Journal of Non-Crystalline Solids 358 (2012) 3243–3247

Contents lists available at SciVerse ScienceDirect

Journal of Non-Crystalline Solids

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

Wide bandgap p-type window layer prepared by trimethylboron doping at high temperature for a-Si:H superstrate solar cell

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ARTICLE INFO

Article history:
Received 8 May 2012
Received in revised form 17 June 2012
Available online 5 October 2012

Keywords:
Wide bandgap window layer;
a-Si:H solar cell;
TMB doping;
PECVD

ABSTRACT

Wide bandgap p-type window layer is necessary for silicon thin film solar cell to obtain excellent performance, such as high open-circuit voltage (V_{OC}), and large short-circuit current density (J_{SC}). Instead of the usually used material, SiC_x:H or SiO_x:H fabricated by incorporating C or O into the Si matrix, and nc-Si:H deposited at a very low temperature, wide bandgap p-type window layer was realized here by doping with trimethylboron (TMB) at a relatively high temperature via plasma enhanced chemical vapor deposition (PECVD). Excellent performance with V_{OC} larger than 900 mV was achieved for p–i–n superstrate solar cell on SnO_2:F coated glass while the p-type window layer was deposited at 200 °C to 250 °C. By investigating the influence of the deposition temperature on the p-layer bandgap and microstructure further, it was found that the compromise between wide bandgap and good quality of the p-layer determined the solar cell performance.

1. Introduction

In order to obtain high open-circuit voltage (V_{OC}) and allow more sunlight to enter the absorber layer, a window layer with wide optical bandgap (E_g) is required for a-Si:H based thin film solar cell. Since the mobility of hole carriers is much smaller than that of electron carriers, the window layer is p-type doped in the current technology [1–3]. For the substrate solar cell, nanocrystalline silicon (nc-Si) is the usual choice for the window layer due to its wide E_g coming from a quantum confinement effect induced by its small crystallite size [4–6]. However, nc-Si needs be prepared with a very high hydrogen dilution (H_2/SiH_4) at a quite low deposition temperature. For example, the condition of $H_2/SiH_4=100$ and the temperature = about 60 °C was utilized in reference [6]. The low temperature fabrication process has little room to be applied for superstrate solar cell, where the p-layer should be deposited firstly and the subsequent layers need to be deposited at a higher temperature about 200 °C. The possible annealing effect may damage the p-layer properties. Alternatively, for superstrate solar cell, the wide E_g is usually obtained by incorporating carbon or oxygen atoms into a-Si:H to form a-SiC_x:H or a-SiO_x:H [7–12]. But the incorporation of carbon or oxygen atoms into the film may induce more disordered structural defects, which will limit the further improvement of the solar cell performance. Obviously, for the p-type window layer of the superstrate solar cell, it will be better if the wide E_g can be realized without other atom addition and can be obtained at a relatively high deposition temperature compatible with the subsequent processes.

Currently, trimethylboron (TMB) is being paid much attention as a better alternative to diborane for the p-layer doping [13–15]. TMB has a superior thermal stability than diborane, and does not decompose into elementary boron in hot zones without plasma contact. And TMB is much less hazardous. More advantageously, one can obtain films with higher E_g by TMB than by diborane, without reducing the electrical conductivity [15]. So, it may be possible to develop a suitable process to obtain wide bandgap p-type window layer at an expected high temperature with TMB doping.

Here, p–i–n superstrate solar cells were fabricated on SnO_2:F coated glasses by plasma enhanced chemical vapor deposition (PECVD). The p-type window layer was prepared by TMB doping. The influence of the p-layer deposition temperature on the solar cell performance was investigated carefully. As a result, excellent solar cell performance with $V_{OC}>900$ mV was obtained in a wide temperature range from 200 °C to 250 °C. Transmission, Raman, and Fourier transform infrared (FTIR) spectra investigations were carried out in detail to reveal the underlying mechanisms.

2. Experimental

The p–i–n superstrate solar cells were fabricated on SnO_2:F coated glasses in a multi-chamber capacitance-coupled RF-PECVD system. The three layers of p, i, n were deposited in different chambers

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http://dx.doi.org/10.1016/j.jnoncrysol.2012.07.040

separately with the optimized $H_2/SiH_4 = 20$. For n-layer and p-layer, the doping was realized by introducing phosphine (PH_3) and TMB, respectively. Finally, aluminum was thermally evaporated directly on n-layer as the back contact. A series of solar cells was fabricated with the deposition temperature of p-layer increased from 100 °C to 400 °C. Further, some representative single p-layers were deposited on quartz and c-Si substrates to check the corresponding E_g, microstructure, and electrical conductivity.

Light current density–voltage (*J*–*V*) characteristics of the solar cells were measured under the illumination of an AM1.5 solar simulator from Newport Corporation. External quantum efficiency (EQE) of the solar cells and transmission spectra of the single layers on quartz substrates were measured via a Spectral Response/QE/IPCE system from PV measurements, Inc. Then E_g was calculated from the obtained transmission spectra by Tauc plot method. Further, Raman or FTIR spectroscopy was utilized for the layers deposited on quartz or c-Si substrates to reveal the layer microstructure. Raman measurement was carried out on a LabRAM HR system from HORIBA Scientific, operating at a wavelength of 488 nm. And FTIR measurement was taken on a Varian 3100 Excalibur system. At last, the dark conductivity of the p-layers was measured by the coplanar electrode method.

3. Results

3.1. Performance of the p–i–n a-Si:H superstrate solar cells

As shown in Fig. 1, the p-layer deposition temperature had a great impact on the solar cell performance. With the deposition temperature increased from 100 °C to 360 °C, the solar cell V_{OC} and fill factor (*FF*) increased firstly, then decreased gradually, whereas the short-circuit current density (J_{SC}) decreased monotonously. As a result, the best conversion efficiency (η) was achieved at a moderate temperature of about 220 °C. And excellent solar cells with V_{OC} > 900 mV could be obtained in a wide temperature range from 200 °C to 250 °C. Such results were attractive for the fabrication of the p–i–n superstrate solar cells. The EQE curves in Fig. 2 show that the solar cell spectral response in the short wavelength range decreased gradually when the p-layer deposition temperature increased.

3.2. Optical bandgap (E_g) and microstructure of the single p-layers

In Fig. 3, five different temperatures were selected for the single p-layer deposition. Transmission spectra of the deposited layers on double-polished quartz substrates were shown in Fig. 3(a). From the transmission spectra, E_g was calculated by the Tauc plot method. The calculation details could be found in references [16,17]. The obtained E_g of the prepared layers was given in Fig. 3(b). As the deposition temperature increased, the p-layer E_g decreased monotonously. When the deposition temperature was as low as 100 °C, E_g was about 1.93 eV. Even when the deposition temperature increased from 200 °C to 250 °C, E_g was still in the range of 1.8–1.9 eV. Fig. 3(b) also presented the p-layer growth rate as a function of the deposition temperature. Clearly, a high deposition temperature accelerated the p-layer growth.

Raman spectroscopy was utilized to check the microstructure of the deposited p-layers. Generally, Si thin film is a mixture material of amorphous phase, crystalline phase, and interface phase. In Raman spectrum, for amorphous phase and crystalline phase, the Si–Si TO phonon mode occurs at about 480 cm^{-1} and 520 cm^{-1}, respectively. The corresponding mode of interface phase exits between the above two positions. The specific Raman spectrum is the scattering sum of the above three phases and thus can be resolved into three Gaussian curves. The structure of the silicon thin film can be deduced by the positions and intensities of the corresponding three Gaussian peaks [18]. Fig. 4 gave out Raman spectra of our deposited p-layers. The deconvolution by Gaussian fitting for the spectra illustrated that all the layers were mainly composed of an amorphous phase.

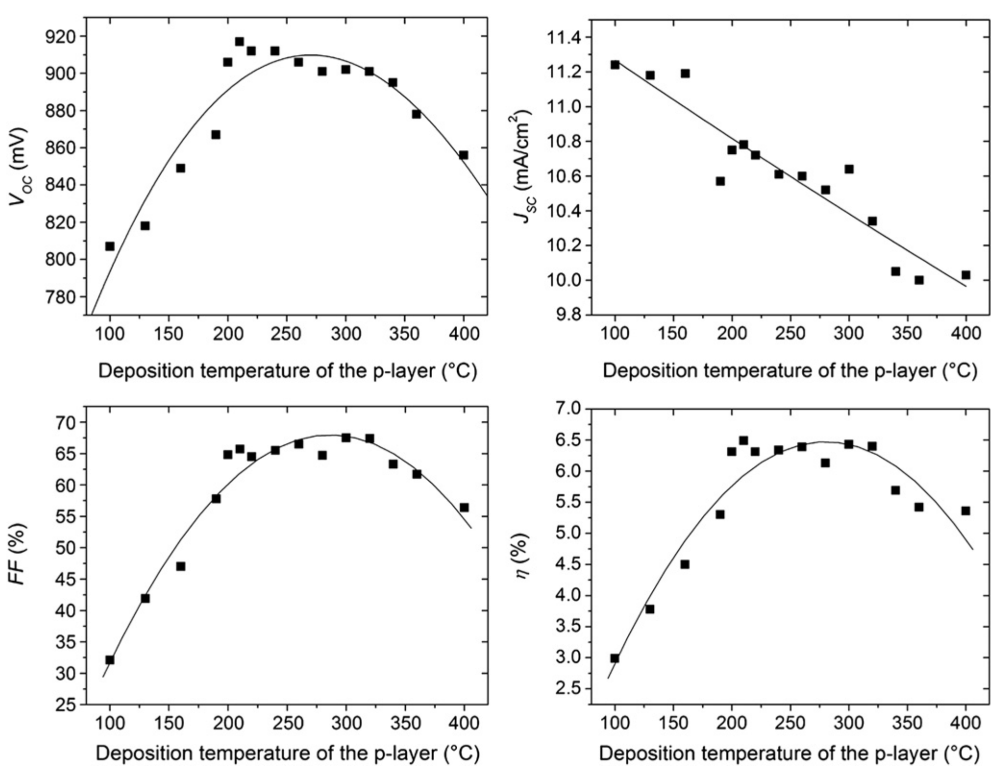

Fig. 1. The p–i–n a-Si:H superstrate solar cell performance as a function of the p-layer deposition temperature, where, V_{OC} was the open-circuit voltage, J_{SC} was the short-circuit current density, *FF* was the fill factor, and η was the conversion efficiency. The solid lines were guides to the eye.