LOW LOSS CMOS

Compatible silicon nitride photonics utilizing reactive sputtered thin films

Silicon photonics (SiP), where photons replace electrons as the carrier medium for information, is a combination of two most important inventions of the 20th century, namely the silicon integrated circuit (IC) and the semiconductor laser. Evatec's Process Engineer **Andreas Frigg** explains how reactive sputtering is a promising new process for cost-effective deposition of SiN for applications like waveguides enabling the rapid growth of data centers.

Photonic integrated circuits (PICs) are manufactured based on customized material platforms such as silicon on isolator (SOI), silicon nitride (SiN), lithium niobate on insulator (LNOI), silica and III-V compound semiconductor such as InP and GaAs. This enables the fabrication of energy efficient, small form factor devices while leveraging existing complementary metal oxide (CMOS) fabrication foundries where thousands of PICs can be fabricated on 200mm wafers in a single batch.

The largest application of silicon photonics is data communication (CAGR 44%), to satisfy the ever-growing demand for bandwidths in data centeRs and for 5G networks. The major advantages of using silicon photonics in this sector are lower power consumption and higher data transfer rates (>100 Gbps) for optical transceiver and receiver. In recent times, integrated microcomb sources have been employed for parallel communication with high data rates using many individually modulated channels. Such wavelength division multiplexing (WDM) telecommunication schemes require optical sources of equally spaced spectral components. The large achievable bandwidths, the small footprint and the intrinsically equal spectral spacing of the optical signal components make Kerr frequency combs generated with high Q silicon nitride resonators promising components for chip-scale terabit/s transmitter.

Efforts are also now being directed to explore opportunities in other application areas, such as medical (biosensors), life sciences (gas sensing and spectroscopy) and automotive LIDAR. These emerging applications require a material platform which overcomes some of the limitations of the predominant silicon on insulator technology.

Silicon nitride (SiN) is an attractive material for waveguides in photonic integrated circuits PICs. It offers a wide wavelength transparency window from visible (VIS) for biophotonics applications, through near infrared (NIR) for telecommunication and LIDAR applications, right out into the mid infrared (MIR) for spectroscopy and gas sensing. It also offers negligible two-photon absorption (β_{TPA}) at 1550 nm and a sufficiently high refractive index (n = 2 at 1550 nm) for tight optical confinement and CMOS-compatible fabrication techniques.

SiN thin films for optical waveguides are commonly deposited by either low pressure chemical vapor deposition (LPCVD) for front-end of line applications or plasma enhanced chemical vapor deposition (PECVD) for back-end of line applications.

LPCVD is a high temperature (>800°C) process that can produce low loss, stoichiometric silicon nitride (Si_3N_4) thin films after post-annealing at ~ 1100°C. However, the high processing temperatures and the resulting high tensile stress limit co-integration with sensitive substrates due to risk of diffusion and crack formation.

The outstanding properties of SiN also make it an attractive material for back-end of line processes (<450°C), for example the hybrid integration of SiN with silicon on insulator (SOI), III–V materials and lithium niobate on insulator (LNOI). This offers the potential for more hybrid integration of SiN (for passive components) on SOI and III–V materials (for active components) can lead to more advanced devices, which require low propagation losses (e.g. optical delay lines) and high-power handling capabilities (e.g. frequency combs).

PECVD SiN depositions are low temperature (< 400°C) processes, which can be used to deposit thin films with low stress. However, PECVD processes introduced Si-H and N-H bonds, resulting in unwanted absorption losses at telecommunication wavelengths. Owing to the combined layer morphology and surface roughness,

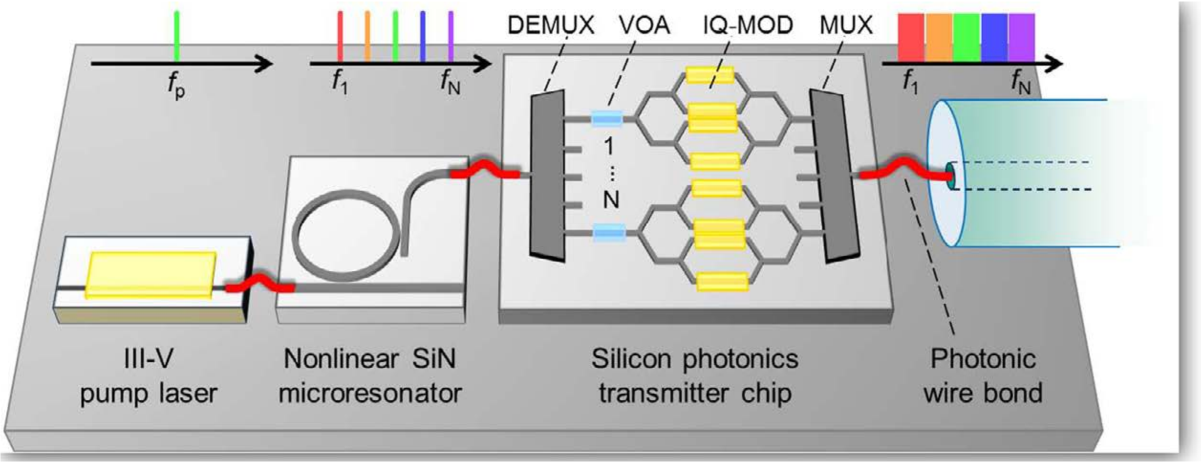

Figure 1. Chip-scale terabit/s transmitter based on a SiN frequency comb

CLUSTERLINE® 200
equipped with BPM

> “THE SYSTEM OFFERS A WIDE AND WELL CHARACTERIZED PROCESS WINDOW FOR SILICON NITRIDE FILMS – RANGING FROM NITROGEN-RICH TO STOCHIOMETRIC AND SILICON-RICH”

waveguide losses are typically in the range of 2 dB/cm, which is too high for certain applications such as Kerr frequency combs and optical delay lines.

Reactive sputtering is a promising back-end-of-line, low temperature deposition method for waveguides and offers lower propagation losses compared to PECVD due to lower H-bond absorption losses, lower surface roughness and denser thin film structure.

We deposited low loss SiN layers at temperatures below 100C using CLUSTERLINE® 200, configured with a Batch Process Module (BPM) equipped with a DC pulsed rotating target source. Compared with RF sputter, DC pulsed techniques are simpler offering better uniformity and higher rates. The SiN thin films were grown from a silicon target in an Ar/N_2 plasma. The system offers a wide and well characterized process window for SiN films, ranging from nitrogen-rich to stochiometric and silicon-rich SiN. The in-film layer stress can be tuned from compressive to tensile by adjusting the DC-pulsed duty cycle and deposition pressure. The unique rotating target source give a uniformity of ±0.25% on 8" wafers and a low particle counts due to the absence of uniformity shapers. The fully SEMI automated cassette-to-cassette handling allows high throughput of 15 pcs 8" substrates per batch. The fully automated wafer handling capability, excellent uniformity and high run to run reproducibility of the system offers a significant advantage compared to PECVD.

Silicon substrates with a 3 micron SiO_2 bottom cladding layer were used for the deposition tests. We investigated the deposition parameters and their impact on surface roughness, stress and optical losses.

Figure 2a shows the influence of the Ar/N_2 ratio on the refractive index, which was measured using an ellipsometer. On increasing the Ar/N_2 ratio the thin film composition could be adjusted from N-rich to stoichiometric and Si-rich SiN. The near stoichiometric SiN thin films yielded the lowest optical losses and stress when compared to N-rich or Si-rich samples. Another limiting factor is stress, which can lead to cracks or delamination of the deposited SiN. This has been a main point of concern in LPCVD SiN thin films, where high tensile stress limits the maximum deposition thickness (~400–700 nm). Film stress measurements were carried out using a laser-based measurement tool. By increasing the deposition chamber pressure, it was possible to reverse the -450MPa compressive stress level into + 150MPa tensile (figure 2b). Figure 2c shows the influence of the DC-pulsed duty cycle on the thin film stress. The duty cycle was changed by modifying the pulse-off time between 0.4 μs to 2.4 μs. All other deposition parameters were kept constant. Increasing the duty cycle reduces the stress level significantly from -500MPa to +200MPa due to the lower pulse power density when running at higher duty cycles. Figure 2d shows the influence on DC power on the thin film stress. It was found that the stress became more compressive when increasing the DC power.

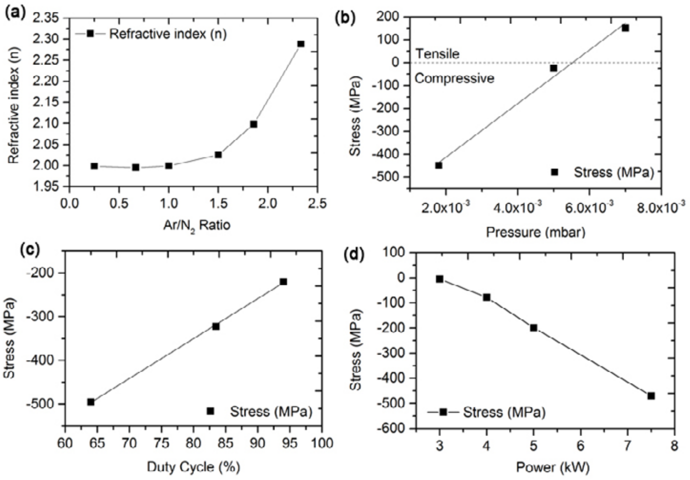

Figure 2 (a) Refractive index for Ar/N2 ratios from 0.25 to 2.3; (b) Stress versus chamber pressure; (c) Stress versus DC pulsed duty cycle; (d) Stress versus DC pulse power.

We achieved SiN thin films with a surface roughness of Rq of 1.2 nm measured by atomic force microscope (AFM), stress value of - 25 MPa measured by a laser based stress measurement tool and slab thin film losses of 1 dB/cm at 1550 nm measured by a prism coupler technique. As a post deposition step we investigated thermal annealing at 400° C in ambient atmosphere. We achieved post-annealed slab thin film losses of approximately 0.25 dB/cm. In order to investigate the effect of hydrogen bonds on material loss for deposited SiN thin films Fourier transform infrared spectroscopy FTIR was used to analyse the IR-absorption losses. The reactive sputtered SiN does not exhibit absorption peaks of Si-H (~2160 cm^{-1}) or N-H Bonds (~3340 cm^{-1}) which are responsible for the high losses of PECVD processed films at 1550 nm telecommunication wavelength.

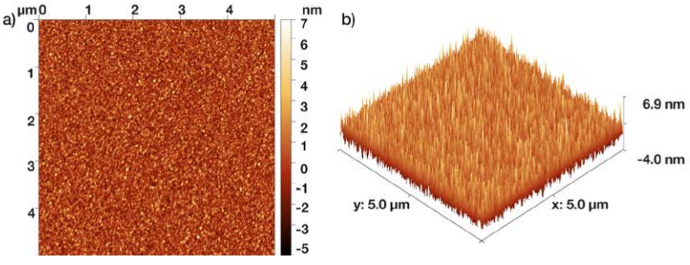

Figure 3a. 2D-plot of SiN roughness measured by atomic force microscope; figure 3b. 3D-plot of the sputtered SiN surface.

Next we fabricated high confinement waveguides and microrings using these films by EBL lithography and ICP etching and were able to achieve linear waveguide losses as low as 0.54 dB/cm at 1580 nm, as well as anomalous dispersion, a nonlinear coefficient of $\gamma = 2.1\ W^{-1}\ m^{-1}$, and a nonlinear refractive index n^2 of $5.6 \times 10^{-19}\ m^2\ W^{-1}$. The achieved waveguide losses are significantly lower compared to SiN waveguides fabricated by PECVD.

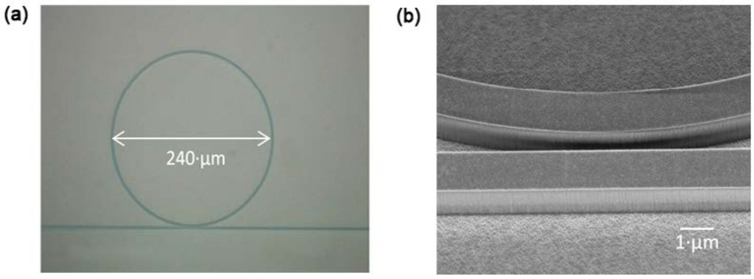

Figure 4. (a) Optical microscope image of a fabricated microring resonator with 120 µm radius and a cross section of 0.85 µm × 1.8 µm. (b) SEM image of the coupling region between bus and microring with a coupling gap of 300 nm.

We characterized the linear propagation loss by analyzing the quality factor of the fabricated microring resonators. The spectral response was characterized using a tunable laser source in the wavelength range of 1500-1600 nm (telecommunication band). The laser light was coupled to the fabricated chip using lensed fibers and inverse waveguide tapers.

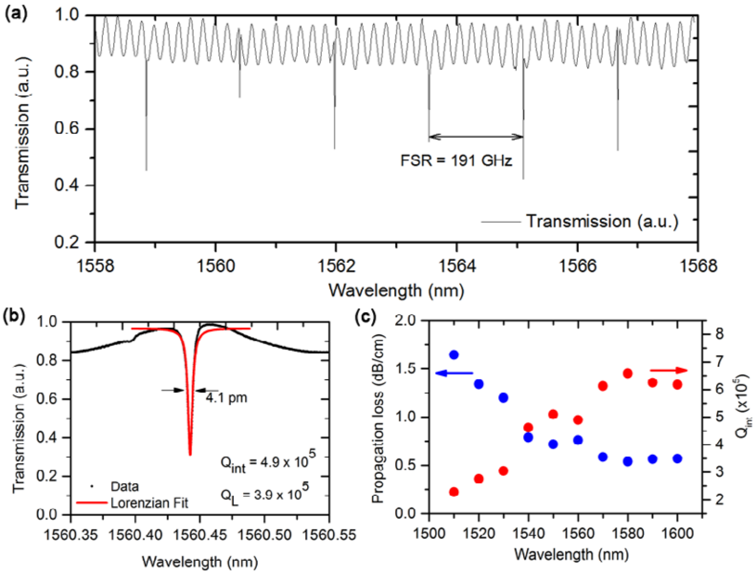

Figure 5a. Measured transmission spectrum of the microring resonator with an FSR = 191 GHz (1.53 nm), figure 5b. a measured resonance at 1560 nm with an intrinsic quality factor (Qint) of 4.9 × 105 corresponding to a propagation loss of 0.76 dB/cm, and figure 5c. propagation losses and intrinsic quality factor in the wavelength range of 1510–1600 nm.

As an application example a 250 nm wide microcomb with a native free spectral range (FSR) spacing of 191 GHz (1.53 nm) was successfully produced using the fabricated microring resonators.

This demonstration paves the way for integration of low loss, anomalous dispersive SiN waveguides onto future multilayer photonic integrated circuits with a peak processing temperature of 400°C, enabling optical microcombs for platforms where they were previously not feasible.

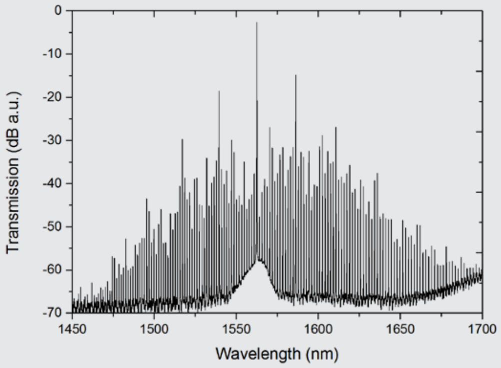

Figure 6. Native FSR spaced frequency comb generated at 850 mW on chip power spanning from λ = 1450–1700 nm.

[1] Andreas Frigg, Andreas Boes, Guanghui Ren, Islam Abdo, Duk-Yong Choi, Silvio Gees, and Arnan Mitchell, "Low loss CMOS-compatible silicon nitride photonics utilizing reactive sputtered thin films," Opt. Express 27, 37795-37805 (2019)

[2] Andreas Frigg, Andreas Boes, Guanghui Ren, Thach G.Nguyen, Duk-Yong Choi, Silvio Gees, David Moss and Arnan Mitchell, "Optical frequency comb generation with low temperature reactive sputtered silicon nitride waveguides", APL Photonics, (2020)