Singlemode InAs quantum dot photonic crystal VCSELs

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An InAs quantum dot photonic crystal vertical-cavity surface-emitting laser (QD PhC-VCSEL) for fibre-optic applications is first demonstrated. Single fundamental mode CW output power of 0.2 mW has been achieved in the 1300 nm range, with a threshold current of 4.75 mA. Side-mode suppression ratio larger than 40 dB has been observed over the entire thermally limited operation range.

Introduction: Vertical-cavity surface-emitting lasers (VCSELs) have attracted much attention in recent years. Singlemode VCSELs are needed for a number of applications, including high-speed laser printing, optical storage and long-wavelength telecommunications. For oxide-confined VCSELs, the current-confined aperture must be less than 3 μm in diameter to ensure stable singlemode operation [1]. However, the large resistance inherited from the small aperture limits the modulation bandwidth and degrades the high-speed performance. The lifetime of the oxide VCSEL also decreases proportionally as the diameter of the oxide aperture shrinks, even when the device is operated at a reduced current [1]. Methods reported to solve the problem include the increase of higher-order mode loss by surface-relief etching [2] and hybrid oxide-implanted VCSELs [3, 4]. Recently, a two-dimensional photonic crystal (2-D PhC) structure formed on the VCSEL surface has been investigated as a control method of lateral mode. Singlemode output was realised from larger aperture photonic crystal VCSELs (PhC-VCSELs) [5, 6]. However, those PhC-VCSELs exhibit relatively high threshold currents (I_{th}) owing to large oxide-confined apertures. For long-wavelength applications, InGaNAs [7, 8] and InAs-InGaAs quantum dot (QD) VCSELs [9] achieved laser emission at 1300 nm. Singlemode operation of the QD VCSEL with PhC is yet to be realised. In this Letter, we report our results on the QD PhC-VCSELs in the 1300 nm range. Single-lateral-mode operation with very high side-mode suppression ratio (SMSR) is demonstrated for the first time.

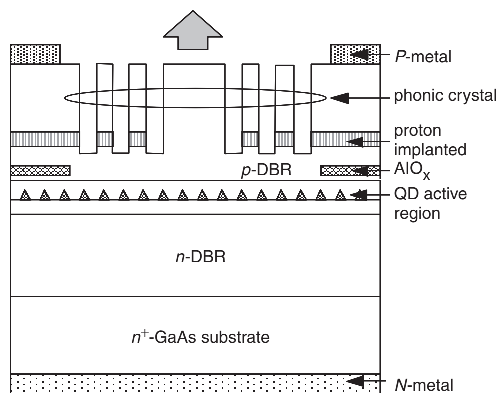

Fig. 1 *Schematic of QD PhC-VCSEL*

Hole etching depth of PhC is 18 pairs out of the 23-pair top DBR having been etched off. The proton implantation position is 10 pairs of DBR layers above active region

Experiment: The epitaxial layers of the QD PhC-VCSEL wafers were grown on n^+-GaAs substrates by molecular beam epitaxy (MBE). The bottom distributed Bragg reflector (DBR) consists of a 33.5-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 23-period *p*-type (carbon-doped) $Al_{0.9}Ga_{0.1}As/GaAs$ quarter-wave stack. Above that, is a heavily doped *p*-type GaAs contact layer. The active region contains 17 undoped InAs-InGaAs QD layers, separated by GaAs barrier layers. Each of the InAs-InGaAs QD layers consists of 2.5 monolayer-thick InAs pyramidal islands and a 5 nm-thick $In_{0.15}Ga_{0.85}As$ quantum well overgrowth layer. The current confinement of the device was achieved by combining selective oxidation with proton (H^+)-implantation. First, mesas with diameters varied from 44 to 68 μm were defined by reactive ion etch (RIE). The AlAs layer within the $Al_{0.9}Ga_{0.1}As$ confinement layers was selectively oxidised to AlO_x. The oxidation depth was about 12 μm towards the centre from the mesa edge so that the resulting oxide aperture varied from 20 to 44 μm in diameter. The oxide aperture was introduced to reduce the lateral optical loss and the leakage current. The p-contact ring with an inner diameter 2 μm larger than the oxide aperture was formed on the top of the p-contact layer. 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 centre were defined within the p-contact ring using photolithography and 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 [5]. This ratio (α/Λ) is 0.5; the lattice constant Λ is 5 μm in the PhC-VCSEL and the etching depth of the holes is about 18 pairs thick into the 23-pair top DBR layer. To ensure better current confinement of the device, proton implantation was carried out with a diameter of 12 μm, followed by an annealing at 430°C under N_2 ambient. The implantation energy was 240 keV, with a dose of 6×10^{14} cm^{-2}, to form an insulating region laying 10 DBR pairs above the active region. Higher implantation energy may introduce more defects in the lateral direction. 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 H^+ implant aperture (12 μm) and the AlO_x layer are used to confine the current flow, while the single-point defect (≥ 12 μm in diameter) photonic crystal is used to confine the optical mode. To clarify the effect of the photonic crystal index-guiding layer, a VCSEL with H^+ implant aperture (12 μm in diameter without PhC) was also fabricated for comparison.

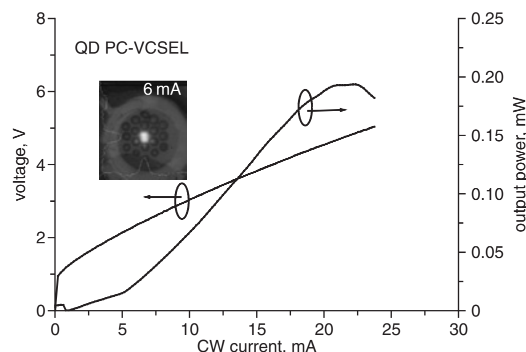

Fig. 2 *CW L-I-V characteristics and near-field image (inset) of PhC-VCSEL (ratio (α/Λ) is 0.5 and lattice constant Λ is 5 μm)*

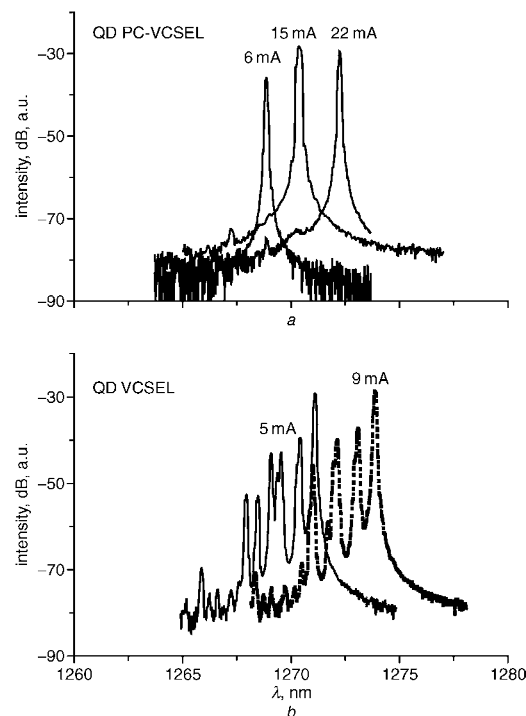

Fig. 3 *Spectra of QD*

a PhC-VCSEL
b VCSEL without PhC holes

Results and discussion: Fig. 2 shows the CW light-current-voltage (*L–I–V*) output and near-field image operated at 6 mA (inset) of the PhC-VCSEL. The VCSEL emits 0.2 mW peak power and exhibits single modes throughout the current range of operation. The threshold current (I_{th}) of the PhC-VCSEL is 4.75 mA. The *I–V* characteristics exhibit higher series resistance for the PhC-VCSEL, which should be mainly due to proton implantation through the p-ohmic contact of the device and blocking of the current flow in the region by photonic crystal holes. The differential series resistance is 170 Ω at 12 mA. The output power could be improved by reducing the series resistance of the PhC-VCSEL. Lasing spectra of the PhC-VCSEL is shown in Fig. 3*a*, confirming singlemode operation within the overall operation current. The peak lasing wavelengths are 1268 and 1272 nm at 6 and 22 mA, respectively. The PhC-VCSEL exhibits an SMSR > 40 dB throughout the current range. For comparison, a lasing spectra of a QD VCSEL without photonic crystal holes shows multiple mode operation as the driving current increased above 5 mA (Fig. 3*b*). The QD VCSEL showed multiple transverse mode characteristics over a broader wavelength span.

Conclusion: We report a singlemode QD PhC-VCSEL with SMSR > 40 dB throughout the operation current range. The present results indicate that a VCSEL using a combined oxide layer with proton implantation for current confinement and photonic crystal for optical confinement is a promising approach to achieve singlemode operation of VCSELs.

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