Low Hydrogen Silicon Nitride Films Deposited by Plasma Enhanced Chemical Vapor Deposition

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ABSTRACT

This work investigates the physical mechanisms that govern hydrogen incorporation into PECVD SiN_x, for a more thorough correlation of N-H and Si-H bond density with propagation losses in SiN waveguides. In particular, the N-H bond in PECVD SiN has been shown to have an overtone at 1550 nm, resulting in substantial propagation losses for optical waveguides at telecommunication wavelengths. With proper optimization of process parameters, we are able to obtain propagation losses as low as -1.6 +/- 0.1 dB/cm at 1550 nm without a thermal anneal.

INTRODUCTION

Though $H:SiN_x$ is used in numerous applications and has been extensively studied, there is increasing interest in plasma enhanced chemical vapor deposition (PECVD) of SiN_x for low temperature photonic applications. However, significant hydrogen incorporation plagues PECVD deposited SiN_x. A high N-H bond density is particularly deleterious for photonic applications at1550 nm. High temperature processes approaching 1000 C are often employed in order to drive out hydrogen, significantly limiting the integration schemes.

While many groups have attempted to decrease N-H bond density merely by decreasing or removing NH_3 as a precursor, this work correlates the effect of all precursor chemistries on propagation loss.

EXPERIMENTAL

Films were deposited in an Applied Materials P5000 PECVD chamber on 6", low resistivity silicon wafers. SiH_4 flow, NH_3 flow, and N_2 flow were varied while measuring refractive index (from 375 nm to 1675 nm), deposition rate, uniformity, and residual film stress of the SiN_x films. Si-H and N-H bond densities were calculated from fourier transform infrared spectroscopy (FTIR).

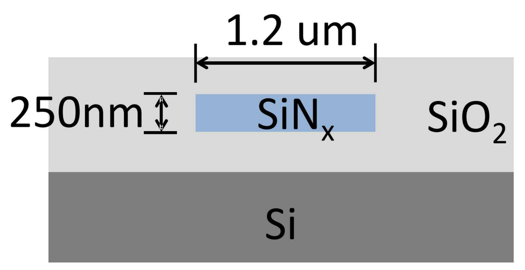
Absorption IR spectra was obtained from a Nicolet ECO-8S FTIR spectrometer, with a spectral range from 400 cm^{-1} to 4000 cm^{-1} -, a resolution of 4 cm^{-1}, and averaged 32 scans per sample.

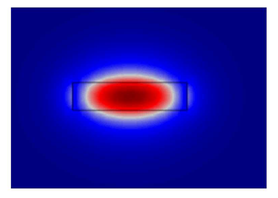
Estimation of the bond concentration [X-H] can be determined by:

$$[X-H] = A_{(X-H)} \int \frac{\alpha(\omega)}{\omega} d\omega = A_{(X-H)} I$$

where $A_{(X-H)}$ is the proportionality factor, ω is the frequency and α(ω) is the absorption coefficient.

Waveguides were fabricated with a 250 nm thickness and 1.2 um width with varying process parameters to correlate process chemistries with propagation loss.





Simulated electric field in X-direction

RESULTS

Effect of SiH_4 Flow

SiH_4 flow was varied from 100 sccm to 400 sccm while the following was held constant: NH_3 flow (115 sccm), N_2 flow (4000 sccm), chamber pressure (4.7 Torr), and RF power (950 W).

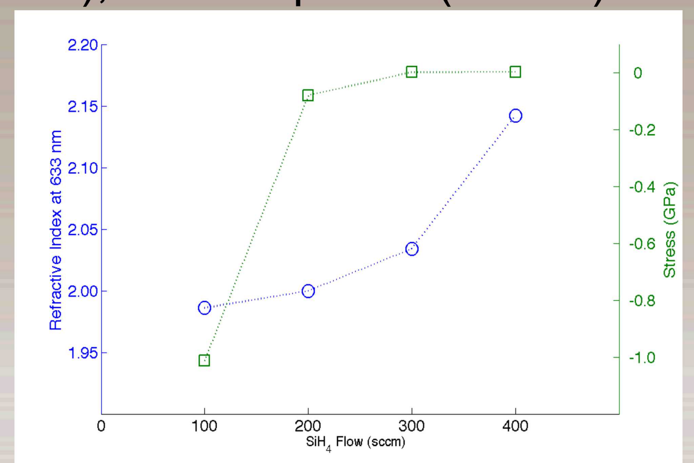


Figure 1. Effect of SiH_4 flow on RI and residual film stress.

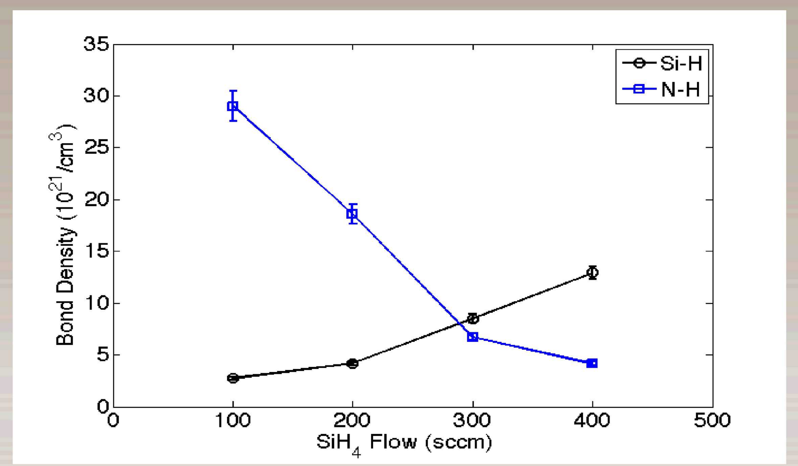


Figure 2. Effect of SiH_4 flow on bond density for Si-H and N-H as calculated from FTIR spectra.

- Si-H bond density increase may be due to increase in Si reactive species in plasma.
- Increasing SiH_4 flow has been shown to increase RF power absorption,[1] which could result in increased $Si-H_x$ species and increased dissociation of N-H.

Effect of NH_3 Flow

NH_3 flow was varied while the following was held constant: SiH_4 flow (300 sccm), N_2 flow (4000 sccm), chamber pressure (4.7 Torr), and RF power (950 W) .

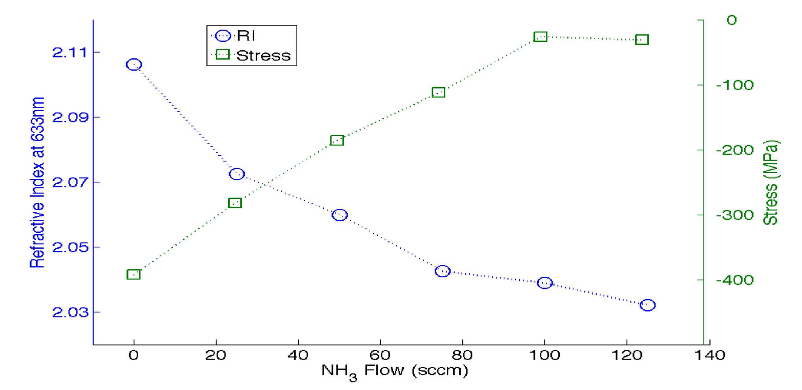


Figure 3. Effect of NH_3 flow on refractive index measured at 633nm and stress.

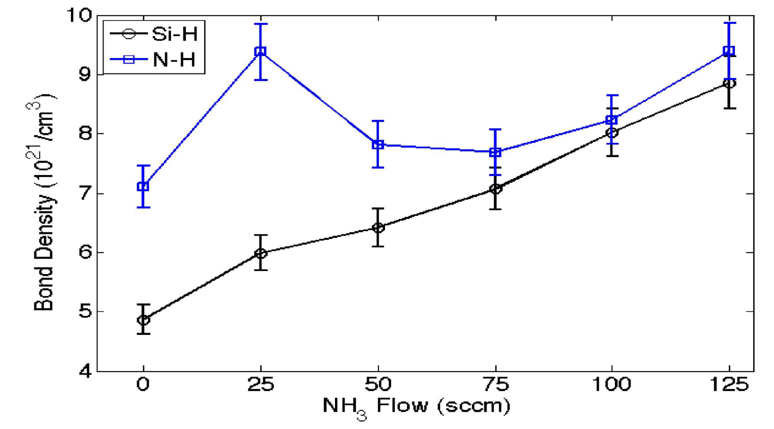


Figure 4. Bond density for Si-H and N-H as calculated from FTIR spectra.

- Addition of NH_3 to a SiH_4 and N_2 plasma has been shown to dramatically decrease the peak of the electron energy probability function from 20 eV to ~1eV as well as narrow the probability distribution.[1]
- Increase of the number of lower energy electrons limits the probability that full dissociation of NH_3 will occur.

Effect of N_2 Flow

N_2 flow was varied while the following was held constant: SiH_4 flow (300 sccm), NH_3 flow (115 sccm), chamber pressure (4.7 Torr), and RF power (950 W).

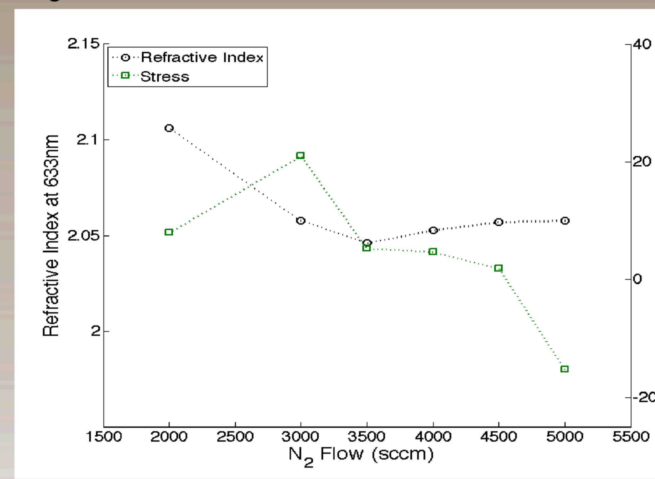


Figure 5. Effect of N_2 flow on refractive index measured at 633nm and stress.

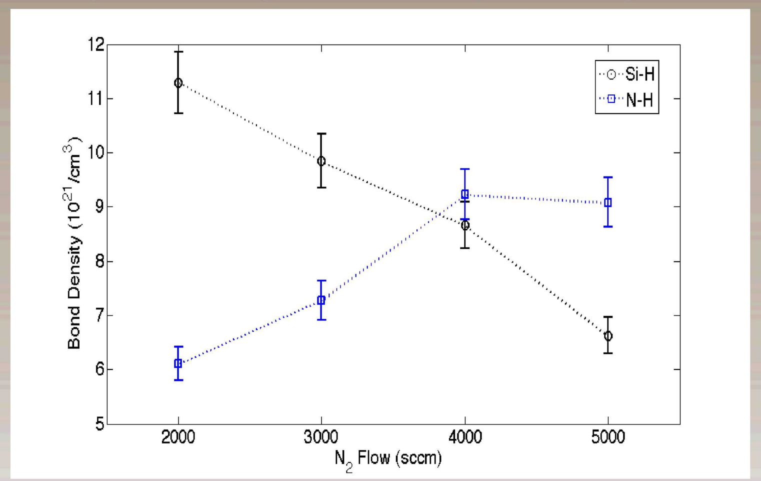
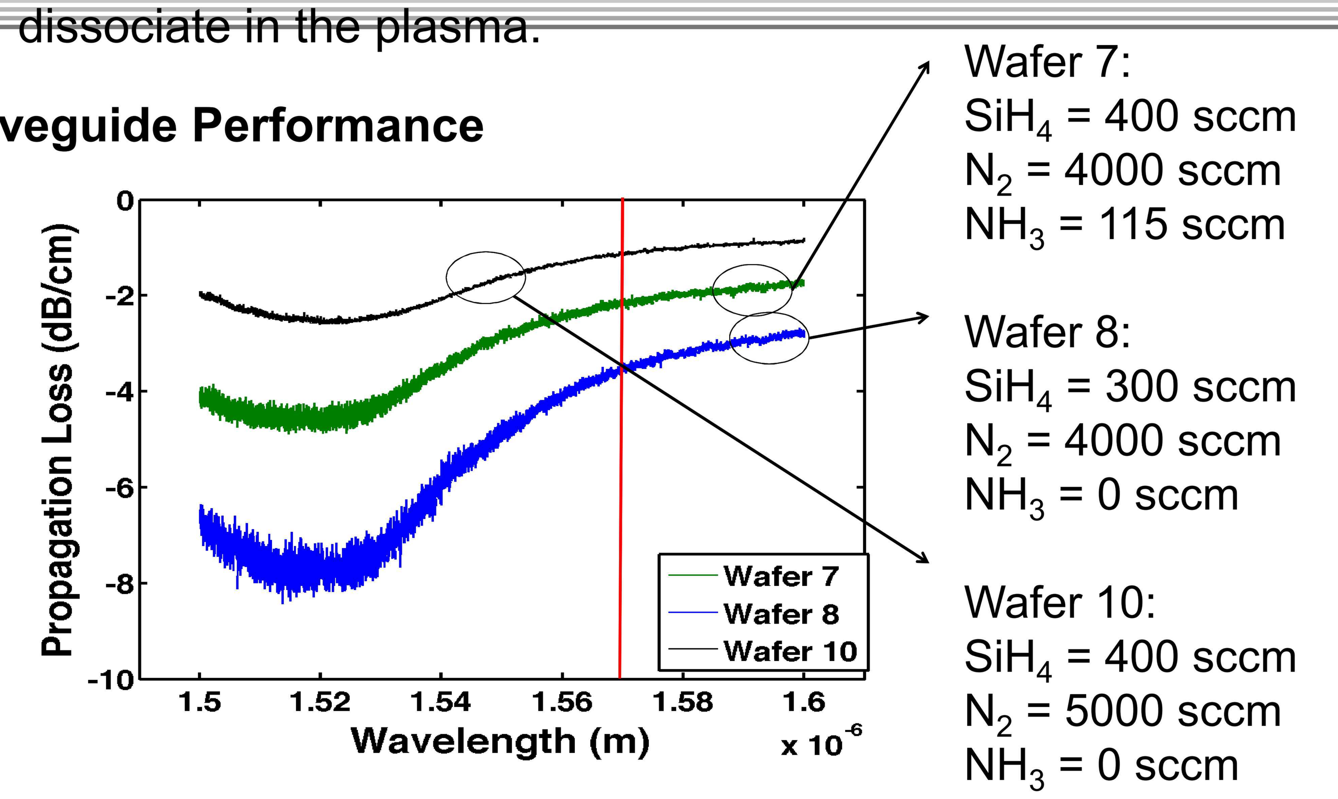
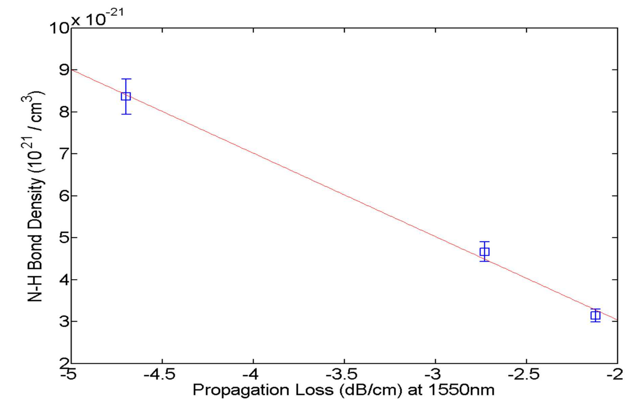


Figure 6. Bond density for Si-H and N-H as calculated from FTIR spectra.

- Ionization and dissociation of N_2 requires electron energy of 18 to 80 eV. At 4000 sccm of N_2, it was observed that both refractive index and N-H bond density saturates, indicating that additional N_2 does not dissociate in the plasma.

Waveguide Performance





- Removing NH_3 as a process gas results in ~ 1.75dB/cm decrease in loss. However, a similar decrease in loss, ~1.6 dB/cm, occurs by increasing SiH_4.
- Linear trend of N-H bond density with propagation loss of waveguides.

CONCLUSIONS

Though generally reported that the largest reduction in hydrogen, and thus absorption loss in a photonic waveguides, can be obtained by removal of NH_3 as precursor, our results indicate that all process gas chemistries must be optimized to decrease loss, including SiH_4 flow.

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[1]Sahu et al., J. Appl. Phys, **16**, 134903 (2014).

From Sahu et al.[1], the threshold energy for dissociation (E_{diss}), ionization (E_{ion}), and emission (E_{emiss}):

$e^- + SiH_4 \longrightarrow SiH_4^* + e^-$ (E_{emiss} ~ 4.0 eV)

$\longrightarrow SiH_3 + H + e^-$ (E_{diss} ~4.0 eV)

$\longrightarrow SiH_2 + 2H + e^-$ (E_{diss} ~2.2 eV)

$e^- + NH_3 \longrightarrow NH_3^+$ (E_{ion} ~ 10.5 eV)

$\longrightarrow NH^+ + H_2$ (E_{ion} ~ 19.4 eV)

$e^- + NH^+ \longrightarrow (NH^+)^* + e^-$ (E_{emiss} ~ 18.0 eV)

$\longrightarrow N^+ + H + e^-$ (E_{emiss} ~ 30.0 eV)