Low propagation loss SiN optical waveguide prepared by optimal low-hydrogen module

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Abstract: We investigated low-hydrogen SiN films prepared by a low temperature (350 ˚C) PECVD method. The impact of SiH_4/N_2 flow ratio and radio frequency power on the hydrogen content in the SiN films was studied. In this work, we demonstrated a low-loss sub-micron SiN waveguide by using the corresponding optimal SiN films. The propagation loss was found to be as low as -2.1±0.2 dB/cm at 1550nm with waveguide cross-section of 700nm×400nm. The results suggest that the SiN films grown by PECVD with low hydrogen can be used in photonics integrated circuits for new generation communications applications.

OCIS codes: (130.3120) Integrated Optics devices; (220.4000) Microstructure fabrication; (230.0230) Optical devices; (130.2790) Guided waves.

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1. Introduction

Silicon nitride (SiN) films have been considered as a potential candidate as optical waveguide materials for various optical devices in passive planar lightwave circuit and multifunctional devices for optical communications and interconnections because of their high refractive index, flexible dimension control and superior interface properties [1, 2]. However, due to the hydrogen bonds in the SiN films, SiN waveguide suffers from the high propagation loss problem. Hydrogen in SiN films is covalently bound to Si and N. Both the N-H bonds and Si-H bonds cause absorption in the telecom spectrum. Especially, the N-H bonds act as absorption centers and their low energy tail lead to undesirable absorption loss in the region of 1510-1565 nm [3-7].

Low pressure chemical vapor deposition (LPCVD) and plasma enhanced chemical vapor deposition (PECVD) are the two most popular methods of depositing SiN films. LPCVD films are deposited at high temperatures (~800 ˚C) with comparatively low H-content [8, 9]. In comparison, PECVD films are deposited at lower temperatures (300-500^{o}C) with higher H-contents. The large disparity between H-contents in the two deposition methods is mostly due to the process-temperature, since high temperature processes provide the high kinetic energy which can (break) drive the hydrogen (bonds) out from the N-H bonds [3, 10]. In order to reduce the content of hydrogen in the SiN films deposited by PECVD, the post-deposition oxidation or annealing at high temperature (600-1050^{o}C) were typically executed [11-13]. However, in terms of utilizing SiN materials as an upper chip level photonic wire devices, the deposition temperature must be compatible with low thermal budget requirement, for instance, the existing active devices. Furthermore, LPCVD is difficult to deposit a single layer of thick enough film due to high stress problem. Therefore, SiN films deposited by PECVD at low temperature with low stress and without post-annealing have become attractive.

Typical PECVD reactions are of the kind $SiH_4 + NH_3 \rightarrow Si_xN_y{:}H + H_2$. Due to the low temperatures and a variety of reactions taking place in the chemistries, undesirable N-H and Si-H bonds are formed in the films. Since the hydrogen comes from the deposition reactants, the density of hydrogen can be reduced by changing the deposition precursors in the experiments.

In this work, the PECVD precursor chemistries are optimized to reduce the H-incorporation in the films by implementing N_2 precursor instead of NH_3. SiN films grown by the low hydrogen reactant PECVD are studied in detail. The effects of different SiH_4/N_2 flow ratio and RF power on N-H and Si-H bonds components have been investigated. Furthermore, a submicron optical waveguide based on the SiN material is fabricated. The propagation loss is measured to be ~2.1dB/cm at 1550nm with the reactants SiH_4/N_2 flow ratio of 80sccm/4000sccm and RF power of 400W.

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2. Experiments

The SiN films were deposited on p-type 8″ Si wafers in a parallel-plate type Applied Materials CENTURA System 5200 PECVD reactor. The films were grown at 350°C and 4.2 Torr pressure. The RF power changed from 350 W to 500 W in different experiments. The refractive index and the thickness of the films were characterized by Optic-Probe 5240i at the wavelength of 673 nm. The hydrogen absorption peaks of N-H (at ~3350cm^{-1}) and Si-H (at ~2200cm^{-1}) in the SiN films were examined by Fourier transform infrared (FTIR) spectrum.

Two kinds of SiN films deposited by different precursors reactions were fabricated. One was utilized by typical precursors of SiH_4, NH_3 and N_2. Among them, SiH_4 and NH_3 were served as reactants and N_2 was used to enhance the plasma, and the flow rates were 460sccm, 4000sccm and 1600sccm, respectively. Another was with low hydrogen precursors reactants of SiH_4 and N_2. The flow rates were 110sccm and 4000sccm, respectively.

For low hydrogen reaction, the effects of SiH_4/N_2 flow ratio on hydrogen bonds were studied. The SiH_4 flow rate was set at 110sccm, 80sccm and 70sccm, respectively, and the N_2 flow rate was changed from 3000sccm to 4000sccm with the fixed RF power of 400W. The effects of the RF power on hydrogen bonds were also discussed. The RF power was varied from 350W to 500W with a step of 50W with the reactants SiH_4/N_2 flow rates fixed at 80sccm/4000sccm. The details of the growth parameters and the corresponding refractive indexes of the SiN films are listed in Table I. It can be seen that the deposition rates of all our SiN films are in the range of 21~35.8 Å/s. The refractive index varies from 1.89-2.32.

Table I Deposition parameters of SiN films

No.	SiH_4:N_2 ratio (sccm:sccm)	RF (W)	refractive index	Dep. rate (Å/s)
1	110:2200	400	2.32	35.8
2	110:3000	400	2.31	32.9
3	110:4000	400	2.30	31.6
4	80:3000	400	2.10	23.1
5	80:4000	400	2.03	22.8
6	70:4000	400	1.93	19.3
7	80:4000	350	2.19	22.8
8	80:4000	450	1.93	21.5
9	80:4000	500	1.89	21.0

Some optimized SiN films were selected for SiN waveguides. A 5μm-thick SiO_2 layer was first deposited on 8″ bare silicon wafers by PECVD. Such thick SiO_2 layer can reduce optical leakage from SiN waveguide into the silicon substrate effectively. The atomic force microscope (AFM) image of the SiO_2 surface after deposition is shown in Fig. 1(a). The roughness is ~2.13 nm. To reduce the scattering loss of the waveguide, the surface of the SiO_2 layer was polished by chemical mechanical polish (CMP), as shown in Fig. 1(b). The roughness after CMP is only ~0.18 nm. Next, a 400nm-thick SiN layer was deposited on the SiO_2 layer. The SiN layer was patterned by 248nm deep UV lithography and etched down till the buried SiO_2 by dry etching process. Finally, a 2um-thick SiO_2 layer was deposited as the upper cladding by PECVD. The width of the waveguide is 700nm. Figure 2(a) is the schematic of the cross-section structure of the waveguide. For efficient coupling light between

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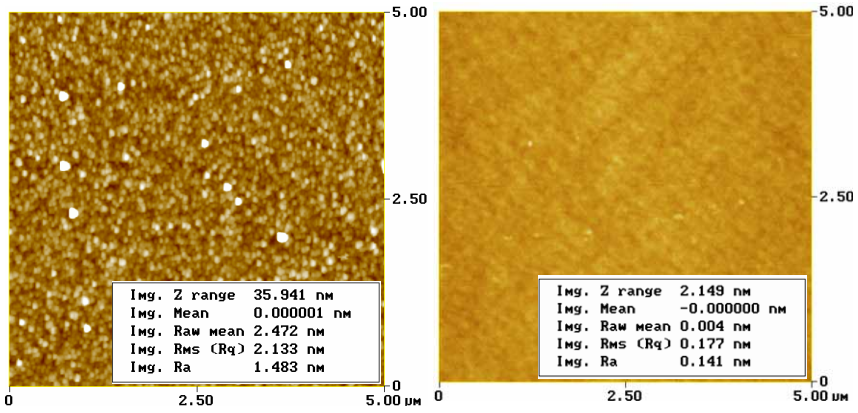
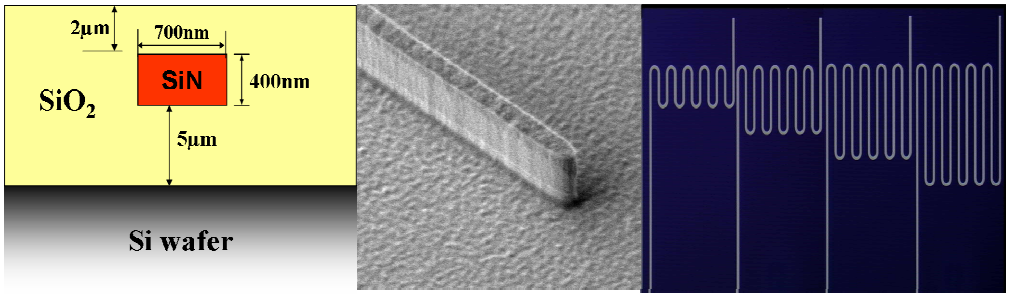
a lensed polarization-maintaining fiber and a sub-micron waveguide, an inversely tapered waveguide was integrated at each end of the waveguides. The tip structure of the SiN waveguide is shown in Fig. 2(b).



(a) AFM before CMP (b) AFM after CMP

Fig. 1. AFM picture of the surface of the deposited SiO_2 layer before and after CMP



(a) (b) (c)

Fig. 2. (a) The schematic structure of the waveguide cross-section; (b) SEM image of the SiN waveguide tip structure; (c) The cut-back pattern of the waveguides.

Our waveguides were designed with various lengths from 3.6mm to 24mm with step of 2.5mm. Thus, the waveguide propagation loss can be determined via a cutback method. The waveguide pattern is shown in Fig. 2(c).

Before the insertion loss measurements, we diced the wafers first, and then polished the coupling facets of the samples with diamond films. We characterized the power of the laser source at 1550 nm with a power meter. Then we connected the laser, waveguide, and power meter with lensed fibers. The focus spot size of the lensed fiber is ~2.5 µm. We aligned the lensed fibers and the waveguide sample with three-dimensional precision stages and measured the insertion loss. The insertion loss was recorded as fiber to fiber loss, which included the coupling losses and the propagation losses of the waveguides.

3. Results and discussion

Figure 3 shows the FTIR absorbance spectra of the typical PECVD and the low hydrogen PECVD films, whose process parameters were described in the experiment section. The absorption humps due to Si-N, N-H and Si-H stretching vibrations are clearly indicated. It can be seen that there are obvious Si-H and N-H bonds in the typical sample, whereas the N-H bond peak is nearly disappeared in the low hydrogen sample. Based on the Si-H and N-H stretching bonds, the concentrations of bonded hydrogen can be derived from the well-known

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calibration factors originally obtained by Lanford and Rand[14]. The equations, which relate the concentrations of N-H and Si-H bonds to the areas of the N-H and Si-H absorbance lines, respectively, are:

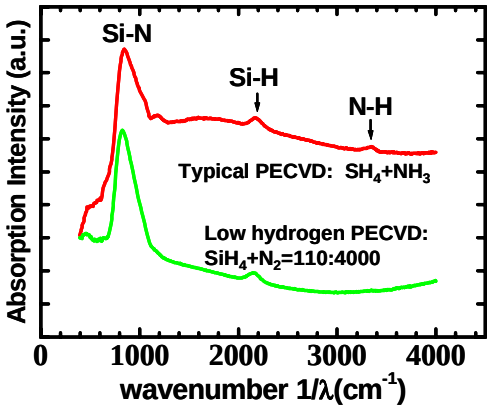
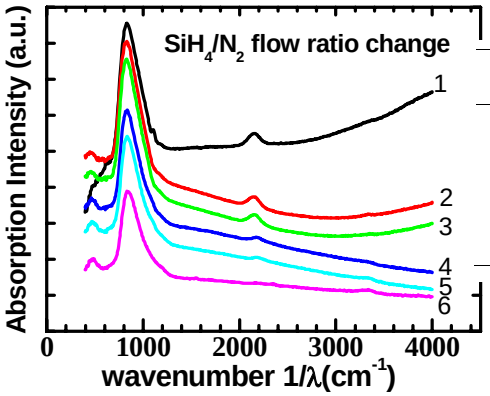


Fig. 3. FTIR absorbance spectra of typical and low hydrogen PECVD SiN films



No.	[Si-H] $10^{21}cm^{-3}$	[N-H] $10^{21}cm^{-3}$	[H] $10^{21}cm^{-3}$
1	14.06	0.11	14.17
2	13.40	0.12	13.52
3	12.14	0.42	12.56
4	6.46	2.85	9.31
5	3.94	5.11	9.05
6	1.07	9.55	10.6

Fig. 4. FTIR absorption spectra as a function of SiH_4/N_2 flow rates in low hydrogen PECVD. The inset shows the Si-H bond, N-H bond and total hydrogen concentration calculated by using the FITR spectroscopy.

$$[N-H]=\frac{1}{2.303\times\sigma_{N-H}}\times\int_{band}\alpha(\omega)\mathrm{d}\omega \quad \text{and} \quad [Si-H]=\frac{1}{2.303\times\sigma_{Si-H}}\times\int_{band}\alpha(\omega)\mathrm{d}\omega$$

Where $\sigma_{N\text{-}H}=5.3\times10^{-18}cm^2$ and $\sigma_{Si\text{-}H}=7.4\times10^{-18}cm^2$ denote the absorption cross-sections for N-H, Si-H respectively; $\int\alpha(\omega)\mathrm{d}\omega$ is the normalized absorption area of the band and $\alpha=\frac{2.303}{t}A$ is the absorption coefficient, in which A is the absorbance and t is the film thickness.

The calculated N-H bond concentration decreases from $6.88\times10^{21}cm^{-3}$ to $0.425\times10^{21}cm^{-3}$, with the total hydrogen concentration (the sum concentration of the N-H and Si-H bonds) decreasing from $1.93\times10^{21}cm^{-3}$ to $1.26\times10^{21}cm^{-3}$accordingly. As is expected, the reduction of the hydrogen contents among the precursor reactants could exactly reduce the hydrogen contents of the SiN films. Some further studies will be discussed below.

The effects of different SiH_4/N_2 flow ratios on the FTIR absorbance spectra of the SiN films are illustrated in Fig. 4, in which the RF power is fixed at 400W. The corresponding N-H, Si-H bond concentration calculations of SiN films are list in the inset of Fig. 4. The results

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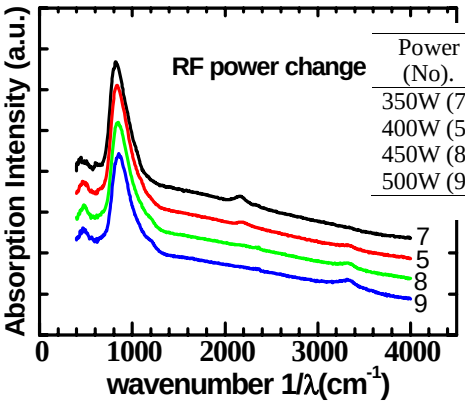
of the calculations indicate that the Si-H bond concentration is decreasing from $14.06\times10^{21}cm^{-3}$ to $1.07\times10^{21}cm^{-3}$ with the SiH_4/N_2 flow ratio. Especially, there is a sharp decrease when the SiH_4 flow rate is reduced from 110sccm to 80sccm. However, the concentration of the N-H bonds exhibits the opposite trend. The formation of the Si-H and N-H bonds appear as a



Power (No.)	[Si-H] $10^{21}cm^{-3}$	[N-H] $10^{21}cm^{-3}$	[H] $10^{21}cm^{-3}$
350W (7)	9.06	1.14	10.20
400W (5)	3.94	5.11	9.05
450W (8)	0.45	9.13	9.58
500W (9)	0.43	13.84	14.27

Fig. 5. FTIR absorption spectra as a function of RF powers, where the SiH_4/N_2 flow rate are 80sccm/4000sccm The inset shows the Si-H bond, N-H bond and total hydrogen concentration calculated by using the FITR spectroscopy.

competitive process. The lowest total hydrogen concentration was gained at sample 5, with the SiH_4/N_2 flow ratio of 80sccm/4000sccm at RF power of 400W.

As shown in Table I, the refractive index and deposition rate of the SiN films continuously decrease with the ratios of SiH_4/N_2 flow rates at an RF power level of 400W. The refractive indexes of the SiN film for Samples 1, 2, 3 (~2.3) are much higher than that of the stoichiometric SiN film, owing to the formation of the Si-rich radicals [12]. There is a large amount of Si-H incorporated with the SiN films when the ratio of the flow rates is high, which is also confirmed in Fig. 4. As to the deposition rate of the SiN films, the reduction is due to the decrease of the reactants.

The effects of different RF powers on the FTIR absorption spectra of SiN films are presented in Fig. 5, in which the ratio of SiH_4/N_2 flow rates is fixed at 80sccm/4000sccm. The corresponding N-H, Si-H bond concentration for the SiN films are listed in the inset of Fig. 5. The calculation results indicate that the Si-H bond concentration steadily decreases as the RF power increases, while the concentration of the N-H bonds increases with the RF power. These results can be explained that the N radicals increase with the RF power, which prefer to bond with H and further form N-H bonds incorporated with SiN films. With the increase of the RF power, the deposition rate decreases continuously due to the occurrence of a strong radical stream on the film surface.

The lowest total hydrogen concentration was obtained at the RF power of 400W. Therefore, we conclude that the RF power of 400W would be the best process condition.

To investigate the optical propagation loss of the low hydrogen SiN waveguide, we characterized the fabricated SiN waveguides using the cutback method. Samples 4 and 5 were selected to fabricate waveguides because of the lower hydrogen concentration observed from the FTIR spectrum. The measurements show that waveguide sample 4 has propagation loss of -2.3±0.2dB/cm, while waveguide sample 5 has a lower propagation loss of -2.1±0.2dB/cm. Figure 6 shows the cutback measurements for the waveguides made from the SiN films sample 5.

For comparison, previous works and this work on SiN waveguides are listed in Table II. The waveguides reported in literature are chosen based on the waveguide structure and working wavelength. To the best of our knowledge, as the cross-sections of the channel waveguides are strictly limited to sub-micron dimension and the working wavelength is in

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communication band (near 1550nm), all the reported SiN waveguides listed in Tabel II are made by high temperature LPCVD except ours grown by PECVD. It can be seen from the table that the SiN films made by PECVD or LPCVD have comparable refractive index. As is well known, LPCVD SiN films suffer from high stress issue and limited deposition thickness.

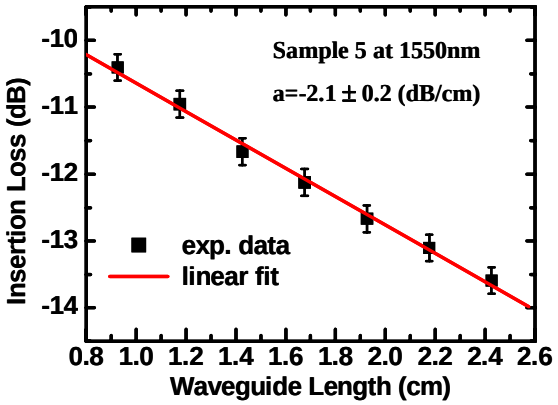

Fig. 6. Insertion loss measurements as a function of waveguide length of sample 5, at 1550nm. The propagation loss is calculated as -2.1 ± 0.2 dB/cm.

The high temperature (750-900°C) required in LPCVD poses a challenge for the optical-electronic device integration. On the contrary, PECVD SiN films used for our waveguides were formed at low temperature (at ~350 °C) with low stress, for example, 600nm-thick SiN film without any cracking was achieved using the same process condition in our previous study. The PECVD SiN waveguides exhibit very low propagation loss at wavelength of 1550nm.

Table-II Comparison of SiN Waveguides

Authors	Waveguide Structure	SiN core Deposition method	Refractive index of SiN	Propagation loss (dB/cm)
Melchiorri et. al. [15]	Channel, alternating SiN/SiO2 layers, 1um×0.5um	LPCVD	~2.19	1.5 (@1550nm)
Philipp et. al. [16]	Channel, 1.2um×0.33um, BOX, Top clad: 10um BPSG	LPCVD	2.06	1.2±0.5 (wavelength not mentioned)
Barwicz et. al.[17]	Channel, 1.05um×0.44um; BOX: 2.54um Top clad: air	LPCVD	2.217	3.6 (wavelength not mentioned)
Daldosso et. al. [18]	Channel, 10um×0.2um Bottom clad: 2um BPSG	LPCVD	~2.0	4.5-5.0 (@1544nm)
This work.	Channel, 0.7um×0.4um BOX: 5um Top clad: 3um SiO2	PECVD	2.03	2.1±0.2 (@1550nm)

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4. Conclusion

PECVD with low hydrogen reactants is an effective method to reduce the hydrogen content of SiN films. Both SiH_4/N_2 flow ratio and RF power can affect the density of the N-H bonds and Si-H bonds. In our experiments, the optimal process conditions are the SiH_4/N_2 flow ratio 80sccm/4000sccm and the RF power 400W. The propagation loss of the corresponding sub-micron (700nm×400nm) waveguide is ~2.1±0.2dB/cm at 1550nm. The temperature is controlled under 350 ^oC in the full process, and no post-deposition annealing is involved. This low hydrogen PECVD SiN film can be a promising solution in photonics integrated circuits for new generation communications applications.

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