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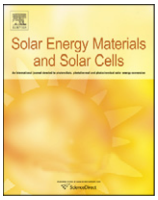

Effect of nanotextured back reflectors on light trapping in flexible silicon thin-film solar cells

Jun-Sik Cho*, Sanghun Baek, Sang-Hyun Park, Joo Hyung Park, Jinsu Yoo, Kyung Hoon Yoon

Solar Energy Department, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon 305-343, South Korea

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ABSTRACT

Nanotextured Ag back reflectors were used to enhance the short-circuit current of flexible silicon thin-film solar cells with an n-i-p configuration by means of optical confinement. A nanotextured topography with a root-mean-square (σ_{rms}) surface roughness of 88.0 nm was successfully induced by abnormal grain growth of Ag films, which was controlled by varying the deposition temperature and film thickness in a direct current (dc) magnetron sputtering process. Effective light scattering of the long wavelengths over 600 nm was achieved on the nano-textured Ag back reflectors, resulting in enhanced absorption of weakly absorbing, long-wavelength light in the hydrogenated amorphous silicon (a-Si:H) and microcrystalline silicon (μc-Si:H) thin-film solar cells. Compared with similar reference cells on flat back reflectors, a 34.4% increase in the short-circuit current density (J_{sc}) for an a-Si:H solar cell and an 11.9% for μc-Si:H were observed in the solar cells on the nanotextured back reflectors, with little reduction in fill factor (FF) and open circuit voltage (V_{oc}). Due to the increase of the J_{sc} by the improved light absorption at the long wavelengths, the conversion efficiency (η) of the a-Si:H and μc-Si:H solar cells increased from 5.59% to 7.60% and from 4.31% to 4.64%, respectively.

1. Introduction

Effective light trapping is a critical component for enhancing the light absorption in silicon thin-film solar cells using a-Si:H and μc-Si:H layers as an absorber [1]. Rough interfaces at the front or back of the active material can increase the path length of the light by scattering and consequently increase its absorption. In the case of Si thin-film solar cells with the n-i-p configuration, the rough interfaces of the active layer are generally induced by the texturing of back reflectors, and therefore, the light trapping efficiency in the solar cells is significantly dependent on the surface morphology of the back reflectors [2,3]. In addition, a high reflectance of the back reflectors to reflect the unabsorbed light back into the solar cell is also required to increase the light-trapping efficiency [4]. Many methods for fabricating the back reflectors with a random texture or a periodic structure have been reported [5–8]. Among them, textured Ag back reflectors, so-called 'hot silver', have been applied successfully to enhance the performance of the flexible Si thin-film solar cells developed by United Solar Ovonic [9]. Although some work to fabricate the texture of Ag back reflectors has previously been conducted, the surface evolution of Ag films caused by changing the deposition conditions and the effect of the surface evolution on the light scattering have not been fully elucidated.

In this paper, nanotextured Ag back reflectors were fabricated on flexible stainless steel substrates by dc magnetron sputtering deposition. By controlling the experimental parameters, such as deposition temperature, working pressure and film thickness, the changes in the surface feature characteristics of nanotextured Ag back reflectors were investigated systematically. A clear quantitative correlation between the surface morphology of nanotextured back reflectors and light-scattering properties were measured in terms of total and diffuse reflectance. The role of nanotextured Ag back reflectors in enhancing the absorption of incoming light and the short-circuit current density is also identified as applicable in flexible a-Si:H and μc-Si:H thin-film solar cells.

2. Experimental

Flexible stainless steel foil (size: 50×50 mm^2, thickness: 100 μm) was used as a substrate. The substrates were cleaned ultrasonically in acetone, isopropyl alcohol and distilled water to remove contaminants on the surfaces. All sputtered films were prepared in a sputtering system equipped with three planar dc magnetron sputtering cathodes, each with a diameter of 100 mm. High-purity Ag and ZnO:Al (2 wt% Al_2O_3) targets were used as the sputtering materials. The SS substrates were statically located at

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* Corresponding author. Tel.: +82 42 860 3214; fax: +82 42 860 3539.
E-mail address: jscho@kier.re.kr (J.-S. Cho).

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the target center at a distance of 100 mm. When the sputtering chamber was evacuated to a base pressure of 5×10^{-7} Torr, a controlled flux of pure argon (99.999%) was introduced into the chamber to act as a sputter gas. The deposition pressure was controlled by a throttle valve positioned in front of the pumping system and monitored with a Baratron gage. The plasma power density was held constant at 2.5 W/cm^2. The film thickness of each sample was varied by adjusting the sputtering time. A series of Ag films were deposited by varying deposition parameters including deposition temperature, deposition pressure and film thickness to induce the nanotextured surfaces. The ZnO:Al (2 wt% Al_2O_3) films acting as a barrier to Ag diffusion were prepared on the Ag films without an additional heat treatment to minimize the effect of the deposition parameters during the ZnO:Al film deposition on the material properties of the Ag films. The microstructure and surface morphology of the deposited films were investigated by scanning electron microscope (SEM) and atomic force microscopy (AFM), respectively. The total and diffuse reflectance spectra were measured by a UV–Vis–NIR spectrophotometer equipped with an integrated sphere in the wavelength range from 300 nm to 1100 nm. Auger electron spectroscopy (AES) depth profiling was performed to investigate the barrier property of ZnO:Al films to Ag diffusion.

The n-i-p substrate-type a-Si:H and μc-Si:H solar cells with an active area of 0.25 cm^2 were fabricated on the ZnO:Al/Ag back reflectors with different surface morphologies by multi chamber plasma-enhanced chemical vapor deposition. The structure of the solar cell consisted of SS substrate/Ag/ZnO:Al/n-i-p Si-based layers/In_2O_3:Sn (ITO)/Ag grid. The p- and n-type silicon thin films were deposited at a deposition temperature of 200 °C with 13.56 MHz radio frequency discharge with SiH_4, H_2, B_2H_6 (1% in H_2), CH_4 (50% in H_2) and PH_3 (1% in H_2) gases. The intrinsic a- and μc-Si:H layers were deposited with 60 MHz very high frequency glow discharge with SiH_4 and H_2 gases. The SiH_4/H_2 ratio is fixed at 0.7 for i a-Si:H and 0.06 for i μc-Si:H, respectively. The i layers were prepared at a working pressure of 300 mTorr and a deposition temperature of 150 °C. A plasma density is 0.41 W/cm^2 for i a-Si:H and 0.82 W/cm^2 for i μc-Si:H, respectively. Details of the experimental set-up and the preparation conditions of the solar cells have been previously listed [10]. The current–voltage (J–V) characteristics of the solar cells were measured at 25 °C using an AM 1.5 G double beam solar simulator.

3. Results and discussion

Fig. 1 shows changes in the SEM images and in the σ_{rms} surface roughness of the 300-nm-thick Ag films deposited on the SS substrates with varying deposition temperatures (T_d). For all the films deposited at $T_d=25$ °C and 100 °C (Fig. 1(a) and (b), respectively), the film had relatively flat surfaces, that comprised small grains below 200 nm. As the T_d increased to 300 °C (Fig. 1(c)), however, abrupt grain growth in the Ag films occurred, and large-sized grains of 400 nm were formed. Additional increasing of the T_d to 500 °C resulted in remarkable increases in the grain size to 900 nm. At the elevated temperature, the surface roughening of the Ag films was accompanied by grain growth, which is supported by the measured σ_{rms} values in Fig. 1(e). The σ_{rms} values of the Ag films deposited at $T_d=300$ °C and 500 °C increased to 25.7 nm and 56.2 nm, respectively, compared with the Ag films at room temperature and 100 °C with σ_{rms}=approximately 7 nm. The dependence of surface roughness of the sputtered Ag films on deposition temperature can be also found in Ref. [3], in which the σ_{rms} values of 250-nm-thick Ag films increased from a few nm to seventy nm with increasing the deposition temperature from 90 °C to 270 °C. Under the same deposition conditions, the growth of lateral dimension of grains was accompanied with the surface texture evolution. The grain growth and surface roughening of the Ag films deposited at high T_d can be explained by abnormal grain growth of the structure zone model (SMZ) [11,12]. In this growth mode, a competition begins between the growth of neighboring grains, and the faster-growing grains overgrow the slower-growing ones, resulting in an increase in the average grain size accompanied by the surface roughening.

Fig. 2 shows the changes in the total and diffuse reflectance (R_{total} and $R_{diffuse}$, respectively) of the 300-nm-thick Ag films as a function of T_d, which were measured with a UV–Vis–NIR spectrometer in the wavelength range of 300–1100 nm. As shown in Fig. 2(a), all the Ag films showed high R_{total} values over 90% on average in the entire wavelength range, except for short wavelengths below 400 nm. In our experiment, the small variation in the R_{total} values of the Ag films is caused by a margin of error of reflectance measurement, because the direct dependence of the R_{total} on surface roughness is not observed and a tolerance of a spectrometer equipped by an integrating sphere reaches about 5% [13]. Strong absorption in the short wavelength region is typically observed in Ag, which is due to the surface plasmonic resonance [3]. However, the light absorption of the Ag films in the spectral range below 400 nm will not be important because the majority of photons with these wavelengths should be totally absorbed in the active layer of the solar cell [5]. In terms of the $R_{diffuse}$ (Fig. 2(b)), higher values were obtained for the rough Ag films deposited at elevated temperature. In the case of Ag films at $T_d=300$ °C, the $R_{diffuse}$ increased to some extent in the wavelength

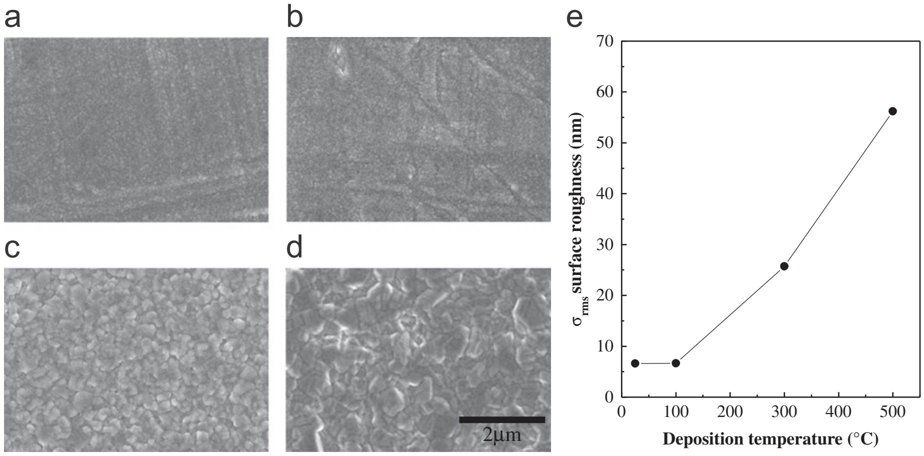

Fig. 1. Changes in the surface morphology and root-mean-square (σ_{rms}) surface roughness of 300-nm-thick Ag films prepared on stainless steel substrates with varying deposition temperature from room temperature to 500 °C. (a) R.T, (b) 100 °C, (c) 300 °C and (d) 500 °C.