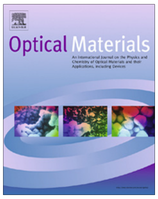
Optical Materials 51 (2016) 245–249

Contents lists available at ScienceDirect

Optical Materials

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



Band gap profiles of intrinsic amorphous silicon germanium films and their application to amorphous silicon germanium heterojunction solar cells

Taweewat Krajangsang *, Sorapong Inthisang, Adrien Dousse, Apichan Moollakorn, Aswin Hongsingthong, Songkiate Kittisontirak, Perawut Chinnavornrungsee, Amornrat Limmanee, Jaran Sritharathikhun, Kobsak Sriprapha

Solar Energy Technology Laboratory (STL), National Electronics and Computer Technology Center (NECTEC), National Science and Technology Development Agency (NSTDA), 112 Thailand Science Park, Phahonyothin Rd., Klong 1, Klong Luang, Pathumthani 12120, Thailand

ARTICLE INFO

Article history:
Received 17 October 2015
Received in revised form 6 November 2015
Accepted 7 November 2015
Available online 11 November 2015

Keywords:
Amorphous germanium silicon
Band gap profile
Amorphous germanium silicon heterojunction solar cell

ABSTRACT

Intrinsic amorphous silicon germanium (i-a-SiGe:H) films with V, U and VU shape band gap profiles for amorphous silicon germanium (a-SiGe:H) heterojunction solar cells were fabricated. The band gap profiles of i-a-SiGe:H were prepared by varying the GeH_4 and H_2 flow rates during the deposition process. The use of i-a-SiGe:H with band gap profile in an absorber layer for a-SiGe:H heterojunction solar cells was investigated. The solar cell using a VU shape band gap profile shows a higher efficiency compared to other shapes. The highest efficiency obtained for an a-SiGe:H heterojunction solar cell using the VU shape band gap profile technique was 9.4% (V_{oc} = 0.79 V, J_{sc} = 19.0 mA/cm^2 and FF = 0.63).

1. Introduction

At present, renewable energy technologies, solar cell in particular, are becoming one of the most promising sources of clean energy. Typically photovoltaic (PV) solar panels can be categorized into two categories: thin films and wafer based crystalline silicon (c-Si). In the case of thin film solar cells, the technology is either based on Cadmium Telluride (CdTe), Copper Indium Gallium (di) Selenide (CIGS) or amorphous silicon (a-Si:H) materials. The multi-junction silicon-based thin film solar cells are attractive candidates for their low cost to high performance ratio (PR) [1–4]. The development of thin film silicon solar cells which are suitable for their in tropical zones has been reported by our group [5–7]. The hydrogenated amorphous silicon germanium alloy (a-SiGe:H) is a promising material for thin film silicon solar cells [8,9]. The optimization of single-junction amorphous silicon germanium (a-SiGe:H) solar cells is necessary to obtain higher efficiencies in amorphous silicon/amorphous silicon germanium (a-Si:H/a-SiGe:H), amorphous silicon/amorphous silicon germanium/microcrystalline silicon (a-Si:H/a-SiGe:H/μc-Si:H) or amorphous silicon/amorphous silicon germanium/amorphous silicon germanium (a-Si:H/a-SiGe:H/a-SiGe:H) double and triple-junction solar cells. Generally, the narrow band gap a-SiGe:H film is used as the absorber layer for the middle cell or bottom cell in multi-junction silicon thin film solar cells [10–15]. The narrow band gap of a-SiGe:H can enhance the spectral response in the long wavelength region and the conversion efficiency of tandem cells [16–18]. However, in obtaining a narrow band gap in a-SiGe:H material, the defect density will increase following the increase of germanium content during film deposition [19–20]. Normally, the properties of a-SiGe:H can be improved depending on the processing conditions, such as the ratio of precursor gases, the generator frequency, the power density, the deposition pressure, the annealing process and the band gap profile [21–25]. As mentioned above, the band gap profile technique can significantly improve the conversion efficiency of the a-SiGe:H solar cells [26–29], and also positively influence the defect density particularly in absorber layer, and at the *p*/*i* and *i*/*n* interface region of solar cell [30–32]. The band gap of a-SiGe:H can be controlled by the variation of germanium concentration using several techniques [33–36]. The V, U and E shape have been developed to enhance solar cell efficiencies [37–40]. It has been reported that the V and U shape show improvement in the open-circuit voltage (V_{oc}) and the fill factor (FF) while the E shape can improve the current density (J_{sc}) [16].

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* Corresponding author.
E-mail address: taweewat.krajangsang@nectec.or.th (T. Krajangsang).

http://dx.doi.org/10.1016/j.optmat.2015.11.012
0925-3467/

In this paper, we present our experimental study to improve the properties of i-a-SiGe:H films using the VU shape band gap profile technique as well as investigate the effect of the VU shape band gap in a-SiGe:H i-layer on the performance of a-SiGe:H heterojunction solar cells.

2. Experimental details

The i-a-SiGe:H films with V, U and VU band gap profile shapes were deposited on Soda-lime glass substrates by 27 MHz very high frequency plasma enhanced chemical vapor deposition (VHF-PECVD) in multi-chamber with a parallel plate configuration. The base vacuum pressure in the deposition chamber was on the order of 10^{-6} Torr using a turbo molecular pump backed up with rotary pumps. We used silane (SiH_4), hydrogen (H_2) and germane (GeH_4) as reactant gases. The band gap profile of the i-a-SiGe:H was prepared by continuously varying the GeH_4 and H_2 flow rate in order to keep the total gas volume during the deposition process the same, meanwhile the flow rate of SiH_4 was fixed. The intrinsic amorphous silicon (i-a-Si:H) films were deposited using SiH_4 and H_2 gases. The substrate temperature, pressure and power density for i-a-SiGe:H and i-a-Si:H films deposition were kept at 200 °C, 500 m Torr and 12.5 mW/cm^2 respectively. The total thickness of i-a-SiGe:H and i-a-Si:H films was maintained at 300 nm. The details of film deposition condition are shown in Table 1. The optical band gaps (E_{opt}) and film thicknesses were measured by spectroscopic ellipsometry (J.A. Woollam, V-VASE series). The measurement data was analyzed using the Tauc–Lorentz model. The dark conductivity (σ_d) and photo conductivity (σ_{ph}) were measured with aluminum (Al) coplanar electrode configuration. The σ_{ph} was measured under standard conditions of 1 sun (100 mW/cm^2), with air mass (AM) 1.5 using a double light source and the filter of a solar simulator.

The a-SiGe:H heterojunction solar cells were fabricated on transparent conductive oxide of Asahi U-type coated glass substrate. The *p*-type hydrogenated microcrystalline silicon oxide (*p*-μc-SiO:H) window layer was doped by 3%-hydrogen-diluted trimethylboron (TMB: $B(CH_3)_3$) and prepared by 40 MHz VHF-PECVD with a power density of 83 mW/cm^2. The *n*-type hydrogenated microcrystalline silicon (*n*-μc-Si:H) was doped by 3%-hydrogen-diluted phosphine (PH_3), and prepared by 60 MHz VHF-PECVD with a power density of 67 mW/cm^2. The a-SiGe:H heterojunction solar cells had a structure of glass/SnO_2/ZnO:Al/*p*-μc-SiO:H (35 nm)/i-a-SiGe:H (300 nm)/*n*-μc-Si:H (35 nm)/ZnO:Al/Ag. The schematic diagram of the a-SiGe:H heterojunction solar cells is shown in Fig. 1. The active area of the solar cells was divided by laser scribing into 1 cm^2 surface areas. The photovoltaic parameters of the solar cells have been investigated under standard conditions (AM 1.5, 100 mW/cm^2 and 25 °C) with a double light source solar simulator. The quantum efficiency (QE) of the solar cells has been characterized by spectral response measurements.

Table 1
Deposition conditions for i-a-SiGe:H films.

Parameters	Value
Gas flow	
SiH_4	7.5 sccm
H_2	32–44 sccm
GeH_4	0.8–15 sccm
Power density	12.5 mW/cm^2
Deposition pressure	500 m Torr
Substrate temperature	25 °C

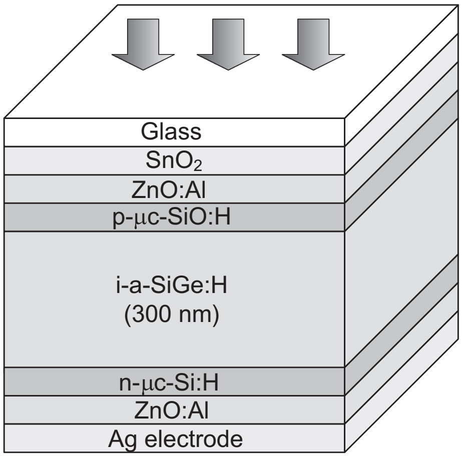

Fig. 1. Schematic diagram of thin film a-SiGe:H heterojunction solar cells.

3. Results and discussions

3.1. Properties of a-SiGe:H films

The optical and electrical properties of i-a-Si:H and i-a-SiGe:H films were investigated. Firstly, i-a-Si:H and i-a-SiGe:H films without band gap profiles were deposited to evaluate the bandgap to GeH_4/SiH_4 ratio dependence and subsequently define the band gap profile shapes in the a-SiGe:H i-layer. Fig. 2 shows a plot of the optical band gap with various profiles. The experimental results show that the optical band gap of i-a-Si:H films at *p*/*i* and *i*/*n* interface had a value of 1.73 eV. Meanwhile, the i-a-SiGe:H (1,2) films which refer to the narrowest band gap point used a GeH_4/SiH_4 ratio of 2.63. The optical band gaps of the i-a-SiGe:H (1,2) films were 1.55 eV. The i-a-SiGe:H (3) film referred to the bend up point of the VU shape, which used a GeH_4/SiH_4 ratio of 1.97 shows an optical band gap of 1.58 eV. After that the i-a-SiGe:H films were deposited grading the band gap using the V, U and VU shapes. Fig. 3 shows the dependence of the optical bandgap for the band gap profile in i-a-SiGe:H films. The i-a-SiGe:H films with the V, U and VU band gap profile shapes had an optical band gap of 1.63 eV, 1.57 eV and 1.60 eV respectively. For comparison, absorption spectra of i-a-Si:H and i-a-SiGe:H with band gap profile measured by Spectroscopic ellipsometry are shown in Fig. 4. In the case of i-a-SiGe:H material, the optical absorption edge was shifted toward lower photon

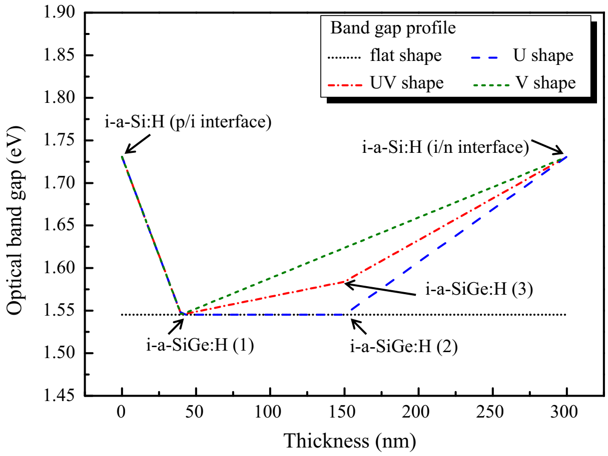

Fig. 2. Plot of the optical band gap profile for the i-a-SiGe:H films. The dash lines are guides to the eye.