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Nonpolar GaN Two Dimensional Photonic Crystal Nanocavities

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Abstract

High quality factor nonpolar GaN two-dimensional photonic crystal (PC) nanocavities have been fabricated and investigated. A dominated resonant mode was observed at 388 nm with quality factor of about 4300 at 77K.

1. Introduction

Photonic crystals (PC), an artifact constructed with periodic index difference materials, have been widely studied and applied to active optoelectronic devices including light emitting diodes (LEDs) and photonic crystal lasers [1-3]. Basically, photonic crystal lasers can be divided into two types including photonic band-edge lasers and photonic defect lasers. For the photonic band-edges lasers, the specific Bragg diffraction would generate at band-edge position to produce surface emitting condition. So the laser oscillation in a large area can be expected and realized high power laser. On the other hand, photonic defect lasers employing photonic bandgap effect can confine the resonant mode in defect nanocavities with a thin membrane suspended in air. Usually, the photonic defect lasers were realized in GaAs or InP system [1, 3]. As for fabrication of thin membrane structure in GaN or ZnO system is relatively difficult. On the other hand, nonpolar GaN-based materials have been drew much attention due to the potential for development of the high performance light-emitting devices. The characteristics of these materials are free of polarization fields which can lead to high optical efficiency and fabrication flexibility [4]. Since there are no reports of nonpolar GaN PC nanocavities, in this letter, high quality factor nonpolar GaN PC H2 nanocavitites have been fabricated and demonstrated. The thin membrane structures were fabricated by focused-ion beam (FIB) and PC defect cavities were defined by e-beam lithography. One resonant mode was observed at 388 nm with quality factor of about 4300 at 77K. Moreover, the degree of polarization was measured to be 64%. Finally, the numerical calculation results were in a good agreement with the experimental results.

2. Experiment and Results

Nonpolar GaN samples were grown on r-plane sapphire by the metal-organic chemical vapor deposition (MOCVD) system. The a-plane GaN sample structure consisted of an ultrathin SiN_x layer, a 30 nm-thick AlN nucleation layer (NL) and a 2 μm-thick un-doped GaN. In the fabrication process, a 300 nm-thick SiN_x layer was deposited by plasma-enhanced chemical vapor deposition (PECVD) on the top of un-doped GaN as the hard mask. Then, poly-methyl methacrylate (PMMA) photoresist layer was coated on the sample by spin-coating. Subsequently, the PC H2 nanocavities were defined by e-beam lithography (EBL) and etched about 300 nm by reactive ion etching (RIE) down to SiN_x layer. Then, the PC patterns were etched down to GaN layer about 300 nm by inductively coupled plasma (ICP) dry etching. Finally, the FIB was utilized to fabricate the thin membrane structure with large air-gap by tilting the sample for ion-beam etching. Fig. 1 shows the SEM images of the nonpolar GaN PC H2 nanocavities. The number after H means the circle numbers removed from the central photonic crystal lattice. The radius and lattice constant of PC are measured to be 26.5 nm and 105 nm, respectively. The thickness of the thin membrane layer is 380 nm. Using plane wave expansion method, the corresponding band gap range of GaN PC H2 nanocavities can be calculated to be 350 nm to 402 nm. The photoluminescence emission peak wavelength of as-grown samples is located at 372 nm with a linewidth of about 20 nm measured by the micro-photoluminescence (μ-PL) system.

The fabricated nonpolar GaN PC H2 nanocavities were tested at 77K. A 325 nm He-Cd CW laser was used as the optical pumping source. The laser beam with a spot size of about 10 μm to cover the whole PC pattern was obliquely incident onto the devices. The μ-PL signal was collected by a 15X objective lens normal to the sample surface or by a fiber with a 600 μm core in the normal plane of the sample. The collected signal was then fed into a spectrometer (Jobin-Yvon IHR320 Spectrometer) with a spectral resolution about 0.07 nm.

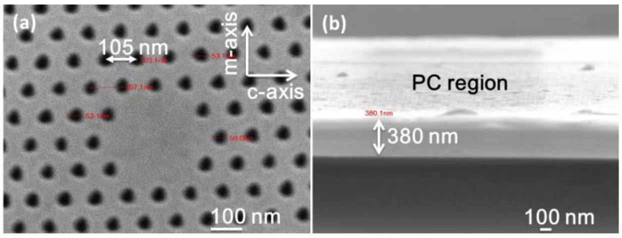

Fig. 1 (a). The plane view and (b) the cross section images of nonpolar GaN PC H2 nanocavities. The radius, lattice constant and thickness are measured to be 26.5, 105 and 380 nm, respectively.

Fig. 2 shows the optical characteristics of the planer sample and nonpolar GaN PC H2 nanocavities in μ-PL spectra. Compared with the emission spectra of planer sample, it can be seen only one resonant mode can be observed at 388 nm which is located in the band gap range. The red curve shows the Lorentz fitting curve of the experimental results. It indicates the linewidth is fitted to be 0.091 nm so that the quality factor can be estimated to be 4300. The high Q factor in the nonpolar GaN PC nanocavities reflects good optical confinement provided by photonic band gap and total internal reflection. This value is comparable with the previous reports of c-plane GaN PC nanocavities [5].

Fig. 3(a) indicates the degree of polarization (DOP) defined as $(I_{max}-I_{min})/(I_{max}+I_{min})$ where I_{max} and I_{min} are the maximum and the minimum intensity of the resonant mode peak. The measured DOP was calculated to be 64% and the polarization direction is along the *m*-axis. Typically, the polarized light can be observed for the *a*-plane GaN due to the fact that the dipole oscillation directions are tend to be perpendicular to the *c*-axis. As a result, the DOP value of the planer nonpolar GaN was measured to be approximately 46%. In order to understand the enhanced DOP value in the PC nanocavities, the 3D finite element method (FEM) was used to calculate the mode pattern at the same resonant wavelength. Fig. 3(b) represents the calculated magnetic field pattern which can be identified as the first order dipole mode. Fig. 3(c) shows the square of electric field pattern in the nonpolar GaN PC nanocavity. The warm and cold colors represent the maximum and minimum value. It can be observed that the strong spot of the electric field is also oscillating along the *m*-axis. The high DOP value of the nonpolar GaN PC nanocavity could be attributed to the specific electric field distribution along the *m*-axis enhancing the dipole oscillation.

3. Conclusions

In conclusion, high quality factor nonpolar GaN PC H2 nanocavities have been demonstrated. The nonpolar GaN PC H2 nanocavities were fabricated by e-beam lithography and the thin membrane layers were realized by focused-ion beam. In the μ-PL spectra, one resonant mode peak was observed at 388 nm with a high quality factor of approximately 4300 at 77K. Moreover, the degree of polarization was measured to be 64% due to specific electric field distribution along the *m*-axis enhancing the dipole oscillation of the nonpolar GaN. The 3D FDTD was carried out for calculation of the resonant wavelength and mode pattern. The calculated results were consisted with experimental results.

Acknowledgements

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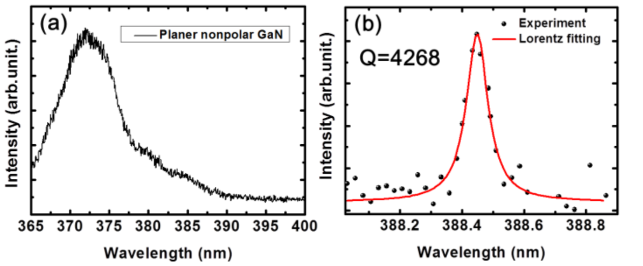

Fig. 2. The measured micro-PL spectra of (a) the planer sample and (b) nonpolar GaN PC H2 nanocavities at 77K. The quality factor of the resonant mode was measured to be 4268.

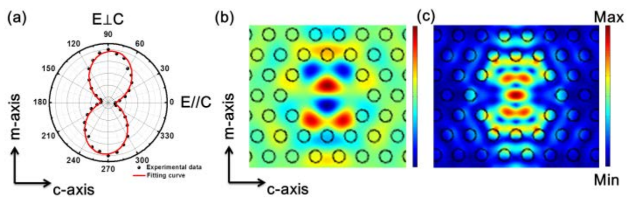

Figure 3 (a) The polar plot of the resonant peak intensity for the nonpolar GaN PC nanocavity. The degree of polarization was measured to be 64%. (b) The magnetic and (c) square of electric field patterns of the nonpolar GaN PC nanocavity at 385 nm using the 3D finite element method.