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Importance of Auger recombination in InAs 1.3 μm quantum dot lasers

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It has been found that Auger recombination is very important in 1.3 μm quantum dot (QD) lasers at room temperature and is the cause of the low characteristic temperature, while in the 980 nm QD lasers radiative recombination dominates.

Introduction: Over the past 20 years there have been considerable efforts to reduce the effective dimensionality of the active regions of semiconductor lasers. Improving technology has allowed the successive fabrication of bulk, quantum well, quantum wire and finally, quantum dot lasers [1]. The main driving reason has been the control of the electron density of states that quantum confinement provides, allowing injected electrons and holes to be ever more restricted to those energies where they can take part in the stimulated emission process. This results, for example, in the prediction that if the electrons can be confined to a single discrete atomic like level in quantum dot (QD) lasers, they will not suffer thermal broadening and the threshold current will be temperature insensitive [2]. However, despite the growth of very good self-assembled layers of quantum dots, the longer wavelength lasers required for optical communication remain stubbornly temperature sensitive [1, 3]. In this Letter we show, from studies of the temperature and pressure dependence of the characteristics of 980 nm and 1.3 μm QD lasers, that the radiative recombination current is indeed temperature insensitive. However, the total threshold current of the 1.3 μm lasers remains very temperature dependent due to strong Auger recombination processes as observed in quantum well and bulk 1.3 μm devices [4, 5]. This implies that even if perfectly uniform arrays of quantum dots can be produced, QD lasers will remain temperature sensitive unless the Auger process can also be eliminated.

Results and discussion: The 1.3 μm quantum dot lasers investigated were broad area GRINSCHE structures with six stacked layers of InAs QDs within $\text{Ga}_{0.85}\text{In}_{0.15}\text{As}$ quantum wells separated by 40 nm GaAs barriers. The width of the top stripe contact was 100 μm . The active region of 980 nm QD lasers was formed by either one or two layers of InAs QDs separated by a 30 nm GaAs spacer. For both wavelengths the active regions were embedded between $\text{Al}_{0.4}\text{Ga}_{0.60}\text{As}$ cladding layers and an AlGaAs waveguide with the Al composition graded between 15 and 30%. The facets were as-cleaved and the cavity length was 1–2 mm.

Both unamplified spontaneous emission from a window milled in the substrate contact and emission from the laser facet were investigated against injected current at different temperatures. Details of this technique were described elsewhere [4, 6]. Fig. 1a shows the temperature variation of the radiative part of the threshold current I_{rad} , which

was determined from the integrated spontaneous emission intensity at the threshold current [4, 6]. As can be seen, I_{rad} is almost independent of temperature as expected for ideal quantum dot lasers. However, Fig. 1b shows that the total threshold current, I_{th} , is very sensitive to temperature in the 1.3 μm devices, indicating the presence of a strongly temperature-sensitive non-radiative path. This is reflected in the decreasing radiative efficiency (measured as integrated spontaneous emission at constant current below I_{th}), η_{rad} , plotted in Fig. 1a. The effect is not due to thermal excitation out of the dot, since the variation is strongest in the 1.3 μm devices where the dots are deepest. Also, no spontaneous emission was observed from the wetting or adjacent layers. The quantum differential efficiency above threshold was independent of temperature, showing that the effect of intervalence band absorption is negligible.

Fig. 1 Temperature dependencies of radiative current, I_{rad} , radiative efficiency, η_{rad} , and normalised threshold current, I_{th} , for 1.3 μm (solid circles) and 980 nm QD lasers with one (open triangles) and two (open hexagons—DQDs) layers of QDs

a Radiative current, I_{rad} , radiative efficiency, η_{rad}
b Normalised threshold current, I_{th}

Measurements of the hydrostatic pressure dependence of I_{th} and the lasing photon energy E_{las} , were carried out using a piston and cylinder apparatus capable of generating 15 kbar [4, 5]. This allowed E_{las} to be varied while keeping all other basic properties of the structure effectively unchanged. Since various recombination mechanisms depend in a different way on E_{las} , this allows their relative importance to be determined.

Fig. 2 shows the variation with applied hydrostatic pressure of I_{th} for the 1.3 μm laser and the 980 nm laser with one layer of QDs. Both structures exhibited similar linear shifts of the lasing photon energy with pressure. The gradients were $dE_{\text{las}}/dp = 10.1\text{ meV/kbar}$ and $dE_{\text{las}}/dp = 8.3\text{ meV/kbar}$ for the 980 nm and 1.3 μm QD lasers, respectively. For the 980 nm QD lasers, I_{th} increases with pressure proportional to the square of the photon energy as expected from a simple analytical model of a laser with only radiative recombination. However, as shown in Fig. 2, the threshold current of the 1.3 μm QD laser decreases by 26% over a 12 kbar. This may be compared with the results for 1.3 μm GaInAsP quantum well lasers where the threshold current decreases by about 10% in the same pressure interval due to a strong Auger recombination contribution of about 50% to the total threshold current [4, 5].

Fig. 2 Normalised threshold current $I_{th}(p)/I_{th}(0)$ against pressure at room temperature for 1.3 μm (solid circles) and 980 nm (open triangles) QD lasers

— normalised dependence $[E_{las}(p)/E_{las}(0)]^2$
 - - - fitting of the experimental points

To interpret the experimental results we have calculated the electron and hole energy levels and wave functions of the 1.3 μm QD structures, and the dependence of the radiative current density on the average number of carriers per dot. The calculations take full account of strain and piezoelectric fields in QDs. The calculations were performed in the framework of an 8×8 k·p model using the plane-wave expansion method. For calculations of the radiative current density we used an equilibrium distribution of carriers in the QD structure, which is valid at high temperatures, $T > 250$ K. The calculated radiative current density at zero pressure and 300 K is 150 A/cm² which accounts for only 24% of the total threshold current measured. To analyse the pressure dependence of the threshold current we used a simple analytical model and estimated that the radiative and Auger currents, I_{rad} and I_{aug} , depend on the photon lasing energy E_{las} as $I_{rad} \propto (E_{las})^l$ and $I_{aug} \propto (E_{las})^m$, with $l=2$, as observed for the 980 nm lasers, and $m=-11/2$ by analogy with quantum well lasers. We also assumed that the pressure dependence of these two current paths comes through the pressure dependence of $E_{las}(p)$, which is measured. We then fitted the measured pressure dependence of the threshold current with the simple formula $I_{th}(p)/I_{th}(0) = (I_{rad} + I_{aug})/I_{th}(0) = x[E_{las}(p)/E_{las}(0)]^l + (1-x)[E_{las}(p)/E_{las}(0)]^m$ with fitting parameter $x = I_{rad}(0)/I_{th}(0)$ as the fraction of the radiative current at zero pressure (see Fig. 2). Hence we estimated that at zero pressure and 300 K the Auger contribution I_{aug} to the total threshold current is 70% and the radiative contribution I_{rad} is 30%, which is in excellent agreement with our direct calculations of I_{rad} . We also note that any combination of l between 1 and 3 and m between -3 and -8 , leads to an Auger contribution I_{aug} which is larger than 58%. Thus, the calculations and the analysis of high-pressure measurements allow us to conclude that Auger recombination in QDs is the most likely reason for the high temperature sensitivity of the 1.3 μm QD lasers, while in the 980 nm QD laser radiative recombination dominates.

Conclusion: We have shown that while the radiative current in both 1.3 μm and 980 nm wavelength quantum dot lasers is indeed temperature insensitive, the total threshold current in the longer wavelength devices is dominated by the temperature sensitivity of a large Auger recombination current, just as seen in bulk and quantum well devices operating at 1.3 μm . Indeed, Auger recombination appears to be

largest of all in quantum dot devices. This implies that, even if perfectly uniform arrays of quantum dots can be produced, QD lasers will remain temperature sensitive unless the Auger processes can be eliminated. Detailed calculations of Auger rates in QDs are now in progress.

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Low-divergence singlemode 1.55 μm VCSEL with 1 mW output power

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Experimental results for a monolithic singlemode vertical-cavity surface-emitting laser (VCSEL) at 1.55 μm are reported. Single-transverse-mode operation with >40 dB sidemode suppression and a peak power of 1.03 mW at 20°C is obtained. Far-field measurements show low divergence with a measured far-field angle of 7.9° at 1 mW output power.

Introduction: Long-wavelength vertical-cavity surface-emitting lasers (LW-VCSELs) in the 1.55 μm wavelength range have generated intense research activity due to their potential as low-cost transmitters in long-haul communication applications. It is critical that LW-VCSELs obtain single transverse-mode operation and a small far-field angle for efficient coupling into singlemode fibre. Monolithic VCSEL designs without external pumping are also highly preferable in order to increase manufacturability and cost-effectiveness.

Several monolithic LW-VCSEL approaches have yielded results for singlemode 1.55 μm operation including regrowth methods [1], metamorphic growth [2], GaAsSb [3] and wafer-fusion [4–6]. Karim *et al.* [4] reported an output power of 0.65 mW at 20°C with no mention of the sidemode suppression ratio (SMSR). Ortseifer *et al.* [1] showed an output power of 0.38 mW at 20°C with an SMSR of over 40 dB. Obtaining high singlemode power has been a challenge in LW-VCSEL research mainly because reducing the oxide aperture or index guide for singlemode operation also increases current density and device heating which limits output power. Another concern is that smaller apertures