Thin Solid Films 569 (2014) 64–69

Contents lists available at ScienceDirect

Thin Solid Films

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

Characterization of a-Si:H thin layers incorporated into textured a-Si:H/c-Si solar cell structures by spectroscopic ellipsometry using a tilt-angle optical configuration

Yoshikazu Tanaka, Nobuyuki Matsuki, Hiroyuki Fujiwara *

Center of Innovative Photovoltaic Systems (CIPS), Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan

A R T I C L E I N F O

Article history:
Received 16 May 2014
Received in revised form 24 August 2014
Accepted 28 August 2014
Available online 6 September 2014

Keywords:
Spectroscopic ellipsometry
Tilt angle configuration
a-Si:H
Textured structure
Solar cell

A B S T R A C T

Hydrogenated amorphous silicon (a-Si:H) layers formed on pyramid-shaped crystalline silicon (c-Si) textured substrates have been characterized by spectroscopic ellipsometry (SE). In particular, for the high-precision determination of textured a-Si:H/c-Si solar cell structures, the SE measurements were performed using a tilt-angle optical configuration, combined with a high-intensity Xe light source. To study the effect of the c-Si texture on a-Si:H layer properties, we have evaluated various a-Si:H layers formed on the different micrometer-scale rough textures (4–24 μm). From the SE analysis that uses the a-Si:H local network model for dielectric function calculation, we have determined the SiH_2 content and growth rate of quite thin a-Si:H layers (<100 Å) formed on the c-Si textures. The SE analysis revealed that the growth rate and SiH_2 content are independent of the pyramid size of the c-Si textures. Nevertheless, the SiH_2 content in the a-Si:H formed on the c-Si textures is smaller by ~3 at.%, compared with the a-Si:H layer on a flat c-Si substrate, due to a slower a-Si:H growth rate observed on the texture substrates. When the texture size is small (<10 μm), on the other hand, the conventional analysis of the (ψ, Δ) ellipsometry spectra becomes difficult and only the growth rate was determined by using an analysis scheme in which the modified Stokes parameters are analyzed. As a result, we have confirmed that the effect of the c-Si pyramid size on the a-Si:H layer is negligible in a-Si:H/c-Si solar cells.

1. Introduction

The conversion efficiency of solar cells consisting of crystalline silicon (c-Si) and hydrogenated amorphous silicon (a-Si:H) heterojunction has reached 24.7% with the highest open-circuit voltage (V_{oc} = 750 mV) among c-Si-based solar cells [1]. Compared with c-Si p–n junction solar cells, the a-Si:H/c-Si solar cell shows a lower temperature coefficient for the efficiency reduction at higher operating temperatures [2–4] and can be considered as one of the most promising solar cells particularly in warmer regions. The high V_{oc} and low temperature coefficient are realized only when the ideal a-Si:H/c-Si heterojunction is formed [2,4] and thus the control of the a-Si:H layer on c-Si is crucial in a-Si:H/c-Si solar cells.

Nevertheless, to suppress the parasitic light absorption in the a-Si:H/c-Si solar cells, quite thin a-Si:H p–i layers with a thickness of ~50 Å have been incorporated [5,6]. Moreover, to reduce the front light reflection in the a-Si:H/c-Si structure, pyramid-type c-Si textures with the {111} facets are commonly employed in high-efficiency a-Si:H/c-Si solar cells [6–11]. In general, this c-Si texture fabricated by alkaline etching of Si(100) substrates has a dimension of ~10 μm [8,10,11]. In a-Si:H/c-Si solar cells, therefore, quite thin a-Si:H layers (<100 Å) are formed on the large c-Si textures and the characterization of a-Si:H/c-Si structures is rather difficult.

When the c-Si texture is adopted in the fabrication of a-Si:H/c-Si solar cells, the short-circuit current (J_{sc}) in the solar cell improves by ~15% [6,7,9]. In this case, however, the V_{oc} value often shows a severe reduction due to the formation of a non-ideal a-Si:H/c-Si heterointerface. In particular, the partial epitaxial growth of intended a-Si:H layers has been reported to occur at the valley position of the c-Si pyramid structure, which in turn deteriorates V_{oc} and fill factor of the solar cell [9]. To improve the performance of textured a-Si:H/c-Si solar cells, isotropic wet etching for the c-Si pyramid textures has been performed [10,11]. At this stage, however, the effect of the c-Si texture size on the a-Si:H/c-Si solar cell is rather ambiguous; Fesquet et al. reported the improvement of the carrier lifetime with increasing texture size [10], whereas a shorter carrier lifetime has also been observed for larger c-Si textures [11]. Accordingly, the characterization of a-Si:H layers formed on the different textures is quite important for the understanding of the texture effect on the solar cell.

For the evaluation of textured a-Si:H/c-Si structures, on the other hand, spectroscopic ellipsometry (SE) in a tilt-angle optical configuration provides an ideal tool [12–14]. In this SE measurement, the

* Corresponding author at: Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan. Tel.: +81 58 293 2691; fax: +81 293 2689.
E-mail address: fujiwara@gifu-u.ac.jp (H. Fujiwara).

http://dx.doi.org/10.1016/j.tsf.2014.08.039

textured samples are tilted so that the specular light reflection on the c-Si {111} facets is measured. By using this configuration, nanometer-scale a-Si:H layers on the c-Si textures have been characterized assuming a flat optical model in the SE analysis [13,14]. Moreover, we have previously developed an a-Si:H dielectric function model that can be used to express the network structure of various a-Si:H layers [15,16]. This a-Si:H network model is based on the finding that microvoids present in the a-Si:H network are surrounded by the SiH_2 bonding state and the amplitude of the a-Si:H ε_2 spectrum in the ultraviolet/visible region shows almost perfect correlation with the SiH_2 content in the a-Si:H matrix [15]. When this a-Si:H model is applied for the SE measurements in the tilt angle configuration, the SiH_2 density in thin a-Si:H layers formed on the textured c-Si slope can be determined [14]. In our previous study, however, only a-Si:H layers deposited on large c-Si textures (~30 μm) were measured [14], as there was difficulty in characterizing the a-Si:H/c-Si structures with smaller size textures due to low reflection light intensities.

In this study, we have performed the SE measurements of various a-Si:H/c-Si structures formed on different c-Si textures with sizes ranging from 4 to 24 μm using a high-intensity Xe source in the tilt angle configuration. By applying the a-Si:H network model, the SiH_2 contents in quite thin a-Si:H layers (<100 Å) deposited on the c-Si {111} facets have been determined. Furthermore, we have established a SE data analysis method for small textured substrates (<10 μm). As a result, we found that the a-Si:H properties are independent of the texture size, although the quality of the a-Si:H layers on the pyramid-type textures is higher than that on flat substrates due to a lower a-Si:H growth rate observed on the textured substrates.

2. Experiment

We prepared pyramid-type c-Si textures by alkaline etching of n-type Si(100) substrates using different etching solutions and process conditions to control the texture size in a wide range from 4 to 24 μm. Fig. 1 shows the scanning electron microscope (SEM) images of the textured c-Si substrates with average texture size (A_{tex}) values of (a) 4 μm, (b) 8 μm, (c) 10 μm, and (d) 18 μm. The A_{tex} values were estimated simply from $A_{tex} = \sum A_j/n$, where A_j and n denote the size and total number of the pyramid-type textures observed in the SEM measurement of a selected area. In this calculation, the contribution of the small pyramids formed at the valley position has been neglected. It can be seen from Fig. 1 that the inhomogeneity of the texture size increases slightly as the texture size reduces.

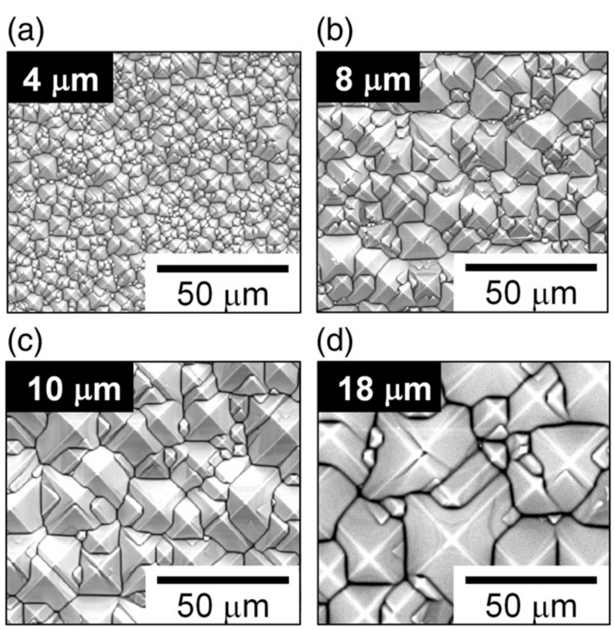

Fig. 1. SEM images of textured c-Si substrates with average texture sizes of (a) 4 μm, (b) 8 μm, (c) 10 μm, and (d) 18 μm.

On the textured c-Si substrates, thin a-Si:H i layers with a thickness of ~80 Å were deposited by a conventional rf plasma-enhanced chemical vapor deposition (PECVD) system [17]. Before the a-Si:H deposition, the native oxide layers on the textured c-Si substrates were removed by dipping the samples into a 5% HF solution for 1 min. The a-Si:H deposition was carried out using a SiH_4 flow of 5 sccm, a pressure of 6.7 Pa and an rf power density of 13 mW/cm^2. To suppress the epitaxial growth on the c-Si substrates [18], a low deposition temperature of 110 °C was used.

3. SE measurement and analysis

The SE measurements were performed by a rotating-compensator instrument [19] (J. A. Woollam, M-2000). Fig. 2 shows the SE measurement in the tilt angle configuration used for the textured a-Si:H/c-Si characterization. Our SE system has the components of external light source/incident unit/sample/detector unit. The external light source is a Xenon lamp of 140 W (Hamamatsu, L9588-04) and the light is introduced into the incident unit through the optical fiber and collimator lens. The incident unit mainly consists of a polarizer and rotating compensator, whereas the optical analyzer is placed inside the detector unit. The light intensity in the detector unit is measured by a multichannel light detector. In our measurement, the spot size of SE is 2 mm in diameter.

In the tilt-angle optical configuration, unlike normal SE measurements, samples are tilted with the tilt angle θ_t so that the flat surface of the c-Si {111} facets becomes normal to the incident plane. In this tilt angle measurement, however, the intensity of the reflected light is significantly low, compared with the case of flat substrates. To maximize the reflection light intensity from the c-Si textures, we have applied i) a high intensity Xenon lamp, ii) a small incident angle (θ_i) of 40° (normally ~75° for c-Si), and iii) a short distance between the sample and detector unit. For the accurate SE measurement using the tilt angle configuration, the precise adjustment of θ_t and the rotation angle ϕ in Fig. 2 is essential. The sample alignment for θ_t and ϕ can be performed relatively easily by simply maximizing the reflection light intensity [14]. It should be mentioned that the top angle of the c-Si pyramid estimated from the measured θ_t value using $2(90 - \theta_t)$ is ~80° (see Fig. 3) and deviates from the ideal value (70.4°) defined by

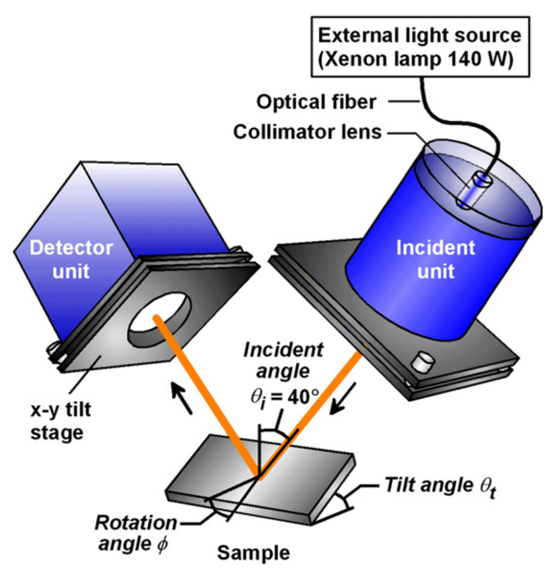

Fig. 2. SE measurement in the tilt angle configuration used for the textured a-Si:H/c-Si characterization.