AIP Applied Physics Letters

III-nitride photonic crystals

T. N. Oder, J. Shakya, J. Y. Lin, and H. X. Jiang

Citation: Applied Physics Letters **83**, 1231 (2003); doi: 10.1063/1.1600839
View online: http://dx.doi.org/10.1063/1.1600839
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/83/6?ver=pdfcov
Published by the AIP Publishing

III-nitride photonic crystals

T. N. Oder, J. Shakya, J. Y. Lin, and H. X. Jiang[a)]
Department of Physics, Kansas State University, Manhattan, Kansas 66506-2601

(Received 22 January 2003; accepted 12 June 2003)

We report the achievement of nanofabrication and characterization of a triangular lattice array of photonic crystals (PCs) with diameter/periodicity as small as 100/180 nm on an InGaN/GaN multiple quantum well using electron-beam lithography and inductively coupled plasma dry etching. Optical measurements of the PCs performed using near-field scanning optical microscopy showed a 60° periodic variation with the angle between the propagation direction of emission light and the PCs lattice. An unprecedented maximum enhancement factor of 20 was obtained for the emission light intensity at wavelengths as short as 475 nm at room temperature with emission light parallel to the $\Gamma-K$ direction of the PCs lattice. The implications of these results to nitride-based optoelectronic devices, particularly in improving the light extraction efficiency in light-emitting diodes both for blue/green as well as UV emitters, are discussed. [DOI: 10.1063/1.1600839]

Photonic crystals (PCs) have recently attracted much interest since the pioneering work of Yablonovitch.[1] Multiple scattering of photons by lattices of periodically varying refractive indices acts to form photonic band gaps (PBGs) in which propagation of certain wavelengths of the electromagnetic waves is prohibited. This can be exploited to control as well as enhance spontaneous emission and/or the light extraction efficiency in a variety of active and passive optoelectronic devices including light-emitting diodes (LEDs). In semiconductor LEDs, about $1/(4n^2)$ of the light emitted radiates through the top and bottom so that, at best, only about 5% of the light emitted is extracted from the top surface.[2] The need for improvement of the extraction efficiency in LEDs is exceptionally great, particularly for deep ultraviolet (UV) LEDs ($\lambda<340$ nm) based on III-nitride wide band gap semiconductors, which are crucial for many important applications, but presently have very low quantum efficiency (QE). More recently, PCs have been employed to enhance the external efficiency of LEDs at $\lambda=925$ nm and longer.[3–5]

Although R&D of PCs has made rapid progress in the last several years, this has mainly been in infrared (IR) regions for communications. No work involving III-nitride materials in the blue/green and UV wavelengths has been reported, due in part to the difficulty in fabrication associated with the nanometer scale periodicity required. It has been reported that for incident light at $\lambda=488$ nm in GaN, the PBG is likely to be observed at lattice periodicity $a=221$ nm.[6]

In this letter, we report the nanofabrication of triangular lattice PCs with diameter/periodicity as small as 100/180 nm on an InGaN/GaN multiple quantum well (MQW) using electron-beam lithography and inductively coupled plasma (ICP) dry etching. The surface morphology of the etched nitride PCs was characterized using scanning electron microscopy (SEM) and atomic force microscopy (AFM). Optical measurements were performed using near-field scanning optical microscopy (NSOM) uniquely configured for UV wavelengths. Remarkable enhancement of the emission light intensity at wavelengths as short as 475 nm of the MQW structure by a factor of 20 was observed at room temperature. A 60° periodic variation of the NSOM intensity with the angle between the propagation direction of emission light from the MQW and the PC lattice was observed. Our results show fabrication achievement not only for the nanometer lattice dimensions but also for the nitride materials. Additionally, the enhancement at 475 nm by a factor of 20 at room temperature marks so far record high enhancement at the shortest wavelength in PBG studies as far as we know.

The InGaN/GaN MQWs were grown by metalorganic chemical vapor deposition on a double side polished sapphire substrate. A 30 nm low temperature AlN buffer layer was first deposited, followed by a 3 μm thick GaN layer. Five periods of $In_{0.2}Ga_{0.8}N$ (3 nm)/GaN (20 nm) MQWs were then grown between a pair of 20 nm thick GaN cladding layers. The PCs were fabricated using electron-beam lithography and ICP dry etching. Triangular lattice patterns of circular holes with different diameters (d) from 60 to 140 nm and different periodicity (a) from 120 to 300 nm were defined in an area of about 12 μm$\times$12 μm on polymethylmethacrylate initially spun onto the nitride samples. A triangle lattice of air holes in a dielectric background has been shown to be one of the most prominent two-dimensional (2D) structures to present PBGs.[7,8] The samples were then developed in a solution of methylisobutyl ketone and isopropyl alcohol. Subsequent dry etching was performed for 30 s using ICP.

Figures 1(a) and 1(b) show SEM images of the nitride PCs after the patterns were etched into the nitride materials with hole diameter/periodicity of 100/180 and 120/300 nm, respectively. The later structure with hole diameter/periodicity of 120/300 nm and an air-fill factor of 29% was extensively characterized. Figure 1(c) shows an AFM line profile across the nitride PCs after etching to a depth of about 200 nm. This etch depth was sufficient to achieve the desired penetration of MQW layers of our structure.

For optical measurements, laser light of wavelength 266 nm was focused onto a small spot of about 3 μm on the sample using the NSOM system specially configured for UV

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

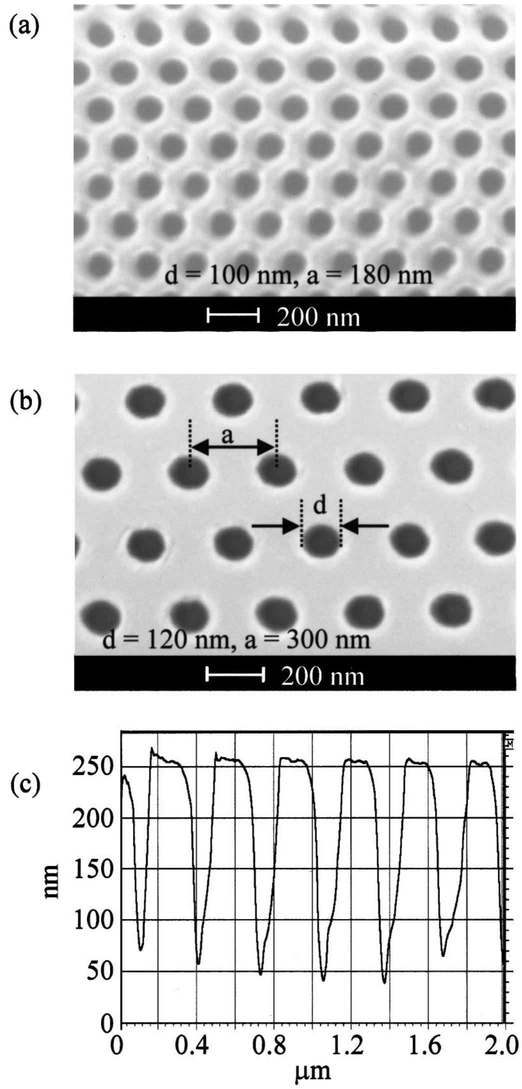

FIG. 1. SEM images of the nitride PCs with hole diameter/periodicity of (a) 100/180 and (b) 120/300 nm. The AFM line profile across the PCs with an etch depth of about 200 nm is shown in (c).

wavelengths. Laser light was pumped onto the unpatterned area of the sample about 10 μm outside the PCs and the emission intensity collected by the NSOM tip placed above the PCs. The emission intensity was also collected at an equal distance from the same pump spot in an unpatterned region of the sample. The experimental setup for this measurement, illustrated in Fig. 2(a), thus enabled direct comparison between the emission light intensity collected in the MQW region patterned with PCs and an unpatterned region. This setup is similar to the one used by Boroditsky *et al.*,[4] where the light generation region is separate from the extraction region patterned with PCs since improvement is sought for light extraction as opposed to spontaneous emission. Typically, the pump region in LEDs is separate from the light extraction region. Figure 2(b) shows a three-dimensional (3D) NSOM intensity image collected above the 12 μm$\times$12 μm region patterned with PCs. The laser pump spot was located about 30 μm from the PCs in the unpatterned region of the sample. Figure 2(c) shows the photoluminescence (PL) spectra at $T=300$ K for the two cases depicted in Fig. 2(a), with the propagation direction of emission light from the laser pump spot parallel to the $\Gamma-K$ lattice direction of

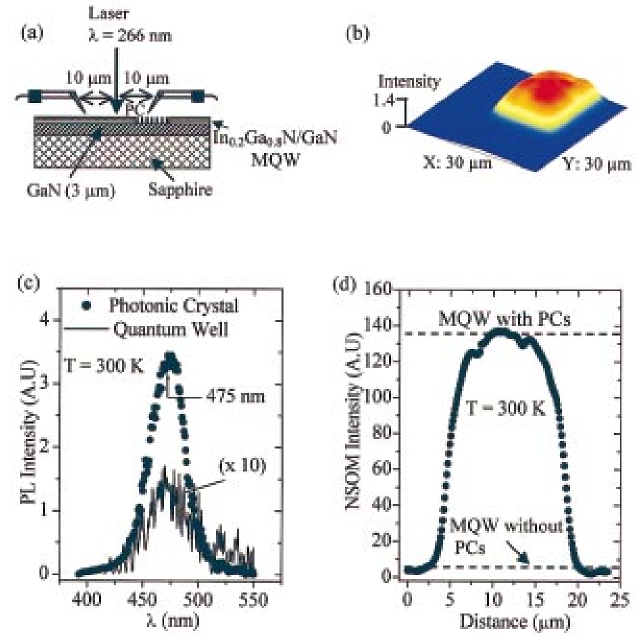

FIG. 2. (Color) (a) Schematic setup for NSOM measurement of the PCs. (b) 3D NSOM intensity image collected above the 12 μm$\times$12 μm region patterned with PCs. (c) PL spectra at $T=300$ K for the two cases in (a), measured by NSOM in collection mode. (d) Line scan across the NSOM image showing an increase in intensity from about 5 units in the unpatterned region of the MQW to about 135 units in the region of the MQW with PCs.

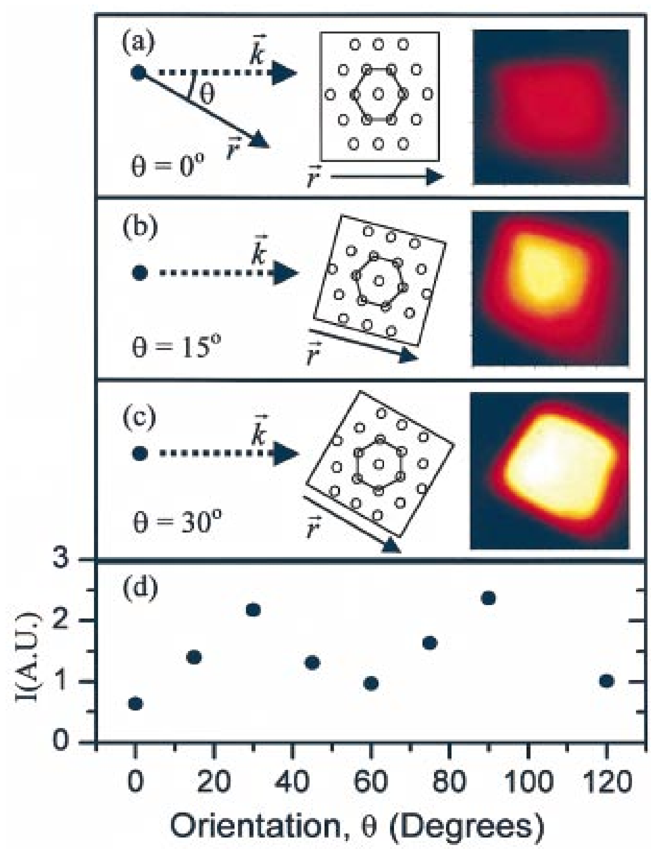

FIG. 3. (Color) (a)–(c) Illustration of the setup and the scanned NSOM intensity image across the PC region for three different orientations: $\theta=0°$, 15°, and 30°. A plot of the NSOM intensity vs θ shown in (d) indicates a 60° periodicity where the NSOM intensity is minimum for $\theta=0°$ or 60° corresponding to the $\Gamma-M$ direction and maximum for $\theta=30°$ or 90° corresponding to the $\Gamma-K$ direction.

the PCs. The emission peak at 475 nm is attributed to localized exciton recombination in the well regions of the MQW structure. From Fig. 2(a), the region patterned with PCs produced a enhancement of the emission intensity of about 20-fold compared to the unpatterned region of the sample. This is definitely an observation of enhancement at the shortest wavelength by PCs. In addition, the enhancement factor of 20 at room temperature is a large value for semiconductor PCs. The line scan across the 3D NSOM image in Fig. 2(b) is plotted in Fig. 2(d) and shows an increase in the NSOM intensity scale from about 5 units in the unpatterned region of the MQW to 135 units in the region of the MQW with PCs, giving an enhancement factor consistent with the PL data shown in Fig. 2(c).

There are two possible ways by which PCs can improve LED output power. The first is by Purcell spontaneous emission rate enhancement due to the band structure and nanocavities of the PCs. The Purcell enhancement factor, f, is defined as[3]

$$f=\frac{3Qg(\lambda/2n)^3}{2\pi V_{\mathrm{cav}}}, \quad (1)$$

where Q is the quality factor, g is mode degeneracy, λ is the wavelength, n is the refractive index, and V_{cav} is the cavity volume. Q is limited to 10–30 at room temperature by the material properties of the semiconductor.[3] For nitride materials, $n \sim 2.4$ and at a wavelength of 475 nm, $V_{\mathrm{cav}} \approx 0.0024\ \mu\mathrm{m}^3$. These lead to a maximum f value of about 5.7 for single mode degeneracy, implying that overall improvement of LED operation by the Purcell effect may be limited.

The second method by which PCs can improve LED output power is by Bragg scattering, which is directly related to the extraction efficiency. Light extraction in this case is enhanced in two possible ways.[4] First, because multiple scattering of photons by lattices of periodically varying refractive indices in the PCs acts to form PBGs in which lateral propagation of the Bloch guided modes is prohibited, light generated in the band gap region can couple only to radiation modes and is radiated outward. The lattice dimensions of the PCs would have to be tuned to match this band gap region. Second, the refractive index periodicity creates a cut-off frequency for guided modes. Guided modes are folded by the PCs at the Brillouin zone boundaries, allowing phase matching to the radiation modes that lie above this cut-off frequency.[3,9] The guided modes that phase match to the radiation modes become leaky resonances of the PCs which Bragg scatter the light emitted from of the active region. The result is significant enhancement of light extraction due to coupling to free space modes in the two cases above.

The center of a PBG in GaN with dielectric constant $\epsilon \approx 8$ is estimated to be at a normalized frequency (a/λ) value of about 0.5 for a triangular air hole lattice structure.[6] The normalized frequency that corresponds to our structure is 0.63 for a wavelength of 475 nm, which implies that photon modes in our structure lie above the cut-off frequency of the guided modes. We therefore believe that the enhancement in our measurement is mainly due to coupling to leaky modes above the cut-off frequency of the Bloch guided modes in our PCs.

In Fig. 3, we show the variation of the propagation direction of emission light from the MQW according to the orientation of the PC lattice. In this measurement, the laser pump spot was about 100 μm from the PC region and the NSOM intensity was collected above the PCs in a 20×20 μm region enclosing the PCs. The sample was then manually turned about the vertical axis at different orientations θ (defined as an angle between laterally propagating emitted light in the MQW and $\Gamma-M$ direction of the PC lattice) ranging from 0° to 120°. Figures 3(a)–3(c) show an illustration of the setup and the scanned NSOM intensity image across the PC region for three different orientations, θ=0°, 15°, and 30°, respectively. A plot of the NSOM intensity versus orientation θ is shown in Fig. 3(d). Clear 60° periodicity is seen in this result, where the NSOM intensity is minimum for orientation of 0° or 60° corresponding to the $\Gamma-M$ direction, and increases threefold for orientation of 30° or 90° corresponding to the $\Gamma-K$ direction of the PCs lattice. This corresponds to an increase in enhancement factor from 7 along the $\Gamma-M$ direction to 20 along the $\Gamma-K$ direction. A typical dispersion diagram of transverse electric (TE) modes in a triangular lattice structure of PCs reveals that the PBG along the $\Gamma-K$ direction is larger than that along the $\Gamma-M$ direction.[8] This possibly translates into a large change in enhancement factor for light traveling along different directions as our data show. In any case, the observed angle dependence in Fig. 3 is a direct demonstration of the PBG effect of PCs.

In summary, we have fabricated triangular lattice PCs with periodicity as small as 180 nm in an InGaN/GaN MQW. The NSOM measurements have revealed that the PCs enhanced the emission light intensity by a factor of 20. Such enhancement can be exploited in nitride-based LEDs to improve the light extraction efficiency in the short wavelength regions. We also observed a 60° periodic variation in NSOM intensity with the angle between the propagation direction of emission light from the MQW and the photonic crystal lattice, which is a direct effect of the PBG.

The authors wish to acknowledge support by grants from DARPA, ARO, ONR, DOE, NSF, and BMDO.

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
[2] M. Boroditsky and E. Yablonovitch, Proc. SPIE **3002**, 119 (1997).
[3] A. A. Erchak, D. J. Ripin, S. H. Fan, P. Rakich, J. D. Joannoupoulos, E. P. Ippen, G. S. Petrich, and L. A. Kolodziejski, Appl. Phys. Lett. **78**, 563 (2001).
[4] M. Boroditsky, R. Vrijen, T. F. Krauss, R. Coccioli, R. Bhat, and E. Yablonovitch, J. Lightwave Technol. **17**, 2096 (1999).
[5] H. Y. Ryu, J. K. Hwang, Y. J. Lee, and Y. H. Lee, IEEE J. Sel. Top. Quantum Electron. **8**, 321 (2002).
[6] A. Barra, D. Cassagne, and C. Jouanin, Phys. Status Solidi A **176**, 747 (1999).
[7] R. D. Meade, K. D. Brommer, A. M. Rappe, and J. D. Joannopoulos, Appl. Phys. Lett. **61**, 495 (1992).
[8] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals, Molding the Flow of Light* (Princeton University Press, Princeton, NJ, 1995).
[9] V. N. Astratov, I. S. Culashaw, R. M. Stevenson, D. M. Whittaker, M. S. Skolnick, T. F. Krauss, and R. M. De La Rue, J. Lightwave Technol. **17**, 2050 (1999).