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Au nanoparticle enhanced thin-film silicon solar cells

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ABSTRACT

Gold nanoparticles (Au NPs) were prepared on the top of the indium tin oxide (ITO) window layer in thin-film silicon solar cells using a magnetron sputtering method. In comparison with the pure ITO film, the samples with the Au NPs show higher optical transmittance. It is found that the photoluminescence (PL) intensities from the ITO films are enhanced significantly by the Au NPs, so do the macroscopic conductance and the microscopic conductive atomic microcopy (C-AFM) current–voltage (I–V) characteristics. It also appears that the surface work function (φ_s) is changed by the Au NPs, the longer time the Au NP deposition, the more Au NPs on surface, the larger φ_s. When the sample is illuminated, its φ_s downshifts due to the local surface plasmon resonance (LSPR) excited by the illumination on the Au NPs. It is found that the short circuit current density (J_{sc}) of the solar cells is increased by as much as 20.78% for the optimized solar cell configuration.

1. Introduction

Gold (Au) nanoparticles (NPs), particularly for small (5–20 nm diameter) particles, are well known for their local surface plasmon resonance (LSPR) properties arisen from collective oscillation of conduction electrons in response to optical excitation [1–4]. The particles have a resonant frequency (SPRF), at which incident light will strongly excite the collective oscillation of electrons. This leads to either strong absorption or scattering of light [5]. It is found that for metal NPs (MNPs), the SPRF is a function of size, shape, distribution, dielectric properties, surface modification, and surrounding environment [6–8]. For example, the LSPR peak of 13 nm spherical Au colloids is at ~520 nm and that of 5–6 nm silver (Ag) NPs is shifted to ~400 nm [9]. By taking advantage of the strong local field enhancement around the MNPs, the improvement in solar cell efficiency can be achieved by the manipulation of light at nanoscale [10–12].

There have been tremendous efforts developing the near-field effect of MNPs for solar cell applications [13–15]. For example, Kirkengen et al. reported the direct generation of charge carriers in c-Si solar cells by embedded MNPs, leading to increased cell efficiency [13]. Using the near-field effects, Hägglund et al. demonstrated increased photocurrents in a silicon solar cell with elliptical Au nanodisks [14]. By taking advantage of the LSPR effect of Ag NPs, Liu et al. achieved significantly enhanced short-circuit current density (J_{sc}) by 17% in single crystalline silicon (c-Si) solar cells [15].

Meanwhile, plasmonic MNP enhanced photoluminescence (PL) has also been actively explored [16,17]. Anger et al. showed that the near-field effect of Au NPs can greatly affect the PL intensities of semiconductors [18]. Ábrahám et al. reported that the LSPR of Au NPs has advantageous effects on the PL properties of ZnO [19]. Chen et al. demonstrated an enhancement of 0.86 mA/cm^2 in J_{sc} and ~0.64% in efficiency (η) for Si solar cells using Ag-NP-enhanced nanophosphor fluorescence [20].

Furthermore, the modification of surface work function (φ) with MNP deposition on indium tin oxides (ITO) has also been observed [21]. As the ITO film is often used as the window material for thin film solar cells, its φ, which affects the efficiency of carrier injection into the ITO/semiconductor interface, is of great importance [22,23]. MNPs are also used to improve the conductivity of ITO films [24,25] to achieve reduced resistance loss, improved collection of carriers, higher J_{sc} and the overall cell efficiency.

In this work, we deposited Au NPs on the top surface of n-i-p type a-Si:H solar cells using a magnetron sputtering system. Note that there is no direct contact between the Au NP and the a-Si, while the ITO layer serves as a barrier in between. The Au NPs gives the highest photocurrent enhancement of 20.79% for the thin film silicon based single junction solar cell. We attribute the photocurrent enhancement to the presence of the plasmonic Au

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NPs due to the improved optical and electrical properties of the ITO film such as the electrical conductance, work function, PL (down conversion) and optical transmittance.

2. Experimental

n-i-p type a-Si:H solar cells were prepared on 0.125 mm-thick stainless steel (SS) substrate using a multi-chamber cluster PECVD-PVD system (MV Systems). Au NPs was deposited on the top of the ITO window layer by a QUORUM Q150R vacuum magnetron sputtering machine using a pure gold target (purity 99.99%). The integrated cell structure is SS/n-a-Si:H/i-a-Si:H/p-a-Si:H/ITO/Au NPs. The thickness of the i layer (absorber layer) is ~260 nm. The sputter current and process pressure were kept at 3 mA and 0.9 mtorr for Au NPs preparation, respectively. The deposition time (t_{Au}) was changed from 1 s to 9 s. The Au NPs were also deposited on glass/ITO film for the characterizations, where the ITO films were prepared using exactly the same condition as in the solar cells. For simplicity's sake, the glass/ITO/Au NPs samples were labeled as T_1, T_3, T_5, T_7 and T_9, corresponding to a series of t_{Au}: 1 s, 3 s, 5 s, 7 s, and 9 s, respectively.

The morphologies of the samples were characterized using a JEM-2100 Transmission electron microscope (TEM) and a Bruker Multimode 8 atomic force microscope (AFM). The average grain sizes of the samples were determined using Nano Measurer 1.2, a statistical particle size analysis software. The optical transmittance spectra were measured using an UV–vis-NIR spectrometer equipped with an integrating

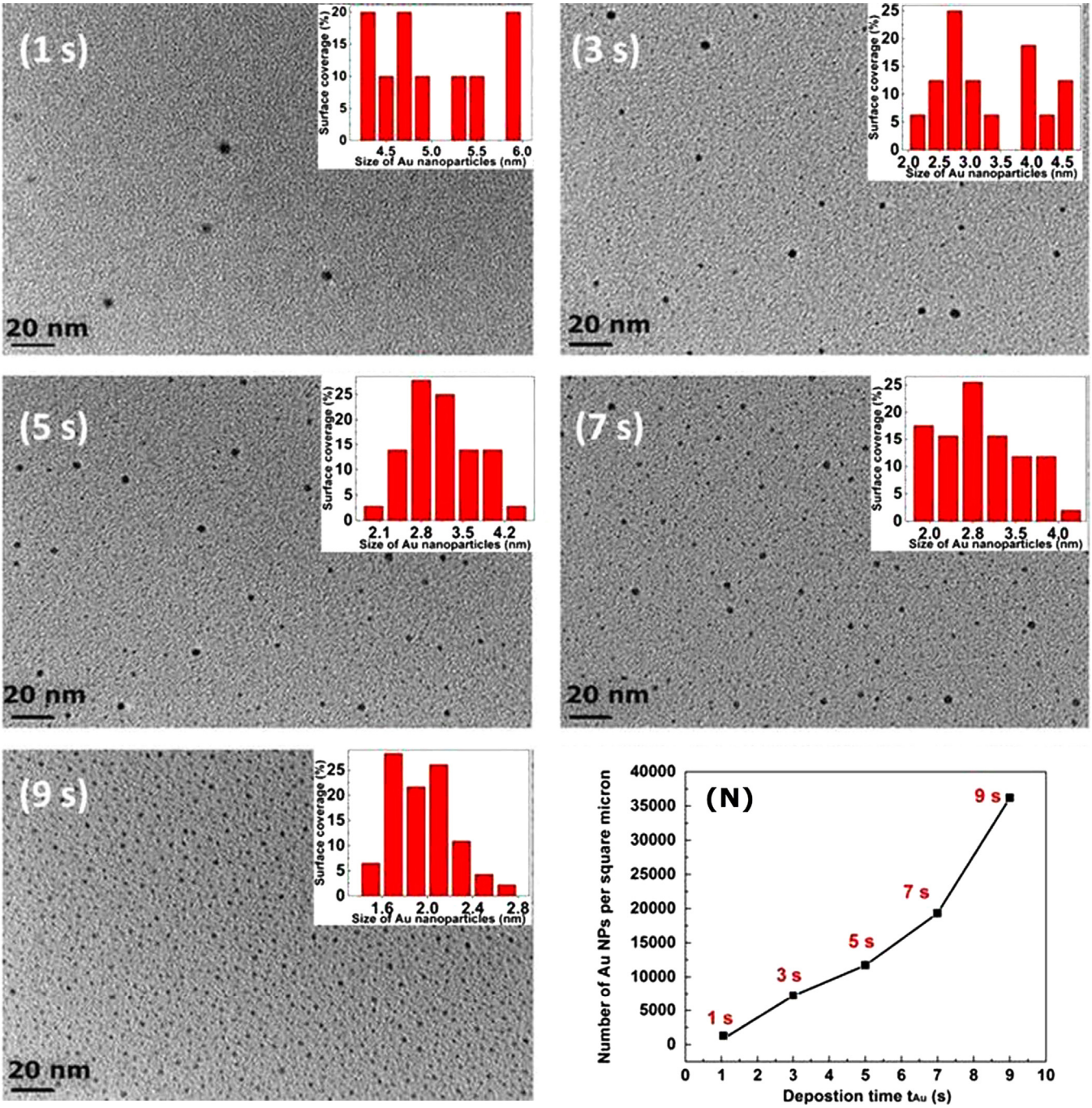

Fig. 1. TEM images for the Au NPs; the insets show the corresponding size distribution histograms. (*N*) shows the number of Au NPs per square micron.