Optical resonance modes in InGaN/GaN multiple-quantum-well microring cavities

K. C. Zeng, L. Dai, J. Y. Lin, and H. X. Jiang[a)]
Department of Physics, Kansas State University, Manhattan, Kansas 66506-2601

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Microrings of varying sizes have been fabricated from $In_xGa_{1-x}N$/GaN ($x\sim 0.15$) multiple quantum wells (MQWs). Photolithography and dry etching techniques including both ion-beam and inductively coupled plasma etching were employed to pattern the III–nitride MQW microrings. Individual microrings were optically pumped and optical resonance modes were observed. The observed mode spacings were consistent with those expected for whispering-gallery (WG) modes within a resonant cavity of cylindrical symmetry, refractive index, and dimensions of the rings under investigation. The results obtained from the microring cavities were compared with those of the III–nitride MQW microdisk cavities. Our results have indicated that resonance modes corresponding to the radial and the WG modes are simultaneously present in microdisk cavities, but only WG modes are available from the microring cavities. Implications of our results on future GaN-based microcavity light emitters have been discussed. © *1999 American Institute of Physics.* [S0003-6951(99)04743-9]

The recent success of III–nitride edge emitters including super-bright blue light-emitting diodes (LEDs) and laser diodes (LDs) (Ref. 1) is encouraging for the study of microcavity LDs and micro-LEDs. Microcavity light emitters are of interest for fundamental studies of cavity quantum electrodynamics as well as for their unconventional lasing characteristics which offer several benefits over the edge-emitting devices, including enhanced quantum efficiency and reduced lasing threshold, due to the confinement of optical modes within the cavities.[2] Micro-LEDs and microcavity LDs are also of high interest for microdisplay, imaging, scanning, optical parallel interconnection, and ultraparallel optoelectronics applications. Several types of microcavities, including microdisk, micropyramid, and microprism cavities, have already been fabricated recently within the III–nitride system.[3–10] For GaN/AlGaN multiple quantum wells (MQWs), the intrinsic optical transitions from both the well and the barrier regions were found to exhibit an approximate tenfold increase in recombination lifetime and quantum efficiency upon formation of microdisks.[3] Optical resonance-mode behaviors were also observed in GaN/AlGaN and InGaN/GaN MQW microdisk cavities and also in GaN micropyramid cavities.[5,6] Room-temperature lasing action with optical pumping in GaN micropyramids has been demonstrated recently.[7]

For a microring cavity, one expects to observe the whispering-gallery (WG) mode,[11] which is described by Bessel functions $J_m(\chi)$ for large m. The WG mode in the microring may be thought of as the light propagation inside the ring which is facilitated by total internal reflection. The periodic boundary condition imposed on the circulating wave gives an effective optical path of $2\pi Rn$, where R and n are the radius and refractive index of the ring, respectively. In this letter, we report the fabrication and optical studies of InGaN/GaN MQW microrings. We show that the WG resonance modes were indeed observed when individual microrings were optically pumped under high-excitation intensities, and the mode spacing was found to be consistent with calculation results.

The InGaN/GaN MQW structure used for this study was grown on (0001) sapphire substrates by metal–organic chemical-vapor deposition (MOCVD) and consisted of a 50 nm GaN buffer layer followed by a 20 period of 45 Å/45 Å $In_xGa_{1-x}N$/GaN ($x\sim 0.15$) MQW and a GaN capping layer. All layers were grown nominally undoped. Photolithography and dry etching were used to pattern arrays of microrings with varying diameters and separation spacings. Two different dry etching techniques were employed. In the early phase of our studies, ion-beam etching was used to prepare III–nitride microstructures. Most recently, the authors' laboratory is employing the inductively coupled plasma (ICP) etching technique to pattern the III–nitride microstructures. ICP etching has been shown to be very effective for GaN etching with high etch rate but minimal ion damage.[12] Figure 1 shows a schematic diagram of the InGaN/GaN MQW microrings. The samples were etched into the sapphire substrate so that no III–nitride material is present between the microstructure. Figure 2 shows the scanning electron microscopy (SEM) images of representative InGaN/GaN MQW micro-

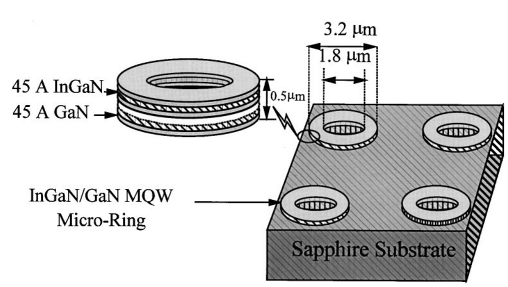

FIG. 1. Schematic diagram of representative InGaN/GaN MQW microring fabricated by photolithography patterning and dry etching.

[a)]Electronic mail: jiang@phys.ksu.edu

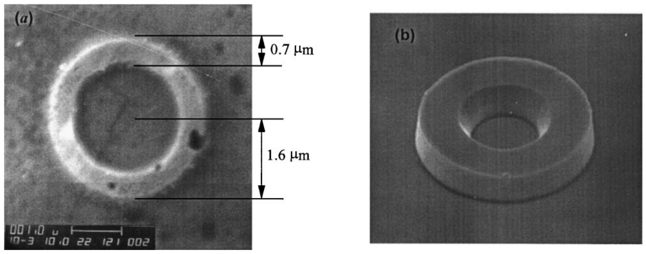

FIG. 2. Scanning electron microscopy (SEM) images of an InGaN/GaN MQW microring fabricated by (a) ion-beam etching and (b) inductively coupled plasma (ICP) etching. Ion-beam etching-induced damage are observable in the cap layer of the ring in (a).

rings prepared by (a) ion-beam and (b) ICP etching. In microrings prepared by ion-beam etching, etching-induced damages are evident. However, the ion-beam etching-induced defects do not inhibit cavity-mode behavior since these defects were only observed on the top capping layer and the optical-mode behaviors are determined by the quantum wells which are buried underneath the capping layer. An UV objective was used in a confocal geometry to optically pump a single microring normal to the sample surface and to collect the emitted light in the direction of the surface normal. The excitation laser and photoluminescence (PL) detection system have been described elsewhere.[13] A focused laser beam spot with a diameter as small as 1 μm was achieved with the objective lens.

A PL emission spectrum obtained at 10 K from the InGaN/GaN MQWs prior to the microring fabrication is plotted in Fig. 3(a), where the emission line at 3.470 eV originates from the GaN barriers. The emission line at 3.288 eV originates from the InGaN wells. The emission lines at 3.198 and 3.108 eV are the one- and two-phonon replicas of the 3.288 eV emission line. An optical emission spectrum measured at 10 K under high pumping intensity for an individually pumped InGaN/GaN MQW microring with an outer diameter of 3.2 μm and inner diameter of 1.8 μm is shown in Fig. 3(b), in which a strong optical-mode behavior is

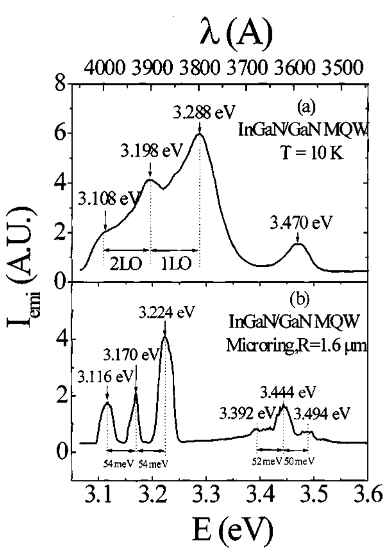

FIG. 3. Low-temperature (10 K) optical emission spectrum from (a) an InGaN/GaN MQW sample prior to microring fabrication; (b) an InGaN/GaN MQW microring with an outer diameter of 3.2 μm and a ring width of about 0.7 μm. Optical resonance modes of the WG-mode type are observed in the microring in (b).

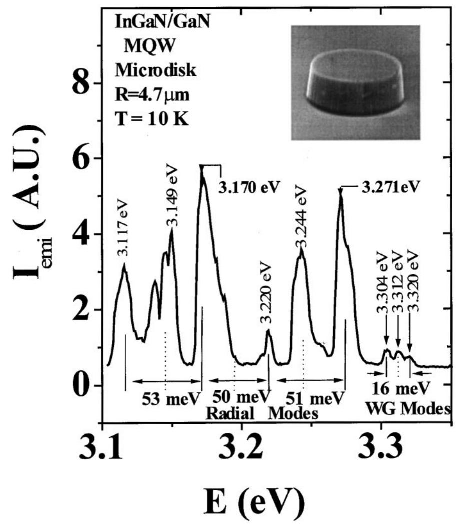

FIG. 4. Optical emission spectrum of an InGaN/GaN MQW microdisk with a diameter of 9.4 μm. Both the WG and radial modes are observed in the microdisks.

clearly evident. Three strong emission lines at 3.116, 3.170, and 3.224 eV, exhibiting a mode spacing of 54 meV, are attributed to WG modes.

The WG mode has a low optical loss due to a total internal reflection, and thus, low threshold for lasing. The effective optical path of $2\pi Rn$ imposed by the periodic boundary condition results in WG eigenmode conditions of

$$2\pi Rn = m\lambda, \quad \text{for large (integer) } m, \tag{1}$$

from which the mode spacing is given by

$$\Delta\lambda_{WG} = \lambda^2/2\pi Rn, \tag{2}$$

or in the energy spectrum by

$$\Delta E_{WG} = hc/2\pi Rn, \tag{3}$$

where h is the Planck constant and λ is the wavelength of light propagating inside the ring cavity. Thus, the calculated mode spacing according to Eqs. (2) and (3) is $\Delta\lambda_{WG} \approx 60$ Å (at $\lambda = 3950$ Å) or $\Delta E_{WG} \approx 50$ meV, by taking $R \approx 1.5$ μm and $n = 2.6$,[14] which agrees reasonably well with the observed mode spacing.

The three peaks at 3.392, 3.444, and 3.494 eV in the high-emission energy region, exhibiting mode spacings of 52 and 50 meV, are also WG modes in accordance with Eqs. (2) and (3). The full width at half maximum (FWHM) of the resonance peaks is between 20 and 28 meV, which is attributed to the width of the microring as well as to the imperfection of the ring walls. From Eqs. (2) and (3), the FWHM of the resonant modes is

$$|\Delta(\Delta_{WG})| = (\lambda^2/2\pi R^2 n)\Delta R = (\Delta R/R)\Delta\lambda_{WG}. \tag{4}$$

In the energy spectrum, the FWHM is given by

$$\Delta(\Delta E_{WG}) = \Delta[(hc/\lambda^2)\Delta\lambda_{WG}] = (\Delta R/R)\Delta E_{WG}. \tag{5}$$

The calculated FWHM of the WG resonance modes from Eq. (5) is $(\Delta R/R)\Delta E_{WG} = (0.7/1.6) \times 54 \approx 24$ meV, which agrees well with the observed value between 20 and 28 meV.

InGaN/GaN MQW microdisks have also been fabricated. The inset of Fig. 4 shows a SEM image for one such microdisks fabricated by ICP etching. In comparison with the microring cavities, a sharp feature of the microdisk cavities is that they can also support an additional resonance-mode type which is described by Bessel functions $J_m(\chi)$ with $m=-1,0,1$ within the microdisk cavity. These modes are dominated by the photon-wave motion along the radial direction of the disks, which we refer to as the radial modes.[5] As illustrated in Fig. 4, in which an optical emission spectrum from an individually pumped InGaN/GaN MQW microdisk (with a 9.4 μm diam) is shown, the InGaN/GaN MQW disk exhibits simultaneously the radial mode with a spacing of about 25 meV and the WG mode with a spacing of about 8 meV. A ratio of the radial-mode spacing to the WG-mode spacing of about π is observed and is expected.[5] Another noticeable feature is that the FWHM of the WG modes exhibited by the microrings is much wider than those of the radial and WG modes in the microdisks, mainly due to the finite width of the ring. However, unique features of the microring cavities include that high-Q values can be obtained relatively easily from the WG mode even in a very small mode volume and the number of modes contributing to lasing is reduced.[15]

In summary, arrays of $In_{0.15}Ga_{0.85}N$/GaN MQW microrings have been fabricated by photolithography patterning and dry etching. Whispering-gallery modes in individually optically pumped $In_{0.15}Ga_{0.85}$/N/GaN MQW microring cavities have been observed. Optical resonance mode behaviors have been compared for the GaN-based microdisk and microring cavities. The presence of the whispering-gallery cavity modes in the InGaN/GaN MQW microrings is a clear indication that III–nitride microring cavity laser is also a possible microcavity laser geometry and that the GaN-based microring laser arrays may also be achieved.

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