Minimizing Losses in TiO_2 Thin-Film Waveguides for Nanophotonic Applications

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Introduction:

Nanophotonics is a growing field within optics that studies the applications and behavior of light and matter on the nanoscale. Developments here have been especially important to integrated optics, an area devoted to combining various optical functions onto a single chip [1]. As light-based devices are becoming more commonplace, improving the efficiency of base chip devices (especially by minimizing loss) is growing in importance.

The Suntivich group at Cornell has been studying such light-matter interactions using titanium dioxide (TiO_2) for integrated optical devices due to its high refractive index (> 2.2), transparency in the visible and infrared (IR) regions of the electromagnetic spectrum, and low-cost [2]. A particular area of focus is on the construction of optical waveguides, which are the basic component for integrated optical applications. These waveguides are composed of a high refractive-index core material surrounded by a lower-index cladding material and light is transmitted through the core via total internal reflection [1]. As the light wave propagates through the material, however, photons are lost due to scattering from defects, impurities, grain boundaries, and interface roughness.

Rayleigh scattering from interfacial roughness (e.g., surface roughness in films and sidewall roughness in structured channel waveguides) is a major source of loss at visible wavelengths. Rayleigh scattering is often significant even within unstructured thin-film planar waveguides and limits the achievable losses in nanophotonic waveguides. Therefore, the goal of this work was to develop planar waveguides from amorphous TiO_2 that exhibit a high refractive index and low planar waveguiding losses. To achieve this goal, we deposited films using radio-frequency (RF) sputtering of TiO_2 and observed how the deposition temperature, pressure, and power affected optical propagation loss, surface roughness, index of refraction, and sputtering efficiency.

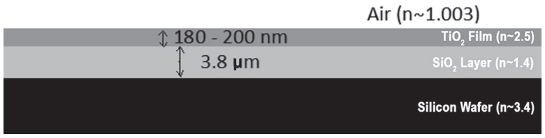


Figure 1: Schematic of a planar TiO_2 waveguide.

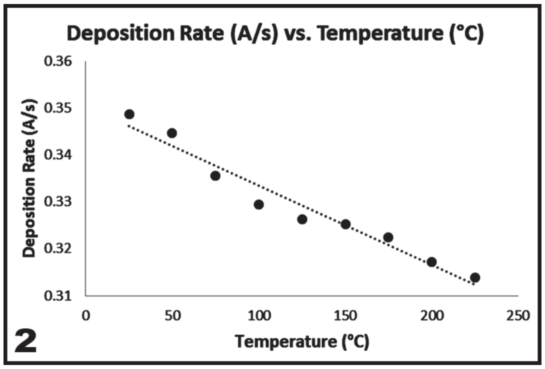
Experimental Procedure:

Sample Preparation. Silicon wafers with a previously grown layer of thermal oxide (3.8 µm) were sonicated and rinsed with acetone, isopropanol, and deionized water. The substrates were then dried with pressurized air and heated on a hot plate to ensure no solvent was remaining. Samples were finally subjected to plasma ashing for 120 seconds to purge any persistent organics from the surface.

Deposition Process. The Kurt J. Lesker PVD75 (sputtering) was used for 6000 s depositions with a TiO2 target and an argon flow of 25 sccm (limit of 50 sccm)/oxygen flow of 0.8 sccm. Figure 1 shows the resulting planar waveguide.

- *Temperature* range tested (at 120 W, 3.5 mTorr): 25°C-225°C in 25 degree intervals.
- *Power* range tested (at 75°C, 3.5 mTorr): 120-135 W, every 5 watts.
- *Pressure* range tested (at 75°C, 120 W): 3.3-3.7 mTorr, every 0.2 mTorr.

Characterization. The refractive index and thickness of the TiO_2 layers were first estimated from the Filmetrics F50 (a thickness mapping system and spectrometer) to help obtain more accurate values using the Woollam variable angle spectroscopic ellipsometer. Surface roughness/morphology was imaged and quantified using atomic force microscopy. Loss was measured using a prism coupler setup with a red laser (λ = 638 nm) and transverse electric/magnetic (TE/TM) polarizers.



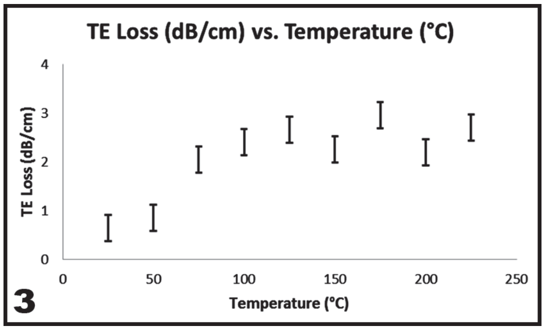


Figure 2, top: *Deposition Rate (A/s) vs. Temperature (°C) graph. Deposition rate was obtained by dividing the thickness of the film by the run time of 6000 s. Higher temperatures lead to thinner films.* ***Figure 3, bottom:*** *TE Loss (dB/cm) vs Temperature (°C) graph. The two data points for each temperature value provide the range of the loss measured. Higher temperature samples have increased loss. The TM Loss graph looks similar.*

Results and Conclusions:

Thickness/Deposition Rate. As the temperature of the deposition increased, the thickness of the film dropped linearly. This relationship can also be understood as higher temperatures leading to a lower rate of deposition (see Figure 2). Increased film density is the most likely cause, as higher temperature TiO_2 molecules have a greater range of motion to find a local energy minimum on the substrate. As the power increased, the deposition rate likewise increased, as a larger amount of plasma hitting the target leads to more molecules being deposited.

Refractive Index. Increasing temperature increases the refractive index linearly. This trend is consistent with the temperature-thickness relationship if we assume that the reduced deposition rate at higher temperature produced higher density films, which exhibit higher refractive indices.

Surface Roughness. The film roughness was minimized between 75°C and 100°C (RMS roughness was ~ 1.1 nm).

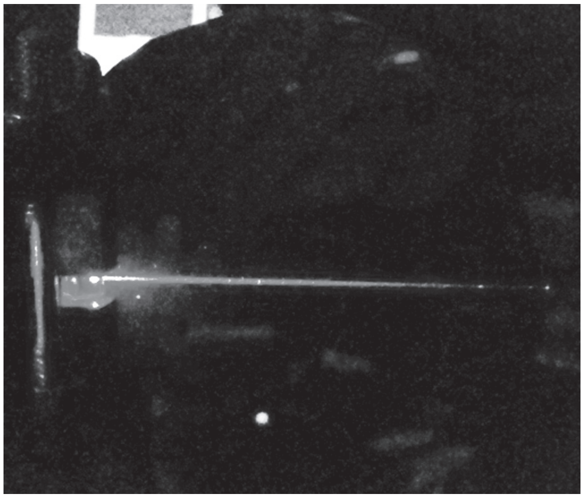


Figure 4: Image of the lowest loss film at 25°C (0.7 ± 0.2 db/cm). The "red light" can still be observed at the end of the wafer, which does not occur at higher deposition temperatures.

Losses. For both TE and TM polarizations of light, losses increased with increasing temperature (Figure 3). At higher temperatures, TiO_2 gradually begins to transition from amorphous to crystalline form. This leads to larger grains that scatter more as they approach in size the wavelength of light used.

Taking into account all of these results, it appears that the ideal deposition parameters (where loss is minimized while still maintaining a high rate of deposition) are at 25°C, 130 W, and 3.5 mTorr (as there was no conclusive relationship between pressure and the film qualities observed above, the pressure of most runs, 3.5 mTorr, can continue to be used). Figure 4 shows the lowest loss film deposited.

Acknowledgements:

I would like to thank Chris Evans, Chengyu Liu, and Dr. Suntivich for their patience and mentorship this summer, the program coordinators and staff at CNF for all of their help, NNIN REU Program for the opportunity, and NSF for the funding under Grant No. ECCS-0335765.

References:

[1] Tien, P.K. "Light Waves in Thin Films and Integrated Optics." Applied Optics, 10(11). 2395-2413 (1971).

[2] Evans, C.C., Liu, C., Suntivich, J., Low loss titanium dioxide waveguides and resonators using a dielectric lift-off fabrication process, Opt. Express. 23 9 (2015), pp. 11160-11169.