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Aluminium induced texturing of glass substrates with improved light management for thin film solar cells

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ABSTRACT

Aluminium induced texturing (AIT) method has been used to texture glass substrates to enhance photon absorption in microcrystalline thin film Si solar cells. In this process, a thin Al film is deposited on a glass substrate and a non-uniform redox reaction between the glass and the Al film occurs when they are annealed at high temperature. After etching the reaction products, the resultant glass surface presents a uniform and rough morphology. In this work, three different textures (σ_{rms}~85, ~95, ~125 nm) have been achieved by tuning the dc sputtering power and over them and over smooth glass, *pin* microcrystalline silicon solar cells have been fabricated. The cells deposited over the textured substrates showed an efficiency improvement in comparison to the cells deposited over the smooth glass. The best result was given for the glass texture σ_{rms}~125 nm that led to an average efficiency 2.1% higher than that given by the cell deposited on smooth glass.

1. Introduction

For thin film silicon solar cells efficient light management plays a crucial role to improve device performance [1]. A common approach to improve light management involves introduction of textured interfaces in the solar cell. Scattering at the interfaces increases the path length of incident light aiming in higher absorption in the active layer and hence, higher conversion efficiency.

In thin film silicon solar cells, light scattering is usually achieved by texturing the front transparent conducting oxide (TCO) [2,3,4], the back reflector [5], or even the substrate with either random [6,7] or periodic [8,9] textures with typical roughness in the range from 30 to 150 nm [1–8]. For efficient light scattering, these textures should be in the dimension range of the incoming light wavelength [10].

Typical textured TCOs are the naturally textured ZnO:B grown by Low Pressure Chemical Vapour Deposition (LPCVD) [2], SnO_2:F grown by Atmospheric Pressure Chemical Vapour Deposition (APCVD) [3], or sputtered and HCl-etched ZnO:Al (AZO) [5]. Besides these "traditional" light trapping schemes, other nanoscale approaches are currently under investigation including photonic crystals [11], nanowires [12], and periodic or periodic-disordered nanostructures [13].

Texturing the substrate is a good alternative compared to texturing the TCO or the back reflector. An optimized textured glass surface will provide a wider range of TCOs which are suitable for thin film solar cells, for example non-texturable TCOs or alternative front contacts, such as carbon nanotubes [14]. Moreover texturing the glass gives the possibility for two fold light scattering at two interfaces (glass/TCO and TCO/silicon) as exhibited in Fig. 1.

In this work the Aluminium Induced Texturing method (AIT) has been used to texture Borofloat glass substrates. In this method, a thin Al film is deposited onto a glass substrate and a redox reaction between the Al and the SiO_2 of the glass is induced by high temperature annealing. The reaction products are wet-etched and the result is a uniform and rough glass surface [15]. The final roughness can be controlled by varying the process parameters such as the etching solution [16,17], the etching time [18], the initial Al thickness [6], the annealing conditions [18] or the Al deposition method [6]. The AIT method can create suitable substrate textures for polysilicon solar cells [16–19] as well as for amorphous and microcrystalline thin film silicon solar cells [18].

In this study, the glass roughness has been controlled by varying the dc sputtering power to deposit the Al, and textures with roughness values of ~85 nm (sample T1), ~95 nm (sample T2) and ~125 nm (sample T3) have been obtained. Over these textures and over smooth glass, an AZO film of 800 nm has been

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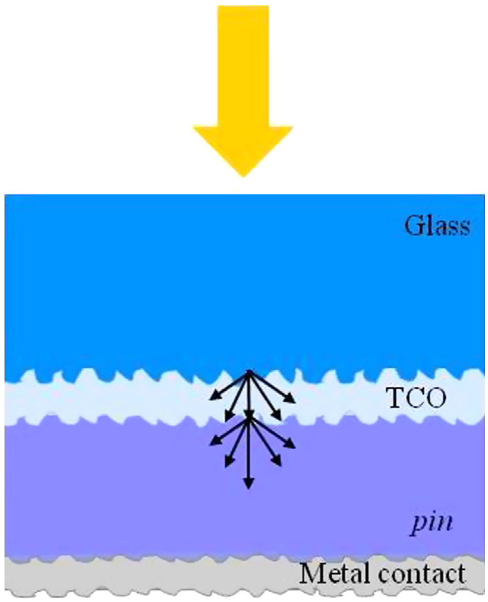

Fig. 1. Schematic light path of a *pin* thin film silicon solar cell deposited on a textured glass surface.

deposited followed by identical μc-Si:H *pin* solar cells. *J–V* measurements have confirmed the suitability of these textures for the growth of μc-Si:H and have shown an increase in the short circuit current that results in an overall efficiency improvement in comparison to the solar cell on flat substrate.

2. Experimental

Three Borofloat 33 glass substrates of 2 mm thick were cleaned in an ISO 7 (10000 type) clean room. Al films of 180 nm were deposited by means of direct current (dc) magnetron sputtering at 60 W (sample T1), 100 W (sample T2) and 150 W (sample T3) over the three cleaned substrates. The Al target was 99.999% pure and had a diameter of 3 in.. The samples were post-annealed at 600 °C during 1 h to induce the chemical reaction between the glass surface and the Al layer and the reaction products were etched with H_3PO_4 at 185 °C.

Over the resultant textured substrates (T1, T2 and T3) and over the non-textured Borofloat glass (referred to as T0), 800 nm of AZO (ZnO with 2 wt% Al_2O_3 and 99.99% pure) were deposited by dc magnetron sputtering at a substrate temperature of 300 °C, using a power density of 220 W and at an Ar pressure of 0.4 Pa.

The morphological study was carried out using a Scanning Electron Microscope (SEM) and an Atomic Force Microscope (AFM). SEM micrographs were obtained through a *Nova Nano SEM 230* from *FEI Electron Microscope.* Insulating samples had to be covered with thin Au layers to avoid the charging of the surface. AFM images were recorded using a *Pacific Instruments* system and the software used for the image analysis was *XEI 1.7.3 of Psia Inc.* and the σ_{rms} values were extracted from areas of 15 × 15 μm^2.

The total transmittance (T) and diffused transmittance (T_d) measurements in the wavelength range 350–1400 nm were recorded using a *PerkinElmer Lambda 950* spectrophotometer equipped with a 150 mm integrating sphere. The haze values were calculated from the quotient between the T_d and T according to:

$$Haze = T_d/T \quad (1)$$

The sheet resistance (R_s) of glass/AZO samples was measured by using a four point probe system (*Jandel RM3*).

Thin film silicon solar cells were deposited on the AZO coated textured glasses and smooth Borofloat glass substrates in the sequence: glass/AZO/μc-Si:H (p)/ μc-Si:H (i)/ μc-SiO*x*:H (n). The cells were covered with radio frequency magnetron sputtered ZnO:Al layer and Ag contact deposited with 1 cm^2 mask to define the cell area. Twelve such identical solar cells were fabricated on each of the substrates tested. The schematic cross section of a solar cell is shown in Fig. 1. The thicknesses of the intrinsic and the doped silicon layers are 1100 ± 25 and 20 ± 5 nm, respectively. Additional details on the deposition process can be found elsewhere [20].

Solar cells were characterised by current–voltage (*J–V*) measurements under AM1.5 illumination using a double source (class A) sun simulator, and by external quantum efficiency (EQE) measurements. The total optical reflection of the cells was measured using a *PerkinElmer Lambda 950* spectrophotometer within a spectral range from 300 to 1300 nm. Although various cells were fabricated on every substrate, the total reflectance, the EQE, and the *J–V* curves shown in this work belong to the best solar cell (highest efficiency) in each one. The average values of the solar cell parameters shown in Table 2 were calculated from all the cells except for those presenting short circuit problems which were 1 or 2 per substrate.

3. Results and discussion

The morphology of T1, T2, T3 and AZO coated samples, T1/AZO, T2/AZO and T3/AZO is studied using SEM and the images recorded at a tilt angle of 60° is presented in Fig. 2.

By increasing the dc sputtering power, the Al particles reach the glass with higher energy and the Al film grows more compact and with greater adhesion to the glass substrate. As a result, the glass surface gets more textured. At dc sputtering powers < 100 W, the resulting glass surface presents a U-shape crater morphology (see Fig. 2a) and c)) with lateral feature sizes of 500–900 nm. When the sputtering is performed at 150 W (see Fig. 2e)) the resulting glass surface becomes highly rough with deeper valleys and smaller lateral sizes. Probably at such high power, the Al atoms have diffused deeper into the glass surface and after completing the AIT process, the result is this highly porous-like structure.

After depositing 800 nm of AZO, the three surfaces present a double texture morphology based on a superposition of a micro- and nano-metric roughness similar to a "cauliflower" surface.

The roughness values can be found in Table 1 and the haze curves in the range 350–1400 nm are presented in Fig. 3. In accordance with the SEM images, both roughness values and haze factor of the textured glasses are found to increase with the sputtering power. When the textured glasses are coated with the AZO, the roughness and haze values are almost unchanged. Only the highest texture, T3, seems to be slightly smoothened which is beneficial to avoid the formation of cracks during the μc-Si:H growth.

A summary with the roughness, sheet resistance, haze value at 600 nm and integrated transmittance in the range 400–1100 nm of all the samples is shown in Table 1. The sheet resistance of the AZO on smooth glass is 9 Ω/sq and increases up to ~10 Ω/sq over T1 and up to ~12 Ω/sq over T2 and T3.

Identical *pin* μc-Si:H solar cells have been fabricated over AZO coated T0, T1, T2 and T3 substrates followed by the back reflector (TCO+Ag) and the total reflectance of the devices in the range 300–1100 nm is exhibited in Fig. 4.

As can be seen from Fig. 4, the solar cells deposited on the textured substrates show a total reflectance significantly lower than that obtained in the case of smooth glass, whose average value is $R_{400-1100}$=45.4%. The roughness increase at the interface