APPLIED PHYSICS LETTERS **86**, 121111 (2005)

Propagation losses of silicon nitride waveguides in the near-infrared range

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(Received 17 December 2004; accepted 2 February 2005; published online 16 March 2005)

Si_3N_4/SiO_2 waveguides have been fabricated by low pressure chemical vapor deposition within a complementary metal–oxide–semiconductor fabrication pilot line. Propagation losses for different waveguide geometries (channel and rib loaded) have been measured in the near infrared as a function of polarization, waveguide width, and light wavelength. A maximum thickness of single Si_3N_4 of 250 nm is allowed by the large stress between Si_3N_4 and SiO_2. This small thickness turns into significant propagation losses at 1544 nm of about 4.5 dB/cm because of the poor optical mode confinement factor. Strain release and control is possible by using multilayer waveguides by alternating Si_3N_4 and SiO_2 layers. In this way, propagation losses of about 1.5 dB/cm have been demonstrated thanks to an improved optical mode confinement factor and the good quality of the interfaces in the waveguide. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1889242]

Silicon microphotonics, where optical and electronic components are merged, is a possible solution to overcome the incoming limits of microelectronic devices (speed, packing, power dissipation,…).[1] Optical waveguides are one of the fundamental building blocks of microphotonics. The choice of the waveguide material determines the wavelength of the signal and the integration density. Various materials for low-loss optical waveguides have been investigated.[2–6] Stoichiometric silicon nitride (Si_3N_4) for the core and silicon oxide (SiO_2) for the cladding could be a suitable choice because of the large refractive index difference ($\Delta n \cong 0.55$), the low scattering losses, the wide transparency window, and the compatibility with Si microelectronic technology. In a recent paper,[7] we have reported an extended study about two-dimensional thin Si_3N_4 waveguides for visible applications and fabricated by low pressure chemical vapor deposition (LPCVD) on Si substrate within a complementary metal–oxide–semiconductor (CMOS) fabrication pilot line, showing that the use of LPCVD reduces the interface roughness and consequently the related scattering losses. The same waveguides have shown optical guided modes also in the 1500–1600 nm range but with large propagation losses (4.5 dB/cm).[8] These large values were explained by the limitation in the waveguide core thickness, which causes a poor optical confinement factor of guided modes. The thin thickness of the core is limited by the large strain present between the core and the cladding layers.

In this letter, we report on Si_3N_4/SiO_2 multilayer waveguides to increase the optical confinement factor and, as a consequence, to reduce optical losses. For the process parameters we are using, the Si_3N_4 layer has a high tensile (1.3 GPa) and the maximum critical thickness is about 250 nm—thicker films tend to crack.[7] Intermediate thin SiO_2 layers, grown between Si_3N_4 films, slightly reduce the total tensile stress of the waveguide core. The multilayer structure allows to obtain an effective waveguide core with a total Si_3N_4 thickness larger than the critical one.

The details about the fabrication process of single layer (SL) waveguides have been already reported.[8] Slab multilayer (ML) waveguides have been fabricated on a 2.5 μm thick SiO_2 buffer layer by alternating three layers of Si_3N_4 and two layers of SiO_2, with thicknesses of 100, 50, 200, 50, and 100 nm, respectively. This results in a total core layer thickness of about 500 nm. The thicknesses of the single SiO_2 and Si_3N_4 layers in the core were chosen to minimize the thickness of SiO_2 layers while having the maximum content of Si_3N_4 in the resulting layer (which translates into a large average refractive index), a good optical mode confinement, and a monomodal behavior at 1550 nm. Lithography and etching defined channel and rib-loaded waveguide geometries, whose nomial widths ranged from 1 to 10 μm. Top cladding is air for the rib-loaded waveguide and a 500-nm-thick SiO_2 layer for channel waveguides. The input/output facets of the waveguide have been realized by a dry etching process and removal of the Si substrates by an anisotropic wet etching with tetra-methyl-ammonium-hydroxide (TMAH). This procedure simplifies the coupling of the light and reduces insertion losses.[8]

Atomic force microscopy (AFM) measurements were performed using a Solver P-47 AFM in intermittent contact mode. Cross-section profile has allowed the measurement of the channel widths or rib widths of the waveguides. Larger than expected values have been found which reflects in a multimodal behavior of the waveguides. To measure the effective modal index n_{eff} of the various optical modes in the planar waveguide, m-line measurements have been performed at 1542 nm. The waveguide supports two guided optical modes: TE_0 ($n_{\mathrm{eff}}=1.656\pm0.001$) and TM_0 ($n_{\mathrm{eff}}=1.521\pm0.001$). From these measured values and by modal simulations,[7] a stress-induced birefringence of the silicon nitride layers is found. In fact, simulation m-line results yield an ordinary n_0 ($\sim$2.1940) and extraordinary n_e ($\sim$2.0863) refractive indices for the silicon nitride layers, which corresponds to a material birefringence of about 5%.

Propagation losses measurements have been performed by using the insertion loss technique for various waveguide

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TABLE I. Propagation losses as a function of waveguide geometry for waveguide width larger than 10 μm. SL and ML refer to single layer and multilayer waveguides, respectively. The waveguide geometry and the silicon nitride etch depth, necessary for obtaining a rectangular structure, are also reported.

		Propagation losses (dB/cm)	
Samples	Waveguides	No polarized light	TE polarized light
SL_1	Channel (plasma etching, 200 nm etched)	4.5±0.5	⋯
SL_2	Strip loaded (plasma etching)	6.0±0.5	⋯
ML_1	Rib loaded (plasma etching, 40 nm etched)	⋯	1.9±0.2
ML_2	Rib loaded (plasma etching, 100 nm etched)	⋯	1.9±0.2
ML_3	Channel (plasma etching, 500 nm etched)	⋯	1.5±0.2

lengths (cut-back method).[7] Waveguides have been measured by coupling-in light from laser diodes (1310 nm, 2 mW; 1544 nm, 10 mW) or from a tunable laser (1500–1600 nm, 10 mW) through a single-mode polarization-maintaining tapered fiber mounted on nanopositioning stages. The transmitted signal was imaged by a microscope objective (25×) matched to a zoom, split by a beam splitter, and sent to a high performance InGaAs camera for modal imaging and to a calibrated Ge photodiode for intensity measurements. Data losses have been obtained by measuring five waveguides for each length (typically five values from 0.5 to 5 cm).

The waveguide propagation loss coefficients of SL and ML waveguides (Table I) are extracted by the slope of the insertion loss versus waveguide length curve. Figure 1 shows an example of the measurements at 1544 nm for sample SL_1, where the linear fit of the data results in a propagation loss coefficient of 4.5±0.5 dB/cm. For the SL waveguides, propagation losses at 1544 nm are larger than the 0.1 dB/cm value found at 780 nm:[7] this is mainly due to the reduction of the optical mode confinement factor at 1544 nm (20% and 40% for transverse magnetic (TM) and transverse electric (TE) polarization, instead of 58% and 75% at 780 nm, respectively). The difference between channel (about 4.5 dB/cm) and strip-loaded (about 6 dB/cm) waveguides reflects analogous trends found at 780 nm.[7]

Polarization resolved propagation loss coefficients at 1550 nm of ML waveguides are reported in Table I and II. Figure 2 shows insertion losses of a channel waveguide (sample ML_3) for TE polarization: the linear fit results in a propagation loss coefficient of 1.5±0.2 dB/cm. The lower losses with respect to the SL waveguides are due to the larger thickness of the waveguide core layer. Rib-loaded ML waveguides show larger losses (about 1.9 dB/cm) than the channel ones, probably because the guiding layer is directly exposed to the ambient thus enhancing scattering losses due to irregularities and defects on the top surface. No significant variation in losses can be attributed to the different etch depth in rib-loaded samples ML_1 and ML_2. This is in agreement with simulations that do not show a substantial difference for the optical mode confinement factor (78.5% and 79% at 1550 nm for ML_1 and ML_2 samples, respectively). Figure 3 shows propagation losses at 1550 nm as a function of waveguide width in the two waveguide geometries. The increasing propagation losses with decreasing waveguide width are due to the increase of sidewalls scattering losses for rib-loaded waveguides.[9]

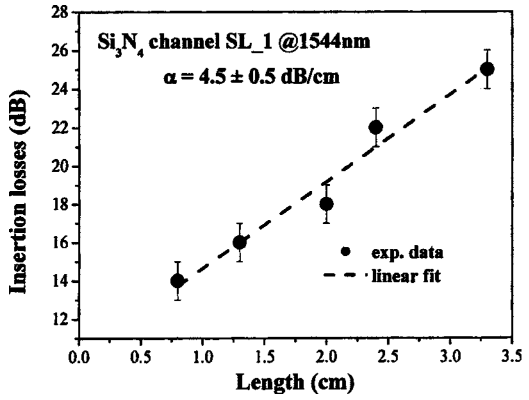

FIG. 1. Insertion loss measurements as a function of waveguide length of a channel single layer waveguide (sample SL_1, 10 μm channel width) at 1544 nm. The propagation loss coefficient is 4.5±0.5 dB/cm.

Table II reports the wavelength dependence of propagation losses in the rib-loaded waveguide (sample ML_1, 15 μm width). We note that TM propagation losses are larger than TE ones. Simulations, in fact, show a greater optical confinement of the TE optical mode. At 1310 nm the propagation losses are quite large (~4.6 dB/cm for TE polarization) and they decrease with increasing the wavelength. This shows that in this wavelength interval the Rayleigh scattering loss are the limiting loss mechanism.[10] Considering the number of interfaces in the core layer, the observed propagation losses are satisfactorily low which suggests that the LPCVD technique allows a good control of the layer deposition and of the interface roughness. However at 1520 nm, increased losses are measured which could be due to the absorption of Si–H vibrational overtones.[4] An increase of optical losses at around 1520 nm have been also observed in LPCVD grown silicon oxynitride (SiON) waveguides,[11] because of a significant hydrogen content.

Reported propagation losses in ML Si_3N_4 waveguides are still high to compete with other waveguide systems [e.g., silicon-on-insulator (SOI) waveguides], where propagation losses lower than 0.1 dB/cm at 1500–1550 nm were measured.[10,12,13] In addition, previous works on silicon nitride and silicon oxynitride waveguides[2–4,14] have reported propagation losses lower than 1 dB/cm in the near-infrared range. The strength of our results is to revalue silicon nitride

TABLE II. Propagation losses at different wavelength for rib-loaded waveguide (sample ML_1, 15 μm rib width) for TE and TM polarization.

	Propagation loss (dB/cm)			
Polarization	1310 nm	1500 nm	1520 nm	1550 nm
TE	4.6±0.3	3.7±0.3	4.4±0.2	1.9±0.2
TM	5.6±0.3	4.3±0.2	5.3±0.2	2.4±0.2

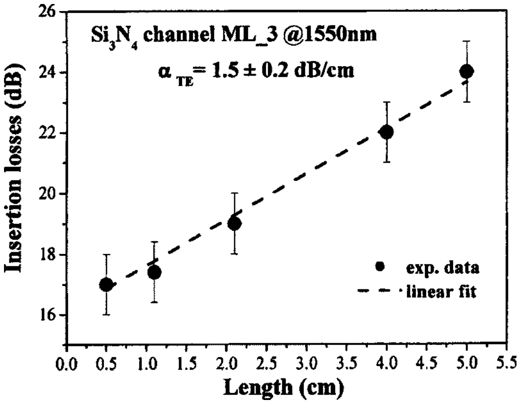

FIG. 2. Insertion loss measurements for TE polarization of input light of a channel multilayer waveguide (sample ML_3) at 1550 nm. The propagation loss coefficient is 1.5±0.2 dB/cm.

for realizing optical waveguides. Si_3N_4-based waveguides have many advantages with respect to other systems: (i) low losses in a wide wavelength range (from the visible to the near infrared) thanks to the low absorption; (ii) Si_3N_4 layers are used in most microelectronic processing which renders the system naturally compatible with standard CMOS processing; (iii) the deposition process itself is very easy and allows a good control of interface roughness; and (iv) the use of a multilayer structure for the waveguide core allows engineering of the strain in these layers such that the waveguide could have zero modal birefringence. This last point is currently under study.

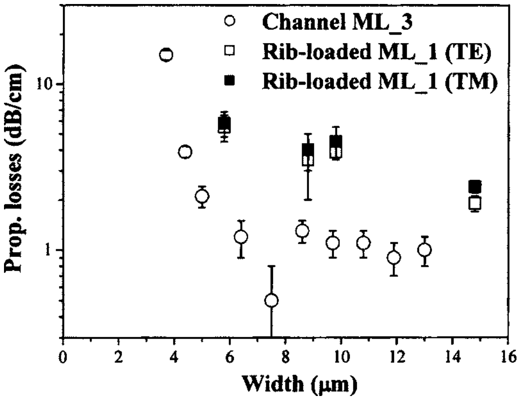

FIG. 3. Propagation losses as a function of waveguide width at 1550 nm for rib-loaded and channel waveguides.

In conclusion, we have fabricated and measured propagation losses in Si_3N_4-based waveguides in the near-infrared range finding a significant decrease when a multilayered core is used. The reported losses have shown that the fabrication processes minimize scattering losses associated with interfaces (roughness) in the core layer. This material system is very promising to achieve high quality polarization insensitive optical devices.

The financial support from Provincia Autonoma di Trento through the PROFILL project is acknowledged.

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