Low-loss D-shape Silicon Nitride Waveguides Using a Dielectric Lift-off Fabrication Process

Qiancheng Zhao¹, Jiawei Wang¹, Nitesh Chauhan¹, Debapam Bose¹, Naijun Jin², Renan Moreira¹, Ryan Behunin³, Peter Rakich² and Daniel Blumenthal*¹

¹Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA, USA, 93106
²Department of Applied Physics, Yale University, New Haven, CT, USA, 06511
³Department of Applied Physics and Material Sciences, Northern Arizona University, Flagstaff, AZ, USA, 86011
*danb@ucsb.edu

Abstract: D-shape Si₃N₄ waveguides are fabricated by dielectric lift-off process. We measure ultra-low loss for a 90nm-thick core of 2.42 dB/m at 1550 nm and a loaded Q-factor of 1.12×10⁹ for a 0.8 mm radius resonator. © 2020 The Author(s)

OCIS codes: (230.7390) waveguides, planar; (250.5300) photonic integrated circuits.

1. Introduction

Low-loss waveguides enable a broad range of photonic integrated circuits (PICs) such as integrated optical gyroscopes [1], atomic clocks [2], narrow-linewidth SBS lasers [3], and optical frequency combs [4]. The performance of these applications requires waveguides with sub-dB/cm propagation loss. Numerous efforts have been devoted to identifying and addressing the limiting factors of waveguide losses [5], among which waveguide sidewall roughness is a dominant factor. Elimination of the sidewall roughness is a key approach to lowering losses.

Waveguide sidewall roughness, often caused by dry etching, can be mitigated by several techniques including Damascene reflow [6], photosist thermal reflow [7], laser annealing [8] and dielectric lift-off. The dielectric lift-off process is usually implemented by depositing a waveguiding structure that has smoother sidewalls. This method is CMOS-compatible and is scalable to large areas, and it has been used in reducing chalcogenide [9] and titanium dioxide [10] waveguide propagation losses. Here we demonstrate a low-loss D-shape high-aspect-ratio silicon nitride (Si₃N₄) waveguide using a silicon dioxide (SiO₂) hardmask created by the dielectric lift-off process. The waveguide propagation loss is 2.42 dB/m at 1550 nm. A loaded Q-factor of 1.12×10⁹ is measured for a 0.8 mm radius resonator. This is the first demonstration of the D-shape high-aspect-ratio Si₃N₄ waveguides. The method of patterning SiO₂ hardmask by the dielectric lift-off process can be applied to other waveguide core materials.

2. Device Fabrication

The fabrication process, illustrated in Fig. 1(a), starts with depositing a 90 nm stoichiometric LPCVD Si₃N₄ film on a thermal oxide (150 nm) silicon (Si) wafer. A ~250 nm LOL2000 lift-off layer and ~550 nm UVN30-0.8 photoresist layer are spin-coated sequentially on the wafer and get exposed by an ASML DUV Stepper. The undercut depth in the LOL2000 layer is controlled by the photoresist developing time, and ~570 nm undercut (Fig. 1(b)) is measured in our experiment to avoid wings after lift-off. A layer of 112 nm SiO₂ is deposited on the photoresist-patterned wafer by RF sputtering Si with oxygen flow. The SiO₂ layer is lifted off by immersing the wafer in n-methyl-2-pyrrolidone (NMP) solvent with ultrasonic heat bath. Special attention has been paid to thoroughly wash the wafer to minimize particle contaminations. The D-shape of the hardmask is transferred into the waveguide core layer by using fluorine-based dry etching. Since the etching ratio of the SiO₂ to Si₃N₄ is close to 1, a one-to-one copy of the D-shape from the hardmask to the waveguide core can be obtained, as shown in Fig. 1(c). A 6 µm SiO₂ upper cladding layer is deposited afterwards, and the wafer is annealed above 1050°C to reduce material loss.
3. Waveguide characterization

The bottom width of the D-shape waveguide is ~0.3 µm wider than the design due to the extruding of the SiO₂ hardmask into the photoresist undercut layer, as shown in Fig. 1(c) and (d). Consequently, the D-shape waveguide has a flatter sidewall surface slope than rectangular waveguide. The sidewall surface is measured to have a RMS roughness $S_N = 607.2$ pm and an average roughness $S_a = 467.0$ pm by AFM in the black boxed region in Fig. 1(d). There are still SiO₂ hardmasks left on top of the Si₃N₄ layer after dry etching (shown in Fig. 1(d)), and they will be buried into the SiO₂ upper cladding layer, leaving negligible discontinuities.

To quantify the propagation loss, optical backscatter reflectometry (OBR) is employed to scan a wide range of spectrum (1525-1610 nm) into a 1 meter-long and 3 µm-wide spiral waveguide, enabling 0.1 nm-level spatial resolution. Fig. 2(a) shows the reflection amplitude measured from the spiral delay, and the propagation loss is curve fitted to be 2.42 dB/m, which is lower than the previous reported value for 90 nm Si₃N₄ waveguides of 4.22 dB/m [11] and 4.65 dB/m [12]. The spiral radius shrinks from 4.05 mm to 121.8 mm from outside to inner. As a result, the propagation loss increases when the light travels towards the end of the spiral due to small radii, as shown in the top right inset in Fig. 2(a). The dashed line approximates where $R = 0.8$ mm is at the spiral delay, beyond which the reflected signal starts to drop sharply due to bending loss. The propagation loss is also verified using the Q-factor (Fig. 2(b)) of a bus-coupled ring resonator that has a radius of 0.8 mm. The loaded Q was measured by using a calibrated unbalanced MZI with FSR of 5.87 MHz. The FWHM of the resonance is 172.31 MHz with a loaded Q of 1.12×10⁶ at 1550 nm. The gap of the resonator is ~1.7 µm and the coupling coefficient is estimated to be 2.45% from measurements. The propagation loss of the resonator is derived to be 2.98 dB/m. The slightly higher loss from Q measurement than from the OBR results can be attributed to that the bending loss starts to become noticeable. If bending loss could be neglected and assuming a critical coupling, a Q of 5.6×10⁶ should be expected with the measured loss from OBR. Considering the ring radius is close to critical bend radii for 90 nm Si₃N₄ strip waveguides [13], the propagation loss of the D-shape waveguide is reasonably low, enabling the possibility for compact integration. In summary, we demonstrate the D-shape high-aspect-ratio waveguides fabricated by dielectric lift-off process which shows lower propagation loss than records.

Acknowledgment and funding information: This work was supported by DARPA MTO APPh contract number FA9453-19-C-0030. The views, opinions and/or findings expressed are those of the author(s) and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.