Singlemode (SMSR > 40 dB) proton-implanted photonic crystal vertical-cavity surface-emitting lasers

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A proton-implanted photonic crystal vertical-cavity surface-emitting laser for fibre optic applications is demonstrated. Ultra-low threshold current of about 1.25 mA, single fundamental mode (SMSR>40 dB) CW output power of over 1 mW, with a pulsed output power exceeding 2 mW has been achieved in the 850 nm range.

Introduction: Vertical-cavity surface-emitting lasers (VCSELs) have attracted much attention in recent years. High-power, singlemode operation is desired 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. However, the large resistance inherited from the small aperture limits the modulation bandwidth and degrades the high-speed performance. Furthermore, the lifetime of the oxide VCSEL decreases proportionally as the diameter of the oxide aperture declines, even when the device is operated at a reduced current [1]. Techniques reported to fabricate fundamental mode from an oxide-confined VCSEL with larger emission area include increasing the higher-order mode loss by surface-relief etching [2] and hybrid oxide-implanted VCSELs [3, 4]. Recently, a two-dimensional photonic crystal (2-D PC) structure formed on a VCSEL surface has been investigated as a control method of lateral mode. Singlemode output with higher output power, were realised from larger aperture photonic crystal VCSELs (PC-VCSELs) [5, 6]. However, those PC-VCSELs exhibit relatively high threshold currents (I_{th}) owing to large oxide confined apertures.

In this Letter, we design a low I_{th}, high-power, single-lateral-mode operation VCSEL by employing proton implantation and a single-point defect photonic crystal index guiding layer.

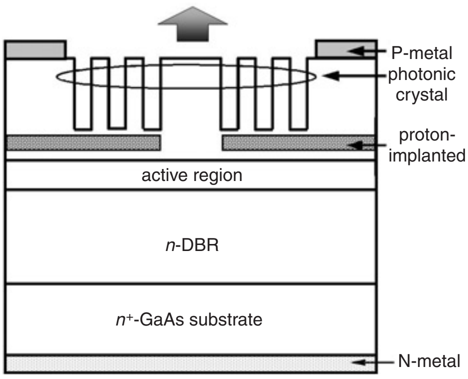

Fig. 1 *Schematic of PC-VCSEL*

The hole depth of PC is 17 pairs out of 22 pairs of top DBR etched off. The proton implantation position is three pairs of DBR layers above active region

Experiment: The epitaxial layers of the PC-VCSEL's wafer structure were grown on the n^+-GaAs substrate by metal-organic chemical vapour deposition (MOCVD). The bottom distributed Bragg reflector (DBR) consists of a 30.5-pair n-type (Si-doped) quarter-wave stack of $Al_{0.12}Ga_{0.88}As/AlAs$. The top DBR consists of 22-period p-doped (carbon-doped) $Al_{0.12}Ga_{0.88}As/AlAs$ quarter-wave stack. Above that is a heavily doped p-type GaAs contact layer. The graded-index separate-confinement heterostructure (GRINSCH) GaAs/AlGaAs active region has an undoped three-quantum-well (3QWs) GaAs/$Al_{0.3}Ga_{0.7}As$, a lower linearly-graded undoped $Al_xGa_{1-x}As$ ($x = 0.6 \rightarrow 0.3$) waveguide layer and an upper linearly-graded undoped $Al_xGa_{1-x}As$ ($x = 0.3 \rightarrow 0.6$) waveguide layer. The proton (H^+)-implanted VCSEL was fabricated before combination with photonic crystal holes. First, the p-contact ring with an inner diameter of 24 to 46 μm was deposited on the top of the p-contact layer and an n-contact was deposited on the bottom of an n^+-GaAs substrate. The device was annealed at 430°C under N_2 ambient. The current confinement of the device, with a diameter of 10 μm, was then defined by proton implantation. The implantation energy was 270 keV, with a dosage of 6×10^{14} cm^{-2}. After that, hexagonal lattice patterns of photonic crystal with a single-point defect were defined within the p-contact ring using photolithography and etched through the p-type DBR by using a reactive ion etch (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 PC-VCSEL and the etching depth of the holes is about 17 pairs out of 22 pairs of the top DBR layers. 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 (10 μm) is used to confine the current flow, while the single-point defect (≥ 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, a VCSEL with a H^+ implant aperture (10 μm in diameter without PC) was also fabricated for comparison.

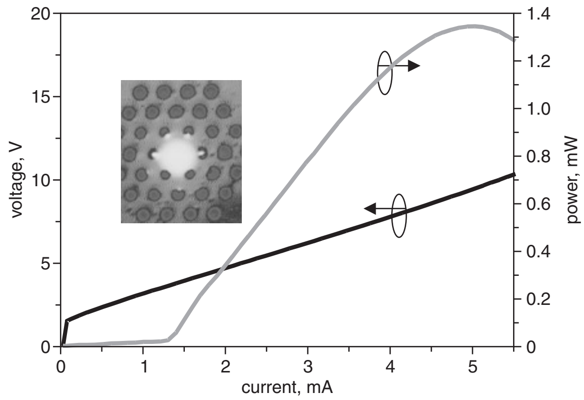

Fig. 2 *CW L-I-V characteristics and near-field image of PC-VCSEL*

The ratio (α/Λ) is 0.5 and the lattice constant Λ is 5 μm
Inset: Near-field image

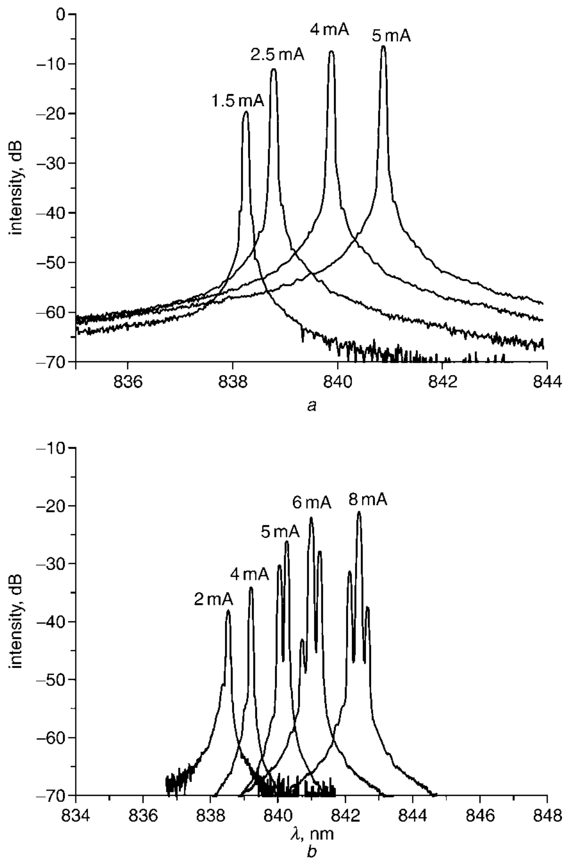

Fig. 3 *Spectra of proton-implanted PC-VCSEL and VCSEL without PC holes*

a PC-VCSEL
b VCSEL

Results and discussion: Fig. 2 shows CW light-current-voltage (L-I-V) output and near-field image operated at 0.1 mA (inset) of the PC-VCSEL. The VCSEL emits over 1 mW peak power and exhibits singlemodes throughout the current range of operation. The threshold current (I_{th}) of the PC-VCSEL is 1.25 mA and the slope efficiency is approximately 0.18 W/A. The I-V characteristics exhibit higher series resistance of the PC-VCSEL, which should be mainly due to proton implantation through the p-ohmic contact of the device and block of the current flow in the region by photonic crystal holes.

The output power could be improved by reducing the series resistance of the PC-VCSEL. Lasing spectra of the PC-VCSEL is shown in Fig. 3*a*, confirming singlemode operation within overall operation current. The PC-VCSEL reveals a side mode suppression ratio (SMSR) > 40 dB throughout the current range. For comparison, lasing spectra of a proton-implanted VCSEL without photonic crystal holes shows multiple mode operation as the driving current increased above 4.25 mA (Fig. 3*b*). As the driving current increases, even higher-order transverse modes emerge. The pulsed L-I characteristics of the PC-VCSEL are also measured and the maximum output power is exceeding 2 mW. Temperature-dependent measurements are under way to verify the nonlinearity characteristics.

Conclusion: We report a high power (>1 mW) singlemode PC-VCSEL with SMSR > 40 dB throughout the operation current range. This PC-VCSEL, with an aperture of about 10 µm, has ultra-low threshold current of about 1.25 mA. The present results indicate that a VCSEL using proton implantation for current confinement and photonic crystal for optical confinement is a reliable approach to achieve high-power singlemode operation of a VCSEL. This concept will be applied to a 1.3 µm VCSEL and other commercial applications in the future.

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