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Annealing effects on the loss and birefringence of silicon oxynitride rectangular optical waveguides

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Silicon oxynitride rectangular optical waveguides have been fabricated by plasma-enhanced chemical vapor deposition and dry etching. The propagation loss and polarization dependent loss in as-grown samples show a substantial reduction after the samples have been annealed. Birefringence measurements before and after annealing on waveguides of different widths suggest that the waveguide modal birefringence is strongly affected by both waveguide geometry and stress in the material. Hence, the modal birefringence can be minimized by designing the appropriate waveguide geometry to compensate for any stress effects. © *2005 American Institute of Physics*.
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Silicon oxynitride has lately emerged as a potentially useful waveguide material because of its low propagation loss of 0.2 dB/cm at 1550 nm and a large variable refractive index.[1–5] The refractive index of the grown films can be easily adjusted continuously over a wide range between 1.46 and 2.0,[6] which will enable the fabrication of waveguides with a large variation of index difference, Δn, between the core and cladding layers. For example, weakly guided waveguides with small Δn are good for mode matching to standard single-mode fibers, whereas more strongly guided waveguides with large Δn are suitable for the fabrication of compact optoelectronic integrated circuits.

In this letter, the fabrication of buried rectangular silicon oxynitride (SiON) waveguides with different widths and having a core index around 1.5 is reported. The spectral loss and spectral polarization dependent loss (PDL) characteristics of the waveguides are compared before and after annealing. Additionally, the modal birefringence of waveguides of different widths is investigated in order to understand the origin of the birefringence and to provide a method of designing waveguides with zero birefringence.

The SiON thin films investigated in this study are deposited by plasma-enhanced chemical vapor deposition (PECVD) on Si wafers. The PECVD parameters are: Radio frequency is 13.56 MHz, power is 60 W, chamber pressure is 600 mTorr, and deposition temperature is 300 °C. The gases used are SiH_4, N_2O, N_2, and NH_3. Different gas flow ratios will change the refractive index of the deposited layer from 1.46 (for SiO_2) to 2.00 (for Si_3N_4) by changing the O/N composition ratio in the SiON.[6] Buried rectangular waveguides are fabricated by depositing, etching, and redepositing multiple layers of SiON of different compositions on the Si wafer. On the same piece of Si wafer, waveguides with different widths are fabricated at the same time. The refractive indices of the core and cladding layers are approximately 1.515 and 1.500 at 1550 nm, respectively. The index difference is about 1%. The thickness of the core layer is about 3.66 μm. The structure of the waveguide cross section is shown in Fig. 1.

The propagation loss of the waveguide is measured by the direct cut back method.[7] The waveguide length under measurement varies from 0.2 cm to 1.4 cm. Polarized light is used to distinguish between the loss in the transverse electric (TE) and transverse magnetic (TM) modes and a tunable laser is used to measure the loss spectrum. Figure 2 shows the loss spectra of the TE mode, TM mode and the PDL of a rectangular waveguide measuring $3.9 \times 3.7\ \mu m^2$. The data shown represent the average values of the measurements on waveguides with different lengths. Both the TE and TM modes in the as-grown films exhibit a huge loss peak around

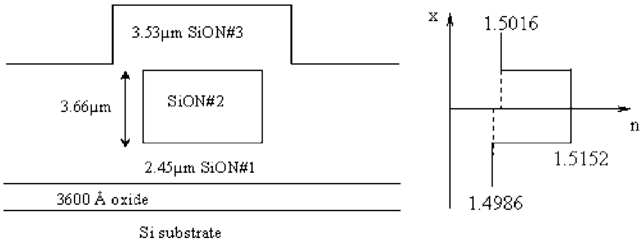

FIG. 1. Cross section and index profile of the step-index channel waveguide.

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TABLE I. Silicon oxynitride film parameters before and after annealing.

Sample No.	Before annealing		After annealing	
	n (1550 nm)	Thickness (μm)	n (1550 nm)	Thickness (μm)
1	1.4986	2.45	1.5098	2.30
2	1.5152	3.66	1.5322	3.38
3	1.5000	4.37	1.5082	4.24
4	1.5141	4.59	1.5315	4.28

1510 nm, which is caused by the absorption of the N–H bonds. Presumably, this strong absorption can be greatly reduced by annealing the materials at 1150 °C under N_2 atmosphere.[8] In order to investigate the annealing effect on the waveguide parameters, such as propagation loss, PDL, and modal birefringence, the SiON waveguides are annealed at 1050 °C under N_2 atmosphere for 1 h. Some film parameters before and after annealing are listed in Table I. Layers 1 and 3 correspond to the cladding layers of the waveguides and Layers 2 and 4 correspond to the core layers of the waveguides. The refractive index and the film thickness are measured by the prism coupling method, which has a measurement accuracy of approximately $1-4\times10^{-5}$. The results show that all the samples have their refractive index values increased and their thicknesses reduced after annealing. This change has been reported to be primarily caused by gaseous release and film densification.[5]

In our experiments, the loss spectra of the TE and TM modes have been measured after annealing, and the significant reduction observed in the loss peak does support the theory that this peak is due to the absorption of the N–H bonds. For a clearer view of the figure, only the TE loss spectrum after annealing is included in Fig. 2. The PDL spectra are also shown, which indicate that the PDL is independent of wavelength in the range measured either before or after annealing. In order to investigate the PDL in these waveguides in more detail, a set of waveguides—which were prepared under the same conditions and which have the same step height of 3.66 μm but different widths—are measured at 1550 nm before and after annealing. Their average PDL values over several measurements on the same waveguides are listed in Table II. It is worth noting that all the data in Fig. 2, including the PDL of the 3.9×3.7 μm^2 channel waveguide, are measured by the direct cut back method on waveguides with different lengths. Besides, the data in Table II including the PDL of the 3.9×3.7 μm^2 channel waveguide are measured by an Agilent Lightwave Polarization Analyzer. All the waveguides belong to the same wafer. The consistency of the data in Fig. 2 and Table II indicates that the random variations from waveguide to waveguide are negligible.

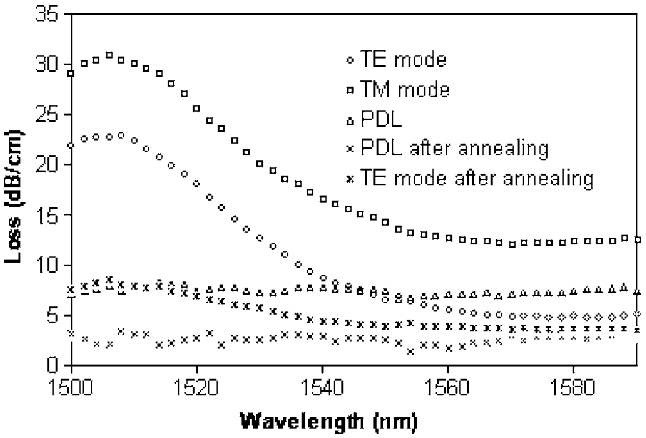

FIG. 2. Loss spectra of the 3.9×3.7 μm^2 buried channel waveguide.

It is interesting to note that although the PDL of the samples listed in Table II is quite large before annealing, it becomes much smaller after annealing. One possible reason for the excessive PDL in as-grown samples is that as the oxynitride material is being deposited on a lattice-mismatched substrate of Si, an inhomogeneous and anisotropic stress distribution is built up during the deposition and waveguide patterning processes. The resultant stress tensor with nonzero off-diagonal elements will tend to couple the TM mode to the radiation mode or cladding mode of the waveguide, as reported in Ref. 9. Hence, this will result in a large PDL before annealing. Furthermore, since the stress tensor is also affected by the waveguide geometry in a complicated manner, it is not surprising to see that the initial PDL varies in an irregular manner with the waveguide width. It also appears that waveguides with a more symmetric geometry (i.e., squarelike) have a smaller PDL. The subsequent annealing process is believed to cause the stress built up inside the material to be more isotropic and also the material to become more homogeneous. As a result, the values of the off-diagonal elements of the stress tensor may be substantially reduced, thus significantly reducing the coupling of the TM mode to the radiation and cladding modes. Therefore, the PDL is substantially reduced by annealing. However, it is observed that there still remains a residual PDL, which does not show any clear relationship with the waveguide width. This residual PDL may be caused by the etched sidewall roughness (which should affect one particular polarization more than the other) and/or any residual anisotropic stress.

TABLE II. Measured PDL and DGD at 1550 nm for samples of different waveguide widths before and after annealing.

Waveguide width W (μm)	Before annealing			After annealing		
	PDL (dB/cm)	DGD (ps/cm)	Birefringence	PDL (dB/cm)	DGD (ps/cm)	Birefringence
4.8	20.47	0.0110	0.00033	1.07	0.0028	0.00008
3.9	8.39	0.0045	0.00013	1.94	−0.0034	−0.000 10
3.0	13.84	−0.0047	−0.000 14	2.46	−0.0157	−0.000 47
2.3	17.95	−0.0265	−0.000 79	1.50	−0.0442	−0.001 33

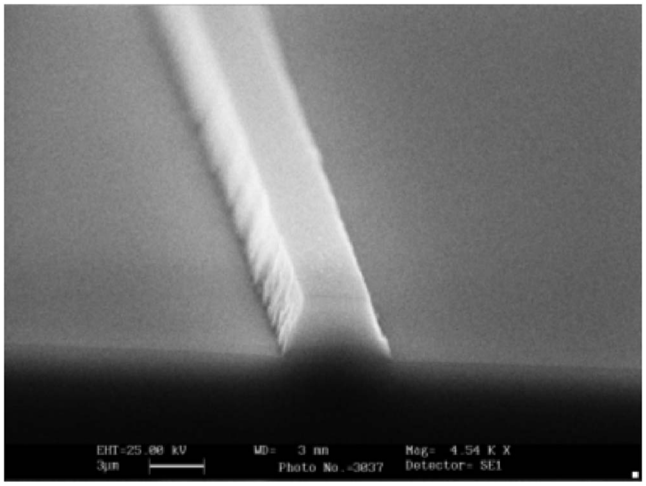

FIG. 3. SEM of the waveguide strip.

The roughness of the waveguide sidewall can be clearly observed in the scanning electron micrograph (SEM) shown in Fig. 3.

The birefringence of thin films has been reported using a variety of measurement methods.[10,11] Here, the modal birefringence of the SiON channel waveguides are investigated and characterized by measuring the differential group delay (DGD) between two orthogonally polarized modes. The differential group delays between these two modes are measured both before and after annealing on the same set of waveguides and the average values over several measurements are listed in Table II. From the measured DGD, the corresponding modal birefringence values are calculated and also listed in Table II. Figure 4 plots the modal birefringence versus waveguide width for these waveguides. It has been known that the internal compressive stress in the uniform oxynitride film is relaxed by annealing at a temperature below 500 °C. When the annealing temperature is between 500 °C and 700 °C, the stress will change to tension. A further increase in the annealing temperature will result in a relaxation of the internal tensile stress.[4] In order to understand the results thus shown, we should note that the waveguide modal birefringence is a function of both the index difference (which also depends on the stress distribution) between the cladding and core layers (Δn) in the two polarization directions and the dimensions of the waveguides. Unfortunately, the stress distribution, the index difference, and the waveguide dimensions will all be changed by annealing.

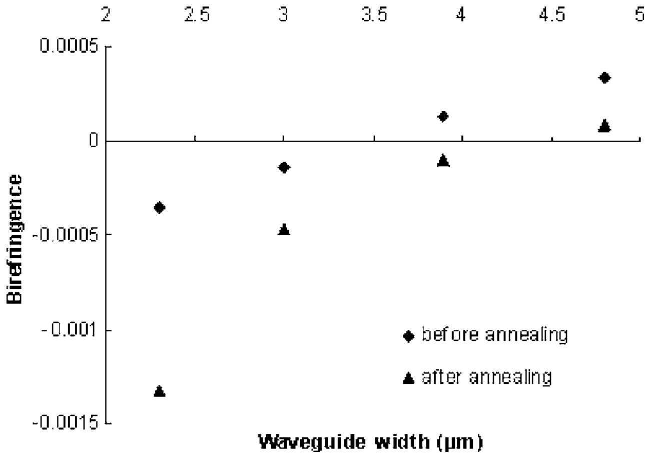

FIG. 4. Modal birefringence as a function of channel waveguide width before and after annealing.

Hence, the change in birefringence due to annealing is too complicated to analyze, especially when it is very difficult to measure the stress in channel waveguides directly. However, one can still observe three interesting characteristics in Fig. 4. First, the birefringence tends to shift downward (i.e., become more negative) after annealing in all the cases. This implies that the modal index change in one of the two directions must always play a more dominant role in the annealing process. In our case, we found that the increase in the effective index of the TM mode is always larger than that of the TE mode. Second, there is a clear variation of birefringence among the samples both before and after annealing. Yet our mode calculation based on the waveguide geometry and the measured material indices cannot account for such a large variation. Hence, we believe a stress effect must also be present, although it cannot be quantified. Third, geometrically more symmetric (squarelike) waveguides tend to have a smaller birefringence, both before and after annealing. In order to achieve zero modal birefringence, one should therefore try to design the channel waveguide in a form close to a square and then fine-tune the geometry to completely nullify the modal birefringence caused by the stress effect.

In summary, buried rectangular channel SiON waveguides have been fabricated on Si by PECVD and dry etching. The propagation loss spectra of the waveguides show an absorption peak around 1510 nm, which can be greatly reduced by annealing. Measurements of loss and PDL before and after annealing suggest that annealing can reduce the anisotropy of the stress and the inhomogeneity of the material. Birefringence measurements before and after annealing the waveguides suggest that the stress changes induced by annealing along the two orthogonal directions are different and will therefore result in birefringence changes. One can therefore make use of these results in designing waveguides with zero birefringence by appropriately adjusting the sample geometry and annealing the samples.

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