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Light Emission Enhancement of GaN-Based Photonic Crystal With Ultraviolet AlN/AlGaN Distributed Bragg Reflector

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Abstract

In this study, we demonstrated two-dimensional (2-D) photonic crystal band-edge coupling operation with an ultraviolet AlN/AlGaN distributed Bragg reflector (UVDBR). A five-fold enhancement in photoluminescence emission was also achieved at 374 nm wavelength. We also employed the photonic crystal band-edge mode examined with plane-wave expansion (PWE) simulation.

1. Introduction

Direct wide-bandgap gallium nitride (GaN)-based materials have attracted much attention or potential applications such as blue, green, and ultraviolet (UV) light-emitting diodes (LEDs) and laser diodes (LDs) [1]. The high reflectivity GaN-based distributed Bragg reflector (DBR) is one of key elements for GaN optical devices such as resonant cavity light-emitting diodes (RCLED) [2] and vertical-cavity surface-emitting lasers (VCSEL) [3]. In this report, we demonstrated light enhancement from the GaN-based photonic crystals with ultraviolet AlN/AlGaN distributed Bragg reflector (UVDBR). The UVDBR structure has center stop band at 375nm and a width approximately 15 nm. Therefore, it can be acted as a mirror to reflect light from the bottom area and played the role as a lower refracted index layer to control the guided modes.

2. Fabrication Process

The 2-D photonic crystal square lattices were fabricated in an ultraviolet GaN-based Distributed Bragg Reflector (UV DBR) structure. This AlN/AlGaN DBR structure was grown by a low pressure Metal-organic Chemical Vapor Deposition (MOCVD) system. The schematic structure of the grown DBR is shown in Fig. 1(a). The growth details were reported in our previous work [4].

To fabricate the photonic crystal lattices, a 300nm Si_3N_4 layer and a 300 nm Polymethylmethacrylate (PMMA) layer were deposited as the masks during the process.) According to the simulation of plane wave expansion (PWE), we can design and utilized photonic crystal structures to inhibit emission of guided modes or redirect trapped light into radiated modes. The photonic crystal square lattice patterns were defined on the PMMA layer by E-beam lithography and the patterns were transferred into Si3N4 layer in reactive ion etching (RIE) with CHF_3/O_2 mixture. The structure was then etched by inductively coupled plasma reactive ion etching (ICP-RIE) with Cl_2/Ar mixture. The mask layers were removed at the end of processes. The size of a fabricated photonic crystal pattern is approximately 50μmx50μm with a lattice constant (a) of 250nm and a hole radius of 0.28a. The etch depth of the holes is approximately 500nm which is pass through undoped GaN layer into DBR region. The schematic structure of the fabricated photonic crystals in AlN/AlGaN DBR is shown in Fig. 2(a). The top view of a SEM image of a fabricated photonic crystal pattern on the GaN-based structure is shown in Fig. 1(b).

3.Results and Discussion

Before characterize the photonic crystal with the AlN/AlGaN DBR structure, the high reflectivity in UV region form the DBR layers was verified by measuring the reflectivity spectrum with an n&k ultraviolet-visible spectrometer as shown in Fig. 2. The dashed curve in Fig. 2 is the simulated reflectivity spectrum from transmission matrix method for the UVDBR. The solid curve in Fig. 3 is the measured spectrum with a normal incident light from 300 to 440 nm wavelength. The ultraviolet DBR has the highest reflectivity of 85% at the center wavelength of 375 nm, with a stop-band width of about 15 nm.

To demonstrate the light enhancement from the photonic crystal structure, the optical pumping was performed by using a frequency-tripled Nd:YVO_4 355 nm pulsed laser with a pulse width of 0.5 ns and a repetition rate of 1 kHz. The device was pumped by an normal incident laser beam with a spot size of 50μm which can cover the whole PC pattern area. The light emission from the sample was collected by a 15 X objective lens through a multi-mode fiber, and coupled into a spectrometer with a charge-coupled device (CCD).

Under room temperature optical pumping condition, a strong resonance from the photonic crystal pattern was observed as shown in Fig. 3(a). The shadow area in Fig. 3(a) is the high reflection region of the UVDBR. The strong emission is only observed within the region due to the DBR effect, as expect. A high resonant mode (black curve) was observed at 374 nm wavelength. A five-fold enhancement in photoluminescence emission was also achieved by comparing with the emission from the unpatterned area.

We also employ 2-D plane-wave expansion (PWE) method to calculate the band diagram of the photonic crystal structure as shown in Fig. 3(b). According to the measurement, the photonic crystal DBR structure with 250 nm lattice constant shown the strong resonance at 374 nm wavelength which is corresponded to a normalized frequency of $a/\lambda=0.67$. This band edge mode is happed near the symmetry point Γ in the band diagram.

4. Conclusions

The strong emission from the GaN-based photonic crystal with UVDBR was achieved. A five-fold enhancement in photoluminescence emission was also observed. This enhancement results from the coupling between electron-hole recombination in the top GaN gain layer and low group velocity modes at band-edge of Γ point. Experimental results show excellent agreement with simulations. Due to the larger enhancement of the devices, we believe the photonic crystal structure with bottom DBR mirror which has the potential to light sources for the future applications.

References

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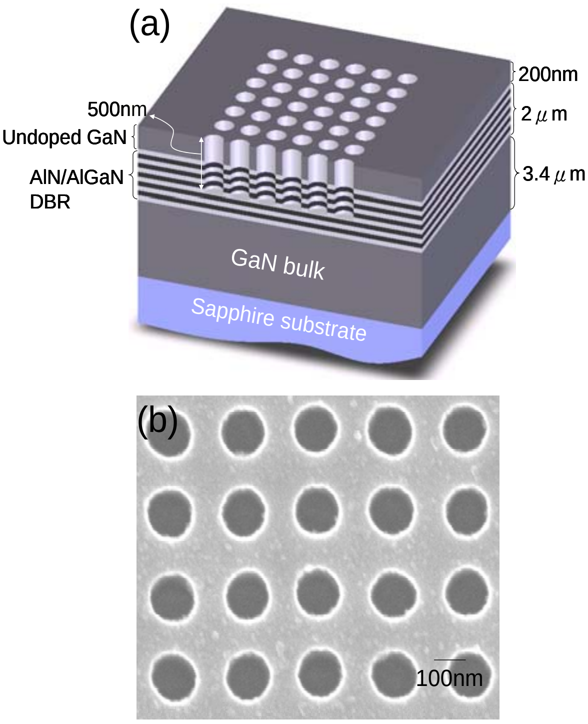

Fig. 1. (a)Schematic structure of the square photonic crystal patterns on epitaxial structure of the UVDBR. (b) Top view SEM images of the photonic crystal structures.

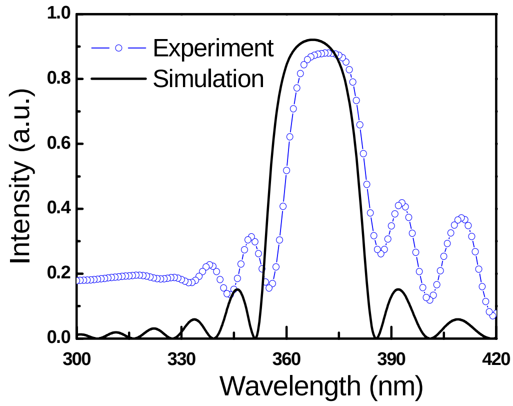

Fig. 2. Calculated (solid) and measured (dash) reflectivity spectra of the UCDBR with a stop-band width of about 15 nm and the center wavelength is 375 nm.

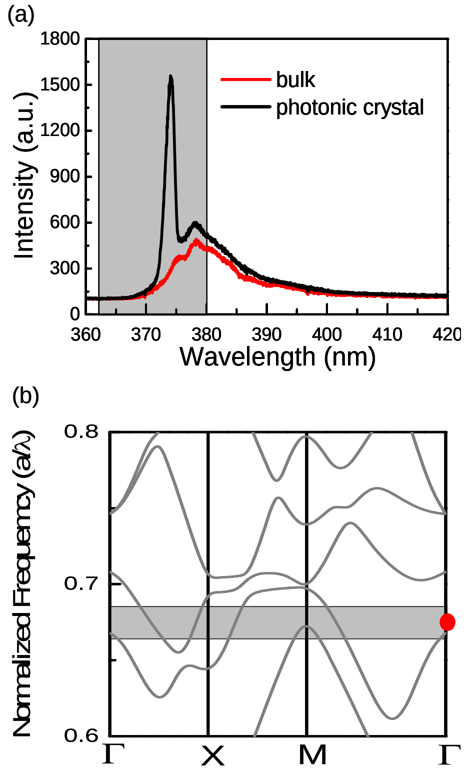

Fig. 3. (a)The measured PL spectra form the GaN photonic crystal structure. The resonant peak is at 374nm wavelength and is located within the high reflection range of the UVDBR (shadow region). (b)The calculated band diagram for 2-D GaN-based photonic crystals with plane-wave expansion method.