Inhomogeneous gain effects in quantum dot lasers

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A comparison of optical and electrical derivative spectroscopy on a dual-state lasing InAs/GaAs quantum dot bilayer device is presented. The junction voltage cannot be described by a quasi-Fermi level separation and only partial clamping above the laser threshold was observed, demonstrating inhomogeneous gain. There is also competition between transverse optical modes which must be taken into account for a full understanding of dual-state lasing.

Introduction: InAs/GaAs self-assembled quantum dots (QDs) are an efficient and high-quality light-emitting material for optoelectronic devices and emission wavelengths between 900 to 1500 nm have been reported [1]. It is well established that three-dimensional carrier confinement within the dots results in a discrete emission spectrum consisting of ground-state (GS) and excited-state (X1, X2) transitions and variations in the dots' size and composition lead to a large inhomogeneous linewidth for each transition. In principle QDs can lase on the GS and the X1 states simultaneously and indeed this has been observed for lasers incorporating several non-interacting QD layers [2]. In that case dual-state lasing was attributed to incomplete clamping of the occupation number/quasi-Fermi level spacing (QFLS) within the gain medium, with the spontaneous emission intensity in the higher excited states continuously increasing above the laser threshold. This contrasts with the QFLS clamping observed in quantum well (QW) and bulk laser diodes which results in the IV curve of the device becoming ohmic above threshold. The dotted lines in Fig. 1 show the transition to ohmic behaviour for a commercial QW 980 nm laser (similar to that observed for bulk lasers in [3]) which contrasts with the solid lines obtained for the QD laser, which exhibits non-ohmic behaviour above threshold. In this Letter we show how voltage derivative spectroscopy may be used to investigate gain effects including dual-state lasing in QD lasers.

Fig. 1 Comparison of IV and LI behaviour for QD bilayer laser (solid lines) and QW laser (dashed lines)

Arrows indicate GS and X1 lasing thresholds and quenching of GS lasing

Devices: The devices considered here incorporate QD bilayers [1, 4], in which two QD layers are closely stacked in order to extend the emission wavelength of the second layer. The initial (seed) layer is grown by deposition of 2.4 ML of InAs at 0.014 MLs⁻¹ onto a pre-annealed GaAs surface at 480°C; this is then capped with a 10 nm GaAs spacer layer at the same temperature before annealing the surface at 580°C and reducing the temperature to 467°C to deposit 3.3 ML of InAs at the same growth rate. This second QD layer was capped with 15 nm of GaAs before raising the temperature to 580°C for subsequent GaAs growth. Photoluminescence studies show that the layers are electronically coupled with the GS emission of the first (seed) QD layer approximately co-incident with the X2 emission of the second QD layer. The investigated device is a standard *pin* separate confinement heterostructure that contains three QD bilayers separated by 50 nm embedded within a 500 nm-thick intrinsic GaAs

active region with 1500 nm-thick AlGaAs cladding layers. Wafers were then processed into shallow-etched ridge waveguide devices having 5 μm width and cleaved into 5 mm lengths.

Performance: The devices showed GS lasing threshold current densities as low as 70 Acm⁻² and slope quantum efficiencies of 50% at room temperature. LI and IV curves obtained at 10°C are shown in Fig. 1. In contrast with the QW laser, the QD laser LI curve exhibits a noticeable increase in slope efficiency at the onset of X1 lasing. Fig. 2 shows the variation of electroluminescence (EL) with increasing current. Multiple mode groups are evident in the vicinity of the GS and X1 spontaneous emission features. However, there is no indication of a transition to an ohmic regime at either the GS or X1 lasing thresholds in the IV curve (Fig. 1). Note that emission from the seed QD layer was not observed, demonstrating efficient electronic coupling within the bilayer.

Fig. 2 $-I^2 d^2V/dI^2$ spectrum of QD laser (solid line) compared with Schottky diode (dashed line), and electroluminescence against wavelength and current showing multimodal nature of laser emission with GS centred at 1340 nm and X1 at 1255 nm

a $-I^2 d^2V/dI^2$ spectrum of QD laser compared with Schottky diode
b Electroluminescence against wavelength and current

Modulation spectroscopy: The IV curve of the QD device does not exhibit any obvious features that can be correlated with the lasing thresholds, suggesting that gain clamping does not occur. To determine the presence of any fine detail second derivative current modulation spectroscopy [5–7] was employed. This involved detecting the device's second-harmonic voltage response to a small current modulation using phase sensitive detection and then multiplying by the square of the current for convenience of interpretation. The resultant $-I^2 d^2V/dI^2$ scale is equal to the steady-state ideality factor multiplied by the thermal voltage $k_B T/e$ in a diode that can be described by a quasi-Fermi level picture. Any sudden change in the ideality factor of the device shows up as a peak in the spectrum.

Results: Fig. 2 compares the results of this measurement on the QD bilayer laser with its optical spectrum. A derivative measurement on a Schottky diode which has a known ideality factor of $\sim$ unity is provided as a reference to demonstrate the instrumental response. Peaks corresponding to the initial GS laser threshold and the subsequent X1 switch-on are clearly identifiable. Partial clamping, which appears as an apparent reduction in ideality factor, is visible as negative displacement of the curve after each threshold peak. Also present are features that can be associated with the appearance of additional laser lines and quenching of the GS lasing. The rising background contrasts with the behaviour of bulk and QW lasers which are known to have a well-defined QFLS [5].

Partial clamping in bulk and QW lasers is usually associated with the appearance of higher-order transverse optical modes (filamentation) [6], as the distribution of carrier density changes across the device. Fig. 3 shows that filamentation is associated with both the X1 laser threshold and the appearance of the second mode group in X1, accounting for the

double-peak in the derivative spectrum at the dual-state lasing threshold. In all the devices tested the peaks could be associated with the onset of lasing (single- and dual-state), the appearance of mode groups and/or filamentation.

Fig. 3 Spatial mode profile of laser emission at various currents, demonstrating appearance of higher-order transverse mode at onset of dual-state lasing

a 100 mA, GS lasing only
b 110 mA, dual-state lasing
c 130 mA, new mode evident
d 140 mA, mode established

Structure visible in the derivative spectrum between the dual-state lasing threshold and the quenching of GS lasing (mode noise) could be competition between transverse optical modes that are lasing on the GS and X1 states either as a spatial hole-burning effect or fast oscillation between the two states [8]. Previous comparisons between a relaxation-bottleneck model of dual-state lasing and experiment used similar width devices and did consider fast oscillations (4 μm [9], 8 and 15 μm [2]) but did not consider filamentation. In fact, the relaxation-bottleneck models are unable to explain quenching of the GS laser emission, therefore the method outlined here may be useful in refining our understanding of the mechanisms responsible for dual-state lasing.

Conclusions: Correlated optical and electrical spectroscopy has been performed on a dual-state InAs/GaAs QD bilayer laser diode. Partial clamping of the occupation number of the QD ensemble was inferred from the IV curve and then directly measured by current modulation spectroscopy. Both the GS and X1 lasing transitions show similar degrees of partial clamping. The junction voltage could not be described by a quasi-Fermi level separation (QFLS) owing to a rising background signal unique to QD devices. The appearance of additional higher-order mode groups was also evident in the derivative spectrum and correlates with changes in the spatial mode profile. These observations show that inhomogeneous gain effects and spatial non-uniformity are important in the understanding of dual-state lasing and carrier distribution of QD lasers.

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