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Low-loss titanium-dioxide strip waveguides by atomic layer deposition

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ABSTRACT

In this paper we describe an approach to reduce the propagation loss in titanium dioxide strip waveguides. We achieved to reduce losses down to 2.4 dB/cm in 1 μm -wide waveguide at $\lambda=1550$ nm.

Keywords: Titanium dioxide, propagation loss measurements, atomic layer deposition

1. INTRODUCTION

Nanophotonic devices are nowadays a field in expansion in the domains of medical sciences, bio-sensing and telecommunication, where the miniaturization, the efficiency and the speed of the components have to be integrated and combined together with electronic chips [1-6]. Especially thanks to silicon photonics, the fabrication techniques at the nanoscale have been developed and optimized to create devices with higher and higher performances. In nanophotonics the main issue is to confine the electromagnetic field and guide it from a structure to another without losing energy during the transfer. Indeed, energy saving is an important aspect to take into account since more complex the device is, higher is the consumption.

To confine light in an efficient way into nanostructure, the material with a high refractive index should be chosen. For the telecommunication domain, which is responsible of the high development of nanophotonics, silicon is an ideal material since it is transparent in the near infrared and especially at $\lambda=1550$ nm, which is the telecom wavelength. Nevertheless, silicon presents some disadvantage like the two-photon absorption, which plays a negative role in non-linear application and tends to increase the losses. Silicon nano-waveguides, with a propagation loss value as low as 2.5 dB/cm have been fabricated [7].

The extension of the applications of nano-devices to the bio-sensing makes silicon less suitable since the material is not transparent under $\lambda=1.1$ μm . Another material, with a high refractive has been found with the titanium dioxide. This material presents indeed a refractive index of $n=2.2$ at $\lambda=1.55$ μm , a large band gap $E_g=3.2$ eV [8] and is transparent in the visible and near infrared region at the same time. This material is also nonlinear and a third order susceptibility has been measured at $\lambda=800$ nm, $\chi_2 = -6.32 \times 10^{-17}$ m²/W [9], in the case of amorphous TiO₂. A recent experimental result, at the telecom wavelength, has shown that the χ_2 of an amorphous thin film of TiO₂, grown by Atomic Layer Deposition is only 50% less than the one measured in a crystalline film [10]. Moreover the recent literature shows amorphous TiO₂ waveguides with low propagation loss around 4 ± 2 dB/cm [11].

Atomic Layer Deposition (ALD) is an ideal method to fabricate TiO₂ thin films. Indeed, ALD allows a very high precision on the control of the thickness over large area of the material and, in addition, the coating is conformal which permits to deposit a uniform layer over non-flat surfaces.

We propose here the study of the propagation loss inside 1 μm -wide amorphous TiO₂ waveguides fabricated by means of the combination of ALD and e-beam lithography. Moreover we present a method [12] to reduce these propagation losses mainly due to the sidewall roughness of the waveguides by virtually removing the interface TiO₂/air when adding a cover layer of TiO₂ on the waveguide by ALD. This work is an extended version of the study published in reference [13].

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2. PRINCIPLE AND METHOD

2.1 Problem

The goal of this paper is to present a novel and elegant method to reduce propagation losses in TiO_2 waveguides. Considered waveguides are intended to work at the telecom wavelength ($\lambda=1550$ nm) and are designed to be monomode at this wavelength. The height of the guides is $h=450$ nm and their width is $w=1$ μm . In this case the fundamental TE and TM modes are allowed to propagate. Figure 1 shows a simulation of such kind of waveguide for both polarizations. On a) and c) is plotted the field distribution in a cross-section plane (x,y) of the waveguide for TE and TM polarization respectively. The solid white line represents the contour of the waveguide (TiO_2) on an SiO_2 substrate.

From Figure 1, one can see the strong overlap between the guided mode and the edges of the waveguide. This overlap leads to propagation losses, which can be increased if the surface state of the waveguide is not perfectly smooth. In the case of a waveguide fabricated using a classical lithographic process, an important roughness appears during the etching process. Indeed, waveguides are created using a chromium mask followed by an etching made with an ICP-RIE machine. The chromium mask protects the top surface of the waveguide, which remains flat and smooth after removing the chromium layer, but a huge roughness is induced on the sidewalls of the waveguide by the non-sharp edges of the mask itself. This is not avoidable easily with classic technological processes.

Figure 1. Field distributions (a and c) and field amplitude along the x-direction (b) and the y-direction (d) corresponding to the white dashed line in a) and c) respectively.

In Figure 2 is presented an SEM picture of a TiO_2 waveguide. One can see the surface roughness of the sidewalls and the smoothness of the top surface protected by the mask. Note that a thin layer of copper has been deposited on the sample in

order to take the picture using SEM. It explains the presence of grains of more or less large diameter on the surface of the waveguide.

Figure 2. SEM picture of a ridge waveguide in TiO_2 on an SiO_2 substrate. One can see the sidewall roughness on the edge of the waveguide and remark that the top surface is almost perfectly smooth. The additional grains are due to the copper layer added on the sample for the imaging process using SEM.

2.2 Method

The method is presented in detail in the reference [13]. It consists of re-coating with a very thin layer of the same material as the waveguide. By adding a layer of a few tens of nanometers of TiO_2 on the structure, we are erasing the small details (lower than the thickness of the additional layer), which means the surface roughness is reduced [12].

The Atomic Layer Deposition is used to perform this layer. ALD is indeed a method allowing a conformal deposition of the material and a very precise control of the deposition thickness.

3. EXPERIMENTS

3.1 Fabricated sample

The sample is fabricated on a Si/SiO_2 (thicknesses are 500 μm and 2 μm respectively) substrate. The TiO_2 guiding layer of 450 nm-thick is first deposited by means of the ALD technique. The waveguide are created using standard e-beam lithography: a chromium layer is patterned with e-beam and etched using reactive ion etching then a final etching step is done to transfer the pattern into the TiO_2 layer. Note that an over etching of this layer is done. Indeed, the device is intended to be re-coated with a few tens of nanometers of TiO_2 and we have taken this additional thickness into account. The result of this process is the waveguide presented in Figure 2.

It is important to note the parameters of the ALD process. It is done at a temperature of 120°C, using TiCl_4 and H_2O as precursors [14]. It leads to a layer of amorphous TiO_2 deposited at a rate of 0.7 nm/cycle. Two types of waveguides have been fabricated on the same chip: straight waveguides and bended waveguides. In both cases, the input and output of the waveguides is composed of a 3 μm -wide waveguide followed by a taper of 100 μm -long helping the coupling to the desired waveguide of 1 μm -wide. SEM pictures of the S-bended waveguides are presented in Figure 3.

Simulations have shown that a re-coating of 45 nm of TiO_2 makes the waveguides multimode. We have then decided to perform measurements only for an additional layer of 15 nm and 30 nm. Moreover a reference sample has also been fabricated. It consists in the same pattern but with the parameters after re-coating of the waveguides: which means a thickness of 480 nm and a width of 1.06 μm . It will be used to prove the efficiency of our method.

Figure 3. SEM pictures of the TiO_2 S-bend waveguides. a) waveguides with different lengths; b) zoom in on one waveguide. The bend radius is $r=50\text{ }\mu\text{m}$, a waveguide of $3\text{ }\mu\text{m}$ -wide is used at the input and output and is connected to the studied $1\text{ }\mu\text{m}$ -waveguide by classical tapers of $100\text{ }\mu\text{m}$ -long.

3.2 Characterization

Figure 4. Algorithm representing the design of the experiment. An additional coating of 15 nm of TiO_2 is deposited by ALD after each measurement of the whole sample (different waveguide lengths).

The characterization setup is composed of a tunable laser (C-band) amplified using an erbium doped fiber amplifier. Light is coupled to the sample and collected by means of lensed fibers and the output signal is observed thanks to an optical spectrum analyzer.

The cut-back method is used to quantify the propagation loss in the waveguides. 10 different lengths of straight waveguides and 4 of S-bended waveguides have been designed and fabricated. The design of experiment is presented in the algorithm of the Figure 4. For each waveguide the transmission is measured (at the telecom wavelength $\lambda=1550$ nm). Each measurement is performed at least three times for statistical purpose. When all the waveguides are measured, an additional layer of TiO_2 of 15 nm thick is deposited by ALD. This process is repeated twice.

The measurements are reported in Figure 5. The data points, the error bars and the linear fit are given for each thickness of the additional layer (0, 15 and 30 nm). The green points correspond to measurements which have not been taken into account in the linear fit. These points have been rejected because the corresponding waveguides are cut or the input or output is damaged. The slope of the linear fit gives us the propagation loss α inside the waveguides.

For the linear waveguides, we have measured $\alpha_{0\text{nm}}=5.0\pm0.5$ dB/cm, $\alpha_{15\text{nm}}=4.6\pm0.5$ dB/cm, and $\alpha_{30\text{nm}}=2.5\pm0.2$ dB/cm for the thicknesses of the additional coating 0 nm, 15 nm and 30 nm respectively. For the S-bended waveguides, we have obtained $\alpha_{0\text{nm}}=21\pm0.8$ dB/cm, $\alpha_{15\text{nm}}=8.6\pm0.8$ dB/cm, and $\alpha_{30\text{nm}}=8.1\pm0.8$ dB/cm. The losses in the straight reference waveguide have been measured at $\alpha_{\text{ref}}=7\pm0.7$ dB/cm.

One can first remark that the values for the S-bended waveguides are higher than for the straight waveguides. This result is expected, since the bends are source of additional losses even if their diameter of 100 μm is enough large to reduce this effect. A second important observation is the very high losses ($\alpha_{0\text{nm}}$) measured with uncoated S-bended waveguides. This may be due to a stitching effect during the patterning with the e-beam. This stitching is reduced by the recoating and then the propagation losses decrease too.

Concerning the straight waveguides, one can note that the propagation losses drop down to 2.5 dB/cm, which is a proof that the technique is efficient since the value is almost three times lower than the one of the reference waveguide.

Figure 6 shows the evolution of the propagation losses as a function of the polarization of the input light. We have reported on this figure the experimental data points and the corresponding linear fits for the S-bended waveguides already re-coated with 30 nm of TiO_2 . The polarization angle is varied between $\theta_1=0^\circ$ and $\theta_5=180^\circ$. The values of the propagation losses for the 5 angles are reported in Table 1.

Table 1. Propagation loss values measured in the S-bended waveguide re-coated by 30 nm of TiO_2 for different polarization angles of the input light.

Angle	Propagation loss (dB/cm)	Correlation coefficient
$\theta_1 (= 0^\circ - \text{TE})$	13.8	0.9919
$\theta_2 (\sim 45^\circ)$	17.54	0.9673
$\theta_3 (\sim 90^\circ - \text{TM})$	18.66	0.9574
$\theta_4 (\sim 135^\circ)$	17.11	0.9896
$\theta_5 (\sim 180^\circ - \text{TE})$	14.26	0.9730

From Table 1, one can note that passing from a polarization to another modifies the propagation losses. Additional measurements, not presented here, have shown that the propagation losses decrease for both polarizations after each re-coating. This can be explained by the fact that when a layer is added on the device, the cross section increases and then the mode is more concentrated in the TiO_2 , which means that the overlap between the field and the edge of the waveguide becomes less important. In reference 13, we have demonstrated that the effective index variation with the re-coating thickness has a more predominant effect for the TM polarization. Moreover, as already observed above in the text in Figure 1, the effect of the recoating should be higher for the TE polarization than for the TM. Nevertheless, one

can see that also for the TM polarization a non-negligible part of the mode overlap the sidewalls of the waveguides. The observed result is then expected.

One can conclude from these observations that the propagation losses decrease for both polarization but for two different reasons. In the case of the TE polarization it is mainly due to the reduction of the sidewall roughness and for the TM polarization to the increase of the effective index of the waveguide.

Figure 5. Transmission measurements through waveguides of different lengths, for different thicknesses of re-coating. a, b and c: straight waveguides; d, e and f: waveguides with S-bend; a and d: not re-coated waveguides; b and e: waveguides re-coated with 15 nm of TiO_2 ; c and f: waveguides re-coated with 30 nm of TiO_2 . The green rectangles represent data points not taken into account for the linear fit (black solid line) and the blue rectangles represent the data points taken into account.

Figure 6. Fluctuation of the propagation loss as a function of the polarization. The polarization has been rotated of 180° between θ_1 and θ_5 . The experimental data points (top) and their corresponding linear fits (down) are plotted.

4. CONCLUSION

In this paper we have presented a method to decrease the propagation losses in TiO_2 sub-wavelength waveguides by using ALD re-coating of the sample to reduce the sidewall roughness. The smallest measured propagation loss has been obtained for a straight waveguide and is of 2.4 dB/cm. This technique can be used with other materials, for example in the case of silicon nitride waveguide coated by ALD aluminum oxide [15].

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