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Short communication

Plasmonic back contacts with non-ordered Ag nanostructures for light trapping in thin-film silicon solar cells

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ABSTRACT

In this work, we investigate the light trapping of thin-film silicon solar cells which apply plasmonic Ag back contacts with non-ordered Ag nanostructures. The preparation, characterization and three-dimensional electromagnetic simulations of these back contacts with various distributions of non-ordered Ag nanostructures are presented. The measured reflectance spectra of the Ag back contacts with non-ordered nanostructures in air are well reproduced in reflectance spectra derived from the three-dimensional electromagnetic simulations of isolated nanostructures on Ag back contacts. The light–matter interaction of these nanostructures is given by localized surface plasmons and, thus, the measured diffuse reflectance of the back contacts is attributed to plasmon-induced light scattering. A significant plasmonic light-trapping effect in n-i-p substrate-type μc-Si:H thin-film solar cell prototypes which apply a Ag back contact with non-ordered nanostructures is identified when compared with flat reference solar cells.

1. Introduction

Thin-film silicon solar cells made of amorphous (a-Si:H) or microcrystalline silicon (μc-Si:H) require an advanced light trapping in order to efficiently absorb incident light of wavelengths longer than 500 nm [1–3]. In this spectral range, the a-Si:H and μc-Si:H absorber layers are optically thin. State-of-the-art thin-film silicon solar cells apply randomly textured interfaces at the front and rear side to scatter and diffract incident light into the device [3,4]. This scattered light is partly guided in the silicon absorber layers which leads to an enhanced short-circuit current density (J_{sc}) of the solar cell.

To further improve the light trapping in thin-film silicon solar cells several, new concepts are studied in the literature. One of these concepts applies light-scattering plasmonic nanostructures [5–8]. At metal nanoparticles or nanostructured metal layers, light can couple efficiently to localized surface plasmon (LSP) [9]. A dominant radiative decay of the LSP resonances induces very efficient scattering of incident light. If this LSP-induced light scattering is directed into the absorber layer of a thin-film silicon solar cell, the metal nanostructures serve as sub-wavelength scattering components that couple incident propagating light into the thin absorber layers of the solar cells. Based on this approach, metal nanostructures placed at the front interface of solar cells have been proposed to reduce the initial reflection of the solar cell as well as increasing the light path in the absorber layer [10,11]. At the rear side of the solar cell, periodic and non-ordered Ag nanoparticles and Ag nanostructures have been applied to scatter incident light such that the light is guided in the absorber layers of the solar cell [12–17].

Recently, we showed by means of electromagnetic simulations that nanostructures on Ag back contacts of μc-Si:H solar cells exhibit particularly promising light-scattering properties for light-trapping [18]. In the present study, such non-ordered nanostructures on the Ag back contact of μc-Si:H thin-film solar cells were experimentally realized. The measured diffuse reflectance spectra of these back contacts are compared to the simulated diffuse reflectance spectra. This allows for a straightforward analysis of the contribution of the plasmon-induced light scattering to the diffuse reflectance spectra of the Ag back contacts with non-ordered Ag nanostructures.

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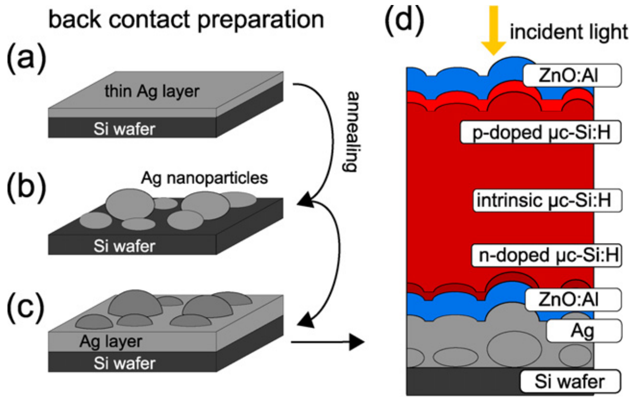

Fig. 1. (a)–(c) Schematic illustration of the preparation of the plasmonic Ag back contacts with non-ordered nanostructures. (d) Schematic cross-section of a n-i-p substrate-type μc-Si:H solar cell deposited on a plasmonic back contact with non-ordered Ag nanostructures.

2. Methods

2.1. Preparation of Ag back contact with non-ordered nanostructures

The fabrication steps from the Ag nanoparticles to the Ag back contacts with non-ordered nanostructures are schematically illustrated in Fig. 1(a)–(c). The Ag back contacts are prepared for the subsequent deposition of a n-i-p substrate-type μ*c*-Si:H thin-film silicon solar cell (see Fig. 1(d)).

Non-ordered distributions of Ag nanoparticles on silicon wafer substrates were prepared by annealing thermally evaporated Ag films for 6 h at 500 °C in a nitrogen atmosphere (see Fig. 1(a) and (b)). During this annealing process, due to the surface tension of the Ag, the Ag films agglomerated into non-ordered distributions of Ag nanoparticles [12–15]. Scanning electron microscopy images of three Ag nanoparticle distributions are shown in Fig. 2. For these samples, the initial Ag film thickness varied from 10 nm to 30 nm. A clear correlation between the initial Ag film thickness and the average size of the Ag nanoparticles is apparent. Finally, the silicon wafer substrates with the Ag nanoparticle distributions were covered with a 200 nm thick dc-sputtered Ag (see Fig. 1(c)). The resulting surface of a Ag back contact exhibits half-ellipsoidal Ag nanostructures.

In this study five distinct types of distributions of Ag nanostructures are investigated which were prepared on nanoparticles obtained by annealing of Ag layers of thickness of 10 nm, 15 nm, 20 nm, 30 nm and 40 nm. These five back contacts are referred to as Type I–Type V. In order to analyze the nanostructure distribution, atomic force microscopy (AFM) images of the back contacts were analyzed with the Advanced Threshold Algorithm of the Particle and Pore Analysis module of the SPIP software [20]. The very sensitive detection level for the algorithm was set to the mean level of plane-fitted AFM data. Those nanostructures with a height to radius aspect ratio below 0.5 and a radius below 3 nm have been excluded. From the detected nanostructure distribution, the area-weighted base radius and the height of the nanostructures were derived.

The diffuse reflectance spectra of the Ag back contacts with non-ordered Ag nanostructures were measured with a spectrophotometer LAMBDA 950 (Perkin Elmer) equipped with an integrating Ulbricht sphere.

2.2. Electromagnetic simulations

The interaction of light with isolated plasmonic Ag nanostructures on the Ag back contact was studied with a three-dimensional numerical solver of Maxwell's equations. The simulations were carried out with the program JCMsuite® which applies the Finite Element Method to discretize Maxwell's equations on a on prismatic grid in all three dimensions [21]. Similar nanostructures than those studied in this work have been investigated in detail with the same method in [18]. From the simulated three-dimensional electric field distributions, power loss spectra as well as the diffuse and total reflectance spectra were calculated.

2.3. Solar cell preparation

We prepared μc-Si:H solar cells in n-i-p substrate configuration with an active cell area of 1 cm × 1 cm (see Fig. 1(d)). The performance of solar cells deposited on (i) a flat reference Ag back contact, (ii) conventional randomly textured Ag back contacts and (iii) a Ag back contact with non-ordered Ag nanostructures were compared. Back contact (iii) is prepared on a Type IV Ag back contacts with non-ordered nanostructures. The preparation is described in Section 2.1. The state-of-the-art random texture of the Ag back contact (ii) is prepared by wet-chemical etching of a rf-sputtered ZnO:Al substrate for 40 s in 0.5 w/w% HCl [3]. On top of all back contacts, a 80 nm (±5 nm) thick ZnO:Al layer was sputtered at room temperature by rf-sputtering. Afterwards, a n-doped, an intrinsic and a p-doped μc-Si:H layer were deposited by plasma enhanced chemical vapor deposition [19]. The thicknesses of these layers are 20 nm (±10 nm), 1100 nm (±25 nm) and 20 nm (±10 nm), respectively. For the front contact, a 70 nm (±10 nm) thick front ZnO:Al layer in combination with Ag finger electrodes was deposited. The external quantum efficiency (*EQE*) of the solar cells is used to evaluate the influence of the plasmonic Ag back contact with non-ordered Ag nanostructures on the light trapping of the solar cell in the relevant spectral region.

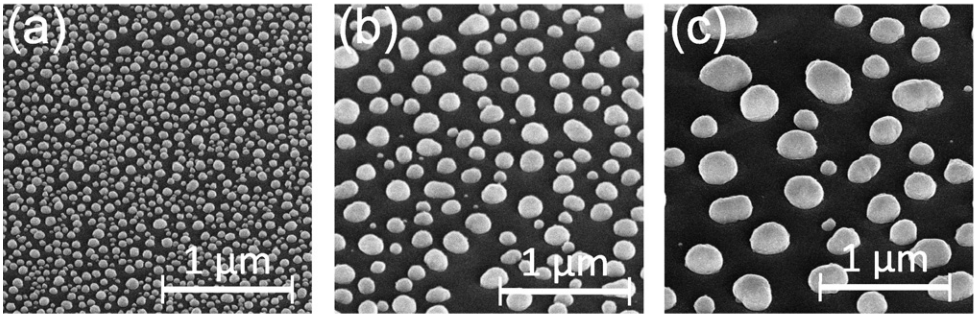

Fig. 2. Scanning electron microscopy images of Ag nanoparticles prepared by annealing of thin Ag films of thickness of 10 nm, 20 nm, and 30 nm from (a), (b), (c), respectively.