Vertical-cavity surface-emitting lasers with periodic gain and aluminium top contacts

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The measurement of the thermal impedance of semiconductor lasers has shown that the size of carrier density effects can depend strongly on the method and a value that neglecting the carrier-associated refractive index changes can result in an underestimate of the thermal impedance. It has been demonstrated that the thermal impedance if ignored.

**Fig. 2 Comparison of thermal impedance measurements**

- \( R = 15.4°C/W \) obtained using DC drive current
- \( R = 36.9°C/W \) obtained using a high frequency modulated drive current and correcting for carrier density induced refractive index changes

for. Fig. 2 shows two sets of results obtained from measurements carried out on a ridge waveguide laser structure as described in [3].

One of these is obtained using an unmodulated drive current and gives \( R = 15.4°C/W \), and the other is obtained using the above method and a value \( R = 36.9°C/W \) is obtained. It is clearly seen that neglecting the carrier-associated refractive index changes can result in an underestimate of the thermal impedance. It has been shown that the size of carrier density effects can depend strongly on the dimensions of the laser waveguide [2].

**Conclusion:** We have presented an improved method for the measurement of the thermal impedance of semiconductor lasers. This overcomes the limitations of previously established methods which ignore the heating effects present within the duration of a current pulse. We have also shown that carrier density induced refractive index changes are significant and can lead to an underestimated thermal impedance if ignored.

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B.S. Bhumbra, G.H.B. Thompson and A.P. Wright (BNR Europe Limited, London Road, Harlow, Essex CM17 9WA, United Kingdom)

References

**Vertical-cavity surface-emitting lasers with periodic gain and aluminium top contacts**


The authors report low threshold current operation of InGaAs/AlGaAs vertical-cavity surface-emitting lasers. A periodic gain structure allows more strained wells to be used than in conventional multi-quantum-well devices, offering advantages for high-power devices. Aluminium oxide contacts grown by molecular beam epitaxy are used on lasers for the first time.

**Vertical-cavity surface-emitting lasers (VCSELs)** are seen as important optoelectronic devices because they give low divergence output beams, they can be tested at the wafer level and they can easily be integrated into arrays. The all-epitaxial bottom surface-emitting variety with strained InGaAs quantum wells and a top metallic contact that also augments the reflectivity of the top mirror [1] is the simplest to fabricate. The InGaAs quantum wells give high gain [1] which allows ultra-low threshold current [2] or high output power [3].

The series resistance, originating from the potential barriers at the interfaces in the reflectors, is a limiting factor. Various compositional grading schemes have been demonstrated to circumvent this problem [2, 4, 5]. Another approach, especially relevant for high-power lasers, would be to increase the number of quantum wells, by which the gain in the cavity could be enhanced. A larger available gain would mean that less reflectivity would be required from the mirrors, which could then be thinner and have less resistance. To date, the maximum number of strained InGaAs quantum wells in low-threshold devices has been three, because the half-wavelength spacers between each gain block are thick enough to decouple the strained regions from one another.

We have compared a sample with a total of six wells, and thinner reflectors, with a more conventional three-well design. State-of-the-art performance was obtained with the latter. The sample with six wells and thinner reflectors, however, exhibited lower resistance and greater maximum power and overall efficiency. We also demonstrate the first use of aluminium grown by molecular beam epitaxy (MBE) as a p-type contact for laser.

Two device structures were grown by MBE on n-type GaAs substrates. The basic design was similar to those reported elsewhere [1, 2], comprising a two-wavelength undoped GaAs cavity with 80Å InGaAs quantum wells located at each of the three optical antinodes inside the cavity. The first sample contained three quantum wells, one at each antinode, separated from each other by half a wavelength (130Å). The second sample contained six quantum wells, two wells with a 100Å GaAs barrier at each antinode. The mirrors were GaAs/AlAs quarter-wave reflectors doped at 5x10¹⁸ cm⁻³ for the lower, n-type, mirror, and 10¹⁷ cm⁻³ for the upper, p-type, mirror. Compositional graded superlattices [4] were incorporated at every GaAs/AlAs interface, and in the p-type mirror the doping was increased in the graded superlattices to 2x10¹⁸ cm⁻³. The lower and upper mirrors contained 24 and 16 pairs, respectively, for the three-well sample, and 39 and 11 pairs for the six-well sample. A GaAs cap doped at 10¹⁷ cm⁻³/p-type was grown on top, and its thickness was designed to match the phase of reflections from the top metallic contact and the top multilayer.

A 0.2µm layer of aluminium was deposited in the growth chamber of the MBE machine after the wafer had cooled to ~20°C. MBE-grown Al has been shown to be a low-resistance ohmic contact to heavily doped p-type GaAs [6], and it makes the post-growth processing extremely simple. Square and circular mesa of various sizes were etched through to the lower mirror by wet chemical etching, using H₃PO₄ at 50°C for the Al and H₂SO₄:H₂O₂:H₂O 5:1:1 at 20°C for the GaAs/AlAs layers. The rough back side of the substrate was polished, but not antireflection coated, and stripes of AuGeNi ohmic metallization were applied along the edges of the wafer. A schematic cross-section of the device is shown in Fig. 1.

![Fig. 1 Schematic cross-section of vertical-cavity lasers](image-url)
Devices were tested under continuous wave (CW) conditions at room temperature by direct probing of the wafer with no heat-sinking. The optical output was measured using either a power meter or a spectrometer with a charge-coupled-device detector array. The lasing threshold was determined from the combination of a sharp break in the power-current curve, the emergence of one or two dominant spectral peaks with a resolution-limited linewidth less than 1 Å and the appearance of a narrow bright spot in the far-field pattern. Power-voltage-current curves for square devices roughly 40 μm long on each side, selected for low-threshold operation, are shown in Fig. 2. The jumps in the power curves result from reflections off the uncoated substrate/air interface which forms a weak third cavity mirror. Higher maximum optical power, up to 2.8 mW, was obtained from six-well 40 μm square devices from another part of the wafer that also exhibited somewhat higher threshold current (16 mA). For these devices the cavity resonance and gain peak are matched at elevated operating temperature rather than room temperature, a feature which can be deliberately designed into high-power structures [3]. Wavelength shifts of around 5 nm were obtained between threshold and maximum power points. Assuming an average temperature coefficient of the refractive index of 2 × 10⁻⁴K⁻¹ [7] the temperature rise was ~70 K. The lowest threshold current density, obtained on the 40 μm² three-well devices, was ~380 A/cm², taking the area of the active layer as measured in a scanning electron microscope. Because of the roughly 30° slope on the sidewalls of the mesa, the top contact area was some 13% less, and if this area is taken for calculations the threshold current density increases to 430 A/cm². The threshold current density was somewhat larger for smaller devices, as edge effects became more important. For example, 24 μm circles, measured at the active layer, gave CW threshold currents and maximum powers of ~2.3 mA and 0.5 mW for three-well devices (threshold current density 490 A/cm²), taking the area of the active layer, and 3.5 mA and 1.2 mW for six-well devices. The smallest devices that could be probed, albeit with inconsistent characteristics, were 10 μm squares. CW threshold currents and maximum powers were ~1.7 mA and 270 μW for three-well devices, and 3.5 mA and 460 μW for six-well devices.

The low minimum threshold current density, equal to the lowest reported CW value [2], attests to the quality of our structures. The six-well devices used VCSELs with a threshold current density double that of the three-well design, but exhibited lower series resistance and higher maximum power as expected. Because of their higher threshold current, six-well devices had a slightly higher threshold voltage, 3.0 V compared to 2.85 V for 40 μm squares, but well above the threshold they gave a higher overall voltage compared to the three-well devices. The threshold voltage for three-well devices was ~2.5 V compared to ~2.1 V for six-well devices. The peak power for three-well devices was ~1.7 mW, while the peak power for six-well devices was ~2.8 mW.

In conclusion, we have demonstrated that use of the periodic gain structure, rather than a normal multiquantum-well structure, in vertical-cavity lasers allows the incorporation of more strained InGaAs quantum wells without resulting in the formation of misfit dislocations. We have also demonstrated the first use of MBE-grown Al as an optical contact for lasers.

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References

Generally graded TLM mesh using the symmetrical supercondensed node

V. Trenkic, C. Christopoulos and T.M. Benson

Indexing terms: Transmission line matrix method, Modelling

An implementation of an improved all-link line symmetrical condensed node for the TLM method is presented. The new node has the advantage of containing no stubs but is still capable of modelling inhomogeneous media on a generally graded mesh. It requires less storage and run time than the stub-loaded and hybrid nodes, or previously-defined nodes. However, it is shown to have reduced velocity error for axial propagation.