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## Lasing characteristics of a GaN photonic crystal nanocavity light source

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Lasing characteristics from photonic crystal defects fabricated on bulk GaN are investigated. The device demonstrates multimode lasing with linewidths as narrow as 2–3 Å, and an enhanced spontaneous emission factor  $\beta \sim 0.045$ . The emission spectra indicate that the laser emission is initiated horizontally in the defect nanocavity and then coupled to the vertical radiation, possibly via photonic crystal Bloch modes or by scattering. © 2007 American Institute of Physics.

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Since GaN and its alloys have become the dominant materials for UV to blue-green semiconductor light sources, much effort has been made on improving the light emission characteristics using photonic crystals (PCs).<sup>1,2</sup> Recent studies of PC structures incorporated in GaN-based light sources have generated many promising results, most prominently enhanced light extraction<sup>3,4</sup> and high  $Q$  cavities.<sup>5</sup> Laserlike emissions via optical excitation have been observed from both the PC membrane nanocavities<sup>5</sup> and the PCs<sup>6</sup> fabricated on InGaN/GaN quantum wells and bulk GaN, respectively. However, the emission linewidths of the reported devices were in the range of 1–2 nm. In this letter, we demonstrate a nonmembrane type, GaN PC nanocavity device that shows multimode lasing characteristics at  $\lambda = 372$  nm with linewidths as narrow as 2–3 Å and an enhanced spontaneous emission factor  $\beta \sim 0.045$ . The lasing and output coupling mechanisms are investigated. Such PC nanocavity emitter has shown great potential in realizing ultraviolet light sources with high efficiency and high spectral purity.

The device structure, schematically shown in Fig. 1(a), was grown by metal-organic chemical vapor deposition (MOCVD) on a  $c$ -plane sapphire substrate. A 30-nm-thick GaN nucleation layer was grown at 550 °C, followed by a 2- $\mu\text{m}$ -thick Si-doped GaN layer grown at 1000 °C. The measured photoluminescence (PL) intensity peaked at  $\lambda = 363$  nm for GaN bulk materials. The PCs with a triangular lattice of air holes were defined and fabricated by electron-beam lithography and inductively coupled plasma etching, with  $\text{SiN}_x$  serving as the etch mask. The nanocavity region, the so-called H2 defect, consists of seven missing air holes, where six defects encircle a center point defect. We have fabricated devices with various nanocavity sizes, namely, the H1, H2, and H3 defects. Each PC pattern has an area of  $\sim 30 \times 30 \mu\text{m}^2$  with the lattice constant  $a = 200$  nm and the radius of air holes  $r$  ranging from 55 to 60 nm for different samples. The etch depth is  $\sim 120$  nm. Figure 1(b) shows the top-view scanning electron micrograph (SEM) of a fabricated PC H2 defect nanocavity. It is important to note that

the photonic band gap for transverse electric (TE) modes is far away from the PL wavelengths of bulk GaN, and thus does not contribute to the light emission of this device.

The device characterization was performed at room temperature using a scanning optical microscopy system,<sup>7</sup> which included an optical excitation source using the third harmonics of a Nd:YVO<sub>4</sub> pulse laser ( $\lambda = 355$  nm) with a pulse width of 0.5 ns and a repetition rate of 1 kHz, a 40 $\times$  microscope objective with numerical aperture = 0.32, and an UV-enhanced charge-coupled device (CCD) spectrometer with spectral resolution of 1 Å. The pump beam was focused to a spot size of 3  $\mu\text{m}$  on the H2 defect region and the PC region. The measured emission is TE polarized. However, in order to avoid the detrimental thermal effects on the device due to the highly focused laser beam, the spectral properties of the PC nanocavity emitters were characterized with an off-focus excitation condition, corresponding to a beam spot size of 40  $\mu\text{m}$ .

The emission spectra were analyzed at different pump pulse energies up to a maximum of 0.95  $\mu\text{J}$ . As shown in Fig. 2, multiple emission peaks were observed at the wavelengths  $\lambda = 371.3, 371.8,$  and 374 nm. The emission from deep donor levels to the valence band can be seen at  $\lambda = 380$  nm.<sup>8</sup> The inset of Fig. 2 shows the emission spectrum

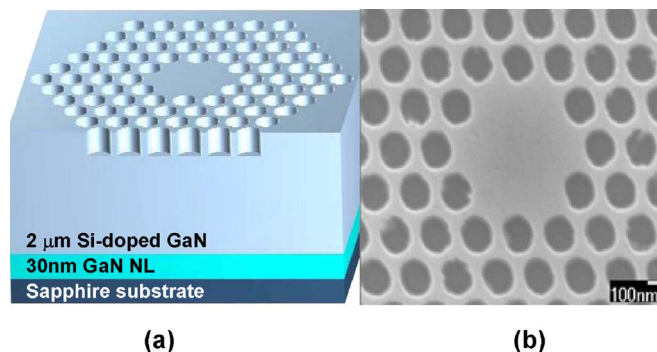


FIG. 1. (Color online) (a) Schematic of the MOCVD-grown device structure. The PC nanocavity was fabricated in the bulk GaN with the etch depth of 120 nm. (b) The top-view SEM image of a PC H2 defect nanocavity with the lattice constant  $a = 200$  nm and the radius of air holes  $r = 60$  nm.

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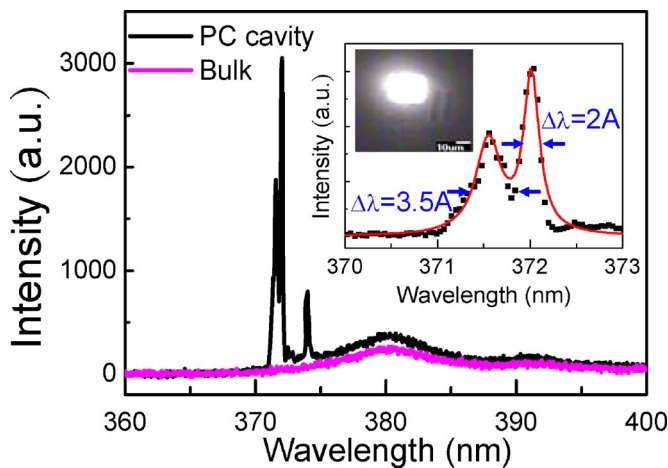


FIG. 2. (Color online) Microphotoluminescence spectrum from a GaN H2-defect nanocavity. The device exhibits multimode emission at  $\lambda = 371.3, 371.8,$  and  $374$  nm. The FWHM is found to be  $\Delta\lambda = 3.5,$  and  $2$  Å for  $\lambda = 371.3$  and  $371.8$  nm, respectively, obtained by a Lorentzian curve fitting, as shown in the inset. A near-field image taken by a CCD camera with a spectral resolution of  $60$  nm/pixel is also shown in the inset.

at the pump pulse energy of  $0.25$   $\mu\text{J}$ . The full width at half maximum (FWHM) was obtained by Lorentzian curve fitting and found to be  $\Delta\lambda = 3.5$  and  $2$  Å for  $\lambda = 371.3$  and  $371.8$  nm, respectively. Since there are shoulder features around the lasing peaks which cannot be fitted well with Lorentzians, the FWHMs could be limited by the resolution of the CCD spectrometer. The inset also shows a near-field image taken by a CCD camera with a spectral resolution of  $60$  nm/pixel. Although, the intensity distribution cannot be resolved in the nanocavity, laser emission was only observed when the excitation beam was focused on to the defect region. Only spontaneous emission (SpE) was observed from the PC or bulk region.

As the emission intensity was plotted versus the excitation at one of the lasing wavelengths,  $\lambda = 371.3$  nm, a soft turn-on behavior was observed, as shown in Fig. 3. The threshold pump pulse energy is found to be  $0.15$   $\mu\text{J}$ , corresponding to the excitation energy density of  $\sim 12$  mJ/cm<sup>2</sup>. The carrier density at the threshold is estimated to be  $\sim 1.8 \times 10^{22}$  cm<sup>-3</sup>, assuming a quantum efficiency of 10%. After

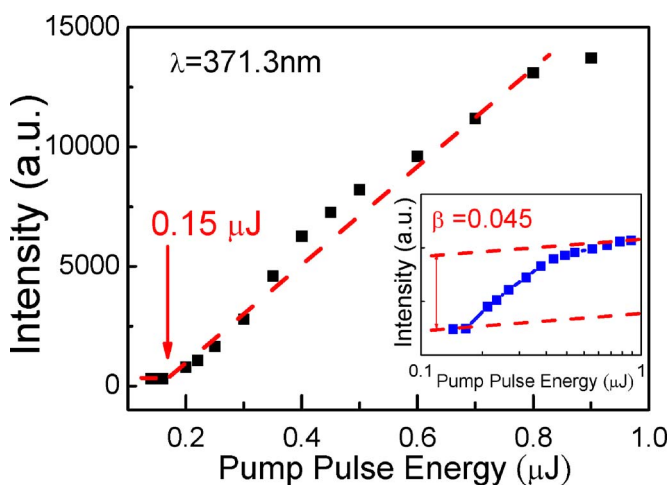


FIG. 3. (Color online) Output intensity vs. the excitation energy at one of the lasing wavelengths,  $\lambda = 371.3$  nm. Lasing occurred at a threshold of pulse energy of  $\sim 0.15$   $\mu\text{J}$ . The spontaneous emission factor  $\beta$  was calculated to be  $\sim 0.045$ , as shown in the inset.

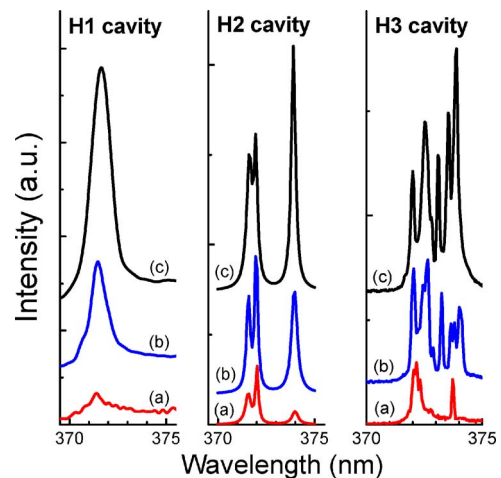


FIG. 4. (Color online) Emission spectra from PC nanocavities of different sizes, denoted as H1, H2, and H3 cavities at three different pumping levels: (a)  $0.25,$  (b)  $0.4,$  and (c)  $0.6$   $\mu\text{J}$ . The H1 defect shows only stimulated emission at  $\lambda = 371.5$  nm with a FWHM  $\sim 2$  nm, while the spectra of H2 and H3 defects show multiple lasing peaks with FWHMs in the order of angstroms. All emission peaks occur between  $371$  and  $374$  nm.

lasing, the output intensity monotonically increases with the increase of the excitation energy. Moreover, as shown in the inset of Fig. 3, the SpE factor ( $\beta$ ) of the GaN PC nanocavity is calculated to be  $\sim 0.045$  at  $\lambda = 371.3$  nm, obtained by normalizing the threshold intensity to be equivalent to one photon output at the threshold.<sup>9</sup> The estimated  $\beta$  is comparable to that of the surface-emitting vertical cavity lasers. Since  $\beta$  is depicted by the coupling efficiency of the total SpE to one of the lasing peaks, we believe that this enhancement is mainly attributed to the reduced modal volume in the nanocavity. Analysis of the other lasing mode at  $\lambda = 371.8$  nm gives rise to the same order of magnitudes in an estimated threshold and  $\beta$ .

In order to clarify the lasing mechanism, we compared the emission spectra from PC nanocavities of different sizes, denoted as H1, H2, and H3 cavities, at three different pumping levels, corresponding to (a)  $0.25,$  (b)  $0.4,$  and (c)  $0.6$   $\mu\text{J}$ , as shown in Fig. 4. The spectrum of H1 defect shows only stimulated emission at  $\lambda = 371.5$  nm with a FWHM  $\Delta\lambda \sim 2$  nm, while the spectra of H2 and H3 cavities exhibit multiple emission peaks with FWHMs in the order of angstroms. Since the three cavities share the same vertical structure, lasing is believed to be originated horizontally due to total internal reflection. The multiple cavity modes could be the superposition of longitudinal modes resulting from different resonance paths in the nanocavities. Moreover, as seen in Fig. 4, the emission peaks from three different nanocavities only occur within a narrow wavelength range of  $3$  nm, between  $371$  and  $374$  nm. Since this range barely overlaps with the PL of bulk GaN, it is important to further investigate the output coupling mechanisms and the origins of the narrow emission wavelength range.

Enhanced coupling of the guided modes to vertical radiation via photonic crystal Bloch modes has been reported.<sup>10</sup> The PC assists in vertical light emission by phase matching the horizontally guided modes to the radiation modes above the light line. The most efficient coupling occurs at the eigenfrequencies with zero in-plane wave vector, denoted as  $\Gamma$  point in the calculated band diagram. A calculated two-dimensional band diagram with refractive index,

$n=2.5$  and  $r/a=0.28$ , shows a few eigenfrequencies, lying between  $a/\lambda=0.535$  and  $0.55$  at  $\Gamma$  point, corresponding to wavelengths between  $\lambda=363$  and  $374$  nm. Further calculations of the photonic density of state near the vicinity of  $\Gamma$  point confirm that the enhanced light extraction is possible, and also the strongest near the lasing wavelengths, but does not limit the light emission to a narrow wavelength range of  $3$  nm.

On the other hand, it has been shown that surface-emitting stimulated emission from GaN bulk materials is possible under high excitation conditions with the help of cracks, burned spots, or surface impurities.<sup>11</sup> The fabricated PC could participate in the vertical coupling by acting as artificial impurities or scattering centers, where the phase-match condition is not required. Since the external optical excitation constitutes the gain region in GaN, the horizontal dimension of the gain region (approximately focused spot size) is in general orders of magnitude larger than the vertical dimension ( $\sim 100$  nm). Therefore, light is preferably amplified horizontally in the defect nanocavity, and then scattered or coupled to the vertical radiation with the help of PCs. Further investigation is required to differentiate the two vertical coupling mechanisms. The narrow emission wavelength range could be a result of saturated absorption near the GaN band edge due to band filling under strong optical excitation.

In conclusion, we have investigated the lasing characteristics and the output coupling mechanisms of a PC H2 nanocavity light source fabricated on bulk GaN. The device demonstrates multimode lasing with emission linewidths as narrow as  $2\text{--}3$  Å, and an enhanced spontaneous emission factor  $\beta\sim 0.045$ . Such device offers a great potential in re-

alizing ultraviolet light sources with high efficiency and high spectral purity.

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