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Reduction of insertion loss after annealing of silicon oxynitride optical waveguides

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The insertion losses of silicon oxynitride (SiON) waveguides have been measured in the 1550 nm wavelength region. The waveguide structure consisted of a 2.0μm SiON waveguide core with a refractive index of 1.50, a 0.5μm SiO_2 upper cladding and a 5.0μm SiO_2 lower cladding with a refractive index of 1.45. It was found that the wavelength-dependent insertion losses of the waveguide were greatly reduced by annealing, and the loss was decreased more than 5.7 dB/cm at 1550 nm after annealing at optimum conditions. The former was attributed to the reduction of the absorption caused by N–H and Si–H vibration modes, and the latter was due to the improvement of the interface roughness and homogeneity in the waveguides after annealing.

Keywords: SiON optical waveguide, insertion loss, annealing, interface roughness
PACC: 8140T, 4270, 7820W

1. Introduction

Integrated optics requires optical slab waveguides with low loss. Telecommunication applications have recently intensified the interest in applications of integrated optics for wavelengths close to 1550nm.[1,2] Specifically, dense wavelength division multiplexing (DWDM) telecommunication systems use several optical wavelengths of light to increase the information capacity of a fibre optic communication system. Some DWDM systems use integrated optics for the optical demultiplexer and other key components.[3]

One of the present authors has demonstrated an integrated concave grating demultiplexer with 120 output channels and a 0.29nm channel spacing around 1550nm wavelength.[4,5] However, it was found that the fibre-to-fibre insertion loss increased dramatically for wavelengths below 1540nm. Simulation for this wavelength-dependent fibre-to-fibre insertion loss has shown that the loss was primarily due to the attenuation of the slab waveguide.

The slab waveguide used in the fabrication of the above device was deposited by plasma-enhanced chemical vapour deposition (PECVD) with silane, ammonia, nitrous oxide, helium and nitrogen. Since the hydrogen-rich precursors, i.e. SiH_4 and NH_3 gases, were used, the hydrogen atoms were incorporated in the resultant SiON layer as a byproduct of the deposition. N–H and Si–H bonds in the layer should give rise to the absorption around 1500nm wavelength as reported by others.[1,6] The purpose of the present study is to reduce the wavelength dependence of the slab waveguide absorption around 1550nm wavelength. By annealing the samples, we tried to drive hydrogen out of the SiON waveguide core without changing the properties of the materials including the claddings. Also, the losses were found to be decreased due to the improvement of the interface roughness and the material homogeneity after annealing.

2. Experimental details

The slab waveguide used in this work is composed of a 2.0μm SiON waveguide core with a refractive index of 1.50, a 0.5μm SiO_2 upper cladding and a 5.0μm SiO_2 lower cladding with a refractive index of 1.45. The layers were deposited by PECVD on silicon wafers. The annealing experiments were carried out in a N_2 atmosphere. To prevent the samples from cracking, the rising rate of the temperature at the beginning of the annealing and the lowering rate after the annealing were controlled to lower than 20 and 5°C/min, respectively.

The set-up used to characterize the insertion

losses of the waveguides is shown in Fig.1. The light source was a tunable diode laser with a wavelength range from 1520 to 1575nm. The laser light was coupled into a single mode polarization-maintaining fibre, which was in turn butt-coupled to one edge of the slab waveguide. A multimode fibre was butt-coupled to the opposite edge of the waveguide. To enhance the coupling efficiency between fibres and the slab waveguide, a type of index matching liquid was used. The output light from the multimode fibre was measured with a germanium photodiode and a lock-in amplifier.

The surface morphologies and structure of the waveguide material were characterized by atomic force microscopy (AFM), X-ray diffraction (XRD) and Fourier transform infrared (FTIR) measurements.

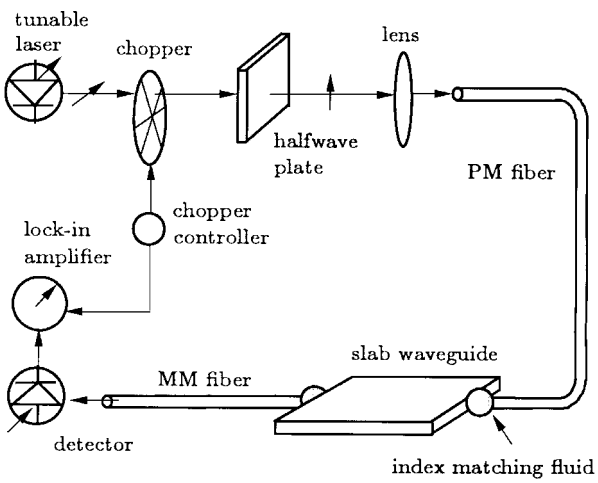


Fig.1. The set-up used to characterize the slab waveguide losses.

3. Results and discussion

As shown in Fig. 1, since the light diverges freely inside the slab waveguide, even if there is no waveguide loss, the signal received by the multimode fibre will still be much weaker than the input signal. Moreover, the coupling loss has to be considered. The coupling loss is mainly due to the mode-field mismatch between the fibre and the slab waveguide, which can be regarded as the same for all the samples. The loss due to reflection at the end of the fibre is negligible because of the use of the index matching liquid. During every measurement the signal received by the multimode fibre after propagating through the slab waveguide was first measured, keeping the laser output power constant and removing the slab waveguide away from between the two fibres which were then aligned to gain a maximum signal from the multimode. The fibre-to-fibre insertion losses for the slab waveguides were then obtained by comparing these experimental data.

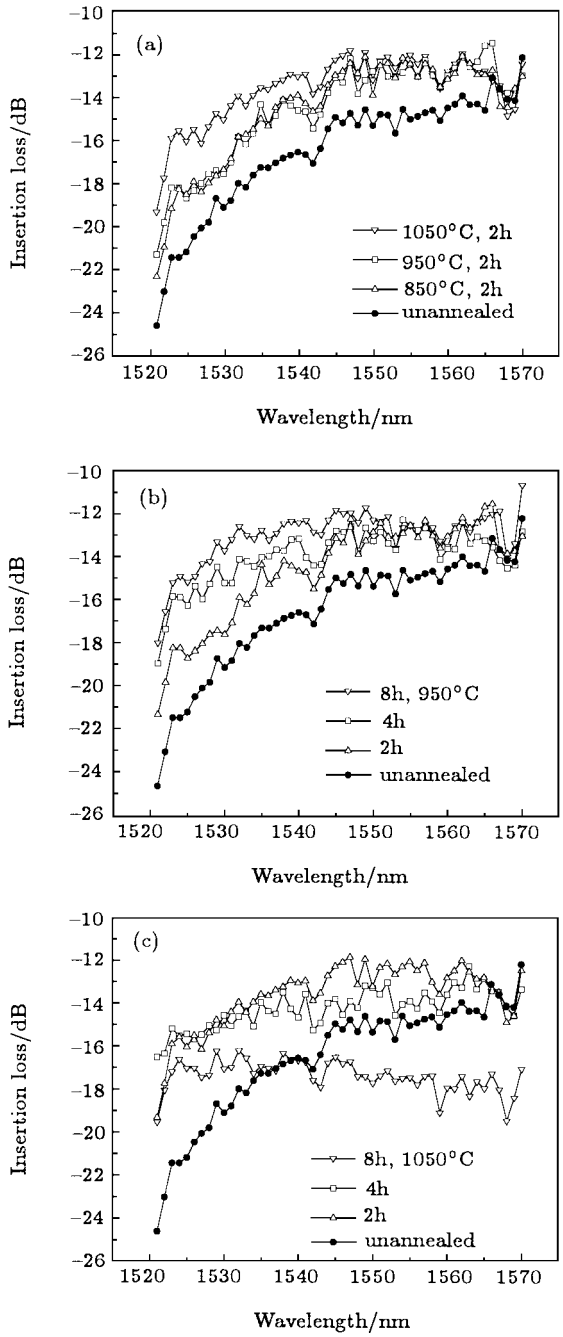


Fig.2. The insertion losses as a function of wavelength for the waveguides annealed at various conditions: (a) at three different temperatures for 2h; (b) at 950°C for 2, 4 and 8h; (c) at 1050°C for 2, 4 and 8h.

By using the above method, the fibre-to-fibre insertion losses of the slab waveguides were measured before and after annealing treatments. No detectable change of the refractive index contrast was obtained after annealing. As shown in Fig.2, the insertion loss

is shown as a function of wavelength for several annealing conditions. Figure 2(a) shows the results obtained for the samples annealed at three temperatures for 2h. It can be seen that annealing treatment not only greatly decreases the losses below 1540nm, but also reduces the losses in the longer wavelength range. The remarkable decrease of the losses can be obtained for the sample after annealing at 1050°C, although the wavelength-dependent loss is still evident in the wavelength range below 1540 nm. In order to further reduce the loss, especially for the wavelength below 1540nm, we extended the annealing time to 4 and 8h, respectively. Figures 2(b) and 2(c) show the comparison of the losses, which are expressed as a function of wavelength, before and after annealing for different annealing times. For the sample annealed at 950°C, we obtain the result as expected, i.e. the losses decrease with the increase of annealing time. For an annealing time of 8h, the loss at 1550nm is decreased by more than 5.7dB/cm. Especially, the loss is almost independent of wavelength in the region of 1530–1570nm. Such an improvement can be attributed to the reduction of the absorption caused by the N–H and Si–H vibration modes. It was found by FTIR absorption measurements that, for SiON films deposited on IR-transparent Si substrates, the absorption band around 1500nm wavelength, which corresponds to the absorption from the first overtone of N–H and the second overtone of Si–H bonds, is greatly decreased after annealing. However, an 8h annealing at 1050°C makes the loss at the longer wavelength increase, as shown in Fig.2(c). This may be related to the structural change of the waveguide material after annealing. Thus, the surface morphology and the structure of the waveguide material have to be characterized before and after annealing treatment.

Figure 3 shows the AFM morphologies for a bare SiON waveguide core before and after annealing at 950 and 1050°C for 8h. It was found that the root mean square (RMS) surface roughness is approximately 10.0nm for the unannealed sample. A treatment of 950°C annealing for 8h makes the surface of the SiON layer become smoother; the RMS surface roughness is less than 8.5 nm. However, as the sample was annealed at 1050°C for 8h, the surface of it becomes even rougher than before, and the RMS roughness increases to 14.5nm. These results are qualitatively consistent with those obtained by insertion loss measurements. The surface roughness of the unannealed SiON layer may be a result of the surface reaction during the deposition, and it reflects, to a certain extent, the fact that the bulk structure of the material is inhomogeneous. Light will be scattered by such an inhomogeneous structure and the interface roughness. For the sample annealed at 950°C for 8h, most of the incorporated hydrogen has been driven out of the layer. At the same time, the bulk homogeneity may be improved and the interface appears smoother. As a result, not only the wavelength-dependent absorption will be reduced, but also the losses from the scattering by the interface and the inhomogeneous material may be decreased. For the sample annealed at 1050°C for 8h, structural changes may occur in the material which becomes more inhomogeneous.

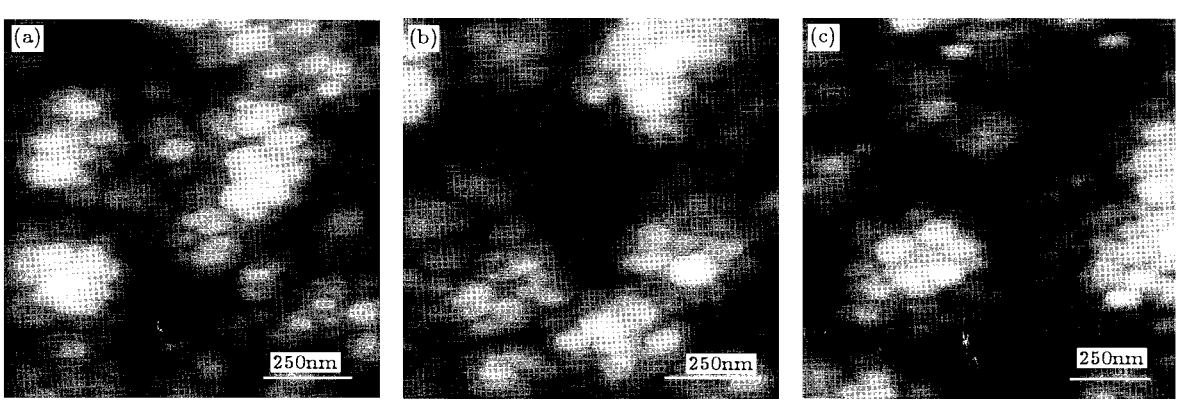


Fig.3. AFM images ($1\times1\mu m^2$) for bare SiON waveguide cores: (a) before annealing; (b) after annealing at 950°C for 8h; (c) after annealing at 1050°C for 8h.

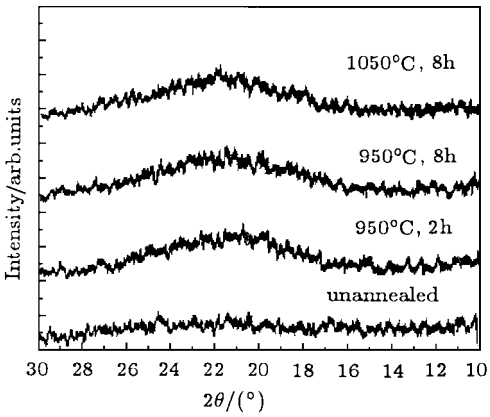


Fig.4. XRD spectra for SiON waveguide cores after annealing at various conditions.

The structure of the bare SiON waveguide core was also examined by XRD measurements. No obvious diffraction signal in the measured 2θ range from 10° to 70° was observed for the unannealed sample, indicating that the structure of the material is amorphous. After the sample was annealed, a band centred at 2θ=21.8° appeared, as shown in Fig.4. This fact suggests that the long-range order of the atom arrangement in the amorphous SiON layer has been enhanced after annealing. As the sample was annealed at appropriate conditions, the improvement of the long-range order of the atom arrangement was favourable for the propagation of light, and the absorption loss will be reduced.

4. Conclusions

The losses of SiON waveguides have been measured in 1550nm wavelength region on samples before and after annealing. The waveguide structure consisted of a 2.0μm SiON waveguide, a 0.5μm SiO_2 upper cladding and a 5.0μm SiO_2 lower cladding. The layers were deposited by PECVD on silicon wafers. It was found that the fibre-to-fibre insertion loss was decreased by more than 5.7dB/cm at 1550 nm after the sample was annealed at 950°C for 8h. The wavelength-dependent losses of the waveguide were greatly reduced after the annealing. The results can be attributed to the reduction of the absorption caused by N–H and Si–H vibration modes and the improvement of the interface roughness and homogeneity of the material after annealing.

Acknowledgments

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