Record low losses in TiO$_2$ channel waveguides

I. Hegeman, E. J. P. Vissers, M. Dijkstra, S.M. Martinussen, P. Muñoz Galindo and S. M. Garcia-Blanco

MESA+ Institute, University of Twente, P.O. Box 217, 7550 AE, Enschede, The Netherlands

TiO$_2$ is a promising material for waveguides, due to its wide transparency window of 370 nm to 5.9 µm [1], high refractive index of 2.4 @ 1550 nm [1], and a high nonlinear index of $2.3-3.6 \times 10^{-18}$ m$^2$/W at 1550 nm [2]. We have fabricated TiO$_2$ channel waveguides on SiO$_2$ with record low propagation losses of 2.3 ± 0.25 dB/cm at 1306 nm. These low losses have been achieved by optimizing the sputtering process to induce less crystallization, as well as optimizing the etching process for reduced sidewall roughness.

Introduction

Research on TiO$_2$ as a waveguide material is rapidly growing since around 2010 [2–11]. Advantages of the use of TiO$_2$ for integrated photonic circuits are included the high refractive index around 2.4 [1,12], which allows to scale down the waveguide dimensions, the wide transparency window ranging from the visible till mid-IR wavelength range [1] and its large non-linear refractive index [3]. TiO$_2$ slab waveguides have been reported with slab losses as low as 0.4 dB/cm at 826 nm for amorphous layers [12] and 3.5 dB/cm at 826 nm for anatase polycrystalline layers [12]. The lowest losses in channel waveguides fabricated using reactive ion etching are 9.7 dB/cm at 632.8 nm [6] and 4 dB/cm at a 1550 nm [7]. Losses as low as 7.5 dB/cm at 633 nm and 1.2 dB/cm at 1550 nm were obtained by using a dielectric lift-off fabrication process [9]. In contrary to the deposition shown in our work, all these layers were deposited using RF sputter deposition.

Applications of TiO$_2$ waveguides were shown using disk resonators fabricated using sol-gel TiO$_2$ layers [13]. Q-factors on the order of $10^5$ were demonstrated. Also micro-bends and couplers were reported in TiO$_2$ [7], which allows the design of integrated optical devices. The high refractive index of TiO$_2$ permits the realization of highly efficient waveguides for waveguide-enhanced Raman spectroscopy [14]. The negative thermo-optic coefficient of $-1 \times 10^{-4}$ °C$^{-1}$ [11] makes TiO$_2$ a useful material to create athermal devices by combining TiO$_2$ with Si$_3$N$_4$ [11,15] or with silicon [8]. The high non-linear refractive index [1,2] together with the high linear refractive index makes TiO$_2$ a promising material for integrated non-linear devices. Octave spanning super continuum generation [3], third harmonic generation [10] and four-wave mixing [2] were demonstrated in TiO$_2$ waveguides.

Waveguide fabrication

Many applications have been demonstrated, however for TiO$_2$ to compete with other platforms such as Si$_3$N$_4$, the losses need to be decreased by optimizing the fabrication processes. We have fabricated TiO$_2$ channel waveguides by optimizing the deposition and etching process parameters.

In our work, the deposition of TiO$_2$ layers is performed by DC reactive sputtering, using a Ti target, a plasma consisting of 18% O$_2$ and 82% Ar, a process pressure of $6 \times 10^{-3}$ mbar and 500 W DC power. The layers are deposited on top of a silicon wafer with a layer of 8 µm thick thermal SiO$_2$. No cladding is deposited on top of the waveguide.
Patterning of the TiO$_2$ layers is performed using UV-lithography followed by reactive ion etching. For the UV-lithography a layer of 1.7 μm thick photoresist is used. The reactive ion etching is done with the Oxford plasma pro 100 Cobra system. The etch parameters are summarized in table 1. Etch recipe A is the recipe as received from the producer of the system. Recipe B is as the recipe after optimization for etching TiO$_2$ waveguides. The ICP power is lowered in order to obtain a more homogeneous etching profile over the wafer. The process pressure is lowered in order to obtain sidewalls close to 90°.

**Characterization**

SEM images of the resulting TiO$_2$ waveguides are shown in figure 1. The optimized etching recipe shows sidewalls with an average angle of 85.2°, making these waveguides suitable for all kinds of structures including ring resonators with small bend radii and couplers. The sidewall roughness is also reduced by the more directional etching.

Figure 3b shows the Raman spectrum, showing a large peak at 520 cm$^{-1}$ corresponding to the silicon wafer. The peaks at 385 cm$^{-1}$ and 638 cm$^{-1}$ indicate the presence of the anatase crystalline phase in the TiO$_2$ channel. Due to the nature of the sputter deposition the phase will be polycrystalline.

<table>
<thead>
<tr>
<th>Setting</th>
<th>A</th>
<th>B</th>
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<tbody>
<tr>
<td>SF$_6$</td>
<td>25 sccm</td>
<td>25 sccm</td>
</tr>
<tr>
<td>O$_2$</td>
<td>6 sccm</td>
<td>6 sccm</td>
</tr>
<tr>
<td>Ar</td>
<td>5 sccm</td>
<td>5 sccm</td>
</tr>
<tr>
<td>Pressure</td>
<td>40 mTorr</td>
<td>10 mTorr</td>
</tr>
<tr>
<td>ICP power</td>
<td>1850 W</td>
<td>1500 W</td>
</tr>
<tr>
<td>CCP power</td>
<td>20 W</td>
<td>20 W</td>
</tr>
<tr>
<td>Temperature</td>
<td>10 °C</td>
<td>10 °C</td>
</tr>
</tbody>
</table>

Table 1: RIE parameters for the etching process without optimization (A) and after optimization (B).
The optical losses were characterized for a 360 nm thick TiO$_2$ waveguide etched using recipe B. The losses were measured at multiple wavelengths ranging from visible wavelengths to the mid-IR. Figure 2a shows a top view image of 1306 nm wavelength light coupled into a spiral waveguide. Figure 2b shows the scattered light intensity as a function of propagated distance. The optical losses are extracted from an exponential fit to the data. The resulting optical losses are 2.3±0.25 dB/cm which are, to our knowledge, the lowest losses at a wavelength of 1306 nm reported to date for etched TiO$_2$ channel waveguides.

Figure 2: (a) Photograph of the waveguide measured, with 1306 nm light coupled in; (b) Scattered light intensity vs propagated distance and a fit of the exponential decay.

Figure 3a shows the losses for varying wavelengths. For wavelengths between 1500 and 1650 nm the error bars increase significantly due to the high noise level compared to the small decay in intensity, so an accurate value for the losses was not obtained. For wavelengths below 1000 nm the losses increase significantly. One of the reasons is the increase of scattering losses with decreasing wavelength. Furthermore the waveguides support 2 TE modes around 1550 nm and at 1306 nm. Below 1000 nm the waveguide starts to support more modes, up to 8 TE modes at 632.8 nm, which makes the behavior of the waveguide unpredictable. The higher order modes could have higher losses compared to the fundamental mode.

Figure 3: (a) Optical losses as a function of wavelength; (b) Raman spectrum of the 360 nm thick TiO$_2$ waveguide, indicating the presence of the anatase crystalline phase.
Conclusion
In this work, we have shown polycrystalline anatase TiO$_2$ waveguides with losses as low as $2.3\pm0.25$ dB/cm at a wavelength of 1306 nm, which is to our knowledge the lowest losses for reactive ion etched TiO$_2$ channel waveguides at this wavelength reported to date. The losses between 1500 and 1650 nm are close to the values obtained by Evans et. al. [7], where a lift-off process is used. The advantage of this fabrication process are the straight side walls, which allows to design micro ring resonators and optical couplers. In order to compare the losses at different wavelengths, the fabrication of single mode waveguides at varying wavelengths is necessary and it is currently ongoing.

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