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Structural analysis of polycrystalline silicon thin films produced by two different ICPCVD approaches

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The structural properties of polycrystalline Si (poly-Si) thin films formed by using ICPCVD and LIA-ICPCVD methods under different H dilution ratios were investigated. Columnar-structured poly-Si films with 82% crystalline volume fraction were obtained by ICPCVD at a lower H dilution ratio of 50%. In the case of LIA-ICPCVD, to obtain nearly the same crystalline volume fraction (80%), a higher H dilution ratio (98%) was required and the poly-Si films obtained were mostly of cone-shaped columnar structure. The reverse effect is due to the difference in the antenna design in these systems, which changes the plasma characteristics. Multilayer deposition process, and subsequent H treatment and annealing were used in ICPCVD for producing highly crystallized poly-Si thin films from microcrystalline Si films. In the case of LIA-ICPCVD, annealing the ITO coated glass substrate in the deposition chamber prior to Si:H film deposition together with the optimization of process pressure yielded highly crystalline poly-Si film.

1. Introduction

In the field of large area electronics, polycrystalline Si thin films have wide variety of applications such as image sensors, thin film transistors and solar cells, etc. [1–3]. Several approaches based on the crystallization of hydrogenated amorphous silicon films such as furnace annealing [4], laser crystallization [5], and metal induced crystallization [6] have been developed to produce poly-Si thin films. However, these methods which are complex and requiring high temperature are either unsuitable on low cost glass substrate or involve long hours to complete the process or result in metal contamination or need additional defect passivation steps to produce device quality Si thin films. Instead of the expensive high temperature deposition processes which result in weakly passivated grain boundaries with insufficient hydrogen in the material, inexpensive low temperature deposition processes can be used to produce poly-Si thin films. The well passivated grain boundaries resulting from the low temperature deposition processes produced highly efficient poly-Si thin films. Despite the small grain size, columnar structured poly-Si thin film produced at low temperature with well passivated grain boundaries is most promising for solar cell applications [7,8].

For direct deposition of poly-Si films at low temperature on glass substrates, capacitively coupled plasma chemical vapor deposition (CCPCVD) method has been used. However, low deposition rate, film damage by radicals and ions, and poor crystallinity at the initial stages of film growth are major problems with this method. Device quality poly-Si films can be obtained by using inductively coupled plasma chemical vapor deposition (ICPCVD) due to its unique characteristics of low plasma potential, low electron temperature, high electron density (10^{12} cm^{-3} at 10 mTorr), spatial confinement of discharge and simplicity of the configuration [9–11]. In order to avoid the problems of designing thick large area dielectric window for large area deposition in conventional ICPCVD system, ICP sources with low inductance internal antenna configuration (LIA-ICPCVD) has been developed for efficient large-area and high-density plasma generation [12]. In addition, it is believed that H dilution plays an important role in determining the crystallinity of Si:H films [13].

In our earlier work, we reported that the crystallinity and grain sizes of Si:H films produced at a substrate temperature of 150 °C using ICPCVD was decreased with increasing H dilution ratios. We also

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showed that the crystallinity of Si:H films produced using ICPCVD at 350 °C was improved by H treatment and annealing [14,15]. In this paper, we discuss the reverse effect of H dilution on the crystallinity of Si:H films deposited at 350 °C by ICPCVD and LIA-ICPCVD. Different approaches to improve the quality of poly-Si films from microcrystalline to polycrystalline state, produced by ICPCVD and LIA-ICPCVD methods are also described.

2. Experimental details

Si:H films were deposited by ICPCVD and LIA-ICPCVD under different H dilution ratios. A mixture of SiH_4 and H_2 was used as the process gas. The ICPCVD process was coupled with a (13.56 MHz) RF plasma source (800 W), which provided a power density of 0.653 W/cm^2. The plasma was generated in a cylindrical stainless-steel vacuum chamber. An inductively coupled azimuthal electrical field produced by a spiral copper coil fixed on top of a dielectric quartz plate on the vacuum chamber generated plasma uniformly over the substrate. A turbo molecular pump backed by a two stage rotary pump evacuated the chamber and a base pressure of 1×10^{-5} Torr was achieved.

The LIA-ICPCVD system had four units of U-shaped internal antenna to decrease the inductance. The internal LIA is covered with an insulator so as to minimize the electrostatic coupling and reduce the plasma damage. A similar system was described in Ref [16]. A power density of 0.612 W/cm^2 was obtained with 13.56 MHz 3000 W RF power which is fed to the internal LIA in the process chamber through a matching box. The base pressure of 1×10^{-7} Torr was achieved using the turbo molecular pump.

X-ray diffraction spectroscopy (XRD), Raman spectroscopy, and scanning electron microscopy (SEM) were used to characterize the microstructures of the Si:H films. The crystalline volume fraction (Xc) was evaluated by the formula, $Xc = (I_{520} + I_{510}) / (I_{520} + I_{510} + I_{480}) \times 100\%$. I_{520} and I_{510} represented the intensity of the crystalline peak at around 520 and 510 cm^{-1}, respectively and I_{480} represented the intensity of the amorphous peak at around 480 cm^{-1}.

3. Results and discussion

3.1. Effect of H dilution on the crystallinity of Si:H films

H dilution ratio (H_2 to $SiH_4 + H_2$) is one of the most important factors that determines the crystallinity of Si films deposited using CVD [13]. Firstly, Si:H films with different H dilution ratios were deposited on glass or SiO_2 by using ICPCVD and LIA-ICPCVD to find the most suitable parameters for fabricating poly-Si films with better crystallinity. In our earlier work, an anomalous effect of decreasing crystallinity of Si films with increasing H dilution ratio was noticed for Si:H films deposited using ICPCVD [14]. In this study, the Si films were deposited at different H dilution ratios with a process gas pressure of 50 mTorr and a substrate temperature of 350 °C. The effect of the H dilution ratio on the crystallinity of the silicon film was almost the same. As shown in Fig. 1, a lower H dilution ratio of 50% was chosen for obtaining highly crystalline poly-Si films using ICPCVD with a Xc of 69.8%, while for H dilution ratio of 65% and 83% were 69.5%, and 69.4%, respectively.

For the Si:H films fabricated using LIA-ICPCVD, different H dilution ratios of 20%, 77%, 95%, and 98% were used. The Raman spectra of these Si samples are shown in Fig. 2. Crystallinity of Si:H films was increased with increasing H dilution ratio. Si:H films with H dilution ratios of 20% and 77% have Raman spectra peak at 480 cm^{-1} which indicated that these are amorphous silicon (a-Si) films. Si:H films with H dilution ratios of 95% and 98% showed a shift of Raman spectra peak towards 520 cm^{-1} with increasing crystalline volume fraction of 63.33% and 65.25%, respectively. The results indicated a strong evidence for H dilution effects on the crystallinity of Si:H films deposited by LIA-ICPCVD and are similar to the H dilution effects on the

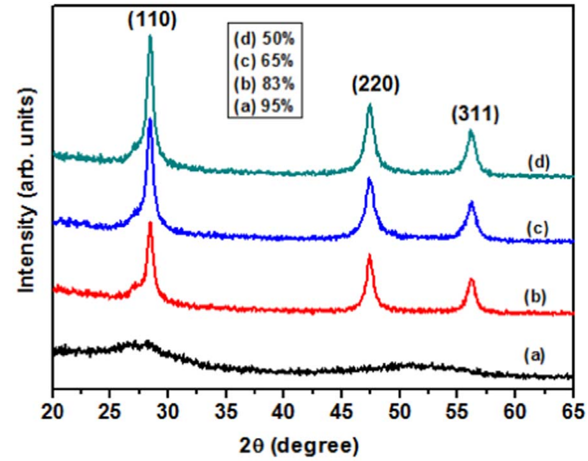

Fig. 1. XRD of the ICPCVD grown Si:H films with different H dilution ratio of (a) 95%, (b) 83%, (c) 65% and (d) 50%.

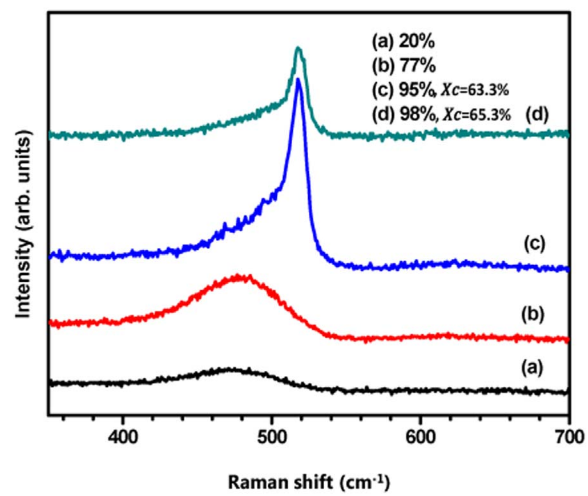

Fig. 2. Raman spectra of the LIA-ICPCVD grown Si:H films with different H dilution ratio of (a) 20%, (b) 77%, (c) 95% and (d) 98%.

crystallinity of Si:H films deposited by conventional PECVD techniques, which is contrary to the H dilution effects on the crystallinity of Si films deposited by ICPCVD. Thus a higher H dilution of 98% was selected for further experiments to obtain poly-Si films.

The disparity between the effects of H dilution ratio on the crystallinity of Si:H films grown by ICPCVD and LIA-ICPCVD arises from the antenna design, as illustrated in Fig. 3. Both these systems utilize the same plasma generation principle and an inductively coupled electric filed produced from a RF power carrying antenna generates plasma. The antenna used in ICPCVD system consists of a spiral copper coil fixed on top of a dielectric quartz plate on the vacuum chamber and that of LIA-ICPCVD system consists of four units of U-shaped low inductance antenna covered with an insulator installed in the vacuum chamber at optimized positions to increase plasma uniformity. Both these systems have the advantages of high plasma density (about 10^{12} cm^{-3}), low plasma potential, low electron temperature, than that in the conventional CVD system [9–11], but spatial confinement of discharges (plasma) around the inductance coil is absent in the LIA-ICPCVD system since the antenna is placed in the vacuum chamber for uniform distribution of plasma. Difference in the design of antenna in these two systems gave rise to different gas-phase transport process of plasma. Thus, the gas-phase transport process of the plasma [17] which determines the crystallization process of Si:H film deposition by increasing or decreasing the densities of SiH_3 radicals, which are most