High-performance 1.5 μm GaInNAsSb lasers grown on GaAs

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Substantially reduced threshold current density and improved efficiency in long-wavelength (>1.4 μm) GaAs-based lasers are reported. A 20 × 1220 μm as-cleaved device showed a room temperature continuous-wave threshold current density of 580 A/cm^2, external efficiency of 53%, and 200 mW peak output power at 1.5 μm. The pulsed threshold current density was 450 A/cm^2 with 1145 mW peak output power.

Introduction: Since the initial demonstration by Fischer and coworkers of a GaInNAs laser at 1.52 μm [1], substantial improvements in device performance have recently been reported [2–6]. Despite this rapid improvement, the threshold current density and external efficiency have remained insufficient for commercial applications. Specifically, only a few continuous-wave (CW) devices have been reported, with threshold current densities remaining above 1 kA/cm^2 and external efficiencies ∼30–40%. Owing to the non-reactive nature of N_2, an RF plasma cell is typically employed to generate reactive nitrogen for molecular beam epitaxy (MBE) growth. Recent improvements in growth technology have focused on eliminating the ion-related damage generated during active-layer growth [7]. By further reducing the non-radiative recombination rate, we demonstrate substantially improved laser performance at 1.5 μm, at maximum output power. The room temperature pulsed threshold current density of 450 A/cm^2 for a 20 × 1220 μm as-cleaved device is equal to the lowest reported GaInNAsSb laser threshold at any emission wavelength [8]. Other room-temperature performance metrics also represent significant improvements over previous reports [6]. The characteristic temperatures for the threshold current density (T_0) and external efficiency (T_1) were 73 and 125K, respectively. Hole leakage is identified as the primary temperature destabilising mechanism responsible for the reduced T_0 and T_1. These results are not only encouraging for the prospects for GaAs-based lasers at ∼1.55 μm, but are also of significant interest for Raman amplifier applications in the S, C and L bands. Raman amplifiers are more efficient than erbium-doped fibre amplifiers when the pump power exceeds ∼300 mW.

Fabrication: Ridge-waveguide lasers were grown by solid-source MBE on a (100) *n*-type GaAs wafer. The growth and fabrication are quite similar to those described in [6]. Group III sources were supplied by effusion cells. Dimeric arsenic was supplied with a conventional valved cracker cell and monomeric antimony with an unvalved cracker cell. An RF plasma cell was used to generate reactive nitrogen. Deflection plates at the exit aperture of the cell, biased at −40 V and ground, were used to minimise the ion flux upon the wafer [7]. Dopants were supplied by silicon (*n*-type) and carbon tetrabromide (*p*-type).

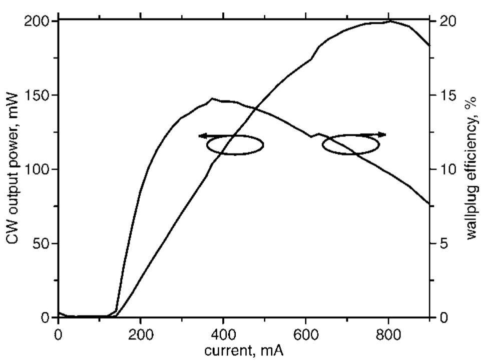

Fig. 1 *Room temperature CW L–I and wallplug efficiency for 20 × 1222 μm device*

The active layer was a single 75 Å $Ga_{0.62}In_{0.38}N_{0.023}As_{0.95}Sb_{0.027}$ quantum well (QW) surrounded on either side by 220 Å $GaN_{0.025}As_{0.975}$ barriers grown at ∼440°C and embedded in a $GaAs/Al_{0.33}Ga_{0.67}As$ waveguide. The lasers were *ex situ* annealed at 740°C for 1 min in a rapid thermal annealing furnace, with arsenic out diffusion minimised by a proximity cap. Ridges were defined with lift-off of Ti/Pt/Au ohmic contacts, followed by a self-aligned dry etch to the top of the GaAs-waveguide. Samples were then thinned to ∼120 μm and Au/Ge/Ni/Au was evaporated onto the substrate side. A contact sinter was performed at 410°C for 1 min. Devices were manually cleaved and mounted epi-side up on a temperature-controlled copper heatsink.

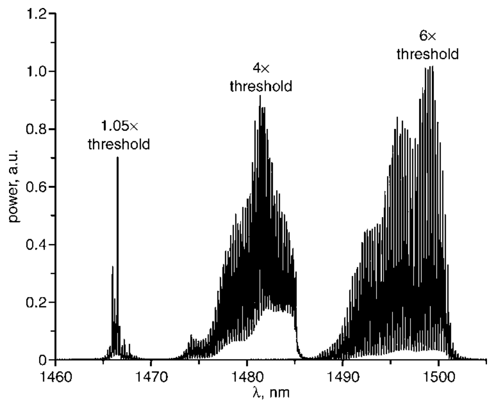

Fig. 2 *Optical spectrum at room temperature for 20 × 1222 μm device at various levels above threshold*

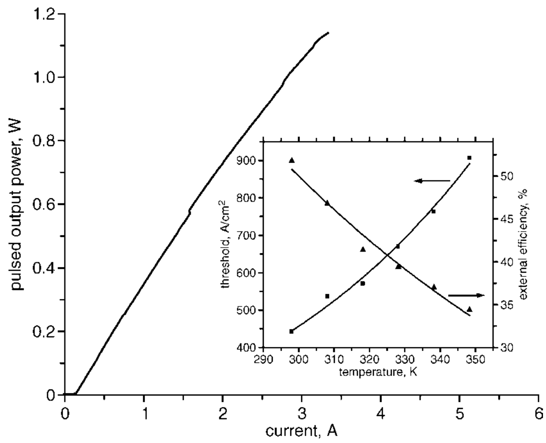

Fig. 3 *Pulsed L–I curve for 20 × 1222 μm device at room temperature*

Inset: Pulsed threshold current density (squares) and external efficiency (triangles) with temperature

Results: Fig. 1 shows the room temperature CW *L–I* curve and wallplug efficiency for a 20 × 1200 μm device with as-cleaved facets. The threshold current density was 580 A/cm^2, the external efficiency was 53%, and the peak output power was 200 mW from both facets. A peak CW wallplug efficiency of 14.8% was measured at 103 mW of output power. As shown in Fig. 2, the device lased at 1.466 μm at threshold and redshifted to 1.502 μm at thermal rollover. Using both the bandgap shift with temperature of 0.58 nm/K and the thermal resistance of 24 K/W, the active region temperature at thermal rollover was estimated to be 80–85°C. Devices lased CW up to 65°C, at a junction temperature of 90–95°C.

Under pulsed operation, the laser produced substantially higher output powers. The room temperature pulsed *L–I* curve (500 ns pulse, 0.1% duty cycle) is shown in Fig. 3. The threshold current density was 450 A/cm^2. The external efficiency was 49% and a driver-limited peak output power of 1.145 W was achieved from both facets. The characteristic temperatures for threshold current density (T_0) and external efficiency (T_1) were 73 and 125K, respectively, as shown in the inset of Fig. 3. These values are lower than those reported in [6], indicating that carrier leakage may be the dominant non-radiative process in these devices. While the monomolecular recombination rate is substantially reduced, the threshold carrier density is likely to be unchanged. As a result, the rate of carrier leakage is not reduced, resulting in a degradation of both T_0 and T_1. While further study is required, carrier leakage and not Auger recombination may be the dominant temperature destabilising effect in these devices. No ‘kinks’ were observed in either the threshold current density or external efficiency with temperature. Such behaviour was previously attributed to the turn-on of Auger recombination in similar devices [6]. At 55°C, the *Z*-parameter at threshold, Z_{th}, was 3.3 [9], confirming the presence of carrier leakage. Auger recombination scales with the cube of the carrier density [10], but carrier leakage scales with the third or fourth power of the carrier density [11]. Therefore, $Z_{th} > 3$ must be caused, at least in part, by carrier leakage. Further, photoreflectance measurements of identical QW structures show the valence band offset between GaInNAsSb and GaNAs to be ~50–60 meV, indicating that holes are the species responsible for the leakage effects.

Conclusions: We have demonstrated the first high-performance dilute nitride laser beyond 1.4 μm. The pulsed threshold current density of 450 A/cm^2 is equal to the lowest reported value for a GaInNAsSb laser at any wavelength and >2× lower than any previously reported GaAs-based device beyond 1.4 μm. Under room temperature CW operation the threshold current density was 580 A/cm^2, the external efficiency was 53%, and the peak output power was 200 mW at 1.5 μm. A significantly higher pulsed output power of 1.145 W was obtained from the same single QW device at room temperature. These performance characteristics all represent a significant improvement over the previous state-of-the-art dilute nitride lasers in the 1.5 μm regime. Hole leakage was identified as the dominant mechanism governing the temperature sensitivity.

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References

1 Fischer, M., Reinhardt, M., and Forchel, A.: ‘GaInAsN/GaAs laser diodes operating at 1.52 μm’, *Electron. Lett.*, 2000, **36**, (14), pp. 1208–1209
2 Ha, W., Gambin, V., Bank, S., Wistey, M., Yuen, H., Kim, S.M., and Harris, J.S.: ‘Long-wavelength GaInNAs(Sb) lasers on GaAs’, *IEEE J. Quantum Electron.*, 2002, **38**, (9), pp. 1260–1267
3 Li, L.H., Sallet, V., Patriarche, G., Largeau, L., Bouchoule, S., Merghem, K., Travers, L., and Harmand, J.C.: ‘1.5 μm laser on GaAs with GaInNAsSb quinary quantum well’, *Electron. Lett.*, 2003, **39**, (6), pp. 519–520
4 Gollub, D., Moses, S., Fischer, M., and Forchel, A.: ‘1.42 μm continuous-wave operation of GaInNAs laser diodes’, *Electron. Lett.*, 2003, **39**, (10), pp. 777–778
5 Bank, S.R., Wistey, M.A., Yuen, H.B., Goddard, L.L., Ha, W., and Harris, J.S. Jr.: ‘Low-threshold CW GaInNAsSb/GaAs laser at 1.49 μm’, *Electron. Lett.*, 2003, **39**, (20), pp. 1445–1446
6 Bank, S.R., Wistey, M.A., Goddard, L.L., Yuen, H.B., Lordi, V., and Harris, J.S. Jr.: ‘Low-threshold, continuous-wave, 1.5 μm GaInNAsSb lasers grown on GaAs’, *IEEE J. Quantum Electron.*, 2004, **40**, (6), pp. 656–664
7 Wistey, M.A., Bank, S.R., Yuen, H.B., and Harris, J.S. Jr.: ‘Real-time measurements of GaInNAs nitrogen plasma ion flux’. Proc. 2003 North American MBE Conf., Keystone, CO, USA, p. 133
8 Setiagung, S., Shimizu, H., Ikenaga, Y., Kumada, K., and Kawukawa, A.: ‘Very low threshold current density of 1.3-μm-range GaInNAsSb-GaAs 3 and 5 QWs lasers’, *IEEE J. Sel. Top. Quantum Electron.*, 2003, **9**, (5), pp. 1209–1213
9 Goddard, L.L., Bank, S.R., Wistey, M.A., Yuen, H.B., Bae, H.P., and Harris, J.S. Jr.: ‘Reduced monomolecular recombination in GaInNAsSb/GaAs lasers at 1.5 μm’. To be presented at IEEE LEOS 2004
10 Sweeney, S.J., Phillips, A.F., Adams, A.R., O’Reilly, E.P., and Thijs, P.J.A.: ‘The effect of temperature dependent processes on the performance of 1.5-μm compressively strained InGaAs(P) MQW semiconductor diode lasers’, *IEEE Photonics Technol. Lett.*, 1998, **10**, (8), pp. 1076–1078
11 Olshansky, R., Su, C.B., Manning, J., and Powazinik, W.: ‘Measurement of radiative and nonradiative recombination rates in InGaAsP and AlGaAs light sources’, *IEEE J. Quantum Electron.*, 1984, **QE-20**, (8), pp. 838–854