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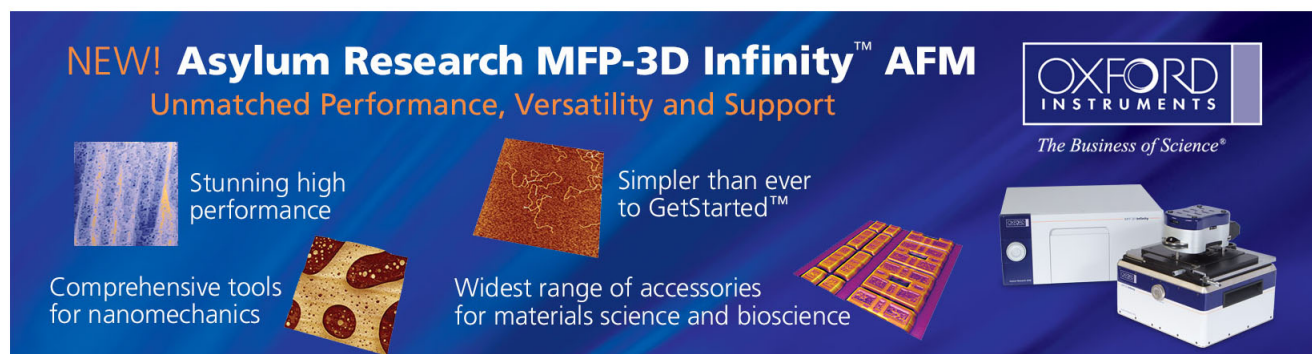
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# Large-area ultraviolet GaN-based photonic quasicrystal laser with high-efficiency green color emission of semipolar {10-11} $\text{In}_{0.3}\text{Ga}_{0.7}\text{N}/\text{GaN}$ multiple quantum wells

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In this study, a multi-color emission was observed from the large-area GaN-based photonic quasicrystal (PQC) nanopillar laser. The GaN PQC nanostructure was fabricated on an n-GaN layer by using nanoimprint lithographic technology. The regrown  $\text{InGaN}/\text{GaN}$  multiple quantum wells (MQWs) formed a nanopillar structure on top of the PQC nanopillars. A lasing action was observed at ultraviolet wavelengths with a low threshold power density of  $24 \text{ mJ}/\text{cm}^2$ , and a green color emission from  $\text{InGaN}/\text{GaN}$  MQWs was also achieved simultaneously. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4775373>]

In recent years, GaN-based material and high-brightness GaN-based light-emitting diodes (LEDs)<sup>1,2</sup> have attracted significant attention because of their wide and direct band gap. In particular, significant efforts have been made to improve the quality of GaN-based LEDs because of their uses, such as in laser diodes,<sup>3-5</sup> solid-state lighting,<sup>6</sup> display technology, traffic signals, color printing, and optical storage.

However, the performance of the light source must be improved, and high extraction efficiencies must be increased. Recent approaches based on surface roughness increase,<sup>7,8</sup> colloidal-based microlens arrays,<sup>9,10</sup> colloidal-based microstructures arrays,<sup>11,12</sup> and photonic crystals<sup>13-16</sup> had been reported in quasi-crystal or defective 2-D grating configurations, which in turn leads to improved light extraction efficiency in LEDs. The photonic crystal structure has a periodic structure with translational symmetry. The periodic structure can exhibit a photonic band gap (PBG) to inhibit the propagation of guided modes<sup>17</sup> and use a photonic crystal structure to couple guided modes with radiative modes.<sup>18-20</sup> Photonic crystal lasers based on the band-edge effect<sup>21-23</sup> possess many advantages, such as high-power emissions, single-mode operation, and coherence oscillation over large areas. E-beam lithography<sup>24</sup> and laser interference lithography<sup>25</sup> have been used to fabricate the photonic crystal structure. However, when comparing the two methods to nanoimprint lithography (NIL), NIL is suitable for mass production of LED devices because of its good resolution and higher throughput with low fabrication costs. This study demonstrates the GaN-based 2D photonic quasicrystal (PQC) structure with the regrowth of GaN pyramids and 10-pair semipolar {10-11}  $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  (3 nm/12 nm) multiple quantum well (MQW) nanostructures, as shown in Fig. 1(a). In addition to the use of semi/non-polar QWs,<sup>26,27</sup> approaches by using various polar QWs with large optical matrix element

designs<sup>28-32</sup> had also been reported for suppressing charge separation and improving optical gain in III-nitride QWs. Experimental results show that the device contains lasing action and different color emission simultaneously. This laser structure can be a potential platform to achieve a multi-color emission from a single device, which benefits future lighting and detection applications. Large-area PQC patterns were defined by the NIL,<sup>33</sup> such as the PQC structures possessing 12-fold symmetry,<sup>33,34</sup> and forming a complete band gap. The regrowth of GaN nanopillars with semipolar {10-11}  $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  MQW is grown by selective area growth (SAG).<sup>35-37</sup> Different wavelength emissions have been studied by changing the ratio of In composition of  $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ , or by controlling the growth rate of  $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  MQWs on the facets of trapezoid microstructures. The semipolar {10-11} planes can also reduce the influence of the quantum-confined Stark effect on the quantum efficiency of LEDs because of the surface stability and suppression of polarization effects.<sup>38,39</sup>

The GaN-based material was grown by a low-pressure metal-organic chemical vapor deposition (MOCVD) system. A 2- $\mu\text{m}$ -thick GaN layer was first grown on a 2-in. C-plane (0001) sapphire substrate. The GaN contained 1  $\mu\text{m}$  undoped GaN and 1  $\mu\text{m}$  n-type GaN and were grown at 1150 °C and 1160 °C, respectively. The photonic crystal patterns were formed using an NIL technique. First, a 400 nm  $\text{SiO}_2$  layer and a 200 nm polymer layer were deposited as the masks during the process (step 1 of Fig. 1(b)). A patterned mold of the photonic crystal structure was then placed onto the dried polymer film (step 2 of Fig. 1(b)). Under high pressure, the substrate was heated over the glass transition temperature ( $T_g$ ) of the polymer. The substrate and the mold were then cooled to room temperature to release the mold (step 3 of Fig. 1(b)).

After defining the photonic crystal patterns on the polymer layer, the patterns were transferred into the  $\text{SiO}_2$  layer by reactive ion etching (RIE) with a  $\text{CHF}_3/\text{O}_2$  mixture and

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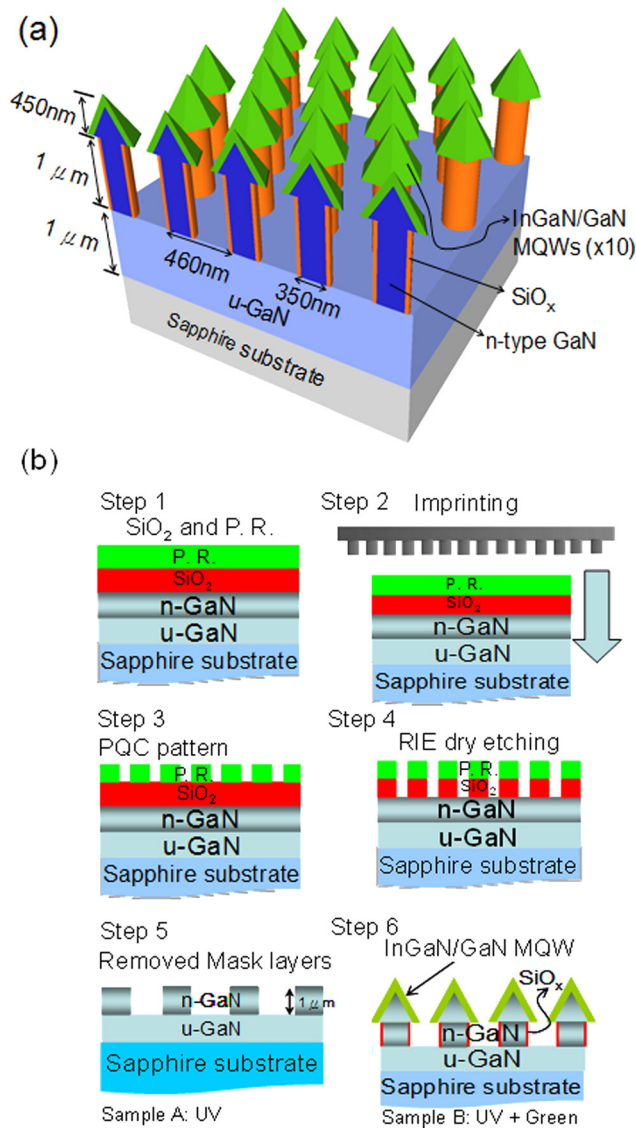


FIG. 1. (a) Schematic structure of the GaN-based PQC structure with the regrowth of semipolar {10-11} GaN pyramids and 10-pair In<sub>0.3</sub>Ga<sub>0.7</sub>N/GaN (3 nm/12 nm) MQW; (b) Illustrations of the fabrication process of nanoimprint technology and the regrowth process.

into the GaN layer by inductively coupled plasma etching (ICP) with a Cl<sub>2</sub>/Ar mixture. The mask layers were removed at the end of the processes. Before the regrowth process, the sample was passivated with porous SiO<sub>2</sub> at the sidewall. The pyramid-shaped n-type GaN structures were regrown on top of the GaN nanopillars at 730 °C. The 450-nm-tall pyramids contain 10-pair In<sub>0.3</sub>Ga<sub>0.7</sub>N/GaN (3 nm/12 nm) quantum wells, which support an emission of approximately 500 nm in wavelength. The fabrication procedure is shown in Fig. 1(b). The total area of the PQC pattern is approximately 4 cm × 4 cm with a lattice constant of (a) approximately 460 nm and a diameter of 350 nm. The etch depth of the nanopillars is approximately 1 μm, as shown in Fig. 2(a) top view and (b) angle view. Fig. 2(c) shows the SEM image of the PQC structure with a semipolar {10-11} In<sub>0.3</sub>Ga<sub>0.7</sub>N/GaN MQW cross-sectional view. To study the optical properties of the GaN-based PQC laser, two GaN PQC samples (samples A and B) were prepared. Sample B is a GaN-based PQC structure with an In<sub>0.3</sub>Ga<sub>0.7</sub>N/GaN MQW regrowth procedure, and Sample A has an identical PQC

structure without the regrowth step. The devices were optically pumped by using a frequency-tripled Nd: YVO<sub>4</sub> 355 nm pulsed laser with a pulse width of 0.5 ns and a repetition rate of 1 kHz. The light emission from the device was collected by a 15× objective lens through a multimode fiber, and coupled into a spectrometer with charge-coupled device (CCD) detectors. Fig. 3(a) shows the measured spectra from the PQC pattern of Sample A (blue curve) and Sample B (green curve) above the threshold and photoluminescence (blue-dashed curve) of GaN. The lasing action was observed at 366 nm wavelength because of the distributed feedback of light at the photonic band edge of the PQC structure.<sup>22</sup> The threshold power density of Sample A is approximately 9.0 W/cm<sup>2</sup>. This ultralow threshold, which is one of lowest reported thresholds for GaN lasers, indicates the strong enhancements from PQC lattices. Sample B has a lasing-mode approximating a wavelength of 366 nm resulting from the PQC structure. The color emission resulting from In<sub>x</sub>Ga<sub>1-x</sub>N/GaN MQW is located in the green range.

Fig. 3(b) shows the light-in light-out (L-L) curve of the GaN PQC laser from sample B. The threshold power density of sample B is approximately 24 W/cm<sup>2</sup>. The value corresponds to a threshold power density of 24 mJ/cm<sup>2</sup>. The threshold of the PQC structure in sample B is higher than the threshold of the structure in sample A. This difference is mainly attributed to geometrical changes of GaN nanopillars and absorption of top InGaN/GaN MQW. Another strong emission of approximately 500 nm wavelength was observed in the PQC structure in sample B. This green light, which is emitted from the top of InGaN/GaN MQW, is shown in Fig. 4(b). When the pump power is over the threshold of UV lasing, the intensity of the green emission is clamped. It is a sign of UV lasing in this multi-color GaN PQC structure. The UV lasing action was supported by GaN in the nanopillars. While the green luminescence was attributed to the absorption from optical pump lasers as well as UV emission from the nanopillars. To have a clear spectrum for the green emission, samples A and B were optically pumped using a continuous-wave (CW) He-Cd laser at 325 nm with an incident power of 48 mW. The measured setup is the same as the micro-PL setup previously described. Fig. 4(a) shows the measured PL spectra under He-Cd 325 nm CW laser pumping. When comparing sample B (green curve) with sample A (black curve), a strong emission peak was observed at a wavelength of approximately 500 nm resulting from the In<sub>0.3</sub>Ga<sub>0.7</sub>N/GaN MQWs structure. The spectrum linewidth is approximately 60 nm. The results show possible applications for LEDs. Fig. 4(b) shows the photography of the PQC structure of sample B during measurement. The white light region is caused the pumping light source of the He-Cd 325 nm CW laser. The UV lasing and green emission modes are corresponded to the band-edge resonant modes of the GaN PQC structure<sup>22</sup> and could be manipulated by photonic crystal geometry and regrowth InGaN/GaN materials. This hybrid platform generates many possibilities for multi-color LEDs or multi-color lasers systems.

In summary, a 12-fold symmetric GaN PQC nanopillar structure was fabricated using NIL technology. The ultraviolet (UV) lasing action was observed at an approximate 366 nm wavelength with an ultralow threshold power density



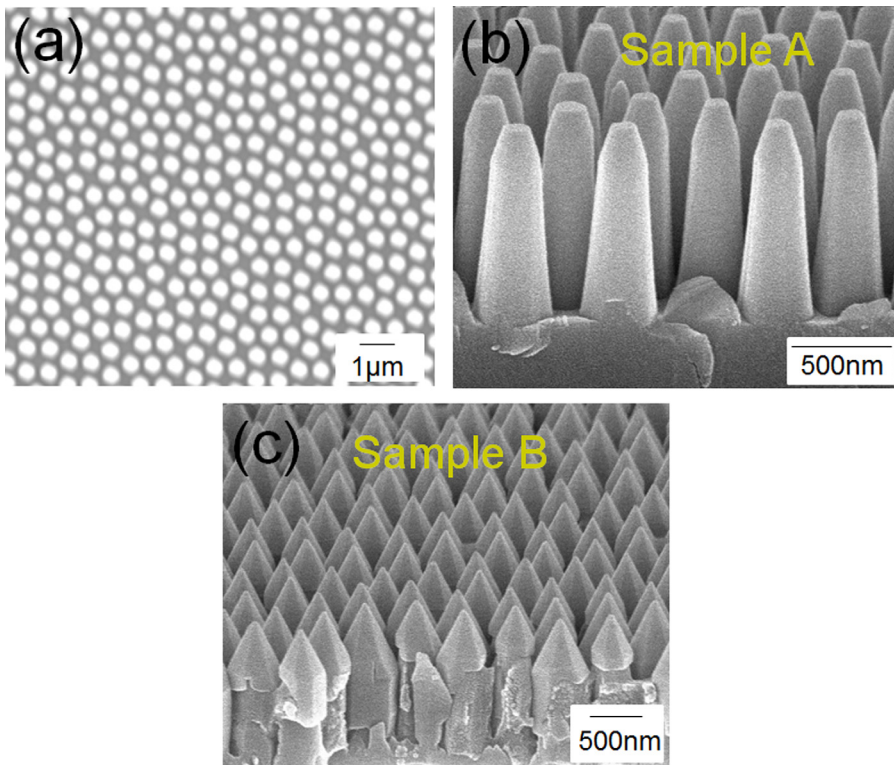


FIG. 2. (a) The top-view and (b) the angle-view SEM images of the PQC structure. (c) The cross-sectional SEM image of the PQC structure after the regrowth procedure.

of  $9.0 \text{ kW/cm}^2$  corresponding to the threshold energy density of  $9 \text{ mJ/cm}^2$ . With the regrowth procedure of the top  $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  MQWs by SAG, UV lasing from GaN PQC and high-efficiency green color emissions from  $\text{In}_x\text{Ga}_{1-x}$

$\text{N}/\text{GaN}$  MQW were simultaneously achieved. These methods of fabrication demonstrated high potential in low fabrication costs, excellent techniques in fabricating semipolar {10-11}  $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  LEDs, and better integration of GaN-based

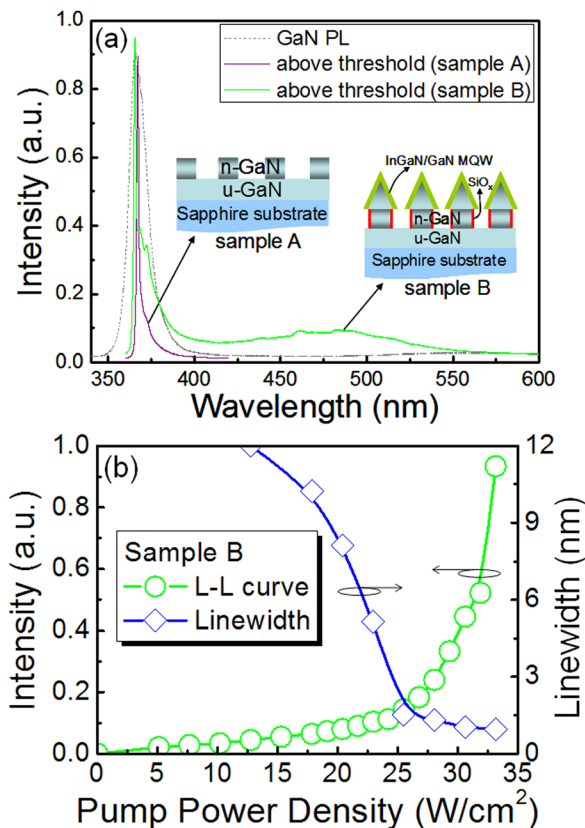


FIG. 3. (a) The measured spectrum of samples A and B above threshold. The lasing wavelength is 366 nm. (b) The light-in light-out (L-L) curve and linewidth narrowing of sample B.

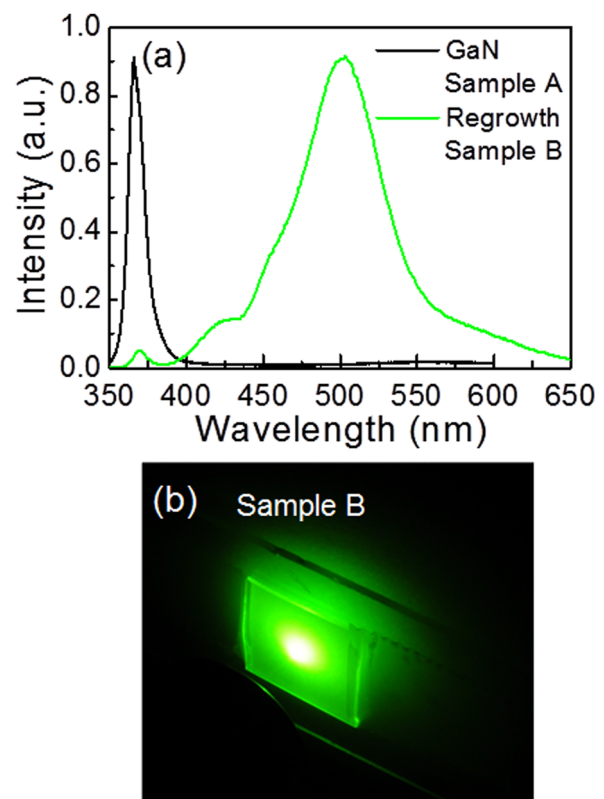


FIG. 4. (a) PL spectra from the PQC structure of sample A (black) and sample B (green) under He-Cd 325 nm CW laser pumping. (b) The photograph of the PQC structures on sample B during the experiment, and the white light on the center caused by the pumping light source of the He-Cd laser.

photonic crystal lasers and multi-color light sources in future applications.

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