Double-layered Ag–Al back reflector on stainless steel substrate for a-Si:H thin film solar cells

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ABSTRACT

An effective light trapping method for substrate-type hydrogenated amorphous silicon (a-Si:H) thin film solar cells is the use of a back reflector (BR) of high roughness, e.g., 'hot silver', which is deposited at temperatures higher than 450 °C. In this work, textured silver-aluminum (Ag–Al) BR films were fabricated by depositing Ag on Al film at Ag-deposition temperatures (T_{Ag}) ranging from 25 to 350 °C. The surface morphology and roughness of Ag–Al films were strongly affected by T_{Ag}. The Al and Ag films were formed entirely of Ag_2Al alloy at T_{Ag} of 330 °C or higher, while the Ag–Al films maintained a double-layered structure at 290 °C or below. Although the films did not undergo alloying at T_{Ag} of 290 °C, the Ag–Al films have a well-developed surface structure with high diffuse-reflectance, compared to Ag films deposited at the same temperature. The conversion efficiency of an a-Si:H thin film solar cell on a flexible stainless steel substrate increased from 7.63% to 8.44% as T_{Ag} was increased from 25 to 290 °C, as a result of more effective light scattering by Ag–Al BRs, producing increased short-circuit current. However, at higher T_{Ag}, Ag_2Al alloy films with sharp crystallite edges were formed, and were not appropriate as BRs. The present work clearly shows that double-layered Ag–Al films fabricated at temperatures as low as 290 °C could be useful back reflectors for substrate-type thin film solar cells.

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1. Introduction

Hydrogenated amorphous silicon thin film solar cells on flexible substrates have received much attention due to the natural abundance of Si-raw materials and an ability to be produced in large area and roll-to-roll processes [1]. Furthermore, flexible substrates have many advantages such as being lightweight and robust compared to glass substrate, which allow the flexible solar cells to be utilized in building integrated photovoltaic applications and mobile devices, etc. However, their conversion efficiency is relatively low because of low light absorbance in a-Si:H layers. Although greater absorption would result from a thicker absorbing layer of intrinsic a-Si:H, it would also lead to more severe light-induced degradation. Further, increases in stabilized efficiency with thickness are limited by the high defect density and low carrier diffusion lengths in a-Si:H [2–4]. An effective method to enhance conversion efficiency without increasing thickness is to employ a back reflector (BR) having a rough surface, which increases the average light path length inside the absorbing layer by reflection and multiple-scattering [5–7]. For substrate-type a-Si:H-based thin film solar cells, textured Ag has been generally used as a BR owing to its high reflectance from visible to infrared wavelengths [8]. Textured Ag BR, so-called 'hot silver', is usually deposited by sputtering at a temperature higher than 450 °C [9–12]. Recently, plasmonic Ag nanoparticles (NPs) are also utilized as BRs due to their

effective light scattering and low absorption from visible to infrared wavelengths. Effective Ag NPs have been obtained by annealing at a temperature higher than 180 °C for 90 min or 400 °C for 60 min [13,14]. However, the prominent improvement of cell efficiency was not reported yet because the use of Ag NPs increased short circuit current (J_{SC}) and simultaneously accompanied the decrease of open circuit voltage(V_{OC}) and fill factor (FF) more or less.

In a previous study, the authors reported that Ag_2Al or Ag_3Al alloy films of high roughness could be fabricated by depositing Ag on Al film at a temperature lower than 400 °C, and the development of high roughness was caused by the alloying of Ag and Al metals [15]. According to the structure zone model [16–19], surface texturing of sputtered metal films can be enhanced by incorporation of impurities, by increase of deposition temperature, and by formation of alloy crystallites [11].

In this paper, we present a fabrication process for Ag–Al films (Ag_2Al alloy or double-layered Ag–Al) on stainless steel (SS) at a low temperature (≤ 350 °C). We also describe their characteristics, including surface microstructure and optical and materials properties, relevant for their use as BR layers of a-Si:H thin film solar cells on flexible SS substrates. Surface roughness and microstructure of Ag_2A1 alloy and double-layered Ag–Al films show a strong dependence on the deposition temperature T_{Ag} when deposited on room temperature-evaporated Al film. We also investigate the performance of a-Si:H thin film solar cells fabricated on SS substrates with Ag–Al film BRs formed at a low temperature. We believe that optimized Ag–Al films fabricated at a low temperature (around 300 °C) can reduce the production costs of substrate-type a-Si:H thin film solar cells, and can also be easily applied to flexible solar cells on lightweight polymer substrates such as polyimide films.

2. Materials and methods

First, 150 nm-thick Al films were deposited on 125 μm-thick SS substrates (Solar grade, POSCO AST) using e-beam evaporation at room temperature. Then, 150 nm Ag films were deposited on the Al films by DC magnetron sputtering at temperatures (T_{Ag}) of 25, 290, 330 and 350 °C, as illustrated in Fig. 1(a). The temperature T_{Ag} is a decisive parameter in whether Ag deposition results in an Ag–Al alloy film being formed, or an Ag–Al double layer. The surface microstructure and roughness of Ag–Al films were examined by scanning electron microscopy (SEM) and atomic force microscopy (AFM), and the crystalline structure of the films was analyzed by X-ray diffraction (XRD). The cross-sectional microstructure and elemental distribution of Ag–Al films were observed using transmission electron microscopy (TEM) and energy-dispersive X-ray

spectrometry (EDS), respectively. Because double-layered and alloyed Ag–Al films fabricated at different T_{Ag} may have different reflectances, an additional 100 nm Ag film was deposited at room temperature on each sample. This addition would eliminate the dependence on whether the Ag–Al film was double-layered or alloyed when studying the role of roughness on reflectance and solar cell performance. The diffuse and total reflectances (R_d and R_t, respectively) were analyzed using a UV–vis–NIR spectrophotometer (CARY 100) with an integrating sphere over the wavelength range 400–800 nm.

To fabricate an a-Si:H thin film solar cell on the Ag–Al film reflector, a 200 nm-thick ZnO:Ga film was first deposited on the additional 100 nm Ag film to act as a diffusion barrier for Ag, using RF magnetron sputtering in a pure Ar atmosphere. The solar cell, based on a SS substrate, was fabricated by adding further layers; the eventual total sequence was: Al film/Ag film/additional Ag film/ZnO:Ga/p–i–n a-Si:H/ZnO:Ga/Al-grid. The layering arrangement is illustrated in Fig. 1(b). We have chosen a substrate/p–i–n configuration, as explained in Section 3.4 below. Layers of p-type microcrystalline (μc-) Si:H, intrinsic a-Si:H, and n-type (μc-) Si:H were deposited using a single chamber system for plasma-enhanced chemical vapor deposition (PECVD) at a substrate temperature of 200 °C. The thickness of the a-Si:H light absorbing layer was 250 nm. Precursor gases for the deposition of a-Si:H films were SiH_4 and H_2, and the p- and n-type doping gases were B_2H_6 and PH_3, respectively.

The external quantum efficiency (EQE) of the cells was measured using an EQE measurement system (IQE-200, Newport). The current density–voltage (J–V) characteristic curves were acquired at room temperature under illumination by a solar simulator (ORIEL Instruments) with an Air Mass 1.5 global spectrum. The aperture area of the solar cells was 0.25 cm^2.

3. Results and discussion

3.1. Surface characterization of Ag–Al films

Fig. 2 shows SEM images of Ag–Al films fabricated at different T_{Ag}. While the film at 25 °C reveals a flat surface as shown in Fig. 2(a), films fabricated at T_{Ag} of 290 °C and higher have rough surfaces and the roughness increases with T_{Ag} as shown in Fig. 2(b–d). For 290 °C, Fig. 2(b) shows microstructures without facets or sharp edges. In contrast, facets and sharp edges appear for films fabricated at T_{Ag} of 330 and 350 °C, and the crystallite size increases with T_{Ag}.

Surface roughness of the Ag–Al films in Fig. 2 was measured using AFM, and the surface images and root-mean-square roughness (σ_{rms}) are shown in Fig. 3. For the samples fabricated at T_{Ag} of 25, 290, 330 and 350 °C, σ_{rms} values were 17.3, 38.0, 63.6 and 75.4 nm, respectively. The σ_{rms} dramatically increases from 38.0 to 63.6 nm as T_{Ag} increases from 290 to 330 °C, and then, from 330 to 350 °C, the size of crystallites significantly increases. It is noteworthy that the critical T_{Ag} for a dramatic change in surface roughness is between 290 and 330 °C.

The AFM measurement of the films with additional 100 nm-thick Ag film was also carried out in order to estimate the influence of the additional film on the surface morphology. The result indicated that the deposition of additional 100 nm-thick Ag film did not change the surface roughness and morphology of the films (see supplementary Fig. S1).

XRD analysis of Ag–Al films was carried out in order to determine the change of crystalline phase with T_{Ag}. In Fig. 4, diffraction peaks at 44.7 and 65.0° originate in Fe (110) and Fe (200) of the SS substrate, respectively. The XRD traces for films fabricated at 25 and 290 °C are very similar, as shown in Fig. 4(a–b), although σ_{rms}
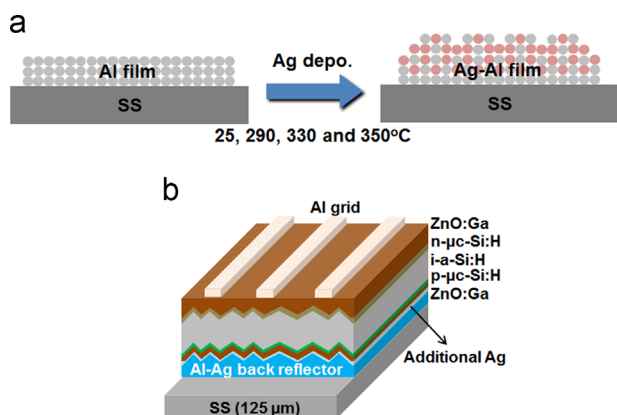

Fig. 1. Schematic diagrams showing (a) the fabrication process of the Ag–Al back reflector at T_{Ag} of 25, 290, 330 and 350 °C and (b) the p–i–n solar cell on SS.