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Silicon oxynitride in integrated optics

Kerstin Wörhoff, René M. de Ridder, Paul V. Lambeck, and Alfred Driessen
MESA Research Institute, University of Twente, P.O. Box 217,
7500 AE Enschede, The Netherlands, e-mail: K.Worhoff@el.utwente.nl

Abstract — **A review on the state of the art of silicon oxynitride deposition at the MESA Research Institute will be given. The recent progress in the application of silicon oxynitride in communication devices will be discussed.**

I. INTRODUCTION

Integrated optics (IO) devices for application in telecommunication are highly demanding on low insertion loss, efficient fiber-to-chip coupling, high compactness (small bending radii) and polarization independent operation.

In most operating communication devices developed within the last decade, low-index contrast waveguiding structures have been applied [1]. The large channel cross-section of these waveguides matches well with the standard optical fiber, but due to the low index contrast large bending radii are required for low bend losses leading to a low integration density. The compactness of IO devices is significantly increased when applying high-index contrast waveguiding structures. Although for these structures the fiber-to-chip coupling efficiency is generally low, this parameter can be significantly improved by a proper design of the fiber-to-chip interface. Silicon oxynitride (SiON) grown by chemical vapor deposition (CVD) is a material which is well-suited for the realization of high contrast waveguides, since the range over which the refractive index of this material can be tuned (1.46-2) is large.

In this contribution we will shortly review on the state of the art of our SiON deposition process and the important properties of this material. Then, the development and realization of a SiON-based high contrast channel structure having the potential of fulfilling *all* the above given demands arising from the telecommunication application will be discussed. Finally, results of the application of this structure in a WDM add-drop device will be shown.

II. SILICON OXYNITRIDE DEPOSITION

High-quality silicon oxynitride waveguides are deposited either by Plasma Enhanced Chemical Vapor Deposition (PECVD) [2] and Low Pressure Chemical Vapor Deposition (LPCVD) [3].

For the growth of the PECVD layers a parallel-plate Electrotech 210 machine with a low frequency (187.5 kHz) RF-generator is applied. The layers are deposited at 60 W plasma power, 650 mTorr pressure, 300°C temperature and N_2O, NH_3 and 2%SiH_4 / N_2 gas sources of which the gas flows can be varied up to a maximum flow of 1400 sccm, 36 sccm and 3000 sccm, respectively. The refractive indices of the layers are tuned by changing the flow ratio between the gases. In principle, the tuning range of the PECVD process comprehends the SiON index range from 1.46 (SiO_2) to 2.0 (Si_3N_4). However, for applications highly-demanding on the accurate adjusting of a specified refractive index, the range from 1.46 to 1.7 is most suited, since in that range the sensitivity of the refractive index to the flow ratio change is low. The deposition rates of the PECVD process are high, 30-50 nm/min.

The LPCVD waveguides are deposited in a Tempress hot-wall quarts-tube reactor from SiH_2Cl_2, O_2 and NH_3 with maximum flows of 100 sccm, 5 sccm and 120 sccm, respectively, at temperatures between 800-900°C and pressures between 50-200 mTorr. The LPCVD process is suited for the deposition of waveguides with refractive indices between 1.7-2. The deposition rates of this process are adjustable between 2-10 nm/min, enabling controlled growth of even very thin layers of several nanometers.

The uniformity over the wafer and the run-to-run reproducibility of the layer thickness (δd) and the refractive index (Δn) are shown in Table 1. The material birefringence, $\Delta n_{TM-TE} = n_{TM} - n_{TE}$, of the SiON layers grown by both CVD processes, shown in the right column of Table 1, is stress-induced.

Table 1: Uniformity and reproducibility of thickness (δd) and refractive index (Δn) and material birefringence for SiON layers with different refractive indices; P-PECVD, L-LPCVD

n	Δn_{wafer}x10^{-4}	δd_{wafer} [%]	$\Delta n_{run\text{-}to\text{-}run}$x10^{-4}	$\delta d_{run\text{-}to\text{-}run}$ [%]	$\Delta n_{TM\text{-}TE}$x10^{-3}
1.464^P	2	3	6	2	0.9
1.488^P	6	0.8	6	1	1.7
1.696^P	5	2	-	-	2.3
2.008^L	4	2	4	0.7	-8.5

Table 2: N-H and Si-H content of as-deposited and annealed (1150°C) SiON layers with different refractive indices

n	$N\text{-}H_{as\ dep}$ [at%]	$Si\text{-}H_{as\ dep}$ [at%]	$N\text{-}H_{anneal}$ [at%]	$Si\text{-}H_{anneal}$ [at%]
1.488^P	3.4	< meas. limit	0.4	< meas limit
1.527^P	6.1	< meas. limit	1.3	< meas limit
1.696^P	17.8	1.4	4.5	< meas limit
2.008^L	5.0	0.2	1.3	< meas limit

For layers grown by both CVD processes, optical losses of slab-type waveguides of below 0.2 dB/cm have been obtained within the visible range of light. At wavelengths around 1550 nm, the optical losses are 1.8 dB/cm and 10 dB/cm for PECVD layer with n=1.488 and n=1.696, respectively. This strong increase is due to absorption caused by vibrational overtones of the N-H and Si-H bonds. The N-H and Si-H content of different SiON layers, shown in Table 2, has been measured by IR-spectroscopy. After annealing at 1150°C the hydrogen content is strongly decreased and the optical losses

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of the layer with n=1.488 is reduced to below 0.2 dB/cm at 1550 nm wavelength.

III. APPLICATION IN OPTICAL COMMUNICATION

A standardized SiON-based waveguiding structure for application in telecommunication devices operating at 1550 nm wavelength has been developed and realized. This structure, which is schematically shown in Fig. 1, has the potential of fulfilling all the above-mentioned requirements of communication devices and is moreover designed for being insensitive to the technological tolerances of the applied processes.

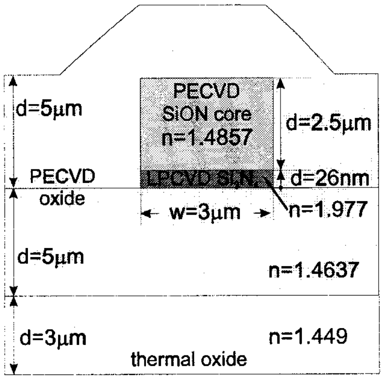

Fig. 1: SiON-based waveguiding structure with parameters

The effective refractive index of this structure is 1.4704 and the polarization dependence of the waveguiding channel is $2x10^{-6}$. This low polarization dependence is attained by compensating the material birefringence-introduced polarization dependence of the SiON channel geometrically introducing a thin silicon nitride layer [4]. Based on the effective index contrast of this structure, $1.4x10^{-2}$, Whispering Gallery Mode bends [5] with a bending radius of 1.6 mm and an optical loss of 0.1 dB/90° have been calculated. A fiber-to-chip coupling loss, due to the mode mismatch between the modal field in the channel waveguide and a standard telecommunication fiber, of 2.5 dB/facet has been calculated. Nevertheless, this overlap loss can be easily reduced by expanding the modal field in the waveguiding channel, e.g. by adiabatically tapering of the channel width. For a channel width of 1 µm, the overlap loss will be reduced to below 0.3 dB/facet.

The SiON waveguiding structure is applied for the realization of a thermo-optically tunable add-drop multiplexer, which is based on Mach-Zehnder interferometer (MZI) filter elements with non-equal branches, as schematically shown in Fig. 2. The MZI filter element is designed for having a 2 nm free spectral range (FSR) at 1550 nm. The filter element has a path length difference of both branches of 820 µm and the MMI-couplers are 35 µm wide and 920 µm long. The bending radius was conservatively chosen to be 7 mm. The angle α is optimized in a way that at given path length difference the dimensions of the device are minimized.

Measurements on the first test device with TE-polarized light showed excellent agreement of the FSR with the designed value. A cross-talk of -20 dB for the cross-state (1-2' and 2-1') and -10 dB for the bar-state (1-1' and 2-2') is measured. This asymmetry can be explained by a non-perfect splitting ratio of the MMI's.

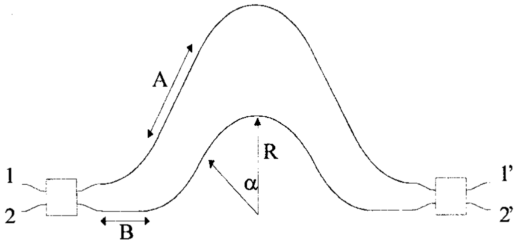

Fig. 2: Schematic view of a MZI wavelength filter with MMI 3-dB-couplers having a path length difference of 2(A-B) with bending radius R and the total subtended angle of arc α,

The thermo-optical tuning behavior of the filter has also been measured. Applying gold heaters with not-yet optimized dimensions, a heating power of 0.8 W was required for tuning the device over a full free spectral range, giving a tuning sensitivity of 0.4 W/nm.

IV. CONCLUSION

The state of the art of controlled fabrication of highly uniform low-loss silicon oxynitride waveguides has been discussed. Based on this material, a channel waveguiding structure has been designed and realized. This channel structure enables the realization of low-loss, compact communication devices with low polarization dependency and high fiber-coupling efficiency. The application of this structure in a thermo-optically tuned MZI filter element has been demonstrated.

ACKNOWLEDGMENT

The authors would like to thank Lucie Hilderink, Gijs Krijnen, Peter Linders and Bertrik Sikken for their contributions to the presented research.

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