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

Citation for published version (APA):

Yoffe, G. W., Vleuten, van der, W. C., Leijts, M. R., Karouta, F., & Wolter, J. H. (1994). Vertical-cavity surface-emitting lasers with periodic gain and aluminium top contacts. *Electronics Letters*, 30(10), 794-795.
<https://doi.org/10.1049/el:19940549>

DOI:

[10.1049/el:19940549](https://doi.org/10.1049/el:19940549)

Document status and date:

Published: 01/01/1994

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Fig. 2 Comparison of thermal impedance measurements

□ $R_{th} = 15.4^\circ\text{C/W}$ obtained using DC drive current
 ○ $R_{th} = 36.9^\circ\text{C/W}$ 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 $R_{th} = 15.4^\circ\text{C/W}$, and the other is obtained using the above method and a value $R_{th} = 36.9^\circ\text{C/W}$ 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.

Acknowledgment: We acknowledge support from the DTI Link Practical Optical Pump Sources (POPS) programme.

© IEE 1994

21 February 1994

Electronics Letters Online No: 19940554

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

References

- 1 PAOLI, T. L.: 'A new technique for measuring the thermal impedance of junction lasers', *IEEE J. Quantum Electron.*, 1975, **QE-11**, pp. 498-503
- 2 WRIGHT, A. P., GARRETT, B., THOMPSON, G. H. B., and WHITEAWAY, J. E. A.: 'Influence of carrier transport on wavelength chirp of InGaAs/InGaAsP MQW Lasers', *Electron. Lett.*, 1992, **28**, pp. 1911-1913
- 3 BHUMBRA, B. S., GLEW, R. W., GREENE, P. D., HENSHALL, G. D., LOWNEY, C. M., and WHITEAWAY, J. E. A.: 'High power operation of GaInAsP/GaInAs MQW ridge lasers emitting at $1.48\mu\text{m}$ ', *Electron. Lett.*, 1990, **26**, pp. 1755-1756

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

G.W. Yoffe, W.C. van der Vleuten, M.R. Leys, F. Karouta and J.H. Wolter

Indexing terms: Vertical cavity surface emitting lasers, Lasers

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 multiquantum-well devices, offering advantages for high-power devices. Aluminium ohmic 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, the limit for coherently strained material [1]. We demonstrate here that the periodic gain concept, which doubles the effective gain [1], can also be exploited to allow the use of more strained quantum wells, 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 lasers.

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 $80\text{\AA}$ $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ 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 ($1300\text{\AA}$). The second sample contained six quantum wells, two wells with a $100\text{\AA}$ GaAs barrier at each antinode. The mirrors were GaAs/AlAs quarter-wave reflectors doped at $5 \times 10^{17}\text{cm}^{-3}$ for the lower, n -type, mirror, and at 10^{18}cm^{-3} for the upper, p -type, mirror. Compositionally 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 $2 \times 10^{18}\text{cm}^{-3}$. The lower and upper mirrors contained $25\frac{1}{2}$ and 16 pairs, respectively, for the three-well sample, and $20\frac{1}{2}$ and 11 pairs for the six-well sample. A GaAs cap doped at 10^{20}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 $0.2\mu\text{m}$ 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 mesas of various sizes were etched through to the lower mirror by wet chemical etching, using H_3PO_4 at 50°C for the Al and $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ 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 metallisation 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

Fig. 2 Room-temperature CW power-voltage-current characteristics of nominally 40 μm square devices from two wafers

- (i) device with three quantum wells (bold)
(ii) device with six quantum wells

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 $2 \times 10^{-4} \text{ K}^{-1}$ [7] the temperature rise was $\sim 70 \text{ K}$. The lowest threshold current density, obtained on the 40 μm^2 three-well devices, was $\sim 380 \text{ A/cm}^2$, 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/cm^2 . 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 $\sim 2.3 \text{ mA}$ and 0.5 mW for three-well devices (threshold current density 490 A/cm^2 , taking the area of the active layer), and 4.5 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 $\sim 1.7 \text{ mA}$ and $270 \mu\text{W}$ for three-well devices, and 3.5 mA and $460 \mu\text{W}$ 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-quantum-well VCSEL gave 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 maximum overall electrical-to-optical power conversion efficiency, 1.2% compared to 1.0%. Although our devices have not been optimised for high-power operation [3], the results show that increasing the number of wells is a possible route to further increasing the output power. Other potential advantages of the less severe requirements for the mirror reflectivity are reduced total thickness and greater scope for making an asymmetric cavity for increased output coupling efficiency.

The use of MBE-grown aluminium for the top contact is very convenient, because it reduces the contamination at the GaAs/metal interface and eliminates a subsequent processing step. We have previously shown MBE-grown Al to be a good ohmic contact to p^+ GaAs for low-current applications such as solar cells [6]. The present devices, the first lasers reported with such contacts, show that it can also be used for current densities up to several kA/cm^2 , although the long-term stability still has to be determined. From our previous measurements [6] we estimate that the contact contributes 1.5Ω to the resistance of the 40 μm^2 square devices, 6Ω to that of the 24 μm circles. This amounts to $\sim 3\%$ of the total resistance of the three-well device when it is operated at twice the threshold current, or $\sim 2\%$ of the resistance of the six-well device.

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 ohmic contact for lasers.

Acknowledgments: The authors thank J.A.A. Stegeman for operating the electron microscope, T.J. Eijkemans for assistance in the optical measurements and F.W. Ragay for valuable discussions. This work was supported by the Dutch Ministry of Economic Affairs through the IOP Electro-Optics program.

© IEE 1994

21 March 1994

Electronics Letters Online No: 19940549

G.W. Yoffe, W.C. van der Vleuten, M.R. Leys, F. Karouta and J.H. Wolter (COBRA Interuniversity Research Institute on Communication Technology, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands)

References

- COLDREN, L.A., GEELS, R.S., CORZINE, S.W., and SCOTT, J.W.: 'Efficient vertical cavity lasers', *Opt. Quantum Electron.*, 1992, **24**, pp. S105-S119
- SALE, T.E., WOODHEAD, J., GREY, R., and ROBSON, P.N.: 'Wide operating wavelength range and low threshold current in $\text{In}_{0.24}\text{Ga}_{0.76}\text{As}/\text{GaAs}$ vertical-cavity surface-emitting lasers', *IEEE Photonics Technol. Lett.*, 1992, **4**, pp. 1192-1194
- PETERS, F.H., PETERS, M.G., YOUNG, D.B., SCOTT, J.W., THIBEAULT, B.J., CORZINE, S.W., and COLDREN, L.A.: 'High-power vertical-cavity surface-emitting lasers', *Electron. Lett.*, 1993, **29**, pp. 200-201
- GEELS, R.S., CORZINE, S.W., SCOTT, J.W., YOUNG, D.B., and COLDREN, L.A.: 'Low threshold planarized vertical-cavity surface-emitting lasers', *IEEE Photonics Technol. Lett.*, 1990, **2**, pp. 234-236
- PETERS, M.G., THIBEAULT, B.J., YOUNG, D.B., SCOTT, J.W., PETERS, F.H., GOSSARD, A.C., and COLDREN, L.A.: 'Band-gap engineered digital alloy interfaces for lower resistance vertical-cavity surface-emitting lasers', *Appl. Phys. Lett.*, 1993, **63**, pp. 3411-3413
- RAGAY, F.W., LEYS, M.R., and WOLTER, J.H.: 'Aluminium layers as nonalloyed contacts to p -type GaAs', *Appl. Phys. Lett.*, 1993, **63**, pp. 1234-1236
- MARPLE, D.T.F.: 'Refractive index of GaAs', *J. Appl. Phys.*, 1964, **35**, pp. 1241-1242

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, can operate on a higher time-step than previous nodes and it is shown to have a reduced velocity error for axial propagation.