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Nano-textured topography introduced at room temperature for light-trapping enhancement

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ABSTRACT

In this paper, a unique two-step method is developed to fabricate a nano-textured SnO_2 coating. Nano-textured topography is successfully introduced at room temperature by evaporating Sn in a relatively high pressure. Nano-textured SnO_2 coating is obtained by annealing in air, with lateral size of nearly 1 μm and root-mean-roughness of over 140 nm. Two structures: substrate and superstrate, are investigated to reveal the light-trapping efficiency. With only 300 nm thick Si absorber layer, the average reflectivity under AM 1.5 illumination spectrum can be limited at 14% and 7%, respectively. This technology is suitable for mass production.

1. Introduction

Light-trapping efficiency is crucial to realize high efficiency of thin-film solar cells [1,2]. The most important step to introduce a light-trapping structure is to fabricate a textured interface of the absorber layer. Hence, the incident light can be scattered into large angles beyond the total reflection angle. This can enhance the light path length in the absorber, and the light absorption ratio can be effectively increased [3]. Many methods of fabricating textured structure have been reported, such as textured ZnO:Al [4,5], SnO_2:F [6], patterned Al [7], etc. However, special processes are needed in all those methods to introduce textured morphology, like etch by diluted acid [4,5], anodic oxidation [7,8], chemical vapor deposition in high vacuum environment [9], increasing the substrate temperature, etc. These treatments will increase the fabrication complexity, leading to a high cost, so they are not quite suitable for mass production. We have investigated several much simpler methods to introduce textured topography, like evaporating Al [10] and nano-Bi_2O_3 islands [11]. However, heating substrate is still necessary in the fabrication processes to introduce textured topography. A simple way to fabricate an efficient light-trapping structure without any special treatment, including heating substrate, is obviously attractive. In this paper, a simple two-step method to fabricate a textured SnO_2 coating is developed. We first introduce a textured Sn coating by heating-evaporation at room temperature in a relatively high pressure of about 1 Pa, and the textured SnO_2 coating is subsequently obtained by annealing the textured Sn coating in air.

2. Experiment

Soda lime glass is used here as a substrate. First, a 200 nm thick Sn layer is deposited on the glass by evaporation from Sn grains (99.999%). Nato-textured Sn morphology can be obtained by evaporating simply in a low vacuum, and the pressure is controlled at 1 Pa in this experiment. Fig. 1(a) shows the surface SEM image of the nano-textured Sn layer. The high pressure during the evaporation leads to a short molecular mean free path of less than 1 cm, and the distance of the evaporating source and the substrate is 10 cm. After certain times of collisions, the evaporating Sn particles arrives to the glass substrate with an uneven space distribution, fabricating a textured topography. After annealing in a furnace in air at 530 °C for 6 h, textured SnO_2 layer can be obtained, as shown in Fig. 1(b). According to Fig. 1, the Sn layer is quite uniformly textured and the subsequently obtained SnO_2 coating maintains the textured morphology well. The average size of the bulge is nearly 1 μm.

A 300 nm thick Si layer is deposited on the textured SnO_2 coating by DC magnetron sputtering from a p-type silicon target (99.999%) to serve as an absorber layer. Thereafter, a 5 nm thick Cu layer is sputtered on the Si layer to transform the amorphous Si (a-Si) to polycrystalline silicon (poly-Si) by metal inducing crystallization (MIC) process [12–15], and a 200 nm thick Ag layer is subsequently sputtered on as a back-reflector. As we discussed elsewhere [10,11], for a ratio of Cu and Si of 1:60, highly crystallized Si can be obtained. Fig. 2 shows the X-ray diffraction

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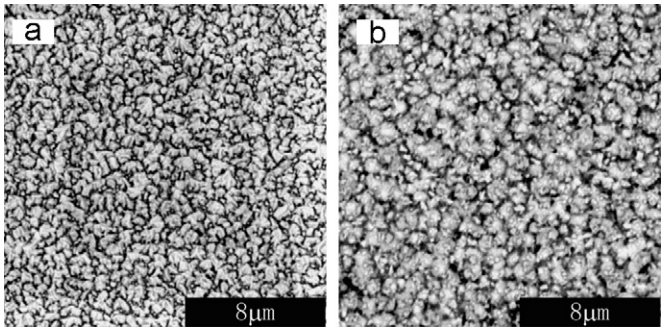

Fig. 1. Scanning electron microscope (SEM) image of (a) textured Sn film and (b) oxidated to be textured SnO_2 film after annealing in air for 6 h at 530 °C in a furnace.

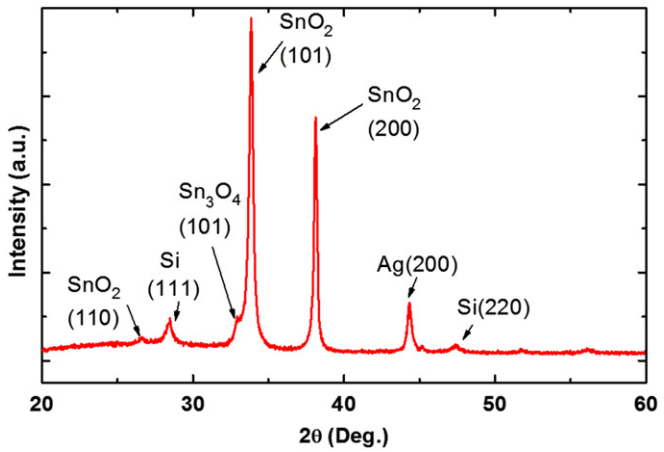

Fig. 2. X-ray diffraction spectroscopy (XRD) of the textured SnO_2 coating with a 300 nm thick silicon layer after metal inducing crystallization (MIC).

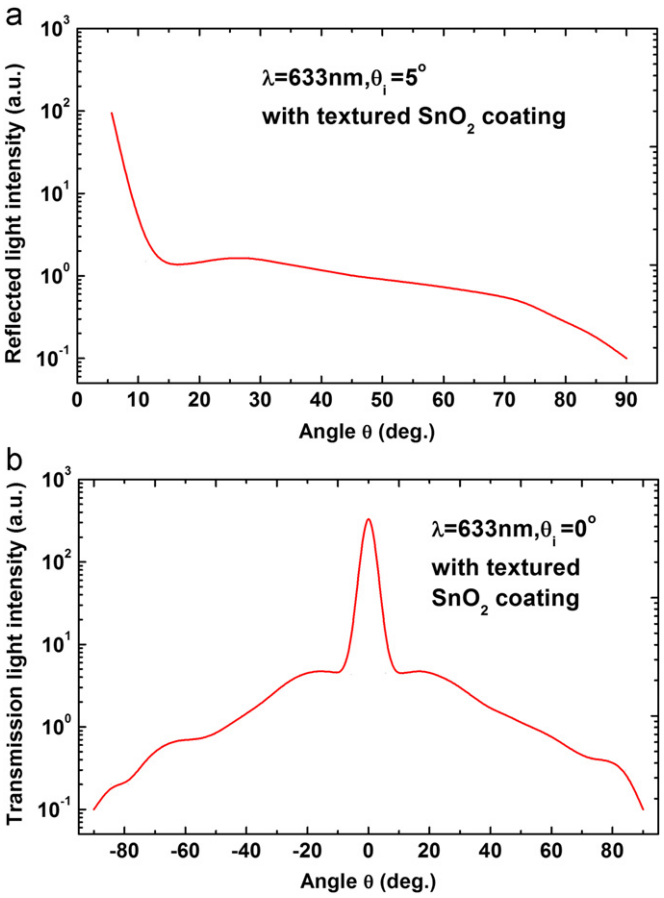

Fig. 3. Angular distribution of (a) the reflected and (b) transmitted light from the textured SnO_2 coated soda lime glass.

spectroscopy (XRD) of the textured SnO_2 coating with a 300 nm thick silicon layer. According to Fig. 2, the Sn layer is totally oxidated. Most of the oxide is SnO_2 and a small fraction of Sn_3O_4 exists.

3. Results and discussion

Light-trapping efficiency relies on the light scattered by the textured coating beyond the total reflection angle [16,17]. To clarify the light-trapping characteristics, angle resolved scattering (ARS), in air by the nano-textured SnO_2 coating, of the reflected and transmitted light is measured as shown in Fig. 3. The incident light used here is a He–Ne laser beam with $\lambda = 633$ nm. For testing the reflected and transmission light intensities, the incident angle is set nearly normal at 5° (θ_i) and normal, respectively. The scattering property is better than the traditional Asahi-*U*-type textured SnO_2 substrate [7]. According to Fig. 3, either by reflection or by transmission, the light can be scattered into large angles effectively. However, it should be noted that, the real scattering characteristics will be different, since the coating will contact with a higher-index absorber layer.

To investigate the light-trapping efficiency, two types of structures, substrate and superstrate, are fabricated. The substrate structure is glass/SnO_2/Ag/Cu/Si, and the light is incident from the Si side as the schematic diagram shown in the inset of Fig. 4(a). The superstrate structure is glass/SnO_2/Si/Cu/Ag, and the light is incident from the glass side as the schematic diagram shown in the inset of Fig. 4(b). Reflectivity of samples with different thicknesses of Si is characterized to reveal the light-trapping efficiency. The thicknesses of Si are tuned from 300 to 840 nm for an increment of 180 nm. The reflectivity of all those samples is characterized by a spectrometer with an integrating sphere (Avaspec-2048 × 14, Avantes Company). Fig. 4 shows the reflectivity properties as a function of wavelength from 400 to 1050 nm, for substrate and superstrate, respectively. According to Fig. 4, when the Si is only 300 nm thick, the reflectivity can be limited below 18% and 10% in the whole wavelength region of 400–1050 nm, respectively. However, the reflectivity does not decrease monotonically with the Si thickness for both structures.

To understand the mechanism, we investigate the relationship between the Rms alteration of the interface and the average reflectivity under AM 1.5 illumination spectrum. As we discussed elsewhere that the alteration of the topography is crucial to the light trapping efficiency [11]. Fig. 5(a) shows the atomic force microscopy (AFM) images of the SnO_2 coating, and Fig. 5(b) shows the surface topography of 300 nm thick Si deposited on the SnO_2 coating. To further clarify the relationship of the topography and the Si thickness, root-mean-roughness (Rms) is also measured by AFM as represented by curve (a) in Fig. 6. The Rms of bare SnO_2 coating is 142 nm. According to curve (a) in Fig. 6, the Rms keeps the value between 150 and 180 nm and does not alter monotonically with the Si thickness. The corresponding average reflectivity under AM 1.5 illumination spectrum is presented by curves (b) and (c) in Fig. 6. Apparently, the reflectivity of the superstrate structure is much lower than that of the substrate structure. This is because the index difference of Si and SnO_2 is lower than that of Si and air. In the superstrate structure, the textured SnO_2 layer does not only scatter the incident light into large angles but also acts as a refractive index transition layer. Besides, the scattering is stronger at the interface of Si and SnO_2, since the wavelength in