Influence of film formation on light trapping properties of randomly textured silicon thin film solar cells

Vladislav Jovanov\textsuperscript{1}, Shailes Shrestha\textsuperscript{1}, Jürgen Hüpkes\textsuperscript{2}, Markus Ermes\textsuperscript{2}, Karsten Bittkau\textsuperscript{2}, and Dietmar Knipp\textsuperscript{1}\textsuperscript{*}

\textsuperscript{1} Research Center for Functional Materials and Nanomolecular Science, Electronic Devices and Nanophotonics Laboratory, Jacobs University Bremen, 28759 Bremen, Germany

\textsuperscript{2} Institut für Energie- und Klimaforschung, IEK5-Photovoltaik, Forschungszentrum Jülich, Germany

E-mail: d.knipp@jacobs-university.de

The influence of film formation on light trapping in silicon thin-film solar cells prepared on randomly textured substrates was studied. Realistic interface morphologies were calculated by a 3D surface coverage algorithm using measured substrate morphology and film thicknesses of the individual layers as input parameters. Calculated interface morphologies were implemented into Finite-Difference Time-Domain simulations to determine the quantum efficiency and absorption in the individual layers of the thin-film solar cells. The investigation shows that the realistic description of interface morphologies is required to accurately predict the light trapping properties of randomly textured silicon thin-film solar cells.
Silicon thin-film solar cells require efficient light trapping to achieve high short circuit currents and increased conversion efficiencies. Depending on the configuration of the solar cells, light trapping is achieved by nanotexturing the front (superstrate configuration) or the back contact (substrate configuration).\textsuperscript{1-10} Nanotextures scatter/diffract the light and increase the optical path length and absorption inside the absorber layer of the solar cell. The nanotextures propagate through the deposited layers of the solar cell. Consequently, both contacts of the solar cell are textured, but the morphology of textures is different.\textsuperscript{3-14} The morphology of nanotextures is modified due to the formation of the silicon film on the textured substrate. In order to optimize the light trapping properties of thin-film solar cells, a detailed understanding of the film formation and influence of the realistic interface morphologies on the light trapping properties are required.

In this letter, an approach to accurately study and predict the light trapping properties of amorphous silicon thin-film solar cells deposited on textured substrates is presented. The approach combines realistic interface morphologies with three dimensional (3D) finite-difference time-domain (FDTD) simulations. The approach is demonstrated for amorphous silicon solar cells prepared on Asahi-U type substrate,\textsuperscript{3,4} but it is also applicable to different types of substrates such as multiscale textured substrates,\textsuperscript{1,15} nanowires\textsuperscript{7,16} and periodically textured substrates.\textsuperscript{8-10,17}

Light trapping in superstrate configuration solar cells is typically realized by using randomly textured transparent conductive oxide (TCO) as a substrate.\textsuperscript{1-5} In this study, a commercial Asahi-U tin oxide (SnO\textsubscript{2}:F) substrate was used.\textsuperscript{1,4} The front contact textures of the Asahi-U type substrate can be described by a random distribution of pyramidal features. The morphology of the back contact is influenced by the front contact textures that propagate through the solar cell. The light trapping properties of the silicon solar cells and consequently the short circuit current depend on the back contact morphology and the optical properties of the dielectric/metal interface.\textsuperscript{2,4,18-20} The optical losses in the back contact can be reduced by introducing a zinc oxide (ZnO) buffer layer between the amorphous silicon p-i-n diode and the metal reflector.\textsuperscript{2,4} However, it has been shown that the optical losses in the back contact with ZnO buffer layer are significantly increased if the back contact morphology exhibits nano-features.\textsuperscript{18,19} Hence, accurate investigation and optimization of the light trapping require a precise model of the back contact morphology. Recently, different methods to determine the back contact morphology of silicon thin film solar cells have been proposed.\textsuperscript{11-14} The presented models show that the back contact morphology is influenced by the thickness of the solar cell layers, morphology of the
textured substrate and deposition conditions of the solar cell.

Fig 1

Figure 1 exhibits experimentally determined cross section of an amorphous silicon solar cell deposited on the Asahi-U substrate (center). The cross section is created by using line scans taken from measured morphologies of the solar cell substrate (left) and back contact (right). The morphology of the Asahi-U substrate was measured by an atomic force microscopy (AFM). After the deposition of the amorphous silicon solar cell, the back contact morphology was also measured by AFM. The nominal thickness of experimentally prepared amorphous silicon solar cell was 300 nm. To scan exactly the same area as for the Asahi-U substrate, special alignment laser markers were used.\textsuperscript{11,12} The measured morphologies in Fig. 1 show that surface textures of the front contact and back contact exhibit significant differences.

To determine the film morphology, deposition conditions of amorphous silicon are taken into consideration. Deposition of low temperature amorphous silicon solar cells is typically achieved by a plasma enhanced chemical vapor deposition (PECVD).\textsuperscript{1-3,7-9,11-13,18} Under standard deposition conditions, it can be assumed that the amorphous silicon film grows in the direction of the local surface normal. Based on this approximation a 3D surface coverage algorithm was developed.\textsuperscript{11,12} Only the substrate morphology (Fig. 1) and thickness of the solar cell layers are necessary as input data to calculate the interface morphologies. The accuracy of the 3D surface coverage algorithm was demonstrated by direct comparison and by power spectral density function of the measured and simulated back contact morphology.\textsuperscript{11,12}

To investigate the influence of the silicon film formation on the light trapping, FDTD simulations were used. The FDTD method numerically solves Maxwell’s equations in 3D and determines the electromagnetic wave propagation in the solar cell structure. From the electric field distribution, the absorption in the individual layers of solar cell and the short circuit current density can be obtained. The solar cell structures for FDTD simulations were defined using calculated and measured morphologies. The measured Asahi-U substrate shown in Fig. 1 was used to define the morphology of the front contact on top of a glass substrate. The glass substrate was represented as non-absorbing dielectric material with refractive index of 1.5. On top of the front contact, the amorphous silicon diode was defined followed by the back contact. The diode was composed of a p-doped (10 nm thickness), an intrinsic (300 nm thickness) and an n-doped layer (10 nm thickness).
morphologies of silicon diode were obtained by the 3D surface coverage algorithm. The back contact was composed of a ZnO buffer layer (100 nm thickness) and silver back reflector. As a reference, a solar cell with identical front and back contact morphology was used. The simulated area was 2.5 x 2.5 μm and the simulation settings were the same for all simulated structures. The simulations were carried out for wavelengths from 300 nm to 800 nm. The optical constants of all materials used in the simulations were determined by experimental measurements.\textsuperscript{21)}

**Fig 2**

Time averaged power loss distributions in the simulated structures for a wavelength of 400 nm are shown in Fig. 2. For the wavelengths shorter than 500 nm, the light gets absorbed in the front of the solar cell without reaching the back contact. Therefore, the power loss distribution for the reference (Fig. 2a) and realistic structure (Fig. 2b) exhibits no differences, since it is determined only by the front contact textures. However, the formation of the amorphous silicon film on the textured substrate leads to a change of the morphology of the p-layer. Consequently, the effective thickness of the p-layer is 12 nm, which is an increase of 25 % compared to the reference structure. Due to the thicker p-layer, the absorption in the i-layer of the realistic structure is reduces when compared to the reference.

**Fig 3**

Figure 3 depicts power loss distributions in the simulated structures for a wavelength of 680 nm. For the wavelengths longer than 500 nm, the light reaches the back contact. Therefore, the morphology of the back contact morphology influences the light trapping. Due to the film formation, the roughness and the size of the back contact features are affected by the film formation.\textsuperscript{11-13) The surface roughness drops with increasing film thickness, while the feature size increases.\textsuperscript{11,12) For the reference structure, there is no change in the surface morphology and the roughness and average feature size of the front and back contact are the same. Consequently, the effective thickness of the i-layer is increased when compared to the reference structure. The effective thickness of the i-layer is 330 nm and exhibits increase of 10 %. Due to the thicker i-layer and smoother back contact, the power loss distribution in the realistic structure (Fig. 3b) is improved compared to the reference (Fig. 3a). From power loss distribution for a specific wavelength, the absorption in the
individual solar cell layers was determined. To determine the quantum efficiency, it was assumed that only electron/hole pairs photogenerated in the i-layer contribute to the photocurrent and that all generated charge carriers are collected.

Fig 4

The absorption in the individual layers of the simulated structures is shown in Fig. 4. The absorption of the back contact is defined as the absorption of light in the silver reflector, the ZnO buffer layer and the n-layer. For wavelengths shorter than 500 nm, the total absorption of simulated structures is the same. The p-layer thickness and absorption for the reference structure (Fig. 4a) are lower than for the realistic structure (Fig. 4b). The higher absorption in the p-layer reduces the quantum efficiency for the realistic structure. Therefore, the quantum efficiency for the reference structure (Fig. 4a) is higher compared to the realistic structure (Fig. 4b). To overcome this problem, the nominal thickness of the p-layer can be reduced when solar cell is deposited on the textured substrate. For wavelengths longer than 500 nm, the total absorption of the reference structure is higher than for the realistic, but the quantum efficiency is lower. The reference structure exhibits higher total absorption due to the high optical losses in the back contact (Fig. 4a). The realistic structure exhibits reduced roughness of the back contact and smoother surface textures. Consequently, the optical losses in the back contact are lower and the quantum efficiency is increased (Fig. 4b).

Tab I

Table I summarizes the trade off between optical losses and the short circuit current. The short circuit current is divided into blue current (300-500 nm) and red current (500-800 nm). The blue current depends on the absorption losses of the p-layer. The increased thickness of the p-layer results in reduced short circuit current by 0.2 mA/cm². The red current depends on the back contact and reflection losses. Due to the realistic interface morphologies, the back contact losses are reduced by 1.9 mA/cm². However, only part of it gets absorbed in the i-layer. The reflection losses are increased by 1.4 mA/cm², while only 0.5 mA/cm² contributes to the short circuit current. To distinguish the influence of the increased i-layer thickness and the back contact morphology on the improved light trapping for longer wavelengths in the realistic structure, additional simulations were conducted. The simulated structure was the same as reference, but with the increased thickness of layers in order to match the effective thicknesses of the realistic structure. For the wavelengths longer than
500 nm, the short circuit current of the structure with increased layer thicknesses is higher by 0.3 mA/cm$^2$ compared to the reference structure. Consequently, the increased thickness of the i-layer improves the short circuit current by 0.3 mA/cm$^2$, while the changes to the back contact morphology contribute by 0.2 mA/cm$^2$.

Previously, the influence of film formation on the light trapping properties of substrates with periodical textures was studied.$^{17}$ The investigation of amorphous silicon solar cells with periodic pyramidal textures showed a distinct effect of the film formation on the light trapping properties. Similar to the results presented in this study, the film formation had a significant influence on the average p-layer thickness. At the same time, the i-layer exhibited increased thickness, while the back contact roughness was significantly reduced. Consequently, amorphous silicon solar cells with realistic interface morphologies exhibited gains in the short circuit current of more than 1 mA/cm$^2$ when compared to the reference.$^{17}$ Furthermore, the realistic film formation was also used to model the solar cells prepared on multiscale textured substrates and textured substrates that exhibit very high aspect ratios like nanowire arrays.$^{15,16}$ Accurate investigation of the light trapping in these types of solar cells is not possible without realistic interface morphologies.

In summary, the influence of realistic interface morphologies on light trapping in amorphous silicon thin-film solar cells prepared on randomly textured substrates was studied. The realistic film formation influences that the average thickness of the solar cell layers is increased when compared to the nominally expected thickness. Consequently, the absorption losses in the p-layer are higher for shorter wavelengths, while the increased thickness of the i-layer is crucial in increasing the short circuit current for longer wavelengths. Furthermore, the film growth leads to smoother back contact morphology which results in reduced optical losses in the back contact. Although results show that the influence of the film formation on the randomly textured substrates is not as pronounced as for the periodic substrates, the presented approach allows for the detailed understanding and investigation of the light trapping. By combining the 3D surface coverage algorithm with optical simulations it is possible to predict the light trapping properties of solar cells prepared on arbitrary substrates. The presented approach is crucial for the investigation of core/shell nanowire solar cells and solar cells on multiscale textured substrates.

**Acknowledgments**

We express our gratitude to X. Xu (FZJ) for performing AFM measurements and to H. Stiebig and P. Magnus for providing us optical data of materials.
References


19) M. van Lare, F. Lenzmann, and A. Polman, Dielectric back scattering patterns for light trapping in thin-film Si solar cells, Optics Express 21(18), 20738-20746 (2013).


21) H. Stiebig and P. Magnus, Malibu GmbH and Co.KG Bielefeld, Germany (personal communication)
Figure Captions

**Fig. 1.** Cross section of the amorphous solar cell with realistic interfaces (center) and experimentally measured morphologies of the front (left) and back contact (right).

**Fig. 2.** Power loss maps for a wavelength of 400 nm. (a) Reference structure and (b) solar cell with realistic interface morphologies. Average thickness of the p-layer is increased for the realistic structure, due to the film formation.

**Fig. 3.** Power loss maps for a wavelength of 680 nm. (a) Reference structure and (b) solar cell with realistic interface morphologies.

**Fig. 4.** Absorption in the individual layers for (a) reference structure and (b) solar cell with realistic interface morphologies.
Table I. Optical losses and short circuit currents

<table>
<thead>
<tr>
<th>Structure</th>
<th>p-layer losses (mA/cm²)</th>
<th>Blue current (mA/cm²)</th>
<th>Back contact losses (mA/cm²)</th>
<th>Reflection losses (mA/cm²)</th>
<th>Red current (mA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>1.3</td>
<td>4.3</td>
<td>4.2</td>
<td>5.4</td>
<td>11.2</td>
</tr>
<tr>
<td>Realistic</td>
<td>1.5</td>
<td>4.1</td>
<td>2.3</td>
<td>6.8</td>
<td>11.7</td>
</tr>
</tbody>
</table>
Fig. 1.
Fig. 2.
Fig. 4.