High-Power Single-Mode Submonolayer Quantum-Dot Photonic Crystal Vertical-Cavity Surface-Emitting Lasers

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***Abstract*—A high-power, wide operation-range single-fundamental-mode InGaAs submonolayer (SML) quantum dot (QD) photonic crystal vertical-cavity surface-emitting laser (VCSEL) for fiber-optic applications was demonstrated. Single-fundamental-mode with a threshold current (I_{th}) of 0.9 mA and maximum continue-wave (CW) output power of 3.8 mW at 28 mA has been achieved in the 990 nm range. A side-mode suppression ratio (SMSR) larger than 35 dB has been observed over the entire current operating range. The far field measurement shows that the beam divergence angle remains very small and almost unchanged between 6.7–6.9°, with the operation range increasing from 3 to 20 mA.**

***Index Terms*—Divergence angle, quantum-dot, single-mode, submonolayer (SML), vertical-cavity surface-emitting laser (VCSEL).**

I. Introduction

VERTICAL-CAVITY surface-emitting lasers (VCSELs) are becoming attractive low-cost, high-performance light sources for various applications including local area networks (LANs), fiber-optic communication systems, data storage, optical computing and different sensors [1] for their unique characteristics such as circular laser beam, low threshold current, low power consumption, high modulation bandwidth, easy polarization control, capability of fabricating dense 2-D laser arrays, and the testing of wafer levels. For short-distance optical interconnects in the chip-to-chip, backplane, and board-to-board fiber transmission, VCSELs emission in the 980 nm range are reliable and can be compatible with the 1300 nm receiver [2]. For high-speed optical data communication applications, single fundamental mode operation of VCSEL sources is beneficial because they can be coupled into the central low-modal dispersion region of a multimode fiber [3] or a single-mode fiber with a smaller core diameter. Traditional oxide confined VCSEL using small oxide aperture below about 4 μm diameter operate in the fundamental transverse mode. However, the small aperture leads to low output power and large resistance, which limits the modulation bandwidth and degrades the high-speed performance of the device. Moreover, the lifetime of the oxide VCSEL also decreases proportionally to the diameter of the oxide aperture, even when the device is operated at a reduced current [4]. Other methods to achieve single fundamental mode operation include the increase of higher order mode loss by surface-relief etching [5], hybrid-oxide-implanted VCSELs [6], [7], and two-dimensional triangular holey structure [8], [9]. Recently, a 2-D photonic crystal structure fabricated on the VCSEL surface has been used as a control method of transverse modes. Single-mode output was realized from larger aperture photonic crystal VCSELs [10]–[12].

The stacked submonolayer growth of quantum dots (SML QDs) presents an alternative approach to Stranski–Krastanow (SK) method, which contain InGaAs QD sheets separated by AlGaAs spacers [13] of growing self-assembled QDs for the 0.85–1.3 μm wavelength range for lasers and amplifiers. The SML QDs can grow with higher density and high uniformity, which can provide high material and modal gain and result in high-power lasing performance, and surpass the SK QD laser [13], [14]. Recently, single-mode SML QD VCSELs have been demonstrated with 1 μm in diameter oxide confined aperture to realize high modulation bandwidth [15]. However, due to the small oxide aperture, the output power is around 1 mW. In this paper, we report our results on using 2-D photonic crystal structure on the InGaAs SML QD VCSELs to achieve larger aperture single-transverse-mode operation with high output power and high side-mode suppression ratio (SMSR).

II. Experiment

The epitaxial layers of the InGaAs SML QD photonic crystal VCSEL wafers were grown on 3 in n^+-GaAs (0 0 1) substrates by molecular beam epitaxy (MBE) in Riber 49 chamber. The bottom distributed Bragg reflector (DBR) consists of a 33-pair n-type (Si-doped) quarter-wave stack ($\lambda/4$) of $Al_{0.9}Ga_{0.1}As$/GaAs. The top DBR consists of a 20-period p-type (carbon-doped) $Al_{0.9}Ga_{0.1}As$/GaAs quarter-wave stack.

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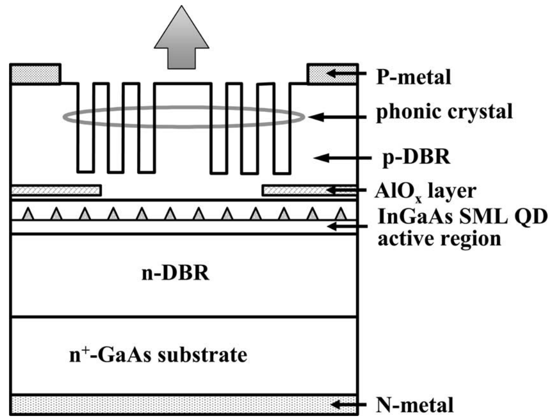


Fig. 1. Schematic of InGaAs SML QD photonic crystal VCSEL. The hole etching depth of the photonic crystal structure is 16 pairs out of the 20 pairs top DBR being etched off.

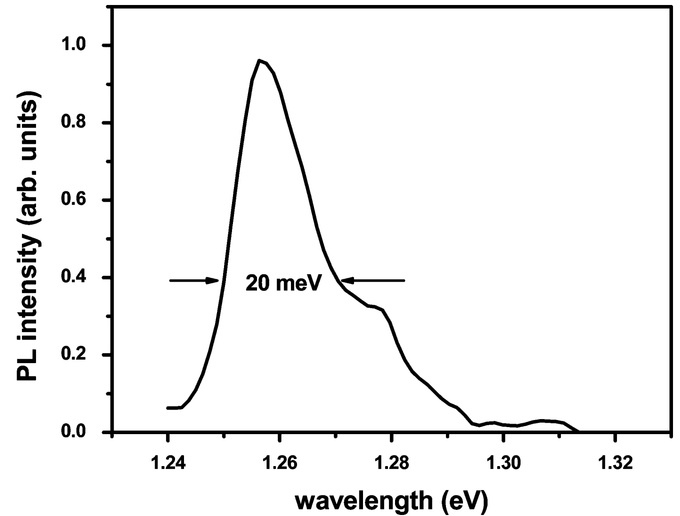


Fig. 2. Room temperature photoluminance spectrum of top DBR removed SML QD VCSEL wafer.

Above that is a heavily doped p-type GaAs contact layer. The undoped 1λ-cavity contains three InGaAs SML QDs layers, separated by GaAs barrier layers. Each of the InGaAs SML QDs layers is formed by alternate deposition of InAs (<1 ML) and GaAs. The current confinement of the device was done by the selectively oxidized AlO$_x$ tapered aperture. Firstly, mesas with diameters varying from 50 to 68 μm were defined by reactive ion etch (RIE). The inner diameter of p-contact ring was 10 μm larger than the oxide aperture and formed on the top of the p-contact layer. The AlAs layer within the Al$_{0.9}$Ga$_{0.1}$ As confinement layers was selectively oxidized to AlO$_x$. The oxidation depth was about 16–17 μm toward the center from the mesa edge so that the resulting oxide aperture varied from 16 to 36 μm in diameter. The oxide aperture was introduced at a minimum of the optical field in order to reduce the lateral optical loss. The AlO$_x$ layer was also used to reduce the leakage current. The n-contact was formed at the bottom of the n$^+$-GaAs substrate. After that, triangular lattice patterns of photonic crystal with a single-point defect in the center were defined within the p-contact ring using photolithography, and were etched through the p-type DBR using RIE. The lateral index around a single defect can be controlled by the hole diameter (α)-to-lattice constant (Λ) ratio and etching depth [11]. This ratio (α/Λ) is 0.5; the lattice constant Λ is 5 μm in the photonic crystal VCSEL, and the etching depth of the holes is about 16-pair thick into the 20-pair top DBR layer. The photonic crystal parameters are chosen not only to provide reasonable lateral index guiding and loss mechanism for the lasing output, but also to leave suitable conduction paths ($\sim 2.5\,\mu$m width) for the injection current to flow through the photonic crystal holes, and then, toward the central laser emission region. The device structure is shown in Fig. 1. By using two types of apertures in this device, we decouple the effects of the current confinement from the optical confinement. The AlO$_x$ layer is used to confine the current flow, while the single-point defect (approximately ≥ 10 μm in diameter) photonic crystal is used to confine the optical mode. In order to clarify the effect of the photonic crystal index-guiding layer, an oxide-confined VCSEL (oxide aperture $= 18\,\mu$m in diameter without photonic crystal structure) was also fabricated for comparison.

III. Results and Discussions

The small part of the SML QD VCSEL wafer was removed from the top DBR by RIE and performed the photoluminance (PL) measurement to investigate the material characteristics of the SML QDs. The PL measurement was carried out by the 532 nm line of an Nd:YVO$_4$ laser with a power density of 265 mW/cm^2, and the emission from the samples was dispersed by a monochromator, and was detected by using a thermoelectrically cooled InGaAs detector. The PL spectrum of SML QD at room temperature was depicted in Fig. 2, and the peak of emission spectrum is 1.257 eV in ground state, which corresponds to 986.5 nm. The spectrum shows very narrow full-width at half-maximum (FWHM) of about 20 meV, representing the highly uniformity of QDs size. The InGaAs SML QD VCSEL devices without photonic crystal were performed CW light–current–voltage (L–I–V) output measurement to characterize the performance of the device, and shown in Fig. 3(a). The VCSEL with a mesa of 50 μm in diameter and oxide aperture of 18 μm in diameter shows a threshold current ($I_{\rm th}$) of 1 mA and a peak power of 12.2 mW at 30 mA. The differential series resistance is approximately 100 Ω at 12 mA. Fig. 3(b) shows the CW L–I–V output of the photonic crystal VCSEL. The near-field image of the photonic crystal VCSEL operating at 4 mA is also shown in the inset. The mesa of the photonic crystal VCSEL is also 50 μm in diameter, and the oxide aperture is of the same size as the device in Fig. 3(a). The photonic crystal VCSEL emits a maximum power of 3.8 mW at 28 mA and exhibits single-mode operation throughout the whole current range of operation. Near-field imaging of the output mode remains to be fundamental TEM$_{00}$ mode at the center of the photonic crystal structure throughout the current operating range. The $I_{\rm th}$ of the photonic crystal VCSEL is 0.9 mA. The differential series resistance of the photonic crystal VCSEL is approximately 125 Ω at 12 mA. The I–V characteristics exhibit slightly higher series resistance for the photonic crystal VCSEL, which would be mainly due to blocking of the current flow in the region by

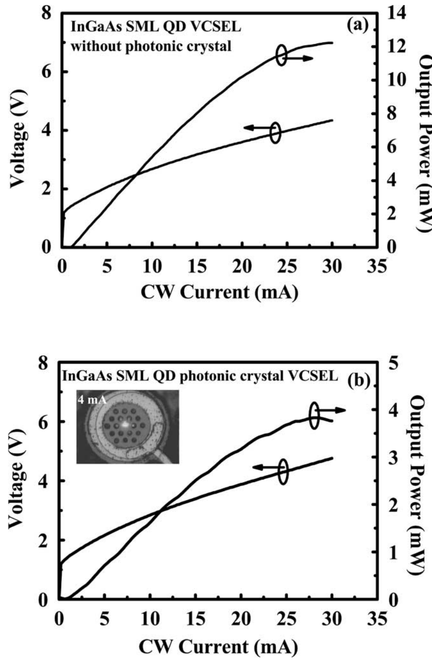


Fig. 3. CW L–I–V characteristics and near-field image (inset) of InGaAs SML QD VCSEL. (a) Without photonic crystal. (b) With photonic crystal. The ratio α/Λ is 0.5 and the lattice constant Λ is 5 μm. The oxide aperture is 18 μm in diameter.

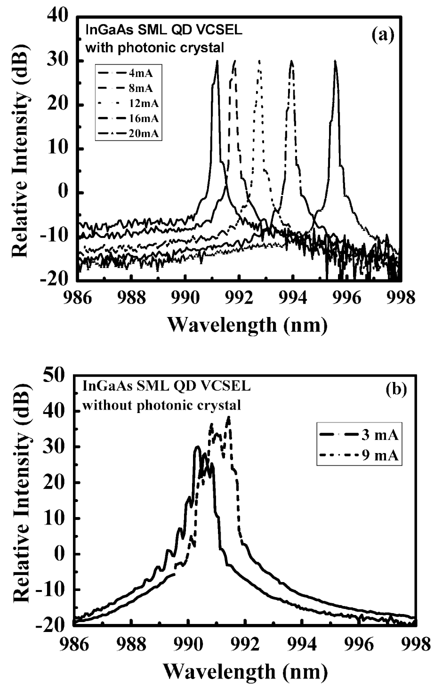


Fig. 4. Spectra of the InGaAs SML QD VCSEL. (a) With photonic crystal structure. (b) Without photonic crystal structure. The ratio α/Λ is 0.5 and the lattice constant Λ is 5 μm. The oxide aperture is 18 μm in diameter.

photonic crystal holes. Lasing spectra of the photonic crystal VCSEL are shown in Fig. 4(a), confirming single-mode operation within the wide operation current from 1 to 28 mA. The peak lasing wavelengths are red shifted from 991 to 995.5 nm when

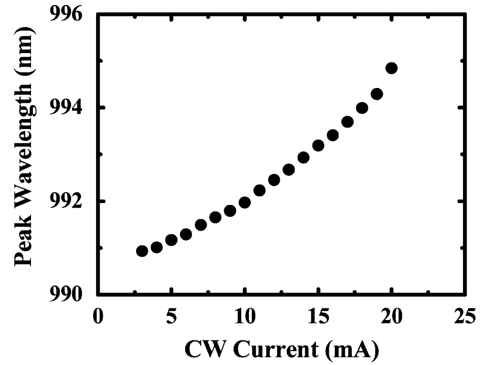
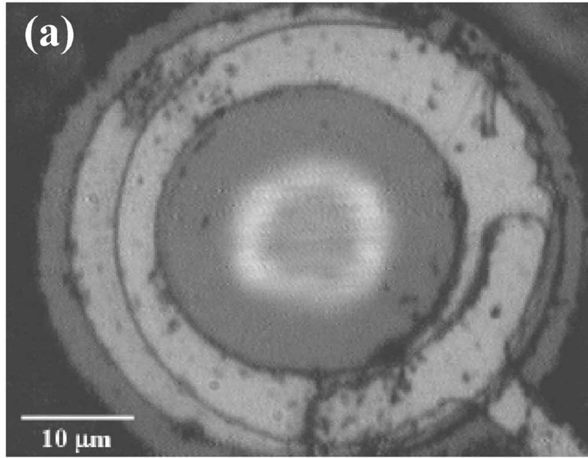
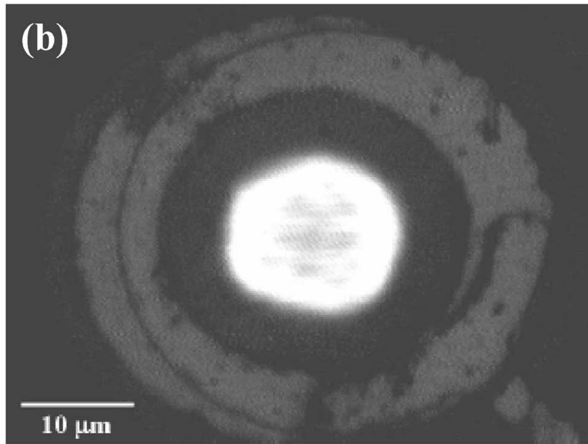


Fig. 5. Current-dependent lasing peak wavelength of the InGaAs SML QD photonic crystal VCSEL.

bias current ranges from 4 to 20 mA. The difference between peak of PL and lasing spectrum results from the detuning of gain spectrum and Fabry–Perot dip of DBR. The photonic crystal VCSEL exhibits an SMSR >35 dB throughout the current range. The peak wavelength versus injection current plot of the InGaAs SML QD photonic crystal VCSEL is shown in Fig. 5. The peak lasing wavelength increases monotonically with the increasing injection current. The increase in wavelength with increasing injection current is mainly due to the increase in junction temperature. The rate of peak wavelength increase with biasing current ($\Delta\lambda\, p/\Delta I$) is approximately 0.15 nm/mA from 3 to 10 mA, and the rate approximately is 0.26 nm/mA from 10 to 20 mA. The rate of peak wavelength is different for different current range, which is mainly because of thermal conduction of the device and the measurement system. The junction temperature of the device does not increase linearly with current. The lasing in QDs is believed to be ground-state transition since all the measured spectra are single mode for the photonic crystal VCSELs. No side mode corresponding to an excited state transition was observed at higher currents. For comparison, lasing spectra of the InGaAs QD VCSEL without photonic crystal holes is shown in Fig. 4(b). It is clear that multiple-mode operation as the driving current is increased above I_{th}. The InGaAs SML QD VCSEL without photonic crystal shows multiple transverse mode characteristics with a broader wavelength span. The near-field images of the VCSEL without photonic crystal are shown in Fig. 6. The near-field image of the VCSEL at 3 mA [Fig. 6(a)] was taken with light illumination to show the relative position of the lasing area with respect to the p-contact ring. The lasing area is annular in shape (15 μm in diameter) with lower intensity in the central region. The near-field images at 9 and 20 mA [Fig. 6(b) and (c)] show lasing areas with higher intensity at the center. The lasing area of the device at 20 mA is about 18 μm in diameter, which is close to the diameter of the oxide aperture. All the near-field images show that the laser beam is of multimode characteristics because of the larger oxide aperture (approximately 18 μm in diameter) of the device. With the same oxide aperture size, the VCSELs with a photonic crystal structure clearly show much better optical confinement. Fig. 7 shows the near-field image of the photonic crystal VCSEL at 10 mA. The laser output is a fundamental TEM_{00} mode at the center of the photonic crystal structure. The TEM_{00} mode is rounded





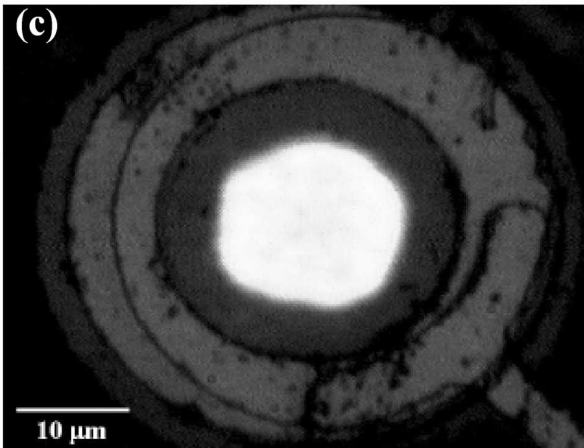


Fig. 6. Near-field images of the InGaAs SML QD VCSEL without photonic crystal. (a) At 3 mA. (b) At 9 mA. (c) At 20 mA. The oxide aperture is 18 μm in diameter.

in shape with a diameter of approximately 4.3 μm. Smaller lasing spots emitting from the nearby photonic crystal holes with lower intensity were also observed. These lasing spots are mainly the scattered and diffracted laser beams from the TEM_{00} beam at the center, which are all emitting with the same lasing wavelength.

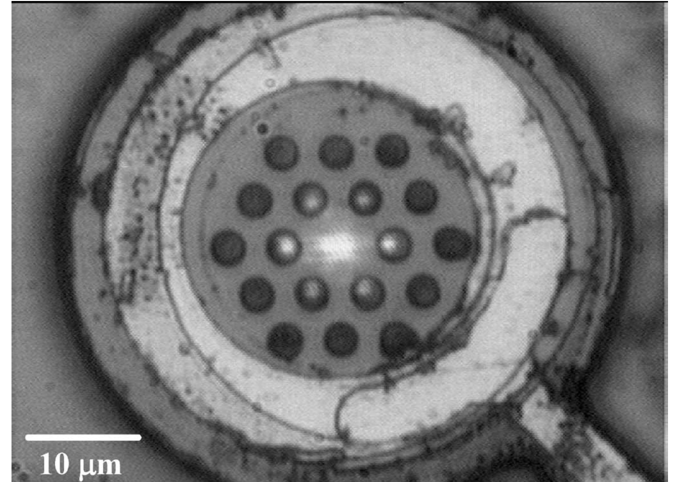


Fig. 7 Near-field image of the InGaAs SML QD photonic crystal VCSEL at 10 mA. The oxide aperture is 18 μm in diameter.

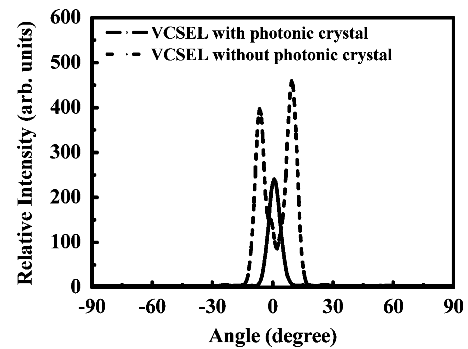


Fig. 8. Beam profiles of InGaAs SML QD VCSEL with and without photonic crystal measured at 10 mA. The oxide aperture is 18 μm in diameter.

The beam profile results obtained from far-field beam pattern measurements at a bias current of 10 mA are shown in Fig. 8. The beam divergence angle is the FWHM of the beam profile. The beam divergence angle of VCSEL without photonic crystal is 21.5°. The two laser emission lobes correspond to multimode laser emission that is annular in shape, as observed by the near-field imaging. This annular shaped laser emission has a low intensity at the center. The lasing output consists of many higher-order modes because of the large oxide aperture (18 μm in diameter). For photonic crystal VCSEL, the beam divergence angle is very small, about 6.7°. Fig. 9 shows the current-dependent divergence angles of the InGaAs SML QD photonic crystal VCSEL and InGaAs SML QD VCSEL without photonic crystal. For the InGaAs SML QD VCSEL without photonic crystal, the divergence angle increases monotonically from 17.2° to 22.8°, with current increasing from 3 to 13 mA. The detector, which measured divergence angle, was saturated when bias current was over 13 mA. For the InGaAs SML QD photonic crystal VCSEL, the beam divergence angle remains very small and almost unchanged between 6.7° and 6.9°, with respect to increasing current from 3 to 20 mA. This divergence

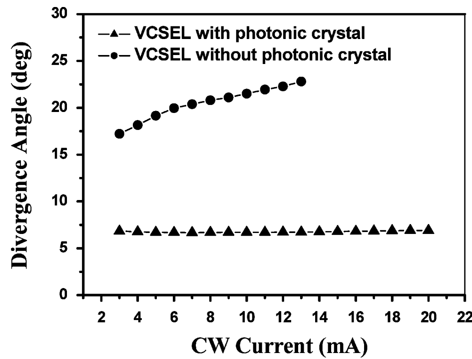


Fig. 9. Current-dependent beam divergence angle of InGaAs SML QD photonic crystal VCSEL (▲) and InGaAs SML QD VCSEL without photonic crystal (●). The oxide aperture is 18 μm in diameter.

angle obviously indicates that the laser beam is well confined by the photonic crystal structure of the device. The photonic crystal structure not only laterally confines the lasing mode, but also provides a waveguide for the TEM_{00}-lasing-mode output with very small divergence.

IV. Conclusion

We have demonstrated a high-power, single-mode InGaAs SML QD photonic crystal VCSEL with SMSR $>$35 dB throughout the current operating range. The maximum output power is 3.8 mW, which is the highest reported for the photonic crystal VCSELs. The beam divergence angle remains very small and almost invariant around 6.8°, within the operation current range from 3 to 20 mA. The beam profile and near-field image of the photonic crystal VCSEL indicates that the laser beam is well confined by the photonic crystal structure of the device. The present results indicate that a VCSEL using an oxide layer for current confinement and photonic crystal for optical confinement is a promising approach to achieve single-mode operation of VCSEL.

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