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

CNF Project Number: 2985-21
Principal Investigator(s): Karan Kartik Mehta[2]
User(s): Oscar Jaramillo[1,2], Joshua Tensuan[2]

Affiliation(s): 1. School of Applied and Engineering Physics,
2. School of Electrical and Computer Engineering; Cornell University

Primary Source(s) of Research Funding: Cornell University

Contact: karanmehta@cornell.edu, oj43@cornell.edu

Primary CNF Tools Used: Metricon, Zeiss Ultra SEM, JEOL 9500, PT770 Etcher, WoollamRC2 Spectroscopic Ellipsometer, AFM, Furnace, Oxford PECVD, Oxford FlexAL

Abstract:

We study HfO_2/Al_2O_3 composites for high-index visible/ultraviolet photonics, exhibiting single-mode waveguides losses of 1.9 ± 1 dB/cm for $\lambda = 405$ nm.

Summary of Research:

Integration of photonic devices in the visible and UV is necessary for several applications such as spectroscopy and control of ion systems on chip [1-3]. However, photonic devices operating in the visible and UV have lagged behind those operating in the near infrared devices since common materials used in photonic devices absorb at short wavelengths, and scattering losses increase as wavelengths decrease.

Alumina (Al_2O_3) is a CMOS compatible material that can be deposited in amorphous form, and has been used to demonstrate single-mode (SM) propagation as low as 3 dB/cm at 371 nm [4]; however, its relatively low index (n~1.7) is a limitation. High refractive index is desirable in many settings since it allows, for example, strong optical confinement, compact device footprints, high efficiency grating devices (grating strengths scale approximately as $\sim(n_{core}^2 - n_{cladding}^2)^2$), and efficient acousto-optic interaction (scaling as n^6). HfO_2 is promising material — a wide band-gap (5.65 eV) [5] with a high refractive index (n~2.1), can be deposited amorphously, and is CMOS compatible. However, its propensity to crystallize results in significant optical loss, and its use in photonics has been limited to settings where the optical interaction length is on the order of 100s of nm [6,7]. Incorporation of moderate proportions of Al_2O_3 dramatically reduces losses in films; this is attributed to inhibited crystallization of HfO_2 [8]. Here, we demonstrate methods to lithographically pattern nanophotonic structures composed of alternating layers of Al_2O_3 and HfO_2, deposited via atomic layer deposition (ALD), and present preliminary SM propagation losses in patterned waveguides formed from the composite.

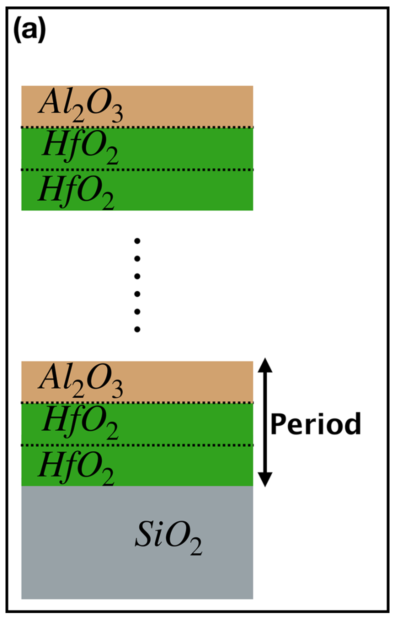

Figure 1: Single layers of HfO_2 and Al_2O_3 are deposited on top of SiO_2 in an inter-layered periodic way. A DC = 0.33 is shown here with P=3 layers.

Our approach to mitigating loss from crystallization relies on depositing alternating HfO_2 and Al_2O_3 layers at different duty cycles (DC) and periods (P) in a plasma enhanced ALD (PEALD) process. Figure 1 shows the structure of the composite films; P represents the total number of layers per period, with DC the fraction of atomic layers per period that are Al_2O_2. Previous work [8], showed that as the DC changes from 0 (HfO_2 only) to 1 (Al_2O_3 only), the refractive index decreases as if the index of the composite was the weighted average of n(Al_2O_3) and n(HfO_2) according to fractional composition. Measurements of slab mode propagation loss at $\lambda = 406$ nm by the prism coupling method showed that losses can be 4.2 dB/cm for a period of three layers and a DC ~ 0.3. In contrast, losses in pure HfO_2 at this wavelength were well above 30 dB/cm. The observed decrease in loss is accompanied by a reduction in index to n = 1.95, though still preserving most of HfO_2's advantage over Al_2O_3.

Work to pattern the composite material into photonic devices was conducted at the Cornell NanoScale Facility (CNF). Devices were fabricated on a silicon wafer with

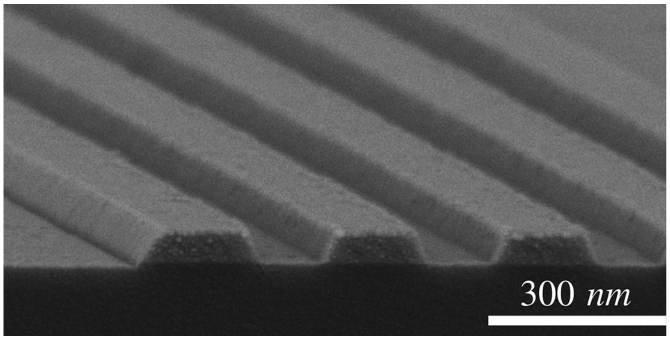

Figure 2: SEM image of ridges etched into the composite films as test structures.

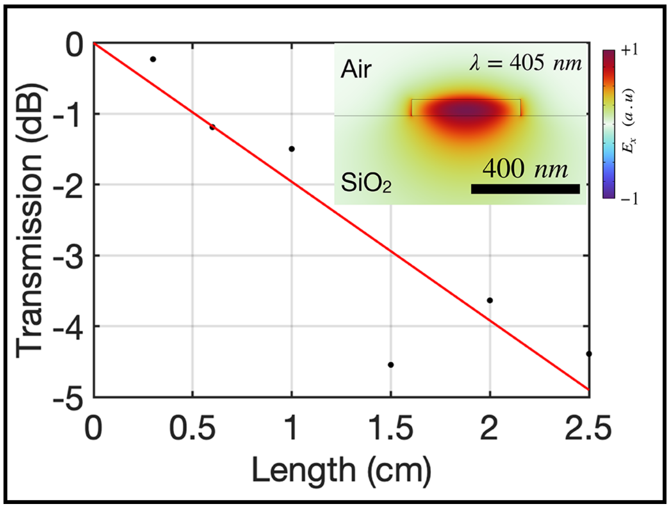

Figure 3: Measured fiber-fiber transmission at λ = 405 nm as a function of propagation length for a 200 by 60 nm waveguide. Points represent measured values, the slope of the fit indicates propagation losses of 1.dB/cm. Inset: Mode profile of measured transmission.

3 mm of thermally grown wet silicon oxide (SiO_2) provided by Rogue Valley Microdevices. Composite films of HfO_2 and Al_2O_3 at DC = 0.33 and P = 3 layers deposited at CNF exhibited material losses of 8 dB/cm at λ = 405 nm (<2 dB/cm at λ = 730 nm) after initial deposition and 2.8 dB/cm at λ = 405 nm (< 1 dB/cm at λ = 730 nm) after a one hour anneal at 800°C.

Test structures to measure propagation losses in SM rectangular waveguides were designed, including fiber surface grating couplers for characterization at λ = 730 nm and at λ = 405 nm. The pattern was defined with electron-beam lithography (JEOL9500) using ZEP520-A resist, and then transferred to the composite material with an inductively coupled plasma (ICP) etching process utilizing a BCl_3/Ar chemistry.

Figure 2 shows an SEM image of the resulting profile for straight waveguide strips in the composite after etching. Preliminary measurements on the resulting structures show losses of 1.9 ± 1 dB/cm for λ = 405 nm in a nominally 400 × 60 nm waveguide with top air cladding (Figure 3). Accounting for a confinement factor of ~33%, we find that propagation losses arising from surface roughness in a patterned waveguide contribute about half of the total propagation losses. SiO_2 cladding is expected to further reduce losses from surface roughness scattering, pushing waveguide transmission to be predominantly limited by the material.

Conclusions and Future Steps:

This work shows that HfO_2 /Al_2O_3 composite layers can be patterned into low-loss and high index integrated photonic structures, enabling high index contrast devices in the visible and UV. Improvement on sidewall roughness and etch profile is in progress, and future work will assess the ultimate material loss limit in this platform. This work may lead to significantly more efficient grating devices, compact footprints, and microresonant structures, among others, for photonics at blue/UV wavelengths as compared to platforms in pure Al_2O_3. High index, deposited waveguide core materials are also likely to be enabling in active electro- and acousto-optic device configurations.

References:

[1] Daniel J. Blumenthal. Photonic integration for UV to IR applications. APL Photonics 5, 020903, 2020.

[2] Galan Moody, et al. Roadmap on integrated quantum photonics. J. Phys. Photonics 4 012501. 2022.

[3] Mehta, K., Bruzewicz, C., McConnell, R., et al. Integrated optical addressing of an ion qubit. Nature Nanotech 11, 1066-1070, 2016.

[4] Gavin N. West, William Loh, Dave Kharas, Cheryl Sorace-Agaskar, Karan K. Mehta, Jeremy Sage, John Chiaverini,and Rajeev J. Ram. Low-loss integrated photonics for the blue and ultraviolet regime. APL Photonics 4, 026101, 2019.

[5] L. Kang, B. H. Lee,W.-J. Qi, Y. Jeon, R. Nieh, S. Gopalan, K. Onishi, and J. C. Lee. Electrical characteristics of highly reliable ultrathin hafnium oxide gate dielectric. IEEE Electron Device Letters, vol. 21, no. 4, pp. 181-183, 2000.

[6] P. Torchio, A. Gatto, M. Alvisi, G. Albrand, N. Kaiser, and C. Amra. High-reflectivity HfO_2/SiO_2 ultraviolet mirrors. Applied Optics, vol. 41, no. 16, pp. 3256-3261, 2002.

[7] Zhang, C., Divitt, S., Fan, Q. et al. Low-loss metasurface optics down to the deep ultraviolet region. Light Sci Appl 9, 55, 2020.

[8] Leonardo Massai. High Polarization Purity and Short-wavelength Optics for Trapped-ion Quantum Systems. Master's thesis, ETH, 2021.