Integrated Gallium Nitride Nonlinear Photonics

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Gallium nitride (GaN) as a wide bandgap material is widely used in solid-state lighting. Thanks to its high nonlinearity and high refractive index contrast, GaN-on-insulator (GaNOI) is also a promising platform for nonlinear optical applications. Despite its intriguing optical properties, nonlinear applications of GaN are rarely studied owing to the relatively high optical loss of GaN waveguides (typically ≈2 dB cm⁻¹). In this paper, GaNOI microresonators with intrinsic quality factor over 2.5 million are reported, corresponding to an optical loss of 0.17 dB cm⁻¹. Parametric oscillation threshold power as low as 6.2 mW is demonstrated, and the experimentally extracted nonlinear index of GaN at telecom wavelengths is estimated to be \( n_2 = 1.4 \times 10^{-18} \text{ m}^2 \text{ W}^{-1} \), which is several times larger than that of commonly used platform such as Si₃N₄, LiNbO₃, and AlN. Single soliton generation in GaN is implemented by an auxiliary laser pumping scheme, so as to mitigate the high thermorefractive effect in GaN. The large intrinsic nonlinear refractive index, together with its broadband transparency window and high refractive index contrast, make GaNOI a promising platform for chip-scale nonlinear applications.

1. Introduction

Gallium nitride (GaN) as a wide bandgap material has been extensively investigated for semiconductor lighting over the past decades. Epitaxial growth of GaN on sapphire (GaN/SiO) by metal–organic chemical vapor deposition (MOCVD) is quite mature, and GaN thin films with excellent crystalline quality can be routinely obtained. The refractive index of GaN at telecom wavelengths is about 2.3 and the GaNOI platform offers high refractive index contrast (≈0.6). With a large bandgap of 3.4 eV, GaN exhibits a wide transparency window, ranging from ultraviolet to mid-infrared. In addition, wurtzite GaN is known to be highly resilient against harsh environment, such as high temperature or high optical power. Thanks to its non-centrosymmetric crystal structure, GaN possesses both \( \chi^{(2)} \) and \( \chi^{(3)} \) nonlinearities, which makes it appealing for electrically tuned chip-based photonic applications as well as second-harmonic generation (SHG).

2. Results and Discussion

2.1. The GaN Microring Fabrication

The microring resonator is fabricated on a 1-μm-thick undoped GaN film epitaxially grown on a c-plane sapphire substrate by MOCVD, which uses a 50-nm thick AlN buffer layer formed by magnetron sputtering for improved crystalline quality. The GaN film thickness is so chosen as to ensure strong light confinement in the waveguide as well as high crystalline quality. The GaN film thickness is so chosen as to ensure strong light confinement in the waveguide as well as high crystalline quality. According to high-resolution X-ray diffraction (HR-XRD) measurement, the full-width at half-maximum (FWHM) of the (002) and (102) 2θ-scan for the 1-μm-thick GaN layer is 115.0 and 351.7 arcsec, respectively (see the Supporting Information for more details), indicating high crystalline quality for the GaN film adopted for microring fabrication. The pattern for microring and associated bus waveguide is formed by electron-beam lithography (EBL) with 600-nm-thick hydrogen silsesquioxane (HSQ) as

Previous study[1,2] shows that the nonlinear refractive index of GaN film at telecom wavelengths is \( n_2 = 10^{-18} \text{ m}^2 \text{ W}^{-1} \), which is about an order of magnitude larger than that of conventional platforms, such as Si₃N₄, AlN, and LiNbO₃. These unique properties make GaNOI platform attractive for compact chip-scale nonlinear photonic applications, such as frequency conversion, supercontinuum, and frequency comb generation. However, apart from very limited reports on four-wave mixing (FWM) and frequency conversion,[1,2] nonlinear applications of GaNOI have rarely been investigated up to now. The main barrier is the relatively large optical loss of GaN waveguides, typically on the order of 2 dB cm⁻¹, corresponding to a quality factor \( Q \approx 10^5 \) for microronators.[1,9–11]

In this paper, we report dissipative Kerr soliton (DKS) generation in high-Q factor microring resonators fabricated on GaNOI platform. With optimized chip design as well as chip fabrication process, intrinsic Q factor up to 2.5 million is obtained, corresponding to a waveguide loss of 0.17 dB cm⁻¹, which is an order of magnitude smaller than previous results.[1,9–11] The threshold for parametric oscillation is as low as 6.2 mW, indicating a nonlinear refractive index of \( n_2 = 1.4 \times 10^{-18} \text{ m}^2 \text{ W}^{-1} \).

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hard mask. The microring is then dry etched by inductively coupled plasma (ICP) based on Cl$_2$/Ar/BCl$_3$ mixture. The dry etching process is optimized to ensure smooth etched surface as well as vertical sidewalls.\[9\] It is found that the BCl$_3$ ratio has a crucial impact on etch rate as well as surface morphology. As shown in Figure 1g,h, both the etch rate and the surface roughness decrease with increased BCl$_3$ ratio. However, a BCl$_3$ ratio greater than 40% would lead to angled sidewalls. Consequently, a BCl$_3$ percentage of 30% is adopted, which ensures a moderate etching rate of 295 nm min$^{-1}$ as well as a root-mean-square (RMS) roughness of 0.50 nm, comparable to that of the as-grown GaN film (0.46 nm). The HSQ layer was removed by 40% HF solution after the ICP etching. To avoid the scattering loss owing to voids formed in the top cladding during plasma enhanced chemical vapor deposition (PECVD), an air-clad GaN microring resonator is adopted in this work.\[13\] Finally, the chip was cleaved by an ultraviolet (UV) laser to enable efficient optical coupling. The fabrication process as well as the scanning electron microscope (SEM) images are shown in Figure 1. The SEM images reveal smooth etched surface as well as nearly vertical sidewalls.

Kerr combs based on high-Q microresonators have attracted much attention, and of particular interest are microcombs operating in DKS states, which enable a variety of applications such as low phase-noise microwave generation, optical frequency synthesis, and photonic radar.\[14\] DKS generation normally requires microresonators with anomalous dispersion. However, similar to most materials, GaN exhibits normal material dispersion at telecom wavelengths. The microresonator therefore needs to be dispersion-engineered by adjusting the ring waveguide geometry to meet the dispersion requirement. The simulated dispersion profiles for TE$_{00}$ and TM$_{00}$ modes in a 60-$\mu$m-radius GaN microring are shown in Figure 2d. Broadband anomalous dispersion for both TE$_{00}$ and TM$_{00}$ is secured with 2.25-$\mu$m waveguide width and 730-nm etching depth. The mode profiles shown in the inset of Figure 2a indicate strong light confinement, with a mode area of 1.4 and 1.6 $\mu$m$^2$ for TE$_{00}$ and TM$_{00}$, respectively. A schematic of the GaNOI microring is shown in Figure 2a. Pulley coupled bus waveguide with a width of 1.1 $\mu$m and a coupling gap of 650 nm is adopted to realize efficient coupling. The width of the bus waveguide is expanded to 3.3 $\mu$m at both facets via a 400-$\mu$m-long taper section to reduce the fiber-to-chip coupling loss. The measured transmission spectra of the GaNOI microring are shown in Figure 2b,c, which shows a free spectral range (FSR) of 330 and 324 GHz for TE$_{00}$ and TM$_{00}$ modes, respectively. The insertion loss is estimated to be 3.7 dB per facet for both TE$_{00}$ and TM$_{00}$ modes. The measured and fitted resonance curves for TM$_{00}$
mode at 1550 nm are shown in Figure 2e. The extracted intrinsic Q factors are $2.5 \times 10^6$ and $1.8 \times 10^6$ for TE$_{00}$ and TM$_{00}$ modes, respectively. The intrinsic quality factor of our GaN microresonator is comparable to that commonly attainable with Si$_3$N$_4$ or LiNbO$_3$ platform.

2.2. Chaotic and Auxiliary Laser Assisted Soliton Comb

Parametric oscillation in the GaN microring occurs when continuous wave pump light with sufficient power is tuned into resonance. The $\chi^{(3)}$ nonlinearity of GaN material can be extracted by measuring the parametric oscillation threshold $P_{th}$ (see the Supporting Information for more details). The parametric oscillation threshold is estimated to be 6.2 mW, corresponding to a nonlinear refractive index $n_2 = 1.4 \times 10^{-18}$ m$^2$ W$^{-1}$. This value is consistent with previously reported results.[1]

Broadband optical frequency comb can be generated with the dispersion-engineered high-Q GaN microresonator. Octave-spanning chaotic comb is recorded at high pump power (on-chip power $\approx 560$ mW), ranging from 125 to 250 THz (see the Supporting Information for more details). In addition to Kerr comb lines, peaks arising from stimulated Raman scattering (SRS) can also be identified, corresponding to excitation of E$_2$(high) and A$_1$(TO) phonons in the wurtzite crystal.[15]

Such chaotic comb exhibits high noise and corresponds to blue-detuned pump laser with respect to the hot cavity mode. Low noise comb in DKS regime corresponds to red-detuned pump laser with respect to resonance, and requires overcoming
Figure 3. a) Experimental setup for DKS generation in a GaN microresonator. Circulators are used to separate light entering and exiting the GaN microring resonator (MRR). TLS, tunable laser; EDFA, erbium-doped fiber amplifier; OSA, optical spectrum analyzer; OSC, oscilloscope; PC, polarization controller; ILP, inline-polarizer; SW, optical switch. b) Converted comb power trace recorded with a scan speed of 1 nm s$^{-1}$. c) Observed soliton-step duration for various sweep speeds. Optical spectrum and RF noise spectrum of single comb line for d) chaotic comb and e) single-soliton comb. The 3 dB band width of the single soliton is $\approx 50$ nm with an FSR of 324 GHz.

Transient thermal effects induced by the sharp reduction in intra-cavity power during transition to soliton states.\cite{14} Such thermal instability is particularly pronounced in materials with high thermorefractive coefficient $dn/dT$ (e.g., $\approx 3.6 \times 10^{-4}$ K$^{-1}$ for AlGaAs), thus rendering soliton states thermally inaccessible.\cite{16,17} GaN is reported to exhibit a thermorefractive coefficient $\approx 10^{-4}$ K$^{-1}$ at telecom wavelengths,\cite{18} comparable with that of AlGaAs. Previously, soliton generation in high $dn/dT$ material is reported by reducing the thermorefractive coefficient through cryogenic cooling,\cite{16} which severely limits its use in many practical applications. Here, we adopt auxiliary laser pumping scheme to mitigate thermal instability\cite{13,19,20} in a GaN microresonator and stably access soliton states at room temperature.

The experimental setup for soliton generation is shown in Figure 3a. First, the influence of thermal effects on soliton-step duration is investigated. Soliton-steps in the GaNOI microresonator
are captured by fast sweeping the pump laser across the resonance. The converted comb power trace recorded with a pump laser of 120 mW at a sweep speed of 1 nm s⁻¹ is shown in Figure 3b, while the soliton-steps obtained with different sweep speeds are plotted in Figure 3c. The soliton-step is extremely short (∼60 ns) and remains basically unvaried as the scan speed is increased by 50-fold, indicating strong thermal effects in GaN microcavity resonator during soliton transition.[21] To mitigate the significant thermal effects, light from an auxiliary laser is counter-coupled into the GaN microcavity. When the auxiliary laser is adequately positioned with respect to the resonance, thermal instability induced by intracavity power drop can be compensated, and the total intracavity power remains nearly unvaried as the pump laser is swept to the red-detuned regime, thus enabling stable access to soliton states.[11,19,20] Although the auxiliary laser is effective in compensating the thermal effects, too high an auxiliary laser power would lead to the generation of broadband comb lines, which cannot be mitigated by the in-line polarizer (ILP) owing to its limited bandwidth.

In our experiment, the pump laser is TM-polarized while the auxiliary laser is TE-polarized. Both modes are in nearly critical coupling regime and offer efficient thermal compensation. Adopting orthogonally polarized pump and auxiliary lights allows simple separation of the DKS comb from the reflected auxiliary comb with an in-line polarizer. The on-chip power for both the pump and the auxiliary lasers is estimated to be 136 mW. Soliton state is accessed by fine adjusting the detuning and power of both pump and auxiliary lasers (see the Supporting Information for more details). As shown in Figure 3e, the single-soliton comb features an optical spectrum with a smooth sech² envelope as well as low RF noise. For comparison, the optical and RF noise spectra for the chaotic state are plotted in Figure 3d. It is seen that the chaotic comb exhibits high noise below 2 GHz. Furthermore, simulations based on Lugiato-Lefever equation (LLE)[22] show good agreement with the experimental results (see the Supporting Information for more information).

Compared with soliton generation at cryogenic temperature, the auxiliary laser pumping offers simple and stable access to soliton states in high thermorefractive coefficient materials. In addition, the cryogenic cooling scheme is plagued by a limited pump power window over which soliton states are thermally accessible, as the thermorefractive coefficient increases with the pump power.[16] On the other hand, soliton generation in a dual-pumped microcavity is not limited by such pump power window, as long as the thermal effects are effectively mitigated by the auxiliary laser (see the Supporting Information for more details).

Table 1. Properties of nonlinear platforms for chip-scale frequency comb generation operating at telecom wavelengths.

| Material          | n   | 𝛾 (2) [pm V⁻¹] | n₂ [10⁻¹⁸ m² W⁻¹] | λTPA [nm] | Mode area [μm²] | FSR [GHz] | Qₙ [× 10⁶] | Pₐ [mW] | Remarks         |
|-------------------|-----|----------------|-------------------|-----------|----------------|-----------|-------------|--------|----------------|
| Al₂Ga₃As₅[2]       | 3.3 | 180            | 26                | 1483      | 0.28           | 1000      | 1.5         | ≈ 0.03 | Bonding        |
| Si₃N₄[4]          | 2   | 0.25           | 0.6              | 440       | 2.3            | 435       | 0.8         | 25     | MOCVD growth   |
| AlN[3,5]          | 2.1 | 6              | 0.23             | 440       | 0.3            | 435       | 0.8         | 25     | Bonding        |
| Diamond[6]        | 2.4 | 0.82           | 0.22             | 450       | 0.81           | 925       | 0.97        | 20     | Bonding        |
| GaN[27]           | 3.1 | 82             | 11               | 1100      | 0.15           | 250       | 0.2         | 3      | Bonding        |
| LiNbO₃[7]         | 2.2 | 54             | 0.18             | 635       | 1              | 200       | 0.4         | 4.2    | Bonding        |
| ChG[28]           | 2–3 | –              | –                | 3         | 1.7            | 133       | 1.3         | 5.4    | OPO            |
| Si₃N₄[5,6]        | 2.6 | 6              | 0.8              | 827       | 1              | 260       | 7.1         | 8.5    | 4H-SiC, microdisk |
| GaN (this work)   | 2.3 | –9[b]         | 1.4              | 729       | 1.6            | 324       | 1.8         | 6.2    | MOCVD growth   |

[b] 𝛾 (2) corresponds to two-photon absorption induced cutoff wavelength of the material. [a] The value of 𝛾 (2) can be found in ref. [3].
Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
Research data are not shared.

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