2007 International Conference on Indium Phosphide and Related Materials
Conference Proceedings
19th IPRM 14 - 18, May 2007 Matsue, Japan

Quantum Dot Superluminescent Diodes - Bandwidth Engineering and Epitaxy for High Powers

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***Abstract* – We present experimental and theoretical work describing the engineering of broadband quantum dot superluminescent diodes for a wide range of applications. The key differences, advantages, and challenges of using quantum dots are discussed.**

***Key words* – Superluminescent diodes, semiconductor lasers, quantum dots.**

I. Introduction

Superluminescent light emitting diodes (SLDs) provide broadband emission for a wide range of applications such as WDM system testing, fiber-optic gyroscopes, and optical coherence tomography. Techniques for broadening the optical spectrum of semiconductor SLDs typically rely upon chirped [1], or intermixed [2], quantum wells. Recently, quantum dot (QD) materials have attracted attention due to their naturally broad emission spectrum [3]. We have recently demonstrated novel techniques for further broadening the emission bandwidth of an InAs/GaAs QDSLD operating around 1250nm, and tailoring of the shape of the emission spectrum using multiple dots-in-a-well (DWELL) layers [4]. In the present work, we discuss methods to tailor the spectral shape of the SLD emission, and to increase the output power. We demonstrate 95nm FWHM broad band SLDs centered at 1270nm, and narrow-band SLDs with 42mW output power. These QD SLD structures were grown by solid source molecular beam epitaxy upon n^+ GaAs substrates. We go on to describe an analytical model for the output power spectrum of a QD SLD, and apply it to a simple undoped QD structure.

II. DESIGN CONSIDERATIONS - QUANTUM DOT ACTIVES

Quantum dots have several differences to quantum well active regions. These differences include; a naturally broad inhomogeneous linewidth, and relatively low saturated gain. One key difference is the saturation of both spontaneous emission and gain at comparatively low current densities. This allows the creation of broad-band superluminescent diodes, but places stringent requirements on material quality.

III. EMISSION BANDWIDTH ENGINEERING

The Gaussian emission spectrum of the QD ground state emission, along with the ability to tune the peak energy allow engineering of the emission spectrum. A flat-topped emission spectrum is obtained if well indium compositions are chosen such that the separation of the peak wavelengths resulting from DWELLs of different composition is equal to the linewidth, σ, of the individual DWELLs. Figure 1 shows the emission spectrum from a sample with 6 identical DWELL layers and a 6 DWELL sample with three sets of two DWELL layers (3x2 design) chirped so as to give ground state emission as described above.

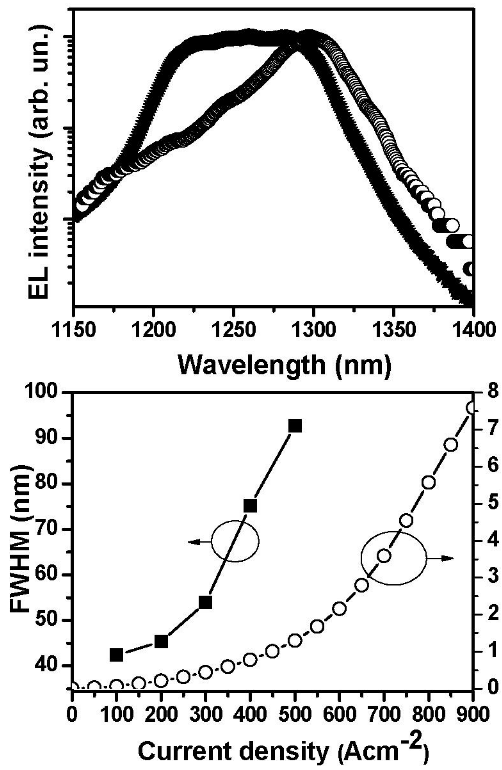

Figure 1. Upper: Comparison of EL from 3 × 2 (solid) and standard DWELL (open) for 500mA. Lower: Power (open) and FWHM linewidth (closed) as a function of CW current are also shown for the 3 × 2 device.

The linewidth and output power as a function of drive current are also shown. Figure 2 shows the evolution of the EL spectrum of the 3×2 design with current from 100 to 600mA, for a 6mm long, 15μm wide SLD at room temperature. This demonstrates the limited range of carrier injection that results in a flat-topped emission spectrum. At low injection levels

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(<200mA) a single peak at 1290nm is observed. On increasing the drive current the peak broadens, eventually becoming flat at a drive current of 500mA. We note that in engineering the spectral lineshape and emission power both length and current density are important factors. The flat-topped emission is only obtained at a specific current density.

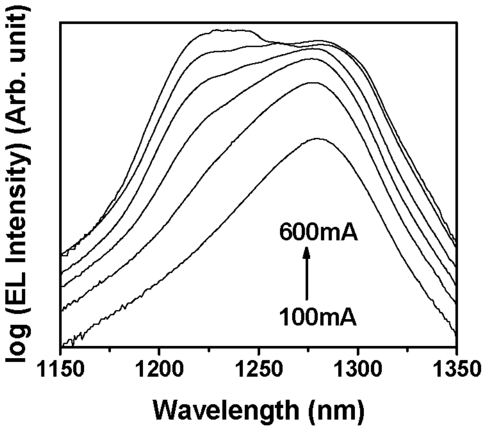

Figure 2. Evolution of the EL spectrum of the 3×2 SLD with current from 100mA to 600mA in steps of 100mA.

IV. EPITAXY FOR HIGH POWERS

The use of a temperature ramp during the MBE growth of InAs/GaAs QDs [5] has allowed record low threshold current densities to be obtained [6]. The increased temperature planarizes the GaAs growth surface improving the quality of subsequent QD layers. However, additional defect removal techniques relying on the evaporation of large defective QDs [7] have resulted in a further reduction in threshold current density, at the expense of emission wavelength. The defect removal relies upon the increase in growth temperature only after 2nm of GaAs cap has been deposited on the DWELL layer. Our previous work [4,6] relied upon 15nm of low temperature GaAs being deposited before this temperature ramp.

Figure 3 shows SLD results for samples with 15nm and 2nm thick low temperature GaAs cap layers. A significant improvement in the L-I characteristics is observed due to an increase in both spontaneous emission efficiency and current-gain characteristics. This curve also serves to illustrate a key difference to the output characteristics of SLDs due to the use of QDs as the active elements. The differential efficiency curve indicates that a super-linear increase in power with current is observed for only a limited range of drive currents. A roughly linear L-I response is obtained at higher currents due to gain saturation. Furthermore, a slight kink is observed at ~800 mA when the ground state saturates and the excited state emission begins to become significant.

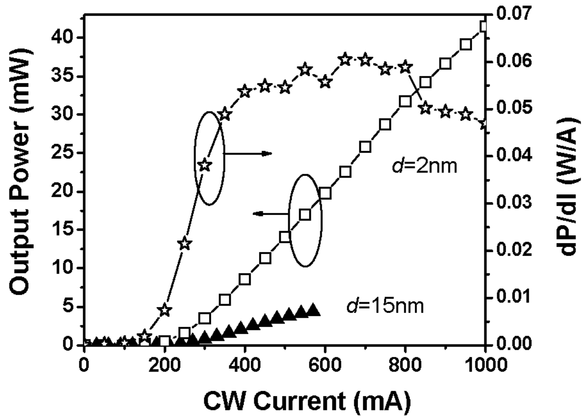

Figure 3. Power versus drive current for 8mm long SLDs for d=15nm (closed triangles) and d=2nm (open squares). The open stars plot the differential efficiency of the d=2nm SLD.

V. ANALYTICAL MODEL

We adopt the formalism of Lee *et al.* [8] who modeled a single pass gain device with ideal bulk/QW characteristics; linear gain and spontaneous emission in current density. The small signal optical power change with length can be written as;

$$\frac{dP}{dz} = \beta P + P_0$$

where P_0 is the radiated spontaneous emission power in the element dz. Integration over length L yields the output power at the facet, P;

$$P = \frac{cS(J,\lambda)}{G(J,\lambda)L}\left(e^{G(J,\lambda)L} - 1\right) \quad (2)$$

Where J is the current density, S(J,λ) is the spontaneous emission, G(J,λ) is the modal gain dependent on the current density, c is a constant pre-factor which includes the effects of the waveguide size and geometry.

Using the random population theory for quantum dots[10], the spontaneous emission as a function of current density S(J) for the ground state and excited state is calculated for an unchirped QD structure and is shown in Fig. 4(a). In calculating the S-J relations we assume a constant value of 300ps for the carrier lifetime and dot density of $4\text{x}10^{10}$ cm^2. Both reasonable values from previous work.

The ground state and excited state gain, G(J), was also calculated as a function of current density and is given in Fig 4(b). We used a value of 28 cm^{-1} for the excited state saturation, and a value of 14cm^{-1} the ground state. Note that we used a value of $g^{sat}_{excited}$ two times the value of g^{sat}_{ground} due to degeneracy of the excited state. It can be observed that the gain is a non-linear function of current density which is consistent with what we would expect for a quantum dot device [9]. The gain-current density values strongly depart from that of the ideal quantum well device i.e. linear gain with current.

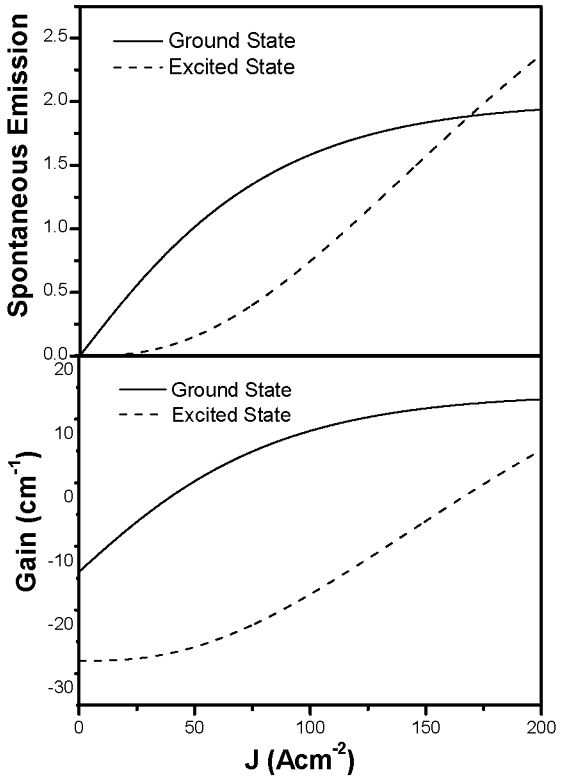

Figure 4. Spontaneous Emission (a) and Gain (b) as function of Current Density, J.

Figure 5 shows calculated gain and spontaneous emission spectra as function of current at a temperature of 300K. The peak of the ground state gain ground becomes transparent at current density of 50Acm^{-2} and 180cm^{-2} for ground state and excited state respectively. Here our model for carrier thermalization allows thermalization of carriers within individual QDs, but not thermalization of carriers from one QD to another, which agrees with our experimental spontaneous EL spectra on mesa diode structures.

Using the gain and spontaneous emission spectrum we can calculate the output power spectrum at different current densities and shows the integrated power/current density curves obtained experimentally and by our model for devices of length 8, 6 and 4mm. The calculated and experimental J-Power curves are shown in Fig. 6. The inset shows the power spectrum of the longest device. A good correlation between modelled and experimental values is obtained at low current densities. Deviations at higher current densities are probably due to the strongly non-linear photon densities present with superluminescent diodes, and suggest that a numerical method may be required to accurately model high power devices.

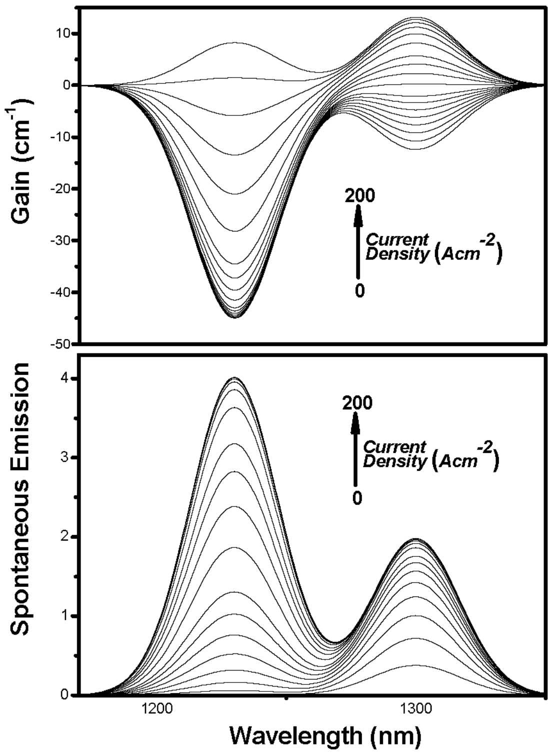

Figure 5. Gain and spontaneous emission spectrum as function of current density at 300K

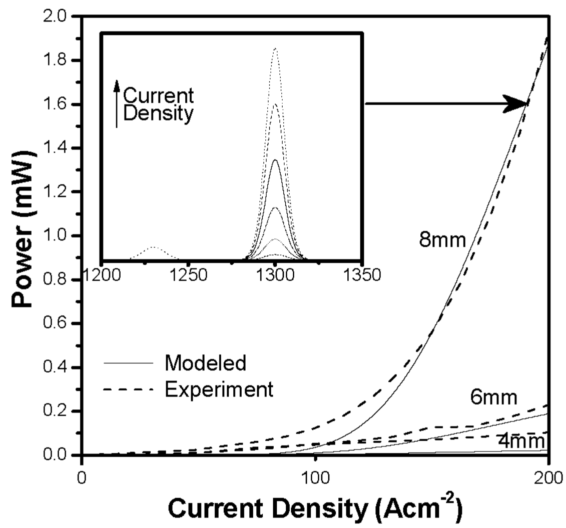

Figure 6. Power as function of current density for modeled and experimental data from, 8mm, 6mm and 4mm cavity lengths. The inset shows the modeled power spectrum as a function of increasing current density for the 8mm device.

VI. CONCLUSIONS

The use of QDs as the active element for superluminescent diodes has been discussed. The engineering of the emission bandwidth by utilising the special nature of QDs has been described, and the interplay between device length and drive current on emission bandwidth and output power has been explained. Furthermore, the sensitivity of QD SLDs to epitaxial quality has been detailed, with defect removal techniques being shown to significantly improve QDSLD performance. An analytical model for the output power spectrum of QD SLEDs has been introduced, with comparison to experimental data showing a good correlation at current densities up to four times transparency.

ACKNOWLEDGMENTS

We gratefully thank partners from within the Nano-UB sources consortium for fruitful discussions. We acknowledge financial support from The Royal Academy of Engineering, EPSRC (Grant EP/D04801X/1), and EU Nano-UB Sources programme.

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