Solar Energy 171 (2018) 907–913

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Controlling performance of a-Si:H solar cell with SnO_2:F front electrode by introducing dual p-layers with p-a-SiO_x:H/p-nc-SiO_x:H nanostructure

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ARTICLE INFO

Keywords:
SnO_2:F front electrode
Dual p layers
p-nc-SiO_x:H
Amorphous silicon solar cell

ABSTRACT

Dual p-type layers consisting of a p-type hydrogenated amorphous silicon oxide (p-a-SiO_x:H) layer and a p-type hydrogenated nanocrystalline silicon oxide (p-nc-SiO_x:H) layer were used as the window layer in a hydrogenated-amorphous-silicon (a-Si:H) p–i–n thin-film solar cell with a fluorine-doped tin-oxide (FTO, SnO_2:F) front electrode. Through this method, high conductivity, which originated from the p-nc-SiO_x:H layer with higher optical bandgap, was imparted to the a-Si:H solar cell. The destabilization problems of Sn^{4+} in FTO were solved by using a high-flux hydrogen plasma during the growth of p-nc-SiO_x:H. The properties of the a-Si:H solar cell were controlled by changing the thickness of the p-a-SiO_x:H and p-nc-SiO_x:H layers. The dual p-type layers in the a-Si:H solar cell exhibited enhanced transmission of holes and decreased recombination current. The p-nc-SiO_x:H film in the dual p-type layers increased the built-in potential in the a-Si:H solar cell to obtain a higher open-circuit voltage and a higher short-circuit current density. Finally, the conversion efficiency of the a-Si:H solar cell was enhanced by 12.90% through the adoption of the p-a-SiO_x:H(7 nm)/p-nc-SiO_x:H(7 nm) nanostructure for the dual p-type layers.

1. Introduction

The hydrogenated-amorphous-silicon (a-Si:H) thin film is regarded as an important material in photovoltaic applications (Reber et al., 2004; Toyama and Okamoto, 2006; Yoon et al., 1998; Choi et al., 2000; Myong, 2014; Turan et al., 2014; Islam et al., 2014; Fang et al., 2017; Liu et al., 2017). When used as the window layer of an a-Si:H solar cell, a p-type layer with optimized design can not only reduce parasitic absorption at short wavelengths, but also improve the built-in potential (V_{bi}) of the solar cell; therefore, a p-type a-Si:H layer also has considerable impact on the short-circuit current density (J_{sc}) and open-circuit voltage (V_{oc}) (Arch et al., 1991; Dutta and Chatterjee, 2004; Belfar and Aït-Kaci, 2012; Fathi et al., 2011; Rodríguez et al., 2011; Dwivedi et al., 2012; Wang et al., 2015). For the photogenerated carriers, holes can be easily hindered in the transport process because the migration of holes is far lower than that of electrons. Therefore, using a p-type layer with high conductivity and wide optical bandgap is the key to optimize the characteristics of the window layer. Some research groups prefer to use high-conductivity p-type hydrogenated nanocrystalline silicon (p-nc-Si:H) as the window layer to improve J_{sc} (Liu et al., 2011; Guha et al., 2013; Yue et al., 2012). Furthermore, the hydrogenated silicon oxide (SiO_x:H) film, a wide-optical-bandgap material, has also been studied as another key material for photovoltaic applications (Isabella et al., 2014; Buehlmann et al., 2007; Das et al., 2008). Compared with p-nc-Si:H and p-type hydrogenated amorphous silicon oxide (p-a-SiO_x:H) films, a p-type hydrogenated nanocrystalline silicon oxide (p-nc-SiO_x:H) film exhibits less parasitic optical absorption and better electrical properties, which makes it a promising candidate for the window layer (Biron et al., 2012; Tan et al., 2015; Wang et al., 2014a,b; Chang et al., 2013; Fang et al., 2016). In addition, a p-nc-SiO_x:H film has better electronic stability than a p-a-Si:H film, especially when the amorphous structure of the Si film suffers from the

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https://doi.org/10.1016/j.solener.2018.07.035
Received 29 March 2018; Received in revised form 20 June 2018; Accepted 11 July 2018

Stabler–Wronski effect, which leads to a decrease in the solar-cell performance (Fritzsche, 1995, Si et al., 2017). Fluorine-doped tin oxide (FTO, SnO_2:F) films, a transparent conductive oxide (TCO) material, is most commonly used as the transparent electrode in thin-film solar modules based on hydrogenated amorphous silicon (a-Si:H) as the light-absorbing material (Myong, 2014; Turan et al., 2014). However, because the Sn^{4+} species in FTO can be destabilized and reduced to its metallic state (Sn^0) upon exposure to a high-flux hydrogen plasma (Choi et al., 2013; Li et al., 2016a), p-nc-SiO_x:H cannot be used in a-Si:H solar cells with the p–i–n configuration and FTO as the TCO. This destabilization and reduction of Sn^{4+} in FTO occur when the p-nc-SiO_x:H film is deposited by a high-flux hydrogen plasma via radio-frequency plasma-enhanced chemical vapor deposition (RF-PECVD) (Bugnon et al., 2012). The resulting degradation in the optical transmittance of FTO leads to low J_{sc} and V_{oc} of a-Si:H solar cells (Masis et al., 2014).

In this work, the FTO/p-a-SiO_x:H/p-nc-SiO_x:H layered structure was introduced to improve the optical and electrical properties of the p side of an a-Si:H solar cell, without affecting the destabilization of Sn^{4+} in the FTO layer. Instead of using a single p-layer consisting of p-a-Si:H, p-a-SiO_x:H, p-nc-Si:H, or p-nc-SiO_x:H, the p-a-SiO_x:H/p-nc-SiO_x:H part of the structure formed the dual p-layers that served as the window layer of the cell.

2. Experimental

The silicon thin-film layers and a-Si:H solar cells were fabricated at a temperature of 210 °C by a radio-frequency plasma-enhanced chemical vapor deposition (RF-PECVD) in a four-chamber cluster system. A mixture of silane (SiH_4) and hydrogen (H_2) gases was used to deposit the intrinsic a-Si:H layer as the absorber layer; trimethylborane (TMB) plus carbon dioxide (CO_2) and phosphine (PH_3) plus CO_2 were added to the SiH_4–H_2 mixture for fabrication of the p- and n-type layers, respectively. The silicon thin-film layers were deposited on glass substrates to investigate their optical and electrical properties. The p–i–n type a-Si:H single-junctioned solar cells were deposited on the FTO front electrode with a ZnO:B/Ag/Al back contact to define the area ($0.25\ cm^2$) of the individual cell (Li et al., 2017)s. The structure and primary components of an a-Si:H solar cell are shown in Fig. 1(a) and (b). Fig. 1(c) shows a schematic illustration of a-Si:H solar-cell structures with different window layers. Type A and type B represent a-Si:H solar cells with a single p-layer (p-a-SiO_x:H) and dual p-layers (p-a-SiO_x:H/p-nc-SiO_x:H), respectively. For the samples of both type A and type B, the total thickness of the p-type window layer was kept at 14 nm, and the a-Si:H solar-cell performance in this work was optimized by controlling the thickness of the individual p-a-SiO_x:H and p-nc-SiO_x:H layers. We treated the FTO front electrode with a carbon dioxide plasma (COP) for a short time to modify the Schottky barrier at the p-a-SiO_x:H/FTO interface to promote hole transport (Li et al., 2016a).

The cross-sectional morphology of the a-Si:H solar cells was characterized with a field-emission scanning electron microscope (FESEM; S-3400, Hitachi, Japan). The optical transmittance and reflectance of the films were measured by an ultraviolet–visible (UV–VIS) spectrometer (Lambda 650, PerkinElmer, USA), and the spectra were analyzed after subtracting the transmittance and reflectance data of the glass substrates. Raman spectroscopy was performed with a Raman spectrometer (LabRAM HR Evolution UV–VIS-NIR, Horiba, Japan) and a laser (wavelength: 325 nm) to investigate the crystalline volume fraction of the p-nc-SiO_x:H layer. The oxygen content was measured by X-ray photoelectron spectroscopy (XPS, Escalab-250Xi, thermal-fisher scientific corp, USA). The current-density–voltage (J–V) characteristics of the a-Si:H solar cells were measured at 25 °C under 1 sun (AM 1.5, $100\ mW/cm^{-1}$) illumination by a dual-lamp solar simulator (WXS-156S-L2, AM 1.5 GMM, Wacom Electric, Japan). The external quantum efficiency (EQE) spectra were obtained with a photovoltaic measurement system (QEX10, PV Measurements, USA).

3. Results and discussion

When a p-type silicon film is used as the window layer, it must have a wide bandgap to reduce parasitic absorption and enhance the spectral response of the a-Si:H solar cell (Li et al., 2013). Fig. 2(a) clearly shows

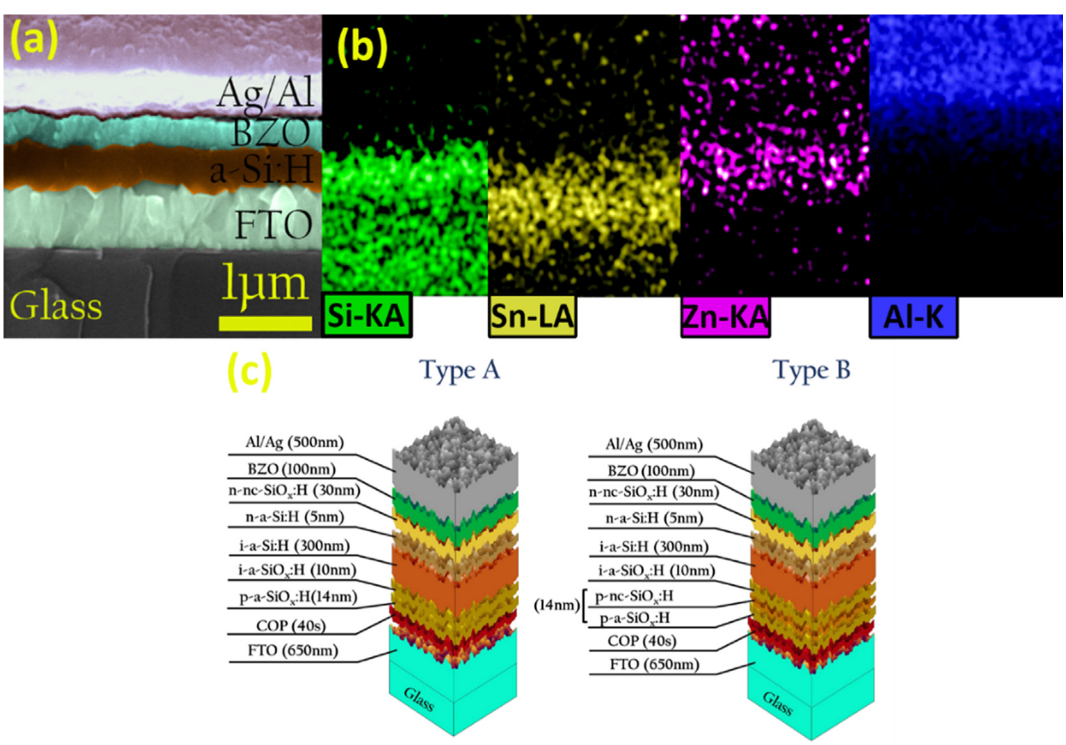

Fig. 1. (a) SEM image and (b) EDX mappings of an a-Si:H solar cell with dual p-layers (p-a-SiO_x:H/p-nc-SiO_x:H) as the window layer. (c) Schematic drawing of type-A and type-B structures of a-Si:H solar cells with a single p-layer (p-a-SiO_x:H) and dual p-layers (p-a-SiO_x:H/p-nc-SiO_x:H), respectively.