Stoichiometric Silicon Nitride Growth for Nonlinear Nanophotonics

CNF Project Number: 2920-20

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Primary Source(s) of Research Funding: Defense Advanced Research Project Agency (DARPA), National Institute of Standards and Technology (NIST)

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Primary CNF Tools Used: Low pressure chemical vapor deposition (LPCVD) furnaces

Abstract:

Chip-integrated optical frequency combs based on integrated photonic resonators are an important technology for realizing precision measurement instrumentation, such as optical atomic clocks, in a compact and deployable format. The combs utilize nonlinear-wave mixing to spectrally redistribute a single-frequency pump laser into a spectrum of equally spaced parametric sidebands and have a behavior that depends on the interplay between dispersion, nonlinearity, dissipation, and gain. Dispersion depends on both the material chosen for the resonator and the geometry of the resonator. Stoichiomeric silicon nitride grown via low-pressure chemical vapor deposition (LPCVD) has been a common choice for this application, but the precise growth conditions have varied in the literature. Here, we study the impact of varying growth conditions, all within the nominally stoichiometric growth regime, on dispersion and frequency comb generation.

Summary of Research:

We received several LPCVD-grown silicon nitride wafers from CNF, with the silicon nitride films grown on a 3 μm thick SiO_2 layer, all on a Si substrate. The parameter varied between the different growth runs was the ratio of the precursors gases, which we stepped between 3:1 (ammonia:dichlorosilane) and 15:1 (ammonia:dichlorosilane).

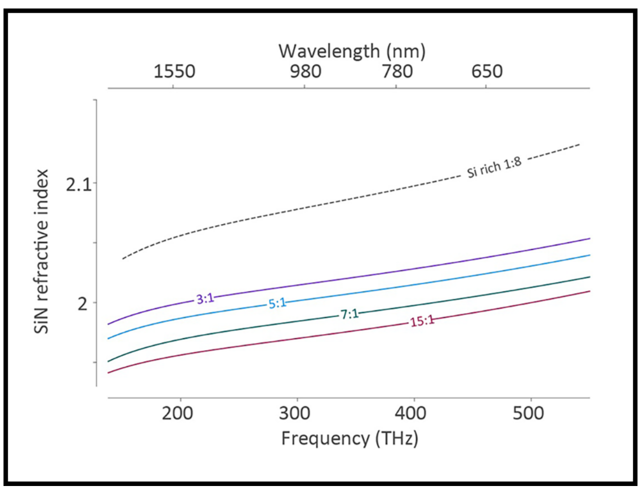

Figure 1: Wavelength/frequency-dependent refractive index values for silicon nitride films grown with varying ammonia:dichlorosilane ratios. 3:1, 5:1, 7:1, and 15:1 films are considered in this work. The refractive index of a Si-rich film (1:8 gas ratio) is shown for reference.

The rest of the processing to create microring resonators was done at NIST, and the fabricated geometries were tested at UMD.

Figure 1 shows results of fits to spectroscopic ellipsometry data, revealing the wavelength-dependent refractive index behavior of the grown films. Although all films were grown within the typical precursor range claimed for stoichiometric films (e.g., ammonia:dichlorosilane > 2:1), there are clear differences between the films, both in terms of the range of refractive index values and the manner in which the refractive index varies (i.e., the dispersion). The impact of the precursor gas ratio on dispersion can be described by a quantity called the integrated dispersion, which in the context of microresonator frequency combs, describes the separation between cavity resonances and an equally spaced grid. This integrated dispersion, which we calculate using finite-element simulations that take the measured refractive index data into account, largely controls the frequency bandwidth of the comb, and is shown in Figure 2 (left side) for a fixed resonator geometry.

We see that both the maximum value of the integrated dispersion and the position of its zero crossings significantly differ as the gas ratio goes from 3:1 to 5:1 to 7:1.

We then model the expected microcomb behavior using the Lugiato-Lefever Equation, which takes these integrated dispersion curves as an input. The predicted comb spectra in Figure 2 (right side) clearly show a significantly different comb bandwidth, with peaks at the extremities of the spectra, known as dispersive waves, having significantly different spectral positions and amplitudes.

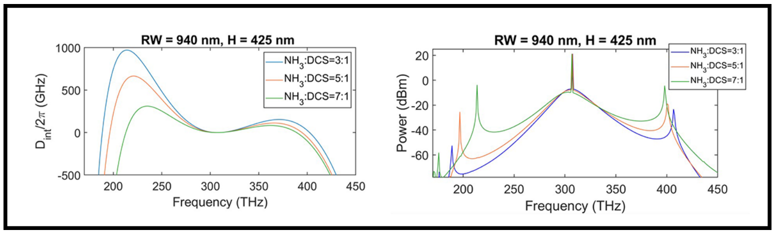

Figure 2: Simulation of the integrated dispersion (left) and expected soliton microcomb spectrum (right) for ring resonators with a fixed geometry and differing SiN films.

To compensate for the shifts in the dispersive wave positions for differing growth gas ratios, we can tune the resonator geometry.

Figure 3 shows the results of measurements indicating such an effect, for resonators fabricated in 3:1 and 7:1 ammonia:dichlorosilane films. Here, the thickness of the two resonators differs by about 10 nm, but the high frequency dispersive waves are at nearly the same position (within 2 THz). In contrast, two resonators with a thickness differing by 10 nm, but fabricated in a fixed gas ratio film (e.g., 7:1), would be expected to show a > 15 THz shift.

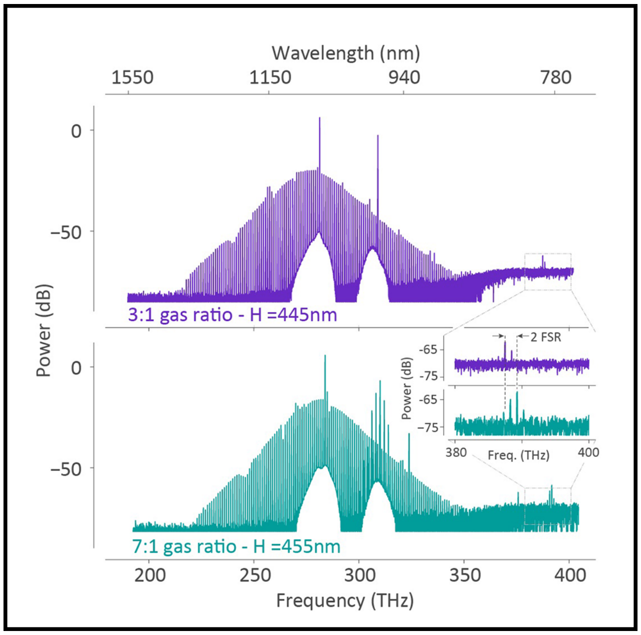

Figure 3: Measured soliton comb spectrum for two devices. The top (bottom) device is grown in a 3:1 (7:1) film, and the bottom device has a 10 nm greater film thickness.

Conclusions and Future Steps:

We have shown that the specific gas ratio within the nominally stoichiometric regime of LPCVD SiN growth has an impact on dispersion and microresonator frequency comb generation. Future work will utilize this ability to adjust material dispersion in combination with geometric dispersion engineering to create broadband microresonator combs to be used in compact optical atomic clocks.

References:

[1] G. Moille, et al, CLEO, SF2A.4 (2021).