250C Process for < 2dB/m Ultra-Low Loss Silicon Nitride Integrated Photonic Waveguides

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Abstract: We report fabrication of CMOS-compatible Si_3N_4 waveguides, including resonators, with 2.0dB/m loss as well as 11.18million loaded Q at 1550nm, using a maximum temperature of 250C during and after Si_3N_4 deposition, enabling system-on-chip integration.

1. Introduction

Integrated photonics requires ultra-low loss (ULL) waveguides to bring bulk optical components to the chip-scale without compromising performance. Low Pressure Chemical Vapor deposited (LPCVD) Silicon Nitride core waveguides, with silicon dioxide upper and lower claddings, are one of the most promising candidates, with losses as low as 0.034 dB/m [1,2]. This LPCVD Nitride growth requires temperatures as high as 800C. Furthermore, high temperature (1050C) annealing is required to drive out hydrogen from the LPCVD silicon nitride and the upper cladding to achieve these ultra low losses [1,2]. Annealing removes N-H bond overtones near 1.5µm [3]. However, there are many cases where one wants to limit the process temperature to under 400C, for example to prevent crystallization in ultra-low loss tantala waveguides [4] and processing on substrates like preprocessed silicon electronic circuits or quartz for athermalization [5.6]. Inductively Coupled Plasma – Plasma Enhanced Chemical Vapor Deposition (ICP-PECVD) with deuterated silane as a precursor gas – is an emerging lower temperature method to grow silicon nitride and silicon dioxide [7,8], without having absorption peaks near 1550nm due to hydrogen bonds, and with low particle counts – which is an issue with sputtered silicon nitride [9]. Recently, ultra-low (<1dB/m) losses have been demonstrated with devices using an annealed LPCVD nitride core, and a deuterated upper cladding oxide which was not annealed [10]. Most work on processes that use both deuterated nitride cores as well as deuterated oxide upper cladding till now however, has been focused on thick core (>650nm) high confinement waveguides for Kerr comb generation [7,8], because of the low stress compared to LPCVD silicon nitride, and have not explored the ultra-low loss regime.

In this work, we present the first demonstration of ultra-low losses of 2.0dB/m in silicon nitride waveguides and ring resonators with Q = 11.18 million, using a anneal-free process involving ICP-PECVD with deuterated silane as a precursor gas, with a maximum temperature of only 250C. We describe the process and test and measurement results, and compare them with LPCVD nitride, and the potential for future use of this process technology.

2. Fabrication

For a proper comparison with LPCVD nitride, we first fabricate (Device 1) 8530.8µm radius single-bus ring resonators, ring couplers, and straight waveguides which use 80nm core LPCVD nitride and 5µm of 250C ICP-PECVD upper cladding silicon dioxide with the deuterated silane precursor. The 4” silicon wafer on which these were grown on had 15µm of thermally grown lower cladding oxide on top as in Figure 1(a). The patterned waveguide cores are 6µm wide and have a bus-resonator waveguide gap of 3.5µm [6]. Another such wafer (Device 2) was processed where the LPCVD nitride was annealed for 7 hours at 1050C before the upper cladding deposition. Next we grow silicon nitride using ICP-PECVD at 250C on a blank 4” silicon wafer, also using the deuterated silane. We measured a total particle count of 145 (particle size 0.16 – 1.6 µm) with a KLA/Tencor Surfscan after deposition and a refractive index of 1.95 at 1550nm for the silicon nitride using a Woollam Variable Angle Spectroscopic Ellipsometer. Finally, we grow 80nm of the deuterated 250C ICP-PECVD silicon nitride on a silicon wafer (Device 3) similar to the first starting wafer, pattern the nitride similarly, and deposit 5µm of the same 250C ICP-PECVD upper cladding oxide.

3. Measurements and Discussion

The waveguide geometry supports the fundamental TE and TM modes only for Devices 1 and 3, but another TE mode also for Device 2. The loaded Q factor at 1550nm for the fundamental TE/TM modes for Device 2’s ring resonator was measured using a calibrated unbalanced fiber MZI with a fringe width of 5.71MHz as in [6]. Similar measurements for Device 1 and 3's ring resonators were taken with a different unbalanced fiber MZI which had a fringe width of 5.87MHz as in Figure 1(c,d,e). The waveguide losses (Table 1) and ring-bus coupling for each mode and device was then extracted by fitting the resonances to a Lorentzian curve. The coupling coefficient between the ring and bus waveguides was also measured independently using ring couplers. Finally, we compare these results with that of fully annealed Tetraethylorthosilicate(TEOS)-PECVD upper cladding oxide and LPCVD nitride cores in Table 1.

We find we can achieve ultra-low losses of 2dB/m (TM mode) and a resonator loaded Q of 11.18 million (TE mode) using only the lower temperature ICP-PECVD process and that the TE mode loss is significantly lower than that of the unannealed LPCVD nitride of 13.6dB/m. The significantly higher TM loss compared to the annealed LPCVD nitride is thought to be due to higher top surface roughness of the ICP-PECVD nitride. Thus, for substrates and processes that cannot exceed 250C, this fabrication process is a promising candidate to make ULL waveguides and systems-on-chip.

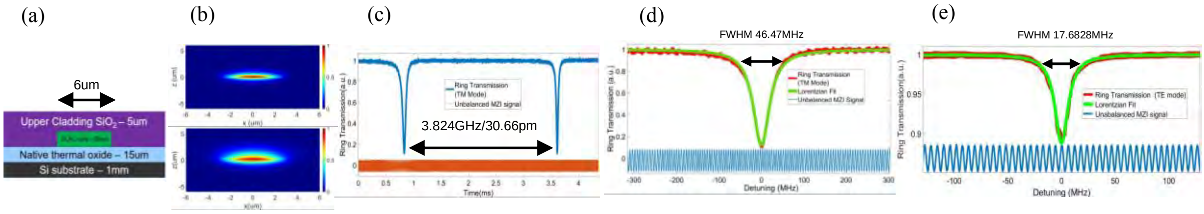

Figure 1(a) Cross-sectional View of waveguide (b) Normalized Intensity Mode profiles of the TE(top) and TM(bottom) in Device 3 (c) Device 3 TM Mode resonances with a FSR of 30.66pm (d) Lorentzian fit to Device 3's TM Mode Resonance(zoomed in) with a loaded Q factor of 4.16 million (e) Lorentzian Fit to Device 3's TE Mode Resonance with a loaded Q factor of 11.18 million

Table 1 Summary of Losses for Different Modes and Material Combinations

Silicon Nitride Waveguide Core Growth Process	**Waveguide Core Annealed?**	**Upper Cladding Silicon Dioxide Growth Process**	**Parameters**	**TM Mode**	**TE Mode**
250C ICP-PECVD with Deuterated Silane as precursor	No	250C ICP-PECVD with Deuterated Silane as precursor (5 µm)	Loaded Q	4.16×10^6	11.18×10^6
			Waveguide Loss	2.04dB/m	2.23dB/m
800C LPCVD	No		Loaded Q	3.78×10^6	1.98×10^6
			Waveguide Loss	1.57dB/m	13.6dB/m
	Yes		Loaded Q	8.49×10^6	25.54×10^6
			Waveguide Loss	0.24dB/m	1.00dB/m
	Yes	TEOS-PECVD and then 1050C, 1150C anneal (6 µm)	Loaded Q	9×10^6	33×10^6
			Waveguide Loss	0.2dB/m	0.8dB/m

3. References

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