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Improved environmental stability for plasma enhanced chemical vapor deposition SiO₂ waveguides using buried channel designs

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Abstract

Ridge and buried channel waveguides (BCWs) made using plasma-enhanced chemical vapor deposition SiO₂ were fabricated and tested after being subjected to long 85°C water baths. The water bath was used to investigate the effects of any water absorption in the ridge and BCWs. Optical mode spreading and power throughput were measured over a period of three weeks. The ridge waveguides quickly absorbed water within the critical guiding portion of the waveguide. This caused a nonuniformity in the refractive index profile, leading to poor modal confinement after only seven days. The BCWs possessed a low index top cladding layer of SiO₂, which caused an increase in the longevity of the waveguides, and after 21 days, the BCW samples still maintained ~20% throughput, much higher than the ridge waveguides, which had a throughput under 5%.

Keywords

silicon dioxide; plasma enhanced chemical vapor deposition; integrated waveguides; waveguide lifetime; water absorption

1 Introduction

The fields of photonics and optofluidics rely on low-loss waveguiding. Often photonic telecommunication devices will use silicon as a waveguiding material because it has a low optical loss in the near-infrared. However, there are many instances in integrated optics when the visible spectrum of light is preferred over infrared and must be used. This is especially true in the biosensor space, where visible wavelengths are used to excite commercial fluorophores. Many oxides and nitrides are transparent in the visible spectrum and compatible with silicon-based fabrication techniques, making them ideal for integrated optics in this spectral range. High-quality SiO₂ layers, in particular, can simply be thermally grown on silicon substrates for use as a waveguide; however, thermal oxide growth requires

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high temperatures, and many integrated optics devices cannot withstand any high temperature cycling without significant damage to the devices. This has led to the use of SiO₂ deposited using low-temperature plasma enhanced chemical vapor deposition (PECVD). Waveguides made using PECVD SiO₂ can achieve optical propagation losses as low as 0.1 dB/cm.¹ The ease of deposition and the low optical loss of PECVD SiO₂ have led to its use in many different integrated optics devices and systems. Some examples of these include interferometric mechanical sensors in micro-optoelectromechanical systems applications,² microresonator sensors in microfluidic applications,³ and liquid-filled waveguides for use in optofluidic biosensing applications.^{4,5}

It is well known that the low deposition temperatures used in PECVD lead to porous SiO₂ films that will readily absorb water from the atmosphere.^{6,7} Annealing at high temperatures (>900°C) can help eliminate these pores, densify the film, and reduce water absorption in the film; however, as stated above, many devices are sensitive to high temperatures and therefore cannot undergo high-temperature annealing.⁸ This means that many devices are made using SiO₂ films that absorb water from their environment. Water absorption in an SiO₂ film can cause key material property changes in the film, such as an increase in the film's refractive index because higher index water fills the low index air pores within the film.⁹ It has been reported that the refractive index in PECVD SiO₂ films increases as much as 1.8%.¹⁰ Postfabrication refractive index changes in a PECVD SiO₂ waveguide can lead to unexpected and difficult to predict changes in waveguiding performance. This is a critical problem when transitioning from a research environment into the commercial market because the devices will be unstable and unreliable over extended periods of time.

It has previously been shown that ridge or rib PECVD SiO₂ waveguides are especially susceptible to detrimental effects of water absorption in the SiO₂ film.¹¹ This is due to the fact that water absorption at the surface of the ridge waveguide creates a high index top layer in the ridge waveguide profile. Once this layer diffuses deep enough into the ridge waveguide, it becomes optically significant and drastically changes the waveguiding behavior of the ridge, specifically the light intensity distribution shifts toward the top surface of the waveguide and much of the light begins to escape the ridge into the rest of the oxide film. Several of the aforementioned devices that use PECVD SiO₂ waveguides use this ridge waveguide design. Devices such as these can suffer from reliability and stability issues due to the water absorption into their PECVD SiO₂ ridge waveguides. In order for them to successfully be introduced into the market, there must be improvement made in these areas. Here, we report that the well-known buried channel waveguide (BCW) structure alleviates much of the reliability issue that exists with PECVD SiO₂ ridge waveguides due to water absorption.

Figure 1 shows the two antiresonant reflecting optical waveguide (ARROW) based SiO₂ waveguide types that were used in this study. Figure 1(a) represents an SiO₂ ridge waveguide defined on top of a dielectric stack, designated as the bottom ARROW layers, which provides visible light confinement on a high-index silicon substrate using the ARROW principle.^{12,13} The single-layer ridge design exposes the guiding SiO₂ core to water and other liquids in the surrounding atmosphere. These are readily absorbed into the

guiding core, creating a nonuniformity in the refractive index profile and causing changes in the optical properties of the waveguide that are difficult to predict and control.

Figure 1(b) shows the BCW structure. The SiO₂ guiding channel sits directly on top of the bottom ARROW layers. The BCW waveguide incorporates a low-index cladding layer directly over the top of the guiding channel. The expected benefit of this structure is that the addition of a protective cladding layer over the high-index guiding core of the waveguide will help shield the light guiding core from any direct water absorption. This preserves the refractive index of the high-index guiding core even if the index of the top cladding is raised due to water penetration.

This letter reports on the systematic comparison of PECVD SiO₂ ridge waveguides and BCWs that were fabricated and exposed to a long-term water treatment. The waveguides were soaked in an 85°C water bath in order to accelerate a study of the waveguide's susceptibility to water absorption. The temperature of 85°C was used in order to ensure that the water did not reach its boiling point and evaporate away. This allowed for long soaking periods at a raised temperature without the problem of drying out the water bath. Changes in the modal confinement and overall transmission properties were measured for these waveguides over a period of three weeks.

2 Fabrication

The waveguide samples were fabricated using standard microfabrication procedures. The first step was to deposit the bottom ARROW layers on a flat silicon substrate via sputtering. In total, there were six of these bottom layers, made up of alternating SiO₂ and Ta₂O₅ films. The thicknesses of these layers were 265 nm SiO₂, 102 nm Ta₂O₅, 265 nm SiO₂, 102 nm Ta₂O₅, 265 nm SiO₂, and 102 nm Ta₂O₅ in order from bottom to top. These ARROW layers provided the bottom optical confinement layer for 635-nm light,¹³ which was the wavelength used in the experiment. The SiO₂ guiding layer was then deposited directly on top of the ARROW layers using PECVD. The deposition recipe was tuned to produce low-stress SiO₂ films (~ -4 MPa) measured using the Zeta 20 3D Profilometer (Zeta Instruments). For the ridge waveguide fabrication, this layer was 6 μm thick, and for the BCWs, this layer was 3 μm thick. After the SiO₂ layer was deposited, standard photolithography techniques were used to pattern and etch a ridge or channel into the SiO₂ layer. A 3- μm -deep ridge was etched into this layer to form ridge waveguides, while the entire 3 μm of SiO₂ was etched to create the channel for the BCWs. Both etches were done using a reactive ion etching inductively coupled plasma dry etch in order to achieve a strong anisotropic etch profile. The ridge waveguides were defined and etched to be 12 μm wide. The BCW channels were fabricated with a width of 7 μm . Both dimensions match waveguide dimensions used in a recent optofluidic biosensor platform⁴ that has demonstrated single molecule sensitivity.

At this point, the fabrication for the ridge waveguide was complete. The waveguides were then cleaved into 1 cm $\times$ 1 cm dies, exposing the waveguide facets for coupling with an optical fiber. The BCWs required another PECVD deposition in order to form the top SiO₂ cladding layer on top of the channel.

For conventional waveguiding to occur within the channels of the BCW, the channel SiO₂ must have a higher refractive index than the surrounding cladding SiO₂. Fortunately, the refractive index of SiO₂ is tunable in PECVD by simply altering the gas flow ratio between the source gases.¹⁴ In this experiment, the channel SiO₂ was deposited with a higher refractive index of 1.472, while the cladding SiO₂ was deposited with a refractive index of 1.463. This difference was achieved by increasing the flow of the SiH₄ by 19% during the channel SiO₂ deposition.

3 Results and Discussion

After fabrication, the waveguides were characterized by their optical throughput measurements and mode images. The waveguides were then submerged in 85°C deionized water and left in the water continuously for an extended period of time. The samples were removed from the water periodically and then recharacterized on the optical setup.

Figure 2 shows the average percent throughput of the 1-cm-long waveguides of each waveguide type versus the time spent in 85°C water. Three ridge waveguides and five BCWs were tested. The throughput of the ridge waveguides dropped below 10% after only seven days in the 85°C water soak. The BCW samples, on the other hand, maintained high throughput in excess of 20% for over 20 days. This shows that, although water absorption still occurred in the SiO₂ cladding layer, this layer in the BCWs kept the high-index guiding cores buried beneath the surface of the waveguide where light can more easily leak out. The cladding layer also protected the high-index guiding cores from any direct water absorption from their environment. The overall effect is that the longevity of the waveguides was improved in the BCWs.

It has been shown that ridge waveguides of dimensions similar to these ridges begin to perform poorly once water has penetrated about 2 μm into the waveguide.¹¹ Assuming that the water has penetrated 2 μm deep into the ridges by day 7—when their throughput dropped below 10%—gives a diffusion coefficient of water into the PECVD SiO₂ films of around $9.3 \times 10^{-14} \text{ cm}^2/\text{s}$, which is within the wide range of diffusion coefficients reported in the literature.¹⁵ After 20 days, the water will have penetrated a full 4 μm into the PECVD SiO₂, which helps explain why the BCWs begin to show a drop in throughput around 20 days in the water bath. The water saturated high-index layer has penetrated close enough to the guiding core to begin to pull power out of the core into the high-index layer.

Top view images of all of the waveguide samples were taken to investigate any visible effects of water absorption on the behavior of the waveguides. These images clearly show the light scattering out of the waveguides. The width of the scattered light was determined for each image, which was defined as the FWHM of a Gaussian fit to the lateral intensity profile of the waveguide, measured 1 mm from the output facet of the chip. Figure 3 shows a graph of this width versus time spent in 85°C water. The data are normalized to the initial width measurement taken on day 0. The three images to the right are example images for a single ridge waveguide for day 0, day 7, and day 8. The yellow line in these images marks where the width of the scattered light was measured. The width of the light from the SiO₂ ridges increases drastically throughout the experiment. This is because much of the light is

beginning to leak from the ridge waveguide into the surrounding SiO₂ film. However, the width of the light scattering out of the BCWs remained very constant throughout the duration of the water treatment.

Cross-sectional mode images were also taken of each of the waveguides. The mode profile of a waveguide is an important characteristic in understanding how a waveguide is operating. Figure 4 shows mode images both before water treatment (top) and after (bottom) for the ridge waveguides and BCWs. Figure 4(a) shows the mode images of an SiO₂ ridge waveguide. Before it was exposed to the water treatment, the waveguide displayed multimode behavior. However, the bottom image shows that after exposure to water, the mode shifted toward the top surface and began to take on an abnormal shape, showing evidence of a high-index top layer in the ridge waveguide.¹¹

Figure 4(b) shows the mode images of a BCW waveguide. The smaller dimensions of the BCW allow for excitation of just the fundamental mode, as shown in the top image. The bottom image shows that after 18 days in hot water, the light still remained well confined in the buried channel. While there are some signs of modal deterioration, there was no guiding outside of the channel.

Waveguides made using PECVD SiO₂ films are susceptible to water absorption in SiO₂. The addition of a low-index cladding layer in the BCW design helps alleviate some of the adverse effects of water absorption in the waveguide. The cladding layer initially protects the guiding channel from any direct water absorption that would create a nonuniform index profile. The BCW design also buries the guided mode beneath the top surface of the waveguide, providing light confinement above the guiding core and preventing light from escaping.

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Fig. 1.
(a) Side-view schematic of the ridge waveguide design and (b) BCW design.

Fig. 2. Average percent throughput for ridge waveguides (triangles) and BCWs (squares). There were three total ridge waveguide samples and five BCW samples.

Fig. 3. Width of light scattering out of the waveguide versus time in water for the ridge waveguides (triangles) and BCWs (squares). Example ridge waveguide images are given to the right of the graph from day 0, day 7, and day 8, respectively; the lines mark where the FWHM was measured on the waveguides.

Fig. 4.

(a) Ridge waveguide mode images before (first row) and after (second row) 85°C water treatment. (b) BCW mode images before (first row) and after (second row) 85°C water treatment.