Photonic crystal point-shift nanolaser with ultimate small modal volume

K. Nozaki, T. Ide, J. Hashimoto, W.-H. Zheng and T. Baba

A photonic crystal nanolaser consisting of only the shift of two lattice points was fabricated by HI/Xe inductively coupled plasma etching. The room temperature lasing was observed by photopumping. The three-dimensional finite-difference time-domain calculation showed that the lasing mode has small modal volume close to \((\lambda/2\pi)^3\). Photonic crystal (PC) point defect nanolasers [1–4], which have very small modal volume, are promising for thresholdless operation and the enhancement of the spontaneous emission rate. Some groups have studied various cavity structures in a PC slab, and reported the lasing operation at room temperature by photopumping. We also observed the strong Purcell effect in the nanolaser by time-resolved photoluminescence measurement, in which more than 15-fold fast carrier decay was confirmed [4]. Recently, Zhang and Qiu theoretically discussed a novel cavity structure consisting of only the shifts of lattice points. The finite-difference time-domain (FDTD) calculation showed that 60 nm lattice shift of two holes without missing airholes can be a nanocavity with a difference time-domain (FDTD) calculation showed that 60 nm lattice cavity structure consisting of only the shifts of lattice points. The finite-difference time-domain (FDTD) calculation showed that 60 nm lattice shift of two holes without missing airholes can be a nanocavity with a modal volume close to \((\lambda/2\pi)^3\) [5]. Such a small mode will further improve the above performance. In this Letter, we report the fabrication of the point shift nanolaser and its lasing operation, for the first time.

In the device fabrication, we prepared a GaInAsP-InP epitaxial wafer having quaternary five compressively strained quantum-wells and separate confinement heterostructure layers. The total thickness of these layers was \(\sim 240\) nm. The photoluminescence peak wavelength was 1.58 \(\mu\)m. The PC airholes were formed by e-beam lithography and inductively coupled plasma (ICP) etching with HI/Xe gaseous source [6]. The membrane structure was formed by HCl selective wet etching. In the ICP etching, we set the HI/Xe flow rate, gas pressure, ICP power and bias power to be 0.2/0.1 sccm, 0.28 Pa, 100 and 300 W, respectively. The HI gas allows the etching at a relatively low temperature of 70°C. Therefore, the e-beam resist ZEP-520A, Zeon Inc., was directly used as an etching mask. This resulted in easy patterning and reduction in sidewall roughness of airholes, compared with the process using an intermediate metal or dielectric mask. Fig. 1a shows the top view of the fabricated device. The lattice constant and the airhole diameter are 0.42 and 0.20 \(\mu\)m, respectively. The photonic band calculation shows that these parameters provide a photonic bandgap (PBG) for a transverse-electric-like polarisation around a wavelength of 1.55 \(\mu\)m. The cavity was formed by shifting two airholes by 80 nm to opposite directions, as shown in Fig. 1a. Around this cavity, 20 rows of airholes were placed to obtain sufficiently high reflectivity of the PBG.

In the measurement, the device was photopumped at room temperature by 0.98 \(\mu\)m-wavelength pulsed laser light. The emission from the device was detected by an optical spectrum analyser. The duty ratio of the pulse was 0.075%. The focused spot diameter of the pump light was nearly 3.5 \(\mu\)m. Fig. 2 shows the mode peak intensity against irradiated power characteristic and the spectra for various pump levels. The clear singlemode lasing was observed with a peak wavelength of around 1.52 \(\mu\)m. The threshold is estimated to be 1.2 mW in pump pulse peak power. This value is almost the same as a threshold of 1.3 mW measured for the single defect cavity of one missing airhole, which was fabricated simultaneously. The lasing was observed only when the pump position overlapped with the cavity position. This clearly indicates that the lasing occurred just at the cavity.

It was difficult to precisely evaluate the near-field pattern of the lasing mode by the used optical microscope. Therefore, we checked the correspondence between the experimental and theoretical results to confirm that of the lasing mode. The FDTD calculation was carried out with the complete three-dimensional model similar to the device in the experiment. We assumed a slab index of 3.5 and eight rows of airholes around the cavity. The lasing spectrum in the experiment is compared with the calculated spectrum in Fig. 3. In the wide wavelength range of 1.45–1.65 \(\mu\)m, the calculation shows the singlemode spectrum, which corresponds well to the experimental result. As shown in Fig. 1b, the calculated magnetic field in the z-direction of the cavity mode shows a single antinode at the centre of the defect cavity. The modal volume according to the definition in [1] was estimated to be 0.012 \(\mu\)m\(^3\), which corresponds to 1.18\((\lambda/2\pi)^3\) for a slab index of 3.5.

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Fig. 1 Fabricated and calculated device

(a) Top view of fabricated device

(b) Magnetic field distribution of cavity mode calculated by FDTD method

Fig. 2 Laser mode peak intensity against irradiated power characteristic

Inset: Lasing spectra
Fig. 3 Experimental and calculated spectra  

**Conclusion:** We fabricated the GaInAsP PC slab nanolaser only with a lattice point shift by HI/Xe ICP etching, and observed the single-mode lasing at room temperature. By the three-dimensional FDTD calculation, the lasing mode was suggested to have an ultimate small volume. Such a small mode will enhance the Purcell effect and/or allows the strong coupling regime between a photon and an electron.

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