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Disordered submicron structures integrated on glass substrate for broadband absorption enhancement of thin-film solar cells

Young Min Song [a], Ji Hoon Jang [b], Jeong Chul Lee [b], Eun Kyu Kang [a], Yong Tak Lee [a,c,d,*]

[a] Department of Information and Communications, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea
[b] KIER-UNIST Advanced Center for Energy, Korea Institute of Energy Research, Daejeon 305-343, Korea
[c] Department of Nanobio Electronics and Materials, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea
[d] Graduate Program of Photonics and Applied Physics, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea

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ABSTRACT

We report the effect of antireflective disordered submicron structures (d-SMSs) on glass substrates for the absorption enhancement of thin-film solar cells. The shape and height of d-SMSs were designed on the basis of the calculation result from the rigorous coupled wave analysis (RCWA) method. The d-SMSs with tapered shape were fabricated on the back side of SnO_2:F covered glass substrate by plasma etching of thermally dewetted silver (Ag) nanoparticles without any lithography processes. The glass substrates with d-SMSs showed very low reflectance compared to that of the glass substrates with flat surface over a wide specular and angular range. Thin-film hydrogenated amorphous silicon (a-Si:H) solar cells were prepared on the opposite side of d-SMSs integrated glass substrates, and the devices exhibited a short-circuit current density (J_{sc}) of 6.84% increased value compared to the reference cells with flat surface without detrimental changes in the open circuit voltages (V_{oc}) and fill factor. Also, it is found that the performance of the solar cells is sustained over a wide incident angle of light.

1. Introduction

Thin-film solar cells made from various semiconductors or organic materials have great potential for the next generation of photovoltaic applications due to their low material cost and easy fabrication, which are ideal for large-scale manufacturing [1–3]. However, the relatively thin photoactive layer does not absorb light effectively, resulting in poor cell performance. In order to improve light absorption in thin-film solar cells, it is essential to reduce the reflection at the top surface of solar cells in the entire light absorbing spectra. For the so-called superstrate type thin-film solar cells, where the active cells are deposited onto a transparent glass covered by transparent conducting oxide (TCO), the reflection at the interface between air and glass should be minimized. Antireflection coatings (ARCs) have been commonly used on the top surface of the device for the antireflection purpose, but it can give zero reflection at only specific wavelength ranges. Moreover, to fulfill the phase matching condition for the interface between air ($n_{air}=1$) and a typical glass (assumption $n_{glass}=1.5$), the refractive index of the ARC layer has to be $n_{ARC}\sim 1.22$, which is not available for thin-film materials.

Recently, submicron structures (SMSs), which are inspired by a corneal of night active insects such as a moth or a mosquito, have been focused on as a more practical method instead of the conventional ARCs for broadband and omni-directional antireflection [4–11]. On the basis of the effective medium theory, for the broadband AR performance, the structures should have, at the same time, a tapered profile and a size smaller than the incident wavelength. Furthermore, the height should be as tall as possible to cover a broader range of wavelengths [5]. However, due to the difficulties of fabricating structure with high aspect ratio (i.e., height/period) on real devices, such kinds of antireflective nanostructures should be optimized to specific regions of wavelengths for practical applications. Despite great efforts to produce the antireflective SMSs on organic/inorganic materials in various ways, there have been only a few studies reported on thin-film solar cells integrated with antireflective SMSs. In this work, we fabricated disordered SMSs (d-SMSs) with thermally dewetted Ag nanoparticles (NPs) on top of the superstrate type thin-film hydrogenated amorphous silicon (a-Si:H) solar cells to improve the light absorption. Thermal dewetting process of thin metal films provides nanoscale mask patterns without lithography process, which enables cost effective fabrication [12–14]. The theoretical calculation based on the rigorous coupled-wave analysis (RCWA) method was utilized for the guidance of geometrical effect of d-SMSs. The antireflective properties of d-SMSs were investigated by reflectance spectra measurement and confirmed

* Corresponding author at: Gwangju Institute of Science Technology, Department of Information and Communications, Gwangju 500-712, Korea.
E-mail address: ytlee@gist.ac.kr (Y.T. Lee).

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by the characterization of the fabricated solar cells. The angle dependence of antireflection performance was also studied.

2. Experimental details

Fig. 1 illustrates the basic structure of thin-film a-Si:H solar cells integrated with antireflective d-SMSs. As shown in Fig. 1, the d-SMSs are fabricated on the glass's surface to provide broadband antireflection. The steps in the d-SMSs fabrication are depicted in the left image of Fig. 1. The process begins with an Asahi VU glass substrate covered with textured SnO_2:F film on one surface, which is then turned over to deposit an Ag thin-film with an e-beam evaporator on the opposite side. The Ag thin-film thickness and evaporation rate were 20 nm and 0.05 nm/sec, respectively. Prior to depositing the Ag film, the glass substrate was first cleaned with ultrasonic agitation in acetone and methanol, followed by rinsing with distilled water. To form Ag NPs, the samples were heated in a rapid thermal annealing (RTA) system at 500 °C for 1 min in a nitrogen environment. During the RTA process, the Ag thin-film breaks up into NPs via the dewetting mechanism [12]. To fabricate d-SMSs with a tapered profile, an overall dry etch process was carried out using an inductively coupled plasma reactive ion etch (ICP-RIE) system in a SF_6/O_2 (40 sccm/10 sccm) gas mixture at room temperature. The process pressure, RF power, and ICP power were kept at 20 mTorr, 100 W, and 200 W, respectively. To remove the residual Ag NPs, the samples were dipped into $KI/I_2/H_2O$ (1 g/1 g/40 ml) solution for 10 sec. Surface morphology of the fabricated d-SMSs on glass substrate was characterized by a field-emission scanning electron microscope (FE-SEM, Hitachi S-4700). The reflectance spectra were evaluated using a spectrophotometer (Cary 500, Varian) with an integrating sphere. For angle dependent reflectance measurement, a variable angle reflectance accessory was used in specular mode.

For the fabrication of thin-film a-Si:H solar cells with d-SMSs, p-i-n structured a-Si:H cells were deposited on the opposite side of the d-SMSs integrated SnO_2:F covered glass. All of these steps were performed using the multi-chamber plasma-enhanced chemical vapor deposition (PECVD) system. As depicted in Fig.1, the solar cells were composed of d-SMSs integrated glass/SnO_2:F/p-i-n cells/Ag back reflector. Each thin film was prepared separately in isolated chambers to prevent cross contamination. Boron-doped a-SiC:H with a thickness of 20 nm and phosphorus-doped a-Si:H with a thickness of 30 nm were deposited in a 13.56 MHz RF PECVD at 200 °C. The 200 nm-thick intrinsic a-Si:H layers were deposited with a 60 MHz very high frequency chemical vapor deposition (VHFCVD). Ag backside metal reflector (300 nm) was coated by a thermal evaporator. The device area was defined to 0.25 cm^2 by Ag metal area, and conventional thin-film a-Si:H solar cells with flat glass surface were also fabricated for comparison. Current density-Voltage (J–V) characteristics of the solar cells were measured by using a solar simulator (WACOM, AM 1.5 G, 1 sun) at room temperature. External quantum efficiency of the cells was also measured by incident photon to charge carrier efficiency (IPCE, PV measurements Ltd.) in the wavelength range of 300–900 nm.

3. Results and discussion

According to theoretical studies, a more gradual transition of the refractive index leads to a smaller surface reflection. This indicates that in order to maximize antireflective properties of the SMS surfaces, high aspect ratio SMS arrays with a gradually changed diameter such as nanotip arrays with a tip height of above 1 μm are highly desired [5]. However, it is difficult to attain such features on glass substrates with conventional dry/wet etch techniques. Consequently, it is crucial to determine an optimum geometry of SMSs in a given height. Fig. 2 shows the calculated reflectance of (a) cone- and (b) truncated cone-shaped SMSs with a period of 300 nm as a function of the SMS height at three different wavelengths (i.e., λ=300 nm, 550 nm, and 800 nm). These calculations were implemented by a three-dimensional RCWA method, and for simplicity, structures with a closely packed six-fold hexagonal symmetry were used instead of disordered structures as shown in insets of Fig. 2. In the truncated cone, the apex diameter was set to 50% of the base diameter. The flat surface (i.e., height=0) of glass exhibits the reflectance of ~4.0% at 300 nm wavelength, and this value slightly decreases as the wavelength increases due to the material dispersion. As the height increases, the reflectance tends to decrease, which results from the gradually changing effective refractive index. The cone-shaped SMSs are more favorable to obtain low reflectance than the truncated cone at taller heights. However, below ~200 nm height, the truncated cone shows lower reflectance at a visible wavelength range. For example, the minimum heights of truncated cone-shaped

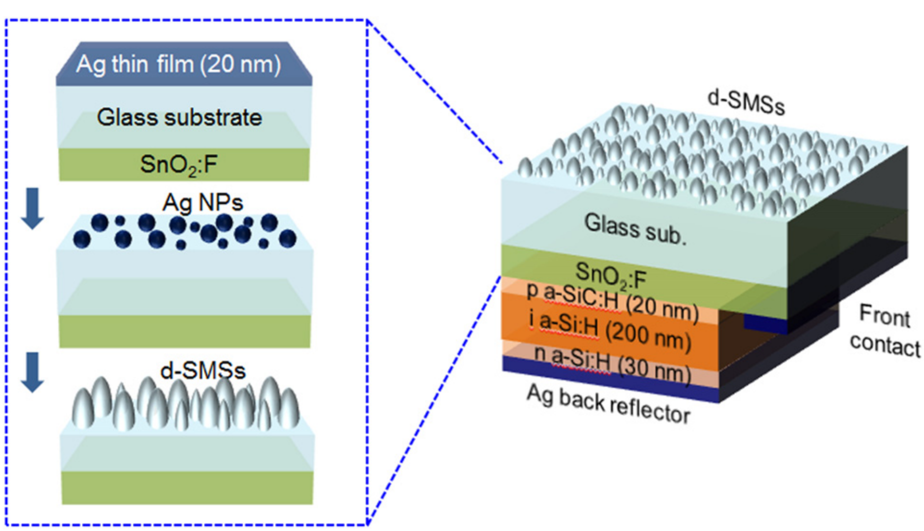

Fig. 1. Schematic illustration of thin-film amorphous silicon (a-Si) solar cells with disordered submicron structures (d-SMSs) for broadband antireflection. The inset on the left shows the fabrication procedure for d-SMSs by using thermally dewetted silver nanoparticles (NPs).