Bifacial a-Si:H solar cells: Origin of the asymmetry between front and back illumination

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Abstract
The asymmetry in performance between front and back illumination of a single-junction bifacial hydrogenated amorphous silicon (a-Si:H) cell is analyzed by numerical simulation using the ASA software and compared to experimental results. It is found that the difference between the band mobility of electron and the one of holes, and especially the difference in the band tail characteristic energy values are responsible for the asymmetry. The latter is characterized by a reduction in the cell current and $FF$ for an illumination through the $n$-layer. The magnitude of this reduction, due to a deficient collection of holes, increases with increasing cell thickness.

1. Introduction
a Si:H cells are designed in such a way to have illumination of the active layer of the device through the $p$-layer. This design rule permits generation of the light as close to the $p$-layer as possible to minimize the length holes have to travel to be collected. As a matter of fact, experiments show that bifacial a Si:H cells exhibit reduced performance when illuminated through the $n$-layer. The situation has been analyzed in details by numerical simulations [1][2], however, with semiconductor models which did not take into account the amphoteric nature of the a-Si:H defects (dangling bonds).

For some uncommon applications of cells deposited on metallic substrates (e.g. solar cells deposited on dials for watches), the use of a $p$-$i$-$n$ configuration is required in order to have the positive contact on the substrate. It is therefore necessary to understand the intrinsic limitations of such devices and to get indications for their optimization.

The main objective of this paper was, therefore, to compare experimentally and by simulation $p$-side (through the $p$-layer) and $n$-side (through the $n$-layer) illumination and (from the simulation) to identify the material and device parameters responsible for the differences in performance regarding the illumination side. We therefore also aim at verifying the basic assumption that the asymmetry is related to a difference in the carrier band mobilities, as identified in the previous simulation studies [1][2], and to quantify the loss for back illumination.
2. Experimental and simulation details

Bifacial cells (0.3 and 1 µm thick) were deposited on ZnO coated glass superstrate (p-i-n) configurations by VHF PE-CVD (Very High Frequency Plasma Enhanced Chemical Vapor Deposition) at temperatures around 200°C in a KAI S reactor at operated at 40 MHz [3]. A second ZnO layer was deposited as a back contact and individual diodes were defined by a patterning of the back ZnO followed by a dry etching of the a-Si:H layers using the patterned ZnO as a mask. All ZnO layers were ca. 2 µm thick and were deposited by LP-CVD doped with boron [4]. Note that these layers exhibit a rather strong natural texturing which enhances light-trapping in the cells.

Measurements of current as a function of voltage $I(V)$ were performed for $p$-side and $n$-side illumination using a two light sources WACOM solar simulator under a AM1.5g like illumination spectra at 100 mW/cm². Measured $I(V)$ were renormalized from current deduced from external quantum efficiency ($EQE$) under AM1.5g illumination, in order to compensate for shadowing effect by the cell contacts.

Simulation of the bifacial cells was performed with the ASA (Advanced Semiconductor Analysis) software [5]. Simple bifacial structures without the glass superstrate and with flat interfaces were simulated using standard electrical and optical parameters (using parameters supplied with the simulation program) for all a-Si:H layers and assuming standard defect model [6][7]. Actual layer thicknesses were used as well as actual ZnO optical parameters. As the objective of this papers were more qualitative than quantitative, we did not attempt to reproduce exactly the $I(V)$ and $EQE$ data of the experimental cells. For the same reasons, no roughness and therefore no light scattering were introduced.
3. Experimental results

$EQE$ (in short-circuit conditions) for $p$-side and $n$-side illumination of 0.3 $\mu$m and 1 $\mu$m thick bifacial cell are plotted in Figure 1. For all cells, the response at long wavelengths is almost identical for $p$-side and $n$-side illumination, while a marked reduction is observed for response in the blue when illuminating the cell through the $n$-layer as well as when increasing the cell thickness. Even though a difference is expected between front and back illumination from optical considerations, due to the higher bandgap of $p$-layers compared to $n$-layers. However, part of this effect can be attributed to a limiting hole collection for $n$-side illumination; this collection problem is also clearly seen when the cell thickness is increased.

![Figure 2](image-url)  

Figure 2  $EQE$ curves for a 0.3 $\mu$m and a 1 $\mu$m thick $p$-$i$-$n$ cells for illumination through the $p$-, resp. through the $n$-layer.

As seen in Fig. 3, illumination through the $n$-layer reduces significantly the current extracted from the cell (compared to $p$-side illumination). For a 1 $\mu$m thick cell, this reduction is approx. 25% in short-circuit conditions. Very small changes in the open-circuit voltage $V_{oc}$ are observed when changing the illumination side, while the field-factor $FF$ is reduced very significantly for the thick cell.
Figure 3  \( I(V) \) curves for a 0.3 µm and a 1 µm thick \( p-i-n \) cells for illumination through the \( p \)-, resp. through the \( n \)-layer, with the corresponding fill-factor \( FF \) values.

4. Simulation results and discussion

Simulations of \( p-i-n \) devices illuminated either through the \( p \)-layer or the \( n \)-layer were performed for various thickness values of the \( i \)-layer. The \( I(V) \) characteristics of these cells are plotted in Fig. 4 while the \( I(V) \) main results are reported in Table 1. Note that any significant effect of light absorption loss in the doped layer could be ruled out, as demonstrated by additional simulation (not shown here). As observed experimentally, illumination through the \( n \)-layer leads (compared to \( p \)-side illumination) to a reduction of the current and \( FF \). This reduction increases with increasing cell thickness. \( V_{oc} \) remains approximately constant in agreement with the experimental results.

Figure 4  \( I(V) \) curves as a function of the \( i \)-layer thickness of \( p-i-n \) cells for illumination through (left) the \( p \)-layer and (right) through the \( n \)-layer.
Table 1  Characteristics ($V_{oc}$, short-circuit current $I_{sc}$, $FF$ and maximum power $P_{max}$) of the $I(V)$ curves plotted in Fig. 4.

<table>
<thead>
<tr>
<th>$i$-layer thickness [nm]</th>
<th>$V_{oc}$ [V]</th>
<th>$I_{sc}$ [mA/cm²]</th>
<th>$FF$</th>
<th>$P_{max}$ [W/m²]</th>
<th>$V_{oc}$ [V]</th>
<th>$I_{sc}$ [mA/cm²]</th>
<th>$FF$</th>
<th>$P_{max}$ [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.853</td>
<td>-76.8</td>
<td>0.704</td>
<td>46.1</td>
<td>0.852</td>
<td>-68.8</td>
<td>0.674</td>
<td>39.5</td>
</tr>
<tr>
<td>250</td>
<td>0.855</td>
<td>-82.3</td>
<td>0.705</td>
<td>49.6</td>
<td>0.854</td>
<td>-73.8</td>
<td>0.665</td>
<td>41.9</td>
</tr>
<tr>
<td>300</td>
<td>0.855</td>
<td>-84.0</td>
<td>0.705</td>
<td>50.7</td>
<td>0.855</td>
<td>-75.1</td>
<td>0.653</td>
<td>41.9</td>
</tr>
<tr>
<td>350</td>
<td>0.856</td>
<td>-84.6</td>
<td>0.706</td>
<td>51.2</td>
<td>0.855</td>
<td>-75.1</td>
<td>0.639</td>
<td>41.0</td>
</tr>
<tr>
<td>400</td>
<td>0.857</td>
<td>-88.9</td>
<td>0.708</td>
<td>54.0</td>
<td>0.856</td>
<td>-78.4</td>
<td>0.626</td>
<td>42.0</td>
</tr>
</tbody>
</table>

In order to reveal more clearly the difference in $p$- and $n$-side illumination, differential plots are shown in Fig. 5 for the $I(V)$ and $EQE$ simulations. We clearly see the reduction in current becoming bigger as we get closer to the maximum power point, resulting in a reduction of the $FF$ as the cell thickness increases. As observed experimentally, the loss is due to the blue part of the illumination spectrum with a broadening towards the red region as the cell thickness increases.

Figure 5  Differential $I(V)$ curves ($p$-side results minus $n$-side results) of $p$-$i$-$n$ cells as a function of the $i$-layer thickness (left) and corresponding absolute value of the differential $EQE$ curves.

The experimental results as well as the simulation clearly demonstrates that the cell performances are limited by the hole collection in the case of a $n$-side illumination. The further the holes are generated from the $p$-$i$ interface, the more difficult it becomes to collect them.
In order to analyze how the hole transport parameters affect their collection, simulation of cells with values of the hole band mobility ranging from a standard value (cf. Fig. 6 caption) to a value higher that the electron band mobility. As seen in Fig. 6 (left), an increase in the band mobility of holes leads to a reduction of the loss in current but it does not change drastically the hole collection problem. Even with mobility values for the holes higher that the one for electrons, we still observed a strong asymmetry between $p$- and $n$-side illuminations. Furthermore the band mobility for holes does not account for the effect of illumination side on the fill-factor.

In contrast, reduction of the characteristic energy of the valence band tail (steeper band tail) leads to the removal of the current loss maximum, close to the maximum power point. This results in the cancellation of the loss in $FF$. The observed loss for $n$-side illumination, especially for thicker cells is therefore mainly due to an asymmetry in the band tail slope (or in the drift mobility) rather than to an asymmetry in the band mobility. From Fig. 6, it is also obvious that other effects are also playing a role even the case of this rather thin diode (0.3 µm thick), especially in reverse bias conditions. These effects are partly due to different optical characteristics for the $p$- and $n$-layer, and also possibly to position of defects not exactly at the centre of the gap and slightly different capture cross-section for holes and electrons.

Figure 6  Differential $I(V)$ curves ($p$-side results minus $n$-side results) of 0.3 µm thick $p$-$i$-$n$ cells as a function of (left) the hole band mobility and (right) as a function of the valence band tail characteristic energy. Electron band mobility was kept constant with a value of 0.002 m²V⁻¹s⁻¹ in both cases, as well as the conduction band characteristic energy of conduction band tail with a value of 0.03 eV. Otherwise, a value of hole mobility of 0.0005 m²V⁻¹s⁻¹ and a value of the valence band tail characteristic energy of 0.043 eV were assumed.
5. Conclusions

Differences in performance between illumination through the $p$-layer and illumination through the $n$-layer of single-junction $p$-$i$-$n$ cells were analyzed experimentally and by numerical simulations. The experimental difference in the cell performance, as well as the change with increasing thickness, is well reproduced by numerical simulation. As already identified in previous studies, hole collection is clearly the limiting factor, leading to a loss in current, $FF$ and efficiency when the cell is illuminating through the $n$-layer. An increase in the $i$-layer thickness leads to an aggravation of the collection problem.

However, our analysis differs substantially on the cause of the reduced hole collection. Previous studies claimed that the reduced band mobility of holes (compared to the one of electrons) was responsible for the cell performance reduction. We clearly recognized this effect in the reduction of the cell current for $n$-side illumination, however, the main parameter responsible for the loss in $FF$ and efficiency is the band tail slope asymmetry. Valence band tail slope, or the drift mobility of holes, is here the main limiting factor.

References


