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ZnO based back reflectors with a wide range of surface morphologies for light trapping in n-i-p microcrystalline silicon solar cells

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Abstract

Surface morphology of ZnO layers with as-deposited thickness between 550 to 1050 nm was varied over wide range by changing etching time. The surface morphology of these ZnO layers was measured by atomic force microscopy (AFM) and statistically analyzed in terms of root mean square roughness and the diameter and depth of the craters. The texture-etched ZnO covered with a Ag and ZnO layers were applied into n-i-p μc-Si:H solar cells as back reflectors. The effects of the back reflector morphologies on solar cell performances were investigated. The link between the morphology, the scattering properties of ZnO layers, and the solar cell performance is discussed.

Keywords: ZnO; texturing; light scattering; solar cells

1. Introduction

In order to increase the optical path length of the light and achieve high absorption even in thin (in the order of μm) intrinsic layers, light-trapping concepts are usually used and are of greatest importance for thin film silicon solar cells. A common way to achieve light trapping in such solar cells is to add back reflectors and textured

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interfaces [1-8]. On back reflectors, the light which is not absorbed can be reflected back into the intrinsic layers. On textured interfaces, the light can be scattered to different directions. If the angle between the reflected light from the back reflectors and the front surfaces of the solar cells is larger than the critical angle for internal reflections, the light will be “trapped” within the solar cell, and thus, light can travel several times within the absorber layers and the optical path length can be significantly improved.

In the superstrate configuration (p–i–n) of thin film silicon solar cells (where the cells are illuminated through transparent substrates, for example glass), randomly textured transparent conductive oxides (TCOs) are usually used for light trapping [3,9]. However, as front contacts in solar cells, TCO layers have to fulfill a number of requirements on its properties, such as texture to provide efficient light-scattering, and also high transparency, appropriate sheet conductance and possibly optical index matching. Thus, the optimization of the light-scattering properties is limited by the trade-offs between these requirements for the TCO layers. Besides this, since the photo-generated current of solar cells is influenced by the transparency and conductance of TCO layers, the relationship between the light-scattering properties of TCO and the resulting gain in photo current cannot be analyzed directly.

These requirements are much relaxed when the substrate configuration (n–i–p) for solar cells is used, where the textured layers for light trapping are placed at the back of the solar cells. This is because the solar cells are illuminated from the silicon layer side and not through these textured layers, which do not have to be optically transparent in such case. We have recently developed solar cells in substrate configuration [10], taking an advantage of textured ZnO surface as a back reflector in solar cells. In this case, the textured ZnO is covered by a Ag and a ZnO film to form a highly reflective substrate for n-i-p solar cells. With this glass/ZnO(etched)/Ag/ZnO substrate, one can adjust the texture of the first ZnO layer flexibly, since its optical and electrical properties of ZnO do not influence the cell performance in such case. In the present work, the effects of ZnO surface morphology on the light trapping in n-i-p solar cells with microcrystalline silicon absorber layers are investigated.

2. Experimental details

ZnO films with different thickness (550, 800 and 1050 nm) were deposited on glass substrates by RF-magnetron sputtering from ceramic targets at 300°C substrate temperature [11]. Texturing was achieved by wet chemical etching in hydrochloric acid at room temperature for varied times, between 10 and 100 seconds. The ZnO surface morphology was measured by Atomic Force Microscopy (AFM). AFM images were evaluated by using Scanning Probe Image Processor™ (SPIP™) software [12], to calculate RMS roughness (δ_{RMS}), diameter (*d*) and depth (*h*) of the craters. The relevant parameters of craters are schematically shown in Fig. 1(a). Selected ZnO layers with different surface morphologies were covered with a thin Ag (200 nm) to evaluate angular resolved scattering. The angularly resolved scattering of such ZnO/Ag back reflectors (ARS_R) were measured in reflection using a laser at λ=550 nm. To be used in solar cells, the etched ZnO layers with different surface morphologies were covered with a thin Ag (200 nm) and a thin ZnO (80 nm) layers and applied together as back reflectors in µc-Si:H solar cells. The schematic illustration of a n-i-p solar cell is shown in Fig. 1 (b). All the solar cells were prepared with nominally identical conditions for silicon and front TCO layers. µc-Si:H layers were deposited in n-i-p sequence by plasma enhanced chemical vapour deposition (PECVD) in a multichamber UHV system. Additional details of the deposition parameters can be found in [13]. The thickness of the µc-Si:H layers was around 1.1 µm. Front TCO (ZnO:Al) layers in the solar cells were deposited on p-layers by RF magnetron sputtering. Solar cells were characterized by current-voltage (I-V) measurements under AM1.5 illumination.

3. Results and discussion

Selected AFM images of ZnO layers with various as-deposited thickness (550, 800 and 1050 nm) and etching times (10, 40 and 80 s) are shown in Fig. 2. It is evident that all ZnO layers show crater-like structures. The crater dimensions increase with etching time for a given ZnO layer thickness but also with ZnO layer thickness at a given etching time.

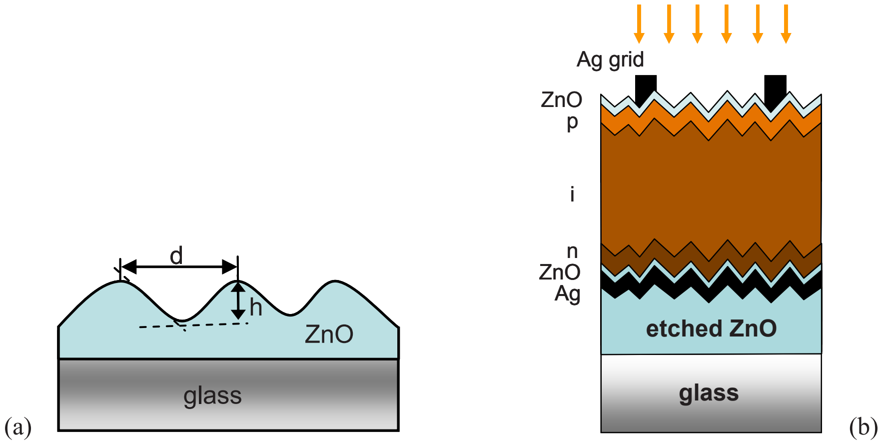

Fig. 1. (a) Schematic profile of a textured ZnO layer on glass, where relevant surface parameters diameter (*d*) and depth (*h*) are shown; (b) schematic diagram of an n-i-p solar cell.

The results of the statistical evaluation of the ZnO surface morphologies, as described in our previous publication [11], are shown in Fig. 3 as a function of ZnO etching time. A wide variation of all parameters (δ_{RMS}, mean *h* and mean *d*) is evident in the figure. It can be seen that δ_{RMS} (Fig. 3(a)) increases from 3-5 nm for un-etched ZnO layers up to a maximum value of around 180 nm in the case of 1050 nm thick ZnO. In the case of thinner (550 nm) ZnO layers, a maximum δ_{RMS} value of around 110 nm can be achieved after 70s etching time. The mean diameter (*d*) and the crater depth (*h*) are shown in Fig. 3(b) and 3(c), respectively. The mean diameter (*d*) and the crater's depth (*h*) can reach the maximum values of around 1250 nm and 500 nm, respectively.

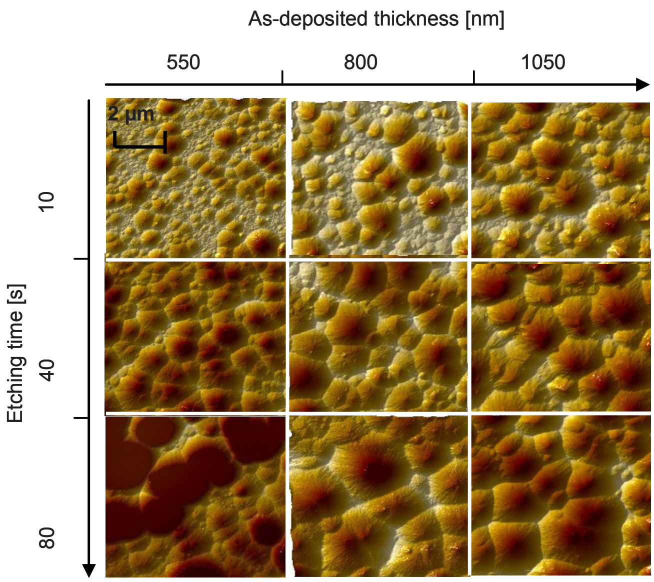

Fig. 2. AFM images of ZnO layers with thickness of 550, 800, and 1050 nm, etched for 10, 40, and 80 s.

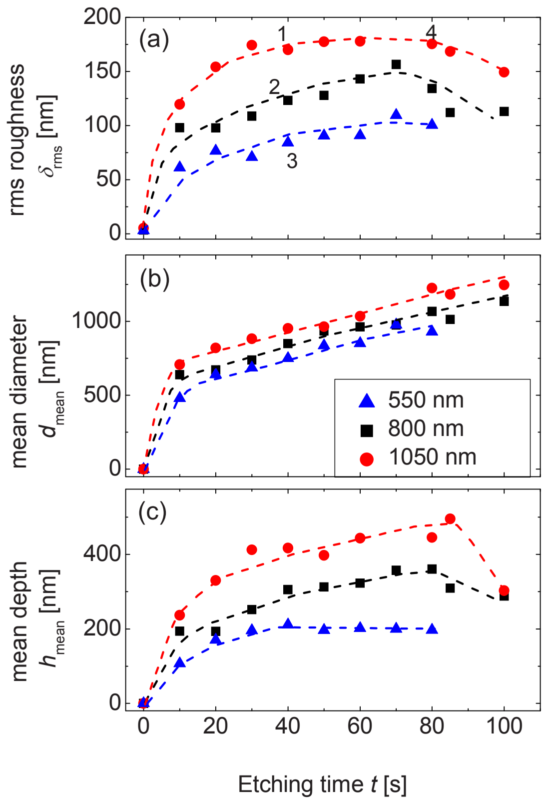

Fig. 3. (a) δ_{rms}, (b) mean diameter *d* and (c) mean depth *h* for ZnO layers with as-deposited thicknesses of 550, 800 and 1050 nm as function of etching time *t*. The dashed lines are to guide the eye. Samples 1, 2, 3 and 4 are selected for comparison (see details in text).

RMS roughness (δ_{rms}) is the most frequently used parameter to statistically characterize surface morphology and analyse the relationship between the surface morphology and the solar cell performance [7,14,15]. In the following, four ZnO layers were selected for preparation of the solar cells. These samples are indicated with numbers from 1 to 4 in Fig. 3 (a) and their properties are summarized in table 1. Here the samples 1-3 represent ZnO layers with varied δ_{RMS} roughness between 170 nm and 84 nm (1050 nm thick and 550 nm thick ZnO layers, respectively, etched for 40 s). Samples 1 and 4 have a similar δ_{RMS} roughness of around 170 nm, but different mean *d* and *h* of the craters.

Table 1. Relevant parameters of selected ZnO layers (samples 1, 2, 3 and 4) and the short circuit current density J_{SC} of the solar cells.

Back reflector	ZnO thickness (nm)	δ_{RMS} (nm)	d_{mean} (nm)	h_{mean} (nm)	J_{SC} (mA/cm^2)
1	1050	170	953	416	24.1
2	800	123	850	305	23.0
3	550	84	750	210	22.3
4	1050	174	1225	495	22.0

Subsequently, μc-Si:H n-i-p solar cells were prepared on these ZnO(etched)/Ag/ZnO back reflectors. Current-voltage measurement results show that the fill factor (FF) and open circuit voltage (V_{OC}) of all the solar cells are almost same: the FF is around 70±0.7%, while the V_{OC} is around 503±4 mV. Significant differences are observed in the short circuit current density J_{SC}, as summarized in table 1. It can be seen that the J_{SC} values increase with δ_{RMS} for samples 1-3 and vary between 22.3 to 24.1 mA/cm^2. While the back reflectors 1 and 4 have quite similar roughness, the resulting J_{SC} values are different: high J_{SC} of 24.1 mA/cm^2 is achieved in the case of back reflector 1 and J_{SC} of only 22 mA/cm^2 in the case of sample 4. The results of Raman measurements show that the silicon layers in these solar cells have very similar crystallinity of around 70±3%, where an error arises mostly from background subtraction. This, together with the invariance of FF and V_{OC} of the different cells indicate that the growth and electrical properties of silicon layers are not influenced by the back reflector morphologies studied here, suggesting that the changes in J_{SC} are related to corresponding differences in light trapping in the solar cells.

ARS measurements can provide additional information on the scattering properties of the back reflectors. The results of ARS for the back reflectors 1, 2 and 3 are presented in Fig. 4 (a). It can be seen that the peak position of ARS shifts from around 55° in the case of sample 1 down to around to around 27° in the case of sample 4. The peak position of ARS shifts to smaller angles with reduction of RMS from 170 to 84 nm. The ARS curves for the samples 1 and 4, which have a similar RMS, are compared in Fig. 4(b). It can be seen that with longer etching time (sample 4) the peak position of ARS shifts to smaller angles around 40°.

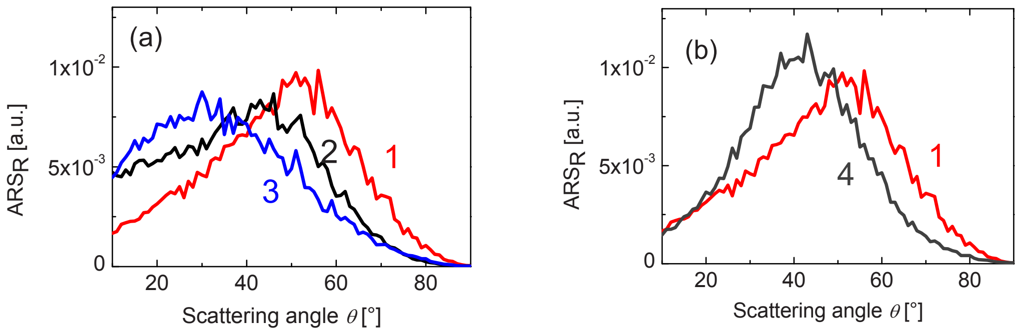

Fig. 4. Comparison of angular resolved scattering curves (ARS_R) for samples (a) 1, 2, 3 and (b) 1 and 4 .

The comparison of solar cells prepared on samples 1 to 3 with different δ_{RMS} indicates that an improved J_{SC} value of 24.1 mA/cm^2 can be attributed to more efficient light trapping in the solar cell, when a back reflector with a higher δ_{RMS} is used. Here, in the case of layer with higher δ_{RMS}, scattering into large angles is achieved as shown in Fig. 4(a). This is also in agreement with a reduction of the crater's opening angle when ZnO as deposited thickness increases, as reported previously [11]. Interestingly, the layers with similar RMS roughness (samples 1 and 4) of around 170 nm result in different scattering properties of back reflectors, as evident in Fig. 4 (b). This may be because layer 4, etched for the longest time of 80 s, has quite large craters and the ZnO layer is partly etched down to the glass substrates (see Fig. 2). For this sample, the carter's mean diameter and mean depth above 1200 nm and 400 nm, respectively, are observed. The resulting ARS curve has a peak position around 40° and thus provides less efficient light trapping in the solar cell, which can account for an observed difference in J_{SC} between cells 1 and 4.

4. Conclusions

We have shown that the lateral and vertical dimensions of ZnO surface structures (craters) can be controlled independently over a wide range by changing as-deposited thickness of ZnO and etching time. For the selected solar cells with varying morphology of back reflectors, an increase in the short circuit current density J_{SC} is accompanied by the shift of the ARS peak position towards higher angles. Our results suggest that RMS roughness can not solely describe the surface morphology and not sufficient to estimate the light-trapping potential of back reflectors. Thus more detailed statistical analysis of the surface morphology, in terms of crater's diameter and depth, is necessary.

Acknowledgements

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