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Substrate effect on ultra-thin hydrogenated amorphous silicon solar cells

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ABSTRACT

We report a comprehensive study of ultra-thin a-Si:H solar cells on various transparent conductive oxide (TCO) coated glass substrates. We find that the highly textured boron doped zinc oxide (BZO) with multi-scale features made with metal organic chemical vapor deposition (MOCVD) outperforms the flat aluminum doped zinc oxide (AZO) deposited by sputtering and the highly textured AZO with only large features after the chemical etching with diluted HCl. We believe that the much larger features than the cell thickness provide only an enhancement of the effective area for increasing the light absorption, while the variable sizes of features similar to and smaller than cell thickness provide- a highly effective light trapping for thin film solar cells. In addition, the ultra-thin a-Si:H solar cell on the BZO has a better *p/i* interface than the cell on the AZO substrates, which leads to a high cell performance. A high efficiency of 8.15% was obtained using an a-Si:H *p-i-n* structure on the BZO with the intrinsic layer of 70 nm.

1. Introduction

With the increase of mass production and technology improvement, crystal silicon (c-Si) solar module efficiency has been increased [1–4] and their manufacturing cost has been steadily decreased in the last decade, which has accelerated the pace towards the grid parity on one hand, but pushed the other photovoltaic (PV) technologies out of the main stream, especially in the utility scale on the other hand. Hydrogenated amorphous silicon (a-Si:H) and microcrystalline silicon (μc-Si:H) based film silicon PV technology is one of the technologies lost its market share significantly because of the low efficiency and metastability caused by the Staebler-Wronski effect [5]. However, thin film silicon solar cell has several unique properties over c-Si solar cells, which makes it suitable for some potential applications in the niche market. For example, a-Si:H based solar cells can be deposited on flexible substrates for flexible PV product [6,7]; on glass with back side transparent electrode for semitransparent solar panels [8–10]. Thin film silicon solar cells are normally deposited on transparent conductive oxide (TCO) coated glass substrates with a *p-i-n* structure, where the *p*, *i*, and *n* represent the *p*-layer, *intrinsic* layer, and *n*-layer, respectively, and with a back contact made of another TCO layer and a metal contact layer such as Ag and Al. The back contact could also use a highly conductive TCO without the metal layer to make semitransparent solar cells for various applications such as building integrated PV (BIPV) with color windows for decoration and electricity generation at the same time and green house for agriculture with electricity generation as well. In order to have enough light transmission, reducing the a-Si:H absorber layer thickness is needed for the semi-transparent solar cells.

In addition, people have tried various techniques to improve the cell efficiency and the stability further to keep thin film silicon solar PV industry alive [11,12]. One of the approaches is to design three dimensional (3D) solar cells on various micro- and nano-structures to make them optically thick to absorb more light and electrically thin to allow a high electric field to collect the photo-generated carriers [13–15]. For this reason, Ultra-thin a-Si:H solar cells (< 100 nm) have attracted a great deal of attentions.

It has been well known that light trapping is one of the important techniques for improving thin film solar cell efficiency. The surface texture on the TCO substrate is the dominant factor for *p-i-n* structured thin film silicon solar cells. In the early days, Fluorine doped Tin dioxide (FTO) is widely used as the TCO for a-Si:H based *p-i-n* solar cells. With the invention of μc-Si:H as the absorber layer [16–18], Al doped Zinc Oxide (AZO) and Boron doped Zinc Oxide (BZO) have been widely used because they are stable under atomic hydrogen condition but FTO

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reacts with the high density atomic hydrogen used in μc-Si:H solar cell deposition. AZO is normally deposited using a magnetron sputtering machine and it is relatively flat in the as-deposited state. A chemical etching process using diluted HCl was proposed by the Julisch group and proven to be an effectively method to increase the texture of AZO [19–21]. The chemically etched and highly textured AZO has been used in μc-Si:H deposition and results in high efficiency μc-Si:H single-junction and a-Si:H/μc-Si:H double-junction solar cells [22,23]. While BZO has been deposited using Metal Organic Chemical Vapor Deposition (MOCVD), on which the textures are generated and controlled during the deposition process [24,25]. The highly textured BZO has also been used in μc-Si:H and results in high efficiency μc-Si:H single-junction and a-Si:H/μc-Si:H double-junction solar cells as well [26,27].

The effectiveness of light trapping depends not only on the textures of the TCO, but also on the solar cell thickness. The very large pyramidal feature has been proven to be a good structure for light trapping in c-Si solar cells [28], but may not be a good choice for thin film silicon solar cells. Because of the significantly reduction of the absorber layer thickness in ultra-thin a-Si:H solar cells, the normally optimized AZO and BZO for μc-Si:H solar cells might not be the good substrates for ultra-thin a-Si:H solar cells. The objective of this paper is to study the structural and optical properties of commonly used AZO and BZO and their correlations to ultra-thin a-Si:H solar cell performance and to search the best TCO substrate for ultra-thin a-Si:H solar cells.

2. Experimental procedures

AZO layers were deposited using a magnetron sputtering system (KJLC Lab-18, base pressure below 1×10^{-5} Pa) on cleaned glass substrate at 325 °C. In order to increase the surface textures, a chemical etching process was made in diluted HCl (5.0%) solution for 45 s. BZO layers were deposited using a MOCVD method on cleaned glass substrates at 150 °C. As a comparison, commercial FTO was used as the baseline. Ultra-thin a-Si:H solar cells with a 70-nm thick intrinsic layer was deposited on the selected substrates using a multi-chamber plasma enhanced chemical vapor deposition system. The substrate temperature was 210 °C for all of the silicon layers. The optimization of the cell performance was available elsewhere [29,30].

The surface structures of the TCO were measured using an atomic force microscopy (AFM) (SPA 400 AFM) with the surface roughness characterized by the root-mean-square (RMS) and the surface height distribution. The conformality of the ultra-thin a-Si:H solar cells on different TCO substrates were measured by using a cross-sectional transmission electron microscopy (X-TEM) (FEI Novanano lab 200). The optical properties of the TCO were measured using an optical spectrometer (Cary 5000) and analyzed by total transmittance and haze spectra.

The solar cell performance was characterized by the current density *versus* voltage (J-V) characteristics measured under an AM1.5 solar simulator (WXS-156S-L2, AM1.45GMM by Wacom Co) with 100 mW/cm^2 of light intensity at 25 °C, and by the external quantum efficiency (EQE) measured with an EQE system (PV measurement QEX10). The EQE curves were normally measured at the short circuit condition (0 V bias), and here also under − 1.0 V and + 0.6 V for the study of carrier recombination losses.

3. Results and discussion

Fig. 1 shows the surface morphologies of the four types of TCO films, where (a) is the MOCVD deposited BZO, (b) the sputtering deposited AZO before the chemical etching, and (c) the sputtering deposited AZO after the chemical etching, and (d) the reference FTO. The images show that the BZO has a rough surface of 83 nm RMS with various sized mountain-like structures. The AZO before the chemical etching is relatively flat with an RMS only 5.9 nm, while its surface becomes very rough (RMS = 135.4 nm) with large crater-like

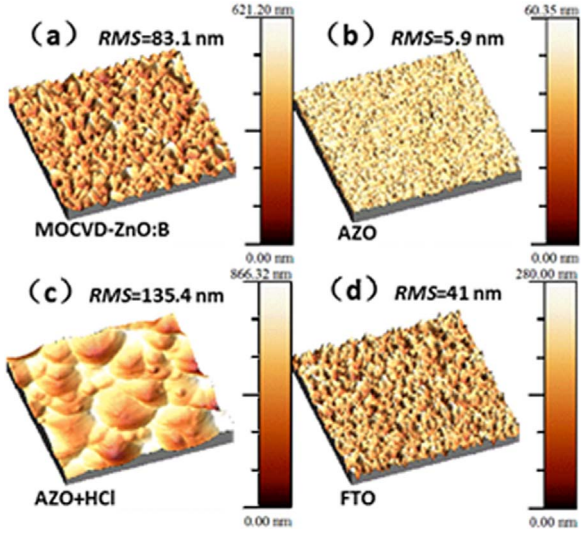

Fig. 1. AFM surface morphology images of various TCO substrates and their RMS roughness values.

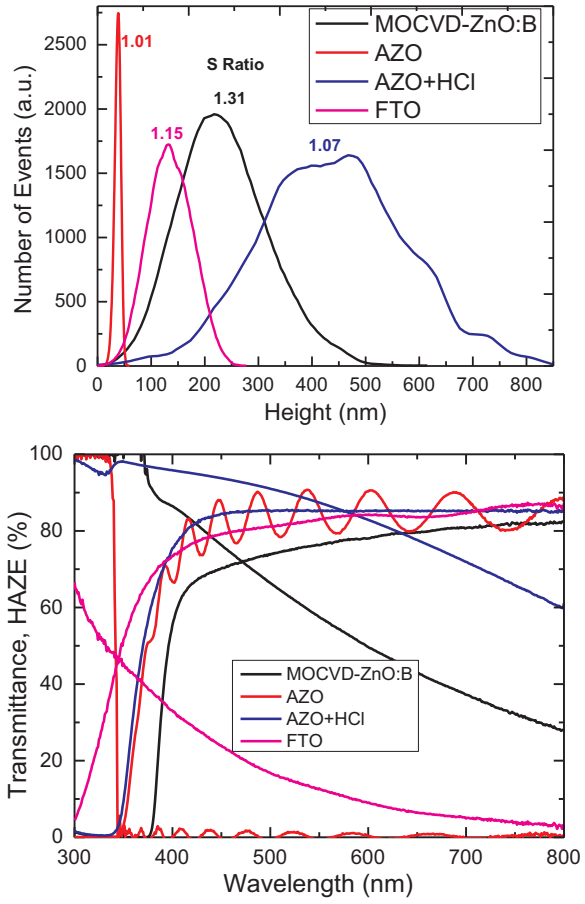

Fig. 2. Upper plot: the height distributions of the four TCO substrates, the lower plot: the transmittance and haze spectra of the four TCO substrates as shown in Fig. 1.

structures after the chemical etching. The FTO has a medium texture with RMS = 41 nm. The upper panel in Fig. 2 plots the height distributions of the four TCO samples along with the S-ratio defined by the total surface area over the base flat area. With the increase of the surface texture, the distribution becomes broad and the peak shifts to a large height number. The etched AZO has the peak position at ~ 500 nm and the distribution extends to 850 nm, which means the biggest distance from peak to valley could reach 850 nm. While the curve