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Strongly enhanced red emission from Eu-doped GaN in a two-dimensional photonic-crystal nanocavity

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Abstract

Eu-doped GaN (GaN:Eu) is a material that can be used for red emission on the GaN platform. We have previously reported on high efficiency red light emitting diodes (LEDs) on this material, while laser diodes (LDs) are our next challenge. In order to realize this, we employed L3-type photonic crystal nanocavities, which have an extremely small mode volume, and a relatively high quality-factor (*Q*-factor). The cavity structure was optimized from the viewpoints of the photonic bandgap and the *Q*-factor. An experimental *Q*-factor of 1.7×10^3 and a maximum 34-fold increase in photoluminescence (PL) intensity, with respect to a conventional GaN:film, was obtained. This is the first demonstration of a 2D-PhC nanocavity coupled with Eu-related luminescence.

1. Introduction

Nitride-based red-emitting optical devices are suffering from low quantum efficiencies as compared to the green and blue region. To realize bright red luminescence, we have focused on Eu-doped GaN (GaN:Eu), which exhibits an ultra-stable emission wavelength independent of current injection level [1], and demonstrated red light emitting diodes (LEDs) using GaN:Eu grown by organometallic vapor phase epitaxy (OMVPE). Recently, we have achieved a highly-efficient GaN:Eu-based LED (maximum external quantum efficiency (EQE) of 9.8%) with a high output power of 1.25 mW at 20 mA [2]. Our next goal is to realize a laser diode (LD) based on GaN:Eu.

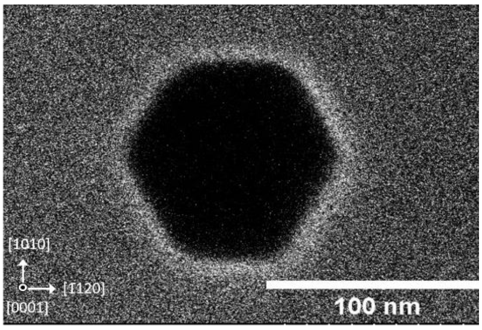

Fig.1 Plane-view SEM image of a typical hole shape in GaN after wet-etching. Circular holes were easily converted to hexagonal shapes, reflecting the wurtzite structure of GaN

2. Simulation and experimental results

To achieve laser oscillation, optical cavities with high quality-factors (*Q*-factors) and small modal volumes (*V*) are required, as the radiative transition probability increases proportionally to *Q*/*V* due to the Purcell effect [3]. Two-dimensional photonic crystals (2D-PhCs), which have small *V* and high *Q*-factors are one of the most prominent candidates to realize this. Though air-holes of a 2D-PhC are typically circular-shaped, we found that circularly-designed holes typically deformed to hexagonal shapes after wet etching, as shown in Fig.1, reflecting the wurtzite structure of

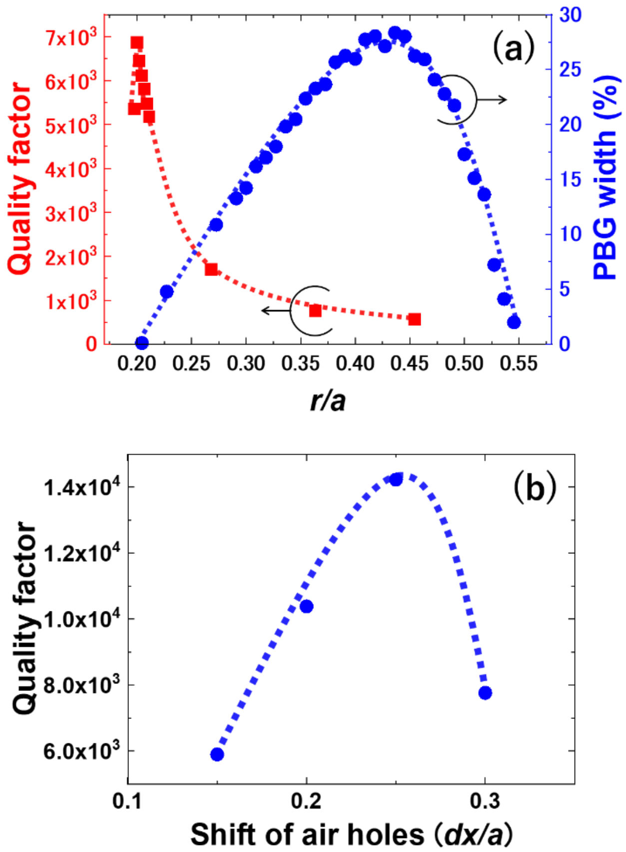

Fig.2 (a) PBG width for the TE mode and *Q*-factors of L3 cavity as a function of *r*/*a*. Even with hexagonal shaped holes, a PBG for the TE mode is available for a wide range of *r*/*a*. The lines are guide to the eye. (b) *Q*-factor optimization as a function of shift value of air holes. The line is a guide to the eye.

GaN. Thus, we designed 2D-PhCs with hexagonal holes using finite difference time domain (FDTD) simulations. The photonic band structure of the GaN 2D-PhCs with hexagonal holes was calculated as a function of *r/a*, where *a* is the lattice constant of the PhC and *r* is the hole radius. As shown in Fig. 2 (a), for a wide range of *r/a* from 0.20 to 0.55, we confirmed the existence of large photonic-bandgap (PBG) for the TE mode, even with the hexagonal shaped holes. A maximum PBG width, normalized by the central frequency, of 28% is achieved with *r/a* of ~0.44.

Herein, based on the FDTD simulations, we initially optimized *r/a* of a L3 cavity for a fixed *a* of 220 nm to obtain a high *Q*-factor. In Fig. 2(a) the calculated *Q*-factors are shown as a function of *r/a*. When *r/a* is smaller than 0.20, the *Q*-factor decreases dramatically because the PBG vanishes as explained above. Furthermore, a too large *r/a* also decreases the *Q*-factor due to the shortened cavity length. Taking into account both *Q*-factor and PBG width, we chose *r/a* to be 0.27 and obtained a *Q*-factor of 1.7×10^3. Subsequently, we introduced a hole-shift at the edge of the L3 cavity outward along the cavity direction to effectively increase the cavity length while maintaining *r/a*. As shown in Fig.2 (b), we optimized the shift-value (*dx*) and the maximum *Q*-factor of 1.4×10^4 was found for a value of *dx* of 0.25*a*.

Finally, we fabricated a L3-shift nanocavity with embedded GaN:Eu using electron beam lithography and dry etching, followed by selective wet etching of an underlying AlInN layer. The successful fabrication of an L3-shift nanocavity with clear hexagonal-shaped holes was confirmed by scanning-electron-microscope. Micro-photoluminescence (PL) spectroscopy was performed at room temperature to optically characterize the nanocavity. Fig.3 shows PL spectra of the L3 cavity. It can be seen that the cavity mode was completely coupled with Eu^{3+} luminescence, resulting in significantly enhanced red emission. The experimental *Q*-factor was determined as 3.1×10^3 and the emission intensity at a wavelength of 621.1 nm was 34 times larger than a conventional GaN:Eu film. Though laser oscillation was not demonstrated explicitly, possibly due to sample fabrication errors, a strongly enhanced Eu luminescence was obtained.

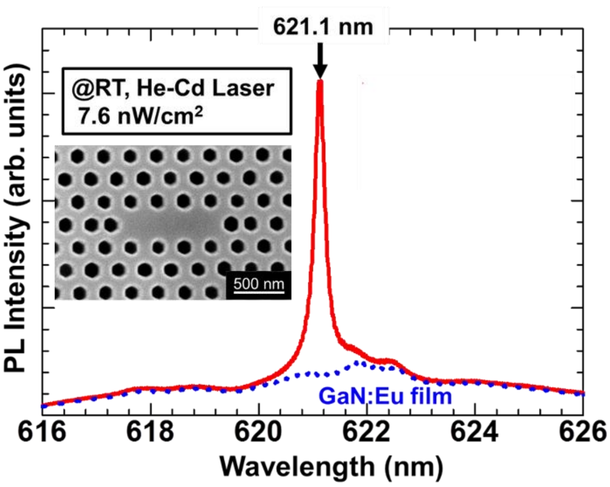

Fig.3 PL spectra from a conventional GaN:Eu film and GaN:Eu with a L3-shift cavity. The experimental *Q*-factor was determined to be 3.1×10^3 and the emission intensity at a wavelength of 621.1 nm was 34 larger than a conventional GaN:Eu film. The inset shows a plane-view SEM image of a fabricated L3-shift nanocavity.

3. Conclusions

With FDTD simulations, the photonic band structure of a PhC with hexagonal-shaped holes was calculated and a large PBG for a wide range of *r/a* was found. The L3 cavity structure was optimized for the PBG width and *Q*-factor. A fabricated L3 showed a *Q*-factor of 3.1×10^3 and an emission intensity enhancement of a factor of 34 compared to a conventional GaN:Eu film. This is the first demonstration of a 2D-PhC nanocavity coupled with the Eu-related luminescence.

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