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Novel Fabrication Technique of Optical Waveguides using Low Density Silicon Nitride Films Deposited by Plasma-Enhanced Chemical Vapor Deposition

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1. Introduction

We have previously reported the anomalously unstable properties of the Si nitride films deposited by plasma enhanced chemical vapor deposition (PECVD) at low plasma power and low substrate temperatures [1]. Such films are easily oxidized in the steam ambient at 200°C.

In this paper, we have intentionally employed the unstable Si nitride films to fabricate optical waveguides. The details of the properties of the unstable Si nitride films are first explained, and then the novel fabrication technique of the optical waveguide is introduced. Finally the characteristics of the fabricated waveguide are demonstrated.

2. Experiment

The Si nitride film was deposited by using the parallel plate type plasma CVD apparatus (Fig. 1). The deposition and annealing conditions are summarized in Table I. The refractive index and thickness of the film are measured by spectroscopic ellipsometry. Annealing was done on the hot plate in the clean room air, or in the furnace flowing varieties of gases such as $H_2O + N_2$, N_2 and O_2.

3. Results and Discussions

3.1 Unstable properties of the low –density Si nitride films

Figure 2 shows the change in refractive index of the film deposited at 350°C as a function of the plasma power. The annealing is carried out at 300°C for 30 min. The change in the refractive index is larger for the lower plasma power. The density thus fabricated Si nitride is only 2.0 g/cm^3 whereas the normal stable PECVD film has the density of 2.5-2.8 g/cm^3. Figure 3 shows the substrate temperature dependence of the refractive index change and annealing behavior in the air at 400°C for 30 min. The maximum refractive index change occurs at a growth temperature of 200°C. This reason was reported in Ref 1. The changes in the refractive index of the films grown at 200°C and 20 W are shown in Fig. 4 for various annealing temperature in the air. Figure 5 shows the FT-IR spectra of the as deposited and annealed film (growth temperature=200˚C, rf power=20 W). The numbers of Si-N and N-H bonds are decreased by the annealing, instead the number of Si-O bonds is increased. Figure 6 shows the transition of Si-O peak height of FT-IR spectrum of the samples annealed in various gas ambient. From this figure it is recognized that H_2O anneal dominantly affects the film property. In contrast, the film property is hardly changed with N_2 and O_2 annealing. From these results it is concluded that the low-density unstable Si nitride is oxidized by the water vapor. Figure 7 shows the Arrhenius plot of the initial changing rate of the refractive index shown in Fig. 4, showing the activation energy of 0.1 eV. This energy may be related to the diffusion process of water molecules into the low-density porous like Si nitride film.

3.2 Novel fabrication technique of optical waveguides using the unstable low-density Si nitride

Figure 8 shows the newly proposed fabrication process of optical waveguides using the unstable Si nitride which is easily oxidized in the steam ambient. In order to stabilize the unstable nature of the film, we have employed the high-temperature annealing at 750°C (see Fig. 9). The low-temperature process such as plasma treatment for the stabilization process should be developed. Figure 10 shows (a) optical micrograph (plan view at the bending part) and (b) SEM photograph of the cross section. No steps are observed at the core/side-clad interface. Figure 11 shows the measurement setup for the propagation loss of the waveguide and the observed output light from the fabricated waveguides (8 and 100 μm width) are shown in Fig. 12. From Fig. 13, the propagation loss of 16 dB/cm is obtained which is large compared with that for the conventional etching process (< 1dB/cm) [2]. The reason is found to be a rough edge of the TiN mask pattern due to the poor lithography technique. A better result is expected to improve the TiN mask patterning process.

In principle, this method has a potential to provide a superior optical characteristics. In the conventional method which uses the etching process, the side wall roughness is inevitable at certain extent [2]. On the other hand in our method, the side clad is formed by the diffusion of water molecules, then the interface roughness at the core/side-clad is expected to be small. The flat surface obtained by this method is another merit.

4. Conclusion

The fabrication condition for the unstable Si nitride films is found. The novel process to fabricate the optical waveguide using the unstable film is developed and the waveguide properties are demonstrated. By using this new technique, a better quality waveguide is expected.

References

[1] T. Kakite, M. Wake, and S. Yokoyama, Electrochemical Society Symposium (Hawaii, October 3-8, 2004) H1-843.
[2] S. Yokoyama *et al.*, J. Vac. Sci. Technol. A 13, 629 (1995).

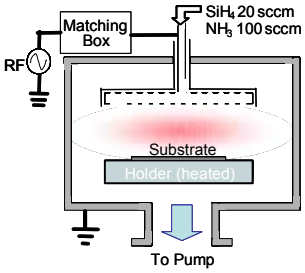

Fig. 1 Plasma CVD apparatus.

Table I Deposition and anneal condition. Diameter of the plasma electrode is 21 cm.

Deposition Condition	
Pressure	1.0Torr
SiH_4 (H_2 90%)	20sccm
NH_3	100sccm
Growth Temp. (°C)	23, 200, 300, 350
Rf Power (W)	20, 50, 100
Anneal Condition	
Anneal Temp. (°C)	200, 400, 500
Hot Plate	Clean Room Atmosphere (Class 100, Humidity 35-40%)
Furnace	H_2O (80°C) + N_2 (2 l/min) N_2 (2l/min) O_2 (2l/min)

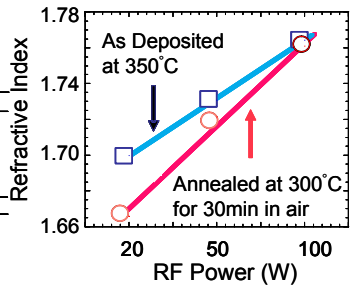

Fig. 2 Change in refractive index after annealing vs plasma power.

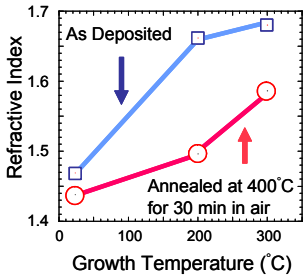

Fig. 3 Change in refractive index vs growth temperature.

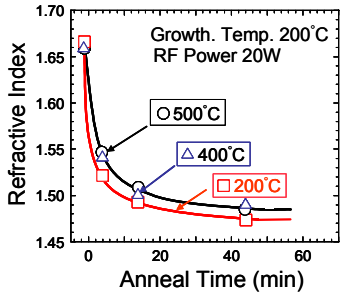

Fig. 4 Refractive index vs anneal time in air

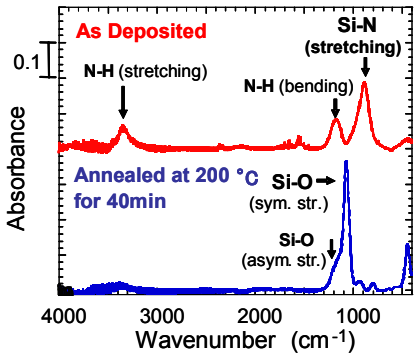

Fig. 5 FT-IR spectra of the as deposited and air-annealed films.

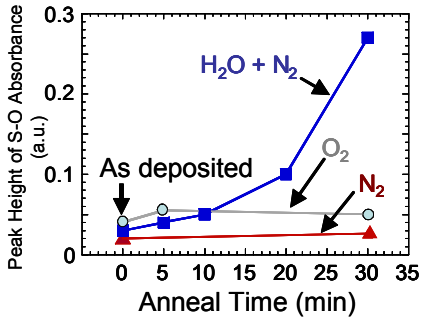

Fig. 6 Transition of Si-O peak height in varieties of atmosphere with anneal time in $H_2O + N_2$, N_2 and O_2 ambient.

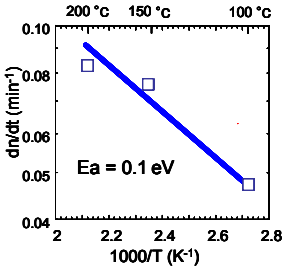

Fig. 7 Arrhenius plot of the changing rate in refractive index for the film grown at 200°C, rf power = 20 W, and annealing in $H_2O + N_2$.

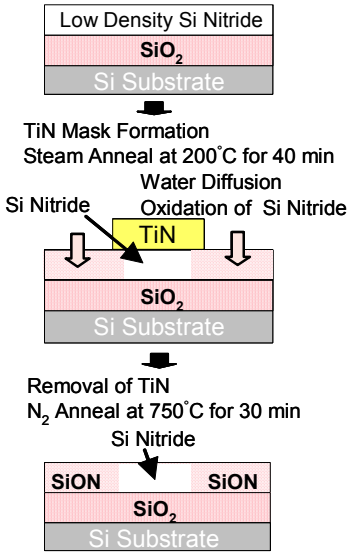

Fig. 8 Newly developed fabrication process of the optical waveguides.

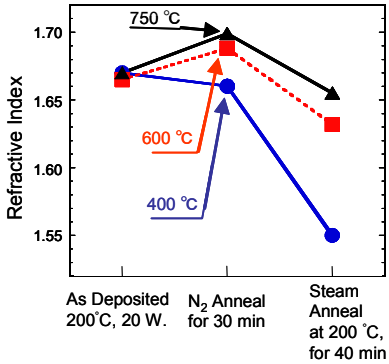

Fig. 9 Anneal behavior of the silicon nitride films. The 750°C N_2 anneal stops the change in the refractive index of the film by steam anneal.

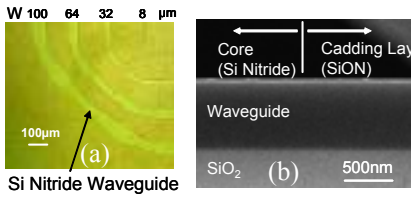

Fig. 10 (a) Optical micrograph (plan view at bending part) and (b) SEM photograph of the cross section. No steps are observed at the core/side clad interface.

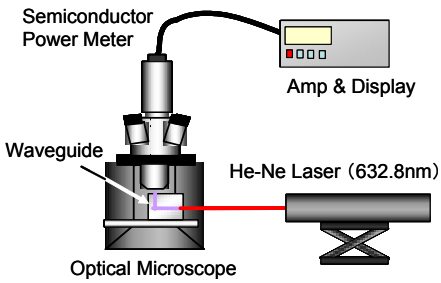

Fig. 11 Optical measurement setup for the propagation loss of the waveguides.

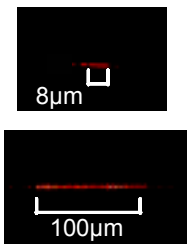

Fig. 12 Observed output light from the fabricated waveguides (8 and 100 μm width).

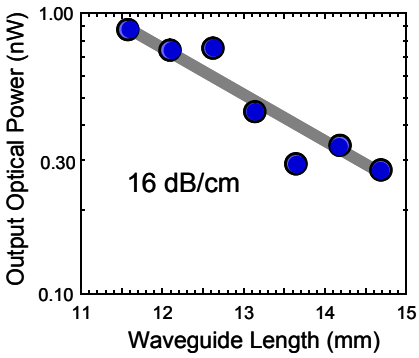

Fig. 13 Output light power vs waveguide length of the 100 μm width waveguide.