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Experimental studies and limitations of the light trapping and optical losses in microcrystalline silicon solar cells

Michael Berginski [a,*], Jürgen Hüpkes [a], Aad Gordijn [a], Wilfried Reetz [a], Timo Wätjen [a], Bernd Rech [b], Matthias Wuttig [c]

[a] IEF5-Photovoltaik, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany
[b] Department of Silicon Photovoltaics (SE 1), Hahn-Meitner-Institut Berlin GmbH, D-12489 Berlin, Germany
[c] Institute of Physics (IA), RWTH Aachen University, D-52056 Aachen, Germany

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ABSTRACT

This study addresses the potential of different approaches to improve the generated current in silicon thin-film solar cells and modules. Decreasing the carrier concentration in the front contact has proven to increase the quantum efficiency and the cell-current density significantly. Additionally, an optically improved ZnO/Ag back reflector and the optimized light incoupling by anti-reflection layers were studied. In this contribution, we show the potential of the different optical components and discuss combinations thereof in order to obtain a maximized cell-current density in silicon thin-film solar cells. Limitations of the cell-current density are discussed with respect to theoretical calculations.

1. Introduction

Silicon thin-film solar cells are promising candidates for future photovoltaic power generation [1,2]. One approach employs hydrogenated amorphous silicon (a-Si:H)-based active layers in single- or multi-junction solar cells [3,4]. In superstrate configuration, the cell is illuminated through a transparent conductive oxide (TCO) on which the silicon-based p–i–n structure is deposited. Due to the intrinsically low absorbance of silicon in the long-wavelength range, photon management is essential. The photon management comprises efficient coupling of light into the device as well as light trapping within the device. In general, the light trapping is achieved by combining the effective light scattering of the front-contact TCO with highly reflective back contacts. This is an important way to enhance the light-path length within the silicon absorber layer. There are still significant losses, however, due to primary reflection of the light caused by refractive-index mismatch and parasitic absorption in the front-contact TCO, doped layers and back contact. In this contribution, we study the significance of different optical improvements based on experimental data. The influence of the front-contact parasitic absorption, the refractive-index matching at the front contact, as well as an optically improved back reflector are studied in detail in microcrystalline silicon (μc-Si:H) solar cells with intrinsic silicon thickness of 1 μm. The experimentally achieved quantum efficiency is compared to calculations based on theoretical models, especially based on the work of Deckman and Wronski [5]. The expected significance for further optical improvements is estimated by employing the theory of Deckman and Wronski. Finally, this model is used to determine the potential of cell-current density by combining different optical improvements.

2. Experimental

ZnO:Al films were prepared on Corning 1737 glass by rf-magnetron sputtering from ceramic ZnO:Al_2O_3 target with 1 and 0.5 wt% Al_2O_3, respectively. The approximately 800 nm thick, initially smooth films (root mean square (RMS) roughness less than 15 nm) became surface-textured with typical RMS roughness of more than 125 nm by wet-chemical etching in diluted hydrochloric acid (0.5% HCl). For refractive-index matching between front contact and silicon, an additional titanium dioxide (TiO_2) layer with thickness of 50 nm was sputter deposited onto the etched ZnO:Al film. A very thin (10 nm) ZnO layer was applied to protect the TiO_2 from reduction in hydrogen-rich plasma during silicon preparation [6]. The back reflector was improved optically

* Corresponding author at: Schott Solar GmbH, Hermann-Oberth Str. 11, 85640, Putzbrunn, Bavaria, Germany. Tel.: +49 894 62 64153; fax: +49 894 62 64209.
E-mail addresses: Berginski@googlemail.com, berginski@gmx.de (M. Berginski).

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by introduction of an evaporated SiO_2 layer with a thickness of 50 nm between back-contact ZnO and evaporated silver. The light-trapping ability of a specific TCO film was characterized by application in solar cells. μc-Si:H layers were prepared using plasma-enhanced chemical vapor deposition at an excitation frequency of 13.56 MHz in a $30 \times 30\,cm^2$ reactor. Details of film preparation and characterization are given elsewhere [3,7–9]. Usually, double layers of sputter-deposited ZnO:Al (80 nm) and thermally evaporated silver (700 nm) served as back reflector and rear-side contact. Optical absorption of the layers was measured by photothermal deflection spectroscopy [10] and in air with a dual-beam spectrometer. The solar cell I/V-characteristics were investigated using a solar simulator (Wacom WXS-140S-Super) at standard test conditions (AM 1.5, $100\,mW/cm^2$, 25 °C). The external quantum efficiency (QE) of the solar cells was calculated from spectral response measured at zero bias. The integrated short-circuit current density was determined using this QE curve employing the AM 1.5 solar spectrum. Henceforth, this calculated current density is referred to as cell-current density j_{QE}. The spectral response measurements were highly reproducible. Thus, the calculated cell-current density j_{QE} exhibited a measurement-reproducibility error of only ±1%.

In the literature, many different approaches have been proposed to derive light-trapping limits from theoretical calculations. Following a statistical mechanical consideration, Yablonovitch and Cody derived a factor of $2n^2$ as the upper limit for light intensity enhancement in a transparent dielectric medium with refractive index n [11,12]. Based on this model, Tiedje et al. presented an extended theory which is much more applicable for solar cells, since the authors also consider a small amount of absorption ($\alpha d < 1$, with α and d being the absorption coefficient and thickness, respectively) in the dielectric medium [13]. The absorption in the dielectric medium is given by

$$A_{\mathrm{Tiedje}} = \frac{\alpha}{\alpha + (4n^2 d)^{-1}}. \quad (1)$$

The corresponding derivation assumes that wave optical effects can be ignored ($d \gg \lambda$), and that the dielectric medium is irradiated from one side. While this front side faces air ($n_{air} = 1$) and has zero reflectivity (no primary reflection losses), the rear side is assumed to be ideally reflective. The light has to be fully randomized within the dielectric medium and the light scattering is assumed to be Lambertian (ideally diffuse). In case of a semiconductor material in which radiative recombination is the dominant recombination mechanism, the calculated absorption A_{Tiedje} can be compared to the QE of a solar cell. The model of Tiedje et al. provides an upper limit for the quantum efficiency since neither parasitic absorption nor primary reflection is considered.

In order to study these loss mechanisms in more detail, the work of Deckman and Wronski can be applied. Deckman and Wronski calculated a theoretical absorption probability F^{enh} using an infinite geometric progression [5]. Again, internal randomization and Lambertian light scattering are assumed. The sums of parasitic absorptions in the front contact and at the back reflector are given by A_{FC} and A_{BR}, respectively. Multiple reflections lead to an absorption in the silicon of

$$F^{\mathrm{enh}} = \frac{1 - (A_{FC} + A_{BR})e^{-2\alpha d} - (1 - A_{FC} - A_{BR})e^{-4\alpha d}}{1 - (1 - A_{FC} - A_{BR})e^{-4\alpha d} + (1 - A_{FC} - A_{BR})n^{-2}e^{-4\alpha d}}. \quad (2)$$

3. Experimental results

First we reproduced two experimental results of previous studies [8,9], which are compared to calculations, and later utilized for optical-limitation estimations of thin-film silicon solar cells.

3.1. Front-contact ZnO:Al transpareny

Our standardly used ZnO:Al front contacts are deposited at a substrate temperature of 300 °C employing a ceramic target with 1 wt% Al_2O_3 target doping concentration (TDC). These films typically have a carrier concentration of $5 \times 10^{20}\,cm^{-3}$. Recent estimations have shown that a carrier concentration of about $2 \times 10^{20}\,cm^{-3}$ might optimally balance the optical and electrical needs [14]. By reducing the doping concentration of the sputter target, the carrier concentration can be controlled over a broad range [8,15]. A TDC of 0.5 wt% combined with a substrate temperature in the range of 350–380 °C has been identified as a promising combination of sputter-deposition parameters for ZnO:Al with optimized balance of conductivity, absorption and light-scattering properties [14].

Fig. 1 shows QE and total cell absorption $1-R_{cell}$ of a single junction p–i–n μc-Si:H solar cell with intrinsic silicon layer thickness of 1.0 μm. A reference front contact (dotted line, TDC = 1 wt%) and the optimized front contact with reduced carrier concentration (full line, TDC = 0.5 wt%) have been used. In the short-wavelength spectral range the QE is higher in the case of the reference front contact due to the Burstein–Moss effect [16,17]. Nevertheless, this effect is more than compensated for by the higher QE in the long-wavelength range in the case of the more transparent front contact with TDC = 0.5 wt% (full line). Altogether the corresponding cell-current density has been increased from 23.1 (reference) to $24.4\,mA/cm^2$ (TDC = 0.5 wt%). As other experiments have shown, even though the electrical conductivity of the front contact is reduced, the improved optical properties can lead to an overall higher conversion efficiency of solar modules [14].

3.1.1. Comparison with calculated absorptions

In order to consider a situation without light trapping, the absorption during two passes of a silicon layer of thickness d is calculated using

$$A_{\mathrm{noLT}} = 1 - \exp(-2\alpha d). \quad (3)$$

This assumes no primary reflection losses and ideal reflectivity at the back contact, but no light scattering.

The theories summarized previously will be used in the following comparison to measure QEs of p-i-n thin-film silicon

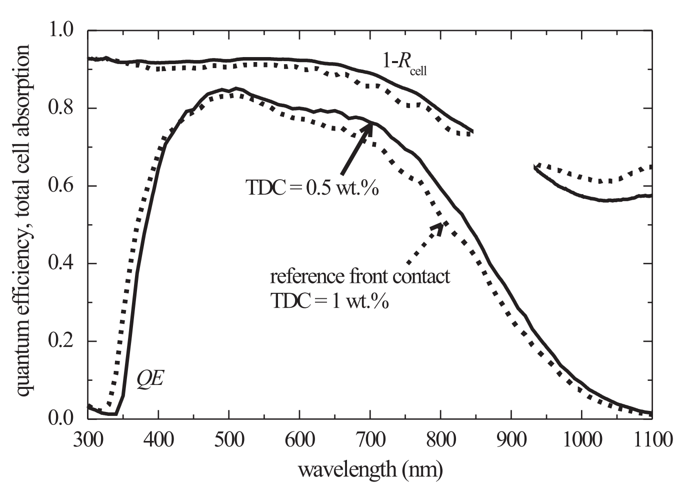

Fig. 1. Quantum efficiency (QE) and total cell absorption $1-R_{cell}$ of μc-Si:H single-junction cells (1.0 μm i-layer thickness) on reference ZnO:Al front contact with TDC = 1 wt% (dashed line) and more transparent front contact with TDC = 0.5 wt% (full line).