HfO_2-Based Platform for High Index Contrast Visible and UV Integrated Photonics

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Abstract:

We investigate photonic devices fabricated within a HfO_2/Al_2O_3 platform for high-index visible/ultraviolet photonics. Our findings show bulk optical losses of 2.8 ± 1.4 dB/cm and single-mode (SM) waveguide losses of 7.9 ± 1.7 dB/cm at a wavelength (λ) of 375 nm. At $\lambda = 405$ nm, SM waveguides show 2.6 ± 0.45 dB/cm. For $\lambda = 730$ nm, we measure a loaded quality factor (Q) of 1,840,000 bounding (SM) waveguide losses to <0.4 dB/cm. These results highlight the potential of $(HfO_2)_x/(Al_2O_3)_{1-x}$ devices and systems for visible and ultraviolet photonics.

Summary of Research:

Photonic integration at visible and UV wavelengths has applications in trapped-ion systems, spectroscopy, and other fields [1-3]. However, most common material platforms for integrated photonics absorb strongly in the UV, and increased surface and sidewall scattering at shorter wavelengths (scaling roughly as $\sim\lambda^{-4}$) pose a challenge in achieving low-loss waveguide structures. Silicon nitride (SiN) is a well-developed material with a high refractive index (~ 2.06 at $\lambda = 405$ nm), but experiences bulk optical losses of approximately 2.5 dB/cm at $\lambda = 461$ nm [4] and higher at shorter wavelengths [5]. Another material, aluminum oxide (Al_2O_3), has been used to demonstrate propagation losses of ~1.35 dB/cm at 369 nm [6,7], but suffers from a relatively low refractive index (~1.68 at $\lambda =$ 405 nm). Hafnium dioxide (HfO_2), a CMOS compatible material, offers a high refractive index (~2.1 at $\lambda = 405$) and a wide band-gap

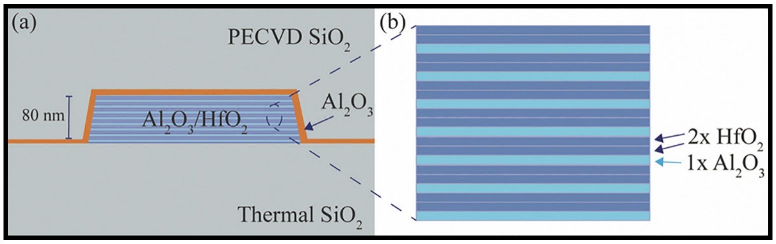

Figure 1: Waveguide cross-section showing an HfO_2-based core, a 4 nm thick Al_2O_3 diffusion barrier and PECVD SiO_2 cladding.

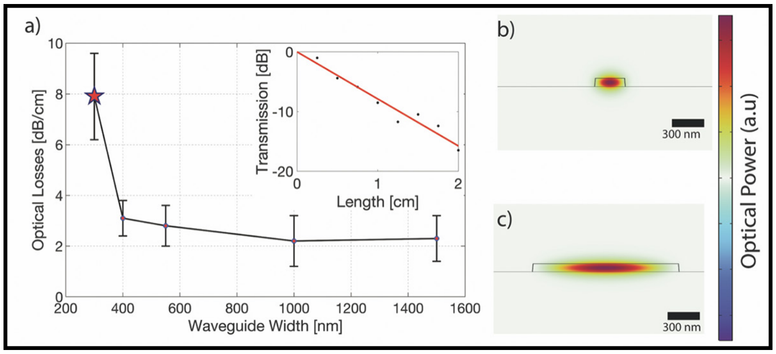

Figure 2: Optical micrograph of a representative device used to measure optical losses. To the right, an SEM image of a grating coupler used to couple light into the device.

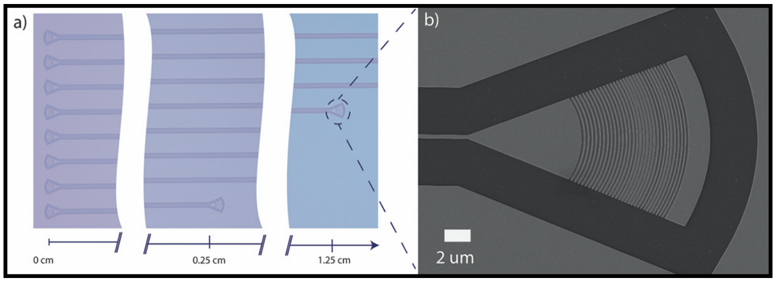

Figure 3: Measured optical losses for varying widths at 375 nm. Inset shows data obtained for a width of 300 nm.

material (5.65 eV) [8], but its tendency to crystallize limits its use in photonics to interaction lengths of ~ 100 nm [9,10]. Here we fabricate fully-cladded single mode (SM) and multimode (MM) waveguides using a low loss and high index HfO_2-based composite (~1.97 at λ = 405), composed of alternating layers of HfO_2 and Al_2O_3 deposited via Atomic Layer Deposition (ALD) [11,12]. We demonstrate an optical loss at λ = 375 nm of 7.9 ± 1.7 dB/cm for SM waveguides and measure bulk optical loss associate to bulk material loss to be 2.8 ± 1.4 dB/ cm at λ = 375 nm, and bound losses < 0.4 dB/cm at 730 nm from resonator measurements, indicating potential for this single high-index platform to span devices from the near UV to visible range.

Our platform consists of an 80nm-thick composite material deposited via ALD on a silicon wafer with 3 μm of thermally grown wet silicon oxide (Figure 1a). The composite material consists of single atomic layers of HfO_2 and Al_2O_3 with a duty cycle (DC) of 1/3 and a period (P) of 3, deposited via ALD at 300°C (Figure 1b). The characterization and choice of specific P and DC are discussed elsewhere [11,12]. After ALD deposition, we dice the wafer into pieces and anneal them at 800°C in a nitrogen environment for one hour. Each chip is processed separately by defining a pattern with electron beam lithography (JEOL9500) using ZEP520-A resist and etching with an inductively coupled plasma (ICP) etch using a BCl_3/Ar chemistry. The samples are then cleaned with a standard RCA clean. We deposit a ~ 4 nm layer of Al_2O_3 as a diffusion barrier and anneal again at 800°C for one hour. Finally, we deposit ~ 800 nm of plasma enhanced chemical vapor deposition (PECVD) SiO_2 as cladding.

We design and fabricate grating couplers to measure optical losses through a cutback configuration. Figure 2 shows subsections of a 4 cm long chip with input couplers and two output couplers at 0.25 cm and 1.25 cm, used to couple light in and out of the device from single-mode fibers. Figure 2b shows an SEM image of a representative grating for λ = 405 nm. We vary the width of the waveguide and measure the optical losses of each structure in order to discern sidewall scattering and bulk absorption. Figure 3a shows the measured optical loss as a function of width, with the inset showing a measurement obtained for a waveguide width of 300nm (indicated with a star on the plot). With increasing width, optical loss associated with sidewall scattering decreases and becomes dominated by bulk material loss. Quasi-TE optical modes measured for widths of 300 nm and 1500 nm are shown in Figure 3b and 3c, respectively. A linear regression analysis [4] enables us to differentiate the fraction of optical loss arising from surface scattering vs. bulk loss. We find material loss to be 2.8 ± 1.4 dB/cm at λ = 375 nm.

Conclusions and Future Steps:

This work demonstrates that HfO_2 can be used to obtain competitive optical loss at λ = 375 and a higher refractive index than Al_2O_3. We observe that optical loss is dominated by sidewall scattering, indicating that fabrication optimization can enable even lower optical losses in SM waveguides. This work may lead to significantly more efficient grating devices, compact footprints, and micro-resonant structures, among others, for photonics at blue/UV wavelengths as compared to platforms in pure Al_2O_3 or SiN. Future work will determine the ultimate loss at shorter wavelengths.

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