This paper first appeared in the eleventh print edition of *Photovoltaics International* journal, published in February 2011.

Light trapping in nanotextured thin-film silicon solar cells

Rahul Dewan & **Dietmar Knipp**, Jacobs University Bremen, Bremen, Germany

ABSTRACT

Conversion efficiencies of thin-film silicon solar cells can be increased by nanotexturing of the cells. This nanotexturing step allows for a larger fraction of the incoming light to scatter and diffract, so that both the total absorption of light in the solar cell and the short circuit current is enhanced. In this study, we investigate the optics of thin-film silicon solar cells by numerically simulating Maxwell's equations by a finite-difference time-domain algorithm. Starting with periodically textured solar cells, the influence of the texture period and height on the quantum efficiency and short circuit current were investigated. With this understanding of the optimized surface texture for periodically textured solar cells, the possibility of interpreting the optics of randomly textured solar cells will be discussed.

Introduction

Reducing the cost and increasing the conversion efficiency is a major objective of research and development on solar cells. An approach that simultaneously achieves these two objectives is the use of light trapping or photon management. Light trapping facilitates the absorption of sunlight by a thin-film solar cell that is much thinner than the absorption length of the material. Thsi study will focus on the analysis of thin-film solar cells based on hydrogenated microcrystalline silicon. Thin-film microcrystalline silicon solar cells have a typical thickness of 0.8–1.5μm, which is significantly less than the thickness of conventional wafer-based silicon solar cells (180–250μm) [1].

Over the last decade, several concepts have been proposed to enhance the absorption of light in thin-film silicon solar cells. Most of these concepts are based on random nanotexturing of the contact layers of the solar cells [2,3]. Conversion efficiencies higher than 10% have been demonstrated for amorphous and thin-film microcrystalline silicon solar cells by introducing randomly textured interfaces in the solar cell [3–5]. For micromorph tandem solar cells, stable efficiencies of up to 11.9% have been demonstrated using textured interfaces [5–6]. A schematic sketch of a single-junction thin-film silicon solar cell on a smooth glass substrate and with textured contact layers is shown in Fig. 1(a) and 1(b), respectively. The yellow arrows indicate the transmitted and reflected light within the thin diode. The optics of solar cells on smooth substrates (Fig. 1(a)) are characterized by the forward and backward propagating waves. By introducing nanotextured interfaces to the solar cell (Fig. 1(b)), the rough surface leads to enhanced scattering and diffraction of light in the device.

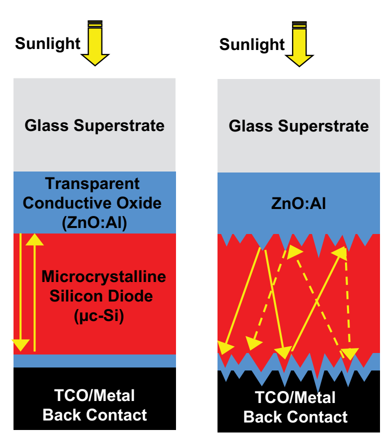

Figure 1. Schematic sketch of a thin-film microcrystalline silicon solar cell (a) on a smooth substrate and (b) on a randomly textured substrate.

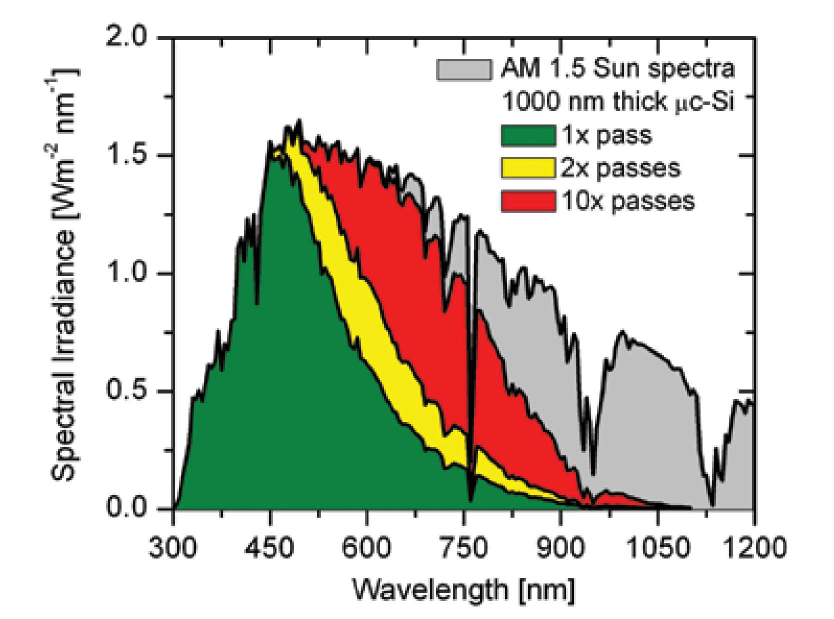

Figure 2. Absorbance of the incident AM 1.5 sun spectra in a 1000nm-thick microcrystalline silicon solar cell for single and multiple passes.

Due to multiple reflections within the silicon layer, the optical path length of the incident light is greatly enhanced. This leads to a distinctly enhanced short-circuit current and quantum efficiency in the red and infrared part of the optical spectrum. The influence of an enhanced optical path length on the incident sun spectrum is shown in Fig. 2.

In order to understand the optical propagation within such thin-film devices, it is imperative to use numerical methods and solve the Maxwell's equations rigorously. By considering the near-field optics, the nanotexturing process for efficient solar cells can be understood and optimized. Maxwell's equations have to be solved rigorously to calculate the wave propagation in such nanotextured devices. The finite-difference time-domain (FDTD) method, finite-element method (FEM), or finite-integration technique (FIT) are commonly used to determine the absorption, quantum efficiency, and short-circuit current of these solar cells.

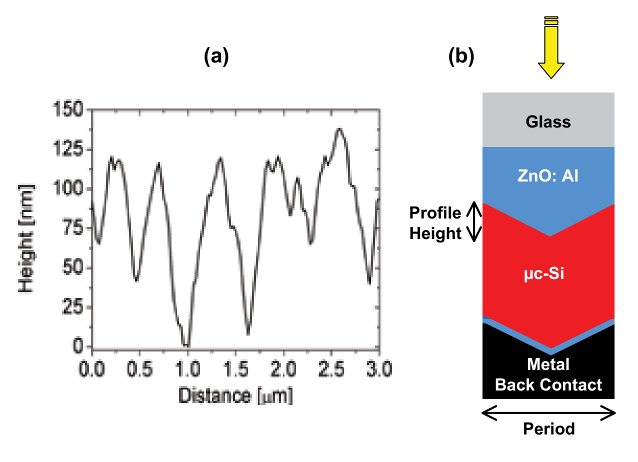

Figure 3. Line scan from the surface of a randomly textured aluminum doped zinc oxide (ZnO:Al) film (a). Schematic sketch of the unit cell of the periodically textured solar cell with an integrated triangular surface texture (b).

For this study, we investigated the wave propagation of nanotextured microcrystalline silicon solar cells using an FDTD simulation tool.

Optical simulation model

Many different concepts have been proposed in an effort to increase the effective thickness of thin-film silicon solar cells. The different approaches encompass wet etching of sputtered transparent conductive oxides (TCOs) [2], direct growth of textured oxides by low pressure chemical vapour deposition (LPCVD) [7], or using textured back reflectors [8]. In the case of thin-film silicon solar cells, randomly textured contact layers – realized by direct deposition of zinc oxide films or etching of sputtered zinc oxide – have resulted in the most efficient solar cells [2–4]. A line scan of the surface profile of such an etched aluminium-doped zinc oxide (ZnO:Al) film is shown in Fig. 3(a). The sputtered zinc oxide film was etched in a dilute hydrochloric acid (HCl) solution for several seconds. The triangular texture of the film exhibits an almost periodic arrangement with a period of around 500nm. Based on these observations, we investigated a solar cell with a periodic triangular surface texture.

A schematic cross-section of the investigated unit cell is shown in Fig. 3(b). It is assumed that the solar cell on a textured substrate can be described by a unit cell, which provides all information on the behaviour of the entire cell. Key parameters of the unit cell are the period and the profile height. The microcrystalline silicon solar cell investigated in this study consists of a 500nm-thick ZnO:Al front contact, followed by a (p-i-n) hydrogenated microcrystalline silicon diode (μc-Si:H) with a total thickness of 1,000nm and a back reflector consisting of an 80nm-thick ZnO:Al layer and a metal reflector. The device structure is consistent with the standard microcrystalline silicon solar cell process used by several research groups such as the Jülich Research Centre and the University of Neuchâtel [2,7]. In order to study the influence of the dimensions of the texture on the optical performance of the solar cell, the period of the unit cell was varied from 50nm up to 6,000nm, while the height was varied from 0nm up to 500nm. The unit cell was illuminated under normal incidence for the entire spectrum of wavelength from 300–1,100nm.

Results and discussion

In order to compare the different surface textures, power loss profiles within the solar cell, quantum efficiency and short-circuit current were utilized. The power loss profile for thin-film solar cells with integrated triangular structures under blue and red illumination are shown in Fig. 4. The period of the triangular profile for all cases was 900nm with heights of 100nm (Fig. 4(a) and 4(c)) and 400nm (Fig. 4(b) and 4(d)), respectively. The respective incident lights have wavelengths of 400nm and 700nm with amplitude of 1V/m. In the

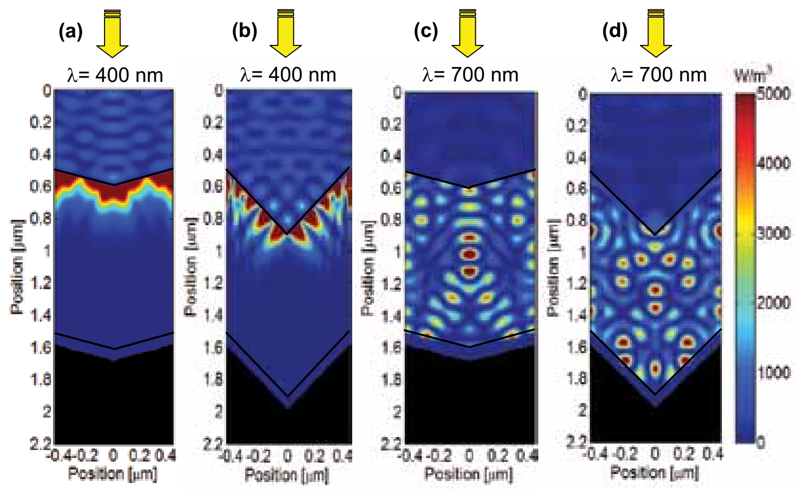

Figure 4. Simulated power loss profile for a textured unit cell with a period of 900nm and profile heights of (a, c) 100nm and (b, d) 400nm under monochromatic illumination of (a, b) wavelength 400nm and (c, d) wavelength 700nm.

case of short wavelength illumination (λ=400nm), the photons get absorbed within the first 200nm of the silicon absorber layer. By having a small period height, as shown in Fig. 4(a), the opening angle of the triangular texture approaches 180°, the short-circuit current being comparable to the current of a solar cell on a smooth substrate. By having an opening angle close to 90°, a 'flame-like' power loss pattern occurs, as shown in Fig. 4(b). The power loss pattern is caused by the formation of evanescent fields at the boundary between the zinc oxide texture and the p-i-n solar cell. This power loss pattern disappears for longer wavelengths of the incident light and smaller periods of the texture.

Due to a low absorption coefficient of silicon for longer wavelengths, the incident light has to be confined in the solar cell. The light can be completely absorbed only if the light completes multiple passes inside the silicon layer. The power loss profile for a structure under monochromatic illumination of wavelength 700nm is shown in Fig. 4(c) and 4(d). Light diffracted by the front and back grating constructively interferes, which leads to a higher absorption of the incident light. For opening angles close to 90°, the power loss in the solar cell is maximized as shown in Fig. 4(d).

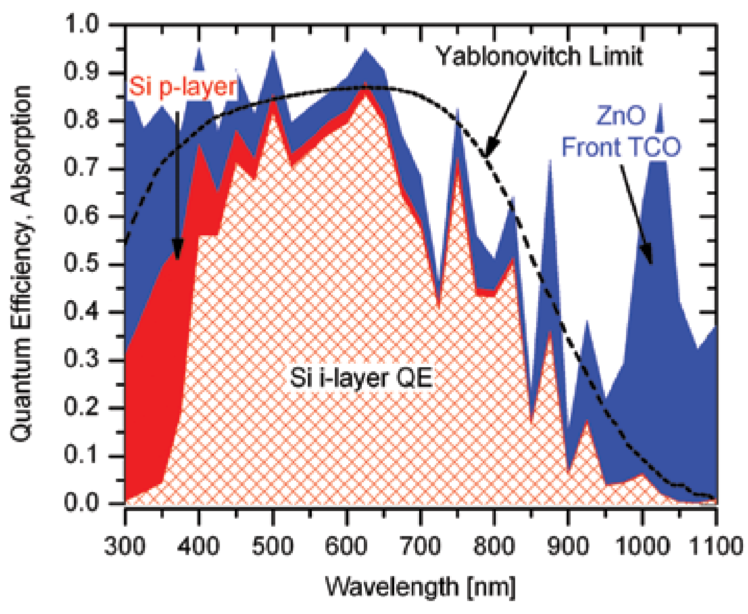

Figure 5. External quantum efficiency of the p-i-n microcrystalline silicon solar cell and parasitic absorptions in the silicon p-layer and front zinc oxide layer. The absorptions in the n-layer silicon and back zinc oxide are not shown since they are almost negligible. The Yablonovitch limit is shown with dashed lines. The thickness of the silicon diode was 1.0µm.

Based on the power loss calculations, the quantum efficiency for the solar cell can be determined. The quantum efficiency is defined as the ratio of the power absorbed in the silicon layer with respect to the total power incident on the unit cell. Details on how to calculate the quantum efficiency are given in [9]. The collection efficiency, taking the electronic properties of the material into account, is assumed to be 100%; in other words, the internal quantum efficiency is assumed to be 100%. Therefore, the determined quantum efficiency defines an upper limit of the achievable external quantum efficiency. Fig. 5 shows the absorption in different regions of the solar cell with a period of 700nm and triangular groove height of 400nm. The quantum efficiency in the i-layer of the silicon diode, along with the parasitic absorptions in the p-layer of silicon and the transparent conductive oxide front contact are also depicted in Fig. 5. The absorption in the microcrystalline silicon n-layer and the zinc oxide layer in the back is very low, accounting for a loss of less than 2–3%. Moreover, since a perfect back reflector was assumed in this case, the loss in the back contact is zero, and therefore these losses are not shown in the image. The thickness of the p-layer silicon was assumed to be 30nm.

The dashed line in Fig. 5 represents the maximum achievable quantum efficiency (Yablonovitch limit) for a silicon solar cell with a thickness of 1µm. Yablonovitch and Cody determined the absorption for a perfectly textured solar cell. However, they did not describe how to realize such a structure. The absorption enhancement compared to a solar cell on a smooth substrate can be $2n^2$ fold (where n is the refractive index of the diode material; for silicon this corresponds to $2n^2 \sim 25$). By considering the unavoidable reflection losses in the front air/ZnO interface and parasitic absorption in the front ZnO layer, the upper limit for the absorption in the 2D textured silicon layer was calculated and plotted in Fig. 5.

> "Due to multiple reflections within the silicon layer, the optical path length of the incident light is greatly enhanced."

Taking the weighted sun spectra AM 1.5, the short circuit current can be calculated from the quantum efficiency. For the case shown in Fig. 5, the total short circuit current was calculated to be 20mA/cm^2 compared to a short circuit current of 12.4mA/cm^2 for a smooth substrate. In terms of the parasitic absorptions, the p-layer and the front zinc oxide layer, both absorb 10% and 30% respectively of

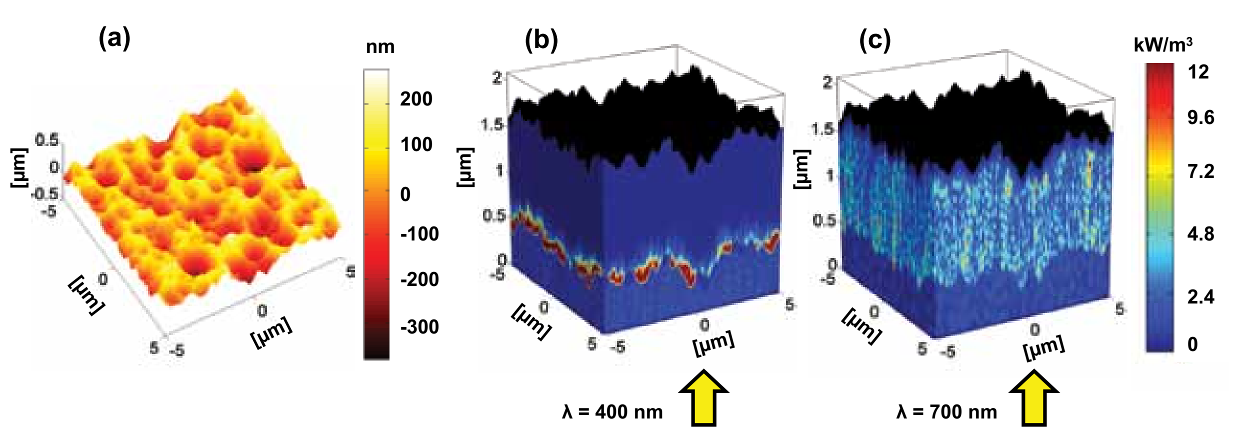

Figure 6. Surface profile of a randomly textured aluminium-doped zinc-oxide substrate (a), showing simulated power loss profiles of the corresponding randomly textured thin-film silicon solar cells under monochromatic illumination of wavelength (b) 400nm and (c) 700nm.

the total absorbed light in the entire solar cell stack. The largest loss in the p-layer is observed for the shorter wavelengths (from 300nm to 500nm), while the layer is almost transparent for the longer wavelengths. Absorption loss in the front zinc oxide layer for shorter wavelengths accounts for almost 50%. For wavelengths ranging from 500nm to 750nm, the absorption in the front zinc oxide is minimized. Optical loss in the aluminium-doped front zinc oxide layer for longer wavelengths increases as a result of the free carrier absorption. When compared to the theoretical absorption limit, more than 30% of the incident light is lost via reflection, and these losses increase as the absorber layer gets thinner. Therefore, a reduction of the reflection should be a key point for the design of ultra-thin solar cells, where the absorber is significantly thinner than the absorption length for longer wavelengths.

The 2D triangular textured solar cells discussed in this study have yielded results that suggest that the optimal period of the texture is in the range of 500–900nm with texture height of 400–500nm [10]. Compared to a solar cell on a smooth substrate, the degree of enhancement in the short-circuit current depends greatly on the period of the triangular profile unit cell. When periods of the texture are smaller than the incident wavelength, enhancement in the shorter wavelengths (300–500nm) of the spectrum is brought about by the improved incoupling of the light into the absorber layer. Longer wavelengths (700–1,100nm) can result in the short-circuit current being distinctly enhanced if the period of the triangular profile unit cell is in the range of the incident wavelength. The latter case exhibits the highest short-circuit current because it best utilizes the diffraction and scattering of light. This enhancement comes from light trapping of the longer wavelengths.

Towards simulations of randomly textured substrates

The simulation of periodic structures provides an understanding of light trapping and allows for optimization of the surface texture. It has recently been shown that the behaviour of quasi random surfaces can be described by the weighted superposition of solar cells with periodic surface texture [11]. Whether or not it can also be applied to random surfaces still remains an open question.

The power loss profile obtained from a simulation of the solar cells on a randomly textured substrate is shown in Fig. 6 for a substrate area of 10 × 10μm². Fig. 6(a) shows the surface profile of a randomly textured zinc-oxide substrate patterned by wet etching in an acid solution. In Fig. 6(b) and 6(c), the power loss profiles of the randomly textured solar cells for incident wavelengths of 400nm and 700nm, respectively, are shown. The dimensions of the device structure were kept the same as before; the randomly textured substrate was integrated into the solar cell in lieu of the triangular grating as was described in this study. Similar to the periodic surface texture, the shorter wavelength (λ = 400nm) gets absorbed within the first few hundred nanometers of the silicon layer. For longer wavelengths (λ = 700nm), the light is scattered and diffracted by the front- and the back-surface texture. Systematic studies of the crater distribution together with optical simulations of textured solar cells are pivotal in order to better understand the optical propagation in such devices.

Summary

As thin-film silicon solar cells get thinner, the necessity for efficiently trapping the incident light within the absorber layer becomes more vital. Surface-textured microcrystalline silicon solar cells with texture periods in the range of 500–900nm offer the most effective conversion of incident light into short-circuit current. For amorphous silicon, the highest short-circuit currents are achieved for periods of 150–250nm, resulting from an enhanced diffraction and scattering of longer wavelengths within the solar cell. In order to understand the complex optical propagation in randomly textured solar cells and maximize the short-circuit current, systematic studies of randomly textured cells together with periodic solar cells will be indispensable.

Acknowledgment

The authors would like to thank H. Stiebig from Malibu Solar, and J. Hüpkes and J.I. Owen from the Institute of Energy and Climate Research (IEK-5) – Photovoltaics, Research Center Jülich for helpful discussions and for providing textured zinc oxide substrates.

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About the Authors

Rahul Dewan is working towards his Ph.D. at the Electronic Devices and Nanophotonics Laboratory, Jacobs University Bremen, Germany. He holds a B.Sc. in electrical engineering and computer science (2006) and an M.Sc. in electrical engineering (2008). Since completing his master's degree, his research work has focused on the understanding of optics in nanotextured thin-film silicon solar cells.

Dietmar Knipp received M.S. and Ph.D. degrees in electrical engineering from the University Siegen, Germany, and the Aachen University of Technology (RWTH), Aachen, Germany, in 1995 and 1999, respectively. Before joining Jacobs University Bremen as an Assistant Professor of Electrical Engineering in 2003, he was Senior Researcher at the Interuniversity Microelectronic Center (IMEC), Leuven, Belgium. His research focuses on photovoltaics, organic electronics and optical sensor technologies.

Enquiries

Prof. Dr. Dietmar Knipp
Jacobs University Bremen
Campus Ring 1
Bremen 28759
Germany
Tel: +49 421 200 3570
Email: d.knipp@jacobs-university.de
Web: http://www.jacobs-university.de/ses/dknipp