GaInNAsSb/GaAs vertical cavity surface emitting lasers at 1534 nm

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Electrically pumped, C-band vertical cavity surface emitting lasers (VCSELs) grown on GaAs are reported for the first time. The VCSELs employed three GaInNAsSb quantum wells separated by GaNAs barriers. Pulsed lasing was observed at 1534 nm, in the ITU C-band, when cooled. These lasers exhibit the longest wavelength reported to date for electrically pumped VCSELs grown on GaAs substrates.

Introduction: The transition from copper wire to optical fibre in local and metro area networks has long been hampered by the lack of inexpensive, thermally stable lasers in the C-band, at wavelengths of 1530–1560 nm, which is the minimum loss window in optical fibre. Vertical cavity surface emitting lasers (VCSELs) promise stable wavelength, economies of scale for arrays, fabrication and testing, and inexpensive, lens-free packaging with optical fibre. Although VCSELs previously have been demonstrated on InP with quaternary, distributed Bragg reflector (DBR) mirrors [1, 2], it has been difficult to grow lasers at long wavelengths using inexpensive GaAs substrates, with electrically injected VCSELs reported only at 1300 nm [3] and 1460 nm [4]. GaAs-based VCSELs offer additional advantages, including higher thermal and electrical conductivity using Al(Ga)As/GaAs DBRs, as well as selective wet oxidation of AlGaAs for electrical and optical confinement. There has been one recent report of an optically-pumped VCSEL with dielectric DBRs [5] and several edge emitting lasers in the C-band [6–8], but to the best of our knowledge, no electrically-pumped VCSELs on GaAs have been reported in the literature to date. We report monolithically grown, electrically pumped GaInNAsSb VCSELs grown on GaAs, operating in pulsed mode at 1534 nm.

Growth and fabrication: The VCSELs were grown on an *n*-doped GaAs wafer by plasma assisted, solid source molecular beam epitaxy (MBE). Arsenic and antimony were supplied by valved and unvalved crackers, respectively. Nitrogen was supplied by a modified SVTA plasma source. The ion flux from the plasma was minimised by using ion deflection plates biased at − 40 V and ground [9]. The bottom, silicon-doped DBR was composed of 31 pairs of AlAs/GaAs, followed by four pairs with a lower Al composition (91%) to prevent oxidation after the dry etch. The top, carbon-doped DBR was 21 pairs of $Al_{0.91}Ga_{0.09}As$/GaAs, with a 40 nm 98% AlGaAs layer for selective oxidation embedded in the first AlGaAs layer. The doping and step-grading profiles for the top DBR were based on those of Yechuri *et al.* [10], modified for MBE growth using two aluminum and two gallium cells at fixed temperatures. Each *p*-doped heterojunction was graded in six steps over 30 nm.

The nominally undoped, one-lambda cavity had three 7.5 nm $Ga_{0.62}In_{0.38}N_{0.03}As_{0.94}Sb_{0.03}$ quantum wells (QWs) surrounded by 21 nm $GaN_{0.04}As_{0.96}$ barriers. A high nitrogen content had previously been shown to be advantageous for low-threshold lasers at long wavelengths [11]. Owing to a shortage of ports on our MBE machine, the DBRs were grown in one machine, and the cavity in another, transferred under ultra high vacuum and an arsenic cap. Further growth details have been reported elsewhere [11, 12].

After growth, one-quarter of the wafer was annealed for 1 min at 680°C. A second GaAs wafer was used as a proximity cap to minimise arsenic evaporation during the anneal. Mesas were defined by a dry etch into the cavity, followed by selective wet oxidation for current confinement. Annular top contacts were defined by evaporation and liftoff of Ti/Pt/Au. Au/Ge/Ni/Au was evaporated onto the backside for the *n*-contact, then annealed at 410°C for 1 min.

Results: Fig. 1 shows the spectrum from a VCSEL with a 14 µm diameter current aperture operating at − 48°C and 110 mA (nominal), with a 0.67% duty cycle, at 1.6 times threshold. Limitations of the pulsed laser driver prevented operation at higher currents. Fig. 2 shows the light intensity against current. The nominal current reported here is greater than the actual peak current. Each 0.1 µs pulse was followed by a long, exponential decay, up to 1 µs in duration, which is believed to be due to parasitic capacitance in the testing stage. The extended pulse width meant that the actual duty cycle was greater than that reported above, and the time-averaged current was higher, although only the peak current contributed to lasing. As a consequence, the threshold current reported here, 70 mA (j_{th} = 45 kA/cm^2), represents an upper bound on the actual threshold current.

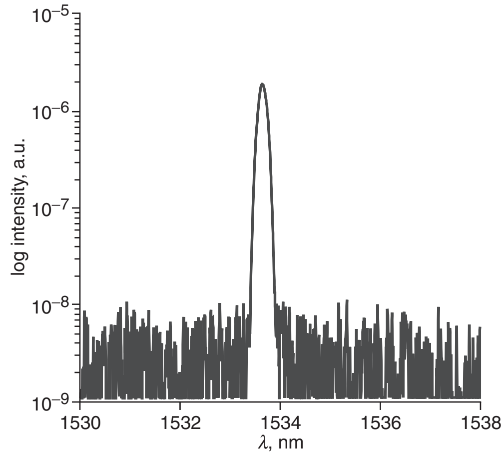

Fig. 1 *Pulsed lasing spectrum at 1.6 × threshold for 14 µm aperture VCSEL*

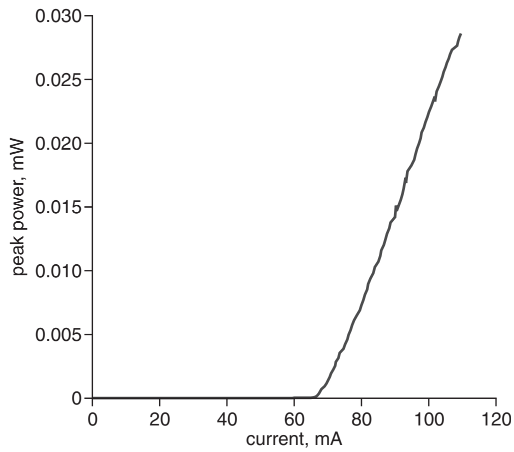

Fig. 2 *Light intensity against current in pulsed operation*

Cooling was required owing to a gain-cavity misalignment. The cavity was designed for 1540 nm lasing at 5°C, using quantum wells designed for 1550 nm edge emitters [7], and refractive index data from Leibiger *et al.* [13]. However, the spontaneous emission from this sample peaked near 1585 nm at room temperature. This 35 nm redshift was consistent with several other samples grown on the same day. The peak gain wavelength therefore had to be temperature tuned to match the cavity. Lasing was observed at temperatures below − 25°C, with a peak output power at − 50°C, which was the limit of the cooling apparatus. Assuming a relative gain/cavity shift of 0.5 nm/°C, the 35 nm redshift would suggest that the peak output power would have been between −70 and −60°C.

We believe that the redshift is related to an anomaly observed in the nitrogen plasma conditions. The anomaly was marked by unusually low reflected RF power from the cell, higher backpressure in the gas foreline, and a decrease in the ratio of atomic to molecular lines in the optical emission spectrum. It remains unclear whether this changed the energy or type of nitrogen species reaching the wafer, or whether it was merely symptomatic of another problem, such as gas contamination. A redshift associated with several kinds of surface damage has previously been observed, but we believe that the present case can be explained by an excessively high nitrogen content. Secondary ion mass spectroscopy (SIMS) showed that the nitrogen concentration was up to 15% higher than intended. Further experiments to identify the causes of the anomaly are underway. Whatever the cause, the cavity was designed to be resonant at only 1540 nm, so the peak gain needed to be thermally tuned to much shorter wavelengths.

Conclusions: We have demonstrated electrically pumped, GaInNAsSb VCSELs operating in the ITU fibre communication C-band at a wavelength of 1534 nm. These are the first such VCSELs on GaAs, to the best of our knowledge. These VCSELs required substantial cooling owing to a large gain/cavity misalignment, but a simple shift in cavity resonance is expected to be sufficient to produce lasing at room temperature. These monolithic VCSELs represent a significant step toward inexpensive lasers for fibre communication.

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