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Growth, Fabrication, and Operating Characteristics of Ultra-Low Threshold 1.31μm Quantum Dot Lasers

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1. Introduction

The incorporation of self-assembled In(Ga)As quantum dots (QDs) within an InGaAs/GaAs quantum well (QW), the so called dot-in-well (DWELL) structure, allows the realisation of low threshold, temperature insensitive lasers operating at the important telecommunications wavelength of 1.31 μm. Such devices provide a viable GaAs-based alternative to current InP-based lasers.

In order to achieve QDs operating at 1.31 μm, ultra low growth rates and atomic layer epitaxy have been employed. However, due to the low density of such long wavelength QDs such laser diodes suffer from gain saturation, resulting in high threshold current density (J_{th}) and poor temperature stability. Through careful optimization, the DWELL method can overcome these problems. Here, we describe advances made in the growth of multiple layer DWELL structures to obtain world leading QD laser performance at 1.31 μm.

2. MBE Growth

The QD density of MBE grown laser structures was optimised via studies of the In composition in the $In_xGa_{1-x}As$ layers, the InAs deposition thickness, and the growth rate. Photoluminescence (PL) and atomic force microscopy (AFM) studies of samples with different In composition in the QW, and with different thicknesses of InAs revealed the optimum growth conditions. Additionally, the use of two separate In sources for growth of InAs and InGaAs layers allows a faster growth rate for the InGaAs QW, resulting in improved crystallographic quality.

Initial growth studies resulted in our realisation of QD lasers operating via the ground state transition at 1.3 μm at room temperature, but only for pulsed current injection and long cavity lengths (5 mm). For this 3-layer DWELL device, the InGaAs QW and 50 nm GaAs spacer layers were grown at 510 °C. For devices grown with this comparatively low growth temperature, insertion of a greater number of DWELL layers was found to be deleterious to laser performance. This degradation with increasing the number of layers is a direct result of the formation of incoherent islands and threading dislocations (shown in Fig.1, b), which reduce the dot density and increase the defect density as the number of layers is increased.

The results of structural characterization are strengthened by the observation of a 5 orders of magnitude greater reverse leakage current as compared with a control QW device without the dots, indicating that the dislocations provide some leakage path through the device. The dislocations could be a result of surface roughness created by Ga migration driven by the strain field associated with large dots, which results in vertically stacked dislocations.

By utilising a high temperature growth step (HTGS), where the first 15 nm GaAs is grown at 510 °C before the temperature is raised to 580 °C for the final 35 nm GaAs, structures are grown with no obvious dislocations (Fig.1, a) The leakage current is correspondingly reduced by more than half. Additionally, the PL intensity of the HTGS structures exhibits a threefold improvement. We believe that the HTGS provides a mechanism for increased Ga diffusion, which has the effect of planarising the surface on which subsequent growth may proceed with nominally identical QD layers.

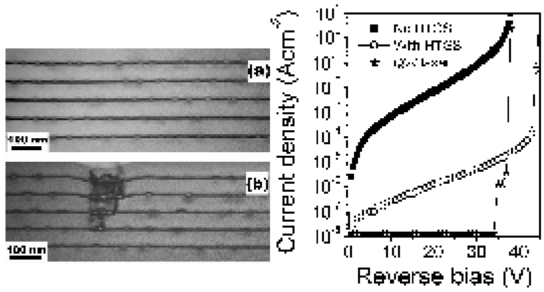

Figure 1: Dark field (200) cross-sectional TEM images of 5-layer InAs/InGaAs DWELL samples with (a) and without (b) HTGS GaAs spacer layer steps. The reverse bias I-V characteristics for each are also shown together with that for a QW laser.

3. Device Performance

3.1 Laser Performance

Standard ridge lasers, etched through the active region to a depth of 3 μm were processed from structures containing 5 DWELL layers incorporating the HTGS GaAs spacer layers. Room temperature lasing via the ground state transition at 1.31mm was achieved through continuous wave (cw) current injection, with a record low J_{th} of 32.5 Acm^{-2} for a laser with uncoated facets, as shown in Fig.2. We believe this figure to be the lowest so far reported for as-cleaved quantum dot lasers. In many reports the operating wavelength of "1.3 μm" quantum dot lasers are considerably shorter than the 1.29-1.33 μm window required for commercial use, or the lasers have highly reflective coatings which significantly reduce the output power.

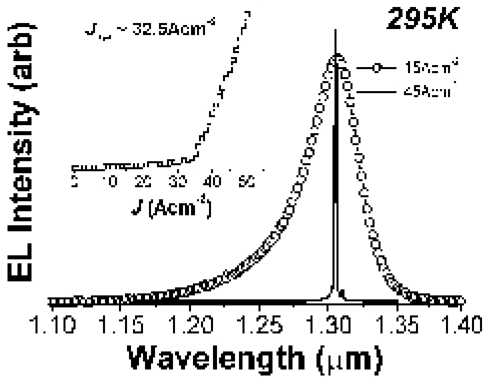

Figure 2: Room temperature characteristics of a 5mm long 5 DWELL laser incorporating HTGS.

For devices of 5 mm cavity length, ground state lasing was achieved at temperatures in excess of 100°C. For industrial application, devices should be short enough to allow high-speed modulation whilst maintaining the ability to operate at high temperatures. For 2 mm length as-cleaved cavities, ground state operation was possible up to 70 °C for standard ridge lasers (again as-cleaved). This was extended to 85 °C with considerably reduced threshold current density, through improved device fabrication. This included a shallow ridge etch (stopped before the active region) and the use of selectively electroplated bondpads.

3.2 Spontaneous emission temperature dependence

A study of a QD laser in which the QDs exhibit a bimodal size distribution has enabled an observation of the thermally activated spectral redistribution of carriers between different subsets of dots and a comparison with the temperature dependence of J_{th}.

The observed negative T_0 regime is demonstrated to result from a transition from population of a limited subset of dots to a Fermi carrier distribution as the temperature is increased to 200K. Above 200K, the rapid rise in J_{th} is consistent with the observation of a reduction in the integrated QD emission (c) resulting from the non-radiative recombination of carriers thermally excited out of dots. A less rapid fall in integrated intensity for higher injection currents (d) suggests that the nature of this recombination is not predominantly Auger recombination.

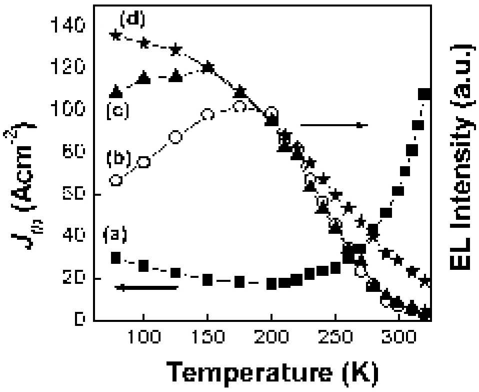

Figure 3: Temperature dependence of J_{th} (a) corrolates with peak EL intensity (b) and integrated intensity for low (c) and high (d) current densities.

3. Conclusions

High growth temperature GaAs spacer layers are demonstrated to suppress the formation of defects in DWELL laser structures, and results in 5-DWELL layer devices operating at 1.31 μm with record low room temperature cw J_{th} of 32.5 Acm-2 for devices with uncoated facets. Operation is also achievable for temperatures up to 85 °C for devices as short as 2 mm. The negative T_0 regime is a result of carrier thermal redistribution, but high temperature fall in integrated intensity indicates that non-radiative recombination is responsible for the rapid rise in J_{th}.

4. Acknowledgements

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