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 (Ga_2S_3) was supplied by Merk Ltd., Poole, Dorset, United Kingdom.

8 November 1994
Electronics Letters Online No: 19950099

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

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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 incorporation 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.

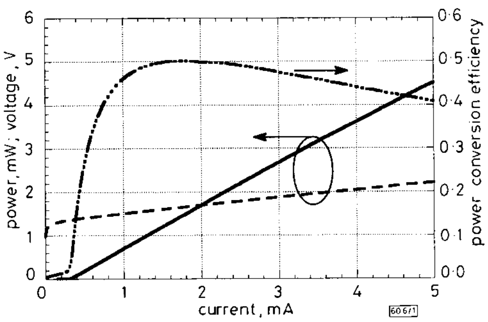

Fig. 1 *Light voltage and power against current characteristics for approximately 7 × 7μm² index guided, top emitting VCSEL fabricated by selective oxidation*

——— 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 guiding. 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 ~2.5K/mW which is the same as for proton implanted devices of this size made from similar epitaxial structures.

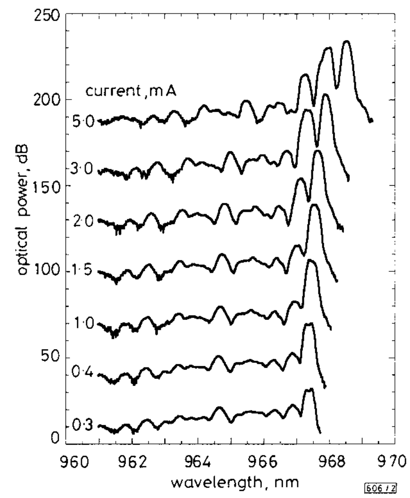

Fig. 2 *Emission spectra at several operating currents*

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.

7 December 1994
Electronics Letters Online No: 19950125

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

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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 ~20mA, which is considerably lower than that of double quantum well lasers on GaAs (100) substrate grown side-by-side.