Solar Energy Materials & Solar Cells 143 (2015) 183–189

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Random versus periodic: Determining light trapping of randomly textured thin film solar cells by the superposition of periodic surface textures

Rahul Dewan [a,1], Shailesh Shrestha [a], Vladislav Jovanov [a], Jürgen Hüpkes [b], Karsten Bittkau [b], Dietmar Knipp [a,*]

[a] Research Center for Functional Materials and Nanomolecular Science, Electronic Devices and Nanophotonics Laboratory, Jacobs University Bremen, 28759 Bremen, Germany
[b] Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung 5 / Photovoltaic, 52425 Jülich, Germany

ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form
19 May 2015
Accepted 8 June 2015

Keywords:
Light trapping
Surface texture
Solar cells
Thin films

ABSTRACT

A simple method is developed to determine the light trapping properties of arbitrarily textured solar cells with high accuracy. The method allows for determining the quantum efficiency and short circuit current density of thin film solar cells prepared on randomly nanotextured surfaces. The light trapping of the randomly textured solar cell is described by the area weighted superposition of periodically textured solar cells. The necessary input parameters for the calculations are determined by analyzing the randomly textured surfaces of the solar cells using atomic force microscopy and image processing. The analysis of the atomic force microscope images and the calculation of the quantum efficiency and short circuit current can be determined from current maps, without complex and time-consuming calculations. The calculated solar cell parameters exhibit excellent agreement with experimentally measured quantum efficiencies and short circuit current densities for amorphous and microcrystalline silicon thin film solar cells prepared on randomly textured substrates. Finally, the work contributes to a comparison of random and periodic light trapping structures.

1. Introduction

Light trapping and photon management in thin-film solar cells is in the focus of intensive research due to its potential in enhancing the short circuit current density while minimizing the material usage [1]. Most light trapping schemes are based on texturing the interfaces of the solar cells [1–12]. Light is diffracted and scattered by the textured interfaces, leading to an increase of the short circuit current density and conversion efficiency [2–12]. Several studies have been carried out to determine and derive optimal surface textures of periodically textured solar cells [4,5,10–13]. However, most of the experimentally used large area substrates are randomly textured, because randomly textured substrates can be manufactured at low cost on square-meter large substrates. Optimizing solar cells on randomly textured substrates is complex. Several authors tried to estimate performances of the thin film solar cells on randomly textured substrates by using measurements of the haze (ratio of diffuse and total transmission) or the Angular Distribution Function (ADF) [14–16]. These measurements, however, cannot be directly correlated with solar cell parameters like the quantum efficiency or short circuit current density. The influence of the textured back contact of the solar cell on the quantum efficiency and short circuit current density is completely ignored. Other approaches use the roughness of the substrates as input parameter to model the light trapping properties of solar cells on textured substrates [17,18]. However, the surface roughness is not sufficient to describe the scattering properties of a surface. None of the proposed methods allow for a detailed description of the optics of randomly textured solar cells. A physically more precise description of the optics in randomly textured thin film solar cells can only be achieved by using rigorous simulation of the optical wave propagation [19–22]. Surface scans of the randomly textured solar cells have been used as input data in modeling such as large and randomly textured nanostructures. However, such simulations are computationally complex and time-consuming.

In this study we propose a method called Quantum Efficiency Superposition Method (QESM), which allows for the calculation of the quantum efficiency and short circuit current density of

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* Corresponding author.
E-mail address: dietmarknipp@gmail.com (D. Knipp).
[1] Current address: Robert Bosch (SEA) Pte Ltd, Singapore.

http://dx.doi.org/10.1016/j.solmat.2015.06.014
0927-0248/

arbitrary textured solar cells without using time-consuming calculations. Silicon thin film solar cells prepared on randomly textured substrates are used as the model system. Together with the quantum efficiencies of periodically textured solar cells, AFM scans of the randomly textured substrate are used as input parameter for the analysis. Because the calculations can be carried out in real time, the method can be easily integrated in the development of silicon thin film solar cells. The method is based on the assumption that the optics of randomly textured solar cells can be described by the superposition of the optical properties of periodically textured solar cells. It is assumed that the surface can be approximated by the superposition of periodically textured inverted pyramids with a hexagonal base. As a more general approach, the surface can be approximated by the superposition of periodically sinusoidal/cosinusoidal textured surfaces, which represent the Fourier decomposition of the surface [23–26]. However, since the experimentally realized structures resemble inverted pyramids we decided to approximate the surfaces directly by inverted pyramids and not by sinusoidal/cosinusoidal textured surfaces. In this method, the coupling of adjacent craters was not covered since we only considered the periodic coupling of a single crater.

The realization and characterization of randomly textured substrates is described in Section 2. The numerical simulation of periodically textured solar cells is described in Section 3. The method on how to calculate the quantum efficiency and short circuit current on randomly textured substrate is introduced in Section 4. The calculated quantum efficiencies are compared to experimentally measured quantum efficiencies. The results are summarized in Section 5.

2. Randomly textured transparent conductive oxides

Randomly textured surfaces can be fabricated by wet etching of sputtered zinc oxide films, or by Chemical Vapor Deposition (CVD) of zinc oxide or tin oxide [27–29]. The surface of the sputtered and subsequently etched zinc oxide film is characterized by a random arrangement of craters, while the surface of chemical vapor deposited film can be described by a random arrangement of pyramids. Fig. 1(a) shows the schematic cross section of a solar cell with textured interfaces. Fig. 1(b) shows a Scanning Electron Microscopy (SEM) image of a textured zinc oxide film with craters, formed by sputtering and subsequent wet chemical etching in an acid.

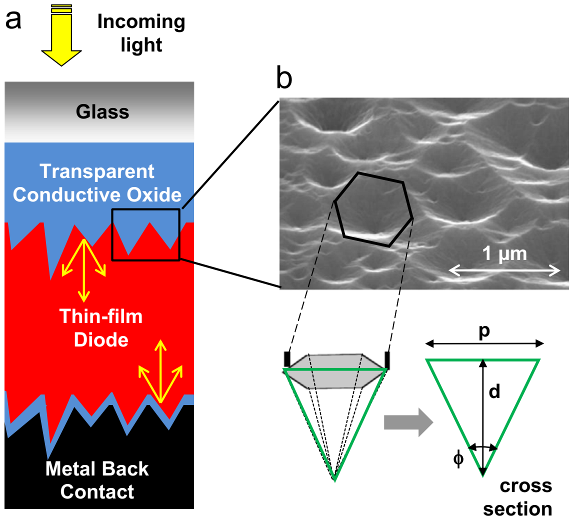

Fig. 1. (a) Cross sectional sketch of a silicon thin-film solar cell with randomly textured interfaces. (b) SEM image of a textured zinc oxide film. The craters on the surface can be approximated by inverted pyramids with a hexagonal base. The dimensions of the pyramid are given by the period (p), depth (d), and opening angle (ϕ) of the inverted pyramid.

Atomic force microscope images of textured surfaces are shown in Fig. 2(a) and (b). The choice for sample area of 10 µm × 10 µm was made such that a statistically significant distribution of the textured surfaces can be captured. The textured zinc oxide films are prepared by radio frequency (rf) magnetron sputtering in an in-line sputtering system at 300 °C substrate temperature. Afterwards the zinc oxide films are textured by a wet etching step in an acid. Films are etched in a diluted hydrochloric (HCl, 0.5 w/w%) and hydrofluoric (HF, 1 w/w%) acid solutions for 50 and 75 s, respectively. A comparison of the AFM images reveals that the HCl etched film, as shown in Fig. 2(b), is characterized by fewer but larger craters. The HF etched film in Fig. 2(a) exhibits a larger number of smaller craters. The difference in the samples can be explained by the differences in the etching properties of HF and HCl. HF molecules are smaller in size than almost all other acid molecules (including HCl), this combined with the weak dissociation enables HF molecules to penetrate deeper into zinc oxide grain boundaries before erosion [29].

The individual craters on the zinc oxide surfaces are separated by an image segmentation algorithm applied to the AFM data [30]. The algorithm first finds all local minima (crater tips) and then subsequently determines the corresponding surrounding borders. The segmentation is illustrated in Fig. 2(a) and (b), where the borders of the individual craters are marked by black lines and the minima (tips) of the craters are marked by white points. The crater-like surface of the zinc oxide films can be approximated by inverted pyramids. The dimensions of the craters are mapped to inverted pyramids with a hexagonal base. As shown in Fig. 1(b), the dimensions of the inverted pyramids can be described by three parameters: the period (p), depth (d) and opening angle (ϕ). Thus every crater on the zinc oxide surface identified by the segmentation algorithm can be characterized by these three parameters. The distribution of the extracted periods and depths are shown in Fig. 2(c) and (e) and Fig. 2(d) and (f), respectively. From the distributions of the periods and depth of the inverted pyramids, it is determined that the HCl-etched sample exhibits a wide range of diameters. Close to 75% of all inverted pyramids on the surface have period in the range of 0.5–1.5 µm. On the other hand, the HF-etched sample has a much narrower period distribution. More than 95% of the inverted pyramids have periods in the range of 0.2–0.8 µm. Both, the HCl etched and HF-etched sample follow a log normal distribution. Most of the inverted pyramids on both surfaces have depths in the range of 50–400 nm. In the case of the HCl-etched surface, 20% of the inverted pyramids have depths between 400 nm and 800 nm.

3. Optics of periodically textured solar cells

Before describing the optical wave propagation of randomly textured solar cells, the optics of periodically textured solar cells is investigated. Optical simulations of amorphous (a-Si:H) and microcrystalline (µc-Si:H) silicon thin film single junction solar cells with integrated inverted pyramid texture are carried out. The 3D optical wave propagation in the solar cell is investigated by rigorously solving Maxwell's equations using Finite Difference Time Domain (FDTD) algorithm [31]. The unit cell's cross section of a periodically textured amorphous (a) and microcrystalline (c) silicon solar cell is shown in Fig. 3. The layer sequence of the silicon solar cell consists of an 800 nm thick aluminum-doped zinc oxide (ZnO:Al) front contact. Afterwards the inverted pyramids (craters) are etched in the zinc oxide film. The periodic surface texture can be described by pyramid period (p) and depth