

Quantum Dot bilayer laser diodes

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Abstract

Optical communication was developed to allow high-speed and long-distance data transmission and is currently a £6bn market. This has also led to the adoption of optical technologies in other areas including the CD, DVD and medical imaging systems. Standardisation of components means that these systems require light sources that operate near the 1310 and 1550 nm telecommunications windows but existing lasers here are expensive due to their high temperature sensitivity.

The exploitation of quantum confinement has led to the development of “quantum dot” (QD) laser material because of predictions of huge gains in performance. Emission wavelengths of InAs/GaAs QD lasers have been extended to the telecommunications window near 1300 nm by various growth technologies and the first commercial devices have recently been brought to the market. However, progress to longer wavelengths has been stalled for several years as well as the speed and temperature sensitivity of these devices falling short of the predictions; partly because QDs are grown by self-assembly resulting in a random distribution of sizes, compositions and strain-states, leading to inhomogeneous broadening which is a departure from the ideal “atom-like” system.

This work details the growth, design and development of QD bilayer laser devices, which offer a unique approach to fixing these shortcomings. When two QD layers are grown close together; the first layer provides a template that allows larger, more uniform QDs to be grown in the second layer, giving greater uniformity and deeper confinement. This has the potential to increase the efficiency and to achieve emission wavelengths out towards the more-commonly used telecommunications window at 1550 nm directly on GaAs substrates. Multiple bilayer laser diodes with inhomogeneous broadening of less than 30meV, lasing at up to 1430 nm and room-temperature photoluminescence at 1515 nm are shown.

Despite the vastly reduced inhomogeneous broadening of QD bilayers, it is still found to be a relevant factor due to the change from de-localised geometries of quantum wells to an ensemble of separate QDs. It will be shown that understanding this is essential for describing the observed optical and electrical behaviour of the laser diodes.

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Chapter 1

Introduction

Optical communication was developed to allow high-speed, long-distance data transmission and currently forms the backbone of most long-haul and metropolitan-area telecommunications networks. It is anticipated that the network will expand further with the increasing uptake of fibre-to-the-home. The development of these optical technologies has also led to their adoption in other areas including the CD, DVD and medical imaging systems. Standardisation of components means that these systems require light sources that operate near the 1310 and 1550 nm telecommunications windows. Sources at these wavelengths are also attractive from a safety point of view because of the large maximum permissible exposure limit for the eyes in this region of the spectrum. However, existing lasers here are expensive due to their high temperature sensitivity.

Light sources for infrared telecommunications were developed using lattice-matched III-V compound semiconductors based on alloys of In, Ga, As and P. The choice of alloy was dictated by the need to avoid excessive build-up of strain from growing layers with different crystal lattice dimensions, while retaining the required emission wavelength. These sources are grown on InP substrates, which are less pure and mechanically inferior (due to the difficulties of growing the crystal under the high vapour pressure of P [2]) compared to GaAs substrates. Also, InP-matched alloys lack the large refractive index contrast available from the GaAs/AlGaAs material system which allows Bragg mirrors to be monolithically incorporated into device structures, thus limiting the development of VCSELs.

The exploitation of quantum confinement was found to improve performance to the degree that virtually all commercial semiconductor lasers now use “quantum

well” (QW) active layers. A QW is a thin semiconductor film embedded within a lower bandgap host crystal. The QW must be thin enough for the wave nature of the electron to be important and they are sometime described as “a waveguide for electrons” [3]. Predictions of further gains in performance have led to further development of “quantum dot” (QD) laser material, where carriers are confined in all three directions [4]. Emission wavelengths of InAs/GaAs QD lasers have been extended to the telecommunications window near 1300 nm by various growth technologies and the first commercial devices have recently been brought to the market*. However, accessing the 1550 nm window has been more difficult and the speed and temperature sensitivity of QD devices fall short of theoretical predictions. This is due in part to the growth by self-assembly which results in a random distribution in the size, composition and strain-state of the QDs. This results in a spread in the emission wavelengths of the QDs (inhomogeneous broadening) - a departure from the ideal ensemble comprising identical, “atom-like” emitters.

The motivation for this work was to develop QD based laser technology towards longer wavelength operation. To do this required both the development of a growth technique for long-wavelength emission and its integration into a standard edge-emitting waveguide device structure.

1.1 Growth technology

Several growth technologies exist for extending the emission wavelength of InAs QDs grown on GaAs substrates and these will be briefly described here. A more comprehensive discussion on growth techniques that are relevant to this work will be presented in the next chapter. Currently the techniques that show promise for long wavelength QD emitters include:

Low-growth rate QDs (LGRQD) are used to produce high-quality samples for photoluminescence studies. They have room-temperature emission wavelengths up to 1300 nm and narrow ground-state emission (approximately 20 meV full-width at half-maximum - FWHM) [5, 6]. Lasers can be made with these QDs but suffer from low gain due to the low dot density.

*Innolume GmbH offers QD-based lasers and amplifiers in the wavelength range 1050 to 1320 nm at the time of writing.

Dots-in-a-well (DWEELL) extend the wavelength of a QD ensemble by surrounding the layer with an InGaAs alloy rather than pure GaAs. This is thought to relieve the strain on the QD islands and may also reduce diffusion of In into the surrounding crystal during growth [7, 8]. The technique is limited in practice to a maximum emission wavelength of 1440 nm at room-temperature. Longer wavelength QDs suffer from thermal quenching of their emission [7, 9, 10]. Most 1310 nm QD lasers are produced using this technique and exhibit good performance.

Dilute Nitrides The incorporation of small amounts of N in InGaAs QWs causes bowing of the bandgap due to an anti-crossing of the conduction band and localised N states pushing the emission wavelength to 1300 nm. Dilute nitrides have shown some promise as a temperature insensitive material for lasers. However, N has low miscibility with InGaAs and its incorporation results in poor material quality with a high density of non-radiative defects, which has to be alleviated by post-growth annealing of the devices [11, 12, 13].

Dilute Antimonides can be used as a strain relieving capping layer (similar to the DWEELL technique) or incorporated into the QD islands. Antimony acts as a surfactant during growth but tends to introduce non-radiative defects when included in quaternary alloys. Emission beyond 1300 nm has been demonstrated and although problems with large FWHM are found, the luminescence efficiency of the QDs is higher with Sb than for high-In content DWEELL structures [14, 15].

GaInNAsSb QWs have been developed where the addition of antimony to a dilute nitride material is found to increase the quality of the interfaces and improve the PL emission at long wavelengths, when careful control of the substrate temperature is employed [16]. Lasers have been demonstrated with low thresholds at 1550 nm (579 Acm^{-2} with 130 mW peak output power [17, 18]) which show this to be a very promising technique.

Metamorphic buffer layers modify the lattice constant and relieve the compressive strain on the QD or QW layers. This is achieved by growing a mismatched material at low temperature to reduce threading defects that may propagate into the device. The substrate is then annealed before further growth [19] and/or a sacrificial QD layer is grown [20] to further reduce defects. Lasers grown using this method generally suffer from high threshold current densities on the order of kAcm^{-2} [19], although recent results show low thresholds (63 Acm^{-2}) are possible [21].

QD bilayers utilise the strain between two QD layers. The lower (seed) layer acts as a template for the growth of the second layer. This growth technique has produced room-temperature emission at 1480 nm [22] and the smallest reported FWHM QD ensembles (< 11 meV [23]). The templating effect of the seed layer allows increased control of the growth conditions of the second (emissive) layer, allowing longer wavelength emission and increased uniformity of the QD ensemble to be achieved [1].

This work will concentrate on optimisation of QD bilayer growth for room-temperature emission in excess of 1500 nm and incorporation of bilayers into laser structures. Lasing from the ground-state (GS) of bilayers at 1430 nm at 250 K is demonstrated as well as bilayer lasers operating at 1350 nm at room-temperature in either the GS or first-excited state (X1), depending on the growth conditions. Two-colour (dual-state) lasing from both GS and X1 simultaneously is also observed, at 1350 nm and 1250 nm respectively.

1.2 Device integration

As QDs are a localised and inhomogeneously-broadened medium, there will be issues related to the transport of carriers into the material and how the resultant optical properties are different from those of homogeneous bulk and QW systems. These will affect both the design of the heterostructure and the electrical coupling of the diode with the QD ensemble. These topics will be briefly summarised in the following sections. The ideas mentioned here will form the basis for the following chapters.

1.2.1 Heterostructure design

The structure chosen for these lasers was a standard separate confinement heterostructure (SCH) [3]. This design uses an AlGaAs alloy for the p and n-type doped regions of a p-i-n diode and GaAs in the central intrinsic region. The bandgap of GaAs is lower than AlGaAs and has a higher refractive index, leading to both carrier confinement and optical waveguiding.

The design of such laser structures with QW active media is well established: the trade-off between maximum possible efficiency (small active volume) and gain (number of layers) is calculable for many material systems [24]. While single-QW lasers

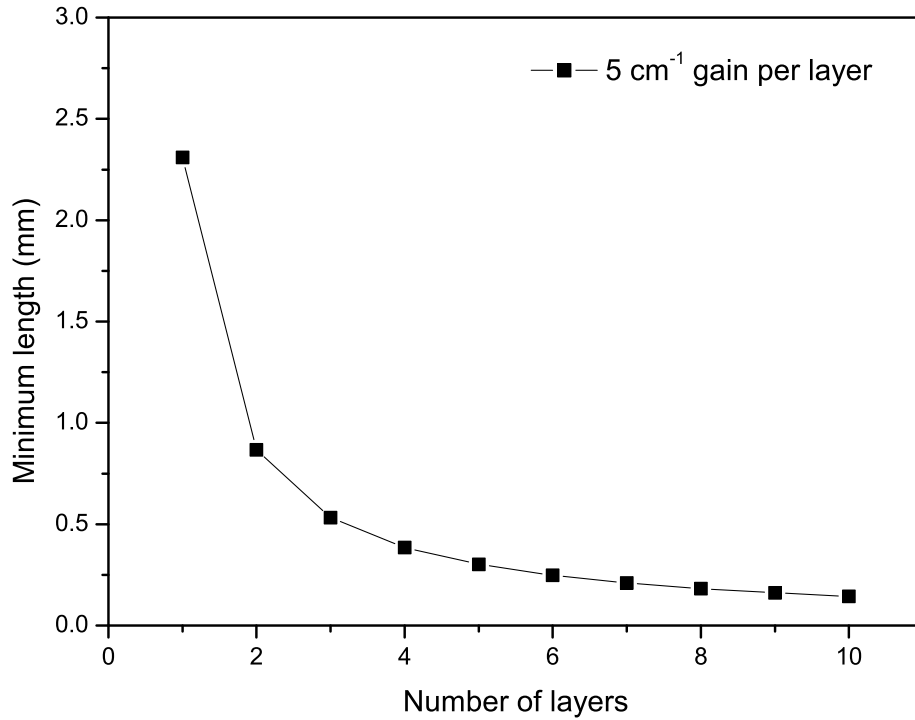


Figure 1.1: The relationship between the number of layers in a QD laser versus its minimum cavity length for lasing to occur. This is plotted assuming a maximum gain per layer of 5 cm^{-1} and internal cavity losses of 2 cm^{-1} .

are the most efficient it is common to include multiple layers of QWs for increased gain and higher-speed operation. Due to their lower areal coverage, QD layers have a limited maximum modal gain of $\sim 5 \text{ cm}^{-1}$ [25, 26][†], so multiple layers are required to overcome the mirror losses. The mirror loss, α_{mirror} can be calculated from the cavity length L and the facet reflectivity R , as shown in Equation 1.1.

$$\alpha_{\text{mirror}} = \frac{1}{L} \ln\left(\frac{1}{R}\right) \quad (1.1)$$

Assuming a GaAs-air interface, $R \sim 0.3$, a 1 mm long device would have $\alpha_{\text{mirror}} \sim 12 \text{ cm}^{-1}$, while a 5 mm device would have a significantly smaller loss of 2.4 cm^{-1} . Real devices have other loss mechanisms present (usually $\alpha_i \sim 2 \text{ cm}^{-1}$ [25, 26]) and so the gain required to reach threshold would be higher.

Taking the intrinsic and mirror losses together and comparing them with the maximum expected gain for a QD layer, then the number of layers vs. length can be calculated according to Equation 1.2:

[†]There is a wide range of quoted values between 1 and 10 cm^{-1} in the literature

$$g_{\max} = \alpha_i + \alpha_{\text{mirror}} \quad (1.2)$$

The results of this simple calculation are shown in Figure 1.1 and from this it is clear that multiple layers are essential for QD laser designs. Therefore the design problem is reduced to being able to grow at least 3-5 identical layers of QD bilayer material within the intrinsic region. An intrinsic region thickness of 500 nm was chosen for this work as a starting point because this is consistent with other designs in the literature. The aim of the growth programme was to demonstrate QD bilayer laser operation with this intrinsic layer thickness and then proceed to optimise the design (in terms of the thickness and number of layers) appropriately afterwards.

1.2.2 The interaction between QDs and the bulk

The complete localisation of the electronic states in the QD material is often considered in a regime where each island acts as an isolated, independent emitter. This independence would apply to every physical process including the capture, relaxation and radiative (or otherwise) recombination of carriers. This marks a significant departure from the properties of a bulk semiconductor or a QW that can be considered as a homogeneous single entity (to a good approximation). However, the QDs are not perfectly isolated from each other because they exist in a layer within the GaAs matrix. Any variation in a given process between individual QDs across the ensemble will cause collective behaviour to emerge. For example, carrier escape is a thermally-activated process and depends primarily on the depth of the confining potential: When the temperature is high enough for carriers to escape the shallower QDs the peak emission wavelength undergoes a collective redshift relative to the peak absorption, consistent with the adoption of a thermal carrier distribution [27]. These collective processes mark a significant deviation from a temperature-independent ideal QD behaviour and impact upon the temperature-sensitivity of QD lasers.

These inhomogeneous gain effects in QD ensembles will be investigated in following chapters using electrical derivative measurements that can be used to observe the behaviour of diode incorporating QD layers. However in the next section, details of the growth, fabrication and operation of QD bilayer lasers will be outlined, demonstrating extension of the emission wavelength of the bilayers to 1515 nm at room-temperature and also long-wavelength lasing (1425 nm) from these structures.

Chapter 2

Quantum dot bilayer lasers

The first part of this thesis concerns the work undertaken to develop the QD bilayer growth technique and the incorporation of these layers into edge-emitting laser devices.

2.1 Quantum dot growth

The idea of producing semiconductor structures to provide three-dimensional confinement was initially thought to require lithography and etching of a planar structure. This was until the self-assembly of small crystal islands was found to provide the answer: InAs has a 7% strain mismatch with GaAs which means that $\text{In}_x\text{Ga}_{1-x}\text{As}$ alloys grown on a GaAs substrate accumulate strain as they are deposited. Under the correct growth conditions, InAs initially deposited on the growth surface will form a compressively-strained pseudomorphic wetting layer (WL). Further deposition of InAs then increases the strain mismatch until coherent three-dimensional islands spontaneously form when the cost in energy for deforming the surface becomes lower than continuing to form the next planar layer. This is called the *Stranski-Krastanow* [28] growth mode.

Importantly, once the islands have been grown they must then be buried into the host crystal; partly so that the islands can be integrated into bulk-crystal heterostructure devices and also to isolate them from the deleterious effects of surface states. Both the formation and burying (or “capping”) processes must be controlled so as to keep

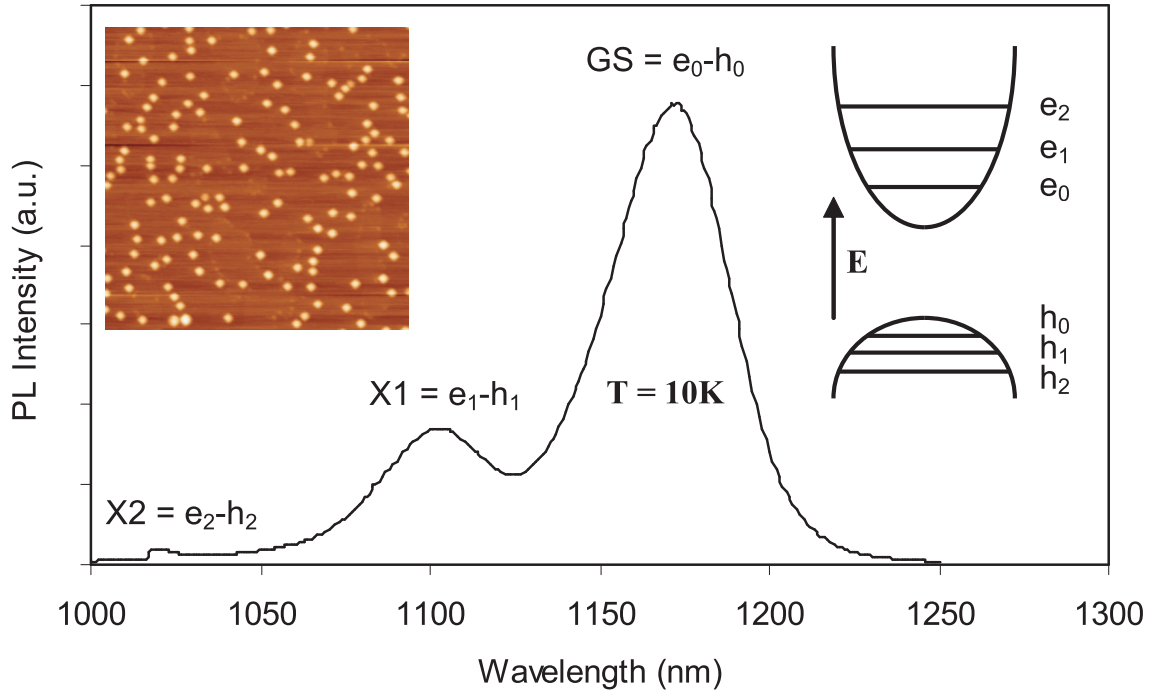


Figure 2.1: PL spectrum obtained at 10 K from a low growth rate QD layer. Inset a $1\ \mu\text{m} \times 1\ \mu\text{m}$ AFM image of a similar un-capped QD layer (left) and a simple schematic band structure showing the confined electron and hole states.

the islands coherent with the host crystal and to control the size, composition and strain state of the QD.

When the island material grown in the Stranski-Krastanow mode has a lower energy gap than its host matrix, a potential well in all three spatial dimensions can be created in the band structure. These islands are then called quantum dots (QDs) and can confine electrons and/or holes, leading to localised states with well-defined energies within the energy gap of the host matrix. The energies of these states are controlled by the size, shape, composition and strain-state of the QD. To decrease the energy of the lowest state (the ground-state or GS) the QD must either be larger in size, have a higher In composition or be under less compressive-strain from the host crystal.

2.1.1 Basic optical properties of Quantum dots

InAs/GaAs quantum dots consist of an InAs island embedded within a GaAs matrix. The lower bandgap of InAs compared with GaAs (0.3 eV versus 1.4 eV at room temperature) creates a potential well in all three spatial dimension for both the

electrons and holes. This three-dimensional confinement of the carriers in the QDs gives rise to discrete energy levels in both the conduction and valence bands and the parity-allowed optical transitions between these levels (GS = e0-h0, X1 = e1-h1, etc.) give correspondingly discrete optical spectra, as shown in the PL spectrum of Figure 2.1. The discrete optical spectra of the QDs leads to them often being termed as “artificial atoms”. The inset on the left shows an AFM image of a similar uncapped QD layer showing the InAs islands, the relative uniformity of their size distribution and their random areal distribution.

2.1.2 Inhomogeneous broadening

The resultant QDs are roughly lens or pyramidal-shaped and have sizes on the order of a 20-30 nm per side square base and 5-10 nm height [29]. The self-assembly process is driven by random fluctuations during growth and therefore unavoidably causes the positions of the QDs to be random and gives a statistical spread in the size-distribution. The random positioning of the QDs is of no importance for laser devices, as the dimensions of the device enclose enough QDs as to always be dealing with a representative ensemble. However the latter effect causes *inhomogeneous* broadening of the ensemble’s optical properties. Assuming for now that each QD is isolated from the rest, only QDs whose peak emission energy is separated from a laser mode by less than their homogeneous linewidth (in the region of 5 – 10 meV at room-temperature and increases for higher carrier densities [30, 31]) are able to contribute to its oscillation; having an inhomogeneous linewidth that is greater than the homogeneous broadening will limit the laser’s efficiency. Therefore growth recipes that result in lower inhomogeneous broadening are desirable.

2.1.3 Stacking multiple layers

As mentioned in Chapter 1 it is important to have a sufficient number of QDs in the active region for there to be enough gain to achieve lasing. As the QDs are deposited as planar layers within the device, it is clear that having several QD layers within the device will give more gain. In material systems where there is no significant strain mismatch, as for the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ alloys, many layers can be stacked without dislocation formation. In this case adding more layers is trivial and only constrained by the dimensions of the active region.

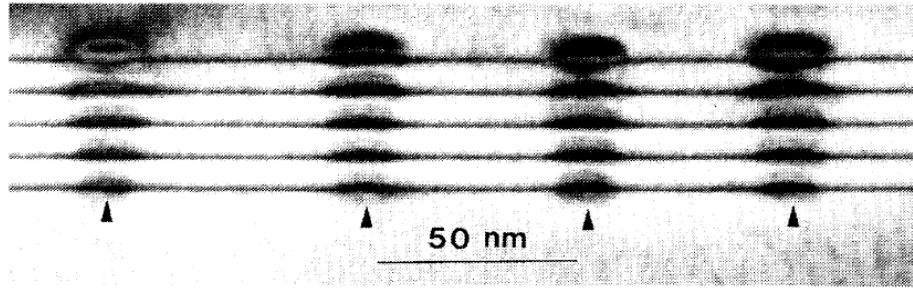


Figure 2.2: XTEM image of vertical correlation [1]

However the strain mismatch between InAs and GaAs means that, when two or more QD layers are stacked in a crystal, strain effects could build up during growth. In the worst case, this means that unless the strain is fully-balanced before starting the next QD layer the critical strain could be exceeded and defects formed. However it turns out that even when this limit is not exceeded, the strain from previous layers influences the properties of subsequent QD layers. Xie *et al.* showed using cross-sectional transmission electron microscopy (XTEM - Figure 2.2) and atomic force microscopy (AFM) how the dots in a lower-layer influence the strain experienced by the layer deposited above them [1]. They found that for a spacer of <170 Å there was a near-perfect vertical pairing of the dots, while for a spacer thickness approximately >570 Å the dot layers were uncorrelated. When the dots were correlated they increased in size with each new layer. This would be a bad thing for a device where the emission wavelengths of the layers should be coincident; it also sets constraints on the number of layers that can be accommodated within the active region due to the large spacer layers needed to achieve this.

Le Ru *et al.* studied the effect of the thickness and morphology of the GaAs spacer between QD layers on their emission [32]. It was found that when a QD layer was over-grown with GaAs, the surface is considerably roughened, leading to the requirement for very thick spacer layers. This could be overcome by annealing the growth surface before depositing the QD layers, a process which smoothes the morphology of the surface. With an anneal step the GaAs spacer layer could be reduced to 40 nm thickness and co-incident emission obtained from the QD layers. Indeed, a similar technique referred to as a “High-Temperature Spacer Layer” has subsequently been used at Sheffield University to produce high-performance quantum dot lasers [33].

The annealing of the spacing layers allows each “repeat” (i.e. QD layer and spacer layer together) to occupy ~ 50 nm of the active region. Therefore, the active region thickness chosen for this work of 500 nm allows the inclusion of up to 10 repeats.

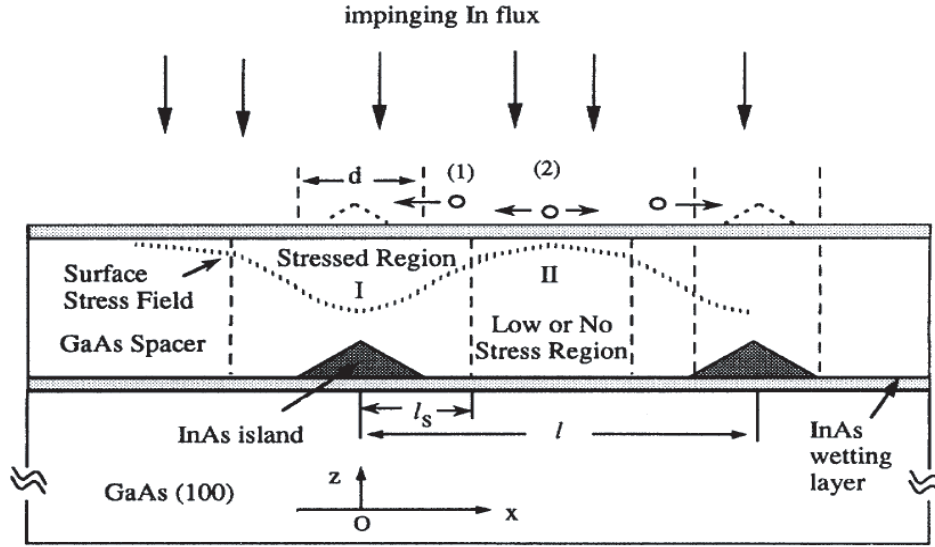


FIG. 4. A schematic representation showing the two major processes for the In adatom migration on the stressed surface: (1) directional diffusion under mechanochemical potential gradient contributing towards vertical self-organization and (2) largely symmetric thermal migration in regions from the islands contributing to initiation of new islands not vertically aligned with islands below.

Figure 2.3: The schematic representation of vertical correlation between QD layers proposed by Xie et al. [1]

2.1.4 InAs/GaAs QD bilayers

With the considerable interest that exists for optoelectronic sources emitting in the 1310 or 1550 nm telecommunications windows, the increasing size of the vertically correlated QDs observed by Xie *et al.* attracted attention for achieving long-wavelength emission (i.e. bigger QDs having lower ground-state energies). However, as mentioned earlier, the emission wavelength is controlled not just by size but also by strain and composition. Simply reducing the spacer to enhance this vertical correlation also results in large blueshifts and bi-modality of the emission [34, 32]. The blueshift has been attributed to the very same strain modulations that cause the preferential nucleation of the dots to achieve the vertical correlation; it has been argued that this strain modulation promotes interdiffusion of the QD material with its host matrix [35]. In the same study, QD bilayers with small spacers were found to exhibit carrier tunnelling effects between the correlated QDs. This electronic-coupling results in quenching of the shorter-wavelength emission and may

be expected to enhance the capture of carriers into the QD ground-state, which would benefit laser devices.

Mukhametzhanov *et al.* found that by depositing more QD material in the second layer the emission wavelength could be extended and the FWHM of the ground-state emission reduced. For example, a redshift from a seed layer emission of 1.175 eV to emission of 1.028 eV (at low-temperature) could be achieved by deposition of 3 ML of InAs in the second layer compared to 1.74 ML in the seed layer [36]. The FWHM of the QD ground-state emission reduced from 75 meV to 25 meV and emission from the seed layer was suppressed. These two later observations are important for devices because seed layer emission would reduce efficiency and reducing the spread of emission energies would help increase the peak gain of the QD ensemble. It was subsequently noted that interdiffusion is a strongly temperature-dependent process: by reducing the substrate temperature of the growth of the second layer and its cap to 480 °C it was found that room-temperature PL emission of 1400 nm could be achieved [22]. With an InGaAs cap the emission of the dot “bilayer” was further redshifted to 1480 nm.

2.1.5 Optimisation of the bilayer

It was found by Howe *et al.* [37] that a spacer layer thickness of 10 nm gave both the optimum electronic coupling and reduction in inhomogeneous broadening. The strain-template effect caused a corresponding reduction in the amount of deposited InAs required to form the upper QD layer. It was also found that the annealing of the growth surface before depositing the upper layer was important to remove any segregated In on the surface that might affect the growth of the QDs [38].

Seed layer density

A study of the effect of seed layer density on emission wavelength was undertaken to investigate the lateral range of the vertical coupling. To vary the density, the growth temperature of the seed layer was varied. As the mobility of the In adatoms on the surface increases with rising temperature, they can travel further before being incorporated into the crystal. This increase in the range of interaction would be expected to increase the distance between InAs islands, reducing the QD density. Figure 2.4a shows that the dependence on density that was expected is indeed

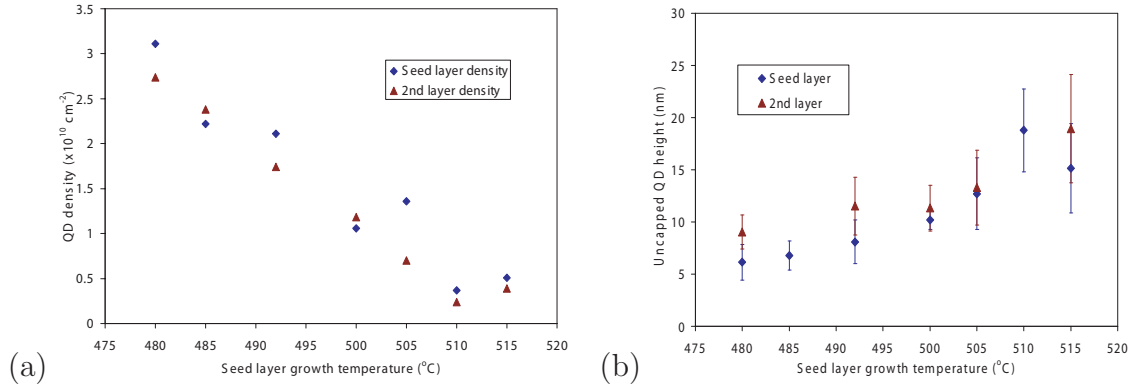


Figure 2.4: The effect of varying seed layer growth temperature on (a) the areal density and (b) the un-capped height of the QD bilayers.

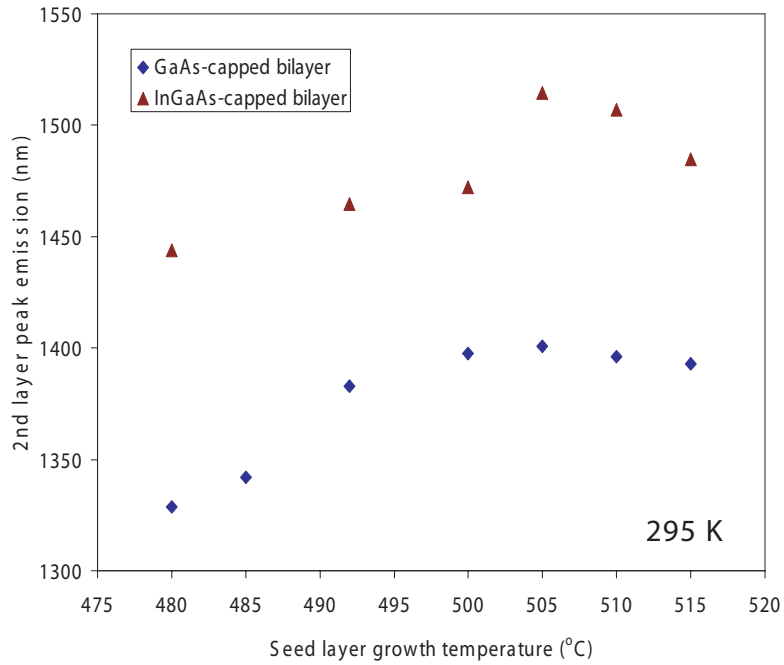


Figure 2.5: The effect of varying seed layer growth temperature on the emission wavelength.

found. The vertical coupling between the two layers has remained throughout the temperature range, as can be seen from the consistent fall in density between the two layers. However the interesting result is the effect on the ground-state emission wavelength (Figure 2.5): > 1500 nm emission from QDs grown directly on GaAs substrates without the use of a metamorphic buffer, dilute nitrogen or antimony as a surfactant.

It appears that, as expected, the shift in wavelength was achieved because as the density drops the indium adatoms on the surface are captured into fewer nucleated InAs islands. This is supported by the dependence of the height of the top layer QDs before they are capped (Figure 2.4b) as they appear to be much larger as the wavelength is extended. Higher aspect ratio QDs such as these will need careful overgrowth themselves and it was found that stacking them into multiple layers was not trivial and will require further work to achieve.

2.2 Growth details

The laser devices were grown according to the recipe shown in Figure 2.6, with the QD layers incorporated so that they are centred within the 500 nm intrinsic GaAs layer. Several series of samples were grown but suffered from various processing issues. Therefore the samples of relevance are listed below. The term “repeat” is used to describe the number of identical layers or bilayers within the active region.

U24093 (LGRQD) Five repeats of single-layer QDs were grown by depositing 2.4 ML InAs at 492 °C at a rate of 0.014 MLs^{-1} . This sample lased under pulsed operation at room-temperature, emitting at a wavelength of ~ 1260 nm. This was intended as a control sample to compare with the QD bilayer lasers.

U27073 (GaAs-capped bilayer) This device contained three repeats of a GaAs-capped QD bilayer with an areal density of $2.7 \times 10^{10} \text{ cm}^{-2}$. Lasing was observed under continuous-wave (CW) operation, with emission from the ground-state at 1340 nm and threshold currents as low as 70 Acm^{-2} at room-temperature for a 5 mm-long cavity.

U27080 (InGaAs-capped bilayer) Identical to the QD bilayer design for U27073 except that a 4 nm thick $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ cap was deposited directly after the InAs deposition of the second QD layer to extend its emission wavelength. Pulsed

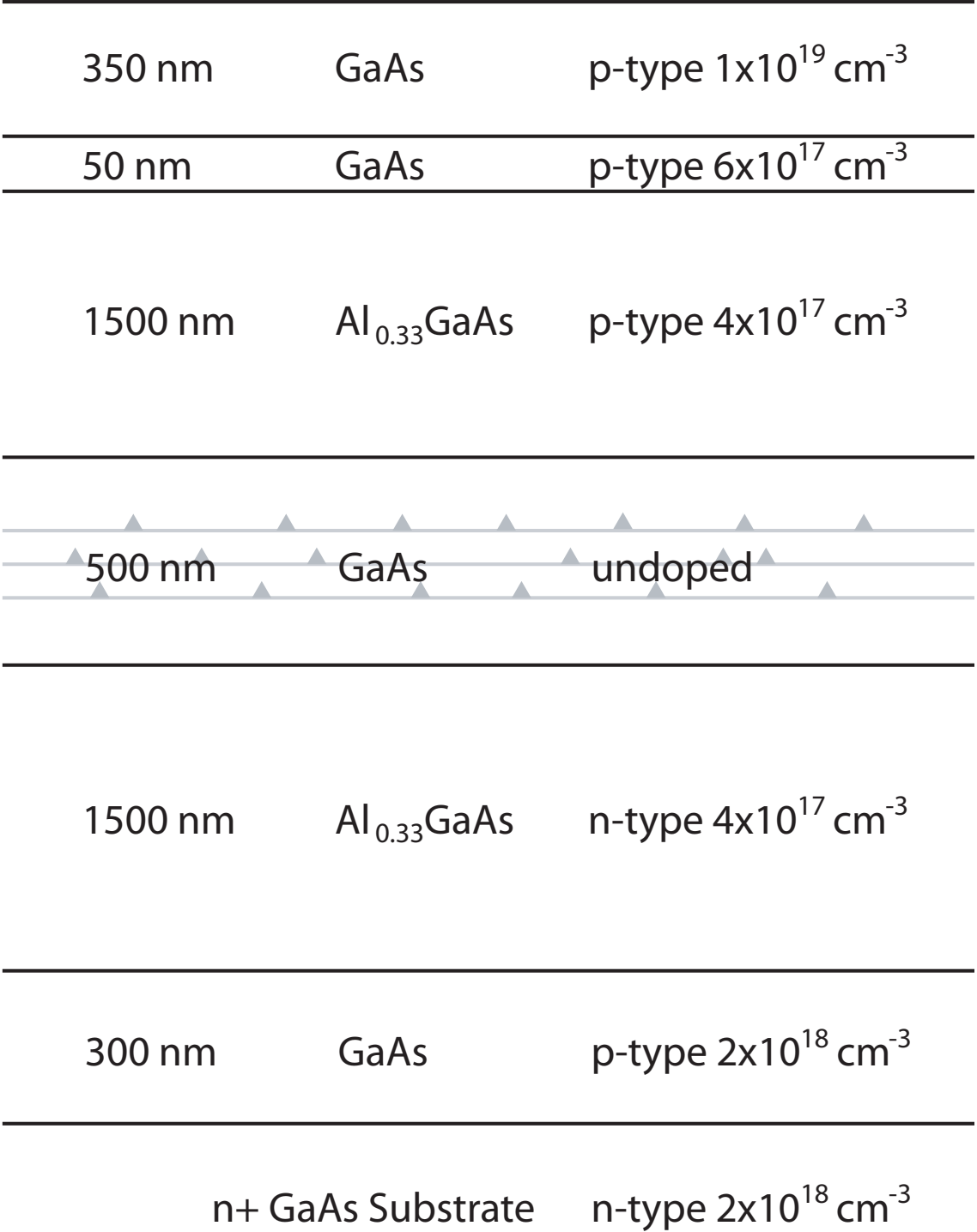


Figure 2.6: The laser heterostructure as grown by the MBE machine.

laser operation in the ground-state at 1425 nm at $-20\text{ }^{\circ}\text{C}$ was observed for a device with a 12 mm-long cavity. At room-temperature the device exhibited laser operation in the excited-state at ~ 1340 nm. The high threshold currents appeared to be due to a suspected contamination of the Ga source in the MBE reactor, which caused high number of defects.

U27038 (GaAs-capped bilayer) For higher modal gain this device contained five repeats of the QD bilayer material used in sample U27073. It exhibited CW lasing at room-temperature with 3 mm-long broad-area ($25\text{ }\mu\text{m}$ wide) cavities.

U28054 (InGaAs-capped bilayer) This device was grown with five repeats of an InGaAs-capped bilayer for comparison with the GaAs-capped version (U27038). Room-temperature emission of 1390 nm was observed with 26 meV FWHM of the ground-state peak, demonstrating good stacking of identical layers. However, laser oscillation was not observed, even in a 5mm-long cavity. This was attributed to device heating problems associated with the poor mounting of the chip that was observed when inspected under a microscope.

The wafers were processed into ridge waveguide lasers 5 and $15\text{ }\mu\text{m}$ wide by 5 mm long at Sheffield University by K. Groom and colleagues, as shown in Figure 2.7. U27073 and U27080 had thick electroplated gold contacts to aid with current-spreading and thermal conduction. The laser chip was then soldered onto a ceramic mount with gold contacts. Electrical connections were made to the contacts on the ceramic mount, which were in turn connected to the chip by $20\text{ }\mu\text{m}$ diameter gold wire-bonds.

2.3 Results

Figure 2.8 shows a light versus current (L-I) curve for 1340 nm QD bilayer laser sample U27073 operated in CW mode. For this measurement, the ceramic laser mount was attached to a copper heatsink using silver conductive paint for good thermal contact. The temperature of the heatsink was stabilised by a Peltier heat-pump, driven by a Thorlabs TED200 PID controller. The heatsink temperature was monitored by an AD590 sensor chip which provided the feedback to the controller. The light output of the front facet was measured by a calibrated InGaAs photodiode mounted onto an integrating sphere (the calibration was performed by the

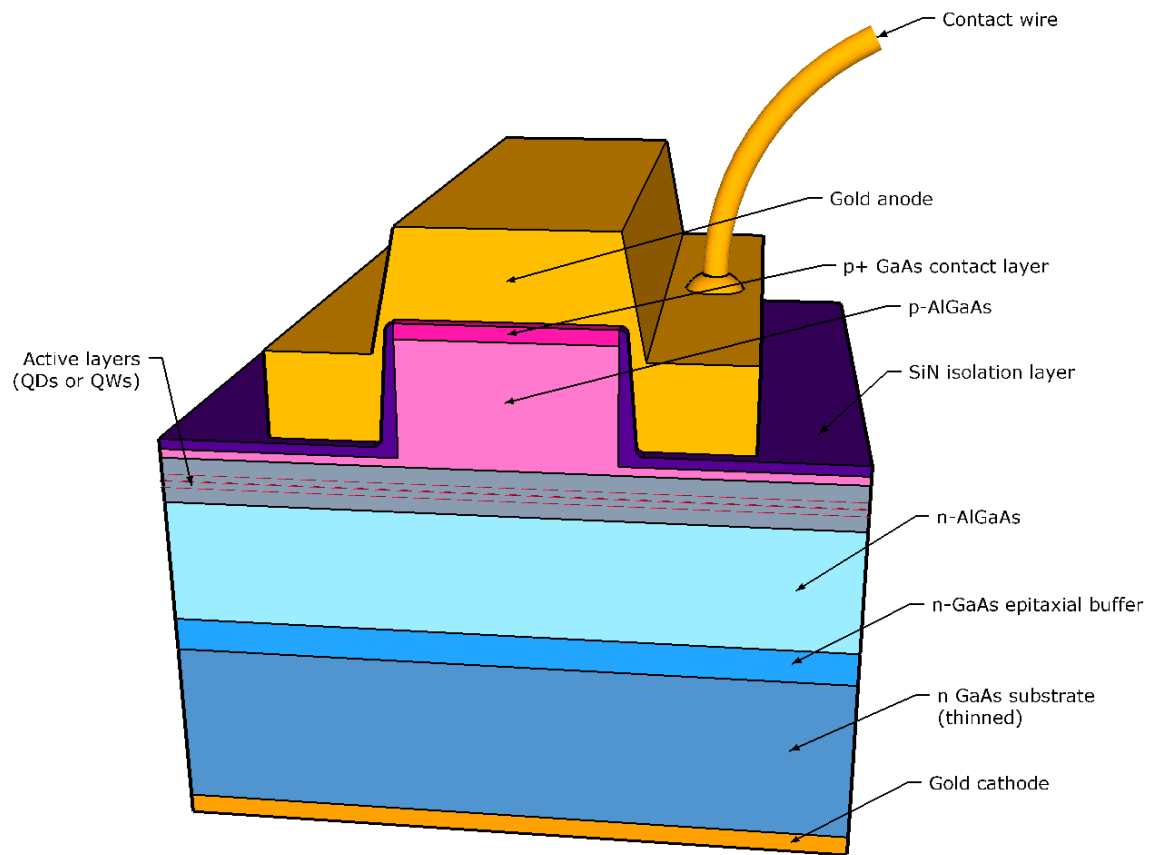


Figure 2.7: Schematic of the laser device showing the heterostructure layers and the ridge waveguide processing.

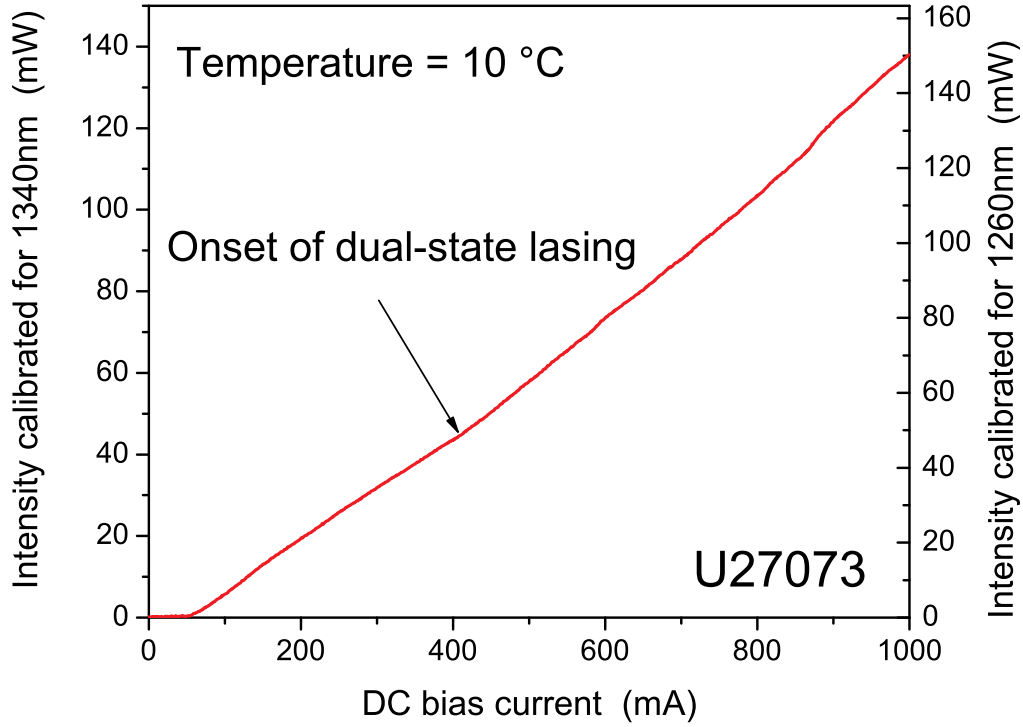


Figure 2.8: LI curve for a 5 mm x 15 μm laser from wafer U27073 operated in CW mode.

manufacturer, Thorlabs, in the same geometry). The bias current was supplied by a Keithley 2520 pulsed laser diode testing system. The results show a low threshold current density of 73 Acm^{-2} and a high slope efficiency giving an output power of between 140 and 150 mW at 1 A bias current. As noted by the kink in the curve at ~ 400 mA, this laser also has a second threshold for lasing on the QD excited-state - *dual-state lasing*. This phenomenon has been reported for other QD laser structures [39]. For a QD bilayer it would be tempting to think that this might not be the excited-state of the dot but instead the ground-state of the seed layer. However, this is not the case because seed layer emission is $\simeq 1200$ nm and the state that lases is 60 meV away from the GS emission, the expected separation between confined states.

This result is supplemented by the lasing of an $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ - capped version, U27080. As shown in Figure 2.9 it lases in its first excited-state at 1345 nm at room-temperature. The highest temperature at which ground-state lasing was observed was -20°C (253 K) at ~ 1425 nm. The threshold current densities were much higher than those of the U27073 lasers. This was believed to be due to contamination of the

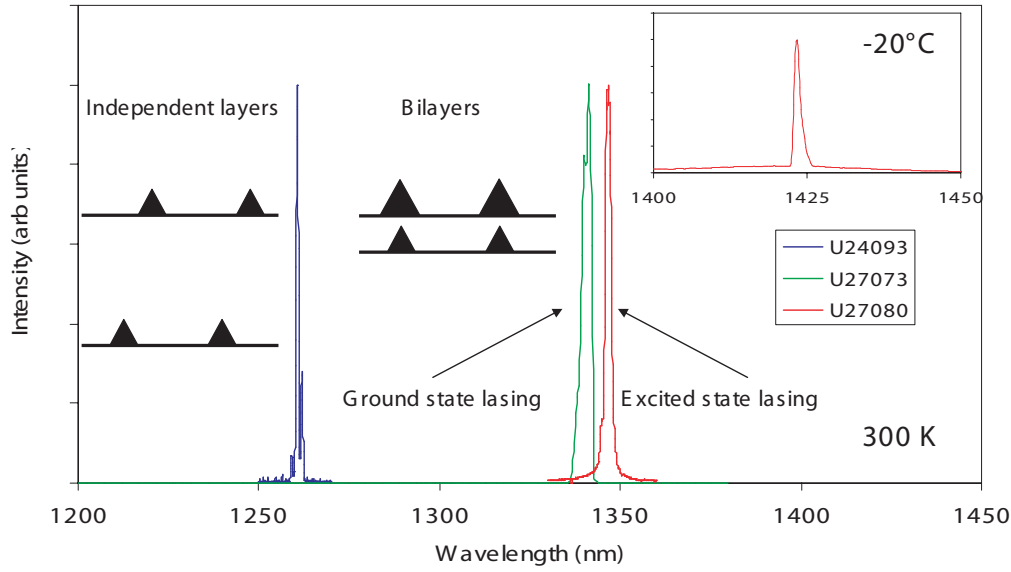


Figure 2.9: Comparison of lasing wavelengths between the more conventional independent dot layer (slow-growth rate) laser and the GaAs and InGaAs capped bilayer laser.

Ga cell in the MBE machine as no further successful samples were grown afterward*. Despite this setback, these two laser samples demonstrate that excited-state QD lasing could be used in the 1310 nm telecommunications window. Excited-state lasing generally shows higher values of T_0 due to higher maximum gain giving a higher differential gain, leading to smaller changes in the threshold current for a given loss [40] and higher modulation speeds [26].

The temperature performance of the QD lasers is shown as a comparison in Figure 2.10. For these measurements, the devices were mounted to the coldfinger of a cryostat with silver conductive paint (except for U28038, which was measured by the thermoelectrically-cooled arrangement described earlier). The threshold current densities of U24093 and 1340 nm emitting QD bilayer lasers (U27073 and U28038) follow a similar dependence to each other. Sample U28038 switches to excited-state lasing above 310 K. As it has five repeats compared to the three for U27073 it should have two-thirds more gain per unit length; it is 3 mm long compared to 5 mm for U27073, also a difference of two-thirds, leading to similar threshold current densities between the two devices.

It can be seen that while these lasers have lower base threshold current densities, their high-temperature performance is limited by poor temperature stability. This

*On the venting the growth chamber, a green-coloured contaminant was present in the Ga source material.

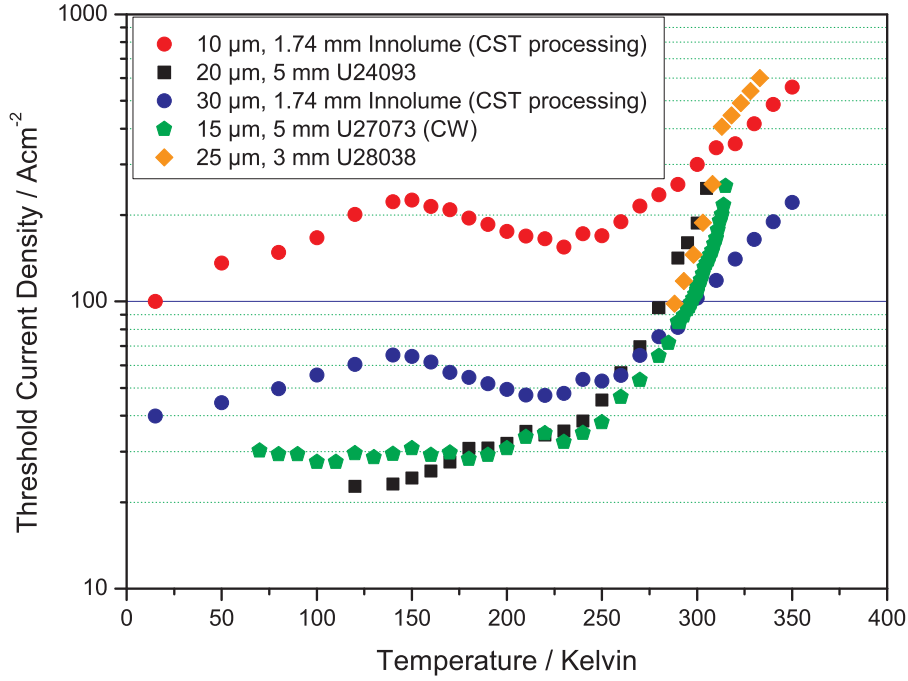


Figure 2.10: Comparison of lasing threshold current densities versus temperature for a range of different devices tested. Most devices were tested with $10 \mu\text{s}$ pulses at 1 % duty cycle.

is a symptom of the relatively low QD densities used in these devices. Having fewer QDs mean that the material's transparency point (i.e. one exciton per QD ground-state) is more easily attained - leading to lower base threshold currents. However, as the maximum available gain is lower, the material has to be driven to higher current densities near room-temperature. Gain compression due to the limited degeneracy of the ground-state will then limit the dynamic gain more severely than for higher-gain material, giving a lower T_0 . Therefore, the combination of good low temperature performance with low T_0 at room-temperature means that further optimisation should aim to increase the number of QDs, either through increasing the areal density of the QD layers or by stacking more repeat layers into the active region.

Figure 2.11 shows the amplified spontaneous emission (ASE) of a laser from the U28054 wafer operated in CW mode. This sample was 1 mm in length and did not reach its lasing threshold. The ground and excited-states are well-resolved, with the noise on the ground-state being due to water absorption. The key result is that five repeats of QD bilayers were stacked and the resulting emission is coincident giving a ground-state emission with a FWHM below 30 meV at room-temperature and low current densities. Comparing with a minimum FWHM of ~ 12 meV for single QD

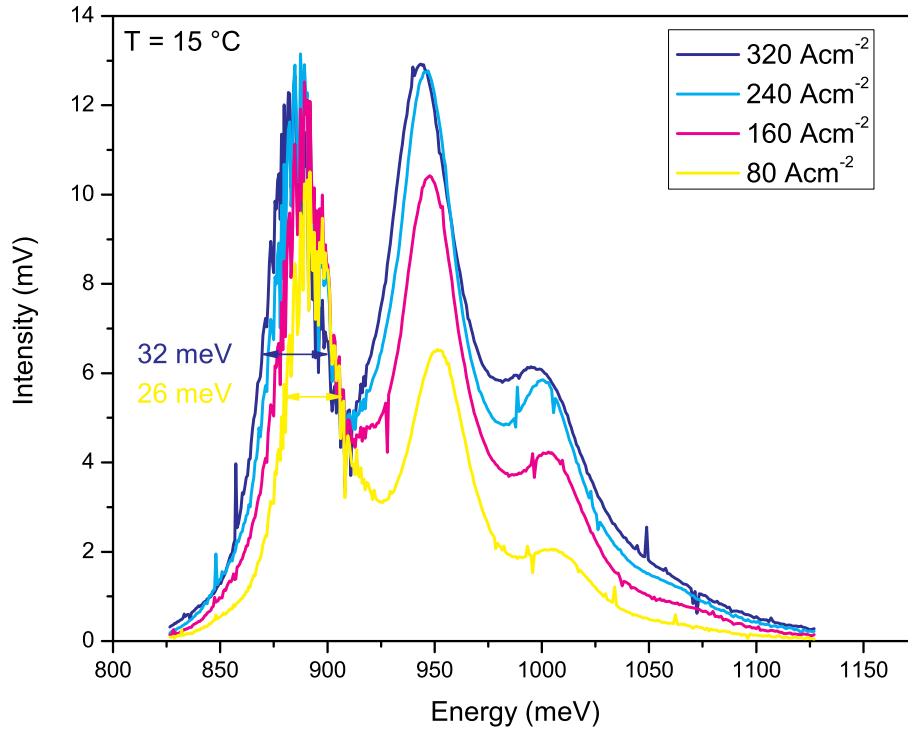


Figure 2.11: The sub-threshold CW emission from a 1mm by 50 μm broad-area device containing 5 layers of long-wavelength GaAs-capped QD bilayers. The bandwidth at low current densities is less than 30 meV.

bilayers at 10 K with ~ 10 meV homogeneous broadening at room-temperature, this demonstrates that the bilayer material can be stacked successfully which is critically important for many practical optoelectronic devices.

2.4 Conclusion

The QD bilayer growth technique can be used to make efficient and long-wavelength laser devices. With further work it may be possible to make long-wavelength QD lasers in the 1550 nm range, while at 1310 nm both ground and excited-state lasers have been demonstrated. In the following chapters the electrical and optical properties of the QD laser will be investigated, particularly exploring the consequences of the localisation effects of the inhomogeneous gain.

Chapter 3

Laser diode I-V spectroscopy

The gain medium of a laser diode is provided by a light-emitting p-i-n junction, Figure 3.1. The relationship of the voltage drop across the junction to the current passing through it (the I-V characteristic) is determined by the relationship of the electron and hole chemical potentials (the difference between them being the voltage across the contacts) to the current passing through the device - the recombination. Recombination is required for current to flow because electrons are injected into the conduction band of the material at the cathode and removed from the valence band at the anode - if no recombination occurs then no current flows. In an ideal light-emitting diode, the only recombination within the device should be radiative and the applied bias voltage should be minimal, so therefore by analysing the behaviour of these two quantities it is possible to learn details of the junction dynamics. The dynamics of the p-n junction are a complicated problem and their precise calculation

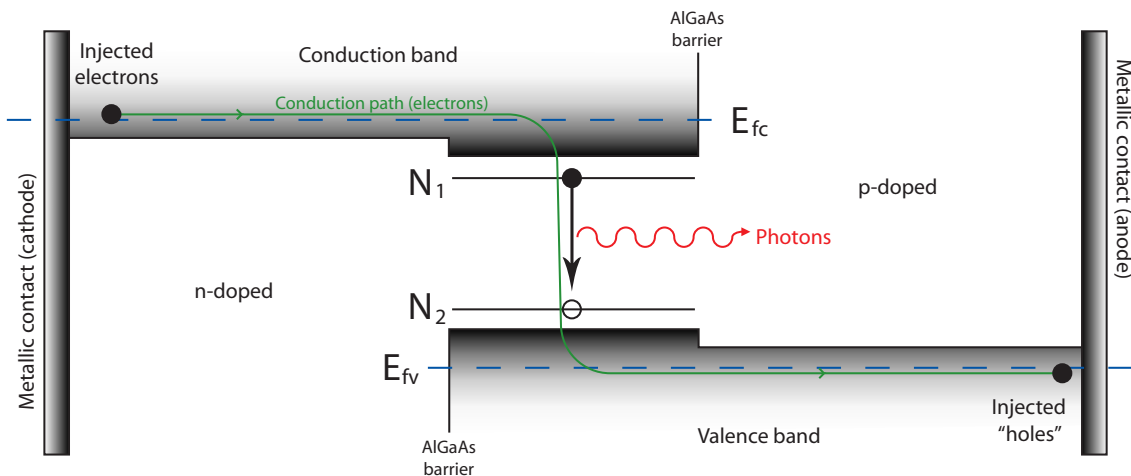


Figure 3.1: Schematic view of the p-i-n junction of a light-emitting or laser diode.

requires a detailed knowledge of the material parameters [41]. However because, for QD laser diodes, the structure and materials are still under investigation and there is no consensus in the literature and so rather than attempt to make a detailed calculation, an empirical study of the junction properties will be the topic of this chapter and has surprising results.

With no external circuit connected to the diode, the electron and holes chemical potentials will attempt to equalise across the device in order to reach a thermal equilibrium. However, when p-doped material with its excess of holes is brought close to n-doped material, with its excess of electrons, the chemical potential must move from being close to the valence band (as it is in the p-doped material) to being close to the conduction band (on the n-side). This is done by the action of the carrier transport processes: drift due to motion of the charged carriers in the electric field and diffusion of the carriers due to their chemical potentials which are, in a simple pure crystal, proportional to the carrier concentrations. At the junction there appears to be an excess of holes on the p-side compared to the n-side, so a diffusion current flows across the junction to balance the concentration. This leaves behind a space charge region because the ionised dopants are negatively charged, resulting in an electric field that attracts the holes to return to the p-side. The same processes happen on the n-side and because the electrons have the opposite charge to the holes, the drift and diffusion currents act in the same direction as for the holes. The drift current flows from the cathode to the anode, while the diffusion current flows from the anode to the cathode. Equilibrium is then established when these two currents balance to give zero net transport across the junction.

For a light-emitting diode such as the ones under study here, the p and n-type regions either side of the junction are of a wider bandgap than the intrinsic region. This results in a large barrier to the holes that prevents a significant current flowing into the n-region and vice versa, prevents electrons flowing into the p-region. Therefore the majority of the recombination must occur in the intrinsic region (and in the case of a QD diode, ideally it should occur in the QDs themselves). This means that the chemical potential of the holes in the valence band can reach equilibrium with the p-side more easily than the n-side, while the chemical potential of the electrons in the intrinsic region can reach equilibrium with the n-side. As a result, an important approximation can be made: that the spacing of the the electron and hole chemical potentials in the intrinsic region carries through the electrical contacts - *the chemical potential spacing (between the electrons and holes) is equal to the bias voltage*. An applied forward bias introduces a current from the anode

to the cathode of the diode. This introduces more carriers into the junction region through the diffusion current and therefore the change in chemical potential that occurs in the junction region is measured as a voltage across the diode. Therefore, monitoring the I-V characteristics of the diode allows spectroscopy to be performed on the active material in the intrinsic region. Of course there are other effects in addition, such as the Ohmic series resistance and the influence of impurities and defects but by performing supporting measurements they can be de-convolved in the analysis.

3.1 I-V characteristics of laser diodes

The gain medium of a laser diode is provided by a light-emitting p-i-n junction whose I-V characteristics are conventionally assumed to be well described by the ideal diode approximation, Equation 3.1 [41], for the purposes of examining experimental data.

$$J = J_S \left[\exp \left(\frac{eV}{\eta k_B T} \right) - 1 \right] \quad (3.1)$$

Here e is the electron charge, V is the potential difference across the junction, k_B is the Boltzmann constant and T is the temperature. η is the ideality factor which in a bulk diode is unity for an “ideal diode”. An ideal diode conducts in forward-bias by either radiative recombination of electrons in the conduction band with holes in the valence band in the depletion region of the junction, or alternatively conduction within the bands across the junction itself (this latter mechanism is suppressed for light-emitting and laser diodes by the presence of the wide-bandgap AlGaAs cladding layers). The ideality factor can also be used empirically to fit to the I-V characteristics of “non-ideal” diodes, giving a value of approximately two for devices where Shockley-Read-Hall recombination via traps is the dominant conduction mechanism and greater than two when the semiconductor junction is degenerate or heavily damaged [42]. J_S is the saturation current density required for the junction to be in thermal equilibrium and is (for a defect-free diode in the dark) equal to the reverse leakage current. This expression therefore provides a starting point for an empirical investigation of the QD laser diode junction properties.

An “ideal” diode contains a potential barrier to the flow of charge carriers through the device. The barrier in question for a light-emitting diode is the energy gap

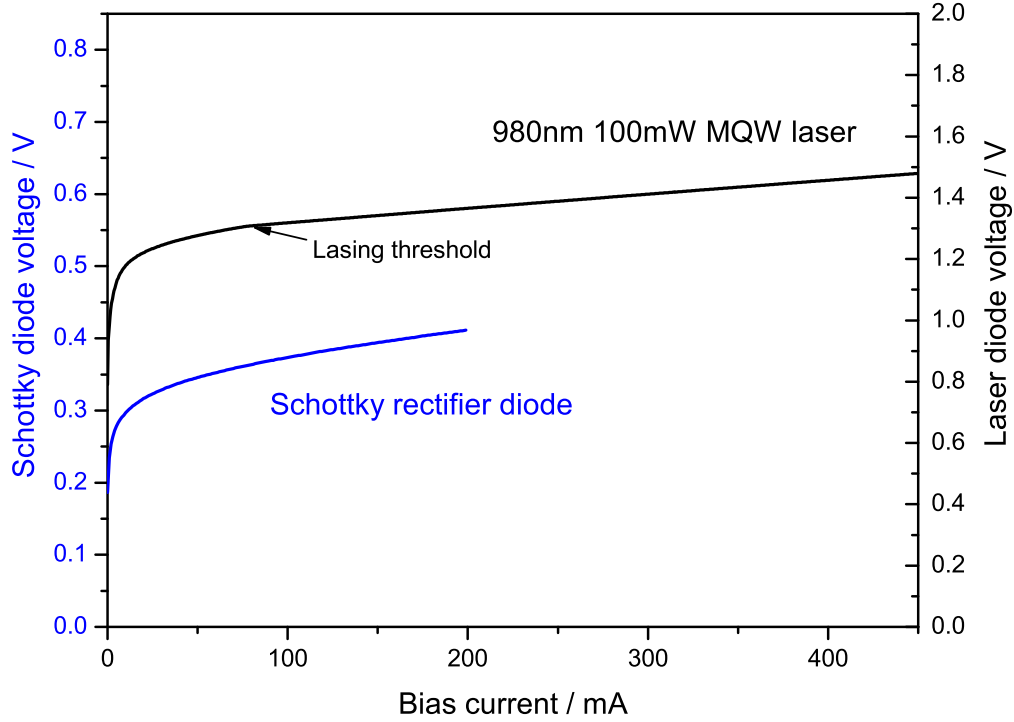


Figure 3.2: Comparison of “typical” I-V curves (normal vs. laser).

between the conduction and valence bands. The rate at which current can flow is proportional to the number of carriers that arrive at the barrier with an equal or greater energy. The exponential term arises because the energy of the carriers is the sum of their thermal energy and the charge multiplied by the voltage. An ideality factor of unity implies that Boltzmann thermal statistics are a valid approximation to describe the charge carriers.

It is useful to re-arrange the ideal diode equation to give the voltage in terms of current for the purposes of characterisation. This is partly for convenience since the experimental arrangements use current sources and also because the ohmic series resistivity (defined here as resistance times area, rather than the usual resistance times length), ρ , can easily be added to the expression to give Equation 3.2. Physically this form of the expression describes the potential energy (eV) that the “next” added carrier must be given to traverse the device.

$$V(J) = \frac{\eta k_B T}{e} \ln \left(1 + J/J_S \right) + \rho J \quad (3.2)$$

As the laser diode works by amplifying its own spontaneous emission [43] it has two regimes of operation. At low currents, spontaneous emission dominates and the

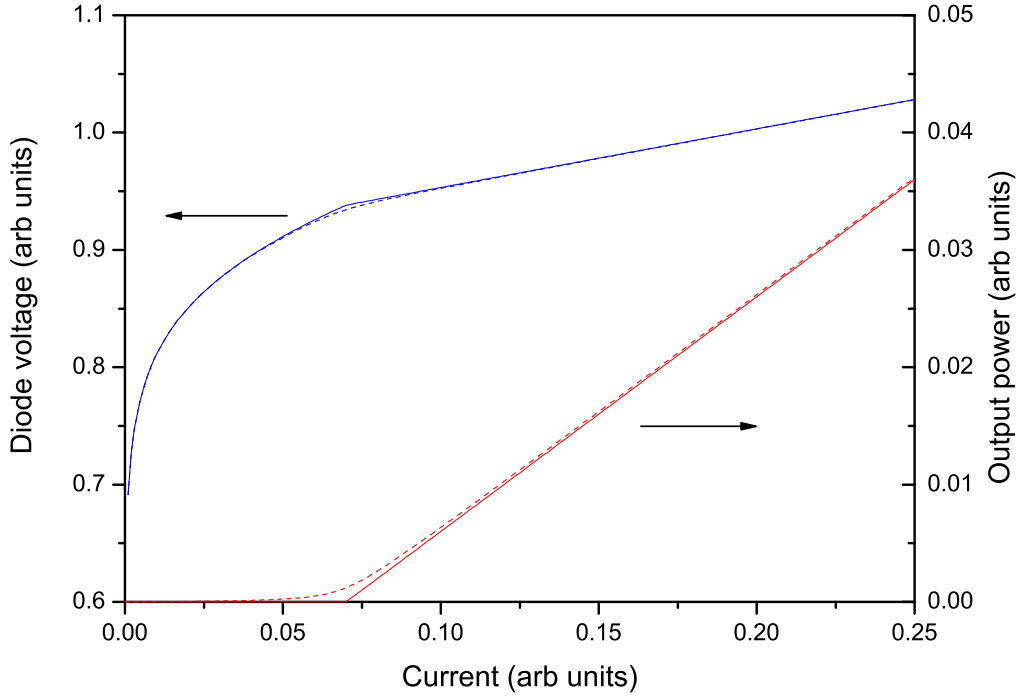


Figure 3.3: Simulated L-I-V curves from the model in Appendix A showing the junction voltage clamping at threshold. The solid line is from a laser with β equal to 10^{-5} while the dashed line has a β of 10^{-2} (This is the fraction of spontaneous emission into the lasing mode and increasing this tends to smooth the threshold transition [43]).

device acts like a “normal” light-emitting diode. In this regime the gain increases with current as the junction region is held further from equilibrium by the applied bias voltage. Once the laser threshold is reached, the gain has balanced the loss in the cavity and stimulated emission now dominates. Any extra injected carriers will recombine much more quickly and it becomes difficult to pull the junction any farther from equilibrium. Therefore, the voltage across the junction is “clamped” at its threshold level. This is also known as saturation or pinning and is accompanied in QW and bulk lasers by a saturation of the spontaneous emission. This was first correctly identified by Eliseev *et al.* in 1969 [44], although others had observed the effect previously [45, 46].

Figure 3.2 shows a schematic I-V curve of a Schottky rectifying diode, together with that of a typical quantum well laser diode for comparison. The key difference between the Schottky and the laser is the change at the laser threshold. As expected the junction voltage of the laser diode clamps at the laser threshold and its I-V curve becomes ohmic above this current. Meanwhile the Schottky diode obeys the ideal diode approximation. Figure 3.3 shows the I-V and L-I results for a simple laser model demonstrating this effect. This model will be described in detail in appendix A.

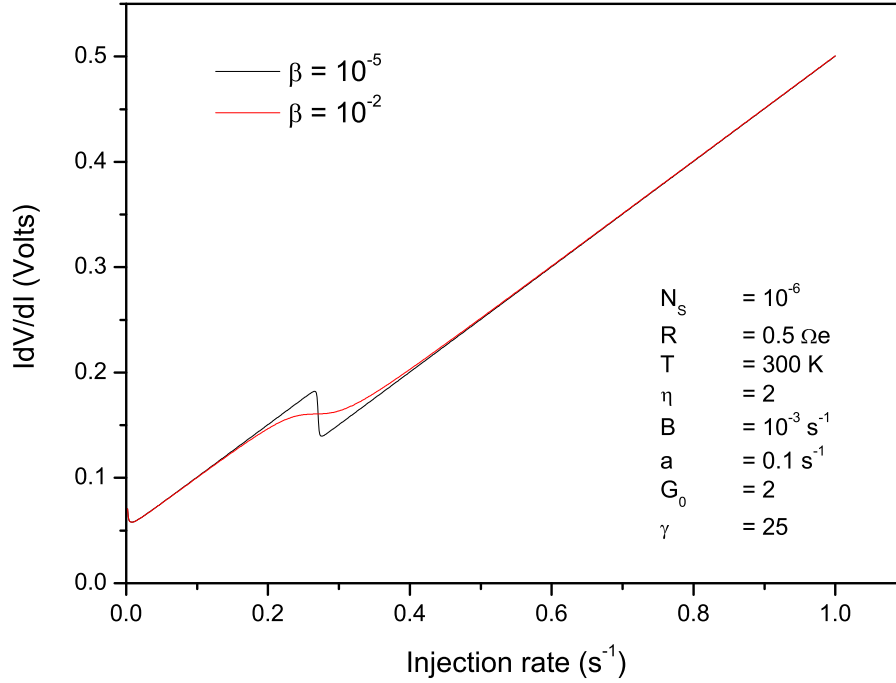


Figure 3.4: Simulation of a $-IdV/dI$ derivative spectrum measurement based on the simplistic rate equation model, for a two values of β . The step at threshold can be clearly identified at an injection rate of 0.27 s^{-1} but is less obvious for the higher value of β

3.1.1 First derivative (IdV/dI) spectroscopy

Derivative spectroscopy has been used in a wide range of applications where fine details of apparently featureless or convoluted spectra need to be resolved. Its application to the I-V characteristics of diodes was pioneered by Paoli and Barnes [47, 48] and it found widespread use in investigations of the effects of ageing, defects and processing faults in early laser development [43] because of its ability to isolate the effects of the material (e.g. the series and shunt resistances that increase with the age of the device) from that of the p-n junction. Recently, this technique has largely fallen out of use and had not been applied to QD lasers before.

An expression for the derivative of an ideal diode's contact voltage (taken from Equation 3.2) with respect to J is shown in Equation 3.3. Taking into account that for most diode devices at typical operational current densities $J_S \ll J$, the J_S term can be neglected. Multiplying by J avoids the reciprocal dependence on J in the first (diode-like) term throughout to give Equation 3.4, a convention that allows a more clear interpretation of experimental data.

$$\frac{dV}{dJ} = \frac{\eta k_B T}{e} \frac{1}{J + J_S} + \rho \quad (3.3)$$

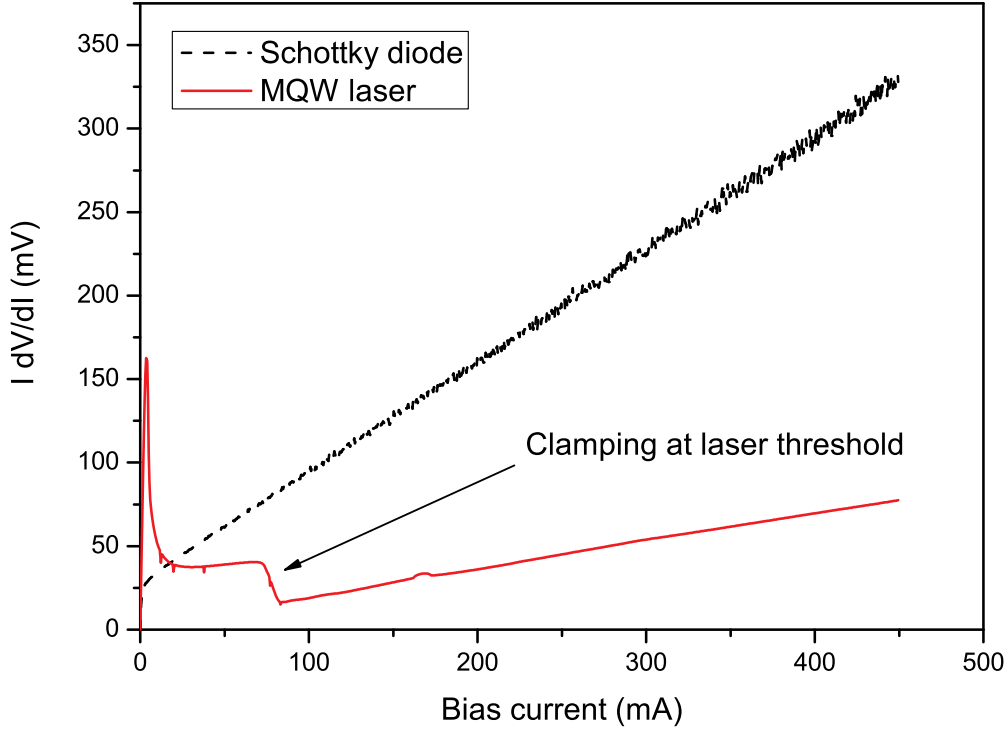


Figure 3.5: Example IdV/dV curves from a Schottky diode and a 980 nm laser. Note the feature at 170 mA and a more subtle deviation from a linear slope at ~ 300 mA.

$$J \frac{dV}{dJ} \simeq \frac{\eta k_B T}{e} + J\rho \quad (3.4)$$

Plotting this expression will give a linear region where the slope is the device resistance and the intercept is the ideality factor, η , multiplied by the thermal voltage $k_B T/e$ - as shown in Figure 3.4. At the laser threshold where clamping occurs, the derivative of the diode-like first term drops to zero, giving a transition to a new linear region which extrapolates back to the origin.

To perform the first derivative measurement the experimental set-up shown in Figure 3.6 was arranged. Temperature control was provided by a thermoelectric-cooled mount (with an AD590 temperature sensor to provide feedback), controlled by a Thorlabs TED200 PID controller. The bias current to the laser was provided by a Thorlabs LDC205 laser diode driver, and the voltage across it was measured by a lock-in amplifier. The current was controlled by a combination of a 10 mV sinusoidal modulation from the lock-in amplifier's oscillator at a frequency of 1 kHz (giving a current modulation of ~ 0.5 mA) and a voltage supplied by a data acquisition card in the PC to set the DC bias. During the measurement, readings of the laser's voltage response to the current modulation were taken at a range of bias

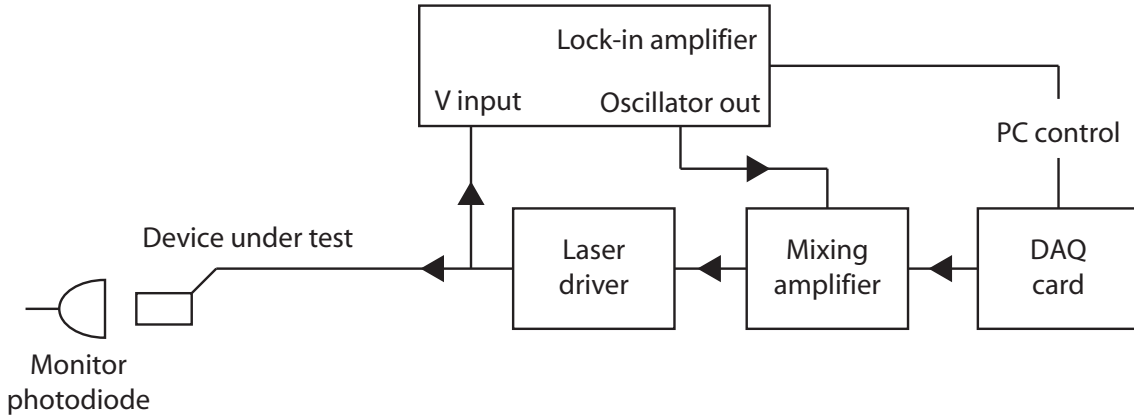


Figure 3.6: Experimental set-up for performing first derivative spectroscopy.

currents. The device voltage and the light intensity were monitored by a Keithley 2520 pulsed laser diode test system, with an InGaAs photodiode mounted on an integrating sphere as the optical detector. The readings were multiplied by the bias current and the calibration factor in the software. The system was calibrated by comparing the readings from a 2 Ohm resistor with the measured voltage.

For the 980 nm quantum well laser diode data shown in Figure 3.5 features are seen in the curve above the threshold current. These features are often attributed to the appearance of laser action in higher-order transverse spatial modes [43]. The reason for this is due to the incomplete overlap between the electric field envelope of the lasing mode and the electrically-pumped active region. Therefore the active area of the device changes at the laser threshold because injected carriers will preferentially recombine by stimulated emission in the regions where there is good overlap. This change of current-path is called *filamentation* and it follows that any changes in the pattern of light emission (the *mode profile*) will cause further filamentation. As the expressions given previously for the junction voltage are dependent on the current density and therefore the active area, it follows that filamentation is *in principle* detectable from such fine details of the I-V data.

3.1.2 Second derivative ($-I^2 d^2V/dI^2$) spectroscopy

Given the ability of modulation spectroscopy to reveal finer features in I-V data we investigated second derivative spectroscopy. Again for ease of interpretation a pre-factor ($-J^2$) is included to avoid reciprocal dependencies and yield dimensions of voltage. The ohmic term of the diode's I-V characteristic is not present in these

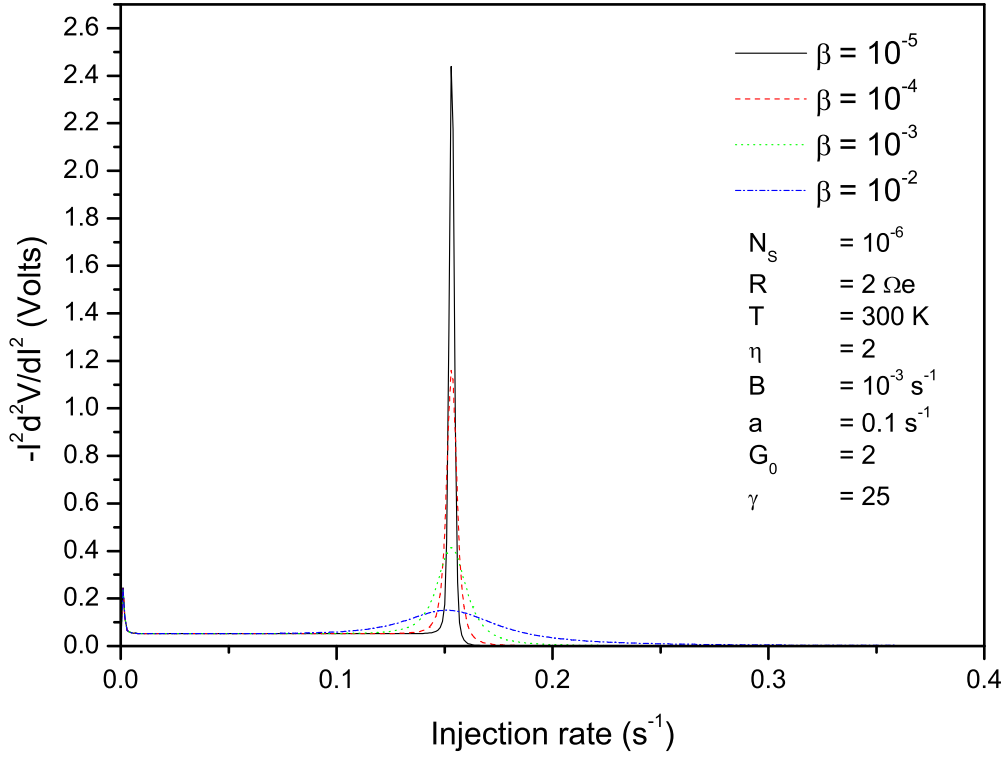


Figure 3.7: Simulation of a $-J^2 d^2V/dI^2$ derivative spectrum measurement based on the simplistic rate equation model, for various values of β .

data as it has no significant second derivative. Therefore the measurement is only sensitive to the behaviour of the p-n junction and takes the value of the ideality factor multiplied by the thermal voltage (Figure 3.7).

The biggest change between the first and second derivative measurements is the presence of a peak at the lasing threshold. The origin of this can be seen if the ideal diode term of the differential resistivity (resistance times area), Equation 3.3 is multiplied by a coefficient so as to allow the term to be “switched off” at the threshold. The resulting expression including what shall be called the lasing fraction parameter $A(J)$ is given by Equation 3.5. $A(J) = 0$ at currents up to the threshold, where it rises to unity. By taking the derivative of this with respect to current and then multiplying by the $-J^2$ factor to avoid the squared reciprocal dependence, Equation 3.6 is obtained. The first term on the right-hand side is the steady-state ideality-factor multiplied by the thermal voltage, as before. The term in JdA/dJ gives rise to the peak at the laser threshold current. It must be noted that when this is measured experimentally it is broadened by the amplitude of the modulation used although the integrated area of this term remains unchanged [49].

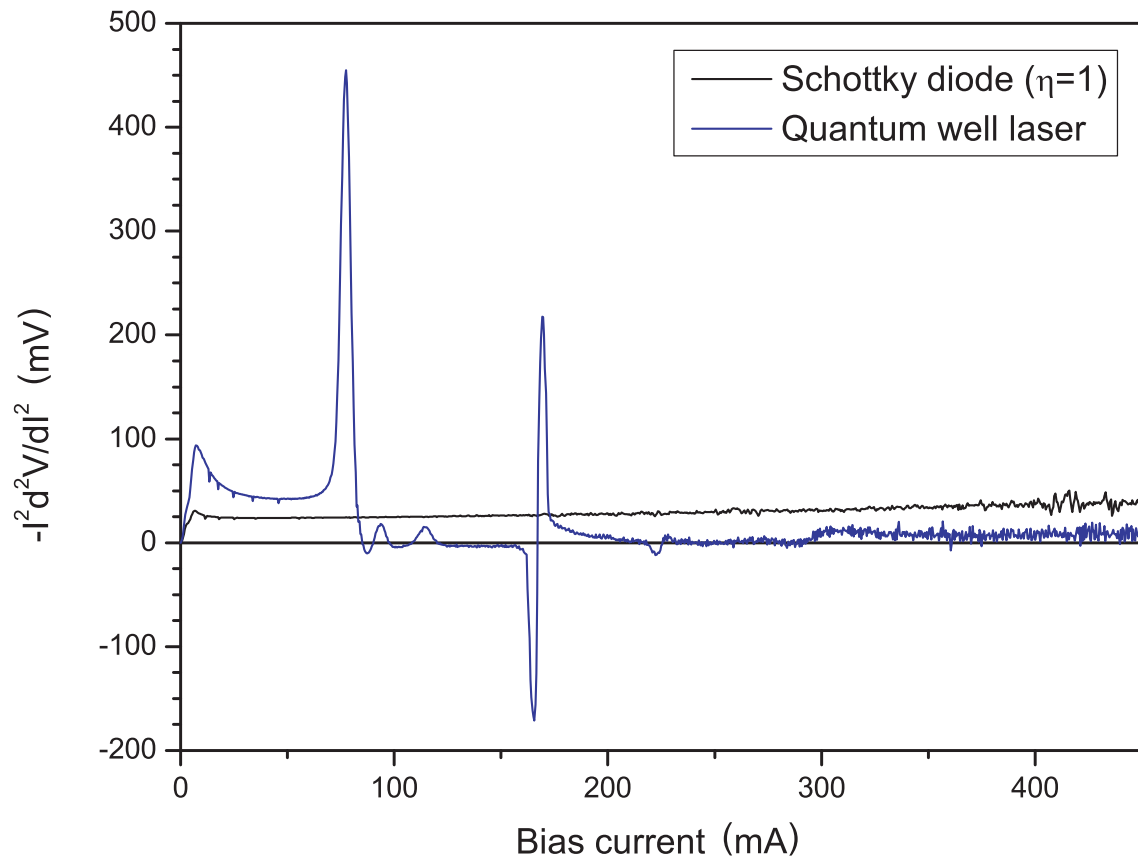


Figure 3.9: Figure comparing the $-I^2 d^2V/dI^2$ measurements of a Schottky diode and an MQW laser.

lock-in amplifier. The effect that causes the mixing is referred to as intermodulation distortion and as this is generally very small in good quality amplifiers it results in negligible crosstalk between the first and second derivative signals. Care must also be taken to minimise crosstalk between the reference signal at the difference frequency. For this reason it was found best to reconstruct the reference by using a non-linear mixer close to the reference input of the lock-in amplifier. The lay-out of this experimental arrangement are shown in Figure 3.8.

A comparison of two devices is shown in Figure 3.9. Both the Schottky diode and QW laser fit well with the measurements and are consistent with the explanations of the I-V and IdV/dI curves presented here. However there are many additional unexpected features visible on the measurement of the QW laser. These features suggest that there are imperceptible changes in the I-V characteristics as the current increases and therefore these should be compared with the detailed optical characteristics to determine if this is due to filamentation.

3.2 Spectroscopy of a multi-quantum well laser

The QW laser studied here was a commercial 980 nm laser diode (part number L980P100 from Thorlabs, Inc.). The diode was not chosen for any particular characteristic that it might share with QD lasers, other than being rated to 500 mA bias current. According to the accompanying datasheet, it is based on an MQW active region.

Figure 3.10 shows the data obtained from this device, obtained at a temperature of 10 °C (as measured by an AD590 temperature sensor). From the L-I curve in Figure 3.10(a) the threshold current of the laser (labelled as feature 1) is 77.6 ± 0.4 mA. At the same current on the I-V curve (b), clamping of the junction voltage occurs. The first derivative spectrum shows this as a clear step down from an offset linear region *i* to the ohmic (i.e. zero-offset) linear curve in regions *ii* to *vi*. Moving to the second derivative spectrum the threshold is indicated by a clear peak and clamping of the junction voltage is confirmed by the signal dropping to zero after the peak.

However there are two additional observations that can be made on the first derivative spectrum. There is a small peak, labelled as feature 4, together with a slight rolling-over of the curve in region *vii*. Feature 4 corresponds to a kink in the emission

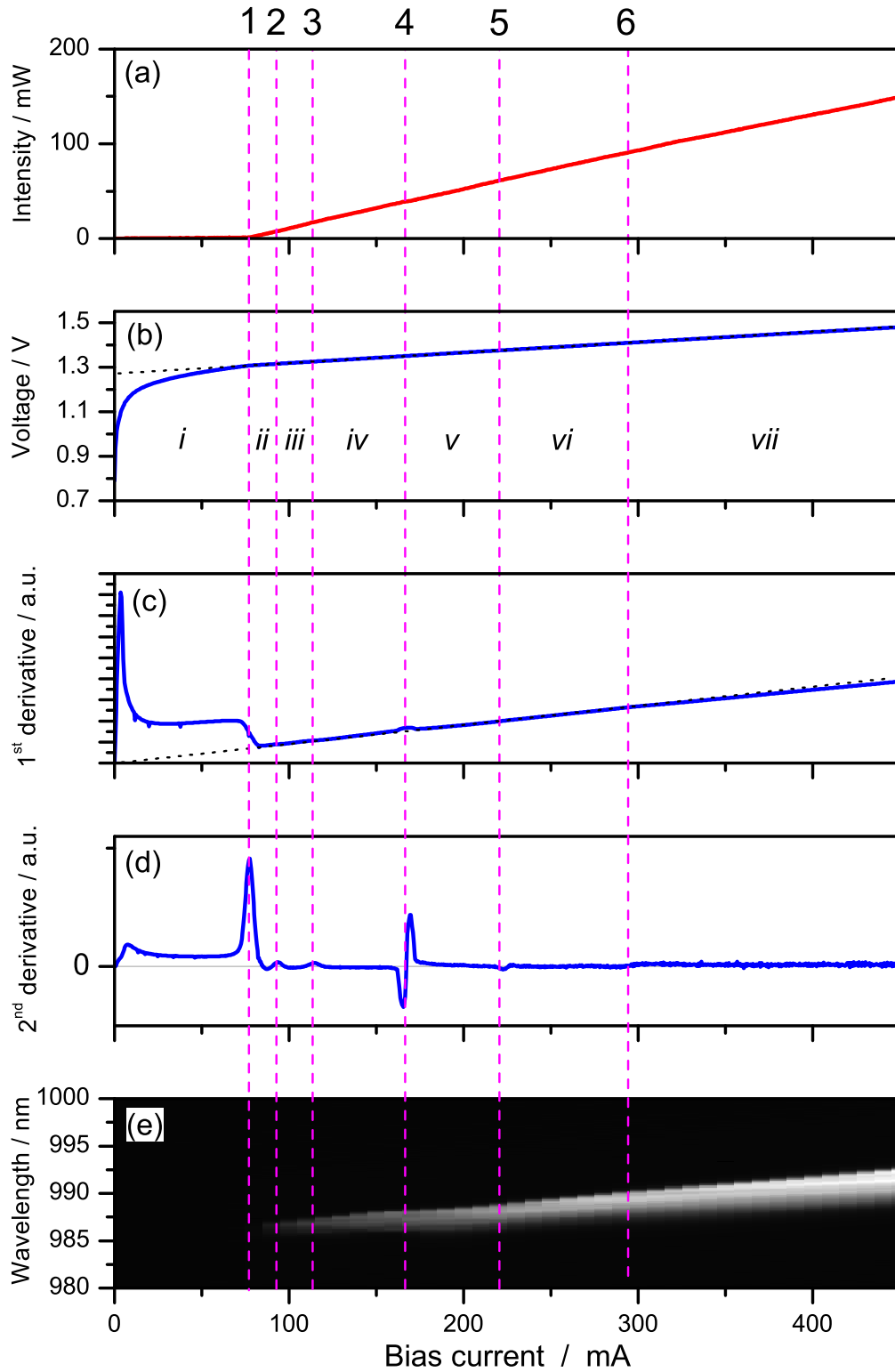


Figure 3.10: Results obtained from the MQW 980 nm laser. (a) L-I curve clearly showing the threshold current. (b) I-V curve showing ohmic behaviour above threshold. (c) The first derivative spectrum clearly showing the saturation at threshold. (d) The second derivative spectrum with a clear peak at threshold and a feature associated with a region of the (e) optical spectra, where a discontinuity in the laser emission evolution can be seen. The identifiable features on the second derivative curve have been labelled 1 to 6, with the intermediate regions labelled *i* to *vii*.

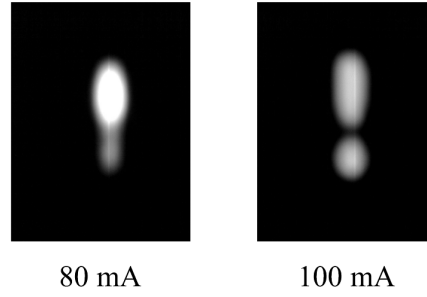


Figure 3.11: A series of mode-profile images, with the growth direction horizontal across the page. Changes in transverse-optical mode profile around feature 2, the bottom lobe is enhanced.

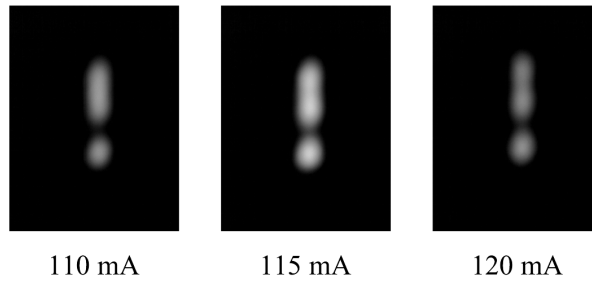


Figure 3.12: The transverse-optical mode profile around feature 3, the top lobe splits into two resolved lobes.

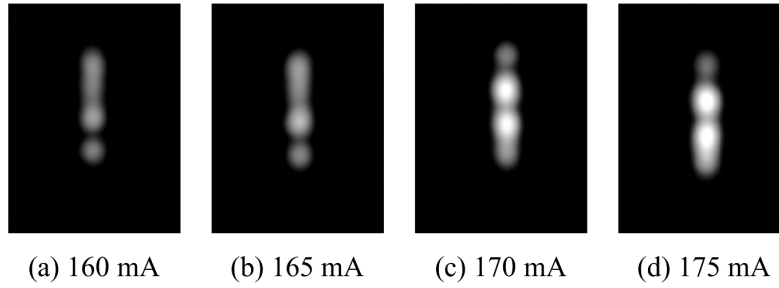


Figure 3.13: Laser mode images of the 980 nm laser around feature 4, the switch in emission pattern is clearly between (b) and (c).

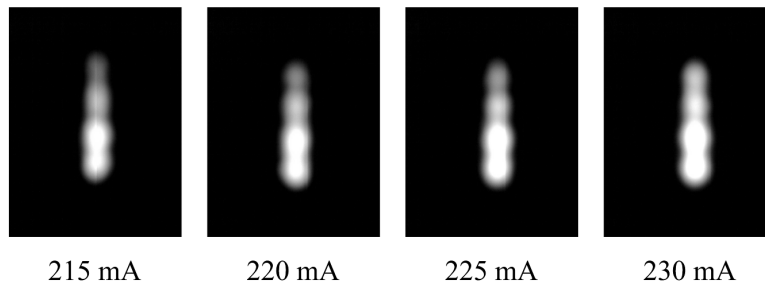


Figure 3.14: Around feature 5, the lobes become more evenly distributed between 215 mA and 225 mA. The change is very subtle but most noticeable on the top lobe.

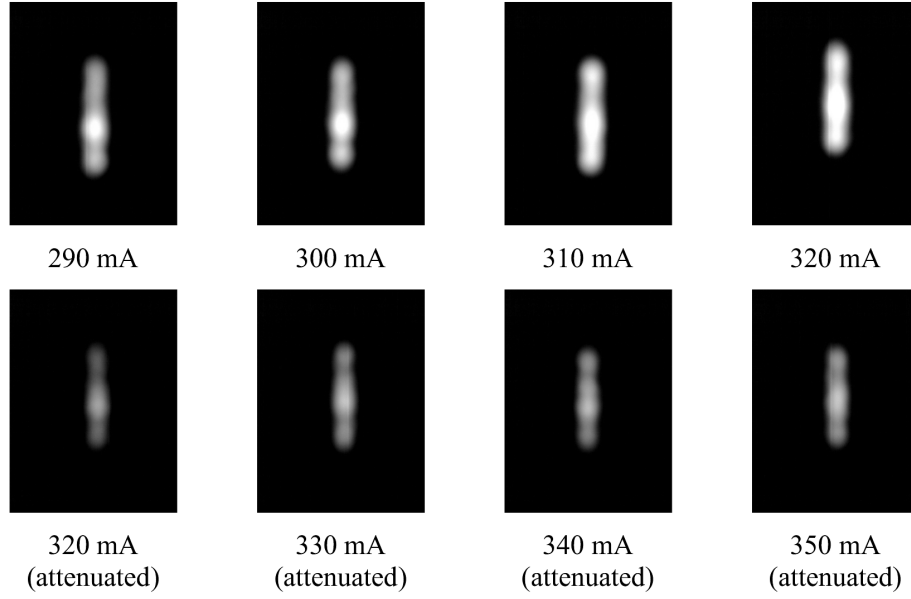


Figure 3.15: Possible broadening of emission pattern in region *vii*?

of the laser that spans region *v* in the optical spectrum. On the second derivative spectrum feature 4 becomes very clearly identified, along with other peaks not previously visible (features 2,3 and 5). The region *vii* is identified by a weak step and is attributed to incomplete clamping of the junction voltage at currents higher than feature 6 (i.e. the $-I^2 d^2V/dI^2$ signal is non-zero).

Paoli [47, 48, 50] assigned peaks of the form of feature 4 as being due to laser-action on higher-order transverse modes. Using mode imaging (Figure 3.13) a definite shift in the already multimodal emission pattern occurs in the region around feature 4 (165 mA to 170 mA).

Therefore the main features of the $-I^2 d^2V/dI^2$ measurement can be correlated with both spectral and spatial changes in the laser emission. Changes to the mode profile around the minor features 2, 3 and 5 are shown in Figures 3.11, 3.12 and 3.14 respectively. Each feature became successively weaker, both on the derivative spectrum and in the profile change, consistent with these two phenomena being associated. An association between the incomplete clamping of region *vii* of Figure 3.10 and any change in profile (Figure 3.15) is less obvious but still present. This shows that filamentation is detectable through the fine details of the I-V characteristics.

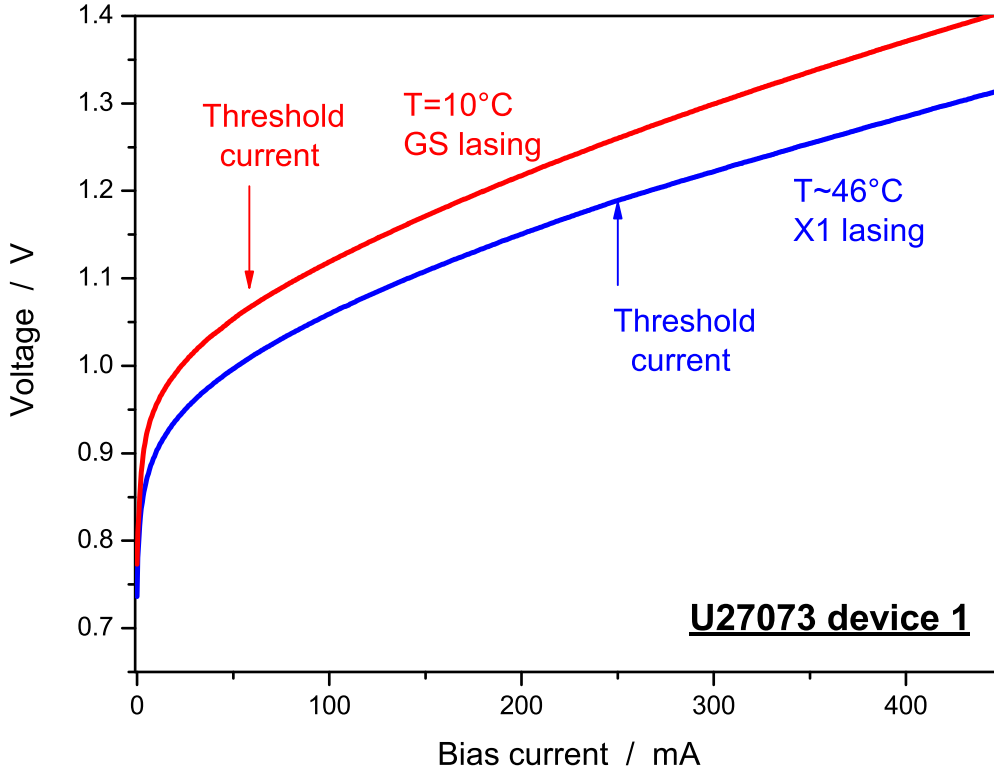


Figure 3.16: Quantum dot laser I-V curves.

3.3 Spectroscopy of a quantum dot laser

The techniques outlined for QW lasers have been applied to several QD lasers. Although similarities are expected the interest lies in the effects that an inhomogeneous gain will have on laser behaviour. Figure 3.16 shows I-V curves for the QD bilayer laser U27073 grown at Imperial, with the processing by Kristian Groom and Ryan Alexander of Sheffield University. There is no clear linear region suggesting that the junction voltage does not clamp at threshold. This is consistent with some degree of de-coupling between the occupation of the localised QD states and the quasi-Fermi level spacing of the bulk crystal host caused by localisation and inhomogeneous broadening of the QDs. This section outlines the behaviour of QD lasers using the results of derivative spectroscopy.

Figure 3.17 shows a room-temperature first derivative spectrum for this QD laser. As might be expected from the I-V data, the laser does not exhibit complete junction voltage clamping at the lasing threshold but there is a *partial* step at threshold. Further analysis of this data is complicated by the continual roll-over of the curve.

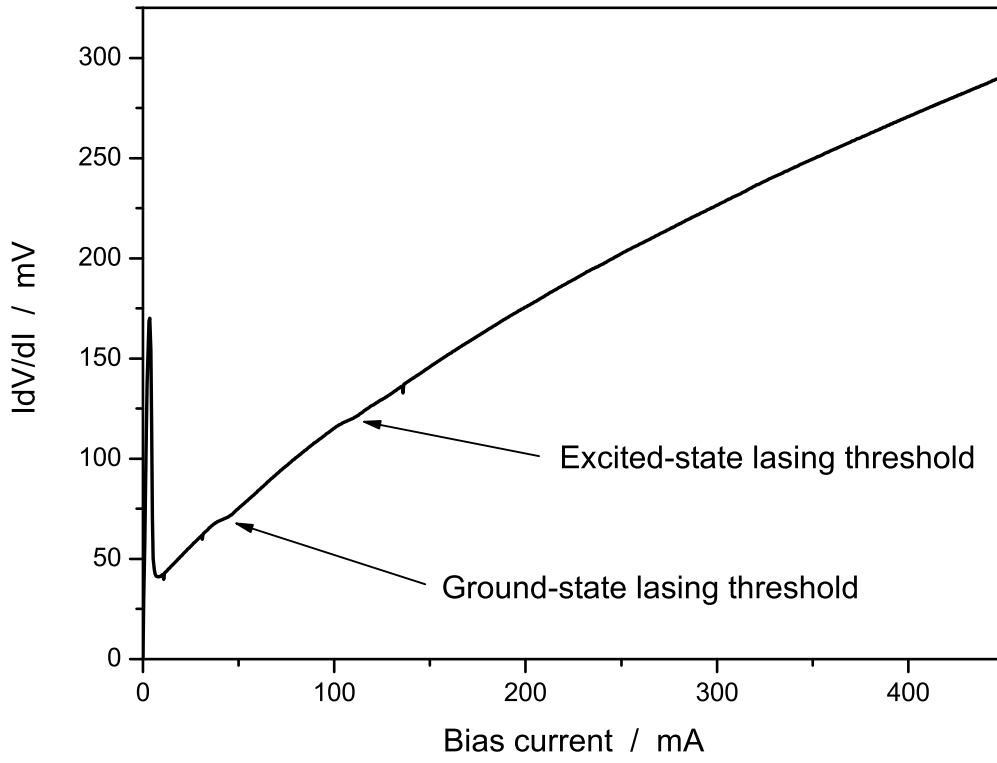


Figure 3.17: Typical quantum dot laser IdV/dI curve.

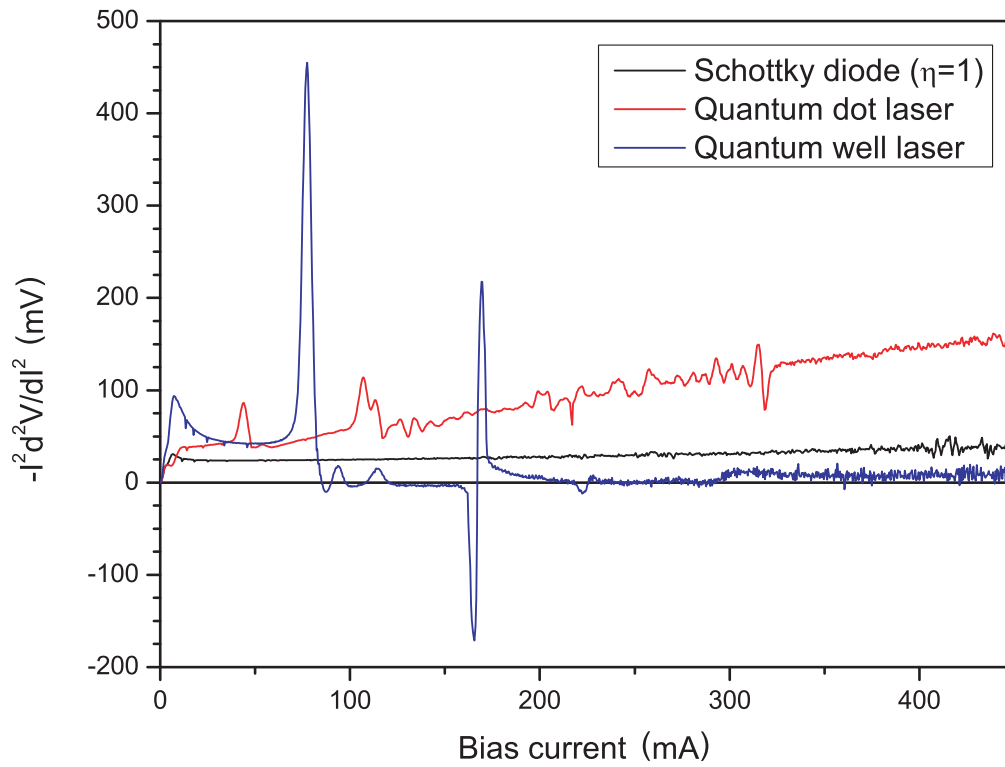


Figure 3.18: Figure comparing the $-I^2 d^2V/dI^2$ spectra from a Schottky diode, QW and QD lasers.

Moving to second derivative spectra, a comparison of three different diode types as shown in Figure 3.18 can be made. From this it can be seen that while the Schottky diode and QW laser fit well with the measurements and explanations of the IV and IdV/dI curves, QD results are more complicated; features can be seen across the entire spectrum on a linearly-rising background.

Figure 3.19 compares the $-I^2d^2V/dI^2$ data with the corresponding optical spectrum. Note that the optical spectrum shows that this laser exhibits dual-state lasing (as mentioned in chapter 2) for currents between 100 - 300 mA. The key observations are that the peaks in the $-I^2d^2V/dI^2$ spectrum correlate with features in the optical spectrum and each of the lasing threshold peaks is followed by a negative displacement of the $-I^2d^2V/dI^2$ curve. The peaks were also observed to correspond to changes in the spatial pattern of light emission, as shown by the facet images in Figure 3.20 for the region around the dual-state lasing threshold. These images show that filamentation occurs and that this must be considered when seeking to explain the dual-state lasing phenomenon.

These techniques have also been applied to QD laser material from other sources, with the results shown in Figure 3.21. These lasers were grown using the DWELL technique and also exhibit peaks due to partial clamping on a linearly-rising background. This suggests that these phenomena are general to QD based devices.

3.4 Conclusions

Clamping and filamentation are common to most semiconductor lasers (to varying degrees) as shown in the previous section. What is new here is that QD lasers exhibit only partial clamping of the junction voltage. The association of the peaks with the onset of filamentation suggests that different spatial regions of the junction are behaving with a degree of independence from each other. Once laser oscillation occurs, these regions' electrochemical potentials will differ and this may result in lateral transport of the carriers between regions, leaving the "global" quasi-Fermi level spacing of the device as an average measure of the junction potential. In Appendix B a simple model is derived that shows that this lateral transport picture of currents flowing between filaments leads to partial clamping. It leaves open the question of whether the "regions" are larger spatial areas/volumes related to the laser light-field or the individual QDs themselves (macroscopic or microscopic

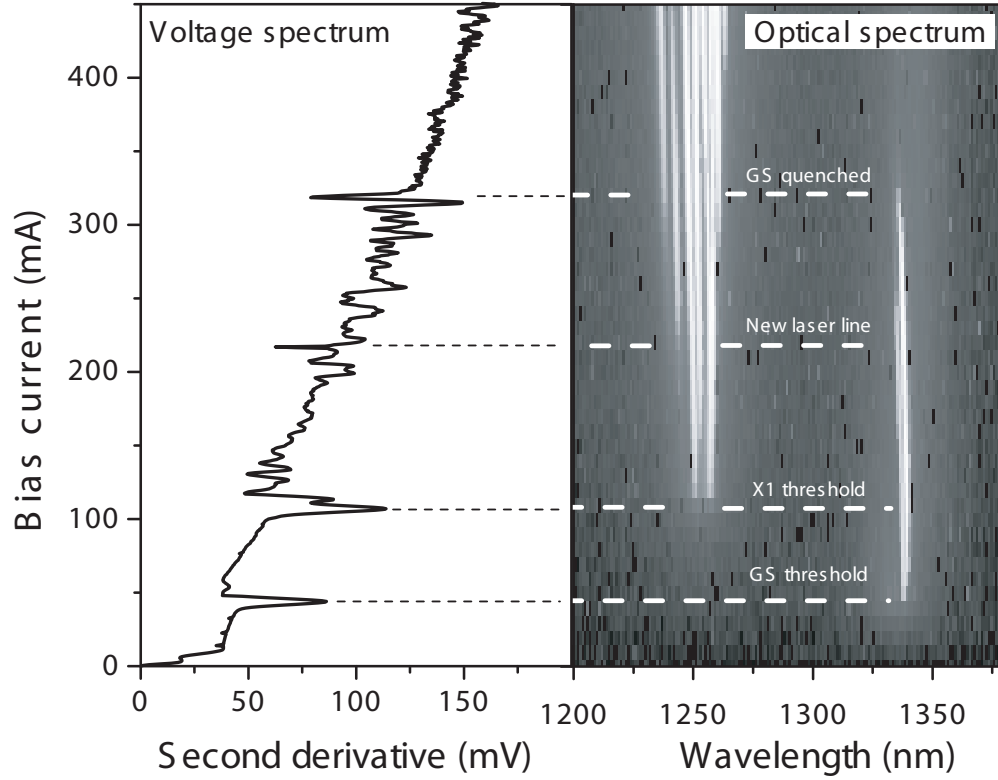


Figure 3.19: Correlated $-I^2 d^2V/dI^2$ measurement (left) and optical spectrum (right). It can be seen that the main peak features are aligned with changes in the optical spectrum.

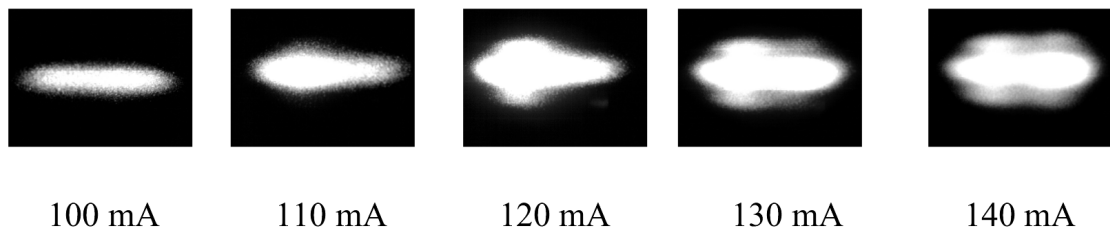


Figure 3.20: Filamentation observed around the dual-state lasing threshold for the same device as in Figure 3.19 by imaging the laser facet. Two higher-order modes appear, corresponding to the two peaks in the $-I^2 d^2V/dI^2$ and optical spectra.

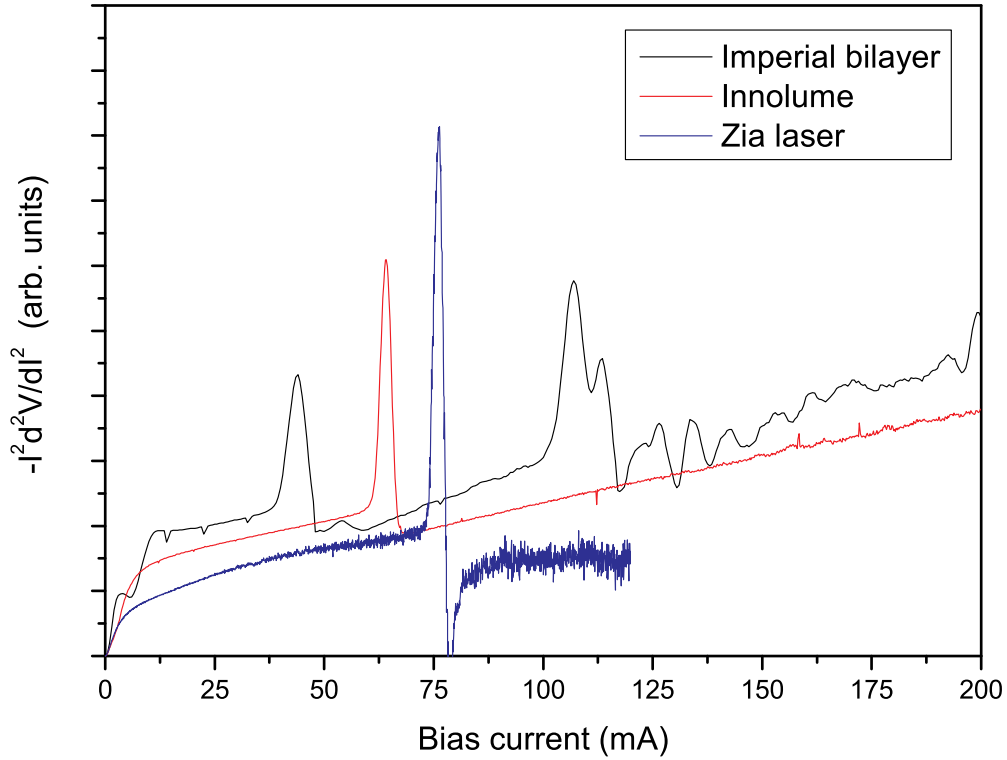


Figure 3.21: Figure comparing the $-I^2 d^2V/dI^2$ spectra of QD lasers from three different sources. The Innolume and Zia laser material was supplied courtesy of the EPSRC Ultrafast Photonics Collaboration. While these other devices have the same heterostructure dimensions, there are five repeats of single QD layers embedded in InGaAs QWs (DWELL) and they emit near 1290 nm.

filamentation). Developing an understanding of these mechanisms is important for designing lasers that, for example, operate on a single transverse mode.

Further study of this behaviour will now be divided between the effects of QDs on the diode junction and the consequences of the effects on laser oscillation.

Chapter 4

The quantum dot diode junction

4.1 Forward-bias photoconductance

In the previous chapter it was shown that derivative spectroscopy of the contact voltage shows some unexpected results when applied to QD lasers. In particular, it was found that instead of a constant $-I^2 d^2V/dI^2$ signal from the diode there was a linearly-rising signal. These results were obtained by modulating the electrically-injected current that biases the device and their origins and consequences are the topic of this chapter. Optical injection provides an alternative method of modulating the carrier density in the active region as an independent experimental check. An advantage of optical excitation is in the choice of wavelength. This can be resonant with the GaAs bulk or the QD material, offering the option of circumventing the series resistance and other effects operating within the device. The method is also simple, as shown in Figure 4.1 - mechanical chopping of a light source focused onto the facet of the laser under test (so as to align with its waveguide), with a lock-in amplifier measuring the contact voltage as means of detecting the response at the frequency of the chopper. This response is a photovoltage proportional to the differential resistance multiplied by the optically-injected current. The system is aligned by connecting the laser under test to the photocurrent input of the lock-in amplifier and maximising the signal. This alignment is double-checked by taking an IR detector card to verify that the emission from the laser under test is collected by the focusing lens. Care must be taken to avoid feedback into the laser cavities, a situation which can be identified by excessive noise in the measurement or fluctuations in the power output of either the injected laser or the laser under test.

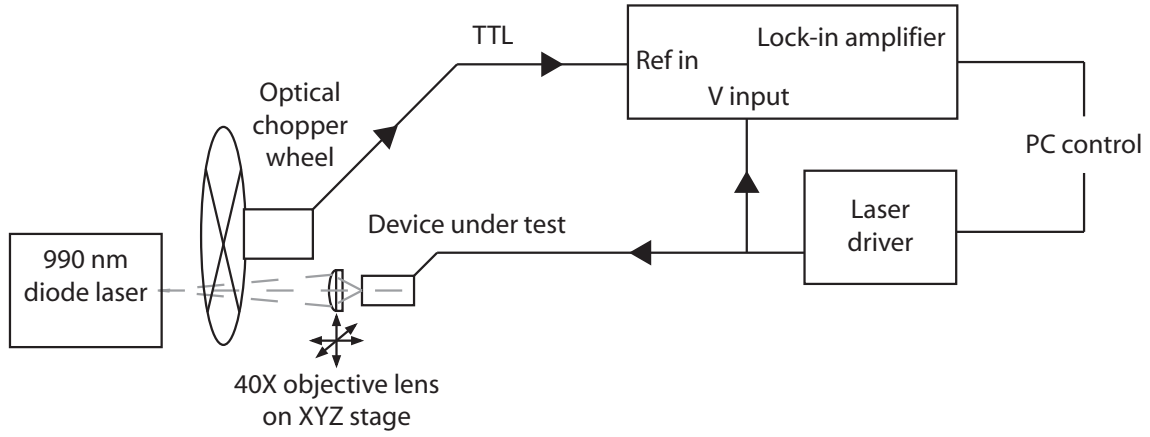


Figure 4.1: Experimental set-up for performing first derivative spectroscopy with optical injection. The 990 nm could be interchanged with a Helium-Neon laser, with emission at 632.8 nm.

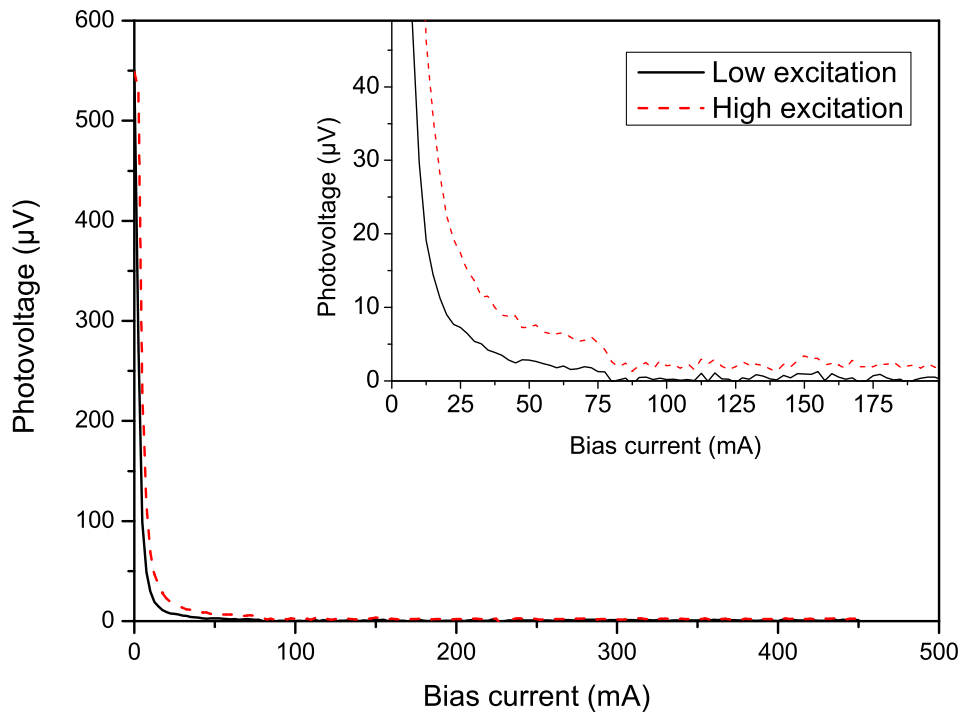


Figure 4.2: Photovoltage measurement on a MQW laser diode obtained at 10 °C. The response of the junction voltage is always positive and the effects of clamping are visible above the threshold.

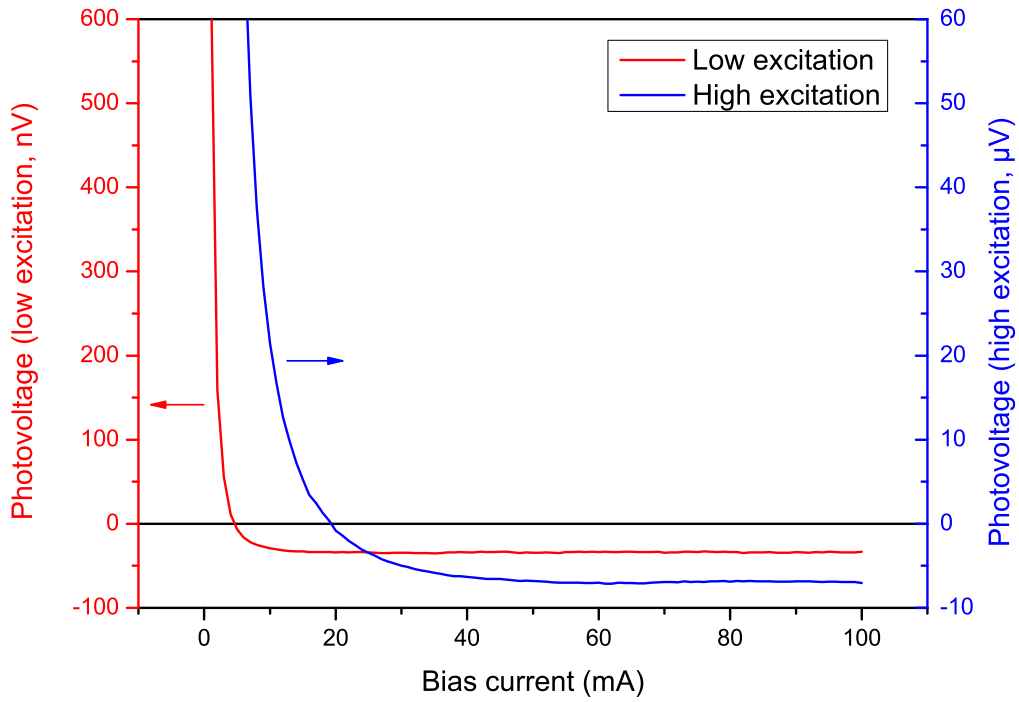


Figure 4.3: The photovoltage of a QD laser diode (Innolume DWELL), non-resonantly excited with a Helium-Neon source (632.8 nm), showing a change of sign and a variation of the zero-crossing with optical excitation power.

Initially a comparison of photo-voltage measurements on MQW and QD devices was made using a Helium-Neon laser (wavelength 632.8 nm). The results are shown in Figures 4.2 and 4.3 respectively. The MQW device behaves as expected; the photo-voltage is always positive because the quasi-Fermi level separation is always increased by absorption of the injected light increasing the carrier density at the junction. However the QD photovoltage shows an unexpected change of sign as the current increases, at a point that varies with the optical excitation level. This effect implies photoconductance - the light reduces the resistance of the device and therefore the contact voltage.

To investigate this further the 980 nm MQW laser was then used to resonantly excite the QD device. Figure 4.4 shows that a sign change is again visible but that the zero-crossing current is constant (at 8.6 mA) with respect to the power of the excitation. Some variation in this value was found depending on the relative position and orientation of the excitation source, with both source wavelengths. The presence of a power dependence that is suppressed by resonant-excitation may be due to the different penetration depths of the excitation sources (with the 980 nm light being waveguided but the 632.8 nm light being absorbed only near the surface of the facet) having different overlap with the electrically pumped area of the device.

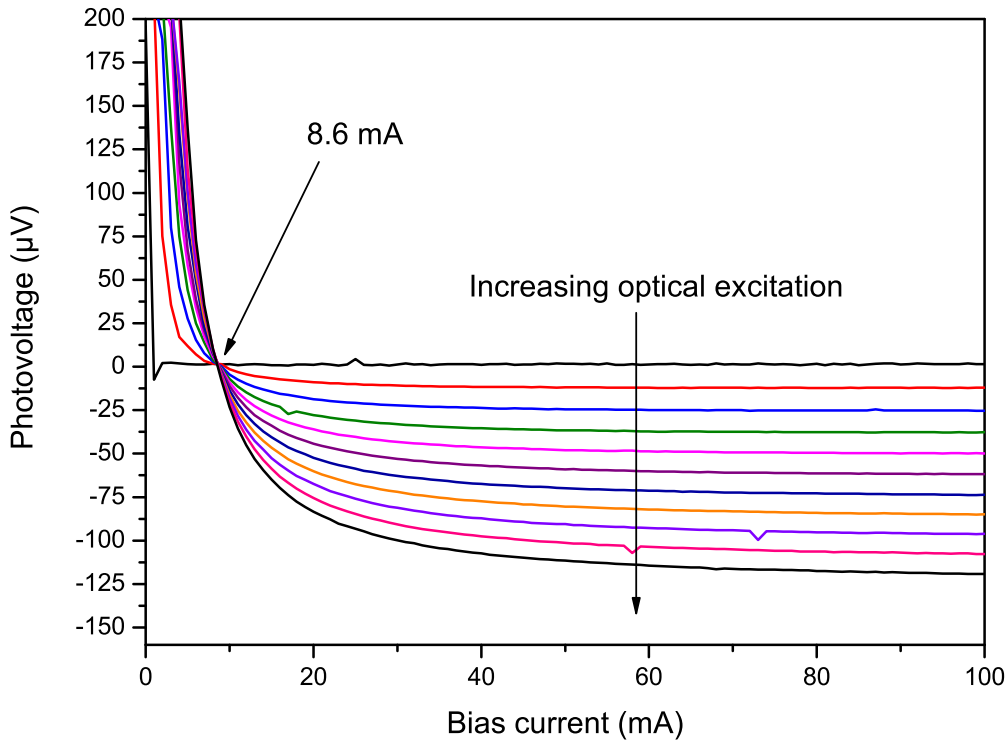


Figure 4.4: Measurement of photo-voltage on a QD laser diode (Innolume DWELL) with optical injection at 990 nm into the QD confined-states. The change in sign is suggested to be the predicted photo-conductance effect. The zero-crossing point shows no excitation power dependence.

Such behaviour has no obvious explanation within the conventional ideal diode approximation, which assumes a single potential barrier with carriers obeying Boltzmann statistics. The barrier for a QD diode is ideally the energy gap between the confined electrons and holes but they are occupying an ensemble of localised and inhomogeneously broadened states. This means that, unless there are processes coupling these confined states, a QD diode cannot be considered as having a single barrier. This together with their low density of states would also invalidate the use of Fermi-Dirac statistics (let alone the Boltzmann approximation) [51, 52]. Therefore, there is no *a priori* reason for the ideal diode approximation to apply to QDs.

However, considering that the volume of the GaAs host matrix is much greater than the InAs QD material, the carriers must diffuse through the bulk continuum before being captured into a confined-state. In QW lasers this diffusion of carriers can act as a bottleneck in some designs [53] (rather than the process of carrier capture into the QW itself). While the capture processes for QDs are not well-known it is reasonable to assume that there is a balance between the carrier density of the GaAs bulk and the occupation of the QD states. Therefore it is possible that the QD states are acting to lower the quasi-Fermi level of the GaAs bulk when they capture

carriers - like traps in a bulk/QW diode; leading to a decreasing junction voltage with increasing current as the dominant contribution to the carrier distribution changes from the GaAs matrix carrier density (high potential), to the occupation of the localised QD states (low potential). This is referred to hereafter as the “trapping” picture for QD-bulk carrier interaction.

The photoconductance then is explained to be because it would become increasingly “easier” to raise the current across the junction as the average energy of the carrier distribution is lowered by confined carriers, at least in the regime where the occupation probability of the QD states are low.

4.1.1 The linear $-I^2 d^2V/dI^2$ background

If this photoconductance effect were a result of the occupation-level of the QDs, rather than being caused by some other photo-sensitive region in the device, then a negative differential resistance of the same form should be detectable in the I-V characteristics of the diode. In the previous chapter it was seen that the QD devices exhibited linear $-I^2 d^2V/dI^2$ backgrounds. This section investigates the mathematical consequence of this background.

While for an ideal diode the $-I^2 d^2V/dI^2$ measurement should produce an approximately constant voltage, as expected by Equation 3.6, the expression can be modified by adding a coefficient ξ to describe the slope gradient to give Equation 4.1. Dividing the J^2 prefactor out of the expression and then integrating this twice with respect to current density gives Equation 4.4.

$$-J^2 \frac{d^2V}{dJ^2} \approx \frac{\eta k_B T}{e} + \xi J \quad (4.1)$$

$$\frac{d^2V}{dJ^2} \approx -\frac{\eta k_B T}{e J^2} - \frac{\xi}{J} \quad (4.2)$$

$$\frac{dV}{dJ} \approx \frac{\eta k_B T}{e J} - \xi \ln(J) + P \quad (4.3)$$

$$V(J) \approx \frac{\eta k_B T}{e} \ln\left(\frac{J}{J_S}\right) + \xi J [1 - \ln(J)] + P J \quad (4.4)$$

Unfortunately this involves a logarithm of a dimensioned quantity, which is physically unacceptable as is it a transcendental function. Therefore a mathematical transformation, Equation 4.5, is applied to give a dimensionally-sound empirical expression, Equation 4.6. Here ρ is the series resistivity (resistance times area) of the device, J_S is the saturation current (as before), η the ideality factor and $k_B T/e$ the “thermal voltage”. J_ξ is an arbitrary term to cancel the units for the logarithm, its physical identity being as a scaling factor for the current density passing into an average QD. For example, if J_ξ were related to the emission rate of the QD ensemble then $\ln(J/J_\xi)$ becomes an approximate measure of the average occupation of the QDs.

It should also be noted that $\xi \ln(1/J_\xi)$ is equivalent to an ohmic resistance offset and therefore difficult to separate from the series resistivity of the device.

$$\xi J [1 - \ln(J)] + PJ \equiv \rho J - \xi J \ln(J/J_\xi) \quad (4.5)$$

$$V(J) \approx \frac{\eta k_B T}{e} \ln(J/J_S) + \rho J - \xi J \ln(J/J_\xi) \quad (4.6)$$

Figure 4.5 shows a plot of the derivative of Equation 4.6 with respect to current, which suggests that the linear background observed by $-I^2 d^2 V/dI^2$ derivative spectroscopy is due to a current-dependent resistance with the same form observed in the photovoltage data, supporting the trapping interpretation and that the effect is due to the QDs, rather than some unknown device effect.

4.2 Temperature dependence of Quantum dots

To further test the trap-like picture, temperature studies were undertaken on the U27073 QD bilayer laser devices. A temperature study was chosen because techniques like deep-level transient spectroscopy (DLTS) use thermal activation to attempt to determine energy levels due to localised trap states that are well separated in energy from the conduction or valence band edges. Carrier escape from the QD states by thermal activation is widely believed to explain quenching of QD photoluminescence at high temperatures [54]. However, models proposed in the literature to describe QD carrier dynamics tend to pay little attention to intermediate temperatures (100 to 250 Kelvin) and there is disagreement over the mechanisms involved with opinion mainly split between phonon interactions [54] and Auger carrier scattering [55, 56].

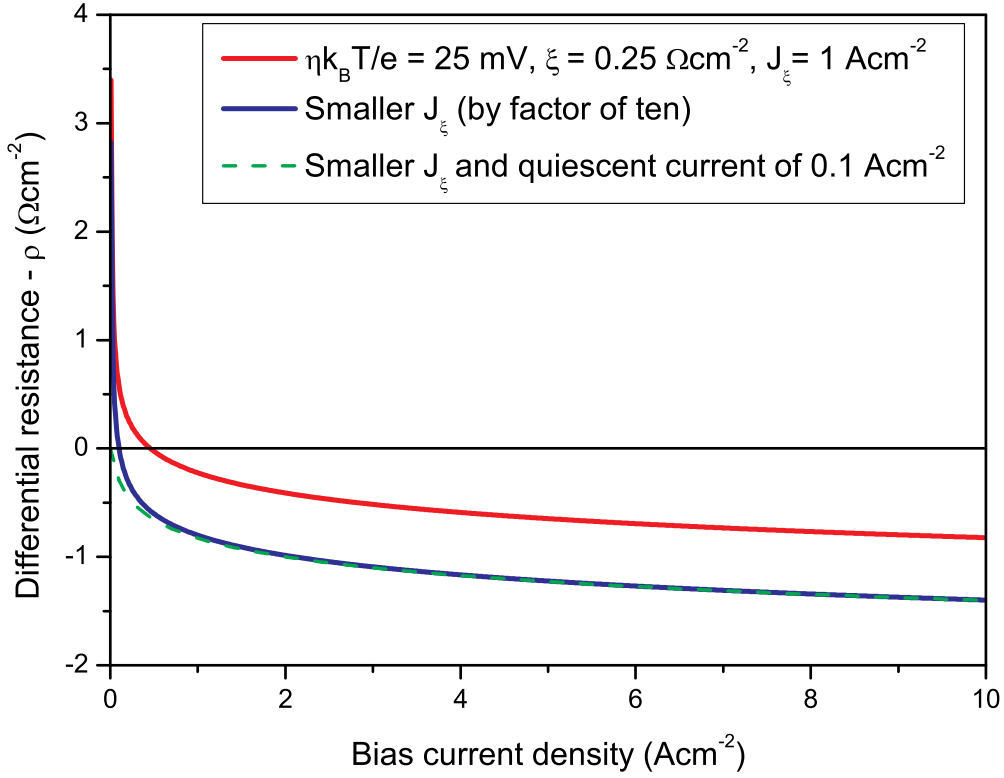


Figure 4.5: Plot of the derivative of Equation 4.6 with respect to current. A negative differential resistance at high forward bias is consistent with the photovoltage results that show a photoconductance effect.

4.2.1 Characterisation by derivative spectroscopy

To determine the characteristics of the QD diode junction, a QD bilayer laser diode sample was mounted in a cryostat and L-I-V (the current dependence of the light intensity and voltage for the device) and $-I^2 d^2 V / dI^2$ measurements performed over the temperature range 80 to 300 K.

To extract the diode intercept voltage and the gradient of the rising background, a linear fit was performed on each $-I^2 d^2 V / dI^2$ curve in a region before the lasing threshold. This region was chosen to be such that the current was sufficiently high to avoid switching-on effects while also low enough not to be affected by the peak at the laser threshold. Such a fit is shown by the dashed line in Figure 4.6. The $-I^2 d^2 V / dI^2$ curves were calibrated by several comparison measurements made on a Schottky diode (comparing its curve with an ideal diode fit to its IV curve) that was maintained at 15 °C. The dominant source of instrumental error was drifting of the relative phases of the reference and modulation signals, which contributed an absolute error of $\sim 0.7 \%$ during the course of the experiment.

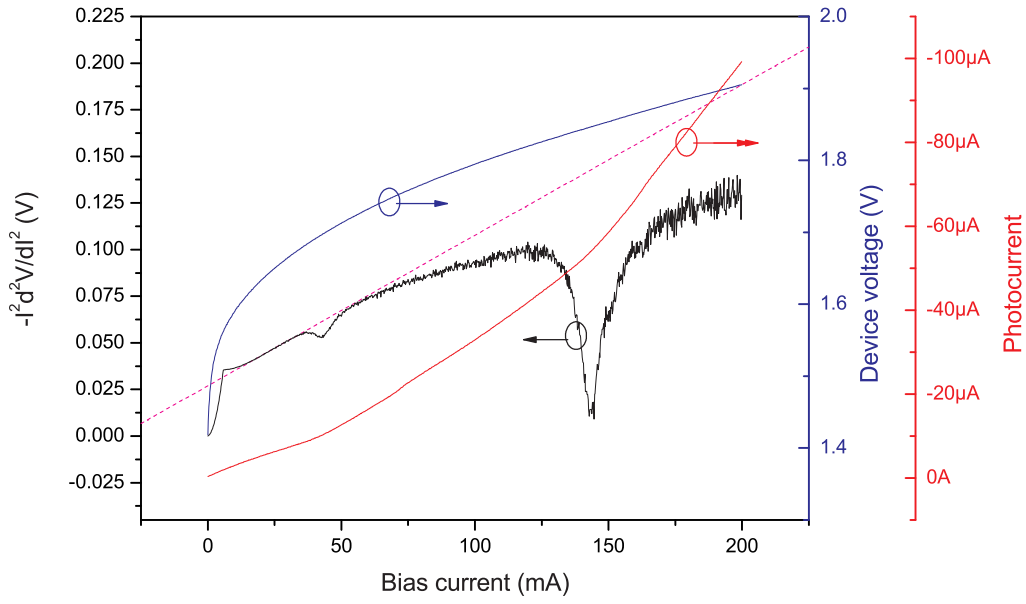


Figure 4.6: $-I^2 d^2V/dI^2$ and LIV results taken at 100 Kelvin from a device on the U27073 wafer. The dashed line shows the linear fit that was used to determine the intercept voltage and the gradient of the rising background.

The saturation current and ohmic resistance terms in Equation 4.6 were then estimated by fitting the expression to the measured I-V curve. The data was fitted between 0.2 and 20 mA to avoid the lasing threshold and also zero-bias because of the sensitivity to the saturation current at low current levels*. The expression used for the fit was Equation 4.7:

$$V(I) = \left[\frac{\eta k_B T}{e} \right] (\ln I - \{\ln A J_S\}) - \left[\frac{\xi}{A} \right] I \ln I + \left\{ \frac{\rho + \xi \ln A J_\xi}{A} \right\} I \quad (4.7)$$

The quantities in square brackets are the fixed parameters taken from the linear fit to the $-I^2 d^2V/dI^2$ data, the intercept voltage $\frac{\eta k_B T}{e}$ and the slope resistivity (resistance times area) $\frac{\xi}{A}$. A is the device area, with no correction for any current spreading that might occur. The quantities in curly brackets are the free parameters for fitting 4.7 to the I-V data. Their form was chosen so that their values are of the same order of magnitude which is important for the least-squares fitting algorithm to converge on an accurate fit. The first parameter, $\ln A J_S$, allows the saturation current density, which varies over more than thirty orders of magnitude, to be calculated. The second parameter includes both the series resistivity and

*Current sources require a quiescent current to always flow in order to operate correctly. This affects the accuracy of the instrumentation near zero-bias, as the actual current supplied to the device will never be *exactly* zero.

the J_η term that balances the dimensions of the linear background term from the $-I^2 d^2 V / dI^2$ data (see section 4.1.1).

4.2.2 Verification of the trapping picture

In Section 4.1.1 it was seen that the forward-bias photoconductance effect was due to the linear background of the $-I^2 d^2 V / dI^2$ spectra. The proposed mathematical model stated that the strength of this effect is directly proportional to the gradient of the background ξ and also introduced another parameter J_ξ as the result of a dimensional analysis. It was noted that the model predicted an ohmic-like $-\xi J \ln J_\xi$ term. By comparing the temperature study of ξ , Figure 4.7, with Figure 4.8, the estimated ohmic resistivity, it can be seen that the data supports the prediction of Equation 4.6 because the two plots show a roughly mirror image behaviour. The plot of the ohmic resistivity term also has a positive offset compared with $-\xi$, as expected because of the series resistivity of the device, ρ .

It was argued above that a trap-like behaviour of the QD confined-states is responsible for this negative term in the I-V characteristic. For this argument to hold it would be expected that as the temperature is lowered and carrier escape from the QDs becomes hindered, that ξ would therefore increase with some reciprocal dependence on temperature. Figure 4.7 shows that, below a point at $T_\alpha \simeq 140$ K, a reciprocal dependence on temperature is a good approximation[†] and this suggests some relationship between thermal energy and ξ . At T_α there is a minimum followed by a slight rise at higher temperatures, until a second peak near a point designated $T_\gamma \simeq 230$ K before falling again with further temperature rises towards room-temperature.

Trapping lifetime

If the trap-like effect is due to the QDs, J_ξ should, in principle, be directly proportional to the rate at which carriers leave the QDs; while J itself describes the capture of carriers and assumes this to be infinitely-fast and efficient. By making the approximation that the series resistivity varies slowly enough with temperature to be considered a constant this allows the “trapping lifetime”, τ_{trap} , to be estimated from

[†]Except for the three lowest temperature points of Device 3. This deviation will turn out to be consistent with the other measurements and is dealt with later.

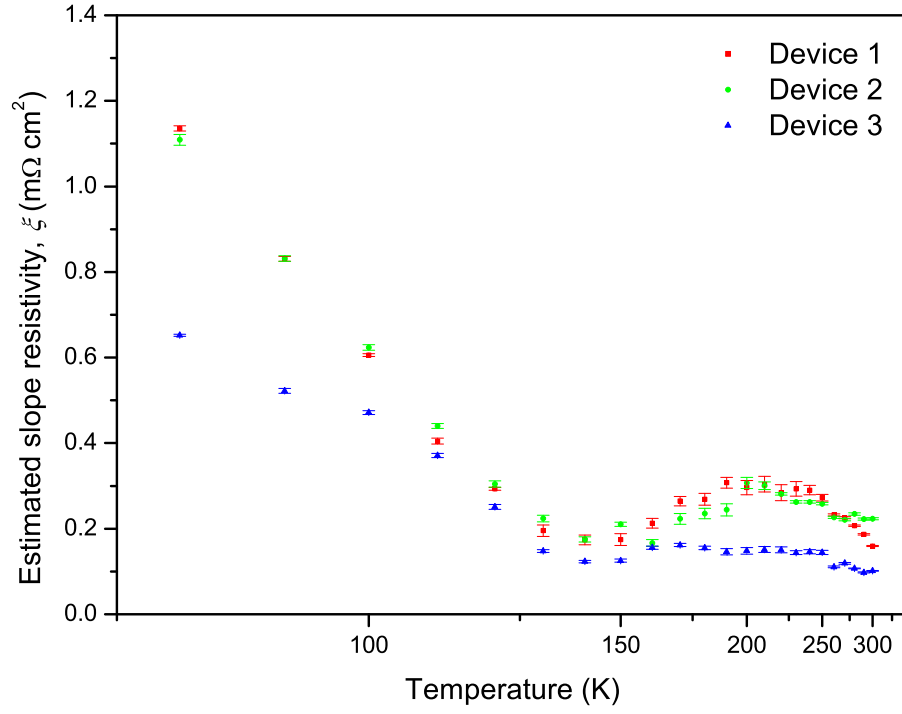


Figure 4.7: A temperature study of the linear $-I^2 d^2V/dI^2$ background's gradient for three lasers from the U27073 wafer. The reciprocal temperature scale was chosen to suggest a thermally-activated behaviour at low temperature (see text).

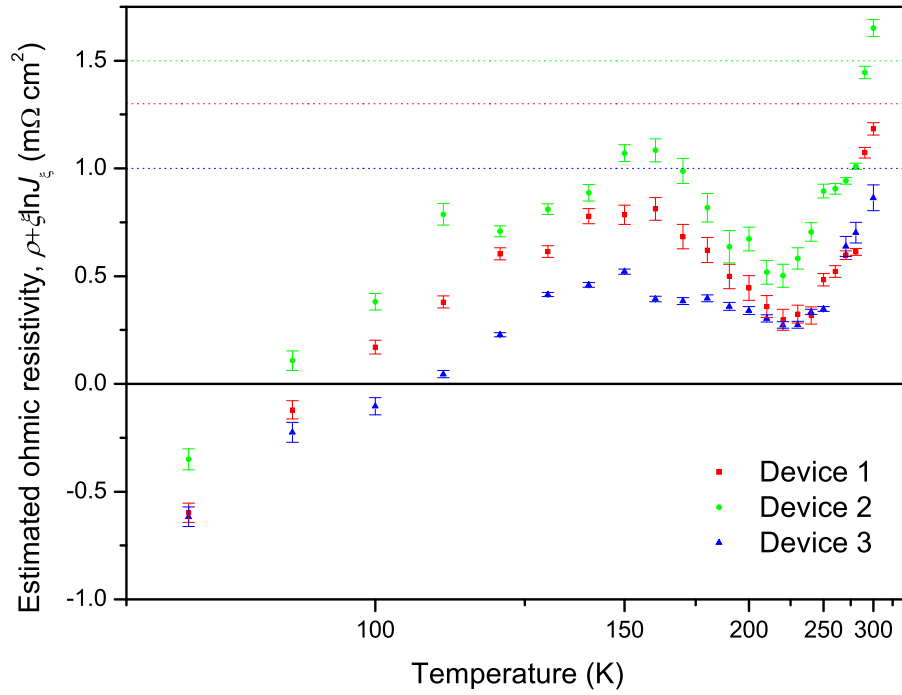


Figure 4.8: A temperature study of the estimated ohmic resistance of the three lasers. The mirror-image behaviour compared with Figure 4.7 supports the proposed empirical diode approximation. The dotted lines show the estimated ohmic resistivity (resistance times area) for each device.

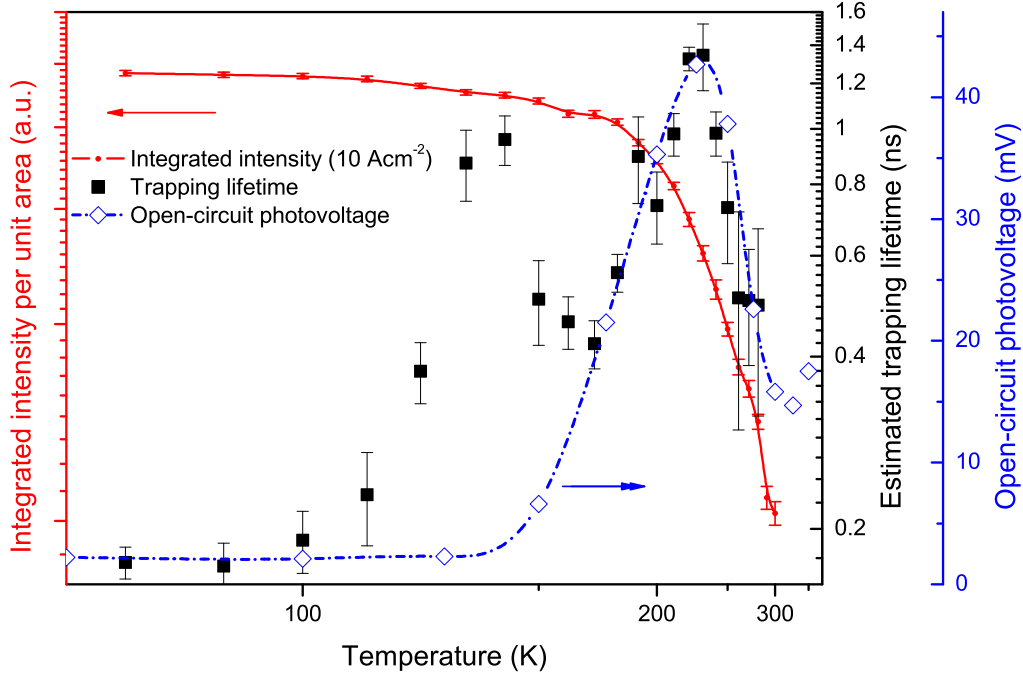


Figure 4.9: Comparison of the estimated trapping lifetime with the integrated ASE intensity and open-circuit photovoltage versus temperature. Note that there are two peaks in the lifetime, with the second peak at T_γ correlating with the photovoltage and the quenching of the ASE intensity.

the distortion of the mirror-image of ξ . Making the assumption that J_ξ is the number of charge carriers per unit time that the QDs dissipate (radiatively or otherwise) the expression becomes a function of the density of QDs in a layer ($\rho_a = 2.5 \times 10^{10} \text{ cm}^{-2}$), the number of layers ($N = 3$), the carrier charge ($e = 1.6 \times 10^{-19} \text{ C}$), the capacity of the ground-state for both electrons and holes ($g_{gs} = 4$), the series resistance times area (ρ) and τ_{trap} as shown in Equation 4.8.

$$J_\xi = \frac{g_{gs} e N \rho_a}{\tau_{\text{trap}}} = \frac{1}{A} \exp \left(\frac{\{\rho + \xi \ln A J_\xi\} - \rho}{\xi} \right) \quad (4.8)$$

$$\tau_{\text{trap}} = g_{gs} e N A \rho_a \exp \left(\frac{\rho - \{\rho + \xi \ln A J_\xi\}}{\xi} \right) \quad (4.9)$$

This can be re-arranged to estimate the trapping lifetime, giving Equation 4.9. This expression assumes that τ_{trap} is equivalent to the carrier lifetime, which is also known as the luminescence decay lifetime and is the reciprocal sum of the radiative and non-radiative recombination lifetimes of the material [43]. Figure 4.9 shows the results of this analysis, with the assumption of a temperature-independent ρ (the values used

are indicated by the dotted lines on Figure 4.8), giving trapping lifetimes in the range 100 ps to 1.4 ns. This is consistent with the values quoted in the literature, which are of the order of 100's of picoseconds to nanoseconds [57, 58, 59].

The assumption of a temperature-independent series resistivity, ρ , is clearly flawed. The actual resistivity here depends on the electrical characteristics of the wiring, contacts, heterostructure interfaces, etc. The resistivity of the bulk semiconductor will depend on the quality of the crystal, the carrier concentrations and their mobilities. Although these can be estimated, it is enough for this analysis to assume that they are not rapidly-varying with temperature. This means that the error introduced by the assumption of a constant resistivity will distort the overall shape of the estimated lifetime data, rather than creating spurious features. This error could be reduced by comparing this data with optical measurements of the QD ground-state luminescence lifetime, as the two should ideally be identical. The comparison with the optical and lasing properties of the devices will be the topic of the next chapter.

The trapping lifetime data is plotted alongside the open-circuit photovoltage generated from a mechanically-chopped Helium-Neon laser beam incident on the laser facet and the integrated intensity of the amplified spontaneous emission (ASE) as measured by a Germanium photodiode with the laser biased at a current density of 10 A cm^{-2} . The lifetime and intensity traces are the average of the three device results. The trapping lifetime shows two peaks, one at T_α and the other at T_γ . The T_γ peak is closely correlated with the peak in the photovoltage data and also with the quenching of the ASE with increasing temperature. The T_α peak is not present in the photovoltage data and appears not to have any effect on the ASE, which undergoes a slight decrease with increasing temperature before it starts reducing significantly above $T_\beta \simeq 190 \text{ K}$, near the local minimum in the lifetime data.

Many studies have linked the temperature dependence of the photoluminescence of QD ensembles to the spreading of confined carriers into higher excited-states with increasing temperature [58]. Ultimately the photoluminescence efficiency is believed to be limited by the complete escape of carriers from the QD, followed by non-radiative recombination in the bulk [54] or Auger recombination [60]. The sudden drop in both the trapping lifetime and the ASE intensity shows that carriers are lost to non-radiative recombination channels. The preceding rise in the photovoltage shows that as the temperature rises to T_γ carrier pairs are escaping from the QDs and increasing the carrier densities in the GaAs bulk matrix of the intrinsic region.

That the carriers are escaping in pairs is necessary for the photovoltage to drive an electrical current around the external circuit.

The temperature dependence of the QD ground-state radiative lifetime is predicted to be dominated by thermal activation of the carriers to higher excited states. This causes the lifetime to increase with temperature as the carriers spend less time in the ground-state. The large energy spacing of the confined energy levels means this effect has a smaller influence on the lifetime in QDs when compared to QW material. Therefore, it is expected that the radiative lifetime will increase before escape is possible, followed by a drop as the temperature becomes sufficient that carriers escaping from the QD potential becomes a significant loss mechanism. This explains the excellent overlap between the logarithm of the trapping lifetime and the photovoltage: The occupation of the bulk states compared to the QD confined-states is, approximately speaking, a balance of the rates of capture and escape from the confined-states. Therefore taking the zero-bias photovoltage to be a measure of the bulk population of the intrinsic region, it should be expected to have a direct proportionality with the escape rate. The logarithm then arises because of the exponential dependence between quasi-Fermi level and carrier density.

The initial peak in the trapping lifetime at T_α is associated with a 25% reduction in the integrated ASE intensity and also with the initial onset of the photovoltage peak. This peak has the same form as the peak at T_γ and suggests that thermal spreading of carriers over excited-states followed by carrier escape is also happening here. However, as there is no correlated feature in the photovoltage measurements this is consistent with non-geminate escape. Assuming a band offset of 2.5:1, the hole energy-level spacing will be ~ 17 meV making holes the more likely candidate for escape by thermal activation than the electrons which have a level spacing of ~ 43 meV. Non-geminate escape of holes would also limit the non-radiative mechanisms to monomolecular recombination alone. This explains the relatively small change in the ASE intensity measured in this temperature range.

Therefore, measurements of the $-I^2 d^2V/dI^2$ linear background compared with the ohmic resistivity of the QD bilayer lasers provide data in support of the trap-like behaviour of the confined-states and allow an estimation of the carrier lifetime associated with the trapping behaviour, the “trapping lifetime”. Two separate mechanisms appear to contribute to carrier escape: geminate escape of the electrons and holes to the bulk material at $T_\gamma = 225$ K, followed by non-radiative recombination quenching the optical emission from the QDs and non-geminate escape of holes to the bulk at $T_\alpha = 140$ K.

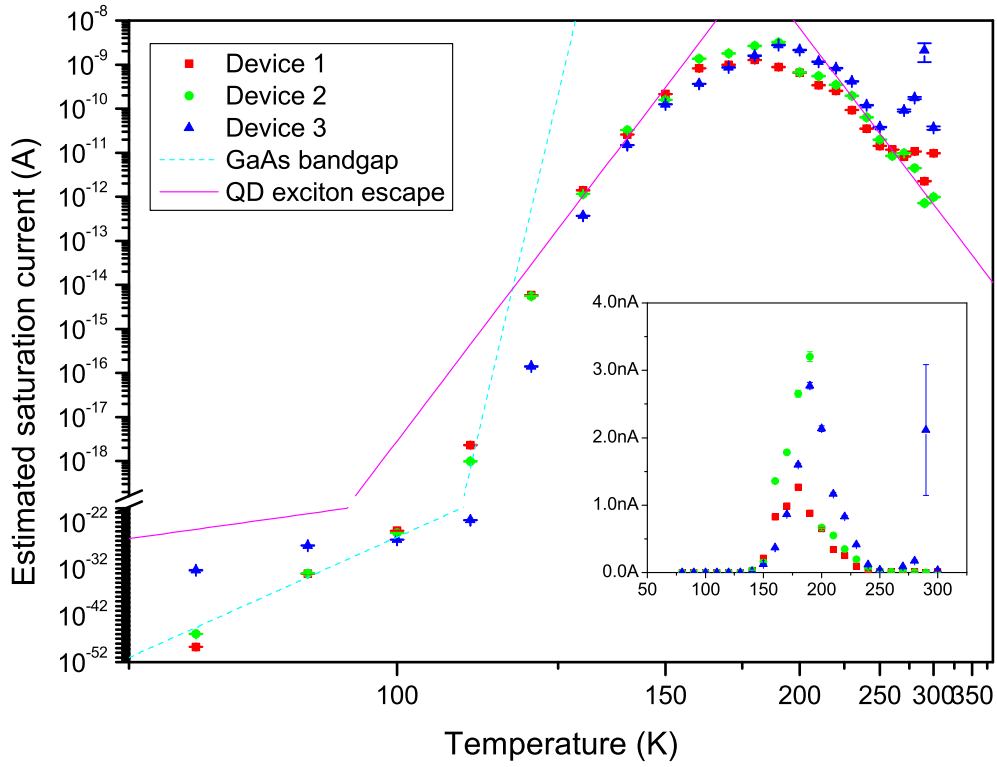


Figure 4.10: A temperature study of the saturation current density vs. temperature for three lasers from the U27073 wafer. The zero-bias voltage was compared with the intercept voltage of the $-I^2 d^2 V / dI^2$ spectra to derive this. The inset shows that the current is small except between T_α and T_γ , peaking at T_β . The main graph is an Arrhenius plot showing that outside of T_α and T_β the temperature dependence can be attributed to thermal activation of the GaAs bulk and geminate escape from the QD.

4.2.3 Carrier escape

The previous sections identified and investigated the departure of a QD bilayer diode from the ideal approximation. As the deviation involves extra terms to the ideal approximation, the remainder of this chapter investigates the temperature dependence of the ideal diode parameters of the QD device.

The saturation current density, J_S , is the first parameter of the ideal diode approximation (3.1) and it is the dominant factor in the switch-on voltage of the diode. It describes the current due to thermal generation of minority carriers that escape from the intrinsic region into the side of the junction where they become majority carriers (at thermal equilibrium) and is also equal to an ideal (i.e. no defects) diode's reverse bias current density [41]. It is of interest because any generation or recombination of carriers within the intrinsic region will affect the diode's saturation current density. Therefore the saturation current density provides another indirect measure

of the interaction between QD confined-states and the bulk. Its importance in the I-V characteristic of the diode comes about because at zero external bias it must be balanced by opposing diffusion currents from the cladding regions. This means that for the double-heterostructure junction used in the devices tested here, holes generated in the intrinsic region that escape to the p-type cladding are balanced by a current from that cladding (while electrons are balanced by the n-type cladding). This description is valid under the conditions of thermal equilibrium with no external bias and because of this it is sensitive to non-geminate escape: if only the holes are escaping the intrinsic they must be balanced with a hole diffusion current while the electrons do not - resulting in a measurable effect on the saturation current.

Figure 4.10 shows the results of estimating the saturation current density from the $-I^2 d^2V/dI^2$ spectra and a fit to the I-V curve (as described above), plotted as an Arrhenius plot. An Arrhenius plot assumes a dependence of the form given in (4.10). Here A is the experimental value, A_0 its limiting value, E_A the activation energy, k_B the Boltzmann constant and T the temperature.

$$A = A_0 \exp\left(\frac{-E_A}{k_B T}\right) \quad (4.10)$$

Thus when the data is plotted on a reciprocal-log plot the gradient of a straight line is proportional to $-E_A/k_B$. Such linear relations arise when a thermally-activated process occurs. Below T_α the saturation current appears to be limited by thermionic emission in the GaAs and then at T_α switching to thermionic emission from the QD ground-state (the line plotted has an activation energy of 450 meV). This cannot easily be attributed to a particular region or process but is indicative that carrier escape is suppressed below T_α . The saturation current then peaks between T_α and T_γ , at T_β (inset in Figure 4.10), suggesting that some form of carrier escape is occurring. However, the quenching of the saturation current coincides with the rise of the photovoltage and the onset of quenching of the luminescence. This is consistent with non-geminate escape because the rise in the photovoltage is associated with geminate escape and that would allow band-to-band radiative recombination in the GaAs to occur, reducing the rate of carrier escape from the intrinsic region and suppressing the saturation current, as observed. The activation energy of the quenching process is of the order of $\sim 400 - 500$ meV, consistent with geminate escape from the QD. A possible alternative, that carrier escape from the seed layer QDs is responsible cannot explain why an effect is observed in both the lifetime and saturation current data but not in the photovoltage data.

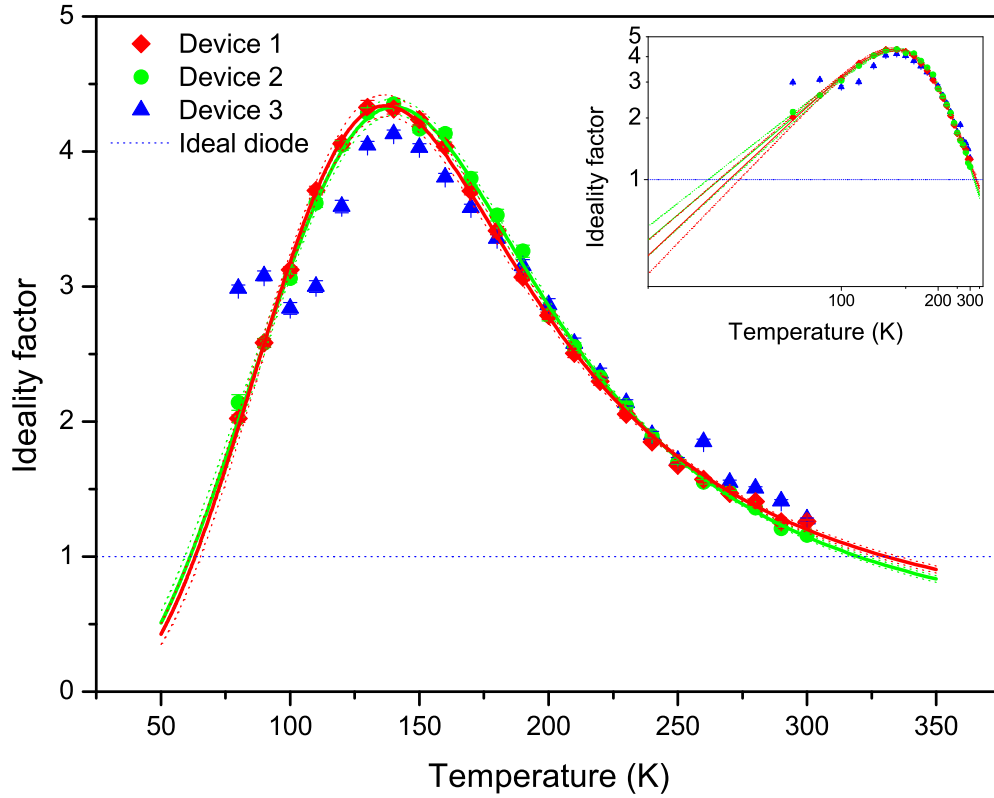


Figure 4.11: A temperature study of the ideality factor vs. temperature for three lasers from the U27073 wafer. The ideality factor is well described by a parallel combination of two thermally-activated processes, peaking at T_α . The rise energy is 16.6 ± 0.3 meV and the fall energy is 60.5 ± 0.7 meV (a direct fit to the fall gives 44.7 ± 1.3 meV). The inset shows an Arrhenius plot of the same data for comparison.

Therefore, the saturation current data is qualitatively consistent with the interpretation that at temperatures below T_α no escape occurs, non-geminate escape occurs at temperatures between T_α and T_γ until geminate escape becomes dominant above T_γ .

4.2.4 Ideality of the diode

The second parameter of the ideal diode approximation is the ideality factor and it relates to the carrier distribution in the junction. For non-degenerate semiconductors η is unity for Shockley band-to-band (e.g. radiative) recombination or two for Hall recombination (i.e. via a defect or impurity state within the band-gap). When the occupancy of states becomes important in a diode junction, the diode is said to be degenerate [41] and the signature of this is often found in the ideality factor which rises to values of 3 or greater [42]. To study this, the intercept of the straight-line

fit to the $-I^2 d^2 V / dI^2$ spectra was divided by the thermal voltage $k_B T / e$ to obtain the ideality factor, η . As defects and impurities are undesirable, high quality diodes should have a unity value of η . The influence of the ideality factor on the junction voltage can be seen in Equation 4.11, taken from the ideal diode approximation (3.2):

$$V_{\text{junction}} \propto \eta \ln \left(\frac{J}{J_S} \right) \quad (4.11)$$

However, the non-degenerate approximation holds only when considering an energy band where the quasi-Fermi level is far enough away that the occupancy of any of the states can be considered to be negligible. This approximation is then useful because it allows the mathematically more simple Boltzmann distribution to be used to describe the states, rather than Fermi-Dirac statistics. For isolated QD states (especially the ground-state where the presence of even one carrier corresponds to 50% occupancy) this approximation is clearly not valid and one might therefore expect a high ideality factor.

Figure 4.11 shows the results of the temperature study of the ideality factor which is well described by a parallel combination of two thermally-activated processes, peaking at T_α . The rise energy is 16.6 ± 0.3 meV and the fall energy is 60.5 ± 0.7 meV, the fit equation being given by (4.12) (a direct fit to the falling slope gives 44.7 ± 1.3 meV).

$$\eta^{-1} = A_{\text{rise}}^{-1} \exp \left(\frac{E_{A,\text{rise}}}{T} \right) + A_{\text{fall}}^{-1} \exp \left(\frac{-E_{A,\text{fall}}}{T} \right) \quad (4.12)$$

The activation energies that describe the rise and fall of the ideality factor are close to those of the expected hole-level spacing, 17 meV and the observed GS-to-X1 splitting of 60 meV, assuming a conduction to valence band offset of 2.5:1 [27, 61, 54]. The fit to the data predicts that the ideality factor will become less than unity at temperatures below about 60 K and above 330 K, although the data is insufficient to verify this.

Below T_α , the hole-spacing activated behaviour suggests that the holes are being excited to higher confined states. This is expected from the trapping lifetime measurements presented earlier and also from lifetime measurements on single-layer QDs in this temperature range [58]. At the same time, photovoltage and saturation current measurements show that carrier escape is not significant below T_α . The hole

quasi-Fermi level will be significantly altered by thermal spreading: The difference in energy between the confined-states is large compared to those in the bulk matrix and therefore even a small number of carriers being thermally-activated will have a large influence[‡].

Holes that have been activated to higher confined states are less able to recombine with ground-state electrons because their band-to-band optical transitions are forbidden by the selection rules [62]. The microstates with thermally-activated holes are designated as “dark” states because of their reduced probability of radiative recombination. The presence of dark states will therefore increase the hole quasi-Fermi level and reduce the diode junction current - leading to an increase of the ideality factor (compare with Equation 4.11).

Above T_α , electrons are able to spread to their higher confined states. They then are able to coincide with the thermally-activated holes in pairings that allow radiative recombination from the higher excited-states (i.e. $X1 = e1-h1$, $X2 = e2-h2$, etc.). This reduces the ratio of dark states to exciton-like “light” states and therefore causes a decrease in the ideality factor.

4.3 Conclusions

This chapter investigated the effects of QD confinement on the diode junction. It was found that, despite the I-V curves of the QD diodes outwardly appearing to follow the ideal diode approximation, the confinement introduces significant effects. In particular, measurements of photovoltage in forward-bias revealed that the QD diode junction exhibits negative differential resistance (NDR) and that this is the origin of the linearly-rising background in the $-I^2 d^2V/dI^2$ spectra. This behaviour was attributed to the QD confinement acting as traps for the electrons and holes. Further investigations of this effect by way of a temperature study were able to provide both supporting evidence for the trapping picture and also estimate the QD trapping lifetime. This was tentatively associated with the luminescence lifetime, a quantity that can be measured directly and will be the subject of investigation in the next chapter. Analysis of the trapping lifetime and comparison with photovoltage and L-I data provided evidence for non-geminate escape of holes at $T_\alpha = 140$ K and

[‡]This is consistent with the minimum in the value of ξ at T_α because if carriers are “trapped” in higher confined-states, then the effect on the quasi-Fermi level spacing from carriers captured into the QDs will be smaller.

geminate escape at $T_\gamma = 225$ K. Measurements of the ideality factor found that hole spreading near T_α appears to be associated with the formation of dark states, whose radiative recombination is forbidden by the selection rules of the QD.

This work extends the application of $-I^2 d^2 V / dI^2$ spectroscopy to QD diodes and shows that they obey a modified ideal diode approximation. As well as providing a greater understanding of how the QD ensemble couples to the diode, this is useful for the reliability testing of QD lasers because it allows the series resistance of the devices to be more accurately determined than from the I-V curve alone. The next chapter will now proceed to investigating how the optical properties of the QD bilayer laser are influenced by these effects.

Chapter 5

Carrier transport and confinement

The previous chapter discussed how the confinement in QDs influenced the electrical properties of p-i-n diodes. Firstly it was found that, the interaction between the carriers in the bulk and the those in the QDs led to a reduction in junction voltage with increasing forward-bias current, a behaviour that is the opposite to that expected for a “normal” bulk/QW diode. Measuring this effect allowed an estimate of the QD “trapping” lifetime to be made from the I-V characteristics. Secondly, holes spreading to dark states (near $T_\alpha \sim 140$ K) and then escaping as the temperature is increased was found to be the driving factor behind the diode parameters.

In this chapter these effects will be verified by comparing the trapping lifetime that was estimated from the I-V measurements with time-resolved PL (TRPL) of the QD GS. Then the behaviour of the GS and X1 lasing thresholds will be examined and discussed in terms of the QD confinement and the presence of dark states. The chapter will then conclude with an investigation into how drift-diffusion carrier transport in a laser is modified by the presence of the QDs.

5.1 Time-resolved photoluminescence

In the previous chapter, the assumption was made that the trapping lifetime (derived from the I-V characteristics) should be equivalent to the luminescence decay lifetime of the QD ground-state. The luminescence lifetime differs from the *radiative* lifetime of an optical transition and is instead often referred to as the carrier lifetime

because it describes the rate at which excitons recombine or escape *by any means*, radiative or otherwise. By this definition the luminescence lifetime is simply the time-constant of the decaying emission, assuming this follows a single exponential decay. It is therefore possible to directly measure the luminescence lifetime by an optical method called time-correlated photon counting (TCPC). In this technique an Ti:Sapphire ultrafast pulsed laser, emitting 3 ps pulses (measured by autocorrelation) at a wavelength of ~ 790 nm, is used to generate electron-hole pairs (excitons) in the sample; the decay time of the resulting photoluminescence signal from the ground-state is then a measure of the QD exciton lifetime. A fast photon-counting detector, in this case a micro-channel plate photomultiplier with an S-1 photocathode, is used to detect the PL signal after it has been dispersed through a Spex 1404 double-monochromator to provide wavelength selectivity. A double-monochromator is chosen because the second stage rejects any scattered light from the first stage, which is important to avoid unwanted cross-talk between the intense excitation pulse and the weaker PL emission. The scattered light is caused by dust, imperfections in the optical surfaces (the mirrors and diffraction gratings) or fresnel reflections from the lenses in the monochromator's spatial filter. A long-pass optical filter was placed before the monochromator entrance, with a nominal cut-off of ~ 800 nm, to further reduce the amount of cross-talk from the laser pulse. As long as the chance of detecting a photon following a single laser pulse is significantly less than unity, the time delays between the detected photons and the laser pulse train can be recorded into a histogram that is proportional to the time-resolved PL signal.

The detected signal will be convolved with the system response, which covers the cumulative effects due to the duration of the laser pulse, dispersion through the optics and the temporal characteristics of the detector. Therefore the detected signal must be carefully compared with the measured response of the system to incident laser pulses. The system response is measured by selecting the central wavelength of the laser emission and recording the detected signal. It is important to attenuate the signal to avoid damaging the detector; this was done by placing a folded lens-tissue in the beam path as this does not introduce any refractive element (as is the case for neutral density filters) that would change the optical path. This is important because the measurement of the system response must be made under conditions as close as possible to those used for the PL measurement, including both the geometry and detected signal strength, so that its measurement is subject to the same distortions as the PL signal. The system response is shown in Figure 5.1.

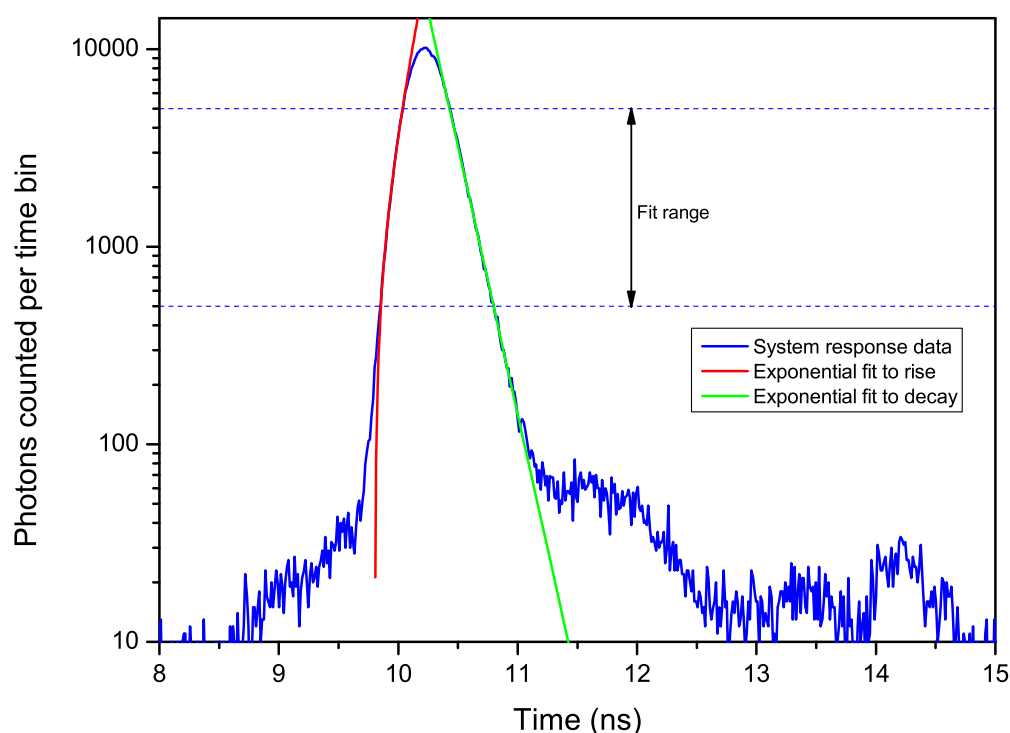


Figure 5.1: The system response of the TCPC equipment. A clean pulse is clearly distinguishable over roughly two orders of magnitude. The decay is a pure exponential with a time constant of 160 ± 2 ps while the rise has the form of a negative offset exponential growth with a time constant of 138 ± 7 ps.

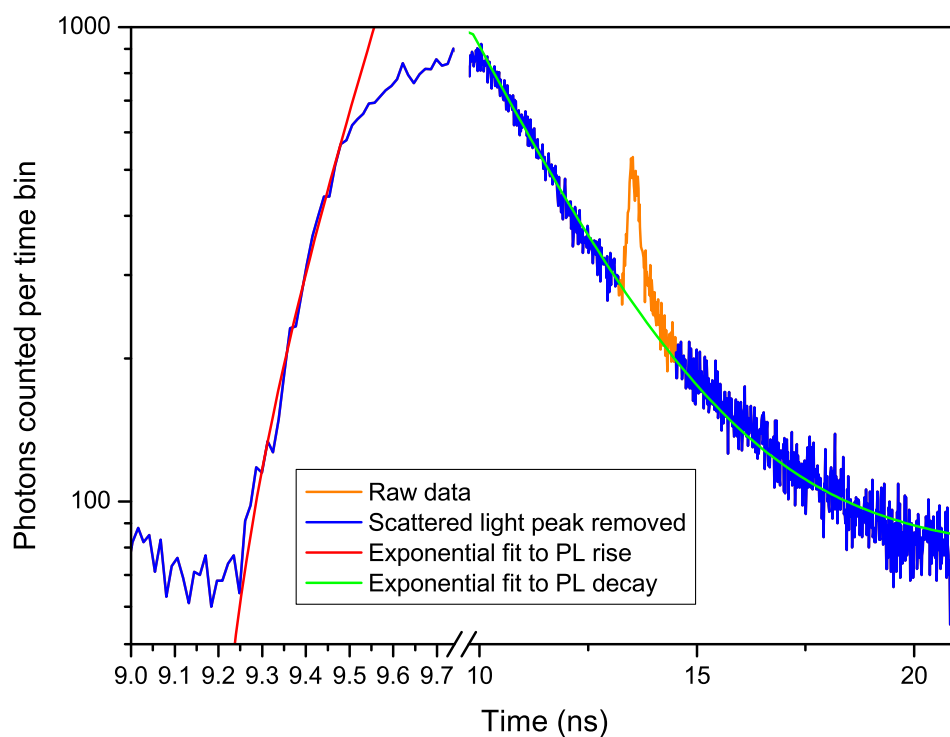


Figure 5.2: A representative TCPC PL trace from the U28038 laser sample. The secondary peak due to scattered light has been neglected, while single-exponential fits have been made to the rise and fall of the data.

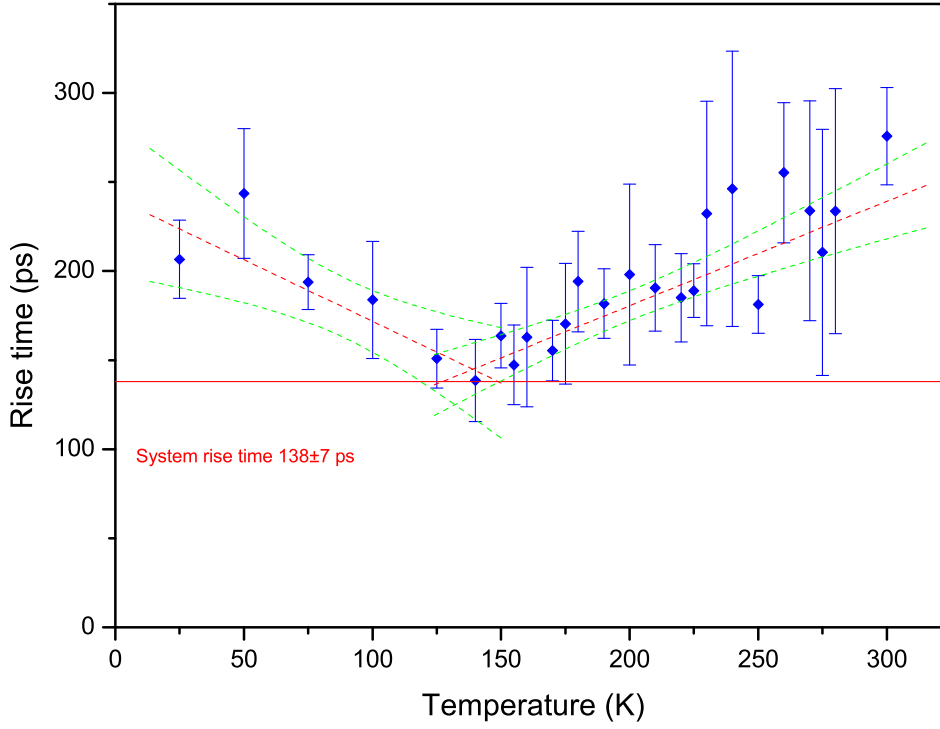


Figure 5.3: The PL rise time constants of the ground-state emission from U28038 plotted against temperature. Note the minimum in the region around T_α . The dashed lines show linear fits to the data on either side of the minimum together with the prediction bands for one standard error.

The S-1 photocathode used is quoted to have a nominal long-wavelength cut-off at 1200 nm. Although the response decays exponentially beyond 1000 nm measurements out to 1500 nm are still possible, albeit at greatly reduced sensitivity. As the wavelengths of interest were around 1340 nm (at room-temperature), a long-pass optical filter was used (with a cut-off at approximately 800 nm) to reduce the effect of scattered light within the system. Even with this filter the data tended to include a secondary peak due to scattered light, as can be seen on Figure 5.2.

Time-correlated PL data was obtained from a laser sample processed from the U28038 wafer (this was a five-repeat version of U27073) for a range of temperatures from 25 to 300 K. The fitted rise and decay time constants are shown in Figures 5.3 and 5.4, respectively. It can be seen that there is a minimum in the measured PL rise time around T_α (~ 140 K). The decay time (the luminescence lifetime) shows a weak dependence on temperature up to 160 K (as would be expected for ideal QDs) before rising sharply to a peak at T_γ (~ 225 K). This is in agreement regarding thermal spreading over excited states causing an increase in the carrier lifetime up to T_γ , above which geminate carrier escape reduces the lifetime. However it is also clear that the trapping lifetime and the luminescence lifetime are not wholly equivalent as the luminescence lifetime shows no feature at T_α . However the PL rise time shows

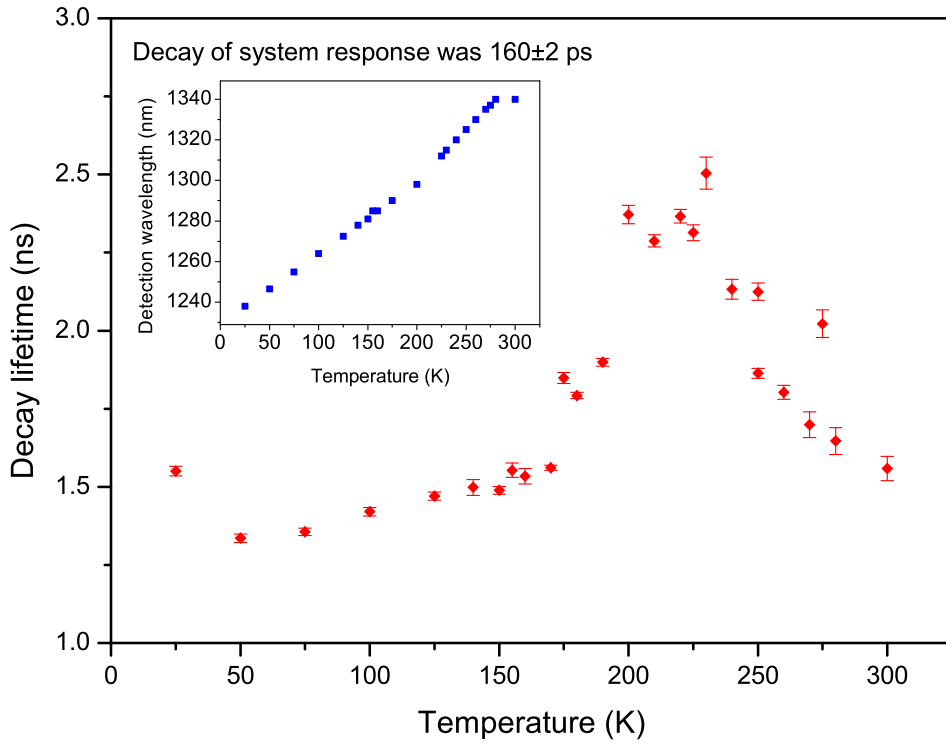


Figure 5.4: The PL decay time constants of the ground-state emission from U28038 plotted against temperature. Note the absence of any peak at T_α observed in the electronic lifetime discussed in the previous chapter.

a minimum that correlates with T_α . As the PL rise time is describing the “filling” of the QD confined-states, in the same sense that the luminescence lifetime is describing the emptying of the states, then it is appropriate to consider the inverse of the PL rise time against the luminescence and trapping lifetimes (Figure 5.5). The peak in the trapping lifetime at T_α is also present in the PL rise rate. Therefore the optical measurements of the QD GS luminescence do agree with the trapping lifetime that was derived from the I-V characteristic but the origin and role of the PL rise will now be investigated further.

5.1.1 PL rise time

In the last section it was shown that there is a peak in the PL rise rate at a temperature T_α that, according to the results presented in the previous chapter, correlates with the presence of dark states due to the holes being scattered to higher confined-states in the QDs. A temperature dependence of the PL rise time is unexpected; previous studies have recorded times on the order of 1-10 ps, attributed to multi-phonon relaxation at low carrier densities and Auger carrier-carrier scattering at

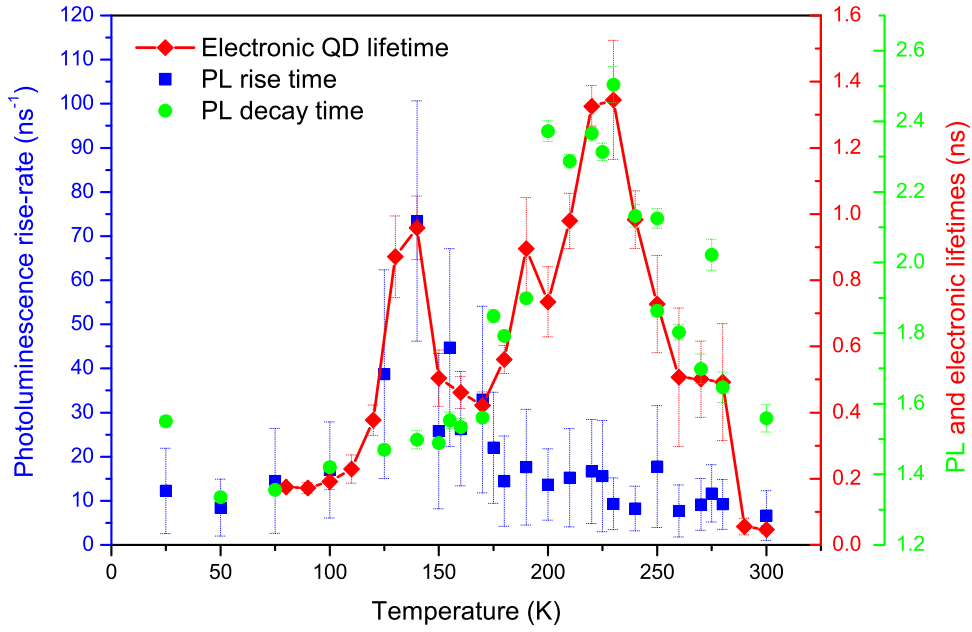


Figure 5.5: A comparison of the PL and electronic decay time constants with the inverse of the PL rise time constant. It can be seen that the two peaks in the electronic lifetime correspond to the PL rise and decay lifetimes, respectively with temperature.

high carrier densities [63, 64]. However it must also be considered that even if carrier capture into the QD (and their subsequent intraband relaxation) were to be infinitely fast, the carriers must still first diffuse through the GaAs matrix of the intrinsic region before this can happen. Carrier diffusion is known to be the dominant limiting-factor in the high-frequency response of many fast QW lasers [53] and has been shown to be important in TRPL measurements of bulk GaAs [65]. Sun *et al.* found that for low density QD samples, hole diffusion in GaAs before capture into the QDs was the limiting factor in their measurements of PL rise time [64]. Therefore there are several possible explanations for the peak in the rise rate at T_α :

Resonant tunnelling between the layers could be occurring in the QD bilayer and the peak in the PL rise rate at T_α is because the alignment of the electronic structure at this temperature allows carriers to be efficiently transferred into the emissive QD. This would increase the rate of capture into the lower confined-states of the QD bilayer. However, this explanation is unlikely because there is no evidence that the confined-states of the upper and lower dots can be considered to be distinct from each other.

Stimulated phonon-emission could be aiding relaxation near T_α . If significant numbers of holes are being excited into dark states at T_α it follows that the relaxation of carriers could be enhanced by the stimulated emission of phonons, especially in QDs that are un-occupied.

Auger hole-hole scattering is likely to occur in occupied QDs when there are significant numbers of holes that have been thermally-excited to higher confined-states. This would mean, according to the picture of Heitz *et al.* [63], that the slower multi-phonon relaxation dominates at temperatures above and below T_α because the “reservoir” of excited holes is comparatively small. Near T_α the excited holes may scatter by hole-hole collisions, leading to fast relaxation times in this region. Cesari *et al.* recently showed that undoped QD optical amplifiers have a faster gain recovery than p-doped amplifiers, which they attribute to the undoped amplifiers having a larger population of excited electrons that allowed fast relaxation by intraband Auger scattering [66].

Diffusion through GaAs before capture into the QD could be show a temperature dependence because the carrier mobility in GaAs is determined by the thermal velocity of the carriers and scattering processes. If the carrier mobility rises with temperature up to T_α and then falls again above this temperature, the time the carriers spend before capture will drop up to T_α and then increase again at higher temperatures - causing the observed variation in PL rise time. This could be possible because when QD layers, consisting of strained material having a different bandgap and lattice spacing to the GaAs matrix (inhomogeneously distributed), are present they will act as major scattering centres within the intrinsic region. The minimum rise time of the PL signal correlates with the effects due to hole scattering in the electronic data at T_α which means that below this point, the mobility may rise with temperature according to the thermal velocity until hole escape becomes a significant source of hole scattering (whether this happens by direct hole-hole scattering, or thermionic emission giving the appearance of a scattering process).

Further investigations into how the TRPL signal changes as the intensity of the excitation is varied and also the areal density (and/or number of layers) of QDs in the device could potentially differentiate between these mechanisms. Effects due to carrier diffusion through the GaAs should be dominant at low excitation densities and it would be expected that the PL rise time would decrease as the QD density is increased. Auger carrier scattering should show a significant dependence on the level of excitation, while being independent of the QD density. Phonon processes would be more challenging to identify, although Devos *et al.* have used two-colour pump-probe measurements of the surface reflectivity to show that QDs emitted strong bursts of acoustic phonons, which they attributed to fast relaxation by coherent

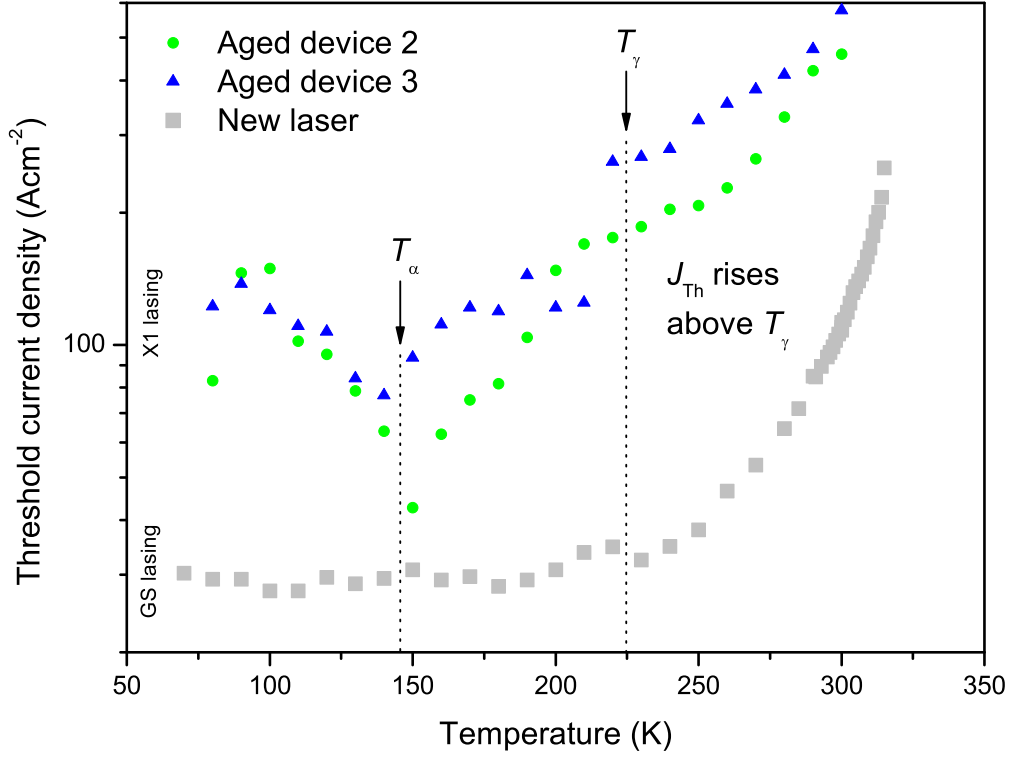


Figure 5.6: A plot of the temperature dependence for the three aged lasers together with the “new” device. The aged lasers all show reductions in J_{Th} near T_α and the increases are above T_γ .

multi-phonon emission [67]. Therefore it is possible to conclude that there are several mechanisms that could cause a peak in the trapping lifetime and PL rise rate at T_α and that further experiments could be performed to test the predictions of each theory. They can be broadly classified as either the dynamics of capture (i.e. diffusion before capture) or the intraband dynamics of the QD bilayer (phonons, tunnelling and Auger scattering). This distinction has important implications for the study of other structures involving QDs that are contrived to deliver increased performance (or other strong localisation), such as the tunnel-injection laser [68, 69].

5.2 Temperature dependence of the laser threshold

Temperature independence of the QD laser threshold was predicted by Arakawa and Sakaki [4] for the case of heavily p-doped material. The latter condition was applied so that only the dynamics of the electrons needed to be considered. However, the experimental results for InAs/GaAs QD lasers showed significant temperature

sensitivity of the threshold and some authors attributed this to an absence of holes in the QD, arguing that the thermal activation of both holes and electrons to higher excited states or the bulk was responsible. The work presented in the previous section showed that the thermal-spreading of the carriers into dark states near T_α and higher exciton-like states towards T_γ affects the PL emission rise and decay times, respectively. This section will deal with the effects that the dark states and carrier escape has on the temperature dependence of the ground and excited-state lasing thresholds.

The temperature dependence of the lasing threshold of the U27073 QD bilayer lasers was measured from the $-I^2 d^2V/dI^2$ spectra that were presented in the previous chapter. These devices had been run in CW mode up to high currents (500 mA) and relatively high temperatures (60 °C) repeatedly during other experiments and this had caused the devices to age, with accompanying increases in the threshold currents. The results are shown in Figure 5.6, plotted against the original temperature dependence of a “new” laser. The aged devices lase on the first excited-state (X1), while the new laser exhibits GS lasing. As the electrical characteristics of all the devices were consistent, it is assumed that the differences in the lasing performance are due to the degradation of the facet reflectivity with age. A significant dip in the excited-state lasing threshold near T_α is evident in the aged devices 2 and 3, while all the devices show a rise in the threshold current at temperatures above T_γ .

5.2.1 The effect of dark states at T_α

One of the key results of the previous chapter was that around T_α the holes are excited to higher confined states while the electrons are not, leading to “dark” states. While it was noted that the dark states cannot recombine to emit light, it follows that they might have some other influence on the optical properties of the QDs. Figure 5.6 showed that near T_α the threshold of the excited-state lasers shows a minimum, while the GS laser is not significantly affected at all. The effect of these dark states on the absorption and gain of the QD states is therefore the topic of this section.

When there is no thermal spreading and only geminate exciton-like carrier pairs occupy the QD GS, the material gain is proportional to the state’s occupation (Figure 5.7(a)-(c)). However, when thermal spreading is present there will be unpaired carriers in the GS and the higher confined-states (Figure 5.7(d)-(f) shows the case

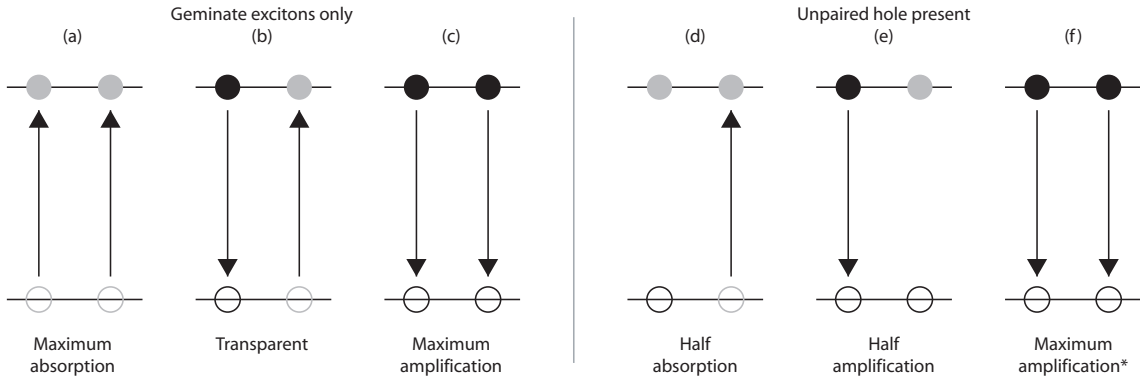


Figure 5.7: Schematic representations of the optical interactions that can happen in a confined state. Black indicates the presence of a carrier and gray an empty state. (a), (b) and (c) show geminate population of the state; (d), (e) and (f) show the same configurations as (a), (b) and (c) (respectively) but with the addition of an unpaired hole, whose effect is to lower the optical absorption of the state (relative to the geminate configurations) by blocking one of the possible absorption transitions. The argument applies equally to unpaired electrons and is applicable to any of the exciton-like confined states of a QD.

for an unpaired hole). As the confined-state can only absorb a photon by exciting an electron from a filled confined-hole state to an empty confined-electron state, the presence of either an unpaired electron or hole can block the absorption of a photon. The result, as can be seen from Figure 5.7, is that a QD state containing an unpaired carrier (either electron or hole) has a lower optical absorption, which will lead to a lower modal loss at the emission wavelength of the QD state containing the unpaired carrier. This argument applies equally to any of the exciton-like QD states, not just the GS.

From the diode ideality factor data presented in the previous chapter it was suggested that as the temperature approaches T_α from below, holes will undergo thermal spreading to higher confined states that leads to a population of unpaired holes in the excited-states; while above T_α the thermal spreading of electrons will act to pair up the excited holes again. Following the argument just described, the presence of unpaired holes in the excited-states will decrease the modal loss of the X1 state, leading to a reduction in the laser threshold for the excited-state near T_α . The GS will also now be occupied with unpaired electrons, meaning that its gain will drop, although the presence of the electron blocks any absorption which means that the change in gain (for the QD containing the dark exciton) is halved. Above T_α the electrons start to be excited to higher states and this reduces the number of dark states and therefore the losses return, bringing the X1 threshold back to “normal”. Therefore, the observation that the X1 lasing threshold drops at T_α while the GS threshold is not significantly affected is consistent with the presence of dark states

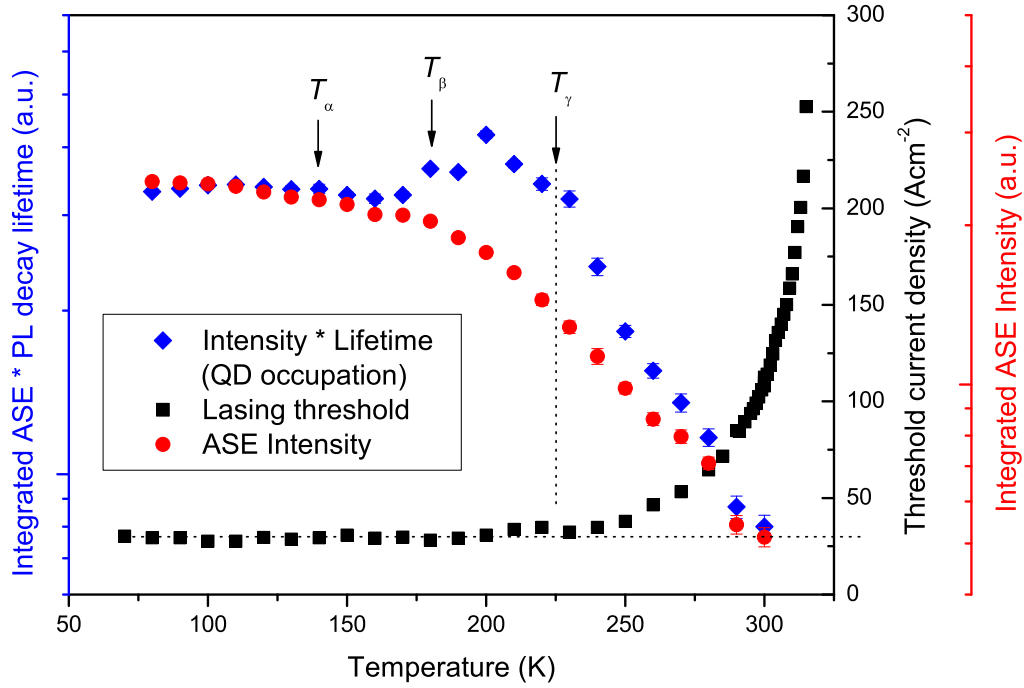


Figure 5.8: A comparison of the integrated intensity alone, as well as combined with the estimated lifetime, against the lasing threshold of the U27073 QD bilayer laser. Note that the laser threshold does not lose temperature insensitivity until above T_γ when the intensity *and* lifetime are both falling with increasing temperature.

due to the thermal spreading of holes. This suggests that the material gain and/or absorption of the ground and higher-excited states can be used as a probe of the carrier distribution within the QDs at intermediate temperatures. This is of interest when comparing the differences between undoped and p-doped lasers and optical amplifiers, as their carrier distributions have been seen to be different near room-temperature [60, 66].

5.2.2 Carrier escape beyond T_γ

Figure 5.8 compares the GS laser threshold current density, the integrated ASE intensity at a bias current density of 5 Acm and the product of the ASE intensity with the PL decay lifetime. It can be seen that it is not the onset of non-radiative recombination at T_β that affects the laser threshold but instead the threshold only rises significantly above T_γ where the product of the emission and lifetime begins to drop.

Intensity is the rate of emission of photons from the QD GS, which is determined by the occupation divided by the PL decay lifetime, therefore the product of the

emission intensity and the decay lifetime is proportional to the occupation at that current density. It can be seen that this product is initially constant, rises just before T_β where it appears to peak before falling. Above T_γ the product drops below its low-temperature value and then the laser threshold starts to rise. The peak above the low-temperature value at T_β has little effect on the laser threshold, which is consistent with carrier pairs being excited to higher confined states: the excitons in the higher confined-states then form a reservoir that can supply carriers to the GS without contributing directly to the modal gain at the GS emission wavelength; the QD occupation is increased but the GS occupation remains constant.

The data presented in this section showed that the temperature dependence of the lasing threshold of the QD bilayer laser departs from the ideal primarily due to geminate carrier escape above T_γ . This does not shed light on the mechanism of the non-radiative recombination that is present above T_β as it is consistent with both pure thermal escape or Auger recombination. It was also shown that X1 lasing shows considerable sensitivity to the non-geminate thermal spreading of holes to higher excited-states near T_α , while GS lasing is not significantly affected. The temperature dependence of the QD bilayer laser threshold for both GS and X1 lasing appears to be closely related to the physics behind the PL rise and fall lifetimes. This is important because it allows a wider range of tests for any detailed theory of QD lasing.

5.3 Lateral transport across QD layers

Lateral carrier transport (i.e. along the plane perpendicular to the growth direction) is relevant to all semiconductor lasers because it determines how the electrically-pumped area of the device responds to the effects of the laser oscillation. This is important because the mode profile of the emission can adversely affect the resolution or efficiency of an optical system - for example, launching light into a single-mode fibre requires a good TEM₀₀ mode to maximise its efficiency.

Carrier transport in semiconductor media is governed by the processes of drift and diffusion. Drift involves the movement of carriers under the influence of an electric field and acts to achieve charge neutrality in the crystal. Diffusion acts to redistribute carriers from areas of high chemical potential to low. In a homogeneous semiconductor these processes are largely independent but in the p-i-n junction, the drift current will still act to enforce charge neutrality in the i-region but its

competition with the diffusion current leaves space-charge regions on either side of the i-region (as discussed at the beginning of chapter 3). The result is a potential difference across the junction that is equal to the built-in voltage less the difference between the electron and hole chemical potentials, as described by equation 5.1. The important point is that, assuming the built-in voltage V_{bi} is constant, the electric field in the lateral directions is now dependent on the differences in chemical potential across the device. E_x is shown in equation 5.2, where A and B are functions that account for how much of the variation in voltage at a given position depends on each chemical potential. The precise form of the electric field is clearly complicated and would require numerical solution.

$$\Delta V(x, y) = V_{bi} - \phi_e(x, y) - \phi_h(x, y) \quad (5.1)$$

$$E_x(x, y, z) = -\frac{\partial V(x, y, z)}{\partial x} = A(z)\frac{\partial \phi_e(x, y)}{\partial x} + B(z)\frac{\partial \phi_h(x, y)}{\partial x} \quad (5.2)$$

As both the electric field and the diffusion current can be described in terms of the chemical potential, the drift and diffusion transport processes become coupled. This coupling effect is well-known, although there are several equivalent physical descriptions referred to in the literature. The three common models used are ambipolar diffusion, electron diffusion and stationary electrons with diffusing holes. Electron diffusion [70] is cited as a useful approximation because of the greater mobility of electrons compared with holes, allowing the neglect of hole transport. The stationary electrons with diffusing holes picture notes that the high mobility of electrons and the conductivity of the n-region act to result in negligible lateral electron current because the negative charge means drift and diffusion act in the opposite sense and enforce a constant chemical potential at the boundary of the junction, while the hole mobility is enhanced by the electric field [71]. Despite their seemingly contradictory nature, these pictures are equivalent because they both acknowledge that the forces determining the motions of the electrons and holes become coupled, allowing the problem to be simplified to the use of an effective diffusion constant for transport in the i-region. Ambipolar diffusion avoids choosing a dominant carrier type by removing the distinction between the electrons and holes, describing their properties as an average of the two species. The difference between the models then lies in precise form of the effective diffusion constant.

The measurements of a negative photovoltage effect in the previous chapter suggest that the chemical potential of either the electrons, holes or both *reduces* with increasing particle number. If this is the case then the direction of the coupled drift-diffusion lateral transport would be expected to be reversed. As lateral transport is important in a device with different spatial lasing modes, $-I^2 d^2 V / dI^2$ spectroscopy was employed to investigate how filamentation was affected by the clamping of the diode junction at the laser threshold. In section 3.3 it was shown that partial clamping means that while the parts of the QD ensemble that are participating in lasing have their occupation level pinned, the QDs that are not lasing are not pinned. The overlap with the lasing mode must be both spatial (where the intensity of the optical mode is high) and spectral (the QD emission wavelength must be separated from the lasing wavelength by less than the homogeneous linewidth). The lasers in this work are not single-mode and have an inhomogeneous linewidth that is greater than the homogeneous broadening, so they will therefore always exhibit partial clamping. This is an advantage for the study of the lateral transport because (as derived in Appendix B) partial clamping is detected using the $-I^2 d^2 V / dI^2$ technique due to the redistribution of current by lateral transport changing the current density in the non-lasing regions, which in turns changes the voltage response at the diode contact.

Figure 5.9 shows two $-I^2 d^2 V / dI^2$ signals from the QD bilayer laser. The low-temperature spectrum exhibits trough features, while the high-temperature spectrum exhibits peak features - suggesting that the direction of lateral transport is occurring in different directions at these different temperatures. This is because a trough, followed by a positive displacement of the $-I^2 d^2 V / dI^2$ signal, indicates that a current is being diverted into the non-lasing regions of the diode at the expense of the current into the lasing region. An MQW laser always exhibits peak features on a $-I^2 d^2 V / dI^2$, meaning a lateral flow from non-lasing to lasing regions, as detailed in section 3.2. As the lateral currents are expected to be reversed according to the arguments given above, the troughs are attributed here to a lateral current flowing away from a lasing region before the carriers are captured into the QD confined-states.

This behaviour was quantitatively analysed by making a fit to the integrated area of the laser peak and relating this to the size of the step in the $-I^2 d^2 V / dI^2$ signal, as shown in Figure 5.10. The results of this analysis are plotted in Figure 5.11. The “negative pinning” occurs up to T_γ which can be attributed to a “reversed” drift-diffusion current, as expected. Above T_β the negative pinning starts to be countered as carrier escape becomes possible, enabling diffusion between the confined-states themselves to occur. As the rate of carrier escape from the dots is in proportion the

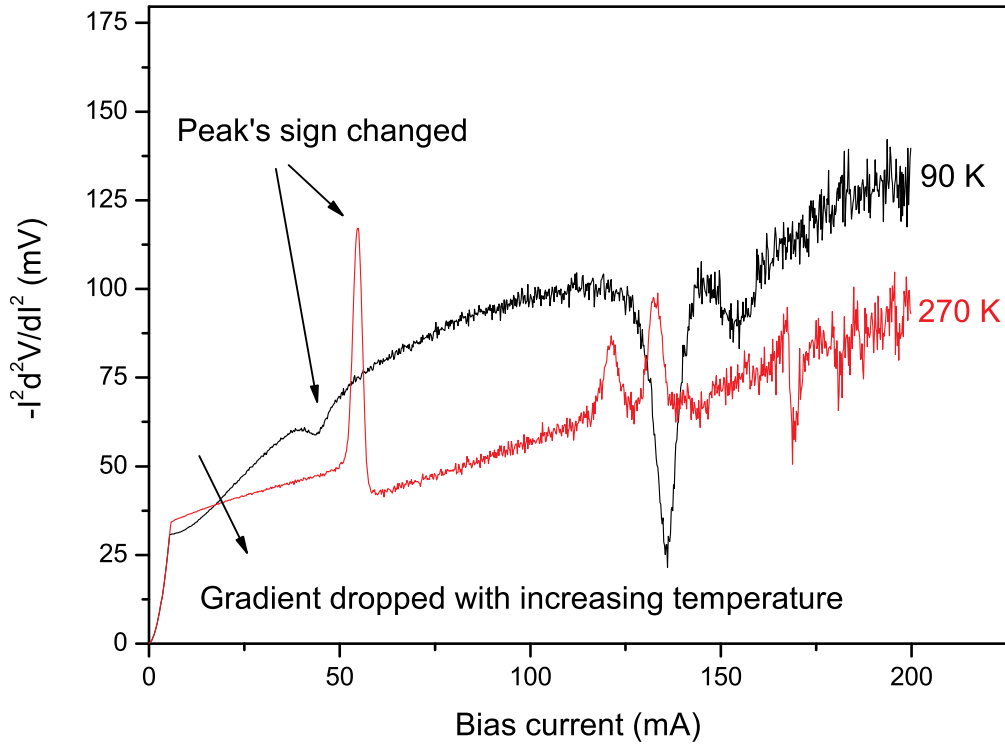


Figure 5.9: The sign-change of the $-I^2 d^2V/dI^2$ peaks shown with the drop in gradient as the temperature is increased as observed on the raw spectra.

number of carriers in the dots, the diffusion due to carrier redistribution should act in terms of the particle gradient and resembled Fickian diffusion. This continues until at T_γ the pinning signal goes to zero as the drift-diffusion currents in the bulk balance with diffusion between the dots. Above T_γ there is a change of sign to the “normal” direction as diffusion between QDs now dominates the lateral transport. This indicates that the onset of geminate carrier escape allows carrier diffusion between the QDs. This behaviour was checked for several lasers (Figure 5.12) and cross-over point was found to correlate with T_γ , once device heating is taken into account. Above T_γ the pinning fraction rises linearly with temperature up to approximately 300 K, above which it becomes superlinear due to device heating as the threshold current rises. A linear relationship with temperature might be expected because the diffusion constant is proportional to temperature; meaning that the area diffused over in a unit time period should increase linearly and with this, the number of dots involved in the diffusion process, with increasing temperature. This is consistent with measurements of carrier diffusion made by spatially-resolving the PL near a sample edge [72] and also measurements of the spontaneous emission clamping in lasers [60], where it is found that lateral transport improves with temperature until “complete” clamping is observed (in undoped QD lasers) at high temperatures.

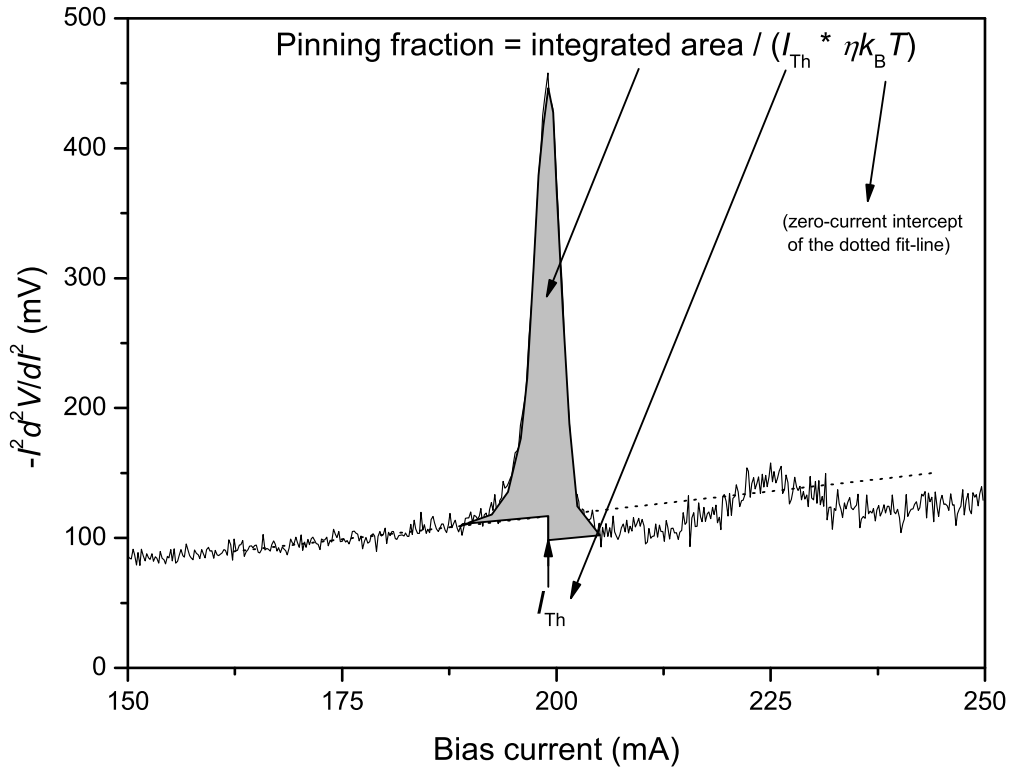


Figure 5.10: An example of how the pinning fraction is determined from a fit to the lasing threshold peak of a $-I^2 d^2 V / dI^2$ spectrum.

In conclusion, this data showed that the presence of QDs in the intrinsic region of the diode affects the lateral transport by reversing the drift-diffusion currents (due to the “trapping” effect as measured from the photovoltage at the beginning of the previous chapter) and suppressing diffusion between dots at low-temperatures. At the onset of geminate carrier escape, Fickian diffusion between the dots quickly dominates and continues to rise with temperature. The result in Figure 5.11 suggests that as the temperature is increased beyond room-temperature the diffusion current will become large enough for the whole QD ensemble to attain thermal equilibrium (i.e. a pinning fraction of unity, as for the MQW laser). This type of measurement will prove useful in analysing the performance of p-doped QD lasers, as these are unable to reach thermal equilibrium even at 100 °C [60] in some cases. Further study could also investigate the consequences of the reversed drift-diffusion current for “mesoscopic” QD devices that are based on single or few dots.

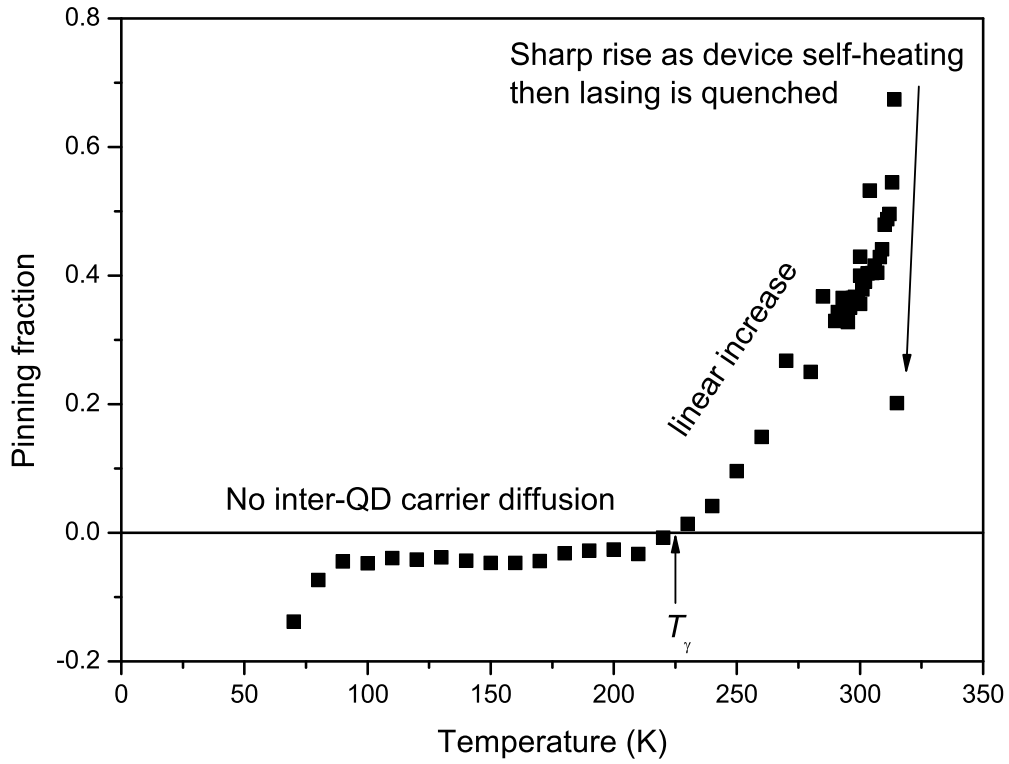


Figure 5.11: A temperature study of how the pinning fraction of the first laser threshold observed on the $-I^2 d^2 V / dI^2$ spectra varies.

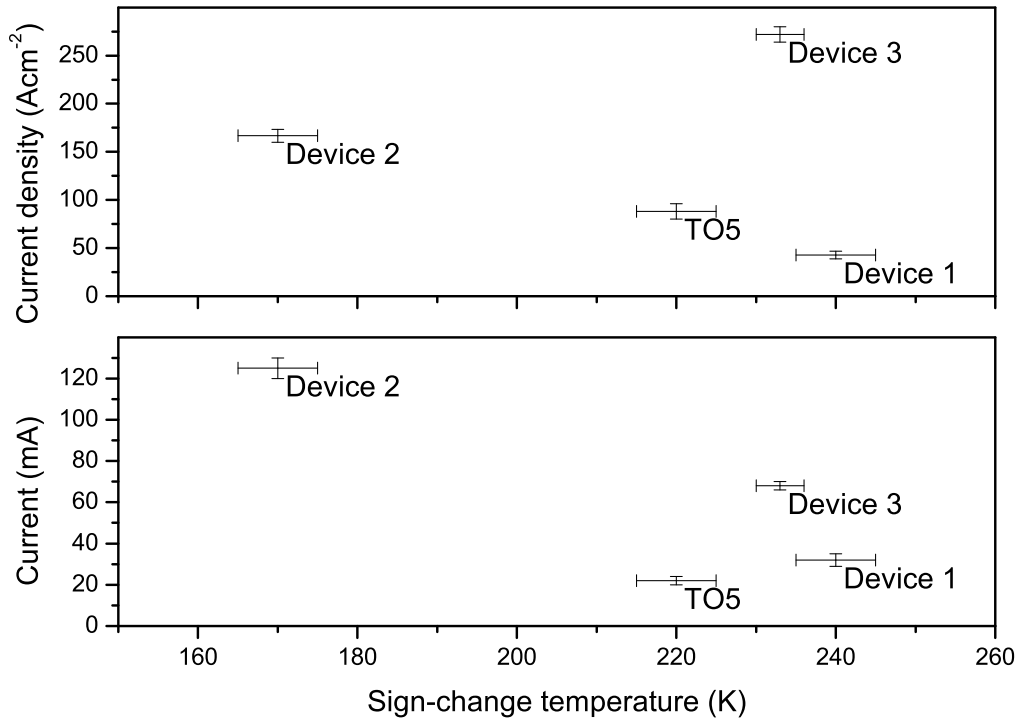


Figure 5.12: The sign-change of the $-I^2 d^2 V / dI^2$ peaks, plotted with current and current density versus temperature to illustrate possible relationship with device heating.

Chapter 6

Conclusions and further work

This work aimed to develop the QD bilayer growth technology for long wavelength emission and incorporate this into edge-emitting lasers with a particular focus on the telecommunications windows at 1310 nm and 1550 nm. QD bilayer lasers emitting at ~ 1350 nm either on the QD ground or excited-state were demonstrated at room-temperature. GS lasing at 1430 nm at 250 K was also shown. The 1340 nm GS lasers exhibited CW operation, with lasing thresholds of less than 100 A cm^{-2} and output powers of over 100 mW. An increased range of room-temperature PL emission wavelengths was also demonstrated, with 1515 nm being obtained by increasing the seed layer growth temperature. The next goal would be to integrate this longer-wavelength QD bilayer material into laser devices, the challenge being to grow multiple identical layers with sufficient optical gain. Other types of devices could also benefit from these long-wavelength QDs, for example resonant-cavity LEDs do not require optical gain and can operate at high speed with good fibre coupling. As they do not have a threshold and use a resonant structure, they have greater temperature-stability than edge-emitting devices. Long wavelength QDs that can operate in the 1310 and 1550 nm at low-temperatures are also desirable for single-photon devices (such as Quantum Cryptography) and as candidates for future Quantum Computing devices.

The development of QD bilayers specifically for edge-emitting lasers could also be extended in two areas: Incorporation of modulation p-doping near the QD layers improves the performance of conventional QD lasers dramatically near room-temperature [26] and therefore its effect on QD bilayers should be investigated. It would also be of interest to look at a slight blueshift to approximately 1290 nm by

lowering the growth temperature. This would increase the seed layer density and consequently, the gain. As the emission wavelength redshifts with increasing temperature it obviously must not exceed the desired wavelength at room-temperature, 1340 nm is therefore “too long” anyway. An InGaAs capping layer may possibly be applied to the bilayer to allow an even larger increase in density, if possible, while maintaining emission near 1300 nm. A successful combination of these two avenues could result in a high-performance QD bilayer laser for applications in the 1310 nm telecommunications window with a minimum of development effort.

In the latter half of this work, $-I^2 d^2 V / dI^2$ spectroscopy was applied to QD laser diodes and compared to a QW laser. There were similarities but the behaviour of the QD laser differed in two aspects: partial clamping of the junction voltage at the laser threshold and the presence of a rising linear background signal. Measurements of the temperature dependence of the diode ideality factor suggested that intraband scattering between the QD confined-states is important in determining the diode properties. The rising linear background was shown to be due to negative differential resistance which was attributed to the “trapping” of carriers by the QDs. Measurements of the filamentation at the laser threshold confirmed this that by showing that, at low temperatures, the re-distribution of current between pinned and non-pinned areas of the device is reversed. This observation was possible because the carrier localisation in the QDs switches off carrier diffusion at low temperatures and suppresses it until the temperature is high enough for the carriers to escape the QD potential. The trapping-effect was quantitatively analysed to extract a QD trapping lifetime which was found to be correlated with the rise and decay time constants of the QD GS time-resolved PL emission. A comparison of these data suggested that for the QD bilayers emitting at 1340 nm at room-temperature thermal-spreading of holes to dark states and subsequent non-geminate escape occurs around 140 K, followed by geminate escape dominating at and above 225 K. These final two observations were found to affect the temperature dependence of the GS and X1 laser threshold currents.

A need for further study on a wider-range of QD material is evident, particularly by studying the effects of the QD density and depth of the confining-potential. The purpose of this will be to check the validity of the analyses presented here, as well as to derive the origin and strength of these effects and to see if any new device applications can be found as a result. The reversal of the drift component of carrier transport is likely to have consequences for “mesoscopic” devices where single or few dots are used. It would also be of great interest to apply these techniques to the

study of p-doped QD lasers because the thermal-spreading and escape of carriers is expected to be suppressed by the addition of excess holes [60].

The study of filamentation in QD lasers is an area that should be investigated in more detail. The initial results presented in section 3.3 suggest that it plays a significant role in QD lasers and particularly in the phenomenon of dual-state lasing. Models of this phenomenon in the literature are largely based on the possible existence of a relaxation-bottleneck for the excitons between the X1 and GS states but this is still a controversial idea and there is no consensus on this subject at present. As the results of the $-I^2 d^2 V / dI^2$ spectroscopy show, filamentation is a fundamental part of a inhomogeneous gain medium and if it responsible for the dual-state lasing phenomenon this would allow for laser design to optimised when maximum GS lasing reliability and output power is required. Also, dual-state lasing could have some novel applications in areas such as all-optical switching - it might be interesting if a laser could simultaneously source light in both the 1310 and 1550 nm telecommunications windows.

Appendix A

Carrier pinning in a simplistic laser model

To illustrate the concept on carrier pinning in a laser, this appendix will derive a simple rate equation model. This model assumes that there is a cavity mode containing P photons, with an homogeneous amplifying medium containing N carriers and spontaneous emission coefficient B . With these considerations equation A.1 can be written, where γ is the cavity loss, G is the active medium's gain and β is the fraction of the spontaneous emission that enters the cavity mode.

$$\dot{P} = (G - \gamma)P + \beta BN \quad (\text{A.1})$$

Taking the steady-state solution for the photon number gives equation A.2. It can be seen that the photon number will rise asymptotically as the gain approaches the cavity loss - clearly showing that it would be un-physical for the cavity's net gain to ever reach zero. This means that increasing the laser output power will be achieved by a balance of increased spontaneous emission and stimulated emission. This makes the laser cavity a *regenerative noise amplifier* where the noise is the spontaneous emission [43].

$$P = \frac{\beta BN}{\gamma - G} \quad (\text{A.2})$$

To obtain an analytical expression for the output of the laser cavity a similar rate equation is defined for the carrier population of the excited state of the transition,

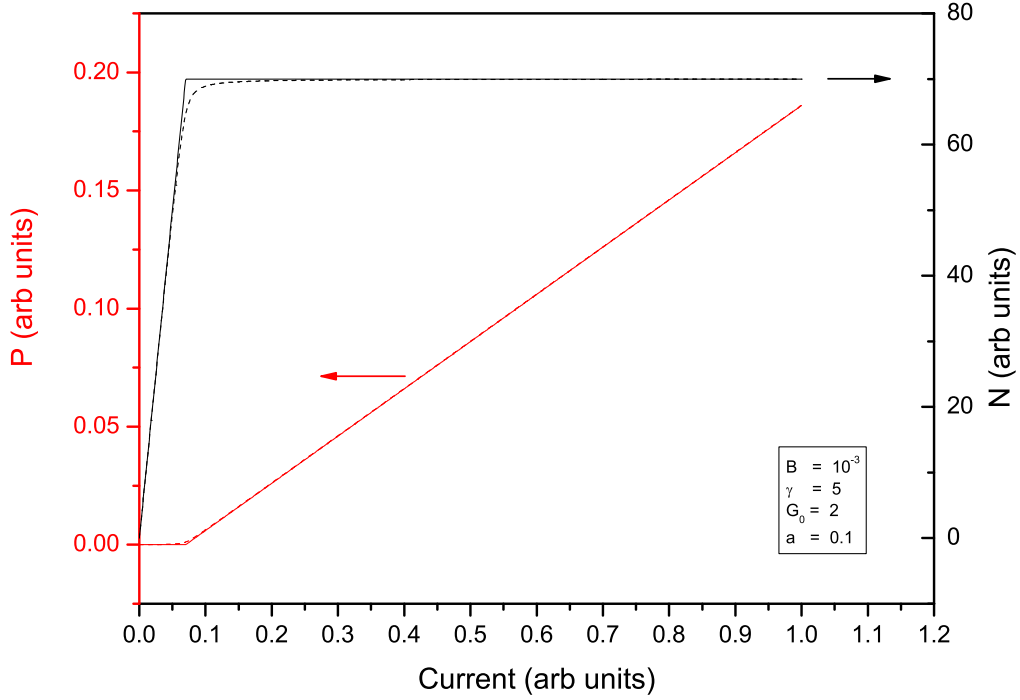


Figure A.1: The modelled LI curve (red) and dependence of the occupation number on current. The solid line and dashed line are for β equal to 10^{-5} and 10^{-2} , respectively.

Equation A.3. This does not take account of any other recombination mechanism (i.e. the carrier lifetime is equal to the radiative lifetime).

$$\dot{N} = \frac{I}{e} - BN - GP \quad (\text{A.3})$$

The gain of the transition is approximated here as an offset-linear dependence on the carrier density in Equation A.4. By choosing this relation the effects of varying the differential gain can be studied.

$$G = aN - G_0 \quad (\text{A.4})$$

By re-arranging Equation A.2 and the steady-state solution of Equation A.3 in terms of N , Equation A.5 is obtained. When re-arranged as in Equation A.6 it is seen to be a quadratic polynomial in P whose solution is Equation A.7.

$$\frac{P(\gamma + G_0)}{\beta B + aP} = N = \frac{\frac{I}{e} + G_0 P}{aP + B} \quad (\text{A.5})$$

$$-a\gamma \cdot P^2 + \left\{a\frac{I}{e} - B[\gamma + G_0(1 - \beta)]\right\} \cdot P + \beta B\frac{I}{e} = 0 \quad (\text{A.6})$$

$$P = \frac{a\frac{I}{e} + \sqrt{\left\{a\frac{I}{e} - B[\gamma + G_0(1 - \beta)]\right\}^2 + 4\beta\gamma Ba\frac{I}{e}} - B[\gamma + G_0(1 - \beta)]}{2a\gamma} \quad (\text{A.7})$$

This gives an analytical expression for modelling the LI curve of the simple laser, as shown in Figure A.1. The pinning of the carrier density can then be observed by substituting P back into either side of Equation A.5 and is shown as the black line (top curve) in Figure A.1. This shows that although the value of N is not truly a fixed value above the laser threshold, it quickly approaches its asymptotic limit. The speed of its approach depends on the efficiency with which the spontaneous emission is coupled into the lasing mode, β . For the type of edge-emitting laser that is of interest here β is small and the pinning is sharp, hence the term “clamping” is often used; while for a microcavity laser which has a high β , the laser threshold loses its distinction (compare the solid and dotted lines in Figure A.1).

Appendix B

Partial carrier pinning

Appendix A showed that a simple homogeneous laser will tend to exhibit pinning of its carrier density at the laser threshold. However when the medium is inhomogeneously broadened and/or strong gain saturation occurs then this pinning effect can be observed to be suppressed [60, 73]. While incomplete carrier pinning in semiconductor lasers is often associated with poor quality devices, the inhomogeneous gain of QD lasers means that this effect is now observed in highly efficient laser diodes and has implications for accurate device modelling. This appendix derives a basic model to explain the origin of the “partial clamping” phenomenon that is seen with the $-I^2 d^2 V / dI^2$ spectroscopy technique.

In the $-I^2 d^2 V / dI^2$ measurements performed on QD lasers in Section 3.3 the fractional step-change in the signal (after the peak) is proposed to be the ration of area of non-lasing areas to the area that is involved in lasing, A . In this picture, there are two parallel current-paths through the device that are connected together at the contacts (i.e. two diodes in parallel, one that lases and one which does not). The lasing diode’s junction voltage is clamped at $V_j(J_{th})$ and so represented by a voltage source, while the other diode is considered as obeying the ideal diode approximation. The series resistances are set to be inversely proportional to the respective areas of the current-path that they represent.

The first stage of the calculation expands the junction voltage, V_j , of the non-lasing diode in terms of the clamped junction’s voltage (since this must be $\leq v_j$) plus a difference voltage. An even bias current density ($J = \Delta J + J_{th}$) is assumed as a linear approximation that should be valid close to the laser threshold.

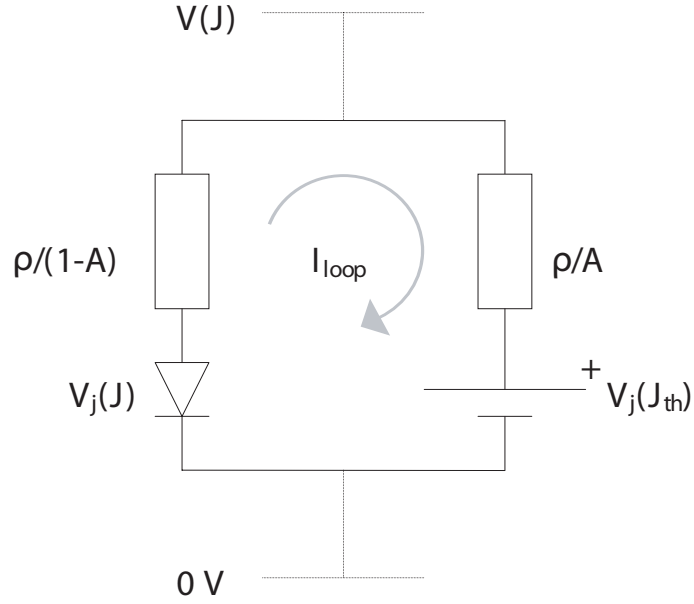


Figure B.1: Simple equivalent circuit model for a QD laser device with non-lasing and lasing filaments (left and right respectively).

$$\begin{aligned}
 V_j(J) &= \eta V_T \ln \left(J/J_S \right) \\
 &= \eta V_T \ln \left(\frac{\Delta J + J_{th}}{J_S} \right) \\
 &= \eta V_T \ln \left(J_{th}/J_S \right) + \eta V_T \ln \left(1 + \Delta J/J_{th} \right) \\
 &= V_j(J_{th}) + \eta V_T \ln \left(1 + \Delta J/J_{th} \right)
 \end{aligned} \tag{B.1}$$

Next, an expression for the current loop I_{loop} , which is induced within the device, is derived by a linear analysis (i.e. neglecting the non-linearity of the non-lasing diode's junction voltage - necessary to gain a simple but approximate, analytic solution):

$$\begin{aligned}
 I_{loop} &= \frac{\sum_{sources} V}{\sum_{losses} R} \\
 &= \frac{A(1-A)}{\rho} \eta V_T \ln \left(1 + \Delta J/J_{th} \right)
 \end{aligned} \tag{B.2}$$

The device voltage is then be calculated by considering the potential difference across the lasing region of the device:

$$\begin{aligned}
V(J \geq J_{th}) &= V_j(J_{th}) + \frac{\rho}{(1-A)} (I_{loop} + I_{bias}) \\
&= V_j(J_{th}) + (1-A)\eta V_T \ln\left(1 + \Delta J/J_{th}\right) + J\rho \\
&= \underbrace{V_j(J_{th})}_{\text{clamped-diode}} - \underbrace{(1-A)\eta V_T \ln(J_{th})}_{\text{voltage-correction}} + \underbrace{(1-A)\eta V_T \ln(J)}_{\text{unclamped-diode}} + \underbrace{J\rho}_{\text{ohmic-term}}
\end{aligned} \tag{B.3}$$

Taking the derivative and multiplying by the current (Equation B.4) recovers the result that the offset of the $-I^2 d^2 V/dI^2$ measurements is proportional to the fractional area of the device that is not lasing.

$$J \frac{dV}{dJ} \propto \begin{cases} \eta V_T + J\rho & J < J_{th} \\ (1-A)\eta V_T + J\rho & J > J_{th} \end{cases} \tag{B.4}$$

This result supports the interpretation of the data obtained by the $-I^2 d^2 V/dI^2$ method as a division of injected carriers between lasing and non-lasing states in different parts of the device or ensemble. It shows that partial pinning is due to lateral carrier transport between non-lasing and lasing filaments.

Appendix C

Numerical simulation of $-I^2 d^2 V / dI^2$ spectrum

The following Matlab computer programme was developed to model the $-I^2 d^2 V / dI^2$ spectra of laser diodes according to the simple model of Appendix A.

*%%% Numerical simulation of a laser diode being measured by $-I^2 d^2 V / dI^2$
%%% derivative spectroscopy*

%%% Written by Peter Spencer, November 2006 to August 2007

clear;

%%% Physical specifications of the laser diode under simulation

R = 2; % Series resistance of the diode
Is = 1e-6; % Diode junction's generation current (A)
T = 300; % Temperature (K)
B = 0.001; % Spontaneous emission coefficient
gamma = 25; % Cavity loss
G0 = 2; % Medium's gain offset
a = 0.1; % Medium's gain coefficient
beta = 1e-5; % Fraction of spont. emission into lasing mode
eta = 2; % Ideality factor of the recombination

%%% Simulation parameters

I_q = 0; % 0.0012; % Quiescent current of the laser driver
clip_amplitude = 10; % Maximum lock-in reading in Volts
clip_signal = 0; % 1 = clip signal, 0 = no clipping
display_IV = 0; % 1 = plot IV curve, 0 = skip
lookup_stepsize = 1e-4; % Size of steps on simulated current axis
lookup_tablesize = 1e4; % Number of steps on current axis
detect_stepsize = 1e-3; % Frequency with which to sample results
cutoff_min = 0; % Low-current region to avoid
max_current = 0.50; % Maximum current to try detection on

[illegible]

```

%% Calculate the signal used to modulate the current supplied to the
%% simulated laser diode.
mod_signal = mod_pkTpk .* ...
    (sin(mod_freqA.*mod_range) + sin(mod_freqB.*mod_range + phi));

%% Calibrate the modulation amplitude by simulating a device with a
%% parabolic V vs. I curve (i.e. its second derivative w.r.t. I is 1).
mod_calibrate_sig = mod_signal.^2 ./ 2;
mod_calibrate_spectrum = fft( mod_calibrate_sig .* windowFunction );
mod_calibrate_spectrum = abs( mod_calibrate_spectrum );
mod_strength = mod_calibrate_spectrum( detect_frequency );

%% Simulate the signal passed to the lock-in at this current.
this_I_signal = repmat(mod_signal,1,size(detect_range,1)) ...
    + repmat(detect_range',size(mod_range,1),1);

%% Avoid reverse bias
this_I_signal = (this_I_signal + abs(this_I_signal)) ./ 2;

%% Add the quiescent current
this_I_signal = this_I_signal + I_q;

%% Now calculated the laser diode's Voltage response.
aa = size(this_I_signal);
aaa = 1;
while aaa < 10      %% THIS IS REQUIRED TO IGNORE RANDOM FAILURES %%
    %% (Presumably this code can fail due to transitory memory
    %% allocation issues - the code still executes fine when retried).
    aaa = aaa + 1;
    try
        this_I_signal = reshape(this_I_signal, prod(aa), 1);
        this_V_signal = interp1q(I,V,this_I_signal);
        this_V_signal = reshape(this_V_signal, aa(1), aa(2));
        aaa = 10;
    catch
        continue;
    end
end

%% Simulate AC coupling on the lock-in amplifier's input
this_V_signal = this_V_signal - ...
    repmat(interp1(I,V,detect_range)',size(this_V_signal,1),1);

%% Measure the spectrum of the calculated Voltage response of the
%% laser diode to the simulated current modulation.
this_V_spectrum = fft( this_V_signal .* ...
    repmat(windowFunction,1,size(this_V_signal,2)) );

%% Record the detected signal from the laser diode as calculated
%% above.
detected_signalX = abs( this_V_spectrum(detect_frequency,:) );
detected_signalY = imag( this_V_spectrum(detect_frequency,:) );
clear this_V_signal;    %% Tidy-up memory ASAP.

```

```

%% Simulate the limited dynamic range of the lock-in amplifier
if clip_signal == 1
    clip_fn_X = [ -100 ; -clip_amplitude ; clip_amplitude ; +100 ];
    clip_fn_Y = [ -clip_amplitude - 1e9 ; -clip_amplitude ; ...
        clip_amplitude ; clip_amplitude + 1e-9 ];
    detected_signalX = interp1(clip_fn_X, clip_fn_Y, detected_signalX);
    detected_signalY = interp1(clip_fn_X, clip_fn_Y, detected_signalY);
end

%% Complete the calculation by converting the detected signal into the
%% current squared multiplied by the 2nd differential of Voltage
%% w.r.t. current, then divided by the thermal Voltage.
signalX = (detect_range-I_q).^2 ./ (mod_strength) .* detected_signalX;
signalY = (detect_range-I_q).^2 ./ (mod_strength) .* detected_signalY;

%% Display the simulated measurement's results.
plot(detect_range, signalX, 'b');
%plot(detect_range, -signalY, 'r');
axis([0 max(detect_range) 0 max(signalX).*1.2]);
xlabel('Current_(Amps)');
ylabel('-I^2d^2V/dI^2_(Volts)');
title('Detection_by_frequency_mixing');

%% Save the results to a text file
QW = [detect_range signalX];
save '2nd_diff_results.txt' QW -ascii -double -tabs

```

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Presentations and publications

Talk: “InAs/GaAs quantum dot bilayer lasers,” *Compound Semiconductors UK 2006* Sheffield University, UK

Poster: “Threshold clamping and inhomogeneous broadening effects in InAs/GaAs Quantum Dot bilayer lasers measured using derivative spectroscopy,” *One day Quantum Dot meeting 2007* Nottingham University, UK

Talk: “Long Wavelength InAs/GaAs Quantum Dot Bilayer lasers,” *Semiconductors and Integrated Optoelectronics 2007* Cardiff University, UK

P. Spencer, E. Clarke, P. Howe and R. Murray: “Inhomogeneous gain effects in quantum dot lasers,” *Electronics Letters* Vol. 43 No. 10 pp. 574 - 575 (2007)

Talk: “Threshold clamping and inhomogeneous effects in InAs/GaAs Quantum Dot Bilayer lasers,” *Condensed Matter and Materials Physics 2007* Leicester University, UK

Talk: “Threshold clamping in Quantum Dot lasers,” *CLEO Europe 2007* Munich, Germany

Talk: “Threshold clamping in Quantum Dot lasers,” *IoP Compound Semiconductors UK 2007* Sheffield University, UK

D.B. Malins, A. Gomez-Iglesias, P. Spencer, E. Clarke, R. Murray and A. Miller: “Quantum-confined Stark effect and ultrafast absorption dynamics in bilayer InAs quantum dot waveguide,” *Electronics Letters* Vol. 43 No. 12 pp. 686 - 688 (2007)

Poster: “Electrical studies of filamentation and carrier dynamics in InAs/GaAs Quantum dot laser diodes,” *One day Quantum Dot meeting 2008* Imperial College, UK

E. Clarke, P. Spencer, E. Harbord, P. Howe and R. Murray: “Growth, optical properties and device characterisation of InAs/GaAs quantum dot bilayers,” *Accepted for publication first quarter 2008, J. Phys.: Conf. Phys.*

E. Harbord, P. Spencer, E. Clarke and R. Murray: “The influence of bimodal size distribution on the excited state lifetimes of InAs/GaAs self-assembled quantum dots,” *Appl. Phys. Lett., to be submitted*

E. Harbord, P. Spencer, E. Clarke and R. Murray: “Radiative lifetimes, carrier dynamics and carrier redistribution in undoped and p-doped quantum dots,” *Phys. Rev. B, to be submitted*

E. Clarke, P. Howe, P. Spencer, E. Harbord and R. Murray: “Effect of seed-layer growth conditions on the optical properties of InAs/GaAs quantum dot bilayers,” *Appl. Phys. Lett., to be submitted*
