Fabrication of GaInAsP/InP Photonic Crystal Lasers by ICP Etching and Control of Resonant Mode in Point and Line Composite Defects

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Abstract—We theoretically and experimentally investigated lasing and resonant characteristics in photonic crystal lasers with point defects and/or point and line composite defects. The finite-difference time domain simulation showed that various resonant modes can occur in arbitrary defect geometries. A GaInAsP airbridge photonic crystal slab with a lattice constant of $\sim 0.42 \mu\text{m}$, a hole diameter of $\sim 0.25 \mu\text{m}$, a sidewall angle of $\sim 90^\circ$, and a sidewall roughness of $\sim 10 \text{ nm}$, was fabricated by Cl_2/Xe inductively coupled plasma etching, in which ions and radicals were balanced by optimizing the gas pressure and the bias voltage. The room temperature pulsed lasing was observed with a threshold irradiated power of 1.4 mW by photopumping. The possibility of the continuous-wave (CW) lasing was also discussed with the estimation of the thermal resistance. The mode control in some composite defects was confirmed from resonant photoluminescence peaks under CW condition.

Index Terms—Defect laser, GaInAsP/InP, ICP etching, photonic band, photonic bandgap (PBG), photonic crystal (PC), semiconductor laser.

I. INTRODUCTION

PHOTONIC crystals (PCs) are multidimensional periodic structures with a lattice constant of optical wavelength order. Because of the strong control of light by the photonic bandgap (PBG), their applications to optoelectronics have become worldwide topics. Since two-dimensional (2-D) PCs can be fabricated by the planar technology with a lithography and a dry etching, many groups have studied point-defect PC lasers [1]–[6] and filters [7], [8] and line-defect PC waveguides [9]–[15]. Here, we focus on the PC lasers.

In most PC lasers, GaInAsP/InP compound semiconductor and the PC-slab structure with the hole arrangement have been used. This material is advantageous to such nanostructure light emitters due to its small surface recombination [16]. To obtain a PBG at its emission wavelength of $\lambda = 1.5\text{--}1.65 \mu\text{m}$, the PC slab is typically designed with a lattice constant of $0.4\text{--}0.5 \mu\text{m}$

and a hole diameter of $0.2\text{--}0.3 \mu\text{m}$. The room temperature lasing by pulsed photopumping was reported for various size point defects [1]–[6]. However, the typical threshold irradiated power is of milliwatt order. In addition, multimode lasing is a problem in a larger cavity due to the many allowed modes. It occurs even in a single defect cavity due to the splitting of degenerate modes [17]. As solutions to these problems, modified defects were studied, which improved the Q factor and restricted the number of modes, [3], [5], [17] but the discussion was limited to single defect cavities. The first purpose of this study is to discuss the dominant factor for the lasing performance and a more universal mode control using a composite of point and line defects with various sizes and shapes.

The second purpose is to establish a fine-etching process of GaInAsP/InP. In the fabrication of PC slabs, holes are opened in a GaInAsP slab of $0.2\text{--}0.3\text{-}\mu\text{m}$ thickness. Since aspect ratios of such holes and bridges between holes are no larger than three, the etching process is generally thought to be easy and has not been fully discussed. Due to the insufficient optimization, the sidewall angle of holes is typically 80° [1]. Such a tilted sidewall causes an etching damage induced into the sidewalls. In addition, the PBG occurs in PC slabs only for the polarization parallel to the slab plane (TE-like polarization), and a loss occurs due to the coupling of this polarization with the orthogonal polarization (TM-like polarization) for tilted sidewalls [18]. Thus, the optimization of the etching for vertical sidewalls and low etching damage is important. As etching techniques of GaInAsP, Cl_2 -based chemically assisted ion beam etching (CAIBE) [1]–[3], [5] and CH_4 -based electron cyclotron resonance (ECR) plasma etching [16], and reactive ion etching (RIE) [7] have been used. In general, however, a smooth-etched profile is difficult to obtain by Cl_2 -based etchings at room temperature due to the low vapor pressure of indium chloride. In the CH_4 -based etchings, a low etch rate and a small aspect ratio are problems. Recently, Cl_2 inductively coupled plasma (ICP) etching is attracting attention as a technique that simultaneously achieves a high etch rate, a high aspect ratio, and a smooth-etch profile [19], [20]. The inductive coupling generates high-density plasma with a high ionization rate, and allows the optimization of etching condition with many independent etching parameters.

In this paper, we present the following three subjects: 1) the mode analysis for line defects, point defects and composite defects; 2) the fabrication of vertical and smooth holes of the GaInAsP PC slab by Cl_2 -based ICP etching; and 3) lasing characteristics in PC slab point defect and composite defect lasers. In Section II, we will show the mode analysis. The discussion

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is limited to 2-D models to simply explain resonant modes in various defect geometries. For this purpose, we used the finite difference time-domain (FDTD) method and the photonic band calculation. In Section III, showing some ICP etching characteristics, we will discuss the optimum condition as well as the etching mechanism in small aperture holes. In Section IV, we will show room temperature lasing and resonant characteristics obtained by pulsed or continuous-wave (CW) photopumping. We will discuss the dominant factor for lasing, the mode control in composite defects, and the thermal resistance, which should be reduced for CW lasing.

II. RESONANT MODES IN VARIOUS DEFECTS

Let us consider a 2-D PC with the triangular lattice of holes (refractive index $n_a = 1.0$) in a background medium (n_b). A 2-D photonic band diagram calculated by the plane-wave expansion method is shown in Fig. 1(a). Here, we assumed a normalized hole diameter $2r/a$ of 0.64 and $n_b = 2.73$ (typical modal index of the slab with a thickness of $0.24 \mu\text{m}$ and an index of 3.4 at $\lambda = 1.55 \mu\text{m}$ for TE polarization). The number of plane waves is 313. A PBG lies in a normalized frequency range $\omega a/2\pi c = 0.262\text{--}0.344$, where c is the light velocity in vacuum. The photonic band diagram for PC with the single line defect in $\Gamma - J$ direction is shown in Fig. 1(b). Here, the number of plane waves is 5253. Bands of two waveguide modes appear in the PBG. They arise from a zone-folded band supported by the index confinement and an anticrossing band supported by the PBG confinement [10], [15]. However, these bands do not necessarily cover all of the PBG range; a cutoff region lies at $\omega a/2\pi c = 0.262\text{--}0.272$.

On the other hand, when a point defect is introduced into the PC, the resonant mode occurs in the PBG. The change of the resonant frequency was calculated by the FDTD method as a function of the point defect size, as shown in Fig. 2. In the calculation, one side of the Yee cell is 20 nm, and the Berenger's perfectly matched layer condition (128 layers) is used as an absorbing boundary condition. Basic structural parameters of the PC are the same as those for Fig. 1. The finite-size model of the PC was a hexagon composed of eight rows of holes from the center to the edge. The size of the point defect is enlarged such that, from H0 to H1, the diameter of the center hole is decreased, from H1 to H2, that of surrounding six holes is decreased, and from H2 to H3, that of further surrounding 12 holes is decreased. In actual FDTD spectra, we observed a narrow splitting of each peak, which arises from the break of degeneracy by a small asymmetry in the modeled structure by the square Yee cell. Such a break of degeneracy is also observed in a fabricated device with a small asymmetry [1], [17]. To simplify the figure, we plotted the average frequency for each splitting modes by a thick curve, while we plotted the frequency for each nondegenerate mode by a thin curve. Fig. 2 shows that the number of modes increases in a larger cavity. The GaInAsP active layer, which will be discussed later, has an emission wavelength range of $\lambda = 1.48\text{--}1.61 \mu\text{m}$. This range corresponds to $\omega a/2\pi c = 0.27\text{--}0.30$ for $a = 0.44 \mu\text{m}$, and this absolutely covers the PBG. Thus, the multimode resonance is an issue in a larger defect.

Fig. 1. Photonic band diagram of triangular lattice hole type 2-D PC. Normalized hole diameter ($2r/a$) = 0.64, refractive index of holes $n_a = 1.00$, and that of background medium $n_b = 2.73$. TE polarization is assumed. (a) PC without defect. (b) PC with single-line defect. The model and Brillouin zone of PCs are also shown.

Figs. 3 and 4 show resonant mode profiles in various line defects, which were calculated by the FDTD method. Fig. 3(a)–(d) are cavities in which 0° , 60° , 120° , and 180° bends of the single line defects are used, respectively. (Here, 0° bend means a simple straight-line defect and 180° bend means a straight line defect terminated at the center.) Fig. 3(e) is similar to Fig. 3(c), but a half diameter hole is placed at the terminated end. Fig. 3(f) is a Y branch composed of three line defects. In Fig. 3(a)–(c), resonant peaks appear at $\omega a/2\pi c = 0.305$ and 0.315 . They are overlapping with the waveguide band. Profiles of these modes in Fig. 3(a) and (c) are not localized but spread along the line defects. Thus, they are considered to be the resonance depending on the waveguide band with zero group velocity. Since the phase change along the line defects is very slow, they are arising from the band edge near the Γ point. For 3(b) and (d), other reso-

Fig. 2. Resonant frequency of the same PC as for Fig. 1, which has a different size point defect. H0–H3 denote point defect cavities with 0, 1, 7, and 19 missing holes, respectively.

Fig. 3. Various cavity profiles and corresponding magnetic field distributions of resonant modes, which are calculated by the FDTD method. Structural parameters are the same as those for Fig. 1. (e) is the single line defect terminated at the center of PC with half diameter hole.

nant modes are observed, which are localized at the bend. Their resonant frequencies are lying inside the cutoff condition of the waveguide band. For Fig. 3(e), the spectrum shows a single peak and the mode is localized at the terminated end of the line defect. The resonant frequency is determined by the half hole diameter, so can be changed by the hole size. In Fig. 3(f), major resonant peaks are lying at 0.268. This frequency is also overlapping with the cutoff region of the waveguide band, and mode profile is localized at the branch.

Fig. 5(a) is the H2 cavity [21], which consists of seven missing holes, and Fig. 5(b) is a composite cavity of H2 and

Fig. 4. Resonant spectra corresponding to Fig. 3(a)–(f).

Fig. 5. Cavity profiles and corresponding magnetic field distributions of resonant modes in point and composite defects. Calculation parameters are the same as for Fig. 3. (a) H2 defect. (b) Composite of H2 defect and three line defects.

Fig. 6. Resonant spectra corresponding to Fig. 5(a) and (b).

three line defects. As shown in Fig. 6, the multimode resonance occurs in (a), while only mode at $\omega a/2\pi c = 0.262$ is very clear in (b). Although there are other weak resonant peaks for (b), the Q factor of the main mode is 1600, while those of other modes are less than 100. This is the evidence that other modes are radiated out from the PC through the line defects. As shown in Fig. 5(b), the main mode is well localized at the cavity even with the line defects. Its profile is almost the same as that of H2 mode at $\omega a/2\pi c = 0.268$. This can be explained such that the optical confinement of mode at $\omega a/2\pi c = 0.262$ is maintained by the cutoff condition of the waveguide band.

We used 2-D models in the above calculations, while we fabricated PC slabs in the experiment, as described in the next section. For a better understanding of light behavior in the three-dimensional (3-D) structure of the PC slab, we showed the air-light line in Fig. 1. In the calculation of Fig. 1, the equivalent index of the slab was assumed as a background index. We showed previously that the 2-D photonic bands well approximate the precise 3-D bands around the PBG [10]. Therefore, the light line of Fig. 1 roughly gives the boundary of the confined mode and the leaky mode. The resonant modes arising from the band-edge characteristic near the Γ point may have a low Q factor, since the band-edge locates above the light line. The localized modes also suffer some leakage loss, since they have in-plane k vector component above the light line. In Figs. 1 and 4, it is expected that resonant modes with frequencies absolutely above the light line have low Q factors. Therefore, a high Q single-mode resonance will be realized by the lowest frequency mode in Fig. 3(d) and (f).

III. FABRICATION PROCESS

We fabricated PC slabs with a triangular lattice of densely packed holes. We used an epitaxial wafer with a GaInAsP active layer of 243-nm thickness. The active layer consisted of five layers of 1% compressively strained quantum well (CS-QW) of 4.6-nm thickness, and the 1.2- μm -quaternary (Q) barrier layer of 10 nm thickness. It also included 1.2-, 1.15-, and 1.1-Q separate confinement heterostructure (SCH) layers of 30 nm in thickness each, both above and below the CS-QWs. Against the strong photopumping, the emission spectrum ranged from 1.48 to 1.61 μm , with a peak wavelength of 1.56 μm . The active layer was covered with 0.5- μm -thick InP layer to suppress the process damage induced into the active layer. The lattice constant of the PC a was 0.40–0.48 μm and the hole diameter $2r$ was 0.20–0.30 μm . Under these conditions, the emission wavelength overlaps with the PBG. In the fabrication process, Ti and Ni were evaporated on the wafer as an etching mask. Next, the resist pattern was formed by electron-beam lithography, and transferred to Ti by CF_4 -RIE and to Ni by Ar ECR plasma etching. Then, holes were formed by Cl_2/Xe ICP etching. After Ti was removed simultaneously with Ni by HF, InP beneath the active layer was selectively etched by HCl solution to form the PC slab.

As an ICP etching machine, we used RIE-200ip of Samco International Company Ltd. It generates ICP plasma by a tornado-type coil. The etching was done on a temperature-controlled 2-in InP wafer with applied rf bias. For a smaller sample, we pasted it on the InP wafer by a thermally conductive grease so that the etched area was kept constant. Basic conditions were bias voltage of 100–300 V, a Cl_2 flow of 20 sccm, and gas pressure of 0.3–2.0 Pa. Xe was mixed into the etching gas to stabilize the plasma. The etch rate drastically decreased for a substrate temperature less than 200 $^\circ\text{C}$, due to the change of the vapor pressure of indium chloride. On the other hand, the increase in etch rate was gradual at above 200 $^\circ\text{C}$ and almost saturated at above 250 $^\circ\text{C}$. Thus, in all experiments, we fixed the temperature to 280 $^\circ\text{C}$, the settable highest temperature of the etching machine.

Fig. 7. Etch-rate versus gas-pressure characteristics for Cl_2/Xe ICP etching of InP narrow aperture hole. Hole diameter is 0.24 μm . Cl_2 flow rate is 20 sccm, and Xe flow rate is 1 sccm. Substrate temperature is 280 $^\circ\text{C}$. Open circles are for bias voltage of 200 V and closed circles are for 220 V.

Fig. 8. Cross sections of holes fabricated by the Cl_2/Xe ICP etching. Bias voltage is 200 V. Other conditions are the same as for Fig. 7. Gas pressure are (a) 0.5 Pa and (b) 1.0 Pa.

As discussed later, the etched profile by the ICP etching is determined by the complex behavior of ions and radicals, which is related with etching parameters. Therefore, the optimization of etching condition is necessary even for the slab thickness less than 0.3 μm . Particularly in this experiment, the hole must reach the InP substrate from the top InP cover layer after the ICP etching. Therefore, an etching depth of ~ 1 μm is necessary. Considering the hole diameter, the aspect ratio of holes is 4–5. Vertical sidewalls of such holes cannot be formed without the optimization of the ICP etching condition. Fig. 7 shows the etch rate of a 0.24- μm -diameter hole measured by changing the bias voltage and the gas pressure. Fig. 8 shows corresponding etched profiles. In general, the etch rate showed two different characteristics with gas pressure. At a bias of 200 V, the etch rate decreased rapidly with increasing pressure up to 1.0 Pa, but it became almost constant for a pressure above 1.0 Pa. Below 0.6 Pa, the bottom shape of holes became taper-like, as shown in Fig. 8(a), while above 1.0 Pa, the side etch became evident, as shown in Fig. 8(b). These characteristics indicate that the etching by vertically incident ions into holes is dominant in a low gas pressure, while the etching by obliquely incident ions and radicals is dominant in a high gas pressure. In a high gas pressure, the mean free path of ions is shortened, so ions collide with other particles in the ion sheath and obliquely enter

Fig. 9. Cross-sections of holes under balanced condition for bias and gas pressure, which can form the vertical sidewall. Bias/gas pressure are: (a) 100 V/0.5 Pa; (b) 200 V/0.7 Pa; and (c) 300 V/1.5 Pa. Other conditions are the same as for Fig. 7.

the holes. As a result, ions that reach to the bottom are limited, which causes the decrease in the etch rate and the increase in the side etch. Moreover, radicals that contribute to the isotropic etch further increase the side etch [22]. On the other hand, in a low gas pressure, vertically incident ions easily reach the bottom and increase the etch rate. However, due to the low vapor pressure of indium chloride, reactive products by the etching at the bottom readhere to the sidewall, and makes the hole shape taper-like. For the vertical sidewall, it is necessary to control the side etch in a high gas pressure and the taper-like shape in a low gas pressure. We realized sidewall angle of 88° – 91° in a middle pressure of 0.7–0.8 Pa, as shown in Fig. 9.

When the gas pressure was fixed and the bias was increased, the etch rate was increased and the hole shape became taper-like. On the contrary, when bias was decreased, the etch rate was decreased, and the side etch was increased. In the former case, the ion sheath became thick, and incident ions were increased, so the etch rate was increased. This reduces the influence of radicals and strengthens the influence of vertically incident ions. Therefore, a high bias condition is equivalent to a low gas pressure condition. In the latter case, ions were not sufficiently accelerated, so incident ions were decreased, and the influence of radicals became dominant. Therefore, a low bias condition is equivalent to a high gas pressure condition. The balance of two etchings is realized by the combination of a low gas pressure and a low bias, or a high gas pressure and a high bias. Let us check the etched profile, when keeping this balance. Holes formed by bias/gas pressure conditions of 100 V/0.5 Pa, 200 V/0.7 Pa, and 300 V/1.5 Pa are shown in Fig. 9. Under the high bias and high gas pressure condition shown in (c), the sidewall is rough, since ions that do not reach to the bottom of holes attack the mask and sidewalls. In the low bias and low gas pressure condition shown in (a), such excess ions are decreased, so the sidewall becomes smooth. The relation between the sidewall roughness and the gas pressure is summarized in Fig. 10. Here, the roughness was measured by a high-resolution scanning electron microscope. The bias was changed simultaneously with the gas pressure so that the sidewall angle of 88° – 91° was maintained. Under low gas pressure and low bias condition, a sidewall roughness of nearly 10 nm was obtained.

IV. DEVICE CHARACTERISTICS

Using the optimum etching condition shown in Section III, the following 12 structures were fabricated: (A) single defect

Fig. 10. Sidewall roughness versus gas-pressure characteristic, which corresponds to Fig. 9.

Fig. 11. Fabricated PC defect lasers. Upper figures are patterns. Lower pictures are (left) airbridge PC slab, (center) H2 cavity, and (right) composite of H2 and 3 line defects.

cavity called H1; (B) three missing hole cavity; (C) ring cavity of six missing holes; (D) H2 cavity; (E) H3 cavity; (F) H4 cavity; (G) H7 cavity, and composite cavities of (H) H2 and 3 lines; (I) H3 and 3 lines; (J) H7 and 3 lines; (K) H7 and 9 lines and (L) H7 and 6 lines, as illustrated in Fig. 11(a). The cross-sectional view of the PC slab, and top views of (D) and (H) are shown in Fig. 11(b). In the measurement, the device sample was placed on a metal submount. Laser light of 980-nm wavelength from a singlemode fiber was focused using $\times 50$ objective lens to $\sim 5 \mu\text{m}$ in diameter at $1/e^2$ of peak intensity, which almost covered the cavity area. The pump laser was driven by pulsed or CW current. The emission from the PC was collected to another detection fiber through the same objective lens, and analyzed by optical spectrum analyzer. Lasing characteristics observed for

Fig. 12. $L - L$ characteristics of PC defect lasers at room temperature under pulsed condition. Open circles are for H2 cavity (D), open triangles are for H4 cavity (F), open squares are for H7 cavity (G), and closed squares are for composite defect (J). Pulse width is 75 ns and the repetition cycle is 500 μ s.

Fig. 13. Spectra for PC defect lasers, which correspond to Fig. 12. Numbers in the figures denote irradiated power in a unit of milliwatt.

(D), (F), (G), and (J) are shown in Figs. 12 and 13. The lasing was confirmed from the abrupt increase in mode intensity for each device. Threshold irradiated powers for those devices were 1.4, 1.8, 1.8, and 2.5 mW, respectively. Here, the measured pulse width of irradiated light was 75 ns and the repetition cycle was 500 μ s (duty ratio of 0.015%). The lasing was also observed up to a duty ratio of 0.98% (the limit of the used driver). For a higher duty ratio, two or three more lasing peaks appeared in the longer wavelength region, which indicates the red shift of the gain spectrum by the temperature increase. Linewidths of the spectra were 0.5–1 nm, which were wider than the resolution limit of 0.3 nm in this measurement setup. It is due to multiple peaks arising from the break of degeneracy, as mentioned in Section II, and the wavelength chirping by the thermal effect and/or by the carrier dynamics. In Fig. 13, only (F) exhibited clear multiple peaks. But for other types of devices, we also observed such multiple peaks in some device samples. We also confirmed the thermal effect; the linewidth was expanded

up to 2 nm in (G), when the duty ratio was increased to 0.98%. Regarding the carrier dynamics, we have no clear evidence, but we doubt it for such device structures with no carrier confinement mechanism.

The effective cavity area of H2 cavity (D) was calculated to be 1.76 μ m in diameter, by integrating the mode energy localized around the cavity and converting it to that in a cylindrical closed cavity. If only this effective area can be photopumped and there is no carrier loss by the diffusion, the threshold power will be 8 μ W for a Q factor of 3000, even considering the typical surface recombination [23] at sidewalls of holes included in the effective area. On the other hand, considering the ratio of the effective area to the light irradiated area, a surface reflection of $\sim 30\%$, a typical absorption coefficient of the slab of 20 000 cm^{-1} , and a slab thickness of 243 nm, the effective pump power corresponding to the threshold irradiated power of 1.4 mW was estimated to be 68 μ W. This difference may arise partially from a lower Q value. However, the dominant factor is considered to be the carrier diffusion that reduces the carrier density inside the effective area. For $Q = 1000$, the experimental result can be explained, when the carrier diffusion length is assumed to be 2.2 μ m. We think that such an extraordinary long diffusion length was effectively estimated by a very fast carrier decay outside the effective area, due to the large surface recombination and the drift current from the effective area to the outside area, which should be caused by the electron potential induced by the strain relaxation in the CS-QW near the holes [24].

In Fig. 12, the threshold irradiated power tends to be higher for a larger cavity, even though the diameter of the spot diameter of irradiated light was as large as 5 μ m and kept constant for these devices. It can also be explained by the influence of the carrier diffusion. As mentioned above, the effective diameter of H2 cavity (D) was much smaller than the spot diameter. Since the outside area was also photopumped, the carrier diffusion was rather suppressed and the minimum threshold was obtained. On the other hand, the effective cavity diameter of H7 cavity (G) was slightly larger than the spot diameter. Under this condition, the carrier diffusion to the outside area, where the photopumped carriers were absent, was enhanced. As shown in Fig. 12, the threshold of the composite defect laser (J) is higher than that of (G). As well as the further enhanced carrier diffusion, the decrease in Q factor is also considered as a reason for this. It was indirectly verified in the FDTD calculation in Fig. 6; the Q factor was calculated to be 1600 for composite cavity (H) at $\omega a/2\pi c = 0.262$, while 2500 for H2 cavity (D) at $\omega a/2\pi c = 0.268$. This indicates the possibility that the optical confinement was slightly weakened in the composite defect against constant rows of holes from the cavity to the edge of the PC.

The CW lasing at room temperature has not been reported yet for a simple slab-type structure. In this experiment, it was also difficult. However, resonant emission peaks were observed for most of all the structures, as shown in Figs. 14 and 15. Here, resonant spectra by the 2-D FDTD calculation are also shown as a reference. It is clearly seen in Fig. 14 that the number of resonant modes was increased by enlarging the cavity size. It is also observed in Fig. 15 that the number of modes in the composite cavities (I)–(L) was reduced, compared with those in H3 cavity

Fig. 14. Comparison of resonant spectra of point defect cavities with various sizes. (a) Defect profiles. (b) Center are resonant spectra by the 2-D FDTD calculation. (c) Spectra in the experiment under CW condition.

Fig. 15. Comparison of resonant spectra of point defect cavities and composite defect cavities. Left, right, and center are the same as those in Fig. 14. (a) H3 cavity and its composite. (b) H7 cavity and its composite.

(E) and H7 cavity (G). This is the evidence of the composite defect effect, i.e., the modes overlapping with the waveguide band is suppressed by the radiation loss. In Figs. 14 and 15, some differences between the theory and the experiment are seen. They are considered to arise from the fabrication error and/or the difference in dimension.

When the CW irradiated light power was increased against the H7 cavity (G), the red shift of resonant peaks was observed. This was caused by the refractive index change of the semiconductor with the temperature increase. The thermal resistance R of the device is

$$R = \frac{\Delta T}{\Delta W} = \frac{\Delta T}{\Delta \lambda} \cdot \frac{\Delta \lambda}{\Delta W}. \quad (1)$$

By plotting the relation between the wavelength shift $\Delta \lambda$ and the change of absorbed power by the slab, ΔW , $\Delta \lambda / \Delta W$ was

estimated to be $0.025 \text{ nm}/\mu\text{W}$. However, this shift not only includes the pure red shift by the temperature increase but also a blue shift by the carrier plasma effect [25]. After this blue shift was taken into account, the pure red shift was estimated to be $0.050 \text{ nm}/\mu\text{W}$. The typical value for $\Delta \lambda / \Delta T$ caused by the index change for a similar GaInAsP slab has been estimated to be 0.11 nm/K [25]. From these results, $R = 0.45 \text{ K}/\mu\text{W}$ was derived. This value is ten times or more higher than that for a GaInAsP microdisk laser [26], which has similar air claddings and a similar cavity area to that of H7 cavity (G). Against such a large value, the temperature increases by 45 K even when the threshold is as low as $100 \mu\text{W}$. The CW lasing and a practical operation will not be obtained unless the effective threshold pump power is less than $25 \mu\text{W}$ or the thermal resistance is drastically reduced by a heat sinking structure. It was shown that the bonding of the slab to a low refractive index substrate with a high thermal conductivity is effective for heat dissipation and CW operation [27]. As another easier method, the introduction of InP post as in a microdisk is supposed. The thermal resistance of InP post of $50 \text{ W/K}\cdot\text{m}$ thermal conductivity, $1\text{-}\mu\text{m}^2$ cross-sectional area and $2\text{-}\mu\text{m}$ height is $0.04 \text{ K}/\mu\text{W}$. This small resistance will reduce the total thermal resistance of the device to ten times lower, which is of the same order as that for microdisk lasers. Unfortunately, the mode profile discussed here has some field intensity near the defect center. Therefore, the post will cause some amount of scattering loss. However, if the mode profile is optimized so that it looks like a whispering gallery mode, as discussed in [28], the scattering loss will be avoided. Once the post structure is realized, the current injection will also be possible, as in microdisk lasers.

V. CONCLUSION

Photonic band and FDTD calculations showed various high Q resonances in point defects, line defects, and composite defects in a 2-D PC. Composite defects have unique potentials for the mode control, such as the singlemode resonance. In the experiment, the Cl_2 -based ICP etching of GaInAsP was optimized by controlling the gas pressure and the applied bias, which suppressed the taper-like shape or the side etch. This allowed a high-quality PC slabs which consisted of holes of $88^\circ\text{--}91^\circ$ sidewall angle and $\sim 10\text{-nm}$ sidewall roughness. Consequently, room temperature lasing by pulsed photopumping was obtained in PC lasers with H2–H7 point defect cavities and a composite defect cavity of H7 and line defects. The irradiated threshold power was 1.4 mW and the corresponding effective pump power was $68 \mu\text{W}$. The comparison of this value and a theoretical value of $8 \mu\text{W}$ indicated that the carrier diffusion strongly accelerated by the surface recombination at holes is a dominant factor that determines the threshold. Therefore, the carrier confinement is one of the most important issues for a high-performance lasing. The measurement of resonant emission spectra under CW condition showed that resonant modes are strongly dependent on the cavity size and that excess modes can be suppressed in the composite defects. A high thermal resistance of $0.45 \text{ K}/\mu\text{W}$ was estimated for a H7 cavity device. Its drastic reduction will be possible by using an InP post at the cavity center.

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