Excited State Bilayer Quantum Dot Lasers at 1.3 μm


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We report the realization of excited state bilayer quantum dot (QD) lasers in the 1.31 μm region. The higher saturated gain and lower scattering time of the excited states of the ensemble of QDs offers the opportunity for high modulation bandwidths. Gain measurements for these structures are discussed and compared to conventional QD laser structures. The extension of QD ground state operating wavelengths to 1.45 μm spanning the O- and E-band is also demonstrated. © 2011 The Japan Society of Applied Physics

1. Introduction

Over recent years, considerable effort has been invested in developing 1.3 μm lasers based on InAs/InGaAs quantum dots (QDs) to the point of their current commercialization. One of the main application areas is in optical communications. For GaAs based QD heterostructures, many of their features (zero chirp, temperature insensitivity threshold, and single photon emission from the ensemble of QD ground states, in addition to low cost) are particularly attractive at 1.3 μm. There is therefore continuing interest in extending the emission wavelength to this region. QD bilayers have been proposed as a route to achieve this. In the bilayer structure, two coupled (electronically and strain) QD layers allow the independent control of density (first “seed” layer), and emission wavelength (second QD layer). Each of the two QD layers may be grown under different conditions, with strain interaction from the smaller QDs in the seed layer fixing the QD density in the larger QDs of the second layer. The second layer may be grown at lower temperature with a slow deposition rate to achieve long wavelength emission. By contrast to quantum well lasers, the modulation dynamics of QD lasers is dominated by damping. In order to achieve high modulation rates, low carrier scattering times to the lasing state and high saturated modal gain of the QDs is required. It has recently been demonstrated that the excited state of QDs exhibit much higher damping limited bandwidths as compared to ground state (QS) lasers. This enhancement was attributed to higher saturated gain (double) and lower scattering time (half) as compared to the ground state. This is of course at the expense of higher operating currents. However, in that report the ground state emission was 1.3 μm whilst the excited state (ES) was at 1.2 μm making such excited state QD lasers impractical for optical communications applications. Here we propose that the technologies to realize long wavelength QD ground state emission can be applied to realize QD excited state emission at 1.3 μm. In this paper we report on the fabrication of QD bilayer materials where excited state lasing is demonstrated between 1.26 and 1.33 μm. This is achieved by using QD material consisting of 5 × bilayer QDs with GaAs caps and 5 × bilayer QDs with InGaAs cap layers. A multi-section measurement of the material allows the peak modal gain of the excited states as a function of current density to be deduced.

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2. Experimental Methods

The laser structures described here are shown schematically in Fig. 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 1500 nm AlGaAs 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 GaAs capped QD bilayers. We refer to this sample as the “GaAs capped bilayer” sample in the following. Each bilayer consists of a seed layer of QDs and an emission layer. Before each QD layer was grown, the surface was annealed under an As flux at 580 °C for 10 min to smooth the growth surface. Thereafter the seed layer was grown at a temperature of 480 °C by the deposition of 2.4 ML of InAs at a growth rate of 0.014 MLs⁻¹, giving a QD density of 2.7 × 10¹⁰ cm⁻². These seed QDs were capped by 10 nm of GaAs spacer layer, also grown at 480 °C, before the temperature was raised again to 580 °C for 10 min to smooth the growth surface and desorb segregated indium. The emission layer was then grown at a reduced temperature of 467 °C by the deposition of 3.3 ML of InAs at the same growth rate as for the seed layer. The QDs were then capped with 15 nm of GaAs also at 467 °C, after which the temperature was ramped to 580 °C for subsequent GaAs growth. The same sequence was repeated for the remaining of the active region with the remainder of the structure grown at 580 °C. The second structure discussed is identical to the GaAs capped bilayer sample except the upper emission layer (second QD layer) is capped by 4 nm of In₀.₁₈Ga₀.₈₂As before subsequent GaAs growth. We term this as the “InGaAs capped bilayer”. Wafers were processed into broad area lasers (15 to 100 μm width) for multiline analysis and 7 μm multi-section devices for variable stripe analysis. Characteristics were measured in the pulsed regime (5 μs pulsed duration, 1% duty cycle) to minimise thermal effects. All measurements were performed at a tile temperature of 298 K. Reference 9 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. 10

3. Results and Discussion

Figure 2 shows normalised photoluminescence (PL) spectra from GaAs and InGaAs capped bilayer test samples at room
temperature. Emission at 1.35 μm (1.43 μm) and 1.26 μm (1.33 μm) for the GaAs capped (InGaAs capped) samples is attributed to emission from the ensemble of ground states and excited states of the QDs, respectively. Figure 3(a) shows electroluminescence (EL) spectra from a structure where lasing is inhibited for bilayer GaAs capped sample as a function of current density. Figure 3(b) shows a similarly obtained family of curves for InGaAs capped sample. The saturation of the long wavelength features in both samples confirms the assignment of excited state emission at 1.26 μm and 1.33 μm for the GaAs capped and InGaAs capped samples, respectively. Figure 4(a) shows EL spectra at room temperature for both sets of samples at 1.34 μm (I_{th} is the ground state lasing threshold). The lasing from the ground state is at 1.34 μm for the GaAs capped bilayer sample, and 1.43 μm for InGaAs capped samples respectively. We note redshift of ~100 nm in the emission wavelength, on InGaAs capping in line with other InGaAs capping studies. Figure 4(b) shows EL spectra at room temperature for both sets of samples at 1.2I_{th} (I_{th} is the excited state lasing threshold). The lasing from the first excited state is at 1.26 μm for the GaAs capped bilayer sample, and 1.33 μm for the InGaAs capped bilayer sample. EL peaks of the GS are ~30 dB lower in intensity than the lasing emission at these currents. Using multi-section devices, the gain spectrum may be determined as a function of current density. Absorption measurements and analysis of gain spectra at long wavelengths indicate an internal loss of 3 ± 1 cm⁻¹ for GaAs capped and 5 ± 1 cm⁻¹ for the InGaAs capped sample. These values for internal loss are combined with net modal gain values to plot the peak
The modal gain per dot of the excited state for both samples as a function of current density in Fig. 5. This value is an important parameter in determining $K$-factor limited band-width. The saturated modal gain for the GaAs and InGaAs capped bilayer samples are determined to be 18 and 12 cm$^{-1}/C_0$, respectively. Gain spectra analysis and transmission electron microscopy images (not shown) suggest the origin of the difference in cavity length required for the GS and ES emission, higher internal loss and lower ground state saturated gain of the InGaAs capped sample is attributed in part to roughness of the lower AlGaAs/GaAs interface between $n^+$ cladding and intrinsic core of the waveguide. The modal gain per QD of the GS and ES of the GaAs capped sample compares very favourably with commercial QD material operating at 1.28 cm$^{-1}/C_2$. Commercial material with four times the number of QDs in the active region ($2^4$ numbers of dot layers, $2^4$ areal densities) but with around double the inhomogeneous line-width exhibits excited state modal gain of $\sim 40$ cm$^{-1}$ at 1200 nm. This represents a $\sim 2$ times increase in modal gain, which is as expected for a homogeneous linewidth of $\sim 10$ meV at lasing, suggesting a larger fraction of QDs are within the homogeneous linewidth of the lasing mode due to the smaller inhomogeneous linewidth. An increase in areal density, achievable by tuning the growth conditions of the seed layer can be expected to enhance the saturated gain of the excited state in these bilayer samples.

4. Conclusions

The realization of excited state QD lasers in the 1.31 µm region has been demonstrated. GaAs capped and InGaAs capped bilayer samples exhibit excited state lasing at 1.26 µm and 1.33 µm, respectively. This offers the opportunity for high modulation bandwidth GaAs based QD lasers. These wavelengths are of significance for a range of data-communications application. Furthermore, these materials allow the extension of GaAs based QD ground-state operating wavelengths to 1.45 µm, offering full coverage in the O- and E-band.

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