

Ag nanoparticle enhanced light trapping in hydrogenated amorphous silicon germanium solar cells on flexible stainless steel substrate

Wei Zi^a, Xiaodong Ren^a, Fengwei Xiao^a, Haoshi Wang^a, Fei Gao^a, Shengzhong (Frank) Liu^{a,b,1}

^a Key Laboratory of Applied Surface and Colloid Chemistry, National Ministry of Education; Institute for Advanced Energy Materials, School of Materials Science and Engineering, Shaanxi Normal University, Xi'an 710119, China

^b Dalian Institute of Chemical Physics, Dalian National Laboratory for Clean Energy, Chinese Academy of Sciences, Dalian, 116023, China

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ABSTRACT

Silver nanoparticle (Ag NP) enhanced back reflector (BR) has been used for effective light trapping in thin-film silicon solar cells. In this letter, we demonstrate experimentally that the photocurrent density of hydrogenated amorphous silicon–germanium alloy (a-SiGe:H) based solar cells are enhanced by as much as 3.0 mA/cm² or 19.5% with medium sized (320 nm) Ag NPs as compared to the specular BR. In addition, it is demonstrated that the optimized Ag NP BR is also effective in multi-junction solar cells. It is believed that it is the appropriated surface morphology of the Ag NPs that leads to the improved light-trapping. It is found that the average haze of the Ag NP enhanced BR can be improved to as much as > 70% throughout the wavelength range 600–900 nm. The atomic-force-microscopy measurement shows that the optimized root mean square roughness of Ag NP BR is about 35.2 nm.

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1. Introduction

Thin-film silicon (TF-Si) based solar cells, for its abundance and nontoxicity of the source materials, flexibility and lightweight, are particularly promising for building integrated photovoltaic (BIPV), household and portable applications [1,2]. To date, the most popular TF-Si based solar cells have included hydrogenated amorphous silicon (a-Si:H), hydrogenated microcrystalline silicon ($\mu\text{c-Si:H}$), hydrogenated amorphous silicon–germanium alloy (a-SiGe:H), and associated multi-junction cells. For these thin film cells, there is a great urge to reduce film thickness as its multiple benefits including increased production throughput, lower production cost, lower degradation and increased stable cell efficiency. Therefore, developing high performance light trapping substrate to achieve improved light absorption and higher photocurrent to allow reduced absorber layer thickness has been the most popular strategy in recent years. There have been a number of different light-management strategies being actively explored, e.g. randomly textured surface [3–8], periodic ordered structure [9–11], electroplated texture [12]. Recently, metal NPs have attracted great interest for their surface plasmon resonance that renders potential to significantly increased scattering cross-sections comparing to their geometrical one [13]. The incident light can be strongly scattered into the absorber layer for increased light path

and therefore photocurrent. Ag NPs are particularly advantageous for its high scattering efficiency over broad spectrum, low cost and potential for low parasitic absorption [14–17]. So far a few techniques have been developed to fabricate the NPs, e.g. self-assembling [18–21], nanoimprint lithography [22,23], chemical synthesis [24,25], etc. Among these techniques, the self-assembling of the Ag NPs has been used in TF-Si solar cells due to its compatibility with the thin-film deposition technology [17–21,26]. In the self-assembly method, the size of the Ag NPs can be regulated through the thinness of the deposited silver film. In the n-i-p type TF-Si cells, significant amount of incident light can pass through the absorber layer without being absorbed in its first pass, the Ag NPs in the BR promote reflection and scatter light back to the absorber layer for further utilization. Using Ag NP BR on glass substrate, Eminian fabricated a-Si:H single junction solar cell and realized 20% increase in short circuit current comparing to the reference cell without the Ag NPs [26]. Using similar Ag NP/ZnO/Ag/glass structure, Tan demonstrated high photocurrent as much as 26.3 mA/cm² using a $\mu\text{c-Si:H}$ solar cell [15]. Unfortunately, these promising results were achieved using rigid glass substrates, it would be more useful to recognize it using flexible substrates. With adjustable bandgap, a-SiGe:H solar cells have shown very good red light response [27–31]. It is particularly useful when it is used in flexible a-Si/a-SiGe:H and a-Si/a-SiGe:H/a-SiGe:H multi-junction structure [32–36]. In this paper, we demonstrate experimentally that the Ag NPs can further improve light trapping of the Ag/ZnO BR in the flexible n-i-p single-junction a-SiGe:H and a-Si:H/a-SiGe:H tandem solar cells for improved efficiency.

E-mail address: szliu@dicp.ac.cn (S.(Liu)).

¹ Tel.: +86-29-8153-0785.

2. Experimental

The structure of the Ag NP based BR is illustrated in Fig. 1. It consists of multiple layers with their corresponding thicknesses given in brackets: stainless steel (50 μm)/Ag (100 nm)/ZnO (80 nm)/Ag NPs/ZnO (60 nm). The Ag NPs were fabricated using a self-assembly method. More specifically, a layer of very thin Ag film was deposited by vacuum sputtering, it was then annealed at 300 $^{\circ}\text{C}$ for 90 min in vacuum to allow sufficient time for the thin Ag film to assemble into Ag NPs. The size of the Ag NPs can be regulated by initial thickness of the thin Ag film. For the present experiment, there are three Ag film thicknesses used: 3, 6 and 12 nm, the corresponding Ag NP BRs are referred to as BR3, BR6 and BR12. The specular Ag BR, consisting only stainless steel/Ag (100 nm)/ZnO (80 nm), was used as the controlled reference.

The size of Ag NPs was obtained using a Hitachi 4800 scanning electron microscopy (SEM). The size distribution was extracted from the SEM images using software ImageJ. The root mean square (RMS) roughness of the Ag NP BR was measured using a Bruker atomic-force-microscopy (AFM) (MULTIMODE 8). The total reflection and scattering of the Ag NPs were measured using a PerkinElmer Lambda 950 spectrophotometer equipped with an integrating sphere. The angular intensity distribution of the Ag NPs was measured with an angular resolved reflection analyzer. The flexible n-i-p solar cells, as shown in Fig. 1 with ~ 250 nm-thick intrinsic a-SiGe:H absorber layers, were fabricated using a multi-chamber plasma enhanced chemistry vapor deposition system. The optical bandgap of the a-SiGe:H was controlled at ~ 1.55 eV by regulating the process gas ratio of SiH_4 and GeH_4 . The current density–voltage (J - V) curves were measured under an AAA solar simulator with 100 mW/cm^2 light intensity in standard test conditions (25 $^{\circ}\text{C}$, AM1.5G spectrum). While the open-circuit voltage (V_{oc}) and fill factor (FF) were determined from J - V measurements, for more reliable comparison, the short-circuit current density (J_{sc}) is calculated from the external quantum efficiency (EQE) measurement using CROWNTECH QT 1000AD, measured in the wavelength range between 350 nm and 900 nm with 10 nm resolution at room temperature. For comparison, the solar cell area is maintained at 0.25 cm^2 .

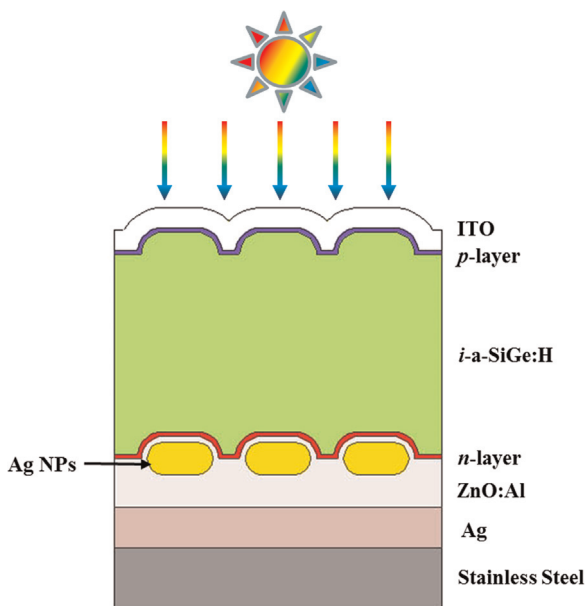


Fig. 1. Schematic device structure of the n-i-p a-SiGe:H solar cells deposited on the Ag NP BRs.

3. Results and discussion

Fig. 2(a)–(c) shows the SEM images of three different Ag NP samples produced using initial Ag coating thickness of 3 nm, 6 nm and 12 nm respectively. It is clear that with increased Ag film thickness, the Ag NP size increases accordingly. As it has been reported that very small Ag NPs show strong resonance absorption and low scattering efficiency [37–39], we intentionally regulated the film thickness and annealing process to prevent formation of the very small particles. Fig. 2(b) and (c) shows the other extreme in which some Ag NPs are not yet fully separated with each other due to insufficient annealing. The mean-particle sizes as calculated using SOFTWARE are (a) 110 nm, (b) 320 nm and (c) 680 nm.

Fig. 3(a)–(c) shows AFM images of the three samples. For comparison, all images were taken over an area of $5 \times 5 \mu\text{m}^2$. The RMS roughness of the three Ag NP BRs are 19.2 nm, 35.2 nm and 50.8 nm respectively. It is clear that the RMS roughness increases as the Ag NP size gets larger.

As the light trapping property of the Ag NPs depends on surface morphology and RMS roughness, we measured the total reflection and scattering spectra of the BRs as a function of wavelength. Fig. 4(a) shows that the total reflection increases as the Ag NPs get larger. For spectrum with short wavelength < 600 nm, most light is absorbed in its first pass through the solar cell, only negligible amount reaches to the BR, therefore the quality of the BR is determined by the reflection characteristics in long wavelength spectrum region. We therefore focused our analysis onto the long wavelength response range 600–900 nm. When the Ag NP size is ~ 110 nm, there is strong absorption between 500 nm and 800 nm, indicating that this size of Ag NPs do have strong parasitic absorption. When Ag NP size increases from 110 nm to 320 nm, the average reflectance of 600–900 nm enhances from 54.4% to 64.0%. Further increasing the size to 680 nm improves the average reflectance to 79.8%. However, the reflectance of the Ag NP BR is still lower than that of the specular BR whose reflectance is higher than 90% in the wavelength range. Fig. 4(b) shows that the scattering intensity increases as the Ag NP size is larger. For spectrum range 636–900 nm, the largest scattering intensity is achieved using Ag NPs of ~ 320 nm, the average scattering intensity is as high as 48.1%. When Ag NP size is reduced to 110 nm or increased to 680 nm, the average scattering intensity is increased by only 29.3% and 36.0% respectively in the spectrum range 600–900 nm. The scattering intensity of the reference Ag/ZnO BR is smaller than 1% as its surface is very specular and almost all light is reflected back along the incident direction. Fig. 4(c) plots the haze (= scattering intensity/total reflection) results, within short wavelength range, it is clear that the haze increases with the Ag NP size. For spectrum range 600–900 nm, the largest haze, as much as 72.5% in average is achieved using Ag NPs ~ 320 nm. It is desired to achieve larger haze as it gives stronger light scattering. Smaller Ag NP size ~ 110 nm and larger ones ~ 680 nm show lower average haze 53.7% and 45.5% respectively for the spectrum range 600–900 nm. The haze of the reference Ag/ZnO BR is close to zero for the same reason mentioned above.

Another measure used to evaluate BR quality is angular intensity distribution, particularly in large angle range. Fig. 5a and b shows light scattering spectra of the Ag NP BRs as a function of scattering angle at wavelengths 700 and 800 nm. The BR12, with Ag NP ~ 680 nm, has strong scattering intensity in small angle for the above two wavelengths. When Ag NP size reduces to 320 nm, the incident light is scattered into large angles more effectively than the other BRs.

As the solar cell efficiency is the final measure of the BR quality, the n-i-p structured a-SiGe:H solar cells were fabricated on the BRs using identical condition in the same deposition runs. Fig. 6 shows the EQE results and the total reflection of the corresponding solar cells. The a-SiGe:H solar cell on the reference Ag/ZnO BR gives a $J_{\text{sc}} = 15.4 \text{ mA}/\text{cm}^2$, calculated from integral of the EQE curve with respect to the AM1.5G spectrum for more accurate valuation.

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