Demonstration of Etch-less Core Definition Process for Low-Loss Glass Waveguide Fabrication


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Abstract— We demonstrate for the first time the selective oxidation of Silicon Oxynitride and use it to create a novel process for etchless waveguide definition. The oxidation process is characterized for SiONx and SiNy films, and the sidewall smoothing mechanism is simulated. Fabricated waveguides exhibited losses of 0.103 dB/cm at 1610 nm and 0.177 dB/cm at 1550 nm, where C-band loss were limited by molecular vibrational resonances.

Keywords: Waveguides, Thermal Oxidation, Silicon Oxynitride

I. INTRODUCTION

The large disparity between the propagation losses of optical fibers and planar waveguides is often attributed to the sidewall roughness of integrated waveguides, created by the etching process. In the silicon-on-insulator platform, numerous groups have addressed this problem with the local oxidation of silicon (LOCOS) [1–4] process, which reduces propagation loss by about an order of magnitude.

The Silicon Oxynitride (SiONx) / Silicon Dioxide (SiO2) planar lightwave circuit (PLC) platform is a mature technology for various applications, in which the oxynitride mole ratio can be varied to tailor the core refractive index. SiONx can also be thermally oxidized [5,6], and it stands to reason that a similar sidewall smoothing technique can be applied to the ubiquitous SiONx/SiO2 glass waveguide platform to define waveguides with reduced sidewall roughness.

In this work we present a characterization of the thermal oxidation of SiONx using spectroscopic ellipsometry, with relation to the chemical processes involved. Additionally, a model for the mechanism of sidewall smoothing is proposed using a 1-dimensional approximation of the diffusion of oxidant species. This is then applied to the fabrication of SiONx waveguides of varying widths, which are subsequently measured with optical frequency domain reflectometry (OFDR) to obtain wavelength-dependent losses [7]. Lastly, the loss spectrum is used to infer the presence of various molecular absorption resonances.

II. SELECTIVE OXIDATION OF SILICON OXYNITRIDE

In a standard LOCOS process, a material with low oxidation rate is used to block the diffusion of oxidant in lithographically defined areas, allowing exposed silicon to oxidize. In the case of SiONx waveguides with SiO2 cladding, we can use a layer of SiONx as the core layer, and block oxidant diffusion in the waveguide core area with SiONx which is essentially SiO2N0 with zero oxygen content. Thus the exposed SiO2N0 is converted into cladding oxide.

Fig. 1 shows a schematic of the core definition process, including the use of thermally oxidized silicon substrates for lower claddings. Deposited SiO2 is used for upper claddings after removal of the Si3N4 oxidation mask.

III. THERMAL OXIDATION OF SILICON OXYNITRIDE

Kuiper et al. proposed in [6] that Silicon Nitride undergoes thermal oxidation with the following reaction:

\[ \text{SiN}_2(s) + 6 \text{H}_2\text{O}(g) = 3 \text{SiO}_2(s) + 4 \text{NH}_3(g) \]  

where the gaseous oxidant, water vapor, replaces nitrogen within a solid silicon nitride molecule, creating solid silica and gaseous ammonia as a byproduct. The rate of oxidation is limited by out-diffusion of the ammonia molecule, which inhibits the reaction rate at the oxidizing interface. Due to the dependence on diffusion, the rate follows an exponential temperature-dependence. Since each nitrogen atom generates a rate-limiting ammonia molecule, the oxidation rate should be highly dependent on the amount of nitrogen in the SiONx film. This is exhibited in Fig. 2, where the SiONx refractive index increases with increasing nitrogen content, and thus shows a lower oxidation rate.

Additionally, water vapor and ammonia will be left in the film at the completion of the thermal oxidation. This fact manifests in two effects impacting waveguide characteristics. First, since NH3 is larger and has a lower diffusion coefficient than H2O, the generated thermal oxide tends to have higher indices (and N2 concentration) at low temperatures. This is likely due to the trapping of NH3 which allows the thermal oxide to undergo thermal nitridation [8]. Secondly, both of these molecules exhibit molecular vibrational resonances in the C-band, via O-H and N-H overtones, so wavelength dependent loss analysis should be able to detect the residual solute gases.

The effect this technique has on sidewall roughness has been investigated by modeling the diffusion of oxidant as spherical point sources along the line-edge of the etched oxidation mask.

This research was supported by the Defense Advanced Research Projects Agency, Microsystems Technology Office, Program: Integrated Photonic Delay (iPhoD), Issued by DARPA/CMO under Contract No. HR0011-09-C-0123. The views and conclusions contained in this document are those of the authors only.
In Fig. 3a, we propagate the diffusion front away from the line-edge (as measured with atomic force microscopy), and calculate the resultant root-mean-square (RMS) roughness and correlation length ($L_x$), shown in Fig. 3b. As diffusion radius increases, RMS roughness decreases and $L_x$ increases. Both of these trends reduce scattering losses [9].

IV. WAVEGUIDE FABRICATION & MEASUREMENT

A 1 mm thick silicon substrate with 15 µm of thermal oxide was used for the lower cladding. Plasma Enhanced Chemical Vapor Deposition (PECVD) was used to deposit 970 nm of SiO$_2$/N$_x$ waveguide core layer, with the O$_2$/N$_x$ gas flow ratio chosen to produce a refractive index of 1.58 at 1550 nm. 1 µm of SiO$_2$ was subsequently deposited as an oxidation buffer, and 50 nm of sputtered Si$_3$N$_4$ for the oxidation mask. Sputtered nitride exhibits a lower oxidation rate than PECVD films, and thus requires less physical etching to pattern. Standard lithographic and dry-etching techniques were used to pattern the oxidation mask with an Archimedean spiral configuration of 26 interleaved waveguides, ranging from 2.5 µm to 15.0 µm in width. Core definition proceeded by subjecting the wafer to steam oxidation for 3 hours at 950°C with a 200 scm flow of dry vapor. The nitride oxidation mask was then removed via dry etch, and 10 µm of PECVD SiO$_2$ upper cladding was deposited in batches, with 1050°C, 3 hr anneals performed after every 4 µm of deposition. The spiral facets were diced (shown in Fig. 4), and light was coupled from cleaved optical fibers to the waveguides with index matching gel to lower reflections.

OFDR was used to measure the backscattered power versus distance into each waveguide, as described in [7]. Analysis of the power vs. distance slopes of full-range OFDR scans (1525 nm – 1610 nm) yielded the losses shown in Fig. 5a, with a lowest loss of 14.7 dB/m for the widest, 15 µm waveguide. These values are average losses over the OFDR scan range, so narrow-band analysis was performed with a 10 nm range, as shown in Fig. 5b, revealing a 20 dB/m range of propagation losses for the 13.0 µm width. This loss spectrum shows a minimum loss of 11.2 ± 0.4 dB/m from 1585 nm to 1610 nm, and the 15 µm width exhibits 10.3 ± 0.8 dB/m from 1590 nm to 1610 nm. The loss peak near 1510 nm is explained by the presence of N-H vibrational overtones. Losses around 1610 nm could be limited by either scatter or SiO$_2$-H & Si-H bonds. This will be determined in the future by fitting the loss vs. width data to scattering loss models.

The authors would like to thank Scott Rodgers, Brandon Knott and Jonathan Doylend for support and helpful discussions.

ACKNOWLEDGMENT

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