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Influence of boron doping on roughness microcrystalline silicon

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Abstract

We have studied roughness of boron-doped microcrystalline Si (μc-Si) surfaces with an emphasis on the influence of heavy doping. μc-Si films were prepared using plasma-enhanced chemical vapor deposition (PECVD) with different boron concentrations in gas phase from 0% to 2%. Growth-induced roughening of μc-Si surfaces was monitored *ex situ* using an atomic force microscope (AFM). With an increase in the deposition time, the surface width (rms roughness), w, of undoped μc-Si surface exhibited usual behaviors; first, (a) w increased, (b) slightly dropped, (c) rose again, and then (d) gradually increased. In the case of B-doped μc-Si, w differently behaved; (a) w increased very soon, (b) slightly dropped, (a′) rose again, (b′) slightly dropped again, (c) rose, and finally (d) gradually increased. The quick increase in w indicates that boron doping promotes the nucleation, and the repeated nucleation is responsible for the behavior (a′)–(b′). Additionally, the nucleation density, that was derived using the lateral correlation length of surface heights, monotonically increased with an increase in the boron concentration. The effects of boron doping are discussed with the catalytic effects and the formation of the surface-covering layer.

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Keywords: Crystal growth; Nucleation; Plasma deposition; Atomic force and scanning tunneling microscopy

1. Introduction

Boron-doped *p*-type microcrystalline silicon (μc-Si) films have been gathering great attention due to their high conductivity and high transparency being appropriate for the window contact layer of *p–i–n* junction solar cell [1,2]. Various fabrication techniques, such as plasma-enhanced chemical vapor deposition (PECVD) [3–7], hot-wire chemical vapor deposition [8,9], and mercury-sensitized photo chemical vapor deposition [10] have been examined for the fabrication of B-doped μc-Si films with different boron sources, i.e. B_2H_6 [3–8,10], BF_3 [4,7,9], and $B(CH_3)_3$ [4,9]. Among them, the PECVD technique with the B_2H_6 source gas has been widely used.

The crystallinity of μc-Si strongly correlates with the conductivity as well as the Fermi level, which are of considerable importance for the photovoltaic performance, and boron doping usually influences the crystallinity. In the case of extremely heavy doping, deposited films often become amorphous with poor conductivity [6–8]. The critical boron concentration depends on the other conditions such as the substrate temperature and the silane concentration in hydrogen, however the degradation of crystallinity should be commonly observed regardless of the kind of doping gases.

The influence of boron doping on the crystallinity must arise from the film growth kinetics. With regard to undoped μc-Si films, roughness evolutions derived from atomic force microscope (AFM) measurements have been investigated in order to reveal the growth behaviors at the initial growth stage, i.e. the nucleation, coalescence, and grain growth [11–14]. Nevertheless, very little effort but for the intensive study employing real-time spectroscopic ellipsometry [4] has been carried out as for the influence of boron doping.

In this article, we present growth-induced roughening of B-doped μc-Si surfaces centered upon the heavy doping

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regime. Moreover, the influence of boron doping on the nucleation is discussed from the result of the nucleation density deduced using fractal concepts [12–14].

2. Experimental details

Boron-doped and undoped μc-Si films were prepared on Corning 1737F glass substrates using rf (13.56 MHz) PECVD at 200 °C with a mixture of SiH_4, H_2 and B_2H_6 gases. SiH_4 concentration in the total gas flow rate was fixed at 0.58%. The boron concentration was controlled in gas phase; the flow rate ratios of B_2H_6 to SiH_4 ($[B_2H_6]/[SiH_4]$) were varied from 0% to 2%. The deposition pressure was 1.4 Torr, and the rf power was 98 mW/cm^2. The above deposition conditions are basically identical with those for the *p*-layer of a thin-film solar cell [15,16]. The maximum deposition time was determined from the time until the resultant film thickness, which was measured using a stylus profiler (Sloan Dektak3ST), reached about 200 nm. Average deposition rates estimated from the 200-nm-thick films were in the range of 0.01–0.03 nm/s.

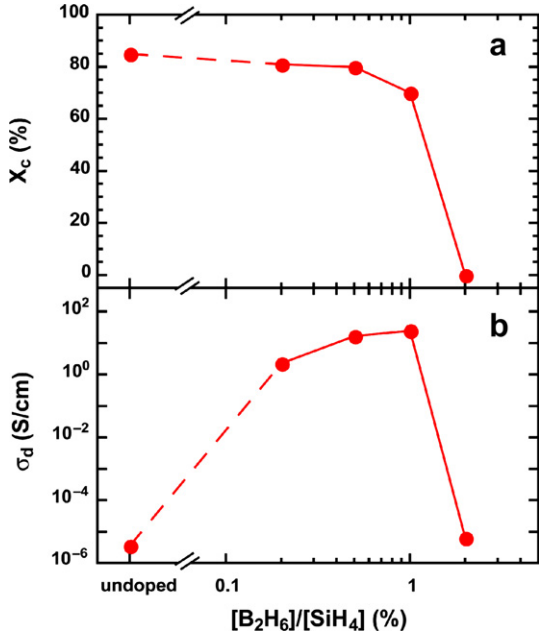

Fig. 1. (a) The crystalline volume fractions X_c and (b) the dark-conductivities σ_d of μc-Si films plotted against $[B_2H_6]/[SiH_4]$. X_c and σ_d were estimated from μc-Si films with a thickness of approx. 200 nm.

The surface widths (rms roughness) of the μc-Si films were obtained from topographic images taken by a AFM system (SII SPA400/SPI3800N) using tapping-contact mode [12–14]. AFM measurements were carried out *ex situ* for a μc-Si film with a certain deposition time prepared on each new substrate. Scan sizes were 1×1–3×3 μm^2; the data points were 256×256. The tip radius of the cantilever was $\leqslant$15 nm. The crystalline volume fraction of μc-Si surface was roughly obtained using a microscopic Raman scattering system equipped with a 514.5 nm Ar^+ ion laser (Renishaw System 1000) [15]. The penetration depth of laser light is within 0.3 μm.

3. Results

Fig. 1 shows (a) the crystalline volume fractions, X_c, and (b) the dark-conductivities, σ_d, of μc-Si films deposited at various boron concentrations. These values were estimated from the μc-Si films with a thickness of approx. 200 nm. At $[B_2H_6]/[SiH_4] \leqslant 1\%$, X_c gradually decreases, while σ_d slightly increases with an increase in $[B_2H_6]/[SiH_4]$. Finally, X_c and σ_d simultaneously drop at $[B_2H_6]/[SiH_4] = 2\%$. These behaviors are qualitatively in good agreement with those against the boron concentration in gas phase reported in the literature [5–9].

AFM surface images of undoped (Fig. 2) and B-doped (Fig. 3) μc-Si films ($[B_2H_6]/[SiH_4] = 1\%$) are displayed as a function of the deposition time. Fig. 4 shows time evolutions of surface roughness derived from the AFM images in Figs. 2 and 3. In Fig. 4, the points labeled A, B, C, D, and E are derived from the corresponding AFM images shown in Fig. 2, and the points in Fig. 4(b) correspond to Fig. 3. Fig. 4(a) revealed that the growth-induced roughness, *w*, of undoped μc-Si surface exhibited usual behaviors; first, (A) *w* increased, (B) slightly dropped, (C) rose again, and then (D), (E) gradually increased. The behaviors are interpreted as roughening owing to (A) the initial nucleation and (B) completing surface coverage by nuclei, and (C)–(E) continuum grain growth [11]. On the other hand, in the case of B-doped μc-Si as displayed in Fig. 4(b), *w* differently behaved; (A) *w* increased, (B) slightly dropped, (C) rose again, (D) slightly dropped again, (E) rose, and finally gradually increased.

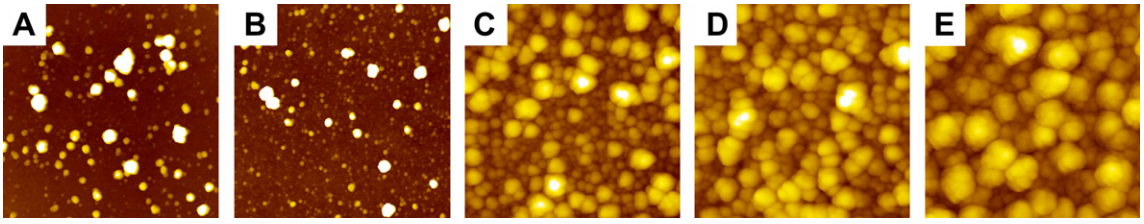

Fig. 2. AFM surface images of undoped μc-Si films deposited at different deposition times [(A) 2216 s, (B) 3324 s, (C) 4432 s, (D) 11080 s, and (E) 16620 s]. The scan size was 1 μm × 1 μm.