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TiO_2 channel waveguides with 0.5 dB/cm propagation losses

(Student paper)

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Scattering represents a major contribution to the optical propagation losses of channel waveguides. By optimization of the reactive sputtering deposition process, volume scattering can be minimized. In this work, we focus on the reduction of surface scattering by applying a chemical mechanical polishing step following reactive sputter deposition of TiO_2 layers. Propagation losses below 0.1 dB/cm at 980 nm of wavelength were experimentally characterized for TiO_2 slabs on oxidized silicon wafers. The propagation loss increases to 0.5 dB/cm at 1550 nm of wavelength for fully etched channel waveguides. Such low propagation loss paves the way for the utilization of TiO_2 in advanced integrated photonics circuits.

Keywords: *Titanium Dioxide, Amorphous, Chemical Mechanical Polish, Optical Propagation Loss, Reactive Sputtering*

INTRODUCTION

TiO_2 is a promising material for integrated photonics. Its high linear (i.e., 2.3 at 633 nm [1]) and non-linear (i.e., 2.3×10^{-18} m^2/W [2][3]) refractive indices together with its negative dn/dT [4] and the possibility of doping with rare-earth ions [5] make TiO_2 very interesting for the realization of non-linear, athermal and/or active integrated optical devices, in combination with more established platforms such as Si_3N_4 [6] and Al_2O_3 [7]. Four wave mixing (FWM) [8] [9] [10], supercontinuum generation [11] and athermal devices [12][13][14] have been recently demonstrated in TiO_2 waveguides.

However, high propagation losses (~3-8 dB/cm at 1550 nm [9][11][13][15]) have prevented TiO_2 from reaching mainstream applications. Both absorption and scattering losses contribute to the final performance of the device. TiO_2 exhibits a bandgap of 3 eV [16], which leads to optical transparency down to visible wavelengths. Absorption in the material can originate from insufficient oxygen in the layer [17] and the incorporation of hydrogen bonds, which introduce absorption bands at different locations in the near-IR. Optimization of the reactive sputtering deposition process leads to layers were the main contributor to losses is surface scattering [18][19].

In this work, we introduce a chemical mechanical polishing (CMP) step after reactive sputter deposition of the TiO_2 layers to reduce the effect of surface scattering on the propagation losses. A reduction in the propagation loss of ~0.3 dB/cm is observed at 978 nm of wavelength in the layers studied, with losses below 0.1 dB/cm at 978 nm on a 131 nm thick TiO_2 slab. Losses after reactive ion etching of the channel waveguides increased by ~0.2 dB/cm for a 277 nm thick polished waveguide.

RESULTS

Two TiO_2 thin films of different thicknesses (i.e., wafers 20211014-A, and 20211014-B) were deposited by DC reactive sputtering in the MESA+ Nanolab TCOater sputtering system. During both deposition processes, the process pressure was kept at 6E-3 mBar and the base pressure at 1E-6 mBar. The temperature of the substrate during the deposition was 25 C. The substrate was rotated at 5 rpm. Gas flows of 80 sccm of argon and 9.8 sccm and 9.6 sccm of oxygen for wafers 20211014-A and 20211014-B respectively, which lead to a relative discharge voltage of 97.5% [17][18], were added to the sputtering chamber. A DC power of 500 W was applied to the titanium target. The thickness of the samples was characterized by ellipsometry. Wafer 20211014-A had an as-deposited thickness of 152 nm while the thickness of wafer 20211014-B was 291 nm. The surface roughness of the as-deposited wafers was characterized by atomic force microscopy (AFM). The two deposited wafers exhibited a surface roughness of 1.3 nm and 1.5 nm RMS respectively after deposition. Table 1 shows a summary of the characterization data of the two deposited wafers.

	Sample #	Thickness	Roughness	Loss@978 nm
Unpolished	20211014-A	152 nm	1.4 nm	0.2±0.1 dB/cm
Unpolished	20211014-B	291 nm	1.6 nm	0.7±0.4 dB/cm

Polished	20211014-A	131 nm	0.3 nm	----------------------
Polished	20211014-B	277 nm	0.3 nm	0.4±0.4 dB/cm

Table 1. Thickness, roughness and optical propagation loss of the two wafers of this study before and after the CMP step.

To reduce the roughness of the films and improve the optical propagation losses, we developed a chemical mechanical polishing process on the thin films using a Mecapol E460 CMP instrument. A solution of Semi Sperse 25 (SS25) slurry in 1 to 2 ratio with DI water with silica nanoparticles of 20 nm diameter was utilized. The pH was controlled to be 7. The details of the process are summarized in Table 2. As shown in Table 1, the surface roughness of the thicker as-deposited TiO_2 layer (20211014-B) was higher than that of the thin wafer (20211014-A). Such increase of RMS roughness with thickness is expected. After polishing, the RMS roughness of both wafers is drastically reduced to ~0.3 nm. Figure 1(left) shows the AFM images of the two wafers before and after CMP step.

Step	Duration	Pad Rotation Speed	Polishing head Rotation Speed	Polishing head Pressure
1. Landing	0 sec.	55 rpm	55 rpm	0.40 mbar
2. Polishing	30 sec.	55 rpm	55 rpm	0.50 mbar
3. Rinsing	60 sec.	55 rpm	55 rpm	0.40 mbar

Table 2. Chemical mechanical polishing process steps at the Mecapol E460 for TiO_2 thin films. A solution of Semi Sperse 25 (SS25) slurry in 1 to 2 ratio with DI water was utilized.

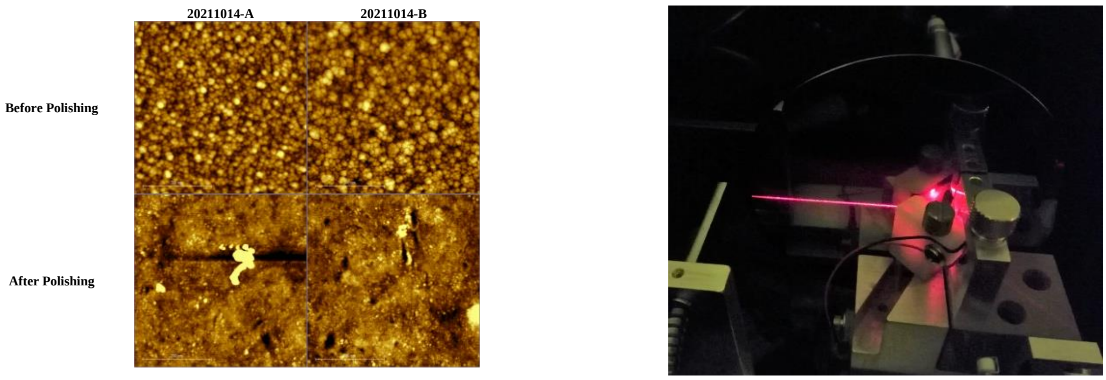

Figure 1. Image of the AFM scans at the center of the two wafers(20211014-A and 20211014-B) before and after CMP (Left); Light strike propagation at 633 nm. Wafer 20211014-B before polishing (right) showing propagation till the end of the wafer.

The propagation losses of the films before and after polishing were measured using a commercial prism coupler instrument (Metricon 2010/M) with a fiber-based propagation loss measurement module. Figure 1(right) shows the light strike at 633 nm as it propagates through the length of the 20211014-B wafer (before polishing). Figure 2 shows the intensity decay of the light strike (978 nm of wavelength) detected by the fiber before and after polishing. By fitting the intensity decay with an exponential model, a value for the propagation losses can be obtained and are summarized in Table 1. In both cases, the propagation losses decreased by ~0.3 dB/cm upon polishing. The thicker TiO_2 layer exhibits higher losses even after polishing, when a similar surface roughness is observed. This effect is attributed to the structure of the TiO_2 during the growth of a thicker layer, as reported by us in an earlier work [17].

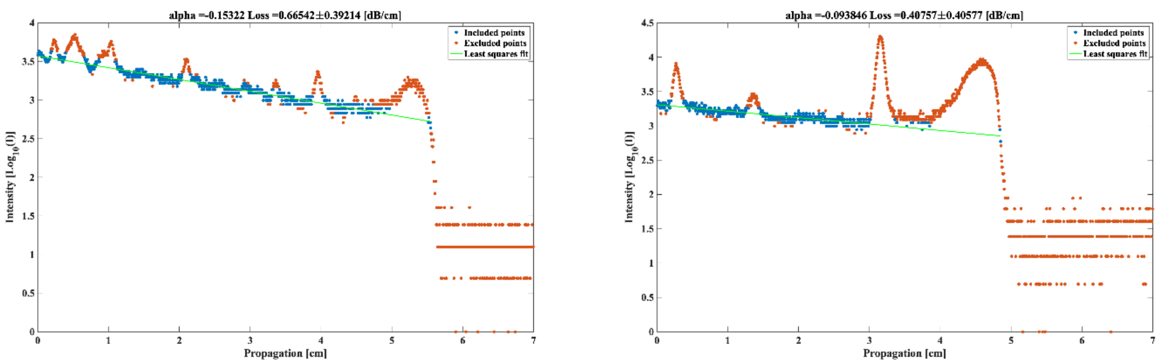

Figure 2. Metricon intensity plot of the scattered light from the light strike as a function of propagation distance for wafer 20211014-B before (left) and after (right) CMP process. The propagation losses extracted from the fit are shown as well as the data points included in the fit. Measurement wavelength 978 nm.

Microring resonator devices with coupling gaps varying between 300 nm and 700 nm and channel waveguides of width 1.1 μm were patterned by electron-beam lithography and reactive ion etching on the polished wafer 20211014-B. A 1 μm thick cladding of PMMA was then deposited over the singulated chips for characterization. The same characterization setup as described in more detail in [19] was utilized, which consists of a tunable laser source around 1550 nm (i.e., Agilent 8164B) and a PM500 nano-positioning stage. Details on how to extract the propagation losses from the measured microring resonator resonances are given in [19]. Using this methodology, propagation losses of ~0.5 dB/cm were measured on waveguides of cross-section 277 nmx1.1 μm at a wavelength of 1550 nm. Such losses are comparable to the propagation losses on other integrated photonic platforms and therefore rends the TiO_2 technology as useful platform for the realization of more complex integrated photonic devices or to be combined with other low-loss platforms.

CONCLUSIONS

The application of a chemical mechanical polishing (CMP) step to the fabrication process flow of TiO_2 waveguides permitted to achieve slab losses as low as 0.1 dB/cm at 978 m of wavelength and channel propagation losses of 0.5 dB/cm in thick channel waveguides of 277 nmx1.1 μm of cross-section. Further improvements on the deposition and etching of the devices could lead to further reduction of the propagation losses, which are however already comparable to the losses reported for other integrated photonic platforms.

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