Laser characteristics with ultimate-small modal volume in photonic crystal slab point-shift nanolasers

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We recently reported the laser operation of a nanocavity consisting only of a shift in two of the lattice points in a GaInAsP photonic crystal slab. In this study, we investigated the laser characteristics in detail. For lithographic tuning, three different modes were observed, and good agreement between the experimental results and theoretical calculations performed using the finite-difference time-domain method was obtained. These results suggest that the fundamental mode has a modal volume of $0.02 \mu\text{m}^3 \sim 2.1(\lambda/2n)^3$, which is the smallest in any kind of laser. Such an ultrasmall modal volume will ensure efficient electron-photon coupling. © 2006 American Institute of Physics. [DOI: 10.1063/1.2206087]

Photonic crystal (PC) slab enables us to form a nanocavity having an ultrasmall modal volume and ultrahigh Q factor due to the strong optical confinement by the photonic band gap (PBG) and the high refractive index contrast.^{1–4} Thus far, the smallest modal volume V_m that has been obtained is $0.03 \mu\text{m}^3$ using a dipole mode in a PC slab point defect laser of one missing hole,¹ and the highest Q factor that has been obtained is $\sim 10^6$ by a line defect passive cavity with some shifted holes.⁵ These cavities achieve efficient electron-photon coupling in an emitting material, because the coupling is enhanced by the mutual resonance and the strong optical confinement of the small V_m ; enhancement of the spontaneous emission rate (Purcell effect) under the so-called weak coupling regime^{6,7} and vacuum Rabi splitting under the strong coupling regime⁸ have been observed in such cavities within the quantum-well or quantum-dot active region. It should be noted, however, that mutual resonance is determined not only by the cavity Q but also by homogeneous broadening of the electronic transition. Therefore, the extremely high Q does not always lead to efficient electron-photon coupling, since the small V_m sometimes becomes more important in determining the efficiency of this coupling. Recently, a theoretical investigation was done by Zhang and Qiu which describes a PC slab point defect cavity consisting only of the shift of two lattice points, i.e., the position of two holes, without the removal of any holes.⁹ By performing a finite-difference time-domain (FDTD) calculation they predicted that this cavity could achieve the smallest V_m of any kind of laser of $2.25(\lambda/2n)^3$, where λ is the modal wavelength in vacuum and n is the refractive index of the slab at the modal wavelength. We fabricated such a point-shift cavity in a GaInAsP slab and caused it to lase by pulsed photopumping at room temperature.¹⁰ In this study, we investigated its laser characteristics in detail and confirmed that they agreed well with the calculated results. The results strongly suggest that the laser action obtained was that of the smallest mode as predicted by the theoretical calculations.

In the fabrication, we prepared a $1.55 \mu\text{m}$, GaInAsP-InP epitaxial wafer with a slab active layer consisting of five quaternary compressively strained quantum wells (CS-QWs)

and separate confinement heterostructure layers. The total thickness of the slab was $\sim 240 \text{ nm}$. Holes arranged in a triangular lattice were formed in the slab by e -beam lithography and HI/Xe-inductively coupled plasma etching,^{11,12} and the airbridge structure was formed by HCl-selective wet etching. The HI gas allows etching at a low temperature of $\sim 70^\circ\text{C}$. Therefore, the e -beam resist was used directly as an etching mask, resulting in a simple and uniform patterning compared with the metal or dielectric mask process. Figure 1(a) shows the top view of the fabricated device and the Brillouin zone of the PC. The cavity was formed by shifting two neighboring holes to opposite Γ - J directions with respect to each other. Around this cavity, 20 rows of holes were added to ensure that the PBG had a sufficiently high reflectivity. The lattice constant a , normalized hole diameter $2r/a$, and normalized hole shift d/a , were designed to be $420\text{--}500 \text{ nm}$, $0.45\text{--}0.58$, and $0.08\text{--}0.20$, respectively. These parameters form a PBG at $\lambda \sim 1.55 \mu\text{m}$ for the in-plane polarization.

The measurement method was the same as that used in Ref. 10. The device was photopumped at room temperature by $0.98 \mu\text{m}$ pulsed laser radiation with a duty ratio of 0.075% and a focused spot diameter of $\sim 3.5 \mu\text{m}$. The emission from the device was detected directly using a sharpened optical fiber tip and analyzed by an optical spectrum analyzer. Clear laser action was observed only when the pump spot overlapped with the cavity. The lowest threshold of 0.4 mW was obtained using the smallest mode, as shown later. Figure 1(b) shows the laser spectra obtained by lithographic tuning of a and $2r/a$ when the hole shift was fixed to 80 nm . As $2r$ increases, the cavity length decreases and hence the mode peak is blueshifted. Although all of the spectra show single mode lasing, the continuity of the spectral shift indicates that three different laser modes A, B, and C appear for the case of lithographic tuning.

Figure 2(a) summarizes the normalized frequency a/λ of these modes as a function of $2r/a$ for all devices. The frequencies of A, B, and C are clearly separated and linearly blueshifted by $2r/a$. Figure 2(a) also shows the dependence of the frequencies on the hole shift d . A relatively large dependence is observed for A and B, while there is a very small dependence for C. In order to specify these modes, we per-

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FIG. 1. Point-shift nanolaser and observed laser characteristics. (a) Top view of fabricated device and the Brillouin zone. (b) Laser spectra observed for lithographic tuning of lattice constant a and normalized hole diameter $2r/a$.

formed a three-dimensional (3D) FDTD calculation, for which the experimental cavity was imaged using a high-resolution scanning electron microscope (SEM) and precisely modeled using a slab index n of 3.4 and 11 rows of holes around the cavity. In Fig. 2(a), the thick dashed lines show the results of the calculation. They are in good agreement with the experimentally obtained data points for A, B, and C. Each calculated line could fit the experimental data points when n and $2r/a$ have errors of $\pm 0.3\%$ and $\pm 15\%$, respectively. Such large errors are not possible given the small fluctuation in GaInAsP epilayers and the resolution of the SEM. Thus, we conclude that the fitting between the experiment and the calculation in Fig. 2(a) is quite reasonable. Figure 2(b) shows the magnetic field distribution normal to the slab H_z for each mode, which was calculated for $a=440$ nm, $2r/a=0.54$, and $d/a=0.18$. Figure 2(c) shows the corresponding spatial Fourier spectrum of the in-plane electric field. It can be seen from the field distributions that modes A and B are those strongly localized around the cavity. B is the smallest mode having a single maximum at the center, while A is the high-order mode having two maxima. In contrast, C has a widely spreading modal profile over the PC area. Since the Fourier spectrum of C shows strong peaks at the J point in the Brillouin zone, this mode is considered to be a two-dimensional Bragg diffraction mode near the photonic band edge, which is slightly modified by the point defect. The resonant frequency of this mode is mainly determined by the parameters of the PC, not of the defect. As a

FIG. 2. Cavity modes in the experiment and FDTD calculation. (a) Normalized frequency shift vs normalized hole diameter characteristics. Plots and solid lines show experimental results, while dashed lines show calculated results. Values in this figure show the hole shift d (nm). (b) Calculated magnetic field (H_z) distribution of each mode for $a=440$ nm, $2r/a=0.54$, and $d/a=0.18$. (c) Spatial Fourier spectrum of each mode. Circular and hexagonal dashed lines denote the air light line and the Brillouin zone, respectively.

result, C was not sensitive to the hole shift d , as shown in Fig. 2(a).

Figure 3(a) shows Q and V_m of the smallest mode B calculated for the normalized hole shift d/a by the 3D FDTD method. Here, we employed the definition of V_m given in Ref. 1. The maximum Q of 65 400 and the smallest V_m of $0.02 \mu\text{m}^3 \sim 2.1(\lambda/2n)^3$ were estimated by taking $2r/a=0.54$ and $d/a=0.14$. Even though Q is generally proportional to V_m , Fig. 3(a) shows an inverse proportional relationship between the two quantities. This suggests that Q is influenced more strongly by the modal frequency and profile than by V_m . For a small d/a around 0.05, the low magnitude of Q is mainly due to the high modal frequency near the air band of the PC slab. For larger d/a , Q is mainly determined by the Fourier component inside the light line, that is, the out-of-plane radiation loss, as shown in Fig. 2(c). In the experiment, it is difficult to precisely estimate the Q factor of the active cavity, because wavelength chirping due to carrier dynamics under the pulsed photopumping condition broadens the modal spectrum. Also, the huge thermal heating in the PC slab under the continuous wave pumping condition¹³ perturbs the estimation of the modal spectrum at the transparent carrier density. Therefore, we estimated the change in the Q factor using the laser threshold. Figure 3(b) shows the threshold versus d/a characteristics measured for mode B. The threshold for $2r/a=0.49$ and 0.52 exhibits valley-type

FIG. 3. Relation between Q factor, modal volume V_m , and laser threshold. (a) The Q and V_m vs $2r/a$ characteristics calculated by FDTD method for $a=440$ nm and $2r/a=0.54$. (b) Measured threshold for samples with various d/a . (c) Measured threshold summarized with laser wavelength. Dashed line shows the PL spectrum for the as-grown wafer.

characteristics and takes their minimum values at $d/a=0.18$ and 0.20 , respectively. They agree well with the characteristics of the calculated Q factor. Figure 3(c) shows the threshold versus laser wavelength characteristics for the same devices. The laser wavelengths at the lowest threshold for $2r/a=0.49$ and 0.52 are 20 and 60 nm longer, respectively, than the photoluminescence (PL) peak of the as-grown wafer of $1.55 \mu\text{m}$. It should be noted that the PL peak of the as-grown wafer and that of the PC slab are not always the same, because the PL spectrum can be redshifted by the strain relaxation in CS-QWs inside the airbridge slab.¹⁴ However, the redshift expected in our experiment is nearly 30 nm. Therefore, this effect cannot reasonably explain the threshold characteristics. Thus, it is concluded that the threshold was determined by the device structure rather than the gain spectrum. This result also suggests that the threshold can be

further reduced by fine tuning of the lowest threshold wavelength to the gain peak.

In conclusion, we have observed three different modes in the point-shift nanolaser in a triangular lattice GaInAsP PC slab. The FDTD calculation supports the premise that one of the laser modes corresponds to that with an ultimately small modal volume V_m of $\sim 2.1(\lambda/2n)^3$. This V_m is the smallest value for any kind of laser. Furthermore, the experimental threshold of this mode was dependent on the calculated Q factor determined by the structure. The maximum theoretical value of Q of $\sim 65\,400$ is sufficiently high when compared with the homogeneous broadening of the quantum-well or quantum-dot active region. This means that ultimately a strong electron-photon interaction should be achievable in such a nanolaser.

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