

Thin-film silicon solar cells with integrated silver nanoparticles

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Abstract

Thin-film silicon solar cells need efficient light absorption to achieve high efficiencies. The standard light trapping approach consists of a randomly textured transparent substrate and a highly reflective back contact. In this case, light scattering at the rough TCO–silicon interface leads to a prolonged absorption path and consequently to an increased short circuit current. In this study, we will discuss a new approach based on silver nanoparticles to improve the light absorption in the thin-film silicon solar cells. Raman and SNOM measurements and theoretical investigations on systems with metallic nanoparticles indicate a strong increase of the electric field in their surrounding when they are irradiated by light. Moreover, nanoparticles with the proper diameter can enhance light scattering. In this study, we have investigated the influence of silver nanoparticles with different sizes on the optoelectronic properties of amorphous and microcrystalline silicon solar cells. The nanoparticles are located at the back contact of the thin-film silicon solar cell deposited in a n–i–p layer sequence.

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1. Introduction

Metallic nanoparticles are of particular interest for different applications such as chemical and biological sensing [1] or optical filtering [2]. More recently they were applied in solar cells and in light-emitting diodes to increase the absorption and the emission of light, respectively. A surface plasmon (SP) that is the collective oscillation of the free electrons in a metallic nanoparticle can result in a strong enhancement of the electric field in its surrounding. High Raman intensities, which are proportional to the square of the electric field, have already been measured and used for Surface Enhanced Raman Spectroscopy (SERS) applications [3,4]. SNOM (Scanning Near Field Optical Microscopy) measurements and theoretical investigations on systems including Ag and Au nanoparticles with a spatial distribution close to the percolation threshold show an amplification by up to 4 orders of magnitude of the intensity of the incident light [5,6]. Moreover, metallic nanoparticles can also result in a strong scattering of the incident light when their diameter exceeds 50 nm [7]. Both

effects, the increase of the local electric field strength and the enhanced light scattering, can contribute to higher photocurrent [8–13]. In this study, small (around 15 nm diameter) and large (around 300 nm diameter) silver nanoparticles were integrated at the back side of amorphous silicon (a-Si:H) and microcrystalline silicon (μ c-Si:H) n–i–p solar cells to investigate their influence on the optical and electrical device properties.

2. Experimental details

Both amorphous and microcrystalline n–i–p solar cells are prepared in substrate configuration on $10 \times 10 \text{ cm}^2$ Corning glass. The cells have an area of 1 cm^2 . A silver mirror and a thin Transparent and Conductive Oxide (TCO) of ZnO are successively deposited at room temperature by rf-sputtering on the glass to realize a highly reflective back contact. Then, a thin Ag nanolayer is deposited by thermal vaporization at a pressure of approximately 10^{-5} mbar. The thickness of the metallic nanolayer controlled by a quartz oscillator is varied between 3 nm and 20 nm. The 3 nm thick Ag layer shows a structure close to the percolation threshold. For an Ag thickness of 20 nm, the nanolayer fully covers the TCO and shows a nearly homogeneous surface. To obtain nanoparticles that are

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well separated from each other, the substrate is annealed at a temperature of 180 °C during several hours. Afterwards, the n-, i- and p-layers are deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD). The thickness of the intrinsic layers of the a-Si:H and $\mu\text{c-Si:H}$ solar cells were 100 nm and 1 μm respectively. As a front contact, we used a 80 nm thick ZnO layer, deposited at 150 °C by rf-sputtering in combination with an Ag grid, deposited by vaporization through a mask. The non-optimized Ag grid leads to a shading of the cell by around 25%. More details concerning the PECVD and sputtering process are given elsewhere [14]. Reflection measurements were carried out on cells without Ag grid using an integral sphere (Ulbricht). Raman measurements were conducted at a wavelength of 647 nm.

3. Results and discussion

3.1. Optical properties of the reflector

The thickness of the Ag nanolayer deposited on the glass/Ag/TCO substrate was varied from 3 nm to 20 nm in order to obtain nanoparticles with different diameter after the annealing step. The reflectivity of the back reflector system consisting of a glass/Ag/TCO-layer stack with a 3 nm and 20 nm thick nanolayer is shown in Fig. 1a and b respectively, before and after the annealing step at 180 °C. In the case of a 3 nm thick nanolayer (Fig. 1a), before annealing the structure is close to the percolation threshold of Ag material. Therefore, a broad minimum of the

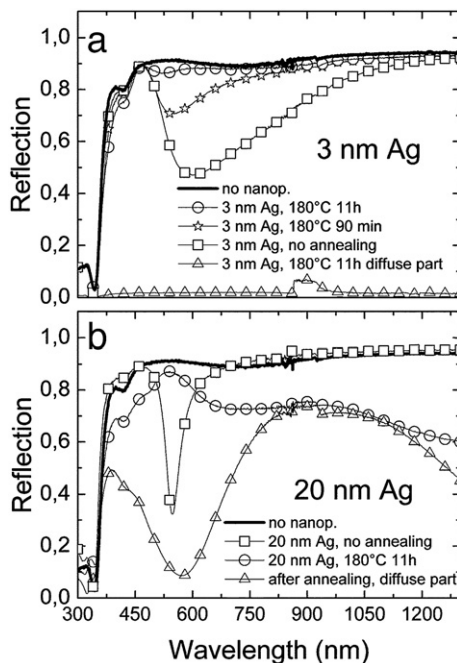


Fig. 1. Reflection measurements of glass/Ag/TCO/nanoparticles substrates with an Ag nanolayer thickness of 3 nm (a) and 20 nm (b). The lines with/without symbols represent the reflection of the substrates with/without Ag nanoparticles. The lines with squares/stars represent the reflection of the substrates with nanoparticles before annealing/after 90 min annealing at 180 °C. The circles/triangles lines represent the total/diffuse reflection of the substrates with nanoparticles after 11 h annealing at 180 °C.

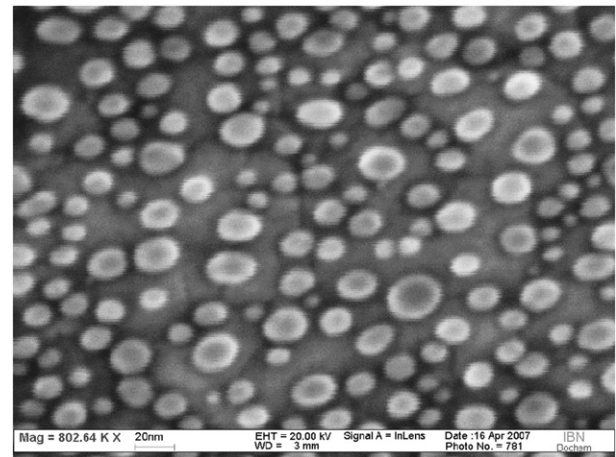
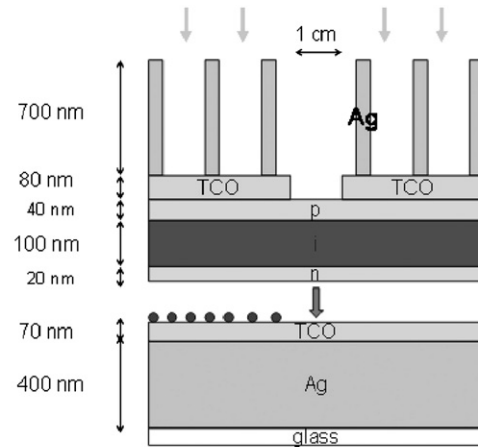


Fig. 2. Sketch of two co-deposited n-i-p solar cells with and without nanoparticles positioned at the TCO/n interface (top). SEM picture (bottom) of Ag nanoparticles on a glass/Ag/TCO substrate produced by vaporization of a 3 nm Ag nanolayer and annealing at 180 °C during 90 min.

reflection at $\lambda=600$ nm (squares) is observed [15]. After 90 min annealing at 180 °C, well separated Ag nanoparticles (see Fig. 2, bottom), with an average diameter of 15 nm are formed and, in particular, the reflectance at $\lambda=600$ nm increases (stars). Longer annealing time further increases the average nanoparticles diameter and the inter-particle distance. After 11 h annealing, the average nanoparticles size is around 20 nm and the reflectivity of the substrates with and without nanoparticles is nearly identical (circles and bold line). In this case the reflection is dominated by the bulk properties of the glass/Ag/TCO and glass/Ag/TCO/Ag layer stacks. No contribution of the diffuse light is detected (triangles).

In the case of a 20 nm thick Ag layer (Fig. 1b), a nearly homogenous surface which may behave as an Ag/TCO/Ag mirror is observed before annealing. Due to interference, a distinct minimum at around 550 nm is observed (squares). For $\lambda>700$ nm, the reflectivity of the back contact with (squares) and without (bold line) the metallic nanolayer is comparable. After annealing at 180 °C for several hours, Ag nanoparticles that are well separated from each other, with a broad distribution of sizes from 100 nm to 500 nm and an average particle diameter of around 300 nm are formed. The distinct minimum

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