Vertical-cavity surface-emitting laser operating with photonic crystal seven-point defect structure

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A vertical-cavity surface-emitting laser with a two-dimensional photonic crystal (PC) structure has been investigated for single lateral mode operation. The PC confined mode can be controlled by the lattice constant, the hole diameter, the etching depth, and the defect structure. A seven-point defect structure is proposed to enhance the confinement effect, which is diluted by finite hole depth of the PC structure. We obtained a pure PC confined mode under room-temperature cw conditions with a PC lattice constant of 2 μm, hole diameters of 1.0 and 1.4 μm, and depths of 1.85 and 1.92 μm, respectively. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1577835]

Lateral mode control of vertical-cavity surface-emitting lasers (VCSELs) is one of the key issues in realizing high-performance optical communication systems in which single mode operation is necessary for long and short wavelength regions. High-power single transverse mode operation is also required for free space data communication applications. Recently, a two-dimensional photonic crystal (2-D PC) structure formed on a VCSEL surface has been investigated as a lateral mode control method.[1–3] One attractive feature of this structure is the enlargement of the emission area compared to that of a single-mode-oxide confined VCSEL with a small aperture which is typically less than 3 μm in diameter.[4] Such a small aperture needed to obtain single-mode operation increases electrical and thermal resistance of the VCSEL and is difficult to manufacture. Therefore, we expect PC confined VCSELs (PC-VCSELs) with an enlarged emission area to have the advantages of lower electrical resistance and higher power output. The large area can be realized because of the specifically tailored refractive index induced by the 2-D PC structure, analogous to the situation in a PC fiber (PCF).[5] As we investigated previously,[6] the effect of the PC, that is, the refractive index reduction, is diluted in an actual device due to the finite etching depth of the PC. We consider this as the reason that previous works[1,2] utilize hole diameters larger than those allowed by theoretical models, assuming infinite hole depths,[3] to enhance the PC effect. In this letter, we experimentally demonstrate seven-point defect structures, which consist of seven missing holes, forming a hexagonal-shaped defect that produces single-mode VCSEL emission.

We consider a VCSEL structure on a GaAs substrate with an 850-nm resonant-cavity wavelength, with a λ-cavity sandwiched by a 25-period top distributed Bragg reflector (DBR) and a 35.5-period bottom DBR. Both DBRs consist of $Al_{0.9}Ga_{0.1}As/Al_{0.2}Ga_{0.8}As$ pairs of layers. The 2-D PC structure with finite etching depth incorporating a single point or a seven-point defect is formed in the top DBR. It is known that the normalized frequency or V-parameter[7] is useful in evaluating the number of guided modes in cylindrical wave guides, an important example being step index optical fibers. The cutoff condition of the first higher mode leads to $V=2.405$, and thus a wave guide with $V<2.405$ is considered to be single mode.[7] In a PC-VCSEL, the effective V-parameter can be expressed by[5,6]

$$V_{\mathrm{eff}}=\frac{2\pi r}{\lambda}\sqrt{n_{\mathrm{eff}}^2-(n_{\mathrm{eff}}-\gamma\Delta n)^2}, \tag{1}$$

where λ is an operating wavelength, r is an equivalent defect radius, n_{eff} is the effective refractive index of the VCSEL cavity[8] without a PC structure present, Δn is the refractive index reduction introduced by the PC structure, and γ is the hole depth dependence factor that accounts for finite etching depth of the PC holes in actual PC-VCSELs.[6] The γ factor can be understood qualitatively as proportional to the spatial overlap between the PC structure and the longitudinal optical power distribution inside the VCSEL structure. Thus, $\gamma=0$ for vanishing etching depth, $\gamma=1$ for infinite etching depth, and $\gamma=0.5$ for holes reaching the middle of the cavity. In the following discussion, the equivalent defect radii of a single-point defect and seven-point defect structures are assumed to be $\Lambda-d/2$ and $\sqrt{3}\Lambda-d/2$, respectively, where Λ is a lattice constant and d is the hole diameter of a circular hole of the 2-D PC structure. Since we need to investigate larger d/Λ ratios than those of PCFs,[5] V_{eff} is slightly modified from its appearance in Ref. 5, with the introduction of the γ-parameter and the modified r in Eq. (1). The refractive index variation Δn can be obtained from the photonic band diagram of an out-of-plane propagation mode,[9,10] calculated by assuming that the PC structure is infinite both in lateral and vertical directions. The refractive index reduction Δn calculated by the three-dimensional plane-wave expansion method[9] is shown in Fig. 1, where a material index of 3.4 is assumed. As shown in the figure, the Δn strongly depends on both the normalized lattice constant and the relative hole diameter d/Λ. As we are assuming $\lambda=850$ nm, a lattice constant of 1 μm corresponds to 1.18 on the lateral axis of Fig. 1. Calculated V_{eff} parameters using the refractive index reduction for the single-point and the seven-point defect structure are shown in Fig. 2, with the relative hole diameter d/Λ as a parameter. In this calculation, n_{eff} of 3.4 is assumed

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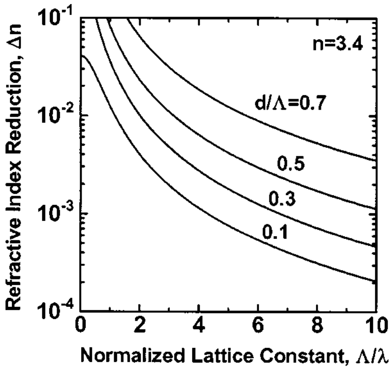

FIG. 1. Calculated refractive index reduction.

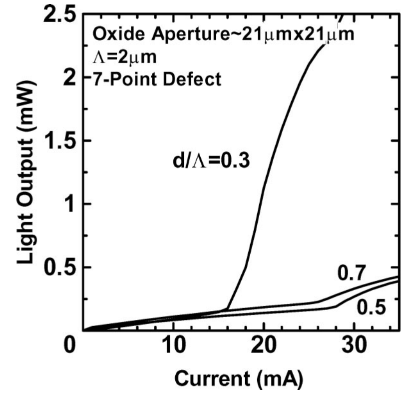

FIG. 3. Typical light output vs. current characteristics of fabricated devices.

and γ is fixed to be 0.032, which corresponds to a hole depth of 15 pairs out of 25 pairs in the top DBR.[6] The PC effect, that is, the refractive index reduction Δn, is diluted by the γ-parameter, as shown in Eq. (1). Therefore, the $V_{\rm eff}$-parameter of a PC-VCSEL is far below the cutoff condition of $V_{\rm eff}=2.405$, if we use d/Λ of around 0.1 similar to a PCF. This implies that the wave guide will only support a single mode. However, the single-mode condition can be easily destroyed by a perturbation of refractive indices introduced by thermal effects or carrier injection. For the preferred PC-VCSEL parameters of a 5-μm PC lattice constant, $d/\Lambda=0.5$, and $\gamma<0.1$, we find from Fig. 1 that Δn is less than 10^{-3}. By comparison, thermal effect in VCSELs can produce $\Delta n \sim 10^{-2}$,[11] which will dominate the wave-guide characteristics. To avoid this problem, Δn should be increased as much as possible, and at the same time, $V_{\rm eff}$ should remain <2.405 to retain the single mode condition. Large d/Λ ratios seem to be effective for this purpose as shown in Refs. 1 and 2. However, the large d/Λ structure will also induce significant scattering loss. Another method of increasing Δn is by reducing the lattice constant, Λ, and choosing a seven-point defect structure, as shown in Fig. 2. Since the equivalent defect radius increases from $\Lambda - d/2$ to $\sqrt{3}\Lambda - d/2$ by introducing the seven-point defect structure, $V_{\rm eff}$ is enhanced by a factor of 2.

To confirm our design, we have fabricated PC-VCSELs, using the VCSEL epitaxial structure described. 2-D PC patterns with seven-point defect structures were delineated on the surface by using electron-beam lithography and were fabricated by using an inductively coupled plasma reactive ion etching (ICP-RIE) technique with $SiCl_4$ as the etching gas.

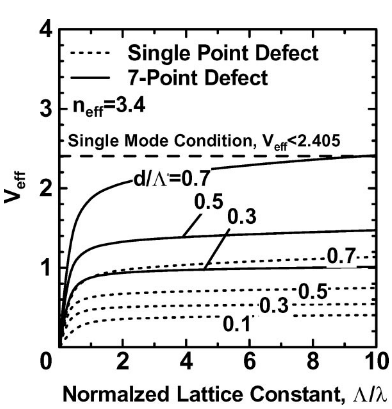

FIG. 2. $V_{\rm eff}$-parameter for single point and seven-point defect structures.

After metallization of top and bottom contacts, square-shaped mesas were formed by conventional photolithography and additional ICP-RIE. Finally, the AlAs layer in the lower DBR was selectively oxidized to define a current aperture. SiO_2 film was used to protect the sidewalls of PC holes during the oxidation process. We made seven-point defect devices with a lattice constant Λ of 2.0 μm and different d/Λ ratios of 0.3, 0.5, and 0.7. Since the etching depth of a small hole depends on its diameter, different hole diameters have different hole depths. Etching depths measured by using a scanning electron microscope are 1.68, 1.85, and 1.92 μm for d/Λ of 0.3, 0.5, and 0.7, respectively. This corresponds to 13, 14, and 15 periods etched into the top DBR, giving γ values of 0.020, 0.024, and 0.032, respectively. If the size of the oxide aperture is comparable to the defect size having the equivalent radius of about 3 μm, the PC confined mode will be affected by the large refractive index step of roughly 0.05 introduced by the oxide layer.[12] Therefore, we used a large oxide aperture size of about 21 μm$\times$21 μm, which is much larger than the defect diameter. This also helps us easily identify the PC confined mode from oxide confined modes with larger modal size. Figure 3 shows typical light output versus current (LI) characteristics of fabricated devices. The device with the smallest d/Λ of 0.3 has the lowest threshold current, but it operated in an oxide confined mode, which was confirmed by its spectrum and near field pattern. The devices with large d/Λ have high threshold currents and low efficiencies above threshold. Both devices operated in PC confined modes. Since the optical fields of these devices were confined in central defect areas, most of the injected current for each device passed through the surrounding 2-D PC confinement region and was wasted. This higher threshold current can be reduced by confining the injected current efficiently into the defect site. The effective threshold current simply estimated by the ratio of the defect area to the oxide aperture area is around 1.5 mA, assuming uniform current density within the oxide aperture. The threshold current density is >6 kA/cm^2, which is higher than conventional oxide confined VCSELs. We attribute this to unintentional scattering loss introduced by the PC structure, rather than reduced current injection efficiency. Lasing spectra of the device with d/Λ of 0.5 is shown in Fig. 4, confirming single-mode operation. The weak peak appearing at a shorter wavelength than the lasing mode is reproducible in all of our devices operating in a PC confined mode, and is

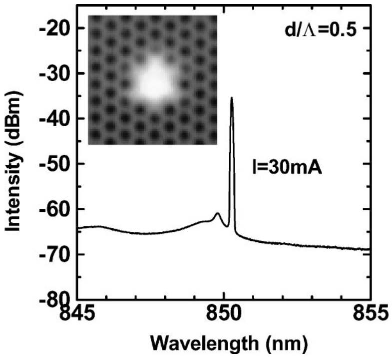

FIG. 4. Lasing spectrum and a near-field pattern of the device with Λ of 2 μm and d/Λ of 0.5.

thought to be one of the oxide confined modes. The near-field profile of the device also is shown in the inset of Fig. 4. Very strong emission can be seen in the defect site, where the hexagonal emission pattern is evidence of the PC confined mode.[2] Thus, the single-mode operation is realized by 2-D PC structure, with a defect size almost double of that of the oxide device with a single-mode operation.

In conclusion, we demonstrated that a seven-point defect structure is applicable to obtain the fundamental PC confined mode. This method is effective to increase the V_{eff} parameter, which is diluted by finite etching depth in actual PC-VCSELs. In this experiment, we utilized a structure with a large oxide aperture to prevent a significant contribution of the oxide aperture to the PC confined mode. A current confinement technique that does not introduce a large refractive index step, that is, an ion-implanted structure, would enable current aperture size to fit PC confined modes. As a result, low threshold current and high efficiency, as well as high output power operation, should be possible.

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