SiO₂ Thin Films Formation by Reactive Evaporation of SiO at a Low Temperature and Its Device Application

T. Sameshima and G. Langguth*
Tokyo University of Agriculture & Technology, 2-24-16, Nakamachi, Koganei, Tokyo 184, Japan
*Max-Planck-Institut, Heisenbergstrasse 1, 70569 Stuttgart, Germany

A reactive evaporation of SiO in an oxygen atmosphere was investigated for SiO₂ film formation on Si. The SiO₂/Si interface had a low trap density of ~10¹⁰ cm⁻² eV⁻¹ for an oxygen pressure of around 1x10⁻⁴ Torr during deposition. The average Si-O-Si bonding angle in the films increased as the oxygen pressure increased up to 1x10⁻³ Torr. It was further increased to 140 degrees via hydrolytical process by H₂O vapor (100 Torr) annealing at 300 °C. An application of the present SiO₂ to gate insulator resulted in fabrication of polycrystalline silicon and amorphous silicon thin film transistors with high mobilities and low threshold voltages.

1. Introduction

SiO₂ formation at low temperatures has been investigated for many applications 1-10. SiO₂ can be used for gate insulator in thin film transistors (TFTs) fabricated on cheap glass substrates for an application to large flat liquid crystal display panels. Moreover, surface passivation with SiO₂ films is important for fabrication of solar cells at a low cost.

This paper discusses optical and electrical properties of SiO₂ deposited by an Si evaporation method. It demonstrates that the oxygen pressure in the evaporation system is an important parameter for forming a SiO₂ structure with large a Si-O-Si bonding angle and a low defect density in the film as well as at the interface. A post deposition annealing with a H₂O vapor of 300 °C makes the film stable with a larger average bonding angle and a narrow bonding angle distribution. This paper also report an application of the present SiO₂ to gate insulator for fabricating polycrystalline silicon and amorphous silicon thin film transistors at 300 °C.

2. Experimental

Ta boats were loaded with SiO powders of 99.99% purity and connected to the electrodes of an evaporation chamber. The silicon substrates were then placed above the Ta boat separated by a shutter in between. The chamber was evacuated to a pressure of 2x10⁻⁷ Torr. We started evaporation by a preheating step just below the evaporation threshold with keeping the shutter closed to remove adsorbed gases in SiO powders. SiO was evaporated in the oxygen ambient, whose flow rate was changed up to 2.5 Sccm corresponding to a pressure of about 1x10⁻⁴ Torr. The deposition rate was 10 nm/min. After film deposition, a post deposition anneal in H₂O vapor was applied to reduce a defect density in the film as well as the SiO₂/Si interface 11). The H₂O vapor pressure was controlled to 100 Torr.

3. Results and discussion

Figure 1 shows the peak wave number and the peak's full width at half maximum (FWHM) of the absorption band caused by Si-O anti-symmetric stretching vibration in the SiO₂ films as a function of oxygen flow rate, which were measured by Fourier transform infrared spectroscopy (FTIR). The peak wave number increased and the FWHM decreased as the oxygen flow rate increased. This result shows that the deposition with a high oxygen concentration in the ambient results in a high average Si-O-Si bonding angle and a narrow angle distribution. The H₂O vapor annealing at 300 °C for one hour further increased the peak wave number and reduced the FWHM for samples fabricated for each oxygen flow rate. For the case of the 2.5 Sccm oxygen flow, the peak wave number reached 1065 cm⁻¹ after the annealing. It gave an average Si-O-Si bonding angle of 140 degrees, which was estimated using a central-force network dynamics model 1,12).

Figures 2 shows the FWHM as a function of the peak wave number for pre-annealed and post-annealed SiO₂ fabricated with different oxygen flow rates. Our own data were compared to thermal oxide films reported by Lukovsky et al. 1), which were formed at different temperatures up to 1150 °C in dry atmosphere. The width of Si-O absorption band was reduced with a higher rate, as the peak wave numbers increased, than that of Lukovsky's data. This result means that the change of SiO₂ structure with the oxygen flow rate and by the H₂O vapor annealing is not mainly caused by thermal relaxation process but a chemical process. We guess that these weak Si-O bonds with a low bonding angle may be broken by H₂O incorporated in the film (hydrolysis) and that Si-OH bonds are formed 8). This hydrolysis would be enhanced with increasing the temperature to 300 °C. Furthermore, two Si-OH bonds would be combined and then Si-O bonding with more stable and a higher bonding angle would be formed.

Figure 3 shows the effective charge density for Al-gate MOS capacitor as a function of the oxygen flow rate. The effective oxide charge density decreased as the oxygen flow rate increased. And the H₂O vapor anneal further reduced the density, especially for samples fabricated with lower oxygen flow rates. The lowest effective charge was
obtained to be $8 \times 10^9$ cm$^{-2}$ at the oxygen flow rate 2.5 Sccm. The interface trapped state obtained from the high frequency C-V curve was $1.2 \times 10^{10}$ cm$^{-2}$eV$^{-1}$, which is comparable to the effective charge density.

The present SiO$_2$ formation and annealing methods were applied to fabrication of n-channel tope gate type poly-Si and a-Si TFTs. The channel region for poly-Si TFTs and source-drain regions for both TFTs were formed by XeCl excimer laser induced crystallization of undoped or doped silicon films. The fabrication temperature was 270 ºC. The H$_2$O vapor anneal was conducted after TFT fabrication. Figure 4 shows transfer characteristics for both TFTs. The maximum field effect mobility and the threshold voltage were 600 cm$^2$/Vs and 1.0 V for the poly-Si TFT, and 2.6 cm$^2$/Vs and 0.9 V for the a-Si TFT. These results show that the present system of SiO$_2$ formation will be useful for low temperature processing.

4. Summary

A reactive evaporation of SiO in an oxygen atmosphere was investigated for forming SiO$_2$ films on Si. The FTIR measurement revealed that the deposited SiO$_2$ films had a higher peak wave number and lower FWHM of Si-O anti-symmetric stretching mode absorption for a higher oxygen flow rate during fabrication. The peak wave number reached to 1065 cm$^{-1}$ for the oxygen flow rate, 2.5 Sccm ($1 \times 10^{-4}$ Torr) by H$_2$O vapor (100 Torr) annealing at 300 ºC for one hour. The average bonding angle was estimated to 140 degrees using the central force model. The FWHM of the Si-O absorption was reduced by these steps to 74 cm$^{-1}$, which is comparable to that of thermal grown SiO$_2$ fabricated ~1100 ºC. Changes in SiO absorption spectra as a function of oxygen flow rate and with the H$_2$O vapor annealing would not be thermal relaxing process but interpreted to be a hydrolytical chemical process. The resulting SiO$_2$ films had a low density of oxide charge interface trapping states, $-10^{10}$ cm$^{-2}$eV$^{-1}$ for the oxygen pressure around $1 \times 10^{-4}$ Torr.

Poly-Si and a-Si TFTs with low threshold voltages and high mobilities were achieved using SiO$_2$ gate oxide layer formed by the present SiO$_2$ formation and laser crystallization. The maximum field effect mobility and the threshold voltage were 600 cm$^2$/Vs and 1.0 V for the poly-Si TFT, and 2.6 cm$^2$/Vs and 0.9 V for the a-Si TFT, respectively.

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References

Fig. 1 The peak wave number and the FWHM of Si-O absorption as a function of the oxygen flow rate for pre-annealed (solid marks) and 100 Torr H₂O vapor annealed 270 C, 1hr (solid marks).

Fig. 2 The FWHM of Si-O absorption as a function of the peak wave number. The data points include pre-annealed and post H₂O vapor annealed SiO₂ films prepared under different oxygen flow rates. The broken line represents data of thermally grown oxide with fabricated different temperature obtained by Lucovsky, et. al. Ref. [1]

Fig. 3 The effective charge density as a function of the oxygen flow rate for samples before and after the H₂O vapor annealing. The effective oxide charge was estimated by difference of the flat band voltage between real samples and the ideal value of 0.89V for Al-gate MOS capacitor.

Fig. 4 The transfer characteristics for n-channel top-gate type poly-Si and a-Si TFT's fabricated using the present SiO₂ formation method.