

## Surface texturing of sputtered ZnO:Al/Ag back reflectors for flexible silicon thin-film solar cells

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### ABSTRACT

Al-doped zinc oxide/silver (ZnO:Al/Ag) back reflectors for silicon thin-film solar cells with an n-i-p configuration were prepared on flexible stainless steel substrates by dc magnetron sputtering. The surface morphologies of the back reflectors were modified by changing the deposition temperature of the Ag films to improve the light-scattering properties on the back reflectors, resulting in the enhancement of the light-trapping effect in the solar cells. By elevating the deposition temperature from room temperature to 500 °C, the surface roughness of the Ag films increased from 6.62 to 46.64 nm. The films at 500 °C had coarse surface features with irregular grain size distributions between 200 and 900 nm, whereas the films produced at low temperatures below 100 °C had smooth surfaces consisting of small grains between 100 and 200 nm. Even after the 100-nm thick ZnO:Al films were deposited on the modified Ag surfaces, the surface microstructure of the ZnO:Al/Ag bilayers was similar to that of the Ag films. The surface roughness of bilayers increased from 7.12 to 39.30 nm with coarsening the Ag surfaces. Haze factor (a ratio of diffuse reflectance to total reflectance) of Ag films was enhanced remarkably from 59% to 74% in a wide wavelength range from 350 to 1100 nm with increasing the surface roughness of the Ag films from 6.62 nm to 46.64 nm. Enhancement in the haze factor was due to the increase of diffuse reflectance on the Ag films, because the total reflectance did not change much with increasing surface roughness of the Ag films. This increasing roughness indicated that the light scattering from the rough surface of the back reflectors improved. The enhanced light scattering from the back reflectors influenced the performance of the solar cells mainly in terms of the short-circuit current density ( $J_{sc}$ ). Compared to the back reflectors with smooth surface features, leading to a  $J_{sc}$  value of 9.94 mA/cm<sup>2</sup>, the back reflectors with large surface roughness improved the  $J_{sc}$  value of the solar cells to 13.36 mA/cm<sup>2</sup> without detrimental changes in the fill factor (FF) and open circuit voltage ( $V_{oc}$ ); they eventually increased the conversion efficiency of the solar cells from 5.59% to 7.60%.

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### 1. Introduction

Silicon thin-film solar cells on flexible substrates are considered the most promising candidates for low-cost solar cells because roll-to-roll processing on flexible substrates allows a higher throughput, and the production equipment requires less floor space [1]. Compared to silicon thin-film solar cells on glass substrates, flexible silicon thin-film solar cells have many advantages, including flexible and unbreakable characteristics, cheap substrates and ease of handling and transportation, which opens new possibilities for the application of photovoltaics, such as easier deployment and better integration into buildings [2,3]. Substrate structures with the n-i-p configuration of silicon thin-films

are usually used for flexible silicon thin-film solar cells, in which metal layers with high reflectance are used as the back reflector [4]. For amorphous and microcrystalline silicon thin-film solar cells, light trapping is crucial to obtain a high current density because the light absorption of the silicon thin-film absorbers is relatively low [5–7]. In the n-i-p substrate structure, one of most efficient methods to enhance light trapping is to make the back reflector surface rough. The textured surfaces of back-reflectors increase the optical path length due to the light scattering on the textured surface at oblique angles and the enhanced internal total reflection at the interface within the cells [8–10]. A variety of techniques to impose randomly and periodically textured surfaces on back-reflectors have been suggested [11–13]. Among them, a bilayer with metal-doped zinc oxide and silver films has already been applied in commercial solar cells. However, there are few systematic reports on the surface texturing characteristics of the ZnO/Ag system and their influence on the performance of n-i-p substrate structured silicon thin-film solar cells.

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In this study, the surface texturing of sputtered ZnO:Al/Ag back reflectors on stainless steel substrates was carried out by changing the surface features of Ag films, followed by the deposition of transparent conducting ZnO:Al film, acting as a barrier to Ag diffusion into silicon layers. The surface morphology of the sputtered Ag films was controlled precisely by varying deposition temperatures. The optical properties, such as total and diffuse reflectance, were investigated for back reflectors with different surface features. The influence of the textured back reflectors on the performance of flexible amorphous silicon thin-film solar cells was also examined.

## 2. Experimental

All sputtered films were prepared on 100- $\mu\text{m}$ -thick, flexible stainless steel (SS) substrates using an in-house dc magnetron sputtering system. Two 4-in. circular-type cathodes using high-purity Ag metal and Al-doped ZnO ceramic targets with 2 wt%  $\text{Al}_2\text{O}_3$  were installed horizontally on the substrate holder (Fig. 1). A target-substrate distance was 100 mm. Using a turbo molecular pump and a rotary pump, the base pressure of the deposition chamber was  $5 \times 10^{-7}$  Torr. To deposit the films, pure Ar gas of 10 sccm ( $\text{ml}/\text{min}$ ) was introduced by a mass flow meter. A working pressure was maintained at 1.5 mTorr during the deposition process by a throttle valve positioned in front of the pumping system. A 30-nm-thick chromium adhesive layer was applied to improve the adhesion between the substrate and the deposited Ag film. Typical deposition conditions for the Ag and ZnO:Al films are summarized in Table 1. Next, 100-nm-thick low-refractive index ZnO:Al films were deposited on flat or textured Ag back reflectors. The microstructure and surface morphology of the deposited films were examined by SEM and AFM analysis. The total and diffuse reflectance of the back reflectors was measured in the wavelength range from 350 to 1100 nm using an integrating sphere. The haze factor of back reflectors was calculated from the reflectance measurement. To investigate the barrier property

of ZnO:Al films to Ag diffusion, AES depth profiling for the solar cells prepared on the back reflectors was performed.

The n-i-p structured a-Si:H cells were fabricated on the flat and textured back reflectors by multi-chamber plasma-enhanced chemical vapor deposition (PECVD). Each thin film was prepared separately in isolated chambers to prevent cross contamination. The solar cells were composed of  $\text{In}_2\text{O}_3:\text{Sn}$  (ITO)/p-i-n Si based layers/ZnO:Al/Ag/SS substrate. Boron-doped a-SiC:H and phosphorus-doped a-Si:H layers were deposited with 13.56 MHz radio frequency discharge. The intrinsic a-Si:H layers were deposited with 60 MHz very high frequency glow discharge. The layers were prepared at a working pressure of 300 mTorr, a deposition temperature of 150 °C and a plasma power density of 0.41  $\text{W}/\text{cm}^2$ . Transparent conducting ITO films were deposited on to the solar cells as the top contact and as an antireflection coating. The device area of 0.25  $\text{cm}^2$  was defined by the ITO electrode area through a metal mask. 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. 2 shows SEM images of the 300-nm-thick Ag films deposited on the SS substrates for the various deposition temperatures, from room temperature to 500 °C. In the case of the Ag films prepared at room temperature (Fig. 2(a)), the film surface showed small grains between 100 and 200 nm distributed uniformly. At a deposition temperature of 100 °C, the surface features of the Ag films were almost identical to those of the films deposited at room temperature, except for a small increase in grain size. As the deposition temperature increased to 300 °C, grain growth of the films was observed, in which the grain size increased to 400 nm, but the uniform size distribution was still maintained. At a higher deposition temperature of 500 °C, however, dramatic changes in the surface morphology of the Ag films occurred. Some of the grains in the films developed abruptly, and their size reached 900 nm, resulting in an irregular distribution of grain sizes. According to previous research [14], in which the microstructural evolution of pure metal films during physical vapor deposition as a function of film growth parameters was described minutely by the structure zone model (SZM), the texture development of metal films during crystal growth is closely related to the different growth mechanisms, which are affected mainly by the deposition temperature and melting point of deposited films. The SZM, characterizing microstructure evolution in pure elemental films, consists of three regions: Zone I corresponds to very low deposition temperatures at which adatom diffusion is negligible; surface diffusion becomes significant in the transition Zone T; and Zone II represents film growth at deposition temperatures for which both surface and bulk diffusion are operative. At high film growth temperature (Zone T), grain coarsening occurs due to the coalescence of small islands with a large surface-to-volume ratio, whereas grain boundaries become immobile in continuous films. Orientation selection during coarsening is incomplete; thus crystallites are nearly random or only weakly textured, and there is a wide distribution of grain sizes. The orientation and size of individual crystallites determines their behavior during subsequent growth processes characterized by the competition among neighboring grains. When the competition between the growths of neighboring grains begins, the faster growing crystals overgrow the slower growing ones, inducing a large variation of morphology. At still higher deposition temperature (Zone II), bulk diffusion becomes significant and grain boundary (GB) migration takes place during coalescence. Large grains with low surface and interface energy grow at the expense of smaller or

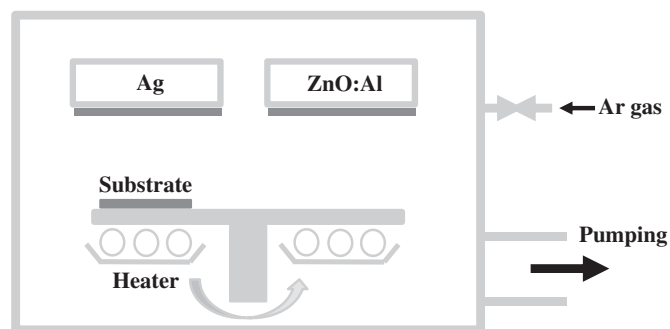


Fig. 1. Schematic diagram of dc magnetron sputtering system for the deposition of the Ag and ZnO:Al films.

Table 1  
Experimental set-up and deposition parameters of back reflectors.

Parameters	Values
Target	4 in.—Ag (99.99%), 4 in.—ZnO:Al <sub>2</sub> O <sub>3</sub> (2 wt%)
Target-substrate distance (mm)	100
Base pressure (Torr)	$< 5 \times 10^{-7}$
Working pressure (mTorr)	1.5
Power density ( $\text{W}/\text{cm}^2$ )	2.5
Sputtering gas and flow (sccm)	Ar, 10
Deposition temperature (°C)	R.T.—500

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