Ultra-high Q Microring Resonators on Gallium-nitride-on-sapphire Platform

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***Abstract*—We demonstrate record microrings on GaNOI platform with small mode area and ultra-high *Q* (4×10^6) by optimizing the device design and fabrication process, corresponding to a propagation loss of 0.1 dB cm^{-1}.**

***Keywords*—Nonlinear optics, microresonator, Kerr frequency comb, gallium nitride.**

I. Introduction

Integrated microresonators with high quality factor (Q) and small mode volume are widely used in nonlinear optics and quantum applications, such as optical frequency combs, dissipative Kerr solitons, self-injection locking and quantum light sources. Microresonators with millions of Q factor have been realized on various platforms, such as Si_3N_4 [1], $LiNbO_3$ [2,3], AlGaAs [4] and AlN [5]. Gallium nitride (GaN) as a wide bandgap semiconductor (E_g = 3.44 eV) exhibits wide transparency window, high refractive index contrast ($n \sim 2.3$) and high nonlinear coefficient ($n_2 = 1.4\times10^{-18}$ m^{2}W^{-1}), which is about an order of magnitude larger than conventional platforms [6]. GaN-on-sapphire (GaNOI) is a novel and versatile platform for integrated nonlinear optics, and has also great potential in quantum applications. Partially etched high Q GaN microrings have been demonstrated by inductively coupled plasma (ICP) dry etching [6,7], enabling the generation of low threshold frequency combs and dissipative Kerr solitons. In order to realize more compact devices and improve the light confinement, fully etched GaN microrings with reduced GaN film thickness and enhanced Q factor are desirable.

In this work, we demonstrate fully etched GaN microring resonators on 700-nm-thick GaN film on sapphire substrate, which exhibit smaller mode area due to enhanced light confinement. By further optimizing the device structure and the fabrication process, the fabricated GaN microrings exhibit ultra-high intrinsic Q factors up to 4×10^6, corresponding to a propagation loss ~ 0.1 dB cm^{-1}. Such a high Q GaNOI platform is attractive for integrated nonlinear optics and quantum photonics.

II. Device Dessign and Fabrication

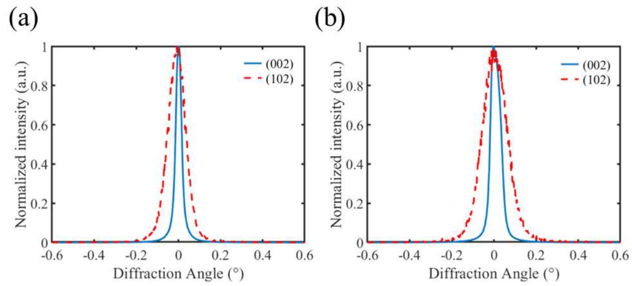

Fig.1. (a),(b) XRD rocking curves of 1-μm and 700-nm thick GaN films along (002) and (102) directions.

The GaN thin film is grown on c-plane sapphire substrate by metal organic chemical vapor deposition (MOCVD). A 50-nm-thick AlN buffer layer is adopted to improve the crystalline quality of the GaN film. Two GaNOI wafers with GaN film thickness of 1 μm and 700 nm are grown. The X-ray diffraction (XRD) rocking curve measurement reveals their full-width at half-maximum (FWHM) along the (002) direction to be 115 arcsec and 207 arcsec, respectively, as shown in Figs. 1(a) and 1(b). The 1-μm-thick GaN film exhibits improved crystalline quality, as the threading dislocations (TDs) due to lattice mismatch between the GaN layer and the substrate reduces with the epitaxial layer thickness. In our previous work, partially etched microrings were fabricated on the 1-μm-thick GaN film. In this work we adopt the 700-nm-thick GaN film for fully etched microring resonator fabrication, as it offers enhanced optical confinement crucial for efficient nonlinear optics. To obtain smooth etched surface as well as vertical waveguide sidewalls, we optimized the ICP etching conditions based on $Cl_2/Ar/BCl_3$ mixture. The adopted parameters for ICP dry etching are as follows: $Cl_2 : Ar : BCl_3$ = 24 sccm : 12 sccm : 9 sccm, while the ICP power and the RF bias are kept at 500 W and −300 V, respectively. The resulting etch rate is about 260 nm/min. We employ atomic force microscopy (AFM) to characterize the surface morphology of the GaN surface before and after etching, and the root-mean-square (RMS) roughness after etching is about 0.3 nm over 5×5 μm^2, better than that of the as-grown GaN film (0.5 nm), as shown in Fig. 2(a).

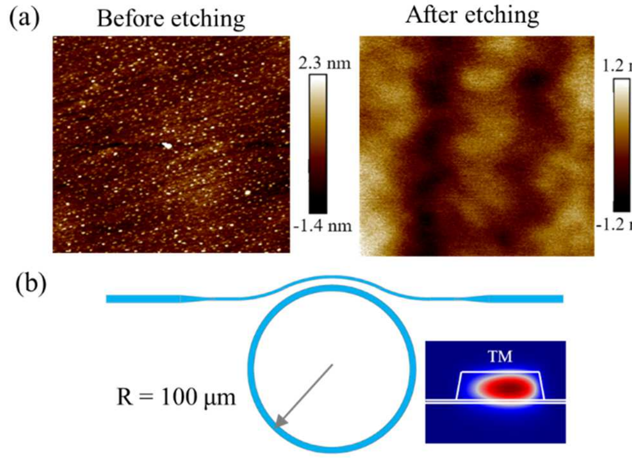

Fig.2.(a) AFM images of the GaN film surface before and after ICP dry etching. (b) Top view of the GaN microring.

The schematic of the air-clad GaN microring is shown in Fig. 2(b). The cross-section of the 100-μm radius GaN ring waveguide is 2×0.7 μm^2 with fully etched structure. The effective optical area of the TM mode is about 0.78 μm^2, which results in improved optical mode confinement compared with the partially etched structure reported in our previous work (~1.6 μm^2) [6]. Pulley coupling scheme with a pulley angle of 10° is employed to ensure sufficient coupling coefficient. The microring pattern is formed by electron-beam-lithography (EBL) with HSQ as hard mask, and transferred onto the GaNOI by ICP dry etching. A 20-nm-thick aluminum oxide (Al_2O_3) layer is deposited by atomic layer deposition (ALD) over the GaN waveguide to reduce the scattering loss of the sidewalls. The chip is cleaved by ultra-violet laser to enable efficient coupling with lensed fibers.

III. Device performance

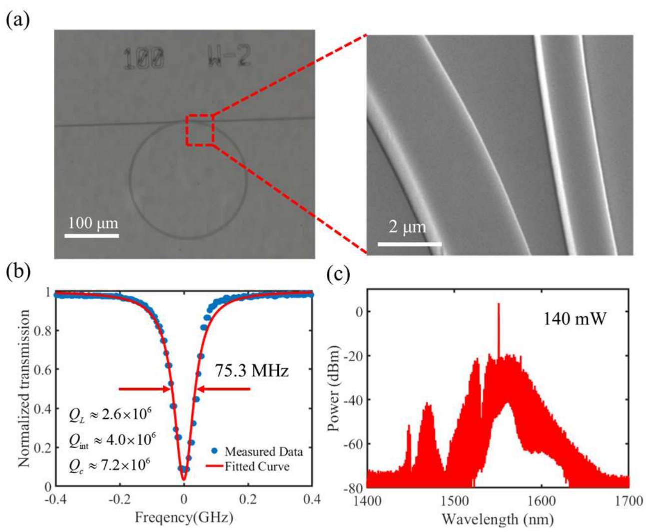

Fig.3. (a) Microscope and SEM images of the GaN microring. (b) TM_{00} mode resonance at 1563 nm. (c) Chaotic frequency comb spectrum.

The microscope and the SEM images of the fabricated GaN microrings are show in Fig. 3(a). The etched GaN waveguide exhibits smooth sidewalls. A tunable laser (Santec TSL-510) and lensed fibers are employed to characterize the GaN microrings. The measured free spectral range (FSR) of the fundamental TM mode is about 193 GHz, in good agreement with our simulation results. The insertion loss is estimated to be 4 dB/facet. The spectrum of a typical resonance at 1563 nm is shown in Fig. 3(b), and the fitted FWHM is about 75.3 MHz. The loaded and intrinsic Q factors are extracted to be 2.6×10^6 and 4.0×10^6, respectively, corresponding to a propagation loss of 0.1 dB cm^{-1}, which is the highest intrinsic Q factor for GaN microresonators reported so far. The spectrum of the frequency comb generated with an on-chip pump power about 140 mW is shown in Fig. 3(c).

IV. Summary

A record ultra-high Q microring resonator with small mode area on GaNOI platform are demonstrated. The extracted intrinsic Q factor is about 4×10^6, which is comparable to that of microrings fabricated on other conventional material platforms. Benefitted from its high Q factor and small mode area, the GaNOI microresonator is promising for a wide range of applications in integrated nonlinear optics and quantum optics.

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