A Comparison of Approaches for Ultra-Low-Loss Waveguides

Jared F. Bauters, Martijn J. R. Heck, Demis D. John, Jonathon S. Barton, Daniel J. Blumenthal, and John E. Bowers
Engineering Science Building, University of California, Santa Barbara, CA 93106, U.S.A.
jbauters@ece.ucsb.edu

Christiaan M. Bruinink, Arne Leinse, and René G. Heideman
LioniX BV, P.O. Box 456, 7500 AH, Enschede, the Netherlands

Abstract: We compare ultra-low-loss silica waveguides with PECVD SiO_2, borophosphosilicate glass (BPSG), and wafer-bonded thermal oxide upper claddings. We demonstrate fiber-like (0.045 dB/m) total propagation loss in planar waveguides with bonded thermal oxide upper claddings.

1. Introduction

In [1], we reported the lowest *single-mode* propagation loss to date, 0.7 dB/m, in a planar waveguide. Due to the thin LPCVD Si_3N_4 core geometry, the core modal confinement was around 3%, and the quality of the cladding material was emphasized in these waveguides. In this work, we compare three upper cladding approaches that can be used in such waveguides: PECVD SiO_2, deposited and reflowed BPSG, and wafer-bonded thermal oxide (Fig. 1). From group index and critical bend radius measurements, we show that the BPSG and bonded thermal oxide approaches are low stress. From spectral measurements of the propagation loss for each approach, we show that waveguides with bonded thermal oxide upper claddings have mitigated impurity absorption loss compared to the PECVD and BPSG approaches. With record low propagation loss below 0.1 dB/m, reduced absorption loss, low dielectric film stress, and short fabrication time, the bonded thermal oxide approach is most attractive.

2. Waveguide fabrication

The waveguides are fabricated on a Si substrate with 15 µm of thermal oxide lower cladding. The Si_3N_4 core (n = 1.98) and the encapsulating SiO_2 (n = 1.45) layers are identical for each approach with details given in [1]. Fig. 1a shows the approach in which 12 microns of PECVD SiO_2 are deposited to complete the waveguide structure. After deposition, the structure is annealed at 1150 °C for 3 hours. In Fig. 1b, 12 microns of BPSG are deposited before a lower temperature (950 °C) reflow step. In the last approach (Fig. 1c), a Si wafer with 15 microns of thermally grown SiO_2 is spontaneously bonded to the waveguide wafer at room temperature. The structure is then annealed for 3 hours at 950 °C in order to strengthen the bond. Since the 15 µm thermal oxide wafers can be produced in batches before fabrication, the wafer-bonding approach is faster and cheaper than the other approaches.

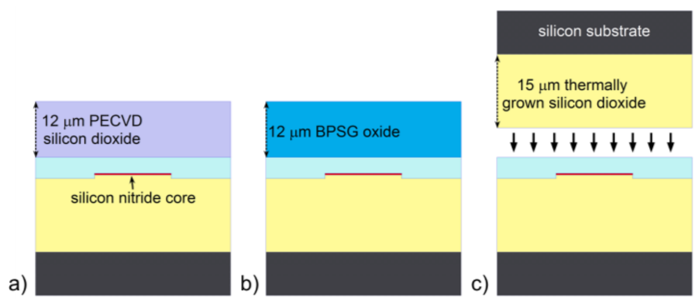

Fig. 1. Overview of the a) PECVD SiO_2, b) reflowed BPSG, and c) bonded thermal oxide approaches compared in this work.

3. Waveguide characterization

Spiraled planar waveguide structures with 50 and 40 nm thick cores are fabricated to characterize the group index, critical bend radius, and propagation loss for the three approaches. The spiral structures include core widths ranging from 3 to 14 µm, but all waveguides begin at a single mode core width before linearly tapering out to the final core width in order to excite only the fundamental TE mode. Coherent optical frequency domain reflectometry (OFDR) is used in the waveguide characterization for its high spatial resolution (10 µm) and spectral capabilities [2].

Fig. 2a shows the group indices measured for 50-nm-thick cores in each approach. The group indices measured for the BPSG and bonded thermal oxide approaches are similar, while those for the PECVD oxide are significantly lower. The dashed lines in the figure show group indices simulated with Photon Design's FIMMWAVE software for two core and cladding refractive index combinations. The simulation core and cladding indices that fit well to the BPSG and bonded thermal data, (1.98/1.46), are close (within 0.01 for each) to the refractive index values typically measured with ellipsometry during fabrication. The indices that fit well to the PECVD SiO_2 data, (1.87/1.47), are significantly different and give an effectively lower index contrast. This data shows that the indices of the dielectric layers are altered in the PECVD approach due to the stress-optic effect. Since the wafer-bonded thermal oxide and BPSG approaches involve lower temperature processes, the difference in dielectric film stress is likely due to the thermal expansion mismatch between the various materials [3]. Though one could eliminate the high temperature anneal from the PECVD approach, the propagation loss due to hydrogen impurities would increase [4].

Fig. 2b shows critical bend radius data measured for 50 nm cores in the three approaches. In this work, we define the critical bend radius as the radius at which bend loss is equal to 0.1 dB/m. Again, the BPSG and bonded thermal oxide approaches give similar data, while the PECVD data is significantly offset. This offset can be explained by a lower mode confinement in the PECVD waveguides due to an effectively lower index contrast. Simulated values are shown with dashed lines, and a good fit to the PECVD data can be obtained only with refractive indices altered by the stress-optic effect. So the lower temperature bonded thermal and BPSG processes are preferred since they have lower stress, and this provides better wafer uniformity, repeatability, and handling. The measured critical bend radius values are obtained by fitting a bend radius dependent loss coefficient to OFDR data from spiraled waveguides. Details of the technique will be presented orally.

Figs. 3 and 4 show the spectral dependence of the propagation loss in waveguides fabricated using the PECVD and bonded thermal oxide approaches. The measured waveguides are spiraled for 1.0 m of total propagation. The circular markers are measured data, while the solid lines are fits of the scattering and impurity absorption loss contributions. Each loss contribution has an assigned color, and each marker, being the sum of these contributions, has its own color weighted accordingly. The central lower axes in each figure provide the "big picture" over the 1.3-1.6 μm wavelength regime, but one should note that the spectral dependence is measured only where the circular markers appear around the 1.32 and 1.56 μm wavelengths. These regions are expanded in the upper left and right axes, respectively, for closer inspection.

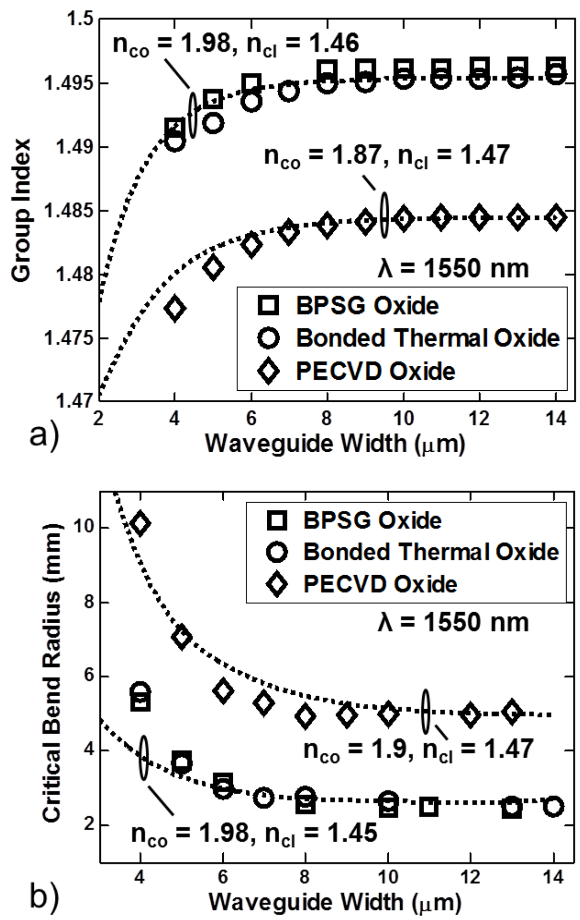

Fig. 2. a) Group index and b) critical bend radius data measured in 50 nm thick cores for the three approaches. Dashed lines are values simulated with the given refractive indices.

Fig. 3 shows the propagation loss in a 50-nm-thick by 6.5-μm-wide waveguide with PECVD upper cladding. In the 1.32 μm wavelength regime (upper left), the scattering loss floor is higher due to the inverse dependence of scattering loss on wavelength [1]. Loss increases with wavelength due to absorption loss for this approach in the regime. The minimum total loss in this regime is (0.45 ± 0.1) dB/m. In the 1.56 μm wavelength regime (upper right), the scattering loss floor is lower, but the loss is high near 1.53 μm due to an absorption peak near 1.52 μm. Away from this peak, however, a minimum total loss of (0.05 ± 0.1) dB/m is measured.

Fig. 4 shows the propagation loss in a 40-nm-thick by 13.0-μm-wide waveguide with bonded thermal oxide upper cladding. The total propagation loss is lower, with a minimum of (0.33 ± 0.03) dB/m, and flat near a wavelength of 1.3 μm, indicating a reduction of absorption loss there. In the 1.56 μm regime, wavelength dependent absorption loss is observed, but the loss is 0.5 dB/m lower than in the PECVD approach near a wavelength of 1.54 μm. Away from the absorption peaks in this regime, a minimum total propagation loss of (0.045 ± 0.04) dB/m is measured. So absorption loss is reduced in the bonded thermal oxide approach, and a lower total loss is measured as a result. Though not shown here, the BPSG approach has a spectral loss dependence similar to the PECVD approach with higher total losses than the bonded thermal approach. These data will be presented orally.

4. Conclusions

We have compared three approaches to fabricating ultra-low-loss waveguides. They include PECVD SiO_2, BPSG, and wafer-bonded thermal oxide upper claddings. Due to the lower temperature process steps, the bonded thermal oxide and BPSG approaches both produce lower dielectric film stress than the PECVD process. Due to reduced impurity absorption losses, the bonded thermal oxide approach has lower total propagation loss than the BPSG and PECVD approaches. The bonded thermal oxide approach also has the advantages of shorter fabrication time and lower cost. Further reductions in hydrogen impurity concentration should also be possible through processes currently used in optical fiber manufacturing.

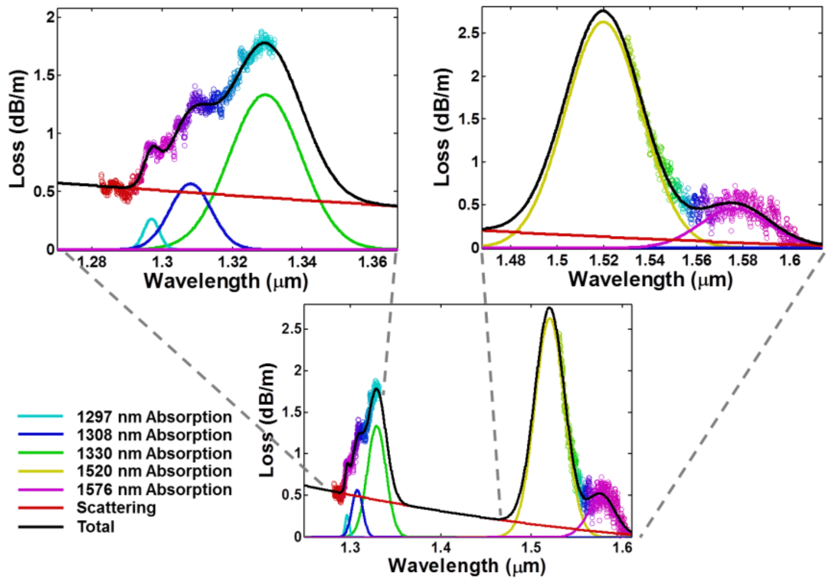

Fig. 3. Propagation loss (circles) vs. wavelength for a 50-nm-thick by 6.5-µm-wide waveguide with PECVD oxide upper cladding. A 10 nm window function is applied in the spectral domain. The solid lines are fits of Gaussians (absorption loss) and a polynomial (scattering loss) to the data. The color key gives the loss type colors and the center wavelengths of the various Gaussian fits.

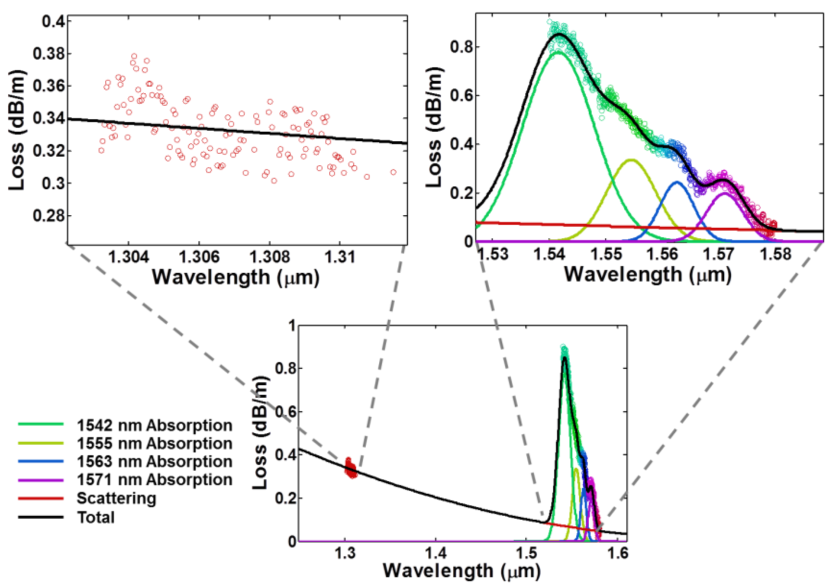

Fig. 4. Propagation loss (circles) vs. wavelength for a 40-nm-thick by 13-µm-wide waveguide with bonded thermal oxide upper cladding. A 50 nm window function is applied in the spectral domain. The solid lines are fits of Gaussians (absorption loss) and a polynomial (scattering loss).

5. Acknowledgements

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6. References

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