

fier would be greater than in a more conventional glass system. Therefore it is necessary to produce very low-loss fibres in order to compete with demonstrated 1.3µm fibre amplifiers.

Acknowledgments: This work was partially supported by a UK SERC/DTI LINK programme (GOAL). B. Dussardier is supported by the European Communities Council (HCM program, n° ERP4001GT921473). Gallium sulphide (Ga₂S₃) was supplied by Merk Ltd., Poole, Dorset, United Kingdom.

© IEE 1995

8 November 1994

Electronics Letters Online No: 19950099

B. Dussardier, D.W. Hewak, B.N. Samson, H.J. Tate, J. Wang and D.N. Payne (Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom)

References

- 1 YAMADA, M., SHIMIZU, M., OHISHI, Y., TEMMYO, J., WADA, M., KANAMORI, T., HORIGUCHI, M., and TAKAHASHI, S.: '15.1-dB-gain Pr³⁺-doped fluoride fiber amplifier pumped by high-power laser-diode modules', *IEEE Photonics Technol. Lett.*, 1992, 9, pp. 994-996
- 2 HEWAK, D.W., DEOL, R.S., WANG, J., WYLANGOWSKI, G., MEDEIROS NETO, J.A., SAMSON, B.N., LAMING, R.I., BROCKLESBY, W.S., PAYNE, D.N., JHA, A., POULAIN, M., OTERO, S., SURINACH, S., and BARO, M.D.: 'Low phonon-energy glasses for efficient 1.3µm optical fibre amplifiers', *Electron. Lett.*, 1993, 29, pp. 237-238
- 3 HEWAK, D.W., MEDEIROS NETO, J.A., SAMSON, B.N., WANG, J., TATE, H.J., PEARSON, A.D., BROCKLESBY, W.S., WYLANGOWSKI, G., LAMING, R.I., PAYNE, D.N., JHA, A., NAFTALY, M., JORDERY, S., and POULAIN, M.: 'Spectroscopy of Pr³⁺-doped low phonon-energy glasses based on halides and sulphides', *SPIE Fiber Laser Sources and Amplifiers V*, 1993, Vol. 2073, pp. 102-117
- 4 BERG, R.W., VON WINBUSH, S., and BJERRUM, N.J.: 'Negative oxidation states of the chalcogens in molten salts. I. Raman spectroscopic studies on aluminium chlorosulphides formed in chloride and chloroaluminate melts and some related solid and dissolved compounds', *Inorg. Chem.*, 1980, 19, pp. 2688-2698
- 5 LE TOULLEC, M., CHRISTENSEN, P.S., LUCAS, J., and BERG, R.W.: 'A new family of vitreous materials: the cesium aluminium or gallium thiohalide glasses', *Mat. Res. Bull.*, 1987, 22, pp. 1517-1523

Selectively oxidised vertical cavity surface emitting lasers with 50% power conversion efficiency

K.L. Lear, K.D. Choquette, R.P. Schneider, Jr., S.P. Kilcoyne and K.M. Geib

Indexing terms: Vertical cavity surface emitting lasers, Lasers

Index-guided vertical cavity top-surface emitting laser diodes have been fabricated from an all epitaxial structure with conducting mirrors by selective lateral oxidation of AlGaAs. Low voltage, a 78% slope efficiency, and a 350µA threshold current in a single device combine to yield a maximum power conversion efficiency of 50% at less than a 2mA drive current. The device operates in a single mode up to 1.5mW.

Insulating aluminum oxide layers formed by the wet thermal oxidation of buried AlGaAs layers have been used for electrical isolation in edge-emitting [1, 2] and surface-emitting [3-5] lasers. The low index, ~1.6 [6], of these same oxidised films has also motivated their use in vertical [7] and lateral [1, 2] waveguide cladding layers for edge-emitters, high index contrast multilayer mirrors [6], and photopumped surface-emitting lasers based on such mirrors [8]. Here we show that such oxides can be used to create index guided, vertical-cavity surface-emitting lasers (VCSELs). Most top-emitting VCSELs are fabricated by means of proton implantation which results in electrical but not optical confinement. Such gain-guided devices have modal properties that are strongly dependent on thermal lensing [9-11], and they do not scale well to smaller diameters because of optical diffraction losses [12, 13]. The incor-

poration of oxides for index guiding circumvents these problems as well as providing current confinement [4, 5] and has led to a four-fold improvement in the power conversion efficiency of VCSEL diodes at low current levels, reaching 50% for the first time.

The index-guided VCSELs were fabricated from an all epitaxial structure similar to that previously used for proton-implanted devices [14]. The design had fewer top mirror periods because the lower optical parasitic loss allows more output coupler transmission. Index-guiding and current aperture layers were formed by selective lateral oxidation as previously described by Choquette *et al.* [4, 5]. Following the wet thermal oxidation, backside and annular topside contacts were deposited and alloyed. For the present results, a device with a ~7 × 7µm² active region was characterised in wafer form on a stage at 20°C under CW operation. The measurements were made using a directly illuminated, calibrated silicon photodiode and an HP4145 parameter analyser as well as a Melles Griot laser diode driver. The instrument and photodiode calibrations were cross-checked against a third, completely independent driver and detector system. The VCSEL was operated CW at 5.0 mA for 4h and showed a monotonic power increase totalling 3% for this period. The absence of near-term degradation indicates that there are no obvious stability problems inherent in the selective lateral oxidation approach.

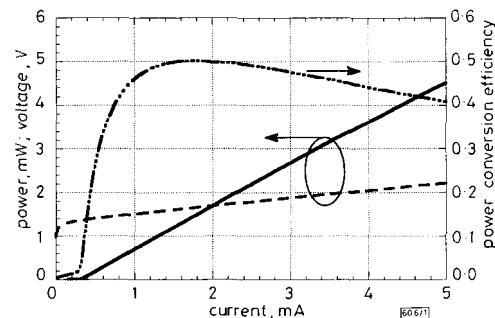


Fig. 1 Light voltage and power against current characteristics for approximately 7 × 7µm² index guided, top emitting VCSEL fabricated by selective oxidation

— light
- - - voltage
... power

The characteristics for this laser as shown in Fig. 1 indicate sub-milliampere threshold current, high slope efficiency, and low voltage operation at low currents. The threshold current of 350µA corresponds to a threshold current density of 700A/cm². The differential quantum efficiency of 78% just above threshold is largely due to the aggressive output coupler design. This excellent optical performance combines with excellent electrical performance originating from the tight current confinement and absence of implant induced damage afforded by selective lateral oxidation [4, 5] and the low lateral and vertical resistance of uni-parabolic mirror grading [14, 15] to yield a maximum power conversion efficiency of 50.2%. This is especially noteworthy in that it occurs at less than 2mA of operating current. A 1mW output power is produced by only 2.04mW of input electrical power corresponding to a power conversion efficiency of 49%, approximately a four-fold improvement over the best previous VCSEL results at this output level [14, 16]. The most competitive result for edge-emitting lasers is ~40% efficiency at 1mW of output power (0.7mA extrapolated threshold current and 75% slope efficiency) for devices produced by growth on nonplanar substrates [17, 18].

The index-guiding of the oxidised laser is evident in the emission spectra plotted on a logarithmic scale in Fig. 2 for several bias currents. The spectra were measured using a 0.31 NA microscope objective to couple the emission into a 50µm core fibre that delivered the light to an HP70951A optical spectrum analyser. Several nonlasing modes can be seen as peaks in the amplified spontaneous emission spectra. Such secondary peaks are absent in the smooth spectra of nominally gain-guided, proton-implanted devices until higher order modes reach threshold. Thus a strong modal structure in subthreshold spectra is indicative of index guid-

ing. The modal spacing is inversely related to the device size. Despite the presence of many modes in the amplified spontaneous emission spectra, lasing occurs initially only in the fundamental mode at the longest wavelength. The laser operates in a single mode with more than 20dB of transverse mode suppression up to 1.5mW of output power at 1.8mA of drive current. Two and then three lasing modes are apparent at currents of 2 and 5mA, respectively. The spectral features shift to longer wavelengths with increasing current indicating a thermal shift in the index. The thermal resistance calculated from the 0.07nm/K wavelength shift and the net dissipated input power is $\sim 2.5\text{K/mW}$ which is the same as for proton implanted devices of this size made from similar epitaxial structures.

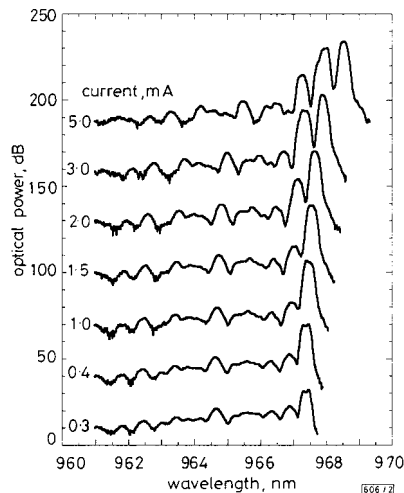


Fig. 2 Emission spectra at several operating currents

Each successive spectrum is offset by 30dB for clarity

In conclusion, we have demonstrated dramatic improvements in VCSEL power conversion efficiency at low currents using an index-guided, top-emitting structure based on selective oxidation. The power conversion efficiency of VCSELs now exceeds that of edge-emitting lasers at an optical output power of 1mW, a level appropriate for a broad spectrum of applications including fibre optic and free space optical parallel communications, optical switching and processing systems, and sensing applications such as spectroscopy and ranging over short distances.

Acknowledgments: The authors would like to thank J. Banas, J. Escobedo, J. Figiel, J. Nevers, S. Samora, and D. Tibbets for technical assistance. This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

© IEE 1995

7 December 1994

Electronics Letters Online No: 19950125

K.L. Lear, K.D. Choquette, R.P. Schneider, Jr., S.P. Kilcoyne and K.M. Geib (Sandia National Laboratories, Photonics Research Department 1312, MS 0603/PO Box 5800, Albuquerque, NM 87185-0603, USA)

References

- 1 KISH, F.A., CARACCI, S.J., HOLONYAK, N., DALLESSASSE, J.M., HSIEH, K.C., SMITH, S.C., and BURNHAM, R.D.: 'Planar native-oxide index-guided AlGaAs-GaAs quantum heterostructure lasers', *Appl. Phys. Lett.*, 1991, **59**, pp. 1755-1757
- 2 MARANOWSKI, S.A., SUGG, A.R., CHEN, E.I., and HOLONYAK, N.: 'Native oxide top- and bottom-confined narrow stripe p-n AlGaAs-GaAs-InGaAs quantum well heterostructure laser', *Appl. Phys. Lett.*, 1993, **63**, pp. 1660-1662
- 3 HUFFAKER, D.L., DEPPE, D.G., KUMAR, K., and ROGERS, T.J.: 'Native-oxide defined ring contact for low threshold vertical-cavity lasers', *Appl. Phys. Lett.*, 1994, **65**, pp. 97-99

- 4 CHOQUETTE, K.D., SCHNEIDER, R.P., LEAR, K.L., and GEIB, K.M.: 'Record performance from vertical-cavity lasers fabricated by selective oxidation', Proc. 14th IEEE Int. Semiconductor Laser Conf., Maui, Hawaii, 1994, Postdeadline paper PD4, pp. 10-12 Postdeadline paper PD4
- 5 CHOQUETTE, K.D., SCHNEIDER, R.P., LEAR, K.L., and GEIB, K.M.: 'Low threshold voltage vertical-cavity lasers fabricated by selective oxidation', *Electron. Lett.*, 1994, **30**, (24), pp. 2043-2044
- 6 MACDOUGAL, M.H., ZHAO, H., DAPKUS, P.D., ZIARI, M., and STEIER, W.H.: 'Wide-bandwidth distributed Bragg reflectors using oxide/GaAs multilayers', *Electron. Lett.*, 1994, **30**, pp. 1147-1149
- 7 SUGG, A.R., CHEN, E.I., RICHARD, T.A., HOLONYAK, N., and HSIEH, K.C.: 'Photopumped room-temperature continuous operation of native-oxide-embedded AlGaAs-GaAs-InGaAs quantum-well heterostructure lasers', *J. Appl. Phys.*, 1993, **74**, pp. 797-799
- 8 RIES, M.J., RICHARD, T.A., MARANOWSKI, S.A., HOLONYAK, N., and CHEN, E.I.: 'Photopumped room-temperature edge- and vertical-cavity operation of AlGaAs-GaAs-InGaAs quantum-well heterostructure lasers utilizing native oxide mirrors', *Appl. Phys. Lett.*, 1994, **65**, pp. 740-742
- 9 DUTTA, N.K., TU, L.W., HASNAIN, G., ZYDZIK, G., WANG, Y.H., and CHO, A.Y.: 'Anomalous temporal response of gain guided surface emitting lasers', *Electron. Lett.*, 1991, **27**, pp. 208-210
- 10 VAKHSHOORI, D., WYNN, J.D., ZYDZIK, G.J., LEIBENGUTH, R.E., ASOM, M.T., KOJIMA, K., and MORGAN, R.A.: 'Top-surface emitting lasers with 1.9V threshold voltage and the effect of spatial hole burning on their transverse mode operation and efficiencies', *Appl. Phys. Lett.*, 1993, **62**, pp. 1448-1450
- 11 HADLEY, G.R., LEAR, K.L., WARREN, M.E., SCOTT, J.W., and CORZINE, S.W.: 'Lateral mode behavior of CW proton-implanted vertical-cavity surface-emitting lasers', Proc. 14th IEEE Int. Semiconductor Laser Conf., Maui, Hawaii, 1994, pp. 147-148
- 12 LEAR, K.L., KILCOYNE, S.P., and CHALMERS, S.A.: 'High power conversion efficiencies and scaling issues for multi-mode vertical-cavity top-surface-emitting lasers', *IEEE Photonics Technol. Lett.*, 1994, **6**, pp. 778-781
- 13 BABIC, D.I., RAM, R.J., BOWERS, J.E., TAN, M., and YANG, L.: 'Scaling laws for gain-guided vertical cavity lasers with distributed Bragg reflectors', *Appl. Phys. Lett.*, 1994, **64**, pp. 1762-1764
- 14 LEAR, K.L., SCHNEIDER, R.P., CHOQUETTE, K.D., KILCOYNE, S.P., and FIGIEL, J.J.: 'Vertical cavity surface emitting lasers with 21% efficiency by metalorganic vapor phase epitaxy', *IEEE Photonics Technol. Lett.*, 1994, **6**, pp. 1053-1055
- 15 LEAR, K.L., SCHNEIDER, R.P., CHOQUETTE, K.D., KILCOYNE, S.P., FIGIEL, J.J., and ZOLPER, J.C.: 'Mirror designs for low-voltage vertical-cavity surface-emitting lasers by metalorganic vapor phase epitaxy', Proc. Conf. Lasers and Electro-optics, Anaheim, California, 1994, pp. 30-31
- 16 SCOTT, J.W., THIBEAULT, B.J., YOUNG, D.B., COLDREN, L.A., and PETERS, F.H.: 'High efficiency submilliamp vertical cavity lasers with intracavity contacts', *IEEE Photonics Technol. Lett.*, 1994, **6**, pp. 678-680
- 17 ZHAO, H., MACDOUGAL, M.H., FRATESCHI, N.C., SIALA, S., DAPKUS, P., and NOTTENBURG, R.N.: 'High efficiency InGaAs/GaAs single-quantum-well lasers using single-step metalorganic chemical vapor deposition', *IEEE Photonics Technol. Lett.*, 1994, **6**, pp. 468-470
- 18 ZHAO, H., MACDOUGAL, M.H., UPPAL, K., and DAPKUS, P.: 'Submilliampere threshold InGaAs/GaAs/AlGaAs laser array elements by single step growth on nonplanar substrates', Proc. 14th IEEE Int. Semiconductor Laser Conf., Maui, Hawaii, 1994, pp. 18-19

Strained InGaAs quantum disk laser with nanoscale active region fabricated with self-organisation on GaAs (311)B substrate

J. Temmyo, E. Kuramochi, M. Sugo, T. Nishiya, R. Nötzel and T. Tamamura

Indexing terms: Semiconductor junction lasers, Semiconductor quantum dots, Vertical cavity surface emitting lasers

Continuous-wave (CW) operation of a strained InGaAs quantum disk laser with nanoscale active-structures self-organised on GaAs (311)B substrate is demonstrated at room temperature. The threshold current is $\sim 20\text{mA}$, which is considerably lower than that of double quantum well lasers on GaAs (100) substrate grown side-by-side.