Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp507-508

Si_3N_4-based optical frequency comb generation featuring front-end CMOS- and Si-photonics process compatibility

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Abstract
In this communication we report about Kerr optical frequency comb (OFC) generation using annealing-free stoichiometric silicon nitride microresonators featuring full process compatibility for monolithic cointegration with front-end CMOS and Silicon optoelectronics. In contrast to *all* prior works, the maximum temperature used in this process flow (~780 °C) permits the generation of 800-nm-spanning OFCs and their monolithic cointegration with Si-photonics components. This work paves the way to time-stable power-efficient Kerr-based broadband sources featuring a full process compatibility with Si photonic integrated circuits (Si-PICs) on CMOS-lines.

1. Introduction

On-chip optical frequency combs (OFCs) generation enable compact broadband sources for novel applications such as low-noise microwave generation, massive parallel data transmission, and ultrafast spectroscopy. Silicon nitride (Si_3N_4) is an ideal platform for on-chip nonlinear optics [1], [2].

Besides, silicon-based photonic integrated circuits (Si-PICs) pave the way towards a brand-new optoelectronics featuring a significant integration potential with cost-effective complementary metal-oxide-semiconductor (CMOS) technology. Moreover, the co-integration of such broadband source with Si-photonics toolbox such as Si-Ge photodiodes [3], high-speed modulators [4], as well as filters and wavelength (de)multiplexers, can increase dramatically the performances for both on-chip Si-based telecom (Fig. 1) and integrated spectroscopy applications.

However, *all prior works* based on stoichiometric Si_3N_4 for OFCs generation use high-temperature annealing (~1200 °C for 3h) to break N-H dangling bonds in the nitride film and outgas any excess hydrogen or oxygen in the film, thus leaving a stoichiometrically pure Si_3N_4 [1], [2], [5], [6] and reducing the absorption in the C-band.

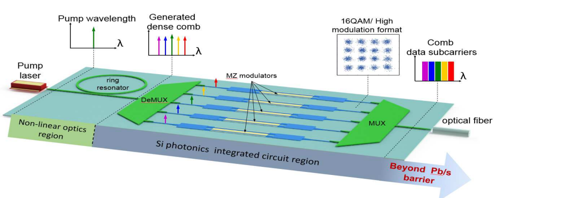

Fig. 1. Principle of ultra-high-speed-rate communications using nolinear integrated optics cointegrated with Si-based optoelectronics on the same chip via standard CMOS-foundry process.

Such thermal annealing eventually leads to cracks as reported in [5], [6]. Moreover, in the context of the co- integration of Kerr combs with front-end CMOS and silicon optoelectronics, such extreme annealing temperature can severely degrade the doped optical circuits because the dopants diffusion would be unacceptably affected. As alternative, optical parametric oscillation has been demonstrated by using the proprietary composition of Hydex waveguides in 2013 [1]. However, the nonlinear parameter γ of Hydex is 6*x* times lower than silicon nitride. Consequently, generating frequency combs in such material needs more power, increasing risks of waveguide fusing. Furthermore, as published recently in 2018, comb generation has been demonstrated using deuterated silicon nitride (SiN:D) deposited at 300 °C [7]. However, this material has a relatively strong thermal shift that occurs from the larger residual hydrogen-related absorption coefficient (compared to purely stoichiometric Si_3N_4 films) making difficult to stabilize the comb in the soliton state. Furthermore, deuterated silicon nitride can be exclusively used as CMOS-compatible back-end, thus preventing the possibility of the co-integration with front-end Si-photonics toolbox. In addition, the nonlinear index of SiN:D can be derived to be much lower than stoichiometric Si_3N_4 because, provided the same quality factor, it demands higher threshold powers in the case of deuterated silicon nitride. Consequently, in the same way of the Hydex, the risk of waveguide fusing is higher.

In this article we report on annealing-free silicon nitride microresonators following a tailored fabrication process that – by minimizing the hydrogen content - can be used to generate frequency combs. Specifically, differently from previous works and existing literature, the authors report here on comb generation using a novel, annealing-free, and crack-free process, constituting a big step toward a full compatibility of Si_3N_4-based films for nonlinear integrated optics with front-end CMOS electronics and Si photonics process flows and their thermal budgets constraints.

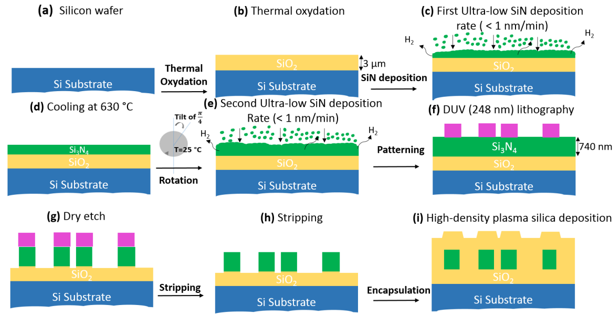

Fig. 2. Annealing-free process for Si_3N_4 waveguides (a)-(i).

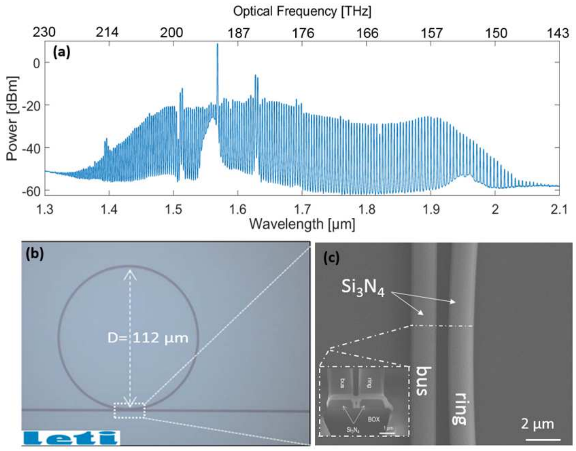

Fig. 3. (a) Optical frequency comb generation using annealing-free silicon nitride microrings. A 800-nm-spanning OFC generation (at P_{in} ~ 1 W) using a 56-radius microresonator with a 1500-nm-wide × 740-nm-tall waveguide dimensions. (b) Optical and (c) scanning electron microscope images of the 56-μm-radius ring resonator.

More important, in contrast to *all* previous publications, such novel process – which does not make use of hour-long high-temperature 1200 °C annealing - does not exceed neither the H_2 annealing thermal budget used for threading dislocations control for Ge-on-Si photodiodes (825 °C) [3] nor the dopants activation temperature (1030 °C) for Si modulators [4].

2. Silicon nitride technology and comb generation

The deposition is carried out with an ultra-low deposition rate (<2 nm/min) to provide a very high quality film, which is denser optically, and offering a higher nonlinear index ($n_2 = 3.6 \times 10^{-19}$ $m^2 \cdot W^{-1}$) [8]. Actually, during the ultra-low rate deposition, the thermal activation energy leaves enough time to silicon and nitrogen to dispose at the nitride film surface via atomic surface migration phenomena, while compelling hydrogen to escape the film.

In order to prevent cracks from appearing and to control strain, the silicon nitride layer is deposited via low-pressure chemical vapor deposition (LPCVD) in two steps counting a 370-nm-thick layer each. Furthermore, between the subsequent deposition stages, the carrier wafer is rotated by 45° in order to distribute the uniaxial strain along the overall film thickness, thus avoiding waveguide cracks formation upon subtractive patterning. Each deposition run is carried out at 780 °C with post-deposition cooling to around 630 °C for 20 minutes to room-temperature [Fig. 2(d)]. Controlled ramp-ups and downs from/to 780 °C at 10 °C/minute are used prior to each deposition. Each deposition is carried out in a vertical chamber under a 112 mTorr pressure using NH_3 and dichlorosilane (SiH_2Cl_2) as precursor gases, respectively introduced in the chamber at 200 sccm and 80 sccm flow rates. By measuring the wafer bow, before and after removing the silicon nitride from the wafer back side, the material morphological characterization revealed a tensile strain around +1200 MPa. Such high tensile strain is a clear indication of the stoichiometry of the material (i.e., minimization of residual hydrogen content), which is, according to our knowledge, the highest tensile strain than all silicon nitrides presented in all prior works. Considering that the high tensile strain of the silicon nitride is an indication of the stoichiometry of the material [6], the high tensile strain of our silicon nitride proves that, following our process, a more stoichiometric silicon nitride can be obtained [6]. Fluoride-based (CF_4-CH_2F_2-O_2) dry etching was used to pattern the Si_3N_4 film previously deposited using 248-nm DUV and 780-nm-thick M78Y resist. In order to avoid the voids formation silicon nitride circuits were then encapsulated by 3-μm-thick SiO_2 cladding layer at 400 °C using high-density plasma-enhanced chemical vapor deposition (PECVD).

The silicon nitride microresonators based on the annealing-free CMOS-compatible process are shown in Fig. 3(b, c). The chips were then continuous-wave pumped via an external C-band EDFA laser + amplifier at 1569 nm wavelength. Quality factors of the microring exceed 600.000, allowing to reach optical parametric oscillation threshold at 80 mW pumping power. Cascaded four-wave mixing (FWM) processes and parametric gain via the anomalous-dispersion-engineered waveguide constituting the microring allow to generate a native-line-spaced OFC counting almost 250 new generated frequencies over a wavelength span of nearly 800 nm (1300 nm - 2100 nm) for P_{in} ~ 1 W. The OFC spectrum is reported in Fig. 3(a).

3. Conclusions

Via such demonstration, we claim the *first-time realization* of annealing-free silicon nitride frequency comb microresonators, following a tailored deposition method, minimizing the hydrogen content. Our annealing-free and crack-free fabrication process provides our devices with the right specification (microring group velocity dispersion and characteristics) to underpin Kerr frequency combs, thus representing a significant step toward the full compatibility of Si_3N_4-based Kerr-comb sources monolithic cointegration with front-end CMOS and Si photonics processing.

Acknowledgements

Authors acknowledge funding from DOPT 2020 program, DNRF-123 Si photonics CoE and the ERC GRAPHICS.

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