cells were measured. As a reference, solar cells with selective high doping only underneath the fingers were fabricated in the same batch.

Laser processing was performed with a Coherent AVIA 355-X solid state laser with a wavelength of 355 nm and a pulse width of approximately 25-30 ns. The pulse energy was adjusted by a variable optical attenuator. The laser beam features a spatial Gaussian beam intensity distribution.

2.2. Doping profiles

By adjusting the laser pulse energy it is possible to influence the resulting doping profile. Larger pulse energies lead to deeper and longer melting of the substrate, thus leading to a deeper diffusion of the phosphorous. This is illustrated in Figure 1.

Although the profiles were acquired on non textured surfaces, the trend of the evolution of the doping profile with increasing pulse energy is also expected on textured surfaces. The differences in the doping profiles are expected to have a significant impact on the quantum efficiency and short circuit current density of the cells.
3. Results and discussion

3.1. Quantum efficiency and short circuit current

Figure 2 shows the internal quantum efficiencies (IQE) of the finished solar cells with the laser pulse energy as a parameter. The measurement takes into account the reflection of the front side metallization of the cells as well as the slightly altered surface due to the laser process, by measuring the front side reflection as described in [7]. Higher pulse energies, thus deeper diffused profiles, yield very low quantum efficiencies at the lower end of the spectrum. This behavior is expected as deep diffused emitters with high surface doping exhibit considerable Auger recombination over a not negligible distance. Thus, spectral response of light at short wavelengths, which generate charge carriers near the front surface, is poor.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{SC,cell}$</td>
<td>Short circuit current density of selective emitter cell [mA/cm$^2$]</td>
</tr>
<tr>
<td>$J_{SC,high}$</td>
<td>Short circuit current density of the highly doped region in selective emitter cell [mA/cm$^2$]</td>
</tr>
<tr>
<td>$J_{SC,low}$</td>
<td>Short circuit current density of the lowly doped region in selective emitter cell [mA/cm$^2$]</td>
</tr>
<tr>
<td>$f$</td>
<td>Fraction of illuminated cell area with high doping</td>
</tr>
<tr>
<td>$E_p$</td>
<td>Laser pulse energy [$\mu$J]</td>
</tr>
<tr>
<td>$M$</td>
<td>Metallization fraction</td>
</tr>
</tbody>
</table>
The impact of this differing spectral response on the short circuit current density $J_{SC}$ is shown in Figure 3. $J_{SC}$ is measured from the illuminated IV curve and also calculated from integration of the external quantum efficiency (EQE). A drastic decrease of $J_{SC,cell}$ with increasing pulse energy can be ascertained: the deep diffused profiles ($E_P > 100 \, \mu J$) generate over 10% less current than shallower ones ($E_P = 60 \, \mu J$). The deviation of the directly measured values of $J_{SC}$ and those calculated from the measured EQE is below 1% for all considered cells here. This allows the use of the quantum efficiencies for further analysis of the laser doped emitters.

### 3.2. Dead layer model

Fischer [8] has proposed an extended evaluation of the internal quantum efficiency [8]. A so called dead layer with thickness $W_d$ models the region of the emitter with collection probability 0 and thus no generated current. This layer thickness is extracted from the measured internal quantum efficiency

$$\text{IQE}_{\text{measured}} = \frac{1}{k} \exp\left(-\frac{W_d}{L_{\alpha}}\right) \frac{1}{1 + \frac{L_{\alpha}}{L_{\text{eff}}}} \tag{1}$$

via linear regression together with a scaling factor $k$, the absorption length $L_{\alpha}$ and the effective absorption length $L_{\text{eff}}$. In Figure 3 the dead layer width $W_d$ (right y axis) is plotted against the pulse energy: over a broad range of pulse energies, a linear increase in dead layer thickness with increasing pulse energy is observed, only at the highest chosen pulse energy the dead layer thickness stays constant. Note that in this regime of pulse energies, the doping depth also increases linearly. The influence of this behavior of $J_{SC,high}$ of the highly doped regions on selective emitter cells is discussed in the next section.

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**Fig. 3.** Short circuit current density $J_{SC}$ and dead layer thickness $W_d$ in dependence of applied laser pulse energy. $J_{SC}$ is measured from the IV light curve and calculated by integration of the EQE. The shifted values of $J_{SC}$ on the y axis are taking the shaded, metalized area into account: $J_{SC,high} = J_{SC}(\text{EQE}) / (1-M)$. As a guide to the eye, polynomial fits are shown for either curve.

**Fig. 4.** Impact of the variation of the short circuit current density of the highly doped region covering an illuminated area $f$ on the short circuit current density $J_{SC,cell}$ of a selective emitter solar cell.
3.3. Impact on selective emitter solar cells

To actually extract the short circuit current density of the highly doped region $J_{SC,high}$ from the quantum efficiency measurement, the integrated value of the EQE needs to be corrected because of the metallization by a factor of $1/(1-M)$. This results in values of $J_{SC,high} = J_{SC}(EQE)/(1-M) = 37.3 \text{ mA/cm}^2$ for the lowest pulse energy (60 µJ) and $J_{SC,high} = 34.0 \text{ mA/cm}^2$ for the highest (140 µJ).

To estimate the effect that a varying short circuit current density of the highly doped regions has on a selective emitter solar cell, the following cell geometry is assumed: an industrial selective emitter solar cell using 156x156x0.18 mm³, 2 Ωcm, p-type Cz-Si wafers is considered. A short circuit current density of 37 mA/cm² is supposed for perfect alignment (width highly doped area = width of metallization finger) conditions. The percentage of the highly doped area $f$, which is illuminated, is varied from 0 to 15% to consider different alignment precision. The short circuit current density on cell level can be calculated through the area weighted mean if the cell geometry, $J_{SC,high}$ and $J_{SC,low}$ are known:

$$J_{SC,Cell} = (1 - M) \cdot \left[ (1 - f) J_{SC,low} + f \cdot J_{SC,high} \right]$$ (2)

The loss in $J_{SC,Cell}$ due to the inclusion of alignment tolerances can be calculated through

$$\Delta J_{SC,Cell} = J_{SC,Cell} \bigg|_{f=0} - J_{SC,Cell} \bigg|_{f>0}$$ (3)

This yields after simplification

$$\Delta J_{SC,Cell} = (1 - M) \cdot f \cdot \left( J_{SC,low} - J_{SC,high} \right)$$ (4)

Depending on the applied level of doping and percentage the highly doped area actually covers, the loss in short circuit current density $J_{SC,Cell}$ can accumulate up to 1 mA/cm². This is illustrated in Figure 4: The loss in $J_{SC,cell}$ is displayed dependent on the measured value for the short circuit current density of the highly doped region $J_{SC,high}$ and its area coverage. To clarify this, values for the loss in the short circuit current $\Delta J_{SC,Cell}$ on solar cell level are given in Table 1. At low coverage fractions $f$ the loss in short circuit current is moderate, i.e. $\Delta J_{SC,cell} < 0.15 \text{ mA/cm}^2$. However, if due to poor alignment, a high percentage of the illuminated area is highly doped, losses in the short circuit current are substantial, and can easily exceed the gain, that was achieved by implementing the selective emitter. Therefore, it is imperative to assure a good alignment between areas of high doping and metallization to avoid excessive losses.

Table 1. Losses in $J_{SC,cell}$ if areas of high doping with poor spectral response are illuminated.

<table>
<thead>
<tr>
<th>Fraction $f$ of illuminated area with high doping [%]</th>
<th>Relation of width of high doping and metallization finger</th>
<th>Loss $\Delta J_{SC,cell}$ if $J_{SC,high} = 37.3 \text{ mA/cm}^2$ [mA/cm²]</th>
<th>Loss $\Delta J_{SC,cell}$ if $J_{SC,high} = 34.0 \text{ mA/cm}^2$ [mA/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (perf. alignment)</td>
<td>1 : 1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>1.5 : 1</td>
<td>0.06</td>
<td>0.13</td>
</tr>
<tr>
<td>4.4</td>
<td>2 : 1</td>
<td>0.12</td>
<td>0.26</td>
</tr>
<tr>
<td>6.6</td>
<td>2.5 : 1</td>
<td>0.18</td>
<td>0.40</td>
</tr>
<tr>
<td>8.8</td>
<td>3 : 1</td>
<td>0.24</td>
<td>0.53</td>
</tr>
<tr>
<td>11.1</td>
<td>3.5 : 1</td>
<td>0.29</td>
<td>0.66</td>
</tr>
<tr>
<td>13.3</td>
<td>4 : 1</td>
<td>0.35</td>
<td>0.79</td>
</tr>
<tr>
<td>15.5</td>
<td>4.5 : 1</td>
<td>0.41</td>
<td>0.92</td>
</tr>
</tbody>
</table>
3.4. Verification on solar cell level

This loss in short circuit current density was verified on solar cell level. Selective emitter solar cells with an area fraction $f = 13\%$ (e.g. 90 µm wide fingers, finger pitch of 1.8 mm and 345 µm width of high doping) of highly doped illuminated area were fabricated as described in Section 2.1. Two pulse energies were applied for the formation of the high doping: 60 and 110 µJ. Table 2 lists both the measured and calculated values for $J_{SC,\text{cell}}$. The values for $J_{SC,\text{cell}}$ are calculated by an area weighted mean of $J_{SC,\text{high}}$ and $J_{SC,\text{low}}$, according to eq. (4). In this calculation, it is assumed that no generation takes place underneath the metallization, which covers 7% of the cell area. $J_{SC,\text{low}} = 39.2 \text{ mA/cm}^2$ is adapted to reproduce the measured values. It can be ascertained that the difference in level of doping strongly influences the resulting $J_{SC,\text{cell}}$. Note that in an actual selective emitter solar cell, alignment tolerances will be chosen that $f = 1-5\%$ and thus the loss in $J_{SC,\text{cell}}$ due to the high doping will be lower than the values presented in Table 2. However, the modeling of $\Delta J_{SC,\text{cell}}$ through equation (4) is experimentally observed on solar cell level and allows prediction of losses implicated by a non perfect alignment of the metallization.

Table 2. $J_{SC,\text{cell}}$ of selective emitter solar cells and calculated losses according to equation (4)

<table>
<thead>
<tr>
<th>Fraction $f$ of illuminated area with high doping [%]</th>
<th>Data base</th>
<th>$J_{SC,\text{cell}}$ of solar cell processed with $E_p=60 \mu J$ [mA/cm²]</th>
<th>$J_{SC,\text{cell}}$ of solar cell processed with $E_p=110 \mu J$ [mA/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 Measured (6 cells)</td>
<td>Calculated</td>
<td>36.06 ± 0.05</td>
<td>35.47 ± 0.05</td>
</tr>
<tr>
<td>13 Calculated</td>
<td>Calculated</td>
<td>36.09</td>
<td>35.62</td>
</tr>
<tr>
<td>0 (ideal alignment)</td>
<td>Calculated</td>
<td>36.35</td>
<td>--</td>
</tr>
<tr>
<td>-- Loss $\Delta J_{SC,\text{cell}}$ (meas.)</td>
<td></td>
<td>0.29</td>
<td>0.88</td>
</tr>
<tr>
<td>-- Loss $\Delta J_{SC,\text{cell}}$ (calc.)</td>
<td></td>
<td>0.26</td>
<td>0.73</td>
</tr>
</tbody>
</table>

4. Conclusion

The quantum efficiency of the highly doped areas in laser doped selective emitter solar cells has been investigated. Adjusting the laser pulse energy, it is possible to influence the doping profile. The variation in doping profile has an impact on the resultant quantum efficiency and thus short circuit current. Deeper diffused profiles exhibit lower quantum efficiency in the short wavelength region compared to shallower ones. A proposed model by Fischer uses the concept of a dead layer for quantification of low spectral responses in the short wavelength region. A linear correlation between the modeled dead layer thickness $W_d$ and the measured short circuit current density $J_{SC}$ is found over a broad range of pulse energies, thus doping profiles. An estimation of the impact of this issue on selective emitter solar cells shows that the increase in short circuit current can be actually undone if excessive alignment tolerances are included in the solar cell. This is verified on solar cell level, clarifying the need for small alignment tolerances.

Acknowledgements

The authors acknowledge the help of Elisabeth Schäffer and Sebastian Schmutzler in measuring the cells. This work was partly funded by the German Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under contract no. 0329849B.
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