Low loss, high contrast optical waveguides based on CMOS compatible LPCVD processing: technology and experimental results

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Abstract

A new class of integrated optical waveguide structures is presented, based on low cost CMOS compatible LPCVD processing. This technology allows for medium and high index contrast waveguides with very low channel attenuation. The geometry is basically formed by a rectangular cross-section silicon nitride (Si_3N_4) filled with and encapsulated by silicon dioxide (SiO_2). The birefringence and minimal bend radius of the waveguide is completely controlled by the geometry of the waveguide layer structures. Experiments on typical geometries will be presented, showing excellent characteristics (channel attenuation $\leq$ 0.1 dB/cm, IL $\leq$ 1.5 dB, PDL $\leq$ 0.2 dB, $B_g \leq 1\times10^{-4}$, bend radius « 1 mm).

1. Introduction

As demand for telecommunication bandwidth increases and the optical fiber networks move steadily towards the customer premises, demand for optical switching and routing components is rising. As a consequence, optical components are replacing electronics for signal processing [1-3]. The adoption rate for optical components is being hampered, however, by their high costs stemming from two major sources: large optical footprint (i.e. high chip real-estate) and high packaging costs. By integrating multiple functions at a higher density on a single optical chip much of these costs can be amortized across several devices. In order to achieve a high density photonic platform, the index contrast and channel attenuation of the waveguide must be sufficiently large and small enough, respectively, to allow for tight curvature and cascading of multiple structures. This opens the pathway to use micro ring resonators as the universal building block in systems capable of providing switching and routing functionality [1,2,4-6].
A new waveguiding technology developed by LioniX BV (patent pending) is able to meet these demands outlined above. It comprises of alternating CMOS-compatible LPCVD layers which are fully transparent for wavelengths from < 500 nm up to 2 μm and beyond. The technology allows for medium and high index contrast waveguides. In this paper we describe the fabrication and performance of two typical waveguide geometries. Both designs exhibit very low waveguide attenuation values but otherwise have totally different characteristics and applications.

2. Waveguide concept

Stoichiometric silicon nitride (Si_3N_4) fabricated using LPCVD processing is widely used in integrated optics, primarily because of its large refractive index (2.0) enabling very compact devices [2,6,9]. The major drawback of Si_3N_4 is its large internal tensile

stress (~1GPa) which limits its layer thickness to ≤350 nm. As a consequence devices fabricated with Si_3N_4 show a very large polarization dependency, thereby severely limiting their use in telecom applications. By combining it with a second layer that has a very large compressive stress, such as LPCVD SiO_2 (TEOS), however, the total stress of the composite layer stack is strongly reduced. As a result the thickness of the total stack can be considerably larger than the critical layer thickness of Si_3N_4 alone [7,8].
This alternating LPCVD layer stack concept can result in a rectangular channel waveguide structure with outstanding waveguiding characteristics and with strongly reduced polarization effects (see section 4). The geometry is basically formed by a rectangular cross-section of silicon nitride (Si_3N_4) filled with and encapsulated by silicon dioxide (SiO_2) as depicted in figure 1.

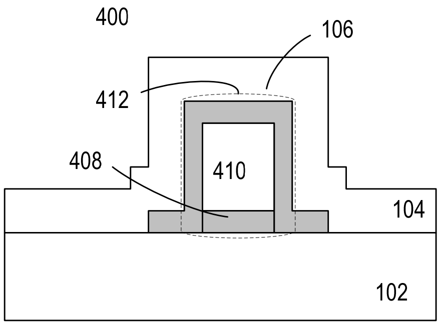

Figure 1. Cross-section of a typical waveguide structure, with LPCVD Si_3N_4 (in grey) as basic waveguiding layer, filled with and in turn encapsulated by SiO_2 (white). Figure extracted from [7].

The channel geometry approximates a "hollow core" system, as it consists of a low index "inner core" of SiO_2 "cladded" with the high index "outer core" of Si_3N_4. The channel is fabricated on a substrate, *e.g.* thermally oxidized silicon. The nitride shell has typical outer dimensions in the order of 1 μm^2, with its exact characteristics depending strongly upon the desired application.
Modal characteristics depend only upon the geometry of the structure, as all composing materials are LPCVD end products with very reproducible characteristics. The whole process is CMOS-compatible and very cost effective as only one photo lithographical step is required.

3. Fabrication

Figure 2 depicts the LioniX fabrication procedure for passive optical channels.

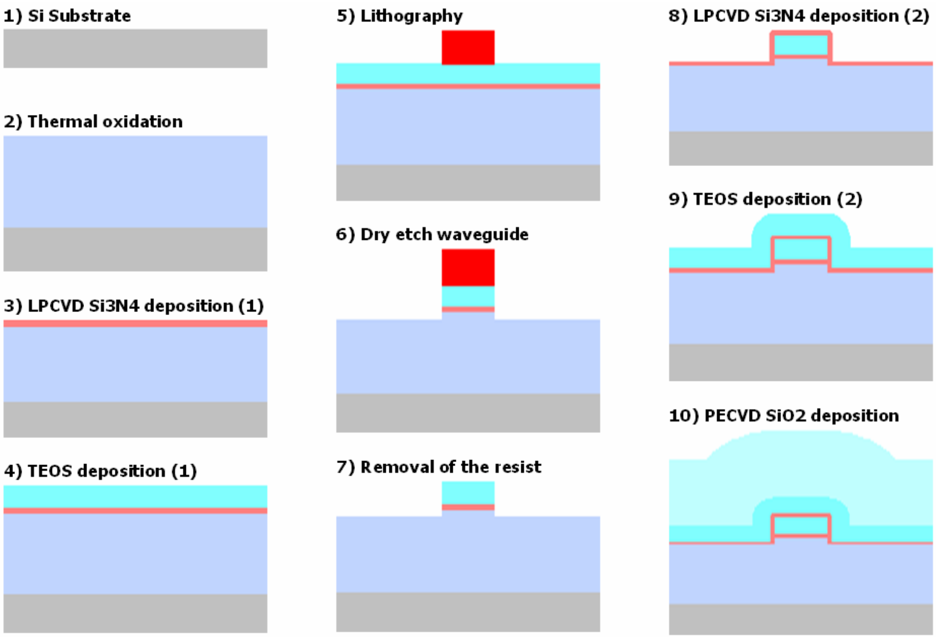

Figure 2 . Flow process scheme as made with Flowdesigner process modeler (PhoeniX BV, Enschede, the Netherlands). Here, the Si_3N_4 is shown in red, and the (different types of) SiO_2 in blue.

The process starts with thermal oxidation of a 100 mm-diameter silicon wafer (1 and 2) to form the lower cladding. Then LPCVD Si_3N_4 (3) and TEOS SiO_2 (4) are deposited. Photolithography is then performed (5), followed by RIE (6), and photo resist removal (7). A second deposition of LPCVD Si_3N_4 (8) as well as TEOS SiO_2 (9) is performed. Finally, a thick PECVD SiO_2 layer (10) is deposited to form the upper cladding.
Although of major importance, the design of the channel waveguide falls beyond the scope of these proceedings and will be described in another publication. Here, we restrict ourselves to two examples of single mode (SM @1550 nm) channel layouts:

1: an A-shaped layout with minimal modal birefringence (see figure 3, left)
2: a non-symmetrical layout with very large modal birefringence (see figure 3, right)

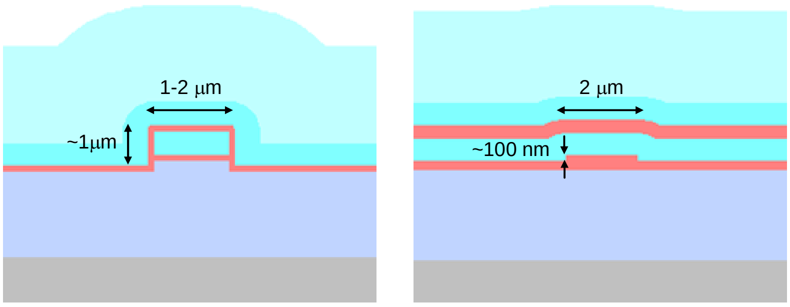

Figure 3. Schematics of two typical channel layouts: an A-shaped layout with minimal modal birefrin-gence (left) and a non-symmetrical layout with very large modal birefrin-gence (right). The nitride layers are shown in red.

Layout 1 demonstrates the ability to tune the modal birefringence to a very small value. The anisotropic RIE etch step (see figure 2, step 6) completely removes the TEOS and Si_3N_4 layer as well as part of the thermal oxide layer. Layout 2 demonstrates a high degree of polarization dependency and very tight bending radii, but with extremely wide fabrication tolerances. Here the RIE procedure (which in this layout is performed *before* the TEOS deposition) removes approximately only half of the first nitride layer thickness. This layout is used in a tunable true time delay (TTD) application, as described elsewhere in these proceedings [9]. Here the channel waveguide is activated by means of heaters fabricated on the top cladding, exploiting the well-known thermo-optical effect [6].

4. Results

The cross-section of the typical waveguides, as fabricated by LioniX, are shown in figure 4. Clearly visible is the close agreement with the designs of both structures.

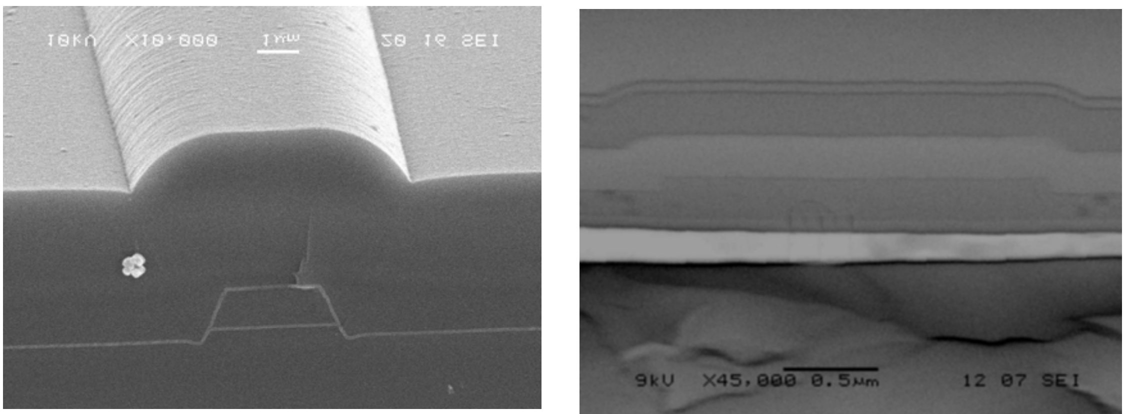

Figure 4. Typical SEM pictures of the two realized structures: the A-shaped geometry (left) and the non-symmetrical geometry (right) with the nitride layers brighter and darker, respectively.

The optical characterization is performed using different techniques, including cut-back and interferometry. These measurements are performed on a variety of differently processed wafers, showing a wide range of parameter settings. Key characteristics as measured on the best samples are given below in Table 1.

Table 1. Measured characteristics of the best samples of the two types of SM channel waveguides as described in section 3.

	Group birefringence (B_g)	Channel attenuation (dB/cm)	Polarization dependent loss (PDL, in dB)	Insertion loss (IL) without spot size converter (dB)
A-shaped geometry	$\leq 1\times10^{-4}$	≤ 0.10	0.12[1]	1.4[2]
Non-symmetrical layout[3]	1.1×10^{-1}	0.12	0.20[1]	8.0[2]

[1]: chip length 3 cm
[2]: here, small core fibers were used (MFD of 3.5 μm)
[3]: minimal bend radius ~400 μm

Several important conclusions can be drawn from the data in Table 1. First the *optical channel attenuation* is very small for both types of geometries, plus further improvement in performance is expected. Second the *(group) birefringence* of the channels is completely adjustable and in good agreement with expectations. For the A-shaped waveguides, the birefringence can be made very close to zero. Third the *PDL* is also low. Finally, the *IL* is very good, especially in case of the A-shaped design (due to symmetry of the channel modes resulting in close to circular modal profiles).

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