Solar Energy Materials & Solar Cells 93 (2009) 980–983

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Solar cell of 6.3% efficiency employing high deposition rate (8 nm/s) microcrystalline silicon photovoltaic layer

Yasushi Sobajima *, Mitsutoshi Nishino, Taiga Fukumori, Masanori Kurihara, Takuya Higuchi, Shinya Nakano, Toshihiko Toyama, Hiroaki Okamoto

Department of Systems Innovation, Graduate School of Engineering Science, Osaka University, Toyonaka, Machikaneyama-cho 1-3, Osaka 560-8531, Japan

ARTICLE INFO

Article history:
Received 14 January 2008
Accepted 21 November 2008
Available online 6 January 2009

Keywords:
Microcrystalline silicon
High growth rate
VHF-PECVD
Solar cell
high-pressure depletion

ABSTRACT

Microcrystalline silicon (μc-Si) films deposited at high growth rates up to 8.1 nm/s prepared by very-high-frequency-plasma-enhanced chemical vapor deposition (VHF-PECVD) at 18–24 Torr have been investigated. The relation between the deposition rates and input power revealed the depletion of silane. Under high-pressure deposition (HPD) conditions, the structural properties were improved. Furthermore, applying μc-Si to n–i–p solar cells, short-circuit current density (J_{SC}) was increased in accordance with the improvement of microstructure of i-layer. As a result, a conversion efficiency of 6.30% has been achieved employing the i-layer deposited at 8.1 nm/s under the HPD conditions.

1. Introduction

Microcrystalline silicon (μc-Si) prepared by plasma-enhanced chemical vapor deposition (PECVD) at a low temperature (∼200 °C) is a promising material for thin film solar cells because of low-cost and stability against light illumination [1]. The μc-Si photovoltaic i-layer is usually relatively thick (1–3 μm) because of its low optical absorption coefficient for the sunlight in long wavelengths. Therefore, for achieving a short production time, or for industrializing the solar cell, developing a high-rate-deposition technique is of great importance. To date, various deposition techniques have been demonstrated [1]. Among them, the device-grade μc-Si deposited at 2 nm/s has been obtained by PECVD methods with very-high-frequency (VHF) excitations [2–7]. Specifically, the deposition at high pressures with high input powers is effective in increasing the growth rate by keeping the low defect density because the high electron density and the low electron temperature can be simultaneously obtained [4]. In our previous study, we have demonstrated very high growth rates of device-grade μc-Si photovoltaic layers employing high pressures of up to 24 Torr [6]. Moreover, applying the μc-Si deposited at 7.1 nm/s to the photovoltaic layer of n–i–p structure solar cell, a high-conversion efficiency of 5.10% has been achieved [6].

However, a programmatic tendency is currently found, i.e., with increasing film growth rate, the conversion efficiency drops when the deposition rate exceeds around 3 nm/s [2–7]. In order to improve the conversion efficiency at the high growth rate, fundamental material properties of the high-growth-rate μc-Si photovoltaic i-layer should be required. Therefore, the relationship between the deposition condition and the microstructure of the high-growth-rate μc-Si should be studied in detail. The analysis of the relationship between the microstructure and the photovoltaic performance is also needed for the improvement of photovoltaic performance regarding the solar cells using the high-growth-rate μc-Si photovoltaic i-layer.

In this article, we discuss the effects of input powers for the μc-Si deposition at high-pressure deposition (HPD) conditions using VHF-PECVD. We also discuss the correlation between structural properties of the μc-Si photovoltaic i-layer and the photovoltaic performance, especially the open-circuit voltage (V_{OC}) and the short-circuit current density (J_{SC}). Finally, we describe a result on the μc-Si solar cell using 8.1 nm/s photovoltaic i-layer.

2. Experiment

Undoped μc-Si films were deposited on glass substrates (Corning 1737F) by capacitively coupled VHF (100 MHz) PECVD with conventional parallel-plate electrodes at 180 °C using a SiH_4/H_2 gas mixture [6,8–10]. The gas purifiers were set just before the

* Corresponding author. Tel.: +81 6 6850 6317; fax: +81 6 6850 6316.
E-mail addresses: sobajima@semi.ee.es.osaka-u.ac.jp (Y. Sobajima), nishino@semi.ee.es.osaka-u.ac.jp (M. Nishino), fukumori@semi.ee.es.osaka-u.ac.jp (T. Fukumori), kurihara@semi.ee.es.osaka-u.ac.jp (M. Kurihara), higuchi@semi.ee.es.osaka-u.ac.jp (T. Higuchi), nakano@semi.ee.es.osaka-u.ac.jp (S. Nakano), toyama@ee.es.osaka-u.ac.jp (T. Toyama), okamoto@ee.es.osaka-u.ac.jp (H. Okamoto).

0927-0248/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.solmat.2008.11.042

mass flow controllers. The SiH_4 concentration ($[SiH_4]/([SiH_4]+[H_2])$) was fixed at 1.5%. The input powers were varied in the range 0.94–2.8 W/cm^2. The deposition pressure was increased from 18 to 24 Torr, accompanied by an increase in the total gas flow rate from 667 to 800 sccm. The electrode gap was 4 mm. The structure of solar cell was glass/textured ZnO:Al/Ag/ZnO:Al/n–i–p/ZnO:Al/Ag grid. The i-layer thicknesses were in the range 2.1–2.5 μm. Details of the fabrication conditions of solar cells are described elsewhere [6]. The active area of solar cells was 0.23 cm^2.

The θ–2θ X-ray diffraction (XRD) measurements with the Cu $K_{\alpha1}$ line (Rigaku RINT-2200) were carried out for deriving the degree of (2 2 0) preferential orientation, $I_{(220)}/I_{(111)}$, where $I_{(hkl)}$ denotes the integrated intensity of the (hkl) phase, as the figure of merit for the μc-Si i-layers. The randomly oriented polycrystalline Si powder showed $I_{(220)}/I_{(111)}=0.67$. Employing the Si–TO phonon Raman spectrum, the crystalline volume fraction, X_C, was roughly estimated as $I_c/(I_c+I_a)$, where I_c and I_a denote the integrated intensities of spectral components at around 520 and 480 cm^{-1}, respectively [8–10]. A Raman system with 514.5 nm line of Ar$^+$ ion laser was used (Ranishaw System 1000). The $\theta-2\theta$ XRD and Raman spectrum measurements were performed on μc-Si deposited on the glass substrate.

As a characteristic value of the below-gap absorption, the optical absorption coefficient at 0.8 eV ($a_{0.8}$) was evaluated by the ac constant photocurrent method (ac-CPM). The ac-CPM was performed below 2.0 eV. Aluminium coplanar electrodes with a gap of 0.2 mm were used. The dc electric field of 2.5 kV/cm was applied. In order to suppress the light trapping effects, the thickness of μc-Si was set to be relatively thin of 1.5 μm.

The photovoltaic performance was evaluated from the current–voltage (I–V) measurement under the air mass 1.5 illumination (100 mW/cm^2). Spectral responses were measured using the lock-in detection system.

3. Results and discussion

Fig. 1(a) shows the deposition rates of μc-Si as a function of input power at deposition pressures 18 and 24 Torr. At 18 Torr, with increasing input power, the deposition rate increases, and then slightly decreases. The decreasing behavior shown in Fig. 1(a) is in good agreement with the tendencies at a low deposition pressure condition reported by Fukawa et al. [11]. The decrease in the deposition rate indicates that silane depleted at the μc-Si surface. In other words, the deposition conditions of $\geqslant$1.9 W/cm^2 are in the high-pressure depletion (HPD) region, being appropriate for the deposition of device-grade μc-Si [4]. At 24 Torr, a higher deposition rate of 8.1 nm/s is obtained with a higher input power of 2.8 W/cm^2, which might also be in the HPD region. Unfortunately, a systematic result has not been obtained due to the difficulty of deposition at 24 Torr.

In Figs. 1(b) and (c), the crystalline volume fractions and the degrees of (2 2 0) preferential orientations are plotted as a function of input power, respectively. For the characterization, μc-Si films with a thickness 2.5 μm were used. The μc-Si deposited at $\geqslant$1.9 W/cm^2, or under the HPD conditions shown in Figs. 1(b) and (c) indicates the (2 2 0) preferential orientation and X_C about 50%. The (2 2 0)-oriented μc-Si with an X_C of approximately 50%, or near the amorphous–crystalline phase transition region, is generally suitable for the photovoltaic i-layer [8,10]. Deposited at 24 Torr with a high input power, the μc-Si film showed X_C of ~50% with the (2 2 0) preferential orientation.

Furthermore, it is well known that the μc-Si films with (2 2 0) preferential orientation possess a columnar structure. In our previous study, the cross-sectional transmission electron microscope (TEM) images of the photovoltaic i-layer deposited at

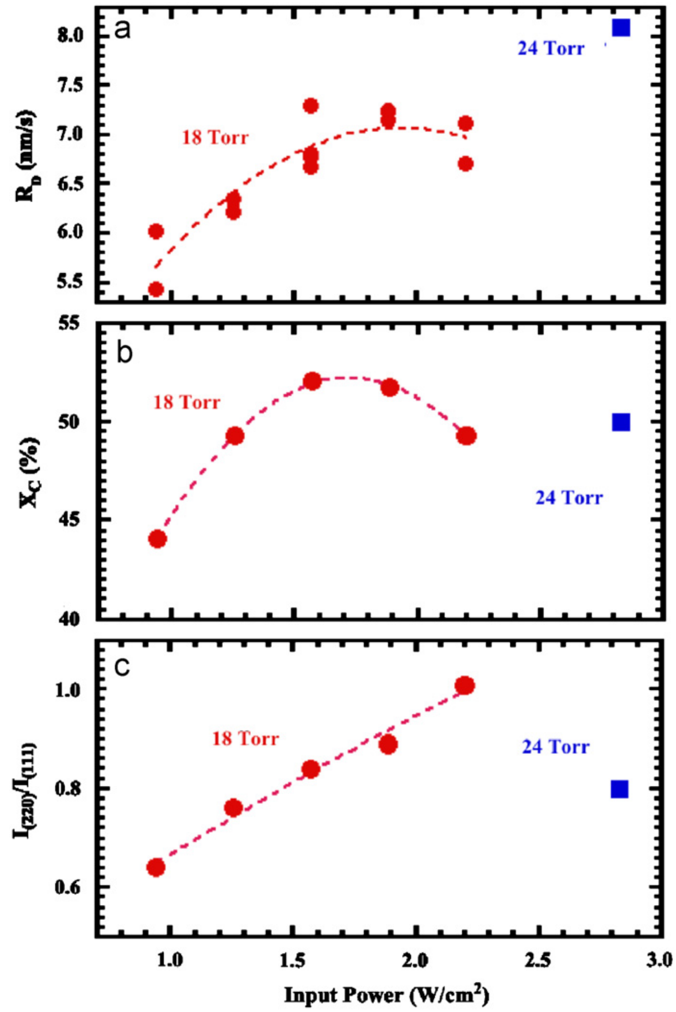

Fig. 1. (a) Deposition rates R_D, (b) crystalline volume fractions X_C, (c) degrees of (2 2 0) preferential orientation $I_{(220)}/I_{(111)}$ of μc-Si plotted against the input powers. The deposition pressures were 18 (●) and 24 (■) Torr, respectively. The dashed lines are guides for the eyes.

7.0 nm/s revealed the dense columnar structure grown directly on the underlying n-layer [12]. From these results, the structural properties are basically in good agreement with those of low-growth-rate μc-Si (<0.5 nm/s) used for a high-efficiency solar cell [13], implying advantages of HPD conditions with high input powers at high deposition pressures for providing the photovoltaic i-layer with a high growth rate of $\geqslant$5 nm/s.

Based on these results, we have applied the high-growth-rate μc-Si films to the n–i–p structure solar cells. In Fig. 2, V_{OC} and J_{SC} are plotted as a function of input power of μc-Si photovoltaic i-layer. V_{OC} has the maximum at 2.2 W/cm^2, i.e., under the HPD conditions. Furthermore, J_{SC} shows a higher value also at $\geqslant$1.9 W/cm^2, in the HPD region.

The below-gap optical absorption usually correlates with the effect of density in the material [14]. The $a_{0.8}$ values of μc-Si deposited at 1.6 and 2.2 W/cm^2 (18 Torr) were estimated as 1.1×10^0 and 6.1×10^{-1} cm^{-1}, respectively, implying a decrease in the defect density with increasing input powers.

Finally, we have achieved the tentative optimum result. Fig. 3 shows an I–V characteristic of μc-Si n–i–p single junction solar cell of which photovoltaic i-layer deposited at 8.1 nm/s (24 Torr, 2.8 W/cm^2). The conversion efficiency of 6.3% (J_{SC}: 22.1 mA/cm^2; V_{OC}: 0.470 V; and FF: 60.7%) has been achieved.