ENHANCED LIGHT DIFFUSION USING SHADOW MASK BASED SURFACE TEXTURING TECHNIQUE

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ABSTRACT: Molybdenum doped zinc oxide (MZO) films have been fabricated on glass for the applications in a-Si/μ-Si based thin film solar cells. To enhance light trapping efficiency, round MZO surface textures were formed on top of a 100nm MZO film using co-sputter deposition through a micro shadow mask. The surface textures, having physical dimensions of 110 nm in height and 120 μm in diameter, evenly spread on the MZO film with a pitch of 300 μm. These surface textures effectively caused ~ 4 % of light diffusion. The diffused light is believed to be able to laterally travel in a-Si/μ-Si thin film absorbers, and its enhancing effect on the solar power efficiency is expected.

1 INTRODUCTION

Surface texturing of a transparent conductive anode has been realized to be an effective process to diffuse solar light laterally into absorbers of a thin film solar cell, leading to an enhanced light trapping efficiency [1-3]. Particularily for amorphous (a-Si)/microcrystalline (μ-Si) based thin film solar cells, the lateral light diffusion is much more important because the a-Si absorber requires a thin thickness (due to the light-induced degradation) and the absorption efficiency of μ-Si is low [1]. Yielding textured surfaces of a transparent conductive anode allows the incident light to travel both in the a-Si/μ-Si thin film abosrbers with an increased path of more than several orders of magnitude. Hence, generating textured surfaces of a transparent conductive oxide (TCO) to serve as the front electrode in the a-Si/μ-Si solar cells is essential in addition to the basic requirements of high optical transparency and low electrical resistance.

Zinc oxide (ZnO) has been a highly noticed TCO material for the applications in thin film solar cells for its low cost, high optical transparency in the near infra-red region and good chemical stability to the hydrogen plasma during a-Si depositions [4-6]. Formtion of textured surfaces when fabricating ZnO films is innevitibly one of the important issues. Up to now approaches that have been proposed to obtain surface textures on ZnO films include the direct growth using chemical vapor deposition [7-8] and the post chemical etching of a spuutered film [9-10]. The optical diffusion effect could also be achieved by the synthesis of optical grating patterns on ZnO film surfaces with the photolithography technique [11-12]. These approaches however are either complicated and expensive such as photolithography patterning or provide limited physical dimensions when using direct growth or chemical etching.

In this article we reported on a novel approach that could fabricate surface textures on molybdenum (Mo) doped ZnO (MZO) films, aiming to promote light diffusion and enhance the light trapping efficiency of thin film solar cells. The surface textures were formed directly on MZO films using a shadow mask attached to substrates during film deposition. Since the physical dimension and the shape of the opening are defined directly on the shadow mask, surface textures with a well-controlled geometry are obtainable without post-treatments. The optical diffusion effect caused by the surface textured ZnO films was investigated.

2 EXPERIMENTALS

Fabrication of surface structured MZO films started with the deposition of a planar MZO film on a 50 mm x 50 mm glass substrate at 300 ^{o}C using a magnetron co-sputter approach. The co-sputtering was condcuted in an Ar plasma with Mo sputtered at a d.c. power of 10W and ZnO at a r.f. power of 150 W. The substrate was placed 10 cm above the sputter sources and was rotated at a speed of 15 r.p.m. The concentration of Mo was controlled by adjusting the opening area of a slit shutter located in front of the Mo sputter source. The initial MZO thickness was set to 100 nm and 200 nm. After the deposition of the planar MZO film, the substrate coated with a 100 nm MZO film was attached with a metallic shadow mask and was placed back to continue the Mo/ZnO co-sputter process. Round surface textures with a height set to 100 nm were formed by the deposition of MZO through the metallic shadow mask. Fig. 1 shows how the round surface textures could be formed onto the MZO film by the shadowing effect of the shadow mask. The MZO coated substrates were finally annealed in vacuum at 350 ^{o}C for 1 h to enhance their electrical and optical properties.

A Hitachi UV 3310 spectrometer and a 4-point probe tool were employed to determine optical transmittance and sheet resistivity of the MZO films, respectively. The doping concentration of Mo was measured using Hitachi S4100-EDS spectrometer, whereas surface morphology of the MZO films was examined using an atomic force microscope (AFM) and a ET-4000 α-step surface profolimeter.

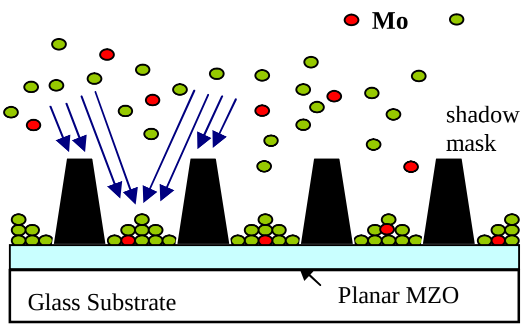

Figure 1: Schematic of cross sectional shadow mask attached to the MZO coated glass substrate.

3 RESULTS AND DISCISSIONS

3.1 Electrical and optical properties of planar MZO films

As mentioned in the experimental procedure, the concentration of Mo could be adjusted by modulating the opening area of a slit shutter placed in front of the Mo sputter source. The effect of doping concentration of Mo on the sheet resistivity and optical transmittance can be seen in Fig. 2(a) and (b), respectively. From Fig. 2(a), the MZO film exhibits the lowest sheet resisivity of 3.2×10^{-3} ohm-cm/□ in this study when doped with 1.85 wt% of Mo. Results from Hall-effect measurement revealed that the dominating factor to the conductivity of MZO film was carrier concentration. That is, MZO film with 1.85 wt% Mo had the highest carrier concentration, similar to the work by Duenow [24]. Since our work was to investigate the effect of MZO surface textures on the optical diffusion, further reduction in the electrical performance of the MZO film was not conducted in the current work.

From Fig. 2(b), one can see the optical transmittance, averaged from 400 to 1100 nm, approximately linearly decreases with the opening ratio of shadow mask or Mo concentration. As the Mo concentration is below 1.85 wt% the optical transmittance is less than 88%. Considering high optical transmittance and conductivity that are required for TCO to serve as a front anode in thin film solar cells, fabrication of surface textures was then solely performed on the MZO film with Mo concentration = 1.85 wt%. In the following sections we will mainly discuss the optical effects caused by the MZO surface textures.

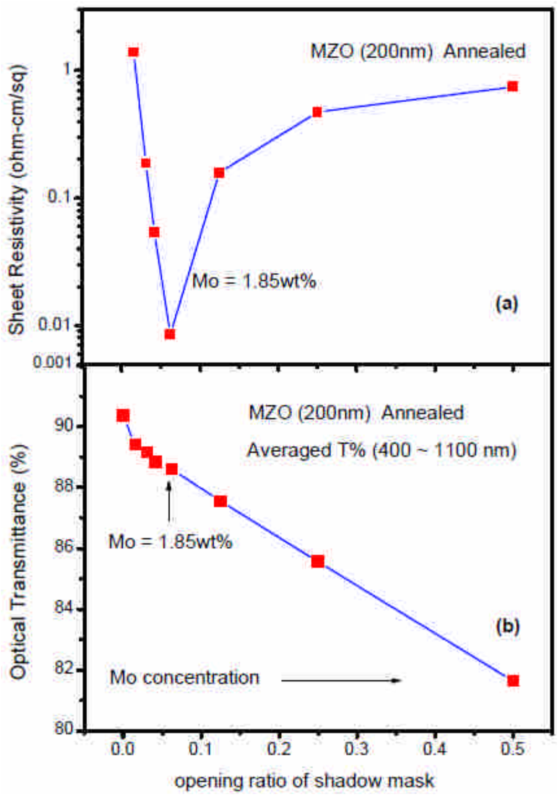

Figure 2: (a) sheet resistivity and (b) optical transmittance as a function of opening ratio of shadow mask (Mo concentration)

3.2 Physical dimensions of MZO films

Figs. 3 shows the optical microscope (OM) image and α-step profile of the surface textured MZO film with 100 nm planar thickness and 100 nm texture height. The shadow spots in the OM image represent where the MZO textures locate. These textures appear nearly identical and spread evenly on the MZO film, indicating that with this shadow mask approach a periodic and well controlled texture pattern can be synthesized. From the a-step profiling, these MZO surface textures are in spherical shape and are separated with a 300 μm pitch. Their physical dimensions were measured to be 110 nm in height and 120 um in diameter that is silghtly larger than the designed size (100 nm in height and 100 um in diameter). With the physical dimensions, these textures were calculated to cover around 12.6% of the total area of the MZO film.

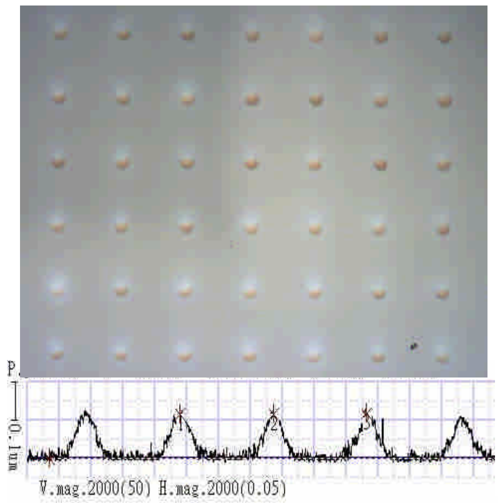

Figure 2: Optical microscopeimage and α-step profile of the surface textured MZO film (200nm)

Results from surface morphology measurement using atomic force microscope revealed that the average surface roughness was 0.9 nm for the MZO film with 1.85 wt% Mo, as can be seen in Fig. 4. In contrast, undoped ZnO film has a rougher surface with Ra = 3.5 nm. This gives evidence that the co-sputter deposited MZO films have rather smooth surfaces. Hence the surface texturing on the MZO film is necessary. Following will discuss the effect of these surface textures on the optical diffusion.

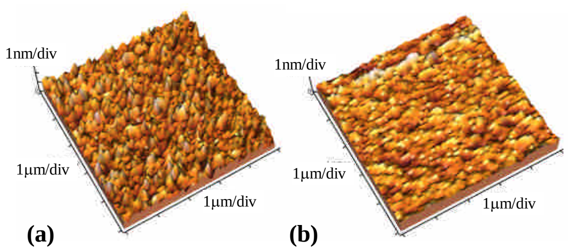

Figure 4: AFM images of (a) undoped ZnO film and (b) MZO film with Mo = 1.85 wt%. Ra is 3.5 nm and 0.9 nm, respectively.

3.3 MZO surface textures v.s. optical diffusion

Fig. 5 shows the optical transmittance of the films (averaged from 400 to 800 nm) measured with light incident at normal angle from both the glass and film sides. It can be seen that no obvious difference between the transmittances measured from both sides, showing that the surface scattering due to the texture is negligible. The optical transmittance drops from 87% to 86.2% when the thickness of MZO film increases from 100 nm to 200 nm, whereas it drops to 82.4% for 100 nm MZO film with a textured surface. Clearly the drop in optical transmittance is less than 1 % when the film thickness is doubled. In contrast, there is nearly 5 % drop when the film was coated with surface textures. We can then assume at least 4 % of the incident photons are deflected when they travel through the textured surface of the MZO film. In other words, the surface textures have caused light diffusion.

We also processed a MZO film with a 100nm/100nm double layer. The optical transmittance of this stacked film is within 1% lower than that of the continuous 200 nm film. Hence the light trapping at the MZO/MZO interface should not be the main cause for the drop in optical transmittance with the surface textured sample. From the discussions above, fabricating surface textures on the MZO film is indeed able to cause light diffusion when light travel through. This is believed to be helpful for enhancing light trapping efficiency of a-Si/μ-Si based thin film solar cells. The effect of the surface textures fabricated with the Mo/ZnO co-sputter approach on the light trapping efficiency will be further investigated.

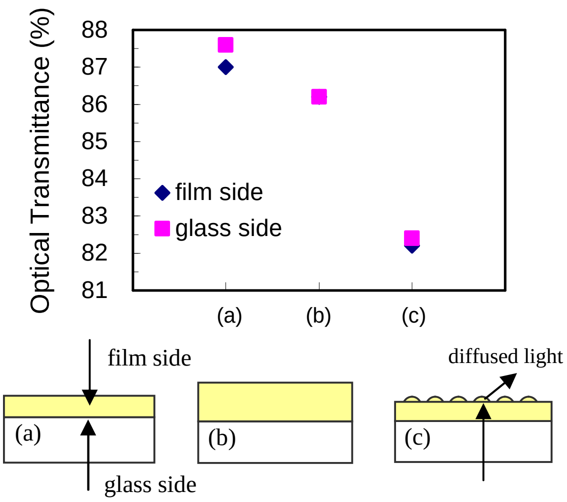

Figure 5: Optical transmittance of MZO film on glass (a) 100nm MZO, (b) 200nm MZO, (c) 100nm MZO with surface textures, measured from both sides of the sample.

4 CONCLUSIONS

This work has demonstrated that round surface textures with 110 nm in height and 120 μm in diameter could be fabricated on MZO films using sputter deposition through a micro shadow mask. The surface textures effectively caused around 4 % of light diffusion. The diffused light is believed to be able to laterally travel in a-Si/u-Si based thin film solar absorbers, and its effect on the solar power efficiency is under investigation.

5 AKNOWLEDGEMENTS

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