Bilayer for extending the wavelength of QD lasers

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Abstract. This paper reports on the analysis of MBE grown bilayer quantum dot (QD) laser material. Specifically, gain and absorption characteristics of 5x ‘single’ QD layers with InGaAs caps, 5x ‘bilayer’ QDs with GaAs caps and 5x ‘bilayer’ QDs with InGaAs cap layers are compared. For an In₀.₁₈Ga₀.₈₂As capped bilayer sample at room temperature, net modal gain is demonstrated beyond 1500 nm.

1. Introduction
The InAs/GaAs QD system has received strong interest due to the evidence of true zero dimensional behaviour at room temperature and above. Whilst typical emission wavelengths are found in the 1000-1300 nm range, longer wavelength QD lasers on GaAs are attractive for datacoms and telecoms applications. Many of the attractive attributes of the quantum dot (e.g. zero and tunable chirp, broadband emission, temperature insensitivity, saturable absorption, single photon emission, etc.,) are particularly attractive at the fibre optic transmission wavelengths of ~1310 and ~1550 nm. However, emission beyond 1300 nm is difficult to achieve, when using independent single layers of InAs/GaAs QDs [1]. The use of bilayers of QDs has been demonstrated as a promising route to obtaining long wavelength emission and lasing [2, 3]. In the bilayer structure, each of the two QD layers is grown at different temperature, with strain interaction from the smaller QDs in the seed layer (first layer) fixing the QD density in the larger QDs of the second layer [2, 3]. In this paper we compare experimentally the gain characteristics of laser devices utilising a fivefold repeat of single QD layers with In₀.₁₈Ga₀.₈₂As capped bilayer sample at room temperature, net modal gain is demonstrated beyond 1500 nm.

2. Experiment
The laser structures described here are shown schematically in figure 1. Growth was carried out on n⁺ GaAs (100) substrates by molecular-beam epitaxy (MBE). The active region for both structures was located in a 500 nm undoped GaAs layer sandwiched between 1500 nm Al₀.₃₃Ga₀.₆₇As cladding layers. A 400 nm p-type GaAs:Be contact layer was grown to complete the laser structure. The active region of the ‘standard’ structure consists of five independent QD layers which we refer to as a “single layer” structure. Before each QD layer was grown, the surface was annealed under an As₂ flux at 580 °C for 10 minutes to smooth the growth surface [5]. The QD layer was then subsequently grown at 485 °C by
the deposition of 2.4 ML of InAs at a growth rate of 0.014 MLs\(^{-1}\), giving a QD density of \(2.4 \times 10^{10}\) cm\(^{-2}\) as measured by AFM on test structures. The QDs were capped by 4 nm of In\(_{0.26}\)Ga\(_{0.74}\)As then 11 nm of GaAs, also grown at 485 °C to reduce Indium segregation. After this the growth temperature was ramped during the next 45 nm of GaAs deposition to the optimum GaAs growth temperature of 580 °C [6]. The same sequence was repeated for the rest of the active region and the remainder of the structure was grown at 580 °C to reduce In-Ga inter-diffusion.

![Figure 3. Single (left) and Bilayer (right) QD laser structures.](image)

3. Experimental dependence of the net modal gain on the pump current density

Length dependent characterization of Fabry-Perot lasers allows a simple determination of the gain characteristics of the laser material [7, 8]. Figure 2 shows the experimental dependence of net modal gain on the drive current density for the single layer QD laser. The curves are obtained by fitting the empirical gain-current relationship given by Zhukov et al. [8]. As cavity length is decreased, there is an increase in the mirror loss (\(\alpha_m\)) to a point where the total cavity loss exceeds the ground state (GS) saturated gain. At this point first excited state (ES1) lasing may occur, accompanied by increased threshold current. As the length is further decreased, so the ES1 state may also saturate, leading to lasing by the second excited (ES2) state etc. From figure 2, we observe ground state (1360 nm) saturation at a net modal gain of ~2 cm\(^{-1}\). The first excited state (1275 nm) saturates at a net modal gain of ~8 cm\(^{-1}\). The saturation of the second excited state is not explored in this case. Due to the in-plane symmetry of these self-assembled QDs, the first excited state has twice the degeneracy of the
ground state. Consequently, the saturated modal gain for the first excited state is assumed to be twice that of the ground state [9]. Considering this, an internal loss (α_i) of ~4 cm\(^{-1}\) may be deduced, with a modal gain of ~6 cm\(^{-1}\) for the ground state and ~12 cm\(^{-1}\) for the first excited state.

Figure 2. Net modal gain for single layer laser as function of current density. Squares represent experimental data. Curves correspond to a fitting by empirical equation from ref [8].

Figure 3 shows the experimental dependence of net modal gain on the drive current density for the GaAs capped bilayer QD laser. We observe ground state (1345 nm) saturation at a net modal gain of ~6cm\(^{-1}\). First excited state (1275 nm) saturates at a net modal gain of ~15 cm\(^{-1}\). The saturation of the second excited state is not explored. If we assume a two-fold increase in degeneracy and saturated modal gain for GS and ES1 of the top QD layer, an internal loss of ~4 cm\(^{-1}\) is again deduced, with a modal gain of 10 cm\(^{-1}\) for the GS and ~20 cm\(^{-1}\) for the ES1. Considering the lower QD areal density and reduced layer number, these figures for saturated gain compare quite favourably with commercial QD material at 1310nm.

4. Measurement of Gain and Absorption spectra

Ref. [10] details the design of the multi-section device, which uses a stripe length dependent measurement to obtain gain and absorption spectra as described by Blood et al. [4].

Figure 4. Net modal gain spectra of InGaAs and GaAs cap bilayer device as measured using the multi-section technique.

The net modal gain spectra of two different bilayer devices with QDs capped by either GaAs or In\(_{0.18}\)Ga\(_{0.82}\)As are shown in figure 4. In this technique, by changing the pumping a series of net modal gain spectra can be obtained, but for comparison we have selected current density of 2857 A/cm\(^2\), where the ground and first excited state is clearly resolved for both the devices. At this current density
for the GaAs cap bilayer sample we observe the GS (1370 nm) and ES1 (1270 nm) net modal gain of 6 cm\(^{-1}\) and 13 cm\(^{-1}\) respectively. Similarly, for the InGaAs cap GS\(^1\) (1450 nm) and ES\(^1\) (1330 nm) net modal gain of 3 and 5 cm\(^{-1}\) are observed. The gain peak wavelength is in good agreement with emission spectra obtained from the laser devices (not shown). Significantly, we observe a positive net modal gain above 1500 nm for the InGaAs cap bilayer device. This is a step towards achieving telecoms devices on GaAs substrates. Figure 5 shows the net modal absorption spectra of GaAs and InGaAs cap bilayer devices, plotted for the same current density (2857 A/cm\(^2\)) also using the multi-section devices. We note that the absorption value at a given wavelength is significantly larger than the corresponding gain [10]. We have also observed that absorption does not vary with the wavelength below the band edge of the material indicating an internal loss value of \(3\pm0.5\) cm\(^{-1}\) and \(6\pm0.5\) cm\(^{-1}\) for GaAs and InGaAs cap bilayer devices.

Finally, it can be seen that the absorption spectra for both the devices is similar in shape, similar in number of features and the peak modal absorption is the same. This indicates that in the bilayer, the QDs of the seed and emission layers have not just strong correlation structurally but also electrically [2].

5. Conclusion

We have shown a method of extending the emission wavelength of QDs on GaAs by using a bilayer growth technique. The GaAs capped bilayer laser demonstrated twice the modal gain for ground and excited states as compared to an InGaAs capped ‘single’ layer QD laser operating at similar wavelength (~1350 nm). InGaAs capping the bilayer of QDs further extends the emission wavelength to 1450 nm. Significantly, by optimization of the QD capping material it is possible to achieve long wavelength emission without sacrificing modal gain. Indeed, net modal gain above 1500 nm is noted, presenting an exciting opportunity towards fabricating optoelectronic devices with all the advantages of QDs in the telecoms windows of 1.31 and 1.55 µm.

Acknowledgements

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