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Low-temperature preparation of phosphorus doped μc-Si:H thin films by low-frequency inductively coupled plasma assisted chemical vapor deposition

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ABSTRACT

The phosphorus doped n-type hydrogenated microcrystalline silicon (n-μc-Si:H) thin films are prepared, at the two low substrate temperatures of room temperature and 200 °C, through a low-frequency inductively coupled plasma assisted chemical vapor deposition. The effect of the substrate temperature on the structural properties of the thin films, such as the X-ray Diffraction (XRD) patterns and the Raman spectra, is studied. The XRD measurements show that the diffraction orientations of the thin films present an obvious change when the radio frequency power is increased from 1300 W to 2300 W. The Raman spectra of the thin films deposited at room temperature unambiguously present a phase transition from the amorphous structure to microcrystalline structure whereas no structural phase transition is observed for the thin films deposited at 200 °C. The effect of the substrate temperature on the crystalline volume fraction of the thin films presents a large difference for the radio frequency power in the range of 1300 W–1700 W, while the difference becomes small when the power is increased from 1700 W to 2300 W. The deposition rate and the radio frequency power-sheet resistance curve of the thin films deposited at room temperature are obviously different from those of the thin films prepared at 200 °C. It is attributed to the joint effect of the radio frequency power and substrate temperature on the doping concentration. The electron energy distribution function of the species in the chamber is mainly distributed in a low energy range.

1. Introduction

Hydrogenated microcrystalline silicon thin films (μc-Si:H) have been receiving amounts of attentions due to their important applications in thin film solar cells and other devices such as thin film transistors and image sensor [1–8]. In comparison with doped amorphous silicon thin films, doped μc-Si:H thin films have many advantages such as high doping efficiency, high mobility, and low absorption coefficient [1]. As is known, μc-Si:H thin films are usually considered as crystallites embedded in an amorphous tissue [9]. The investigation of the structural transition from the amorphous to microcrystalline phase is interesting [10,11].

The μc-Si:H thin films are usually fabricated by the plasma enhanced chemical vapor deposition (PECVD) and hot wire chemical vapor deposition (HWCVD) [12–17]. The fabrication of typical μc-Si:H thin films is often at high substrate temperature higher than 300 °C [16,18]. Low-temperature deposition is desirable in that low temperature causes less damage to the thin films. Furthermore, high deposition rate is important for industrial applications. However, as is well known, the deposition rate of typical PECVD is usually low.

In comparison with previous reports [9,19–23], in the present study, phosphorus doped n-μc-Si:H thin films are fabricated and studied by a low-frequency inductively coupled plasma assisted chemical vapor deposition at the low substrate temperature of room temperature and 200 °C. The effect of substrate temperature on the structural properties of the thin films such as the X-ray Diffraction (XRD) patterns and the Raman spectra is studied. The crystalline volume fraction and the deposition rate of the thin films are determined. The effect of the two substrate temperatures on the deposition rate and the sheet resistance of the thin films are investigated. A real time, *in-situ* plasma diagnostics of Langmuir probe is used to reveal the plasma properties of the species in the chamber such as the electron energy distribution function and the electron temperature.

2. Experimental details

A low-frequency (460 kHz) inductively coupled plasma assisted chemical vapor deposition (LF-ICPCVD) is used to fabricate the n-μc-Si:H thin films [24–28]. The schematic diagram of the low-frequency inductively coupled plasma assisted chemical vapor deposition is shown in Fig. 1. Through the fused silica plate, the radio frequency power is transferred into the stainless steel chamber. Thus, a discharge is generated and remained in the chamber. In the present study, the shape of the chamber is a cylinder with a height of 33 cm

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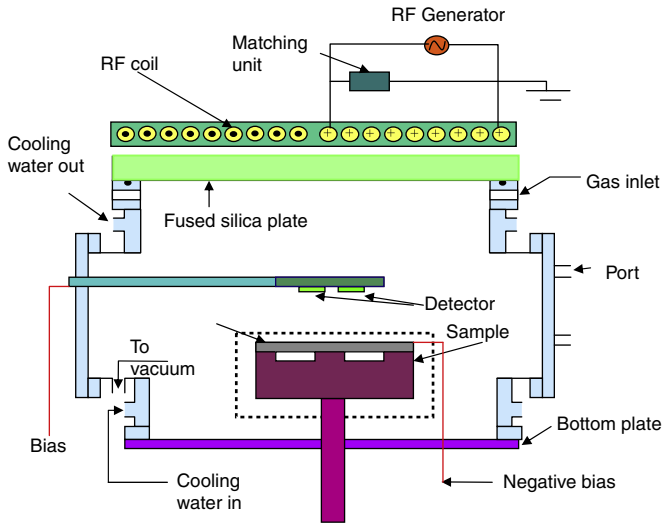

Fig. 1. The schematic diagram of low-frequency inductively coupled plasma assisted chemical vapor deposition.

and a radius of 16 cm. The LF-ICPCVD technique has an advantage of high-efficiency gas usage. For conventional PECVD, highly diluted hydrogen is usually requested. However, low hydrogen dilution and even no hydrogen dilution are requested for LF-ICPCVD.

Prior to the n-μc-Si:H thin film deposition, the chamber is evacuated to a base pressure of 5×10^{-5} Pa. SiH_4, PH_3, and H_2 are used as reaction gasses to prepare n-μc-Si:H thin films on glass substrates. In the present experiment, the flows of SiH_4, PH_3, and H_2 are set at 3, 0.8, and 10 sccm, respectively (sccm defines cubic centimeters per minute at standard temperature and pressure). The working pressure is fixed at 2.0 Pa. The radio frequency power is increased from 1300 W to 2300 W.

One of the structural properties of the n-μc-Si:H thin films, i.e. the XRD patterns, is characterized by the Siemens D5005 X-ray diffractometer using Cu$K\alpha$irradiation ($\lambda=0.15406$ *nm*). In the present measurement, the scan type is the locked coupled mode. The operating voltage and the current are 20 kV and 5 mA. The Raman spectroscopy is determined by the Renishaw 1000 micro-Raman system using a 514.5 nm laser for excitation. The grain size is calculated from the XRD data using the well-known expression. The crystalline volume fraction is determined using the deconvolution of Raman spectrum. The surface morphology of the n-μc-Si:H thin films is characterized using the JEOL JSM-6700F field emission scanning electron microscope (SEM). In the present measurement, the operating voltage is 5.0 kV. The thickness and, hence, the deposition rate of the n-μc-Si:H thin films are determined by the cross-sectional SEM measurements. The sheet resistance and the doping concentration are measured by the Ecopia HMS-3000 Hall effect measurement system at room temperature. A real time, *in-situ* plasma diagnostics of Langmuir probe is used to measure the plasma properties in the chamber, in particular, the electron energy distribution function and the electron temperature. In the present study, the home-made Langmuir probe is a cylindrical probe. The conducting wire inside the probe is properly shielded to prevent radio frequency interference. The probe is powered by AC (50 Hz) variable voltage by using a variable transformer.

3. Results and discussion

3.1. X-ray diffraction

The structural properties of the n-μc-Si:H thin films are investigated by the XRD, where the thickness of the thin films is around 100 nm. Fig. 2 (a) shows the radio frequency power dependence of the XRD patterns of the n-μc-Si:H thin films deposited at room temperature whereas Fig. 2 (b) corresponds to the radio frequency power dependence of the XRD patterns of the thin films prepared at 200 °C.

It is seen in Fig. 2 (a) that no diffraction peaks are observed when the radio frequency power is set at 1300 W. Under this condition, the structure of the thin film is amorphous, as confirmed by the Raman measurement (see the following Raman measurement section). When the radio frequency power is increased from 1700 W to 2300 W, an obvious diffraction orientation (111) appears, which is located at around 28.1°. The obvious directions (220) and (311) appear when the radio frequency power is increased to 2300 W. The Scherrer expression $d=k\lambda/\beta\cos(\theta)$ is adopted to estimate the grain size, where k is a constant determined by the geometry of the crystallites (0.89 is adopted in this paper), λ ($=0.154187$ nm) is the wavelength of the Cu$K\alpha$ monochromatic X-ray radiation, β is the full width at half maximum of diffraction peaks, and θ is the diffraction angle [13]. Using the Scherrer formula, we calculate that the grain size of the thin films along (111) increases from several nanometer to 23 nm when the radio frequency power is increased from 1700 W to 2300 W. In comparison with Fig. 2 (a), it is seen from Fig. 2 (b) that high radio frequency power is helpful to promoting the intensity of the diffraction patterns. No obvious peaks are observed for the radio frequency power of 1300 W. However, it is not a pure amorphous structure, as indicated by the Raman data (see the following section on the Raman measurement). It can be found that the intensity of the diffraction patterns is still not strong when radio frequency power is increased to 2300 W. It is seen in Fig. 2 (a) and (b) that the

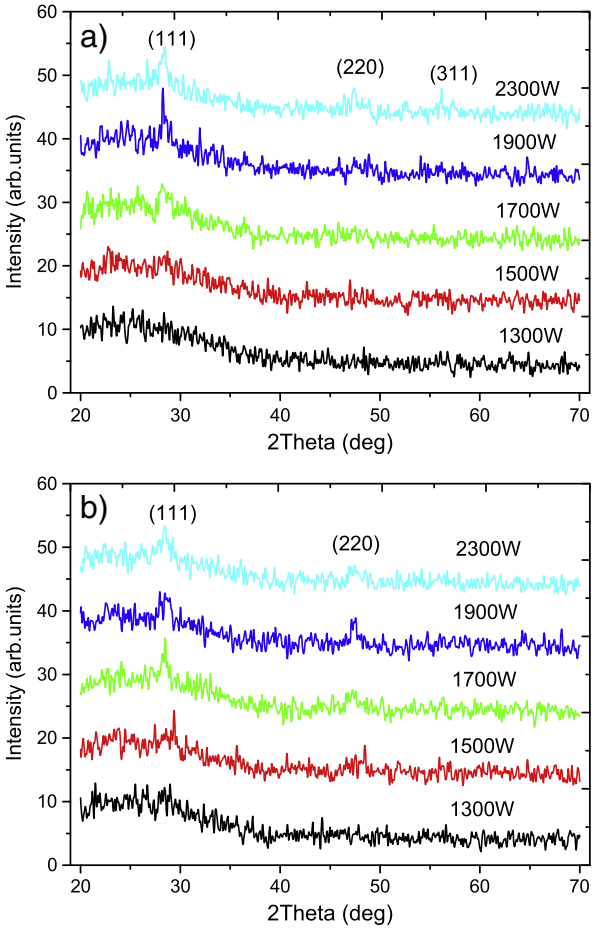

Fig. 2. The radio frequency power dependence of the XRD patterns of the n-μc-Si:H thin films deposited at room temperature (a) and 200 °C (b).