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On the potential of light trapping in multiscale textured thin film solar cells

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ABSTRACT

The light propagation in multiscale textured thin film silicon solar cells is studied experimentally and numerically. The short circuit current and energy conversion efficiency of multiscale textured amorphous silicon thin film solar cells are increased compared to nanoscale textured substrates. A gain of the short circuit current of 1.3 mA/cm^2 is achieved for the multiscale textured solar cell, resulting in short circuit current densities of 16.8 mA/cm^2 and energy conversion efficiency of 10.7%. The light propagation in the solar cells is determined by Finite Difference Time Domain simulations in three dimensions using realistic interface morphologies. The realistic interface morphologies of solar cells are calculated by 3D algorithms. The optical simulations reveal that the interface morphology of the back reflector of the multiscale textured solar cell has a distinct influence on the short circuit current and quantum efficiency. By tuning the optical losses of the metal back reflector, the short circuit current can be increased beyond 18 mA/cm^2.

1. Introduction

Thin film solar cells are promising devices for harvesting the sunlight. High energy conversion efficiencies and short circuit currents can be achieved by efficient light trapping (photon management). Commonly, the absorption of light is enhanced by texturing the front contact (solar cells in superstrate configuration) or back contact (solar cells in substrate configuration) [1–11]. The textured front contact of the solar cells has the function to improve the incoupling and scattering of the incident light. The back contact textures elongate the optical path length of the light that reaches the back reflector, while minimizing the optical losses of the back contact. Experimental and theoretical studies have been carried out to determine optimal surface textures of silicon thin film solar cells [2,12–16]. The optimal surface textures represent a compromise between the light incoupling (shorter wavelengths) and light trapping (longer wavelengths) [4,5,8]. As an alternative approach, multiscale textures have been proposed. Multiscale textured substrates exhibit a combination of textures with at least two different size scales. In this combination, small scale features scatter shorter wavelengths, while larger scale surface features refract longer wavelengths. Different approaches have been developed to realize the multiscale texture. Asahi Glass has proposed a process in which the multiscale surface textures are fabricated by controlling the deposition process of the transparent conductive oxide [17]. Large surface textures with dimensions in the range of 1 μm are grown by a chemical vapor deposition (CVD) process. Afterwards, small surface features are grown on top of the larger surface texture. Tokyo Tech developed a process in which the glass substrate is textured by a reactive ion etching (RIE) process [4,8]. The etching process leads to the formation of micrometer large surface features on the glass substrate. Boron doped zinc oxide (ZnO:B) film is then deposited on top of the textured glass substrate using Low Pressure Chemical Vapor Deposition (LPCVD) process. A modified process has been developed by Tan et al. where a hydrogen doped indium oxide film is prepared on the textured glass to provide sufficient electrical conductivity. Afterwards, the zinc oxide film is deposited by low pressure chemical deposition [18]. The University of Neuchâtel has used nanoimprint lithography to pattern glass substrates coated with a spin-on-glass. Afterwards, the ZnO:B film is prepared by the LPCVD [5]. High short circuit currents have been observed for all approaches, where the gain of the short circuit current mainly occurs for longer wavelengths [4,5,8,15–17]. Even though high

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short circuit currents have been achieved, clear rules for the optimization of the solar cells have not been developed.

The aim of this study is to investigate the light propagation in multiscale textured solar cell by a comparison of the experimental and optical simulation results. Modeling of the optics in the multiscale textured solar cell is complex, because morphologies for all interfaces have to be known. To address this problem, we have developed a model that allows for determining the interface morphologies of silicon thin films prepared on arbitrary substrates. This model also allows for determining the effective thickness of the silicon layers on the textured surface which deviates from the nominal thickness of the layers. The increased thickness of the films is caused by the film growth on a 3D surface. Finally, to provide a realistic description of the optical properties of the metal back reflector an effective medium approach is used. Previous investigations have showed that the back reflector has a distinct influence on the light trapping of the solar cell, and that the short circuit current is limited by optical losses of the back reflector [6,9,13]. Therefore, optical properties of the metal back reflector have to be accurately modeled to describe the experimental results. For the first time, the different methods and approaches are combined to provide a realistic model of the interfaces, determine the effective thickness and to create a realistic model of metal reflectors.

The fabrication of the multiscale and nanoscale textured solar cells is described in Section 2. Experimental results of the nanoscale and multiscale textured solar cells are presented in Section 3. The optical simulation model is introduced in Section 4. The optical simulation results of the silicon solar cells are described in Section 5. Different strategies on how to minimize optical losses of the back reflector and increase the short circuit current are also presented, before summarizing the results in Section 6.

2. Device fabrication

Fig. 1(a) and (c) show Scanning Electron Microscope (SEM) images of soda-lime glass substrates before the zinc oxide (ZnO) film deposition. Fig. 1(b) and (d) show SEM images of front ZnO films after the deposition. To fabricate glass substrate for multiscale textured solar cells (Fig. 1(c)), the flat glass substrate (Fig. 1(a)) is textured by using a reactive ion etching (RIE) process with carbon tetrafluoride (CF_4) as an etchant gas. The plasma treatment is carried out at a gas pressure of 13 Pa and power density of 1.5 W/cm^2. After the plasma treatment, the glass substrate exhibits a root mean square (rms) roughness of 360 nm. The surface of the etched glass substrate (Fig. 1(c)) can be described by an arrangement of concave shaped craters. The front transparent conductive oxide (FTCO) layers are prepared by depositing ZnO:B films onto the glass substrates by LPCVD process (Fig. 1(b) and (d)). The front ZnO films have a thickness of approximately 1.6 μm. The FTCO layer of the nanoscale textured solar cell is characterized by pyramid textures (Figs. 1(b) and 2(a)). On the other hand, the FTCO layer of the multiscale textured solar cell can be approximated by hexagonally arranged convex shaped micro textures with nanoscale pyramids on top (Figs. 1(d) and 2(c)). Cross-sections of nanoscale and multiscale textured amorphous silicon solar cells are shown in Fig. 2(b) and (d), respectively. The chemical vapor

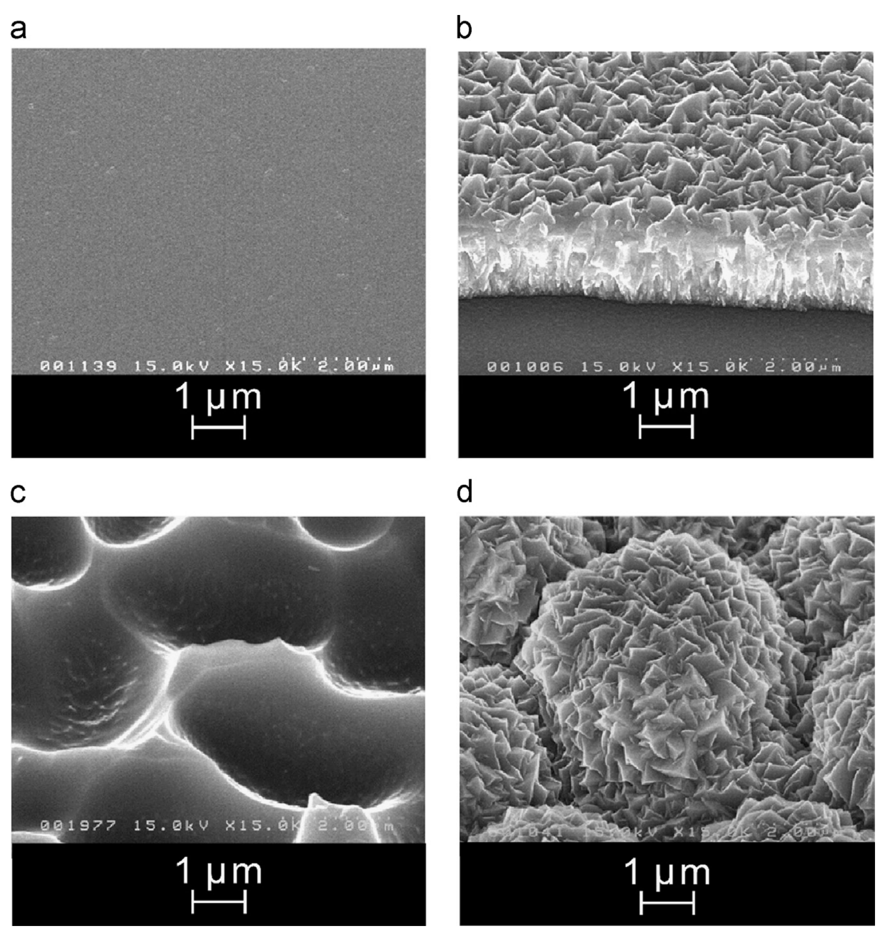

Fig. 1. SEM images of soda-lime glasses prior to ZnO film deposition at gas treatment pressure of (a) 0 Pa and (c) 13 Pa. SEM images of ZnO films as a function of glass-substrate treatment gas pressure of (b) 0 Pa and (d) 13 Pa.