Control of seed layer for a low temperature formation of polycrystalline silicon with high crystallinity and a smooth surface

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(Received 4 February 1999; accepted 26 March 1999)

We have successfully improved the surface roughness and crystalline fraction of polycrystalline silicon (poly-Si) films formed on quartz substrates at 300 °C by controlling its initial growth. Seed layers were formed by eliminating charged species incident on the substrate during the initial growth in electron cyclotron resonance silane and hydrogen plasma-enhanced chemical vapor deposition and poly-Si films were subsequently formed on the seed layers with charged species. As a result, control of ion bombardment on the initial growth was found to be a key factor for forming poly-Si films with smooth surfaces and high crystallinity at low temperatures. © *1999 American Vacuum Society.* [S0734-211X(99)08403-6]

I. INTRODUCTION

Polycrystalline silicon (poly-Si) thin films have been expected to be applied to thin films transistors (TFTs) and peripheral circuits of liquid crystal displays (LCDs). To obtain high quality poly-Si films with large grains, a low pressure chemical vapor deposition (LPCVD), a solid phase crystallization of amorphous silicon and so on have been employed. However, in these methods, a substrate annealing of about 600 °C is needed. Glass substrates used in the LCD fabrication process have a deformation point of ~500 °C. Poly-Si films are, therefore, required to be formed at low temperatures below 400 °C. Recently high quality poly-Si films have been obtained on glass substrates using a laser annealing method. On the other hand, plasma-enhanced CVD (PECVD) has a great potential to form poly-Si films over a large area of the substrate with only one process, but the difficulty is that the crystallinity of device quality has not been achieved at low temperatures. Amorphous silicon layers are first formed at the initial growth of poly-Si on amorphous material substrates such as a glass, which leads to low conductivity. Recently, Zhou *et al.* reported that poly-Si films without the amorphous interface layer were formed by a high H_2 dilution of SiH_4 in a triode type PECVD.[1] The mechanism reducing the amorphous interface layer, however, has not yet been clarified.

Moreover, the synthesis of poly-Si films with smooth surfaces is essential for application to TFTs. The surface of poly-Si films formed by PECVD is commonly too rough to apply the films to TFTs. Although a smooth poly-Si film surface is strongly desired, the promising growth method of poly-Si films to satisfy the smooth surface and high crystallinity at the same time has never been proposed.

In previous work, we reported that controlling ion bombardment on the substrate by supplying positive biases to the silicon substrate improved the crystallinity of poly-Si films.[2] Moreover, we have developed a novel technique to eliminate the charged species incident on the insulator substrates, and it was found that the crystallinity and the surface roughness of poly-Si films formed without charged species improved.[3] With this technique, there was, however, a problem of the deposition rate being too low. Moreover, the effect of ion bombardment during nucleation on the growing film have not been elucidated yet. In this study, therefore, we have focused on the effects of ion bombardment on the nucleation of poly-Si films at the initial growth stage. The novel technique to completely eliminate ions incident on the substrate was applied to control the initial growth stage on insulating substrates in electron cyclotron resonance (ECR) PECVD by employing a mixture gas of SiH_4 and H_2. This technique enabled us to investigate the effects of ions on the nucleation of poly-Si and successfully synthesize the seed layers for a low temperature formation of poly-Si with a smooth surface and high crystallinity. The two step growth (TSG) method, where seed layers were formed without charged species and the poly-Si was subsequently grown on the seed layer with charged species, has demonstrated that is can form poly-Si films with a smooth surface and high crystallinity at a low temperature.

II. EXPERIMENT

The experimental apparatus was a typical ECR PECVD system with a divergent magnetic field. Details of it are described in a previous report.[2] Poly-Si films were formed on quartz substrates. The CVD conditions optimized for obtaining better crystallinity were as follows: a total pressure of 0.5 Pa, gas flow rate of $SiH_4/H_2=8/72$ sccm, microwave power of 300 W, a floating substrate bias and substrate temperature of 300 °C. To eliminate the charged species incident on the substrates in the plasma, a device, with two permanent magnets set parallel with a 3 cm separation, was installed 7 cm above the substrate. The magnetic flux density was designed to be 0.3 T at the center of these magnets to eliminate charged species completely.

The crystallinity of the poly-Si films was investigated by Raman spectroscopy and the crystalline fraction X_c was evaluated by decomposing the measured Raman spectra into

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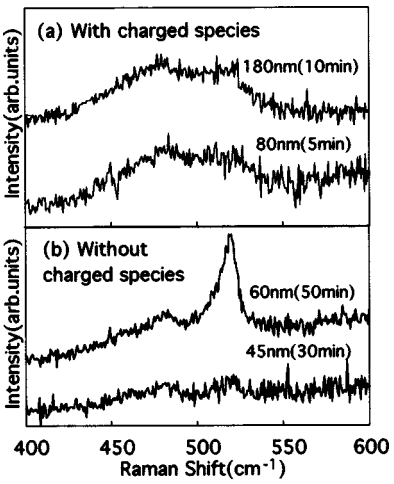

FIG. 1. Raman spectra for the poly-Si films formed (a) with and (b) without charged species in the initial growth.

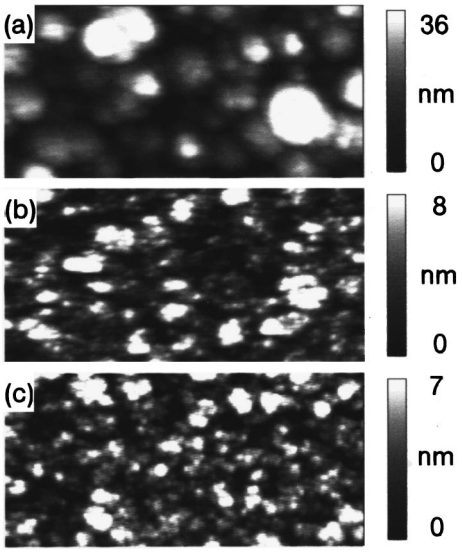

FIG. 2. AFM images (500 nm×1000 nm) of the films formed (a) with and (b) without charged species and (c) by two step growth.

three peaks, namely, an amorphous peak ($480\,cm^{-1}$), a microcrystalline peak ($510\,cm^{-1}$), and a crystalline peak ($520\,cm^{-1}$).[4] The surface morphology and root mean square (rms) of its roughness were evaluated by an atomic force microscopy (AFM) operated in ultrahigh vacuum ($<4\times10^{-7}$ Pa). The AFM apparatus was connected to the ECR chamber and the sample formed in the ECR chamber was transferred to the AFM chamber without exposure to air. The crystalline structure was also observed by transmission electron microscopy (TEM).

III. RESULTS AND DISCUSSION

Figure 1 shows Raman spectra of poly-Si films formed with charged species and without charged species. The film thickness and the deposition time are shown in each spectrum in Fig. 1. The deposition rates with and without charged species were about 3 and 0.2 Å/s, respectively. In the films of 80 nm in thickness formed with charged species, an amorphous broad phase ($480\,cm^{-1}$) was observed, while a crystalline silicon peak ($520\,cm^{-1}$) was not observed. The crystalline silicon peak appeared in the film 180 nm in thickness. Therefore, the thickness of the interface layer was evaluated to be less than 180 nm in the film formed with charged species. On the other hand, in the films formed without charged species, the crystalline peak was observed in the film 60 nm in thickness. It was found that the interface layer in the films formed without charged species was estimated to be less than 60 nm, which was much thinner than that with charged species.

Although the crystallinity at the interface of the films formed without charged species was improved greatly, the deposition rate decreased up to 1/10 compared with that with charged species. The TSG technique was demonstrated in this study. For the first step, the seed layer was formed without charged species. Second, the film was formed on the seed layer with charged species. The TSG process has been completed in a vacuum. The CVD conditions of the first step were the same as those of the second step except for using the permanent magnets. Figure 2 shows AFM images of the films formed with and without charged species and using TSG. The thicknesses of all the films were 500 nm. As shown in Fig. 2(a), the grain size and the rms of the surface roughness of the films formed with charged species were about 150 and 12 nm, respectively. From TEM, it was confirmed that the grains observed in the AFM images were amorphous phases. On the other hand, the surfaces of the films formed without charged species were found to be much smoother than those formed with charged species and the rms roughness was calculated to be 3 nm as shown in Fig. 2(b). In the TSG method, the surface of the film at the first step was as smooth as that shown in Fig. 2(b). Figure 2(c) shows the surface morphology of the film after second step growth with charged species. The roughness was remarkably reduced to 3.8 nm compared with that (12 nm) of the films formed continuously with charged species (using conventional ECR PECVD). These results indicate that the surface structure of films is determined at the initial growth step and control of the initial stage leads to the great improvement in surface roughness.

Figure 3 shows the Raman spectra of the films formed by TSG and with charged species, namely, continuous growth (CG) by conventional ECR PECVD. The plasma conditions at CG were the same as those at the second step in the TSG. The crystalline fractions of the films formed by TSG and CG were estimated to be 62% and 30%, respectively. The transmission distance of the Ar^+ laser for Raman spectroscopy is estimated to be about 500 nm when the film thickness is 500 nm. It was considered, therefore, that the Raman spectra included information on the interface layer as well as on the bulk poly-Si layer, and the difference between the crystalline fractions of the two films was mainly due to the quality of the interface layer. From these results, it was found that the crystallinity of the interface layer was improved considerably by using the TSG method, and that the crystalline phase

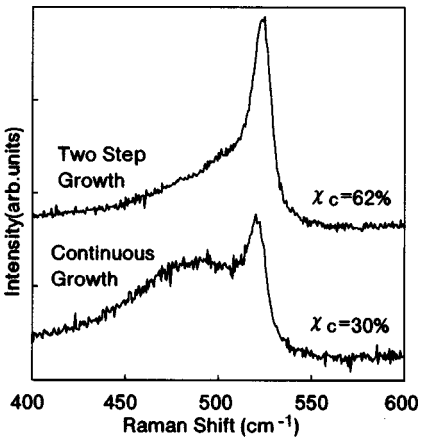

FIG. 3. Raman spectra of the films formed by two step growth (upper panel) and the continuous growth (lower panel).

without the thick amorphous intermediate layer grew on the seed layer at the second step, although the ions bombarded the seed layer in the same way as conventional ECR PECVD. These results indicate that control of charged species at the initial stage significantly improves the surface roughness and crystallinity at the interface layer.

IV. CONCLUSION

We have investigated the effects of ion bombardment on the crystallinity and surface structure of the initial layer formed with and without charged species in ECR PECVD. The surface roughness of the film and the thickness of interface layer were remarkably reduced by eliminating charged species. Moreover, we have developed the TSG method, where the seed layer was formed without charged species and the film was subsequently formed with charged species on the seed layer. The surface roughness and crystallinity of the poly-Si films were greatly improved by using the TSG method. As a result, it was found that the charged species considerably affected nucleation at the initial stage, and control of charged species at the initial stage led to the formation of poly-Si films with high crystallinity and smooth surfaces.

ACKNOWLEDGMENTS

The authors thank Dr. Mineo Hiramatsu (Meijo University) for use of the Raman spectroscopy system. This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports, and Culture, Japan.

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