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Multilayer silver nanoparticles embedded in graded-index dielectric layers

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ABSTRACT

A pulsed laser deposited SiO_2/Ag/ZnO/Ag/TiO_2 multilayer structure is studied to enhance the light trapping capability of thin-film solar cell. Structural and optical properties of structure are studied with scanning electron microscopy, x-ray diffraction, photoluminescence and UV–visible spectroscopy. Proposed geometry improves the extinction spectra and quenches photoluminescence in comparison to TiO_2/Ag and SiO_2/Ag/ZnO geometry. Finite-difference time-domain (FDTD) simulations indicate a promising effect of the proposed geometries on thin-film solar cells. Twofold enhancement in total quantum efficiency of an optimized multilayer plasmonic graded-index thin-film solar cell is observed in comparison to the pristine solar cell. Results suggest a more concerted study of multilayer plasmonic nanostructures with graded-index anti-reflection coatings to improve the performance of thin-film photovoltaic devices.

1. Introduction

A polished silicon wafer reflects almost 37% of the incident light [1]. Reducing reflections and improving absorption are the main concerns of photovoltaic researchers. Surface Texturing is a common method to trap the incident wavelength which otherwise could not be absorbed by silicon [2,3]. Texturing the semiconductor reduces reflections and increases the chance of light absorption by bouncing back the incident light into the substrate. Surface texturing is achieved by etching out the faces of the crystal plane in crystalline silicon wafers, or by etching the pyramids (with a size of 2–10 μm) into the silicon surface upwards from the surface [2]. This practice works well with crystalline silicon solar cells but cannot be implemented on thin-film solar cells where total device thickness is usually in the range of 1–2 μm. In thin-film solar cells, an anti-reflection (AR) coating is used which has an optical thickness equal to the quarter of the interest wavelength [4,5]. A single AR coating can minimize reflections for a particular angle of incidence and a particular wavelength only. However, multilayer AR coatings reduce reflections over a board spectrum. Multilayer AR coating can be very efficient when arranged in graded index structures. Multilayer AR coatings can be realized by gradually decreasing the refractive index of AR coating from semiconductor to air [5,6]. V. Sharma et al. recently studied the effect of graded Si_xN_y AR films and observed decrease in surface reflections [7]. Chun Deng et al. fabricated refractive-index-graded broadband AR coatings by mixing silicon and glass and, reduced spectral reflectance to 2.2–5.5% for a wavelength range of 400–1000 nm [8]. Illhwan Lee et al. studied refractive index grading layers for various optoelectronic devices and observed favorable results [9]. Hence, optimized graded-index multilayer AR coatings promote the broadband omnidirectional flow of incident light [5–12].

Plasmonic nanoparticles finds applications in sensors [13], nonreactors [14,15], transparent electrodes [16,17], moisture resistant films [18] etc. Recently plasmonic nanoparticles have been explored as an alternative technique to trap the incident light in thin-film solar cells [19–28]. When an electromagnetic wave incidents on a metal nanoparticle surrounded by some dielectric material, it stimulates surface plasmon resonance (SPR) [19,20]. SPR gives rise to scattering and near-field concentration of light well beyond the geometrical cross section of the nanoparticles [21]. It improves the optical path length of incident light and increases the probability of light absorption in the absorber layer [24,25].

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Metal nanoparticles are surrounded by dielectric material and at resonance, evanescent fields propagate at the interface of two media [20,21]. The penetration depth of the evanescent field in a material is decided by its optical properties. A favorable combination of materials improves the forward scattering of incident light in the underlying layer. The SPR can be tuned with different combinations of metal and dielectric materials. A particular distribution of metal nanoparticles in a dielectric media covers a particular region of the spectrum [19,20]. Different particle distributions show SPR shifting pertaining to each other [19,21]. Plasmonic structures in stacked geometry evolve exciting results. The combination of different distributions in a single system promotes continuity of resonance wavelengths over broad spectra, and the resulting multilayer inherits the characteristic of each distribution simultaneously [22,23]. In this way, a wide spectrum of incident electromagnetic waves can be scattered efficiently in the underlying layer. It can be very beneficial to trap the incident light in thin-film solar cells.

A gradual increase in the refractive index of buffer layer from air to the underlying absorber layer promotes the unidirectional broadband characteristic of an AR coating and; multilayer plasmonic structure surrounding by suitable dielectric material can scatter the incident light over a wide spectrum. These light trapping mechanisms simultaneously can be very beneficial for trapping the incident light and could be a novel AR solution for thin-film devices. In this work, we use multilayer plasmonic nanoparticles embedded in a suitable graded refractive indexed layer for the first time. Graded refractive indexed layer can guide the light scattered by multilayer plasmonic structures in the absorber layer further. In this paper, multilayer metal/dielectric structures are fabricated for photovoltaic applications. TiO_2, ZnO, and SiO_2 thin films are arranged one after another to realize the graded-index anti-reflection layer. Silver nanoparticles are considered at the interface of two dielectrics to achieve a multilayer plasmonic effect. The proposed structure is tested theoretically on thin-film solar cells and their total quantum efficiencies (TQE) are calculated.

2. Method

All the depositions are carried out on cleaned glass substrates. KrF pulsed laser deposition system is used to deposit thin-films of ZnO, TiO_2 and silver nanoparticles. The energy of the PLD system is fixed at 200 mJ for all the depositions. The operating wavelength of the laser is 248 nm. The substrate to target distance is fixed at 4 cm for all the depositions. A repetition rate of 5 Hz is used for all the depositions. 100 cleaning shots are used prior deposition of each layer to avoid contamination. 500 laser shots are used to deposit 50 nm thick ZnO film at room temperature. 750 laser shots are used to deposit 50 nm thick TiO_2 film at room temperature. A 40 mtorr partial pressure of oxygen gas is maintained to deposit thin films of ZnO and TiO_2. 500 shots are used to deposit well-separated silver nanoparticles [26,27]. (6×10^{-6}) Torr vacuum is maintained to deposit silver nanoparticles. Substrate temperatures of 373 and 473 K are used to obtain two different distributions of silver nanoparticles [27]. Various optical and structural properties of the films are studied by Perkin Elmer Lambda 35 UV–visible spectrometer, Bruker high-resolution X-ray diffractometer (HR-XRD), TESCAN MIRA-3 scanning electron microscope (FESEM) and Perkin Elmer photoluminescence spectrometer (PL).

3. Results and discussions

A graded-index AR coating is a promising arrangement to implement with plasmonic nanoparticles. Plasmonic nanoparticles can use the light guiding property of graded-index AR and trap the incident light effectively in the underlying substrate. 50 nm-thick ZnO and 50 nm-thick TiO_2 are stacked one after another over silica substrate to obtain the graded-index AR film as shown in Fig. 1. Refractive index of graded-index layers decreases from TiO_2 (2.614) to ZnO (2.004), from ZnO to SiO_2 (1.459) and from SiO_2 to air (1). Silver nanoparticles are deposited at the interface of the two dielectrics.

Fig. 2 represents the HRXRD of the geometry. CuKα emission line (1.541 Å, 40 kV, 40 mA) coupled to a germanium monochromator is used to study the sample at a scan rate of 1°/min. The peaks at 31.73° and 34.37° correspond to (100) and (102) plane of ZnO nanoparticles respectively (JCPDS-ICDD, PDF no. 89-1379). The peaks at 38.14° and 64.60° correspond to (111) and (220) plane of silver nanoparticles, respectively (JCPDS-ICDD, PDF no. 89-3722). The peaks at 47.38°, 49.51°, 51.90° and 55.12° correspond to (211), (022), (220) and (202) plane of TiO_2 nanoparticles, respectively (JCPDS-ICDD, PDF no. 21-1750).

Both layers of silver nanoparticles are deposited at different substrate temperatures. Substrate temperatures of 373 and 473 K are used to deposit silver nanoparticles at the interface of (SiO_2 & ZnO) and (TiO_2 & ZnO) respectively. Fig. 3 (a) shows the FESEM image of silver nanoparticles (d_2) deposited on the glass substrate at 373 K. An average nanoparticle size of 18 nm is observed in this case. An accelerating voltage of 20 KV and, working distance (WD) of 5.24, 4.36 and 5.08 mm are maintained to capture Fig. 3(a), (b) and (c) respectively. Fig. 3 (b) shows the FESEM image of silver nanoparticles (d_1) deposited on ZnO nanoparticles at 473 K.

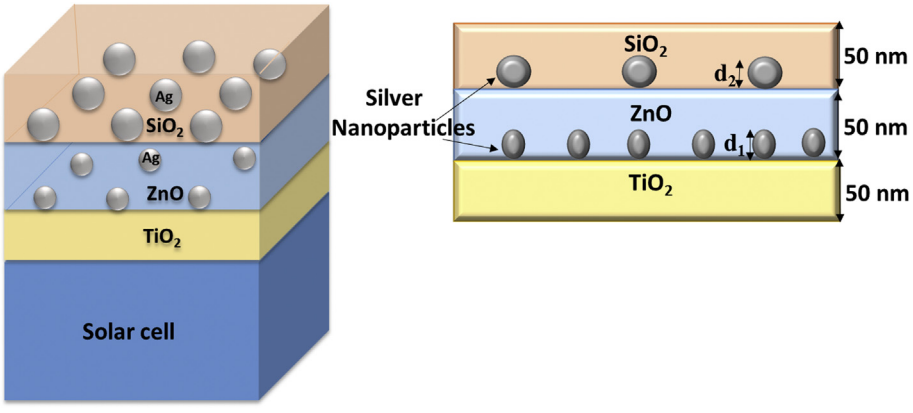

Fig. 1. Schematic of the geometry.