Reduction of hydrogen induced losses in PECVD-SiO_xN_y optical waveguides in the near infrared

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The hydrogen in PECVD-SiO_xN_y was studied with IR spectroscopy and ERD analysis as function of the O/N ratio and the annealing treatment up to 1150 °C. The results were compared with measured spectral waveguide losses.

Introduction

Silicon oxynitride is a flexible material for use as planar optical waveguides because by changing the composition (O/N ratio) the refractive index can be tuned from 1.46 to 2.0¹. Several methods can be used for deposition: PECVD, LPCVD and sputtering. The advantages of PECVD are easy control of composition, high deposition rate and low stress. A disadvantage is the high hydrogen content, up to 30 at%. Absorption bands from Si-OH and N-H at resp. 1380 nm and 1510 nm have to be reduced for telecommunication applications². It is known that the amount of hydrogen can be reduced by annealing, but this complicated process depends strongly on the deposition conditions³.

Experimental

SiO_xN_y films were deposited with a parallel plate PECVD reactor (Electrotech 310) with dual frequency plasma generator, 187.5 kHz and 13.56 Mhz. The deposition conditions are given in table I.

Table I. Deposition conditions.

Parameter	Value
Substrate temperature	300 °C
RF frequency	187.5 kHz
RF power	60 W
Process pressure	86 Pa
SiH ₄ + N ₂ flow (2% SiH ₄)	1000 sccm
NH ₃ flow	3 sccm
N ₂ O flow	0 - 1000 sccm

The substrates were bare 3" silicon wafers for the analysis and oxidised wafers for waveguide structures. Samples of the wafers were annealed in a tube oven at 700, 1000 and 1150 °C under nitrogen flow. The composition of thin (140 nm) films was determined with RBS and ERDA. Furthermore the hydrogen content and bonding type was determined by transmission IR spectroscopy using films of around 1 µm thick. The hydrogen concentration was evaluated from the IR peak area of the N-H peak at about

3370 cm⁻¹ and the Si-H peak at about 2230 cm⁻¹ using the calibration factors from Lanford and Rand⁴.

Waveguide loss spectrum

In figure 1 a loss spectrum of a SiO_xN_y waveguide on top of a thermal oxide buffer layer is given. The peak at 1510 nm is the first overtone of the N-H vibration. The shoulder at about 1400 nm corresponds with the Si-OH absorption band, but no Si-OH absorption is observed in the transmission spectrum. It is therefore likely that for some reason the background has changed. Si-OH absorption peaks are only observed in PECVD SiO₂ films.

Fig.1. Loss spectrum of the zero-order mode of a SiO_xN_y waveguide with refractive index of 1.7 and a thickness of 0.9 µm. Bufferlayer 2.8 µm thermal oxide. The single point is a single wavelength measurement at 1523 nm.

The losses measured at 632.8 nm were about 1 dB/cm for as deposited waveguides and below 0.5 dB/cm after a moderate anneal at 500 °C⁵.

Composition as deposited films

The O/N ratios of SiO_xN_y films have been varied by changing the N₂O flow. The refractive index can be varied from 2.0 for no N₂O flow to 1.52 for a N₂O flow of 1000 sccm. The composition of the different films prepared according to the conditions in table I, is presented in figure 2. The amount of hydrogen clearly depends on the O/N ratio in the film. The amount of Si-H in the nitride is high. It reduces sharply upon incorporation of O in the film.

In table II we present the hydrogen concentration as determined with IR spectroscopy of films with $n=1.7$ for two plasma generator frequencies and pressures.

Fig.2. Composition as function of N_2O flow. The atomic fraction of each element is given by the distance between the lines below and above its name. The hydrogen fraction is split into two fractions bonded to resp. nitrogen and oxygen.

Table II. Hydrogen content (at%) for different deposition conditions.

Pressure → Frequency ↓	40 Pa			86 Pa		
	SiH	NH	ΣH	SiH	NH	ΣH
187.5 kHz	1	25	26	4	20	24
13.56 MHz	9	18	27	18	12	30

The lowest hydrogen content is reached with low frequency and high pressure, our standard process. Furthermore the Si-H content is high for the high frequency and pressure. As we will see in the following this influences the annealing behaviour strongly.

Annealing

We observed several effects after annealing, a reduction of the hydrogen content (fig.3), a decrease of thickness and refractive index and a change in stress from compressive to strong tensile. Films with a refractive index above 1.6 cracked at 1000 and 1150 °C annealing. The initial Si-H amounts in these films are larger than 4 at%, while the Si-H amounts in the not cracked films are < 1 %. The same trend was observed after annealing of the samples mentioned in table II, all samples cracked at 1000 °C, except for the one made with 187.5 kHz and 40 Pa, which cracked only at 1150 °C.

Conclusions for waveguides

The above results show that there is a combination of deposition parameters and annealing treatment possible for which the final hydrogen content is rather low. On bases of the measured loss in figure 1

and the amount of N-H in that film we expect that the waveguide absorption loss can be calculated from the fraction N-H by the next equation:

$$\text{loss(dB/cm)} = 0.8x[\text{N-H}](\text{at}\%)$$

Fig.3. The total hydrogen fraction before annealing (Δ) and after annealing at 700 °C ($\circ$), 1000 °C ($\square$) and 1150 °C (∇). The grey area covers the conditions where cracking of the film occurs.

The expected losses at the absorption maximum at 1510 nm for two annealed films are given in table III. These values are rough estimates. At a wavelength of 1550 nm the values will be substantial lower.

Table III. Expected absorption losses for annealed SiO_xN_y waveguides.

n	[N-H] in at%	loss in dB/cm
1.52	0.7	0.6
1.6	2	1.6

Our conclusion is that we have shown that low loss PECVD SiO_xN_y waveguides for use in telecommunication applications are possible in spite of the high initial hydrogen concentration in these films.

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