Proton implanted singlemode holey vertical-cavity surface-emitting lasers

P.O. Leisher, A.J. Danner, J.J. Raftery, Jr., and K.D. Choquette

Wedge-shaped holes have been fabricated in the top mirror of proton implant confined vertical-cavity surface-emitting lasers. The index confinement and selective loss introduced by these patterns improved the performance by both increasing the singlemode power and reducing the threshold current of the lasers. A maximum single fundamental mode power of 3.5 mW with a simultaneous reduction of lasing threshold compared to an unmodified laser was observed. Multimode operation was suppressed over the entire laser operating range.

Introduction: Vertical-cavity surface-emitting lasers (VCSELs) have a number of applications that may require single fundamental mode operation, including short-haul optical data communication, spectroscopic sensing, and small atomic clocks. Several methods have been employed for achieving single fundamental mode operation in a VCSEL, including small oxide aperture confinement [1], surface relief etching [2], hybrid oxide-implant structures [3], and holey and photonic crystal structures [4–8]. Wedge-shaped holey structures in oxide-confined VCSELs have shown singlemode (both fundamental and non-fundamental) operation [9]. Although proton implantation for current confinement supports single fundamental mode operation, devices with large implant apertures are only singlemode at very low currents.

In this Letter, wedge-shaped holes surrounding a proton-implant confined VCSEL are used to achieve single fundamental mode operation. This structure has several advantages over oxide confined devices. First, implant devices are inherently singlemode at threshold, and only lase in a few higher-order transverse modes at higher current, whereas oxide devices with similar aperture sizes are strongly index-guided from threshold to saturation [10]. Because of this, the loss to higher-order modes that is introduced by the holey structure causes the threshold current to increase in oxide-confined devices. For proton-implanted VCSELs, the absence of higher-order modes around threshold minimises the increase in threshold current due to the holey structure. Moreover, the index confinement provided by the pattern actually reduces the threshold current. Secondly, because thermal lensing is a weak effect, the holey structure allows the optical confinement to be decoupled from the current confinement, providing another degree of freedom that can be used for optimisation. Finally, the wedge-shaped holes can enable tailoring of the radial index profile, which is difficult to achieve in oxide-confined [11] or photonic crystal VCSELs.

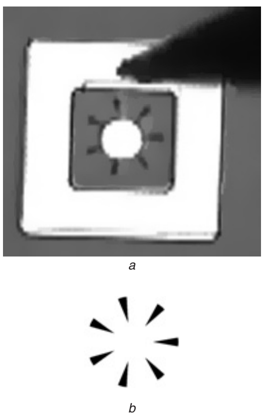

Fig. 1 *Near-field optical image of wedge-shaped holey VCSEL lasing in fundamental mode and diagram of wedge-shaped holey pattern*

a Near-field optical image
b Wedge-shaped holey pattern

Device description and fabrication: The VCSEL device structure contains a bottom *n*-type 36-period distributed Bragg reflector (DBR) consisting of alternating layers of $Al_{0.16}Ga_{0.84}As$ and $Al_{0.92}Ga_{0.08}As$, an undoped active region with five GaAs quantum wells, and a top *p*-type 21-period DBR, all of which were grown by metal organic vapour phase epitaxy and designed for an operating wavelength of 850 nm. A backside contact (AuGe/Ni/Au) was deposited to form an ohmic contact to the *n*-type substrate, and top ring contacts (Ti/Au) were lithographically patterned and formed by liftoff after the metal deposition. Protons were implanted at 330 keV with a dose of 4×10^{14} cm^{-2}. Photoresist pillars in the centre of each top ring contact served to mask and define the lasing apertures for the implant process. Electron beam lithography was used to define the wedge-shaped patterns, and Freon reactive ion etching (RIE) was used to transfer the pattern to an SiO_2 mask. Large isolation mesas were lithographically defined and similarly transferred to the SiO_2 mask. The isolation mesas and wedge holes (see Fig. 1) were simultaneously etched approximately 15 periods into the top DBR using $SiCl_4$/Ar inductively coupled plasma RIE. The wedge-shaped holey VCSEL diodes operate continuous wave (CW) at room temperature.

Fig. 1*a* shows a near-field image of a wedge-shaped holey VCSEL lasing in the fundamental Gaussian-like mode. In this study, the ion implant aperture was fixed at 10 μm in diameter with seven wedges patterned around the implant aperture, as illustrated in Fig. 1*b*. Each wedge was designed to be 5 μm long with a 20° arc length. The penetration of the wedge tips into the aperture region defined by the implant was varied from 0 to 4 μm.

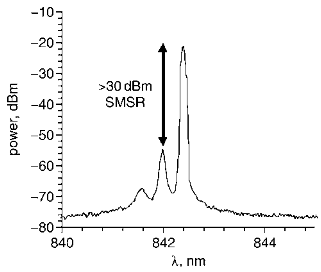

Fig. 2 *Optical lasing spectrum taken at rollover*

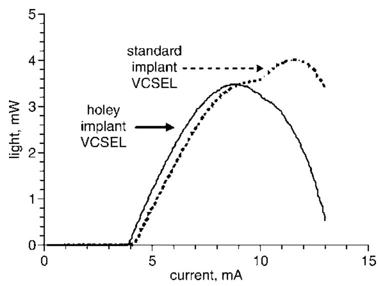

Fig. 3 *Output laser power against injected current for control and wedge-shaped holey VCSELs*

Measurements: Continuous-wave measurements were performed to obtain output power against injected current (LI) characteristics and optical spectra for the VCSELs during operation. Fig. 2 illustrates the optical spectra at maximum power for one device. Singlemode operation was achieved for all nine devices in this study, with sidemode suppression ratios (SMSRs) greater than 30 dB from threshold to rollover. Fig. 3 shows the LI characteristics for the same VCSEL, along with the LI characteristics for the control VCSEL, which has no etched pattern in it. This control device exhibits a threshold of 4.2 mA with a maximum singlemode power of 3.25 mW, and becomes multimode at an injection level of 9.5 mA. After etching the wedge-shaped holey pattern, the threshold is reduced to 3.9 mA, and the singlemode output power increases to 3.5 mW, with singlemode operation being maintained to maximum power at rollover.

The effect of the penetration of the wedge tip into the implant aperture region was also characterised. Fig. 4*a* illustrates the lasing threshold, Fig. 4*b* the maximum singlemode power, and Fig. 4*c* the differential quantum efficiency, all against the penetration of the wedge tip into the proton-implant aperture region, with lines drawn corresponding to the control device for reference. In all cases, a decrease in threshold current was observed. The decrease in threshold current is due to index optical confinement, which has been introduced by the etched holes. The increase of the slope efficiency for devices, the tips of which penetrate less than 3 μm, is consistent with reduced diffraction loss at threshold compared to gain-guided proton implanted VCSELs. The holes introduce significant loss to the higher-order modes, but not much to the fundamental mode, allowing all power in the fundamental mode to be extracted with greater than 30 dB SMSR.

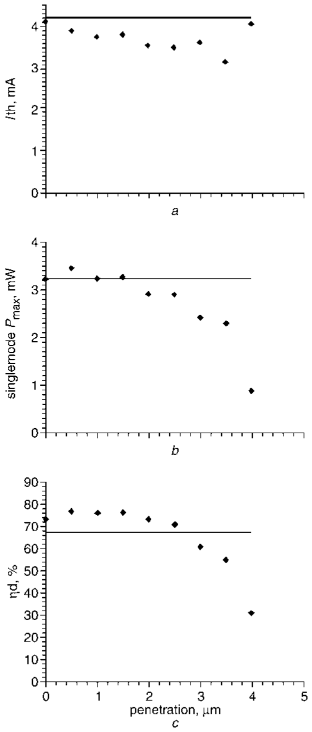

Fig. 4 *Threshold current, maximum singlemode power, and differential quantum efficiency against penetration of wedge tip into implant aperture*
Values for unetched control device plotted as straight solid line for reference

Conclusions: Wedge-shaped holes have been fabricated and characterised in proton-implant VCSELs. Continuous-wave measurements indicate this holey structure can decrease threshold current, increase maximum singlemode output power, and increase the efficiency of the VCSEL. With further refinement of the wedge-shape and implant diameter, to form a more optimum radially graded index profile, greater enhancement of the singlemode VCSEL output is expected.

1 July 2005
Electronics Letters online no: 20052394
doi: 10.1049/el:20052394

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References

1 Jung, C., *et al.*: '4.8 mW singlemode oxide confined top-surface emitting vertical-cavity laser diodes', *Electron. Lett.*, 1997, **33**, (21), pp. 1790–1791
2 Martinsson, H., *et al.*: 'Transverse mode selection in large-area oxide-confined vertical-cavity surface-emitting lasers using a shallow surface relief', *IEEE Photonics Technol. Lett.*, 1999, **11**, pp. 1536–1538
3 Young, E.W., *et al.*: 'Single-transverse-mode vertical-cavity lasers under continuous and pulsed operation', *IEEE Photonics Technol. Lett.*, 2001, **13**, pp. 927–929
4 Unold, H.J., *et al.*: 'Photonic crystal surface-emitting lasers: tailoring waveguide for single-mode emission'. Proc. of 27th European Conf. on Optical Communication, Amsterdam, The Netherlands, 2001
5 Song, D., *et al.*: 'Single-fundamental-mode photonic-crystal vertical-cavity surface-emitting lasers', *Appl. Phys. Lett.*, 2002, **80**, pp. 3901–3903
6 Yokouchi, N., Danner, A.J., and Choquette, K.D.: 'Vertical-cavity surface-emitting laser operating with photonic crystal seven-point defect structure', *Appl. Phys. Lett.*, 2003, **82**, pp. 3608–3610
7 Yokouchi, N., Danner, A.J., and Choquette, K.D.: 'Two-dimensional photonic crystal confined vertical-cavity surface-emitting lasers', *IEEE J. Sel. Top. Quantum Electron.*, 2003, **9**, (5), pp. 1439–1445
8 Danner, A.J., *et al.*: 'Transverse modes of photonic crystal vertical-cavity lasers', *Appl. Phys. Lett.*, 2004, **84**, pp. 1031–1033
9 Furukawa, A., *et al.*: 'High-power single-mode vertical-cavity surface-emitting lasers with triangular holey structure', *Appl. Phys. Lett.*, 2004, **85**, pp. 5161–5163
10 Choquette, K.D., *et al.*: 'Low threshold voltage vertical-cavity lasers fabricated by selective oxidation', *Electron. Lett.*, 1994, **30**, pp. 2043–2044
11 Choquette, K.D., *et al.*: 'Scalability of small-aperture selectively oxidized vertical cavity lasers', *Appl. Phys. Lett.*, 1997, **70**, pp. 823–825