Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1141-1142

Large Area of Ultraviolet GaN-based Photonic Quasicrystal Laser

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Abstract

In this study, GaN-based 12-fold symmetry photonic quasicrystal (PQC) nanopillars were fabricated on an n-GaN layer using nanoimprint lithography technology. Under optical pumping condition, a lasing phenomenon was observed at 366 nm wavelength with a low threshold power 0.009 kW/cm^2. We also employed the photonic quasicrystal bandedge mode examined with finite-element method (FEM) simulation.

1. Introduction

Wide and direct bandgap of GaN-based materials have been attracted much attention for applications such as light emitting diodes (LED) and laser diodes (LD)[1]. The high brightness GaN-based light-emitting diodes (LEDs) have made it possible to apply in traffic signals, backlight in liquid crystal displays, and solid state lighting. The blue LD can serve as the light source of high density data storage in high definition digital versatile disk (HD-DVD) which is one of the popular data storage tools. Nevertheless, due to the applications, the high extraction efficiency of the light source needs to be improved and promoted. In general, there are two main methods to improve light extraction by mean of photonic crystal structure. One is the use of the photonic band gap (PBG) to inhibit the propagation of guided modes; the other is utilizing photonic crystal structure to couple guided modes to radiative modes.

E-beam lithography and laser interference lithography have been used to fabricate the photonic crystal structure. However, compared the two methods mentioned above to nanoimprint lithography (NIL)[2], NIL is suitable for the mass production of the LED and LD devices owing to its good resolution and higher throughput with low fabrication cost. In this paper, we demonstrated large area GaN-based 2-D photonic quasicrystals (PQC) structure. Such as the photonic quasicrystal structures possess 12-fold symmetry [3] and form a complete bandgap. Experimental results reveal that the device have lasing action with low threshold power density.

2. Fabrication Process

The following shows the fabrication flow of PQC structure. The GaN-based material was grown by a low pressure Metal-Organic Chemical Vapor Deposition (MOCVD) system on two-inch diameter (0001)-oriented sapphire substrates using trimethylgallium and trimethylaluminum as group III source materials and ammonia as the group V source material. A 2 μm thick GaN was first grown on a 2-inch C-plane (0001) sapphire substrate. The GaN contained 1 μm undoped GaN and 1 μm n-type GaN and were grown at 1150℃ and 1160℃, respectively. The photonic quasicrystal (PQC) lattices were formed by nanoimprint lithography (NIL) technique. First, a 400 nm SiO_2 layer and a 200 nm polymer layer were deposited as the masks during the process. Then a patterned mold of PQC structure was placed onto the dried polymer film. By applying a high pressure, the substrate was heated to above the glass transition temperature of the polymer. After that, the substrate and the mold were cooled down to room temperature to release the mold. The photonic quasicrystal (PQC) lattice patterns were defined on the polymer layer and the patterns were transferred into SiO_2 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 PQC structure contained the lattice constant a of 460 nm, diameter r of 160 nm, and the depth of 1 μm as shown Fig. 1(a) the schematic structure and (b) the scanning electron microscope (SEM) images (top view and angle view).

3. Results and Discussion

To demonstrate the lasing action from the photonic quasicrystal 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 50 μm. 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 lasing emission from the photonic quasicrystal pattern was observed as shown in Fig. 2. Figure 2(a) shows the measured spectra from the PQC pattern below (black-curve) and above (red-curve) threshold, and photoluminescence (gray-curve) of bulk GaN. Obviously, the lasing action was observed at 366 nm wavelength due to the distributed feedback of light at a photonic band edge of the PQC structure. The light-in and light-out (L-L) curve and the linewidth narrowing were shown in Fig. 2(b). Its threshold power density is approximately 0.009 kW/cm^2. This ultra-low threshold, which is one of lowest report thresholds for GaN lasers, also indicates the strong enhancement from photonic quasicrystal lattices.

In order to understand the lasing mode, we performed finite-element method (FEM) to calculate the transmission spectrum [4] of the PQC with the incident angles of 0, 5, 10, 15, 20 and 25 degrees as shown in Fig. 3(a). Since the

symmetry of this PQC, we can confirm the photonic band gaps with the spectra with. By comparing the experimental data and simulation, the observed lasing mode is corresponded to the normalized frequency is a/ λ ~1.25(circular point) around the bandedge, which is labeled with mode A. Fig. 3(b) shows the calculated mode profile of the mode A, which indicates the high symmetry of this operated mode in the PQC structure.

4. Conclusions

In short, a 12-fold symmetric GaN PQC nanopillars structure was fabricated using nanoimprint lithography (NIL) technology. The UV lasing action was observed around 366 nm wavelength with an ultra-low threshold power density of 0.009 kW/cm^2. And experimental results show excellent agreement with simulations. Due to the larger lasing emission of the device, we believe the large area of photonic quasicrystal structure which has the potential to light sources for the future applications.

References

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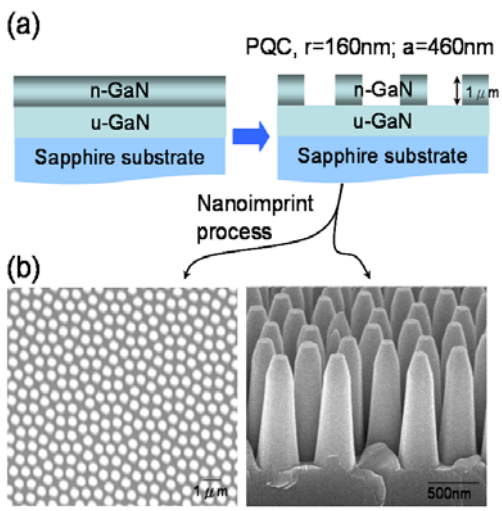

Fig. 1. (a) The schematic structure of the photonic quasicrystal patterns on epitaxial structure of GaN. (b) Top view and tilted angle view SEM images of the photonic quasicrystal structures.

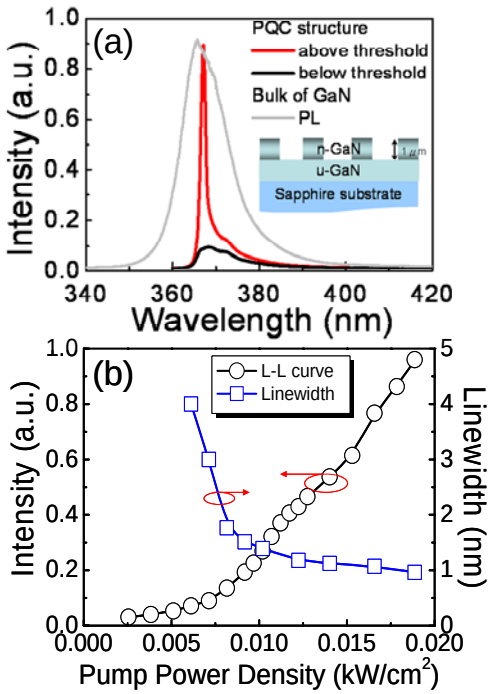

Fig. 2. (a) The measured spectrum of the PQC laser below (black) and above (red) threshold. And the photoluminescence (gray-curve) of bulk GaN. The lasing wavelength of the PQC is 366nm. (b) The light-in and light-out (L-L) curve and linewidth narrowing.

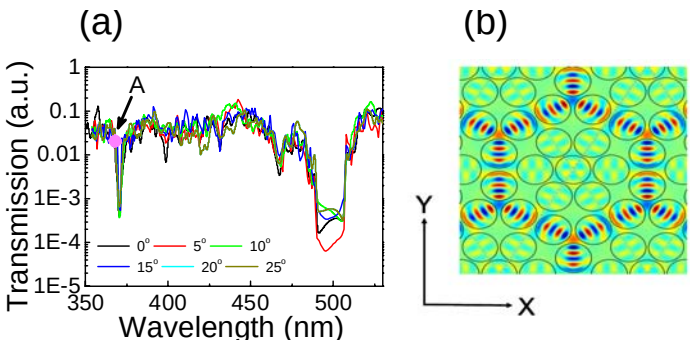

Fig. 3. (a)Transmission spectra as a function of normalized frequency a/ λ of the PQC structure. (b) The simulated mode H_z profile of mode A.