Room-temperature continuous-wave 1.55 μm GaInNAsSb laser on GaAs

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The first low-threshold 1.55 μm lasers grown on GaAs are reported. Lasing at 1.55 μm was observed from a 20×2400 μm as-cleaved device with a room-temperature continuous-wave threshold current density of 579 A/cm^2, external efficiency of 41%, and 130 mW peak output power. The pulsed threshold current density was 550 A/cm^2 with >600 mW peak output power.

Introduction: The proposal by Kondow and co-workers [1] of GaInNAs active regions for temperature insensitive GaAs-based lasers has led to significant success in the 1.3 μm regime, and performance currently exceeds that of competing InP-based devices. This effort has yielded InGaAs/GaAs lasers that emit out to ~1.25 μm with exceedingly low-threshold current densities [2], and emission has been extended to 1.3 μm with <1% nitrogen and little degradation of device performance [3]. However, the 1.55 μm regime offers significant advantages for metro area networks (MANs), in terms of repeater-less transmission distances and bit rates, especially if dispersion-shifted fibre is employed. Low-power 1.55 μm vertical-cavity surface-emitting lasers (VCSELs) possess many advantages for use as transmission sources for MANs but are challenging to produce on InP [4, 5].

GaAs substrates offer many advantages for VCSELs, including high-quality native oxide layers for current and optical confinement and Al(Ga)As/GaAs distributed Bragg reflector mirrors with high index contrast and high thermal conductivity. Moreover, dilute-nitride active regions should retain many of their advantages at these longer wavelengths, including low carrier leakage (large conduction band offsets) and high differential gain (high compressive strain and large electron effective mass). High differential gain is particularly promising as it could significantly reduce the threshold carrier density and, hence, the effects of Auger recombination, intervalence band absorption (IVBA), and carrier leakage. Mitigating these mechanisms would dramatically improve the temperature stability of both the threshold current and external efficiency.

Progress in the long-wavelength dilute-nitride lasers has advanced significantly in recent years, as illustrated by Fig. 1 (adapted from [6]). The addition of antimony and mitigation of ion-related damage during molecular beam epitaxy growth (MBE) enabled room-temperature, continuous-wave (CW) operation and the first truly low-threshold current densities at 1.5 μm [7, 8]. Excellent results were subsequently obtained without the use of antimony, but with somewhat higher thresholds [9]. However, lasers at the ultimate target of 1.55 μm still exhibit exceedingly high threshold current densities [10, 11]. We present the first low-threshold, CW, 1.55 μm lasers on GaAs. As seen in Fig. 1, laser thresholds are comparable to dilute-nitride lasers at shorter wavelengths.
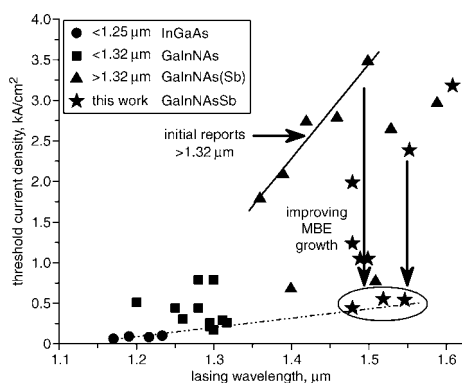

Fig. 1 *Summary of recent GaAs-based laser results [2, 6, 8, 9, 10, 11]*

Circles indicate InGaAs results, squares indicate 1.3 μm range lasers, triangles indicate 1.5 μm range lasers with linear fit to early results (solid line), and stars represent this work. Extrapolation of shorter wavelength results (dashed line) fits well with results of this study

Growth and fabrication: Samples were grown by solid-source MBE on (100) *n*-type GaAs wafers. The growth and fabrication are quite similar to those described previously [7, 8]. 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 on the wafer [12]. The active layer was a single 75 Å $Ga_{0.62}In_{0.38}N_yAs_{0.973-y}Sb_{0.027}$ quantum well (QW) surrounded on either side by 210 Å strain-compensating GaN_zAs_{1-z} barriers grown at ~440°C. Post-growth annealing was performed in a rapid thermal annealing furnace, under a nitrogen ambient, with arsenic outdiffusion minimised by a GaAs proximity cap. To extend the emission wavelength to 1.55 μm, the nitrogen content was progressively increased from $y=2.2$ to 3.0% in the QW and from $z=3.1$ to 4.0% in the barriers. Optimally annealed photoluminescence (PL) spectra of the different samples are shown in Fig. 2. No trend in the optical quality was observed, despite the substantial increase in nitrogen content to extend the emission. Additionally, the optimal post-growth annealing temperature yielding the highest PL efficiency was constant among the samples. The optimal annealing temperature is a measure of the thermal budget of the active region that dictates whether the metastable active region can withstand the *in situ* annealing effects of top cladding layer growth without degradation [13]. Previous devices at 1.55 μm suffered from *in situ* over-annealing because of the low optimal annealing temperature of the active region [10, 13]. Additionally, the increased QW nitrogen content is advantageous for VCSELs because the reduced compressive strain enables the growth of more QWs without strain relaxation.
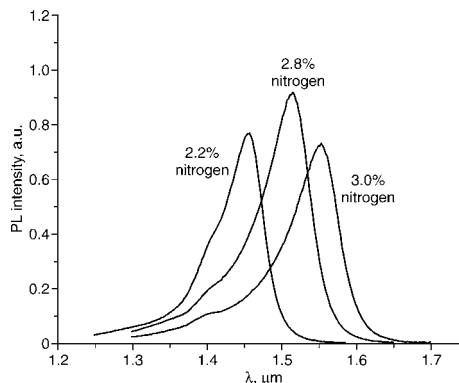

Fig. 2 *Annealed PL spectra against nitrogen content*

Lasers consisted of a single 75 Å $Ga_{0.62}In_{0.38}N_{0.03}As_{0.943}Sb_{0.027}$ QW ($+2.48\%$ strain) surrounded on either side by 210 Å $GaN_{0.04}As_{0.96}$ barriers (-0.81% strain) embedded in a GaAs/$Al_{0.33}Ga_{0.67}As$ waveguide. The lasers were *ex situ* annealed at 740°C for 1 min. 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 episide up on a temperature controlled copper heatsink.

Lasing characteristics: Fig. 3 shows the room-temperature CW L-I curve for a 20×2400 μm device with as-cleaved facets. The threshold current density was 579 A/cm^2, the external efficiency was 40%, and the peak output power was 130 mW from both facets. The device lased at 1.55 μm as shown in the optical spectrum taken at $1.2 \times$ threshold (inset Fig. 3). Under pulsed conditions (1 μs pulse, 1% duty cycle), the device produced >600 mW of kink-free output power, with a threshold current density of 550 A/cm^2. The characteristic temperatures for the threshold current density (T_0) and external efficiency (T_1) were 71 and 171 K, respectively, near room temperature. These values are comparable to those obtained from low-threshold 1200 μm-long devices at 1.5 μm [8]. Lasers containing slightly less nitrogen lased at 1.52 μm, with comparable performance (Fig. 1).

A cavity length study, under the assumption of a logarithmic current-gain relation, was performed at room temperature on the 1.55 μm lasers to extract the important device quantities: gain coefficient (g_o) of 1800 cm^{-1}, transparency current density (J_{tr}) of 240 A/cm^2, internal efficiency (η_i) of 62%, and internal loss (α_i) of 4.8 cm^{-1}. Somewhat higher values of g_o and J_{tr}, as compared to the values at 1.5 μm, are

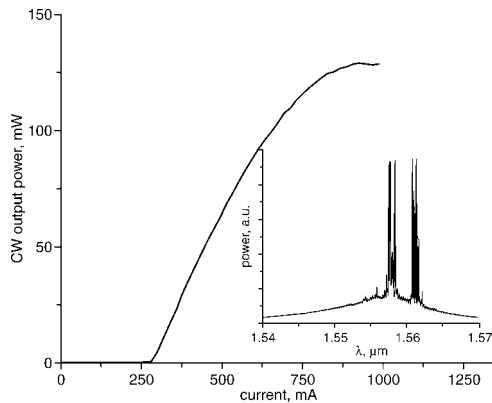expected owing to the increased electron effective mass for higher nitrogen content.

Fig. 3 *Room temperature CW L-I for 20 × 2400 μm device*
Inset: Optical spectrum at 1.2 × threshold

Conclusions: We have demonstrated the first low-threshold GaAs-based laser at 1.55 μm with a pulsed threshold current density of 550 A/cm^2. This represents more than a fourfold reduction compared with previous reports and is comparable to GaAs-based lasers at shorter wavelengths (Fig. 1). Under room-temperature CW operation, the threshold current density was 579 A/cm^2, the external efficiency was 41%, and the peak output power was 130 mW ($>$600 mW pulsed). This work validates the GaInNAsSb/GaNAs active region for use in 1.55 μm GaAs-based VCSELs owing to its high optical quality and sufficiently low strain for multiple QW active regions.

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