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Influence of substrate direct current bias voltage on microcrystalline silicon growth during radio-frequency magnetron sputtering

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Abstract

Hydrogenated microcrystalline silicon (μc-Si:H) thin films were prepared on glass, aluminum-covered glass and Si wafer substrates at various substrate bias voltages (V_{sb}) between –400 and +50 V, and the influence of V_{sb} on their structural properties was investigated. The crystallinity (crystalline volume fraction and crystallite size) of the μc-Si:H films deposited on glass remained unchanged with respect to V_{sb}. For μc-Si:H films deposited on aluminum within the V_{sb} range of –20 to +50 V, the crystallinity also remained unchanged and showed the same crystallinity as that of the films deposited on glass substrate. However, the crystallinity of the μc-Si:H films deposited on aluminum-covered substrate was reduced as V_{sb} decreased from –20 to –100 V, and the film at V_{sb} = –400 V was completely amorphous.
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1. Introduction

Hydrogenated microcrystalline silicon (μc-Si:H) is a material of great interest for large area electronic devices such as solar cells [1] and thin film transistors [2], because of its high carrier mobility [3] and low light-induced degradation [4] compared to hydrogenated amorphous silicon (a-Si:H). Good control over the crystallinity, i.e. crystallite size and crystalline volume fraction, is important for the performance of these devices [3,6,7]. Here, the preparation of μc-Si:H thin films by radio-frequency (RF) magnetron sputtering yielded results which indicate that the hydrogen partial pressure ratio [8] and substrate temperature [9] are very important parameters. The surface diffusion lengths of the film precursors adsorbed on a film-growing surface are enhanced by covering the surface with hydrogen atoms, and by elevating the substrate temperature, resulting in the formation of μc-Si:H films with a high degree of crystallinity [10]. Moreover, in our previous study [11], we found that the target DC bias voltage used to control the kinetic energy of the sputtered silicon atoms, affects the crystallinity of the resulting films. It is suggested that an enhanced surface diffusion of sputtered silicon atoms on a film-growing surface is achieved when the atoms have sufficient kinetic energy, and/or when the thermal relaxation of the silicon network at the film-growing subsurface occurs through kinetic energy transfer to the film-growing surface. The latter reason suggests that ion bombardment of the film-growing surface might be one of the most important factors for improving the crystallinity of the μc-Si:H films. However, the influence of ion bombardment on the μc-Si:H growth is still under debate. On one hand, ion bombardment has been reported to prevent μc-Si:H growth [12], while on the other, using ion bombardment with an appropriate low kinetic energy is thought to enhance the μc-Si:H growth [13].

In the present study, in order to elucidate the effect of ion bombardment on μc-Si:H growth, we prepared silicon films by RF magnetron sputtering at various substrate DC bias voltages, and investigated their structures by X-ray diffraction (XRD), Raman scattering spectroscopy and Fourier-transform infrared (FT-IR) spectroscopy measurements.

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2. Experimental details

Silicon films were deposited on Corning glass, aluminum-covered glass and silicon wafer substrates using a RF (13.56 MHz) magnetron sputtering system (SPF-210H; Anelva). The aluminum film was connected to the substrate holder electrically through a substrate mask of stainless steel. The DC bias voltage (V_{sb}) of the substrate holder was varied between –400 and +50 V, which was controlled with respect to the grounded chamber. The target used was a silicon wafer (75 mm in diameter, n-type, and 0.8–1.3 Ω cm). The gas flow rates of hydrogen and argon used were 6 and 2 sccm, respectively, resulting in a hydrogen partial pressure ratio of 40% [8]. A total gas pressure of 8 Pa [14], and an RF power of 100 W were employed. The distance between the target and the substrate holder was 50 mm, and the substrate temperature was 250 °C.

Film thicknesses were measured using a surface profiler (Alpha-Step 500; Tencor Instruments). XRD patterns were measured using an X-ray diffractometer (RINT200 Ultima; Rigaku) over a range of $2\theta = 10$–60°. The mean crystallite sizes were determined from the full widths at half maximum of the XRD peaks using Scherrer's formula [15]. Raman scattering spectra were measured with a laser Raman scattering spectrometer (NRS-1000; Jasco) using a semiconductor laser of 532 nm wavelength, over a range of 200–700 cm^{-1}. The crystalline volume fraction, X_c, was estimated from the formula, $X_c = I_c/(I_c + I_a)$, where I_c and I_a are the integrated intensities of the Raman peaks attributed to the crystalline (~520 cm^{-1}) and amorphous (480 cm^{-1}) phases, respectively [11,16]. FT-IR transmission spectra were measured using FT-IR spectrometer (Spectrum2000, Perkin-Elmer) over the range between 400 and 4000 cm^{-1}, with a resolution of 1 cm^{-1}. Hydrogen content was calculated from the integrated intensity of the $Si–H_n$ stretching mode with an absorption cross section of 1.4×10^{20} cm^{-2} [17].

3. Results

3.1. XRD patterns and Raman spectra

Fig. 1 shows the dependence of the deposition rate on V_{sb}. The open circles and closed triangles represent the silicon films deposited on Corning glass and aluminum-covered substrates, respectively. The deposition rates on glass and aluminum-covered substrates are the same, and remained unchanged for V_{sb} values between –400 and +50 V. However, the variation in V_{sb} led to structural changes in the films deposited on aluminum-covered substrates, as discussed later. These indicate that the deposition rate could not be controlled by V_{sb} which gives rise to changes in processes on the film-growing surface.

Fig. 2 shows the XRD patterns of silicon films deposited on aluminum-covered substrates at $V_{sb} = 0$, –50 and –100 V. An XRD peak at $2\theta = 38.5^\circ$ originates from aluminum (1 1 1) plane and is excluded from the discussion.

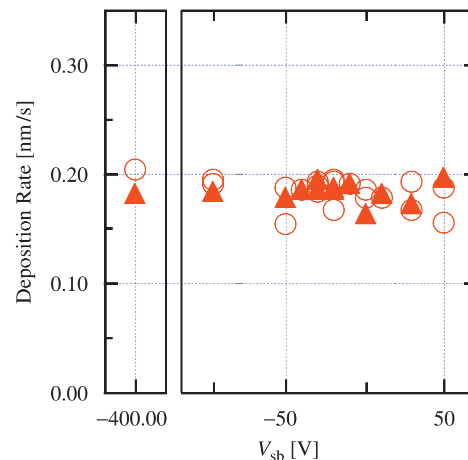

Fig. 1. Dependence of deposition rate on V_{sb}. The open circles and closed triangles represent the silicon films deposited on Corning glass and aluminum-covered glass substrates, respectively.

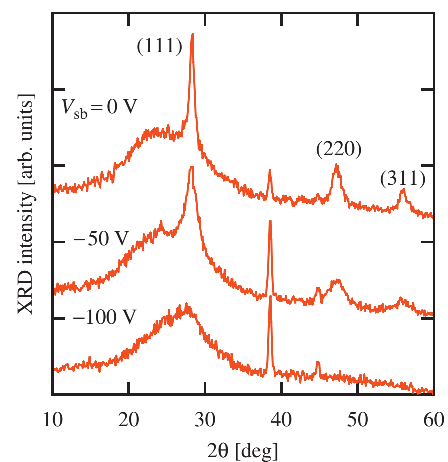

Fig. 2. XRD patterns of silicon films prepared on aluminum at $V_{sb} = 0$, –50 and –100 V. A peak at $2\theta = 38.5^\circ$ is assigned to the aluminum (1 1 1) plane.

The XRD patterns of the $V_{sb} = 0$ and –50 V films showed three XRD peaks at $2\theta = 28.4^\circ$, 47.3° and 56.2°, which are attributed to (1 1 1), (2 2 0) and (3 1 1) planes of crystalline silicon, respectively. Here, the peak intensities were observed to decrease with a concomitant broadening of the peak widths, as V_{sb} increased negatively. For the $V_{sb} = -100$ V film, neither of the (2 2 0) and (3 1 1) XRD peaks were observed, although a signal corresponding to the (1 1 1) XRD peak was just visible. These findings indicate that negative V_{sb} values prevent μc-Si:H growth.

Raman spectra of the silicon films discussed above are shown in Fig. 3. Here, the Raman spectra of the $V_{sb} = 0$ and –50 V films showed an intense peak at 520 cm^{-1} due to the crystalline silicon phase, together with a broad tail in the lower wavenumber region. This reveals that these films are microcrystalline. However, as V_{sb} was decreased from 0 to –50 V, the peak intensity at 520 cm^{-1} decreased. Moreover, the $V_{sb} = -100$ V film showed only a single peak at 480 cm^{-1}, suggesting it was practically amorphous, despite

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