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Optics Letters

TiO₂ microring resonators with high Q and compact footprint fabricated by a bottom-up method

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Titanium dioxide (TiO₂) microring resonators (MRRs) with high quality factors (Qs) are demonstrated by using a new, to the best of our knowledge, bottom-up fabrication method. Pattern platforms with a T-shaped cross section are first defined by etching a thin top layer of silicon nitride and a thick bottom layer of silica and partially undercutting the silica. Then, TiO₂ is deposited on the platforms to form the TiO₂ waveguides and devices. TiO₂ MRRs with different bending radii, waveguide widths, and gaps in the bus waveguide are fabricated and measured. The intrinsic Q (Q_{int}) is achieved to be $\sim 1.1 \times 10^5$ at the telecommunication wavelengths, corresponding to a bend waveguide loss of 3.9 dB/cm while the compact MRR with a radius of 10 μm can still sustain a Q_{int} of $\sim 10^5$. These results not only unfold the feasibilities of the proposed bottom-up method for fabricating TiO₂ waveguides and MRRs with high Qs and compact footprints but also suggest a new approach for fabricating waveguides in other materials, of which direct etching is not easily accessible. © 2020 Optical Society of America

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Titanium dioxide (TiO₂) has recently evolved as a promising candidate for photonic integrated circuits (PICs) by possessing high linear and nonlinear indices, a large bandgap (>3 eV), a uniquely negative thermo-optic coefficient, and a large transparency window from visible to mid infrared wavelengths [1–18]. Besides, the possible compatibility with the mature silicon complementary metal oxide semiconductor (CMOS) fabrication process also endorses TiO₂-based PICs in terms of scalable manufacturing [19]. Among different PIC devices, the microring resonator (MRR) is a fundamental building block for many applications that enhances the local optical field intensity in a small area. TiO₂ MRRs have also been widely studied and play a vital role in applications like thermal optical filters [15] or Raman sensing [18].

Several methods have been demonstrated to pattern TiO₂ waveguides, including ion implantation [1], wet etching [2], dry etching [3–13], and lift-off [14,15]. Among them, the

top-down method, in which TiO₂ film is first deposited and then selectively etched with a mask, has normally been used. However, different from selective etching of silicon, silica, and silicon nitride, which have been intensively optimized and easily accessible, selective etching of TiO₂ remains a challenge, especially for fabricating sub- μm -wide waveguides with dry etching like reactive-ion etching (RIE). This may be attributed to the fact that most of the Ti-contained etch products have a high boiling point and are not easily volatile during the ion etching [20], and that Ti/TiO₂ is a hard material itself that acts as the hard mask for etching other metals [21,22]. These not only challenge the mask selection for TiO₂ etching, but also produce rough sidewalls with residues. Whereas thick UV sensitive polymer resists could perform as the etch mask, the fabricated TiO₂ waveguide exhibited a high loss (5.5 dB/cm [3]) or possessed a very thin TiO₂ core of 140 nm despite a quite low loss of 0.68 dB/cm [4]. Meanwhile, the thick UV resists are not suitable for fabricating sub- μm structures, especially for the small gaps between an MRR and the bus waveguide. Sub- μm -wide TiO₂ waveguides could be fabricated with a metal mask, but the waveguide losses were usually high, which inevitably resulted in TiO₂ MRRs with moderate intrinsic Qs (e.g., 2.2×10^4 at the wavelength of 635 nm [6], 8.9×10^4 at 1550 nm [10], 7.35×10^4 at 1550 nm [13]). In order to avoid TiO₂ etching, lift-off processes have been developed for high-Q TiO₂ MRRs (2×10^5 [14], 1.55×10^5 [15]). However, limited by the weak confinement of TiO₂ waveguides fabricated with the lift-off process, MRRs usually had large footprints, e.g., with a radius of 150 μm [14] and 200 μm [15].

Here, we demonstrate a new bottom-up method for fabricating TiO₂ waveguides and MRRs. In this method, TiO₂ waveguides are formed by depositing TiO₂ on pattern platforms with a T-shaped cross-section profile, which is fabricated by deep etchings to the thin top layer of silicon nitride (Si₃N₄) and the thick bottom layer of silica (SiO₂) and an undercut etching with a hydrofluoric (HF) acid solution. Thus, the direct dry etching to the TiO₂ material is avoided and all the involved etching processes are indeed easily accessible in today's laboratories or foundries. Measurements to the fabricated TiO₂ MRRs show intrinsic Qs of $\sim 1.1 \times 10^5$, comparable to that from the lift-off

Fig. 1. Bottom-up fabrication flow for TiO_2 waveguides. (a) Si_3N_4 deposition on the oxidized Si wafer. (b) Cr deposition. (c) E-beam lithography and Cr etching. (d) Si_3N_4 etching. (e) SiO_2 deep etching. (f) SiO_2 wet etching. (g) TiO_2 deposition. (h) TiO_2 polishing with HF.

processes, and MRRs with sub- μm waveguide widths or a small radius of $10\ \mu\text{m}$ exhibit close Qs. These results not only verify the high feasibilities of our bottom-up method for fabricating high-Q TiO_2 MRRs, but also suggest a new approach for waveguide fabrication in other materials of great importance but few off-the-shelf fabrication processes.

The proposed bottom-up fabrication flow is illustrated in Fig. 1. Starting with a Si wafer with a $2.4\text{-}\mu\text{m}$ oxidized SiO_2 layer, a thin (50 nm) layer of Si_3N_4 is first deposited with a low-pressure chemical-vapor-deposition (LPCVD) method [Fig. 1(a)]. Then an 80-nm chromium (Cr) layer is deposited by electron beam evaporation [Fig. 1(b)]. Next, the waveguide patterns are defined by e-beam lithography, first on ZEP resist and then on Cr by dry etching [Fig. 1(c)]. The Cr etching is completed in a RIE machine with a gas mixture of chlorine (Cl_2 , 65 sccm) and oxygen (O_2 , 15 sccm) at a substrate temperature of 50°C , a pressure of 15 mTorr, and a platen power of 15 W. With Cr as the hard mask, the thin Si_3N_4 layer is first dry-etched with a gas mixture of carbon tetrafluoride (CF_4 , 20 sccm) and hydrogen (H_2 , 10 sccm) at a substrate temperature of 0°C , a pressure of 3 mTorr, and a platen power of 5 W [Fig. 1(d)]. Then a deep etching is carried out to etch through the $2.4\text{-}\mu\text{m}$ -thick SiO_2 layer with the Si substrate being a little etched in [Fig. 1(e)]. A gas mixture of octafluorocyclobutane (C_4F_8 , 40 sccm) and oxygen (O_2 , 5 sccm) at a substrate temperature of 55°C , a pressure of 6 mTorr, and a platen power of 180 W is used for the deep etching. After stripping the residual Cr in Etchant 18 solution, 5% HF solution is used to etch SiO_2 for 5 min with $\sim 130\text{ nm}$ cut on both sides. This leaves pattern platforms with a T-shaped cross section [Fig. 1(f)]. Then TiO_2 is deposited by ion-beam sputtering (IBS), as described in our previous work [13]. One can deposit as thick TiO_2 as needed, as long as the SiO_2/Si etching is deep enough. Here, a 350-nm-thick TiO_2 layer is deposited. Finally, the TiO_2 waveguides are polished by the 5% HF solution for 3 min with 250-nm-thick TiO_2 left.

Figure 2(a) shows the scanning electron microscopy (SEM) image of a TiO_2 waveguide after the TiO_2 deposition but prior to the HF polishing. From the SEM image, rough sidewalls are found. This is because the incident particle beam sputtered out from the Ti target to the sample has an angle far beyond the optimal angle with the sidewall surfaces of the $\text{Si}_3\text{N}_4/\text{SiO}_2$ pattern platform and the TiO_2 core and, hence, yields TiO_2 with very low density [23] or even porosity grown on the sidewalls. Tremendous scattering loss would be introduced by such sidewalls, which, however, can be mitigated by the HF etching for 3 min, as shown by the SEM image in Fig. 2(b). Meanwhile,

Fig. 2. SEM images of the TiO_2 waveguide fabricated by the bottom-up method (a) before and (b) after the HF polishing. (c) SEM images of the racetrack MRR (a) and (d) cross-section of the straight coupling region.

since there is more/wider low-density TiO_2 on the sidewalls towards the bottom and the HF etching is faster for such low-density TiO_2 than the denser TiO_2 on the top surface, the TiO_2 core is shaped to be inversely trapezoidal by the HF polishing. After polishing, the waveguides are narrowed down and gaps between the bus waveguide and the MRR are inevitably large, i.e., $>260\text{ nm}$. Racetrack structures are used to guarantee sufficient light coupling into the resonators, as shown by the SEM image in Fig. 2(c). Radius and straight length of the MRRs are denoted as R and L , respectively, and L is $20\ \mu\text{m}$ for all our fabricated MRRs. Figure 2(d) shows the SEM image of the cross section of the straight coupling region of a fabricated TiO_2 MRR. In the figure, the T-shaped $\text{Si}_3\text{N}_4/\text{SiO}_2$ pattern platform and the inversely trapezoidal TiO_2 waveguide core can be more clearly recognized. The top and bottom widths of the waveguide core are denoted as w_1 and w_2 , respectively. Moreover, the gap in the bus waveguide is defined as the distance between the upper borders of the two inversely trapezoidal TiO_2 waveguide cores.

We have fabricated TiO_2 MRRs with two different waveguide widths, i.e., $w_1 = 1370\text{ nm}$ ($w_2 = 1180\text{ nm}$) and $w_1 = 870\text{ nm}$ ($w_2 = 680\text{ nm}$). The narrower one is a single-mode waveguide while the wider one can support higher-order modes. Here, we only focus on the transverse-electric (TE_0) polarization. Figures 3(a) and 3(b) show the simulated electric field intensity distributions of the fundamental mode (TE_0) profiles for the wider and narrower waveguides, respectively, at the wavelength of 1550 nm . The effective refractive index is calculated to be 1.745 and the effective mode area is $0.51\ \mu\text{m}^2$ for the wider TiO_2 waveguide at 1550 nm , while they are 1.597 and $0.34\ \mu\text{m}^2$ for the narrower one. Meanwhile, power confinement ratios in the TiO_2 core are calculated to be 63.3% and 60.4% for the wider and the narrower waveguides, respectively. While the narrower waveguide may be preferred for, e.g., nonlinear applications due to a smaller effective area [24], the wider one may exhibit a lower loss since the mode apparently overlaps less with the sidewalls, which couldn't be perfectly smooth under current fabrication techniques.

Figure 4(a) shows the measured and normalized (to a straight TiO_2 waveguide) transmission spectra of the fabricated TiO_2

Fig. 3. Electric field density distribution of the mode profile for the TiO₂ waveguides with the width (a) $w_1 = 1370$ nm and (b) $w_1 = 870$ nm. Here, the wavelength is 1550 nm.

MRRs with $w_1 = 1370$ nm, $R = 130$ μm and gaps of 310 nm (red) and 360 nm (blue). The spectra show that the extinction ratios (ERs) increase with the increasing wavelength and the decreasing gap, both of which indicate a stronger light coupling to the MRR. Thus, it can be deduced that the MRRs are under-coupling. By using the same method as that in Ref. [14], we have used the Lorentzian curve to fit the spectrum around each resonance and extracted the loaded $Q(Q_{\text{load}})$ and intrinsic $Q(Q_{\text{int}})$ and calculated the bend waveguide loss at each resonant wavelength. Figure 4(b) shows the extracted Q_{int} (filled circles) and loss (filled triangular) of the two MRRs at each resonant wavelength. Q_{int} of both the two TiO₂ MRRs distributes around 1.1×10^5 (dashed blue line) in the whole investigated wavelength range from 1520 nm to 1620 nm. The waveguide loss can be attributed to scattering and absorption. We use a simple formula to fit the waveguide loss α as a function of the wavelength, as shown by

$$\alpha = \frac{a}{\lambda^4} + b, \quad (1)$$

where λ is the wavelength and a and b are coefficients to be fitted. The first part represents the Rayleigh scattering loss, which originates from the sidewall roughness or the scatters inside the TiO₂ core and is inversely proportional to the fourth power of λ [25]. The second part is a constant representing the TiO₂ absorption loss since the power confinements in the waveguide core are almost constant, i.e., from 64.3% at 1520 nm to 61.0% at 1620 nm. Thus, a and b are fitted to be $13.5 \times 10^{12} \text{ nm}^4 \text{ dB/cm}$ and 1.6 dB/cm , respectively, and, therefore, $\alpha = 3.9 \text{ dB/cm}$ at 1550 nm. The solid blue line in Fig. 4(a) shows the fitted curve.

The solid blue line in Fig. 5(a) shows the measured and normalized transmission spectrum of a fabricated TiO₂ MRR with $w_1 = 870$ nm, $R = 130$ μm , and gap = 460 nm. We have also calculated the coupling efficiency between the bus waveguide and the MRR, as shown by the solid red line in Fig. 5(a). The coupling efficiency increases from 0.08 to 0.25 as the wavelength increases from 1520 nm to 1620 nm. Around 1555 nm, the resonator is around the critical coupling, i.e., the coupling efficiency equals the single-round trip loss of the MRR (assuming no loss in the coupler [26]), showing the largest ERs more than 25 dB. The MRR is under-coupling at wavelengths shorter than 1555 nm and over-coupling at wavelengths longer than 1555 nm. With this, the Q_{int} of the MRR and the waveguide loss at each resonant wavelength are extracted and shown by the green dots and the red dots in Fig. 5(b), respectively. The Q_{int} around 1550 nm is about 0.9×10^5 . We also use Eq. (1) to fit the loss as a function of wavelength, as shown by the solid blue line in Fig. 5(b), and a and b values are fitted to be $24 \times 10^{12} \text{ nm}^4 \text{ dB/cm}$ and 1.22 dB/cm , respectively. Thus, the

Fig. 4. (a) Measured transmission spectra of the fabricated TiO₂ MRRs with $w_1 = 1370$ nm, $R = 130$ μm , and different gaps. (b) The extracted intrinsic Q and waveguide loss of the MRRs at each resonant wavelength. The solid blue line shows the fitting to the loss as a function of the wavelength, and the dashed blue line indicates $Q_{\text{int}} = 1.1 \times 10^5$.

Fig. 5. (a) Measured transmission spectrum and calculated coupling efficiency of a fabricated TiO₂ MRR with $w_1 = 870$ nm, $R = 130$ μm , and gap = 460 nm. (b) The extracted intrinsic Q and waveguide loss at each resonant wavelength. The solid blue line is the fitting to the waveguide loss as a function of the wavelength.

total loss at 1550 nm is 5.4 dB/cm with scattering and absorption accounting for 77% and 23%, respectively. Partially due to less light being confined in the TiO₂ core, the absorption loss of the narrower waveguide is slightly smaller than that of the wider one. However, the contribution of the scattering to the total loss

Fig. 6. Measured transmission spectrum of a fabricated TiO_2 MRR with $w_1 = 1370$ nm, $R = 10$ μm , and gap = 360 nm. The inset shows the close-up spectrum and the Fano-like fitting around the resonance at 1565.411 nm.

in the narrower waveguide is apparently larger since more field overlaps the sidewalls.

Thanks to the large refractive index of TiO_2 , a TiO_2 MRR may confine light in a very compact dimension, which can considerably strengthen the light-matter interaction or boost the nonlinear effect. We have also used the proposed bottom-up method to fabricate TiO_2 MRRs with very compact footprints. Figure 6 shows the measured and normalized spectrum of a TiO_2 MRR with $w_1 = 1370$ nm, $R = 10$ μm , and gap = 360 nm. The free-spectral range (FSR) is measured to be 9.8 nm. The inset shows the close-up spectrum (blue dots) around the resonance at 1565.411 nm. Meanwhile, a Fano-like fitting (red line) is used to fit the measured spectrum by taking into account the influence of the Fabry–Perot (F-P) cavity formed between the two facets of the bus waveguide. From the fitting, one can extract a linewidth of 25 pm resulting in a Q_{int} of 1.006×10^5 and a bend waveguide loss of ~ 4.2 dB/cm, which are the same as that extracted from a pure Lorentzian fitting due to the very weak influence of the F-P cavity and at the same level as that of the large MRRs (i.e., $R = 130$ μm). This clearly shows the feasibility of our proposed bottom-up fabrication method for TiO_2 MRRs with very compact footprints.

In summary, by first fabricating pattern platforms with a T-shaped cross section and then depositing TiO_2 to form the waveguide, we have demonstrated a new bottom-up method for fabricating TiO_2 waveguides without direct dry etching to the TiO_2 . With this method, TiO_2 MRRs are fabricated and intrinsic Q values of $\sim 1.1 \times 10^5$ are achieved, comparable to the state-of-the-art results [14,15]. The fabricated TiO_2 MRR with a bending radius of 10 μm can sustain a Q value of $\sim 10^5$, showing the strong confinement of the TiO_2 waveguide and the feasibility of the proposed bottom-up method for fabricating very compact TiO_2 MRRs. Measurements and analysis of an MRR with the TiO_2 single-mode waveguide suggest that the scattering loss is dominant while the absorption loss is still not negligible. The scattering loss may be further lowered down by optimizing the metal mask etching. Meanwhile, more optimization to the TiO_2 deposition, e.g., finer adjustment to the O_2 flow during the reactive sputtering, is needed to reduce the absorption loss [4]. Apart from being used for the fabrication of the TiO_2 waveguides and MRRs with high Q s and compact footprints, our method can also be seen as a simple way to validate the feasibility of waveguides with new materials, especially the ones whose etching is complex to optimize or contaminates the existing fabrication line.

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