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# Comparative study of InGaAs quantum dot lasers with different degrees of dot layer confinement

K. M. Groom, A. I. Tartakovskii,[a] D. J. Mowbray, and M. S. Skolnick
*Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, United Kingdom*

P. M. Smowton
*Department of Physics and Astronomy, Cardiff University, Cardiff CF24 3YB, United Kingdom*

M. Hopkinson and G. Hill
*Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, United Kingdom*

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We report a comparative study of the gain and lasing characteristics of two different InGaAs quantum dot (QD) laser designs, with multiple QD layers separated by barriers of (A) GaAs or (B) GaAs/AlGaAs. A higher degree of carrier confinement in structure B results in superior lasing characteristics at elevated temperatures. However, at temperatures below 130 K these devices demonstrate inhomogeneously broadened gain spectra, resulting in lasing over a much wider energy range than for structure A. The results are consistent with inefficient, low temperature interdot carrier transport in devices based on structure B. © *2002 American Institute of Physics.*
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The use of semiconductor quantum dots (QDs) as the active region of injection lasers is expected to result in significant reductions of device threshold current[1] and temperature sensitivity.[2] Practical devices generally require multiple dot layers, necessitating a careful design of the barriers separating these layers to enhance dot carrier capture and to reduce carrier thermal evaporation at high temperatures. However, the physical localization of carriers in different dots and suppressed communication between QD layers may produce an inhomogeneously broadened system with independently lasing subsets of dots, resulting in broadband lasing emission.[3–6] A full and systematic investigation of different laser active region designs is therefore important.

In this work we compare the characteristics of two very different QD laser designs, consisting of multiple QD layers grown within either a single, wide GaAs quantum well or multiple, narrow quantum wells (see inset, Fig. 1).[7] The latter design is expected to increase the dot carrier confinement but may also restrict carrier transport between layers. The temperature dependence of the threshold current and the forms of both the spectral gain and lasing spectra are found to be very different for the two designs. These differences are explained in terms of their very different physical structures.

Laser structures with either three, five, or seven layers of self-assembled QDs were grown by molecular beam epitaxy. The QDs were formed by depositing 7 monolayers (ML) of $In_{0.5}Ga_{0.5}As$ at a rate of 0.5 ML/s and a substrate temperature of 530 °C. In structure A (see Fig. 1) the QD layers, grown with a separation of 7 nm, are contained within a single wide GaAs quantum well (QW). In contrast, for structure B (see Fig. 1) each QD layer is positioned in the center of an individual 7 nm GaAs quantum well, with the wells separated by 10 nm $Al_{0.15}Ga_{0.85}As$ barriers. For both structures the waveguide core was completed with two 60 nm $Al_{0.15}Ga_{0.85}As$ barriers and 1.2 $\mu$m thick $Al_{0.6}Ga_{0.4}As$ doped cladding layers. Ridge lasers of dimension $(500-3000\,\mu\text{m}) \times (5-15\,\mu\text{m})$ were formed by etching through the active region. Optical measurements were performed using a variable temperature He cryostat and a 0.75 m spectrometer with a liquid $N_2$ cooled Ge detector.

Previous studies of multiple InAs QD layers have demonstrated a vertical correlation of the dot positions for interlayer GaAs thicknesses $\leqslant 9$ nm.[8] For devices with structure A (interlayer separation 7 nm) an alignment of dots along the growth direction is therefore likely but is unlikely for structure B (interlayer separation 17 nm). Furthermore, Solomon *et al.*[9] find that the emission spectrum narrows and shifts to lower energy for thin interlayer separations, attributed to the coupling of electronic states between dots in adjacent layers. A comparison of the low temperature ($T = 5$ K) photolumi-

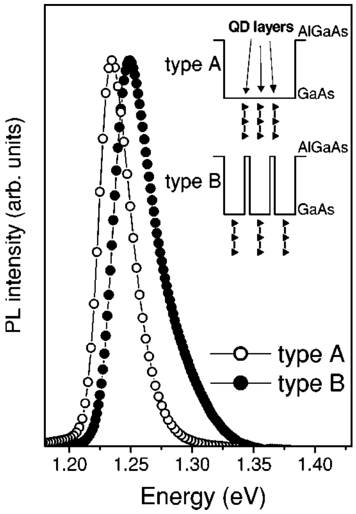

FIG. 1. PL spectra measured at $T = 5$ K and sample structures.

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[a] Electronic mail: a.tartakovskii@sheffield.ac.uk

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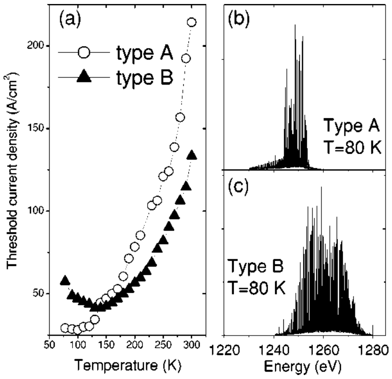

FIG. 2. (a) Threshold current density vs temperature for 1 mm×15 $\mu$m devices of structures A and B, with five QD layers; (b) and (c) 80 K lasing spectra for the devices of (a), recorded for $J = 3J_{\text{th}}$.

nescence (PL) spectra (Fig. 1) reveals a small (17 meV) redshift and linewidth reduction (34–31 meV) between structures B and A, consistent with weak interlayer electronic coupling in the latter structure. This is in agreement with Bayer *et al.*[10] who find relatively weak electronic coupling for an interlayer separation of 7 nm.

Figure 2(a) shows the temperature dependence of the threshold current densities, $J_{\text{th}}^{\text{A}}$ and $J_{\text{th}}^{\text{B}}$, for 1 mm×15 $\mu$m size devices with five QD layers. For both devices the threshold current density increases with increasing temperature for $T > 130$ K. This behavior is in agreement with previous observations[11] and results from carrier evaporation from the dots. However, importantly, at 300 K $J_{\text{th}}^{\text{B}}$ is $\sim$1.5 times smaller than $J_{\text{th}}^{\text{A}}$, a difference that is observed for samples of various ridge dimensions and containing three, five, or seven QD layers. A 3.1 mm cavity device with structure B and seven QD layers exhibits a very low 300 K $J_{\text{th}}$ of 47 A/cm$^2$. This improved room temperature performance for structure B results from the increased carrier confinement provided by the individual quantum wells. In contrast, for $T < 130$ K, $J_{\text{th}}^{\text{A}} < J_{\text{th}}^{\text{B}}$ for all devices investigated, with $J_{\text{th}}^{\text{B}}$, unlike $J_{\text{th}}^{\text{A}}$, increasing with decreasing $T$ [Fig. 2(a)], reaching a value approximately twice $J_{\text{th}}^{\text{A}}$ at 78 K.

Despite their very similar spontaneous emission spectra (see Fig. 1) the previously presented results suggest that different carrier interaction and transport processes occur in the two structures. Such differences are also likely to affect the form of the gain spectra, which were determined, as a function of injection current, using the Hakki–Paoli technique.[12,13] Below threshold, light spontaneously emitted within the laser cavity undergoes repeated reflections from the facet mirrors and is subjected to either constructive or destructive interference. This produces Fabry–Perot-like oscillations in the emission [see inset of Fig. 3(b)], the depth of which is a function of the roundtrip cavity gain or the net loss ($\gamma$) of the system. $\gamma$ is related to the peak-to-valley ratio of the oscillations, $r$, by

$$\gamma = \frac{1}{L}\ln(R) + \frac{1}{L}\ln\left(\frac{r^{1/2}+1}{r^{1/2}-1}\right),$$

where $L$ is the cavity length and $R$ is the mirror reflectivity. Hence, by measuring $r$ as a function of wavelength, the gain ($-\gamma$) spectrum can be determined. At lasing wavelengths the Hakki–Paoli technique can only be used to determine the gain up to the point of threshold where the loss coefficient equals the mirror loss (the first term on the right-hand side of the above equation) and $r = \infty$. For conventional lasers the gain for nonlasing wavelengths will clamp at threshold due to the presence of a homogeneously broadened gain spectrum. However, as shown below, QD lasers may have an inhomogeneously broadened gain spectrum if there is inefficient interdot carrier communication. In this case the gain at nonlasing wavelengths will continue to increase even after lasing occurs elsewhere. Because it is a spectrally resolved technique, the Hakki–Paoli method can be validly applied in this postthreshold regime to determine the subsequent behavior of the gain due to nonlasing dots.

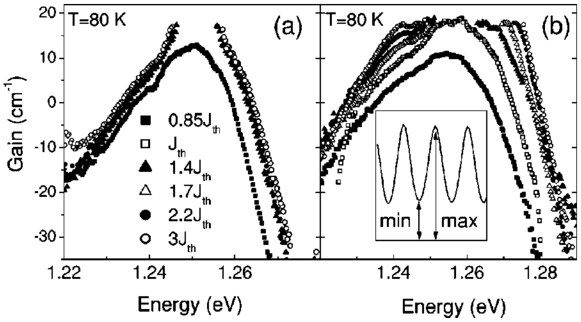

FIG. 3. Gain spectra recorded at $T = 80$ K for different injection currents: (a) structure A, (b) structure B. The cavity length for both devices is 0.5 mm. The inset (b) shows the Fabry–Perot-like oscillations in the emission.

Figure 3 shows gain spectra ($T = 80$ K) for five QD layer devices for the same fractions of the threshold current. For structure A the gain spectra are relatively narrow. The gain approaches the value required for lasing (23 cm$^{-1}$ for the cavity length of 0.5 mm) over a narrow energy range of ($\approx$10 meV) and above threshold the whole gain spectrum clamps, consistent with a homogeneously broadened system. In contrast the gain of structure B [Fig. 3(b)] is much broader ($\approx$35 meV) and exhibits no clamping at nonlasing wavelengths for currents greatly in excess of the threshold value. Lasing first occurs for this device at 1.256 eV. However, the gain to higher and lower energies does not clamp for $J > J_{\text{th}}$ but continues to increase until the value necessary for lasing at a particular energy is reached. This is the direct observation of an inhomogeneously broadened gain spectrum for a QD laser.

The very different gain spectra for the two structures result in significantly different low temperature ($T \leqslant 150$ K) lasing spectra. An example ($T = 80$ K) is shown in Figs. 2(b) and 2(c) where it is seen that for structure A the dominant lasing modes occur over an energy range $\approx$5 meV while for structure B they occur over a much greater range of $\approx$20 meV. In contrast, but in agreement with previous reports,[3–6] at elevated temperatures both types of device exhibit similar lasing spectra with a reduced number of lasing modes.

The experimental data are consistent with very different carrier transport processes for the two structures. Although structure B exhibits a superior room temperature $J_{\text{th}}$, due to the increased confinement provided by the individual quantum wells, at low temperatures the characteristics imply a restricted communication of carriers between different quantum dots. This leads to an inhomogeneously broadened gain spectrum and hence lasing over a wide spectral range. In

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addition the initial decrease of the threshold current density as the temperature is increased to 150 K (the so-called negative $T_0$ regime) [Fig. 2(a)] is consistent with the proposed explanation for this behavior in terms of a transition from a nonthermal to a thermal distribution of carriers within the dot ensemble as interdot carrier transport via thermal excitation becomes possible.[14]

The experimental data imply efficient, low temperature carrier transport between the dots of structure A but not structure B. While low temperature carrier transport between dots in different layers (interlayer transport) will be hindered by the QW barriers in structure B, and may be enhanced by the presence of electronic coupling in structure A, the present results also indicate that the intralayer carrier transport is very different for the two structure types.

In conclusion, the characteristics of QD lasers with two very different active region designs, with the dot layers separated by thin GaAs barriers (A), or grown in individual GaAs/AlGaAs QWs (B) have been studied. Although both structures exhibit similar spontaneous emission spectra, they show major differences in their gain and lasing properties. Structure B exhibits superior high temperature lasing characteristics but the low temperature performance is compromised by inefficient interdot carrier transport. As a consequence the low temperature gain spectrum is inhomogeneously broadened, resulting in lasing over a wide spectral range. In contrast the gain spectrum of structure A is consistent with that observed in conventional bulk and QW lasers, exhibiting a complete clamping once a subset of dots reaches lasing. This leads to lasing over a considerably narrower spectral range than for structure B.

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