Efficient FWM-based Wavelength Conversion in Deuterated Ultra-Silicon-Rich Nitride (USRN:D)

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Abstract— **We demonstrate highly nonlinear devices fabricated on deuterated ultra-silicon-rich nitride (USRN:D). Waveguides with nonlinear parameters as high as 166 W^{-1}m^{-1} are used as wavelength convertors, attaining a conversion efficiency of -43.2 dB over a waveguide length of just 1 cm.**

Keywords—Nonlinear Optics, Silicon-Rich Nitride, Four-Wave Mixing, Nonlinear Wavelength Convertors

I. INTRODUCTION (*HEADING 1*)

Since their initial demonstration in 2017 [1], deuterated silicon-nitride (SiN:D) devices have been demonstrated in a number of works including frequency comb generation [2, 3] and ultra-low-loss waveguide devices [4]. The substitution of hydrogen for deuterium in the low-temperature (<400°C) Plasma-Enhanced Chemical Vapour Deposition (PECVD) processes retains backend complementary metal-oxide semiconductor (backend-CMOS) compatibility of the film deposition process while mitigating deleterious absorption losses at telecommunications wavelengths arising from Si-H and N-H bonds present in conventional hydrogenated silicon-nitride (SiN:H) films.

Concurrently, silicon-rich nitride (SRN) has been demonstrated as a promising platform for nonlinear integrated optics in the recent decade due to its high optical nonlinearity and optical bandgap in excess of the two-photon absorption limit (>1.6 eV) at the telecommunications bands near 1550 nm. Of the SRN chemistries presented in literature, ultra-silicon-rich nitride [5] has presented with the highest $\chi^{(3)}$ nonlinearity at 2.8 × 10^{-17} cm^2/W (~500 W^{-1}m^{-1} in waveguides) while retaining a high optical bandgap of 2.1 eV. USRN utilizes conventional silane gas, and therefore still possesses Si-H bonds in its films.

In this work, we demonstrate devices fabricated on deuterated ultra-silicon-rich nitride (USRN:D). The waveguides possess a linear refractive index of n = 2.96 at 1550 nm and a device nonlinear parameter of 167 W^{-1}m^{-1}, corresponding to a film Kerr nonlinearity of 1.23 × 10^{-17} m^2/W.

II. FABRICATION AND CHARACTERISATION

The films are deposited using Inductively-Coupled Plasma Chemical Vapour Deposition (ICPCVD) at a temperature of 250°C using SiD_4:N_2 gas ratio of 8:3 on a silicon substrate with 5 μm of thermal oxide, yielding 430 nm thick films capable of supporting anomalous dispersion. Linear refractive index and extinction coefficient (Fig. 1a) are determined using variable-angle spectroscopic ellipsometry (VASE), yielding a linear refractive index of 2.96 at 1550 nm and an optical bandgap of 1.97 eV, determined using Tauc's Plot (Fig. 1b). Atomic-Force Microscopy scans of the surface (Fig. 1c, 3 μm × 3 μm scan area, tapping mode in air) reveal an as-deposited surface root-mean-square roughness of 0.18 nm, close to many state of the art silicon nitride devices, which enables the realisation of low-loss devices without the need for additional surface-smoothing techniques such as chemical-mechanical polishing, reducing the fabrication complexity of the films. Figure 1d shows the Attenuated Total Reflectance Fourier-Transform InfraRed (ATR-FTIR) spectroscopy of the USRN:D film, evidencing the absence of Si-H and N-H bonds in the film given the flat absorption curves at 2157 cm^{-1} to 2250 cm^{-1} and 3290 cm^{-1} to 3464 cm^{-1} respectively, replaced by Si-D and N-D bond absorption peaks occurring at 1515 cm^{-1} and 2360 cm^{-1}.

We fabricate microring and racetrack resonators and waveguides on the platform using electron-beam lithography and reactive ion etching. Subsequently, 2 μm of SiO_2 is deposited on the surface of the devices via ICPCVD to form the upper cladding. Racetrack resonators with an optical path-length of 971 μm (~87 GHz free spectral range) and a cross section of 0.6 μm × 0.43 μm (W × H) close to critical coupling present with consistent intrinsic quality factors (Q_i) exceeding 100,000 from 1500 nm to 1600 nm with a peak of 120,000 at 1547 nm (Fig. 2a). Q_i in optical resonators fabricated using USRN:H previously presented with quality factors closer to 30,000, with the use of USRN:D yielding a 3-fold decrease in the round-trip loss of the microresonators.

Continuous-wave pump (1550 nm) and signal (1549 nm) sources are coupled using a 50:50 splitter-coupler into a 1 cm long waveguide with a measured propagation loss of 4.78 dB/cm and inverse tapers with insertion losses of 4.17 dB/facet. The pump and signal wavelengths are deliberately kept 1 nm apart to limit conversion-efficiency reduction due to phase-mismatch, providing a better estimate of the nonlinear parameter. The measured on-chip pump and signal powers are 7.1 mW and 0.38 mW respectively, resulting in an idler generated on the red side of the pump with a conversion efficiency of -43.2 dB and a raw off-chip output of -57.6 dBm.

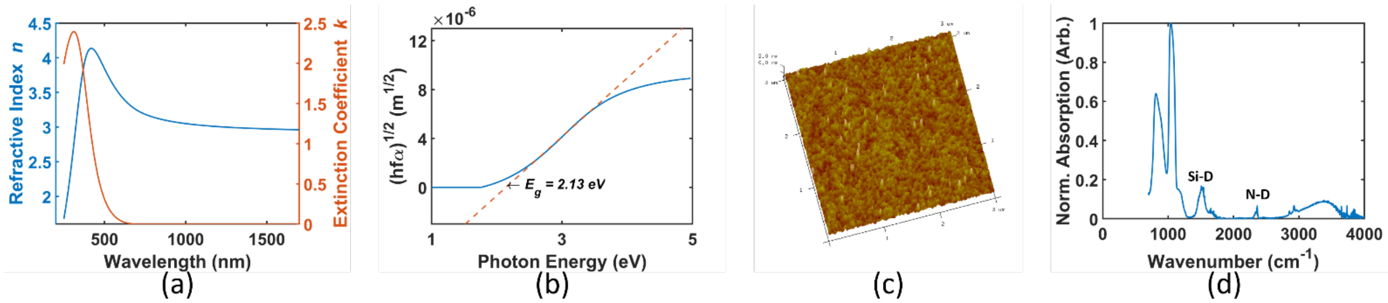

Figure 1 Film characterisation results showing (a) Linear refractive index (—) and extinction coefficient (—) of the USRN:D film (b) Tauc's Plot showing the converted absorption curve (—) and linear fit (--) derived from the extinction coefficient. The extracted optical bandgap is 2.13 eV (c) AFM scan of the wafer surface with 0.18 rms roughness as-deposited (d) ATR-FTIR with marked Si-D and N-D peaks in the absorption spectra

Despite the significantly lower signal powers, an idler is observed on the blue side of the signal line with an off-chip output power of -63.6 dBm due to the high Kerr nonlinearity of the USRN:D film. From conversion efficiency of the red idler, the nonlinear parameter γ of the waveguide can be determined using $\mathrm{CE} = \gamma^2 P_p^2 L^2 e^{-\alpha L}$, where γ is the device nonlinear parameter in $W^{-1}m^{-1}$, P_p is the on-chip pump power, L is the waveguide length, and α is the waveguide propagation loss. The calculated waveguide γ of 166 $W^{-1}m^{-1}$ corresponds to a film Kerr nonlinearity of 1.23×10^{-17} m^2/W, almost 2 orders of magnitude higher than Si_3N_4 platforms, making USRN:D a promising platform for low-loss, highly nonlinear optical devices.

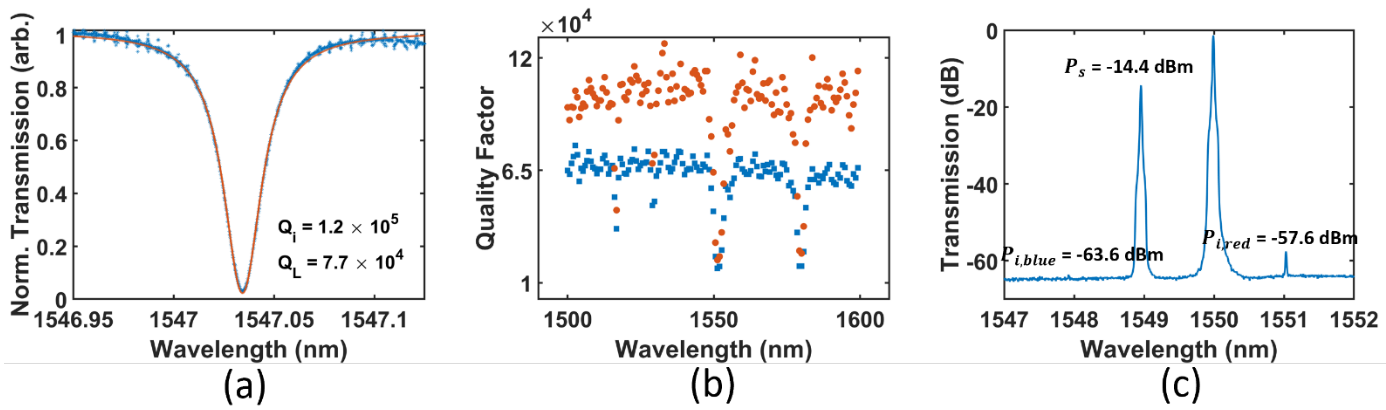

Figure 2 Device characterisation results showing (a) Normalized transmission (—) and Lorentzian fit (—) of a resonance in a USRN:D racetrack resonator with an optical path-length of 971 µm (~87 GHz FSR) showing an intrinsic QF of 120,000 and a loaded QF of 77,000 (b) Loaded (blue squares) and intrinsic (orange circles) quality factors of the ring resonator shown in (a). Dips in the quality factor correspond to regions with strong intermodal coupling (c) FWM output from a 1cm long USRN:D waveguide with a cross section of 0.6 µm × 0.43 µm (W × H), yielding an on-chip CE of -43.2 dB

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