Effects of annealing on optical properties of TiO$_2$ planar waveguides

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Outline

Introduction: TiO$_2$ for nanophotonic applications

Optimization of optical parameters of TiO$_2$ thin films

Results: Reduction of Propagation Losses through Annealing
Introduction

Applications of TiO$_2$ thin films

- photocatalysis
- solar cells
- reflective coatings
- dielectric layers
- nanophotonics
Introduction

Applications of TiO$_2$ thin films

photocatalysis
solar cells
reflective coatings
dielectric layers

nanophotonics
Introduction

Why TiO$_2$ for nanophotonics?
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Highly transparent for $\lambda \geq 400$ nm
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High nonlinearity: $n_2 \geq 30 \times n_{2, SiO_2}$ at 1064 nm*

Introduction

Why TiO$_2$ for nanophotonics?

Highly transparent for $\lambda \geq 400$ nm
High refractive index: $n_0 \approx 2.4$ at 800 nm
High nonlinearity: $n_2 \geq 30 \times n_{2,\text{SiO}_2}$ at 1064 nm

Potential applications:
- photonic crystals, nonlinear optics,
- active devices, passive devices
In order to exploit these properties, we require TiO$_2$ thin films with:

- high linear index ($n_0$)
- low propagation losses
- high nonlinearity ($n_2$)
Optimization of TiO$_2$ Thin Films

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deposition method
deposition parameters
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  - e-beam evaporation
  - atomic layer deposition
  - non-reactive sputtering
  - reactive sputtering
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- amorphous films
- high index ($n_0 = 2.34$)*
- low loss (0.4 dB/cm)**

*λ = 826 nm
** Fundamental mode, TE polarization, λ = 826 nm
Optimization of TiO$_2$ Thin Films

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- deposition method
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- post-deposition annealing
Annealing of TiO$_2$ Thin Films

Annealing can cause transitions between different phases of TiO$_2$, which have different optical properties.

In the literature*

<table>
<thead>
<tr>
<th>Phase</th>
<th>Anneal Temperature ($^\circ$C)</th>
<th>Refractive Index ($n_0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amorphous</td>
<td>As deposited</td>
<td>2.1</td>
</tr>
<tr>
<td>Anatase</td>
<td>300</td>
<td>2.2</td>
</tr>
<tr>
<td>Rutile</td>
<td>700-900</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Annealing of TiO$_2$ Thin Films

Annealing can cause transitions between different phases of TiO$_2$, which have different optical properties.

In the literature

Little to no discussion of the effects of annealing on the waveguiding properties of TiO$_2$ thin films.
Annealing of TiO$_2$ Films

Goal: Determine if losses can be improved via annealing
Annealing of TiO$_2$ Films

Goal: Determine if losses can be improved via annealing

Films were deposited onto oxidized silicon wafers using Reactive Sputtering under ambient conditions.

<table>
<thead>
<tr>
<th>Film Properties</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Thickness</td>
<td>310 nm</td>
</tr>
<tr>
<td>Refractive index ($n_0$)*</td>
<td>2.34</td>
</tr>
<tr>
<td>Phase</td>
<td>Amorphous</td>
</tr>
<tr>
<td>Propagation losses**</td>
<td>&gt; 15 dB/cm</td>
</tr>
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</table>

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** Fundamental mode, TE polarization, λ = 826 nm
Annealing of TiO$_2$ Films

Several anneals were conducted between 100 and 800° C.

Each anneal was conducted:

- for 180 minutes
- in an oxygen environment (250 sccm)
Results

Film Characterization Methods

Refractive Index: prism coupling
Crystalline phase: Raman spectroscopy
Propagation losses: prism coupling
Results

Prism Coupling

![Image of Prism Coupling](image-url)
Results

Prism Coupling
Results

Refractive index*

*λ = 826 nm
Results

Refractive index

*λ = 826 nm
Results

Crystalline Phase

![Graph showing Raman Shift vs Intensity](image-url)
Results

Crystalline Phase

![Graph showing Raman shift with peaks at 300 cm⁻¹ and 520 cm⁻¹](image)

- Si (520 cm⁻¹)
- Si (300 cm⁻¹)

200°C
Results

Crystalline Phase

TiO$_2$ film is non-crystalline.
Results

Crystalline Phase

TiO$_2$ film is amorphous.
Results

Crystalline Phase

![Graph showing Raman shift vs. intensity with peaks at 250°C and 200°C.](image)
Results

Crystalline Phase

Results

Crystalline Phase

TiO$_2$ film shows some anatase structure

- 250°C
- 200°C

Raman Shift (cm$^{-1}$)

Intensity (a. u.)
Results

Propagation Loss

TiO$_2$ waveguide
Guided light
Results

Propagation Loss

Fundamental mode, TE polarization, $\lambda = 826$ nm
Results

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Propagation Loss

Fundamental mode, TE polarization, $\lambda = 826$ nm
## Results

<table>
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<th>Propagation loss* [dB/cm] ± 0.05 dB/cm</th>
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<td>100</td>
<td>4.60</td>
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Loss measurements stable over time at room temperature.
### Results

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Results

Implications

- low loss TiO$_2$ thin films fabricated through low temperature process
  - compatible with hybrid technologies
  - for integrated optics

Potential Drawback

- phase transition above 200º C
  - potential devices limited to lower temperatures
Conclusion

Annealing at low temperatures (< 200\(^\circ\) C) results in:
- amorphous films
- no change in index (2.34)
- decrease in propagation losses (up to 1.28 dB/cm)
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Annealing at higher temperatures results in:
- anatase films
- higher index (2.38)
- higher propagation losses (> 15 dB/cm)
Conclusion

We have reduced planar propagation losses in TiO$_2$ thin films by annealing.

TiO$_2$ thin films show promise for nonlinear nanophotonics.
Acknowledgements

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