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HAZO/AZO structure with improved full spectrum performance for high-efficiency thin-film solar cells

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ABSTRACT

Advanced light management currently plays an important role in high-performance solar cells. In this paper, a HAZO/AZO structure that was produced using RF-magnetron sputtering with segmented hydrogen mediation was proposed to further simultaneously enhance the transmittance and light trapping capability at full solar spectrum. Compared to the standard AZO front contact, the total transmittance at short wavelength and haze at full spectrum were remarkably enhanced by 5.1% and 20.7%, respectively. Additionally, the resistivity of the HAZO/AZO structure was enhanced by 16.9%. When applied as front electrodes, the spectral response of a-Si:H and μc-Si:H solar cells increased. The quantum efficiency of the a-Si:H solar cell improved by 7.9% (from 59% to 66.9%) at 400 nm. An initial efficiency of 8.69% with J_{sc} over 27 mA/cm^2 was obtained for the μc-Si:H solar cell. Finally, an a-Si:H/a-SiGe:H/μc-Si:H triple-junction solar cell was obtained with the initial efficiency over 15%, which illustrates a promising and potentially cost-effective alternative structure to further improve the high-quality transparent electrodes for high-efficiency thin-film solar cells.

1. Introduction

An a-Si:H/a-SiGe:H/μc-Si:H triple-junction structure is currently proposed by United Solar and LG Electronics [1,2] to realize a high conversion efficiency over 16%. This triple-junction structure offers a more efficient usage of the solar spectrum, which suggests a possible approach to exceed the current inadequate efficiency limit of thin-film silicon (TFS) solar cells, and the structure is a promising candidate in terms of the power conversion efficiency. Further development and implementation of efficient light management in high-performance TFS solar cells [3–7] are considered the most important research area. In the p–i–n type solar cell deposited on transparent conductive oxides (TCOs), lights are introduced and trapped by the TCOs with high transmittance and textured-surface morphology. Thus, the performance of TCOs plays a crucial role in the high-efficiency TFS solar cells and forms a significant part of the photovoltaic research and development [1,5–8].

The sputtered aluminum-doped ZnO (AZO) has high electrical conductivity, low cost, thermal stability, and non-toxicity; can be easily textured using a simple wet-etching process; and is an important building block in a-Si:H, μc-Si:H and a-Si:H/μc-Si:H solar cells [8–10]. However, when it is applied in the triple-junction structure, both transparent and light-diffusing structures should be further ameliorated to satisfy the rigorous light management requirement over the full solar spectrum [1]. In a triple-junction solar cell, a more suitable spectral splitting is needed to achieve a better current-matching among corresponding sub-cells, thus maximizing the resultant current output. In the meanwhile, a great light trapping over the full solar spectrum will efficiently improve the spectral response of each component, especially for a-SiGe:H middle cell that cannot obtain benefit from the ZnO:B/Ag/Al back reflector. Benefited from the effective light trapping in the long-wavelength range, the requirements on the thickness and germanium content of a-SiGe:H middle component will be both reduced. Then the electrical performance and stability of corresponding triple-junction solar cells will be efficiently improved.

Based on the Burstein–Moss effect and plasmon absorption, a transmittance competition between the short-wavelength region and near-infrared region (NIR) is restricted for AZO films with different carrier concentrations. Improved transmittance near the optical band gap with good NIR response for ZnO films using hydrogen mediation has been obtained by different research groups [11–14], which provides a promising approach to resolve the dilemma. Unfortunately, an effective scattering texture with a root-mean-square (RMS) roughness higher than 100 nm have not

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been obtained for both hydrogen-mediated ZnO films with and without etching [11,14–16], which hinders the application of this highly transparent electrodes in triple-junction solar cells.

In the present work, we notice the simple, single step to further improve the light management of AZO films for applications in high-efficiency triple-junction solar cells. An in situ double layer (DL) AZO structure with hydrogenated AZO (HAZO) and AZO are realized using segmented hydrogen mediation. Significant improvements of light transmittance around the optical band gap and light scattering in the NIR are detected using a single deposition and etching process. Each promotion is tested using a-Si:H and μc-Si:H solar cells. Then, an initial efficiency over 15% was obtained to confirm its applicability for high-efficiency triple-junction TFS solar cells. Thus, this HAZO/AZO structure with improved full spectrum performance may provide a promising and potentially cost-effective alternative to further improve the high-quality front contact and the performance of thin-film solar cells.

2. Experiment

The films were prepared on Corning eagle XG glass using RF magnetron sputtering from a ceramic $ZnO:Al_2O_3$ target (1 wt%) in a KJLC Lab-18 sputtering system. The in situ HAZO/AZO films were performed using segmented hydrogen mediation. At the beginning of the deposition, hydrogen was introduced into the sputtering atmosphere to obtain a 500 nm thick HAZO layer. Then, the hydrogen circuit was cut, and a 500 nm thick AZO layer was obtained in pure Ar plasmon. Thus, a combined HAZO/AZO film with a thickness of approximately 1 μm was obtained. The sputtering chamber was maintained at a base pressure below 1×10^{-5} Pa before every deposition, and the distance between the target and the substrate was maintained at 190 mm. Low pressure (1 mTorr) and high power density (3.3 W/cm^2) were used with the substrate temperature of 325 °C. The flow rate of hydrogen was set at 0.3 sccm, whereas the argon flow rate was maintained at 5 sccm.

The sheet resistance, hall mobility and carrier concentration were measured at room temperature using the van der Pauw method in the HL5500 Hall System (Accent, York, UK). The film thicknesses were measured using a Dektak 3030 profilometer (Veeco Instruments Inc., Woodbury, USA). The bonding states of the films were analyzed using an Axis Ultra X-ray photoelectron spectrometer (Kratos Analytical Ltd, Manchester, UK). A SPA 400 atomic force microscope (AFM) (SII Nanotechnology, Inc., Tokyo, Japan) was used to characterize the surface morphology. The perpendicular specular (T_{spe}) and total transmittance (T_{tot}) were measured using a Cary 5000 spectrophotometer (Varian Co., Palo Alto, USA), which was equipped with an integrated sphere in the spectrum range of 300–1100 nm. The transmittance haze (H_T) was determined as the fraction of diffuse (scattering angels exceeding 5°) transmittance that constituted the total transmittance: $H_T=[T_{tot}-T_{spe}]/T_{tot}\times100\%$.

The HAZO/AZO and standard AZO films were applied as the front contact for the single-junction a-Si:H, μc-Si:H and a-Si:H/a-SiGe:H/μc-Si:H triple-junction thin-film solar cells. The intrinsic layer of a-Si:H single-junction solar cells was fabricated using a radio frequency plasma-enhanced chemical-vapor deposition (RF-PECVD) process with a thickness of 140 nm, and an Al back contact was used. The intrinsic layer of the μc-Si:H single-junction solar cell was prepared using the very-high-frequency plasma-enhanced chemical-vapor deposition (VHF-PECVD) technique with a thickness of 2.0 μm, and a ZnO:B/Ag/Al back reflector structure was used in the μc-Si:H single-junction solar cell and triple-junction solar cells to improve the long-wavelength response. The Al back contact with an area of 0.253 cm^2 was used to define the area of the solar cells.

The current–voltage characteristics (JV) were measured under 1-sun (AM 1.5, 25 °C, 100 mW/cm^2) using a Wacom WXs-156s-l2 dual beam solar simulator. An excellent simulation of the AM1.5 spectrum was obtained from the superposition of the simulator's two filtered light sources with adequate calibration. The external quantum efficiency (EQE) was measured, and J_{sc} was calculated from the EQE by integrating EQE (λ) with the AM 1.5 spectrum.

3. Results and discussion

3.1. Optical and light-trapping properties

Three major critical parameters of the TCO affect the solar cell performance: conductivity, transmittance, and haze. A high transparency in full spectrum normally introduces high J_{sc} for TFS solar cell by reducing the parasitic light absorption. Fig. 1 shows the spectral transmittance in the wide spectrum range (300–1100 nm) (a) and emphasis in the short-wavelength range (350–500 nm) (b) for different samples. It is observed from Fig. 1(a) that all samples have an absorption tail near 350 nm. Although the tiny hydrogen mediation did not show any broadened optical band gap, which was reported in previous studies [12,13], the transmittance promotion is significantly favorable for a-Si:H solar cells, as shown in Fig. 1(b).

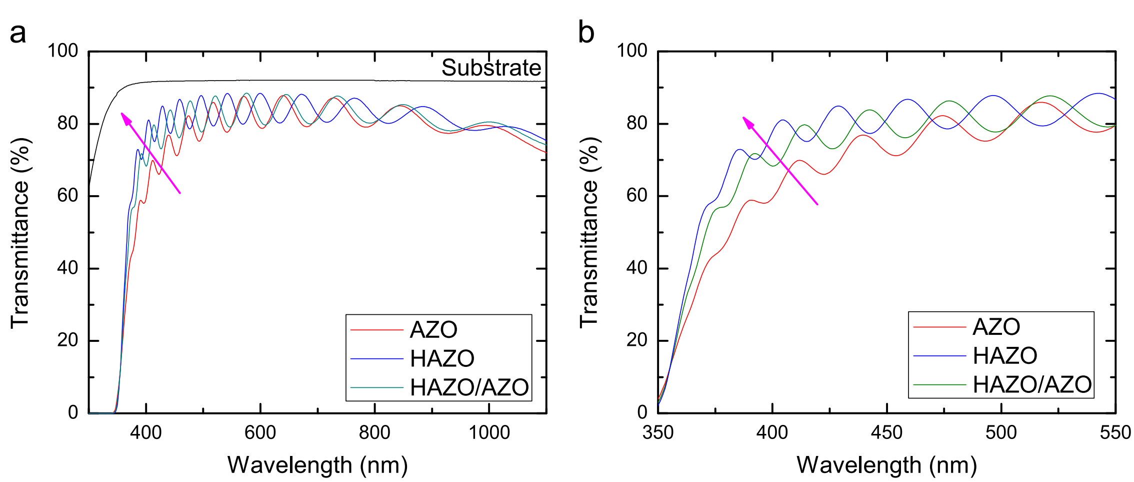

Fig. 1. Spectral transmittance of AZO, HAZO and HAZO/AZO films in the (a) wide spectrum range (300–1100 nm) and (b) short-wavelength range (350–500 nm).