Modeling and characterization of InAs/GaAs quantum dot lasers grown using metal organic chemical vapor deposition

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We report on the lasing characteristics of three- and five-stack InAs/GaAs quantum dot (QD) lasers grown by metal organic chemical vapor deposition. By increasing the number of stacked dot layers to 5, lasing was achieved from the ground state at 1135 nm for device lengths as short as 1.5 mm (no reflectivity coatings). The unamplified spontaneous emission and Z ratio as a function of injection current were also investigated. While the five-stack QD lasers behaved as expected with Z ratios of ≈ 2 prior to lasing, the three-stack QD lasers, which lased from the excited state, exhibited Z -ratio values as high as 4. A simple model was developed and indicated that high Z ratios can be generated by three nonradiative recombination pathways: (i) high monomolecular recombination within the wetting layer, (ii) Auger recombination involving carriers within the QDs ("unmixed" Auger), and (iii) Auger recombination involving both the QD and wetting layer states ("mixed" Auger), which dominate once the excited and wetting layer states become populated. © 2007 American Institute of Physics. [DOI: 10.1063/1.2409612]

I. INTRODUCTION

Quantum dot (QD) lasers continue to attract interest due to their potential for improved device performance. Over the past decade many of their predicted advantages have been demonstrated. For example, low threshold current densities on the order of 20 A/cm² per dot layer^{1–3} and high thermal stability with characteristic temperatures as high as 300 K at room temperature^{3–5} have been reported. Lasing at 1.3 and 1.5 μ m has also been achieved by capping InAs quantum dots with thin InGaAs capping layers.^{2,6–9} However, it is still difficult to achieve all of the above characteristics in one device, with only a few such reports.^{3,4} Furthermore, the majority of QD laser studies use molecular beam epitaxy as the growth technique. In comparison, there are very few reports of InAs/GaAs quantum dot lasers grown using metal organic chemical vapor deposition (MOCVD),^{5,10–16} and high performance, long wavelength quantum dot lasers grown by MOCVD are still an elusive goal.

In this paper we report on the lasing characteristics of MOCVD grown lasers with three- and five-stacked layers of QDs in the active region. In order to avoid degradation of the QDs, the upper AlGaAs cladding layers were grown at 600 °C, which is 100° below optimum. The impact of this low growth temperature on device performance is studied by comparing two reference quantum well (QW) lasers. Finally, to gain a better understanding of the carrier dynamics, the Z -ratio dependence on injection current was investigated for the QD lasers. The Z ratio is often used for QW devices to gain insight into the dominant recombination mechanisms^{17,18} and is defined as

$$Z = \frac{d(\ln J_{\text{tot}})}{d(\ln \sqrt{J_{\text{sp}}})}, \quad (1)$$

where J_{sp} represents the current density consumed by spontaneous emission and J_{tot} is the total injected current density which also includes the nonradiative recombination terms. In the case of quantum wells the total injected current density can be related to the carrier density (N_{QW}) by the simple relation

$$J_{\text{tot}} \propto q(A_{2D}N_{\text{QW}} + B_{2D}N_{\text{QW}}^2 + C_{2D}N_{\text{QW}}^3), \quad (2)$$

where A_{2D} , B_{2D} , and C_{2D} are the coefficients for nonradiative monomolecular, radiative bimolecular and nonradiative Auger processes, respectively. Z ratios of 1, 2, or 3 therefore correspond to nonradiative monomolecular, radiative, and Auger recombinations, respectively, and noninteger values indicate that more than one process is significant. Our Z -ratio measurements as well as those presented by others¹⁸ show very different behavior for the QDs. We find that the Z ratio for the three-stack QD lasers, which operate from the excited state, reaches values as high as 4 prior to lasing. This suggests that the simple relation [see Eq. (2)] above does not apply for the more complex quantum dot/wetting layer system. To better understand the underlying cause, a simple model was developed which considers the combined quantum dot, wetting layer, and GaAs barrier system. This model highlights the need to avoid carrier population of the excited and wetting layer states which can lead to increased nonradiative Auger and monomolecular recombination pathways. This model and its important outcomes are described in Secs. IV and V.

II. EXPERIMENTAL DETAILS

Thin p -clad laser structures as shown in Fig. 1 (Ref. 19) were grown using a low pressure (100 mbar), AIXTRON

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FIG. 1. Schematic of the thin *p*-clad laser structure.

200/4, horizontal flow MOCVD reactor. The sources used were trimethylindium, trimethylgallium, trimethylaluminum, and AsH₃ with H₂ as the carrier gas. Silane and CCl₄ were used for *n*- and *p*-type doping, respectively. The quantum dot active region is sandwiched between two undoped AlGaAs graded index layers, each 0.16 μm thick. In order to minimize the time spent by the QDs at elevated temperatures the top *p* cladding is kept thin, consisting of a 0.45 μm Al_{0.45}Ga_{0.55}As confinement layer and a 0.1 μm, highly doped, GaAs contact layer. The bottom *n* cladding consists of a 1.8 μm Al_{0.45}Ga_{0.55}As and a 0.25 μm Al_{0.3}Ga_{0.7}As layer. Further details on the laser structure can be found in Ref. 19. All of the layers below the QD active region were grown at 700 °C, whereas the top *p*-type cladding layers were grown at 600 °C. At temperatures above 600 °C the quantum dot photoluminescence (PL) blueshifts and degrades significantly.²⁰

Laser structures with either three- or five-stacked layers of InAs/GaAs QDs in the active region were grown. The QDs were always grown at their optimum growth temperature of 520 °C. Slightly different growth conditions were used for the three- and five-stack layers, as summarized in Table I. In both cases, the growth conditions resulted in $\approx 3 \times 10^{10}$ dots/cm² per buried layer. The dot layers are separated by 30 nm GaAs spacer layers, and smoothing procedures were used to ensure that the growth front of each spacer layer was replanarized prior to deposition of the QDs.²¹ This resulted in strong room temperature PL from the stacked QD layers with similar emission wavelength and linewidth as that of a single layer. It is also worth noting that the final 20 nm of each GaAs spacer layer was grown at 600 °C.

To investigate the effect of *p*-cladding AlGaAs layers grown at low temperatures, two reference thin *p*-clad structures containing InGaAs quantum wells were also grown.

TABLE I. Key growth parameters used for the QDs.

QD layers	V/III ratio	Deposition time (s)	Deposition rate (ML/s)	GRI
3	40	7.7	0.25	None
5	10	7.9	0.25	5 s, no AsH ₃

FIG. 2. To calculate the *Z* ratio, unamplified spontaneous emission was collected from the device sidewall as indicated.

Both QW devices are identical except for the temperature (either 600 or 650 °C) used to grow the top *p*-cladding layers. The QW active region consists of two 7 nm In_{0.2}Ga_{0.8}As QWs separated by a 10 nm GaAs spacer layer. This results in lasing at 970 nm. Both the lower cladding layers and the QW active region were grown at 700 °C. These results are discussed in Sec. III B.

The laser structures were fabricated into 4 μm ridge waveguides using standard lithography and wet chemical etching. Due to the thin upper cladding layer the etch depth was carefully optimized to avoid excess device scattering losses. The mirror facets were left as cleaved (no reflectivity coatings applied) and the devices tested in pulsed mode with a duty cycle of 5% (25 kHz, 2 μs pulse). Unless otherwise specified, the devices were tested at 7 °C. Where current densities are quoted they were calculated using the area of the ridge waveguide and therefore overestimate the current density by a factor of 2–2.5 as a result of current spreading.

To calculate the *Z* ratio the unamplified spontaneous emission was collected from the sidewall parallel to the stripe (not the mirror facet), as shown in Fig. 2. While this is not as ideal as measuring the spontaneous emission through a top contact window, it has been shown to give adequate results.^{22–24} We estimate that at most 10% of the light is reabsorbed as it propagates through the unpumped QD region away from the ridge. Spontaneous emission was also collected from the sidewall with varying stripe-sidewall distances. This indicates only slightly higher reabsorption of the wetting layer emission compared to that of the quantum dots. We therefore believe that measurement of the side wall spontaneous emission is sufficiently reliable for this study. The *Z* ratio was determined by taking the gradient of a plot of $\ln_e J$ against $\ln_e(\sqrt{L})$, where *J* and *L* are the injection current density and light output, respectively. As well as measuring the total light output, electroluminescence spectra were also measured which allowed the QD component to be separated from that of the wetting layer.

III. RESULTS

A. Lasing characteristics of three- and five-stack QD lasers

Figure 3(a) shows a lasing spectrum for a QD device with three-stacked layers of QDs and a cavity length of 4.9 mm. The photoluminescence spectrum for the same sample prior to device fabrication is also shown for comparison while the inset shows the shift in lasing wavelength with

FIG. 3. Lasing spectra for (a) a three-stack QD device and (b) a five-stack QD device. PL spectra prior to device fabrication are also shown for comparison. The inset to each figure shows the variation in lasing wavelength with device length.

cavity length. For each cavity length investigated, the lasing emission was much shorter than the PL peak, indicating that the devices lased from the excited states. Lasing from excited states is a common observation for QD lasers where the ground state gain is limited to between 2 and 10 cm^{-1} per QD layer, while the excited states and even the wetting layer are capable of providing much higher gain.^{1,14,25–28} The limited ground state gain has been attributed to a number of factors including (i) the low QD surface coverage, (ii) incomplete filling of the QD states,^{29,30} (iii) inhomogeneous broadening of the dot states due to the large size distribution inherent to the Stranski-Krastanov (SK) growth mode, and (iv) a low wave function overlap within the dots.³¹

Figure 3(b) shows a lasing spectrum for a five-stack QD device. The photoluminescence spectrum for the same sample prior to device fabrication is again shown for comparison. Due to the different QD growth conditions used for this device, the PL is centered at 1135 nm instead of 1180 nm as for the three-stack QD device. The inset to Fig. 3(b) shows the shift in lasing wavelength with cavity length for this five-stack laser. Clearly, the increased gain volume enables the five-stack device to lase predominantly from the ground state for cavity lengths as short as 1.5 mm. At cavity lengths shorter than 1.5 mm, the lasing wavelength drops rapidly. This indicates that the gain provided by the QD

FIG. 4. Inverse differential efficiency vs device length for the three- and five-stack QD lasers.

ground state is insufficient to overcome the higher cavity losses of these shorter devices. Therefore, in order to sustain lasing, higher lying QD states or even the wetting layer are populated, shifting the emission to shorter wavelength. A similar behavior is also observed for the three-stack laser [see inset to Fig. 3(a)].

Figure 4 shows plots of inverse differential efficiency versus cavity length for the three- and five-stack QD lasers. Linear fits to the data were used to determine absorption losses of 8 and 11 cm^{-1} for the five- and three-stack devices, respectively, while both structures showed internal quantum efficiencies close to 100%. However, due to the considerable scatter of the data points, an accurate calculation of the internal quantum efficiency is difficult. The higher optical loss for the three-stack lasers is most likely a consequence of their excited state lasing, which leads to higher threshold currents and in turn higher free carrier absorption.

Figure 5 shows the threshold current density as a function of device length for the three- and five-stack QD lasers. The threshold current density increases rapidly at cavity lengths shorter than ≈ 2 and ≈ 1.5 mm for the three- and five-stack lasers, respectively. This is correlated with a rapid decrease in the laser wavelength due to saturation of the QD

FIG. 5. Dependence of the threshold current density on cavity length for the three- and five-stack QD lasers.

FIG. 6. Comparison of two reference QW lasers with top AlGaAs cladding layers grown at either 600 or 650 °C. (a) Inverse differential efficiency and (b) threshold current density as a function of device length. All measurements were made at 20 °C.

gain (see Fig. 3). The threshold current density for the five-stack lasers is lower than that of the three-stack lasers for all device lengths. This is attributed to the ground state lasing of this device which avoids population of the excited states. The Z-ratio measurements presented in Sec. III C indicate that population of the excited states can lead to further nonradiative recombination pathways which can substantially increase the device threshold current.

Even for the best five-stack QD devices, threshold current densities of 1.0–1.5 kA/cm^2 were typical and are higher than expected. These high threshold current densities are attributed to several effects. The first of these is current spreading which leads to a larger effective area into which current is injected. A comparison of 50 and 4 μm stripe widths indicates that the threshold current density of the 4 μm stripes is overestimated by a factor between 2 and 2.5 due to current spreading effects. The second factor is related to the relatively low growth temperature used for the upper AlGaAs cladding layers and is discussed in more detail in the following section.

B. Effects of growing AlGaAs cladding layers at low temperature

AlGaAs layers grown at low temperature are known to be of poorer quality.³² To investigate the effect this has on laser performance, two reference QW lasers, with *p*-cladding layers grown at either 600 or 650 °C, were investigated. For both of the QW lasers the bottom cladding layers and QW active region were grown at 700 °C. Figures 6(a) and 6(b) compare the inverse differential efficiency and threshold current density, respectively, for these two reference QW devices. Clearly the lower growth temperature doubles the threshold current density. For example, at a device length of 1 mm, the average threshold current density increases from ≈ 530 to 1100 mA/cm^2 . This means that devices with

FIG. 7. Z ratio as a function of injection current density for (a) the two reference QW lasers (3 mm length, measured at 20 °C) and (b) the three- and five-stack QD lasers (2.8 and 2.5 mm, respectively).

AlGaAs cladding layers grown at low temperature have a lower injection efficiency and must be driven harder to achieve the same carrier recombination in the active region. This is likely due to an increased concentration of nonradiative recombination centers in the upper AlGaAs cladding layers grown at lower temperature. The lower growth temperature also increases the optical losses from 2.4 to 3.6 cm^{-1} , possibly due to increased free carrier absorption and/or scattering, and leads to a slightly poorer internal quantum efficiency.

Interestingly, the QW devices with *p*-cladding layers grown at lower temperature showed a larger scatter in the performance data such as threshold current density and inverse differential efficiency [see Fig. 6(a), for example]. This indicates that the larger scatter may be related to the poorer quality AlGaAs layers.

C. Z-ratio measurements

Z-ratio measurements were made for both the QD and reference QW devices. Figure 7(a) shows typical plots of the Z ratio as a function of injection current density for the two QW lasers. Both QW lasers show similar Z-ratio behaviors. The Z ratio close to 1 at low injection currents indicates that nonradiative recombination dominates, whereas the Z ratio close to 2 just prior to lasing indicates that radiative recombination is significant. However, in the case of the 600 °C growth temperature, the Z-ratio curve is stretched out towards higher current densities. As discussed in Sec. III B, the lower cladding growth temperature reduces the injection efficiency, which essentially scales the injection current. How-

FIG. 8. (a) Spontaneous emission measured at 20 °C from the sidewall of a three-stack InAs/GaAs QD laser (2.8 mm long) for injection currents up to threshold. (b) Modeled electroluminescence spectra assuming a mixed Auger term ($C_2=0.5$). The insets show the integrated quantum dot and wetting layer components as a function of injection current density.

ever, as long as the injection efficiency is the same at all injection currents, the Z-ratio values are unaffected. This is because the Z ratio is defined as a gradient of natural logarithms [see Eq. (1)]. For example, if the Z-ratio values for the 600 °C device are plotted against only half the injection current density, then the two QW Z-ratio curves match closely. This is in agreement with the doubled threshold current densities observed for the device with the lower 600 °C *p*-cladding growth temperature.

Figure 7(b) shows Z-ratio curves for the three- and five-stack QD lasers. The five-stack QD laser, which lases from the ground state, demonstrates similar behavior to the QWs with the Z ratio quickly reaching values of 2 and slightly higher prior to lasing. The three-stack laser, which operates from the excited state, exhibits very different behavior with its Z ratio reaching values of 4 and above. These high Z-ratio values suggest a more complex recombination mechanism within the quantum dot/wetting layer system, possibly related to the excited state lasing of this device. To better understand the origin of the high Z ratio, a simple model was developed which considers the QDs, wetting layer (WL), and GaAs barriers and this is the subject of the next section.

FIG. 9. Schematic of the quantum dot/wetting layer band structure used for modeling.

Before describing the model it is important to mention one other experimental result. This is the relatively small amount of spontaneous emission observed from the wetting layer at high injection currents, in comparison with that from the QDs. Figure 8(a) shows electroluminescence spectra collected from the sidewall of the three-stack QD device. The inset shows the integrated QD and wetting layer emission components. Saturation of the QD emission is clearly observed with increasing injection current. The wetting layer emission appears at injection current densities above 890 A/cm² but contributes little in comparison with the QDs. This adds an extra restraint on the model which must account for reasonably high injection currents without significant wetting layer spontaneous emission.

IV. MODELING

In order to better understand the Z-ratio results for the three-stack QD laser, a simple model was developed which takes into account the QDs, wetting layer, and GaAs barriers, although the barrier contribution turns out to be negligible in both experiment and model. Figure 9 shows a schematic of the QD band structure used for the modeling and the assumed allowed transitions. Transmission electron microscopy studies have shown that the capped InAs quantum dots are small with a diameter and height of 10–12 and 3–4 nm, respectively. Therefore several confined electron levels seem reasonable while it is generally assumed that there are more hole levels than electron levels.^{33,34} The general approach and equations used by the model are described below while the main parameters are summarized in Table II.

The model assumes equilibrium behavior, shown by others to be appropriate at room temperature when large inhomogeneous broadening is present³⁵ and uses a single valence and conduction quasi-Fermi level to describe the combined quantum dot/wetting layer system. As in Ref. 34 the valence quasi-Fermi level was determined for a given conduction quasi-Fermi level by assuming charge neutrality for the combined wetting layer/quantum dot system using the relation

TABLE II. Parameters used for the Z-ratio modeling (Refs. 33 and 37–40).

Parameter	Value
Dot density (cm^{-2}) (N_{dot})	9×10^{10} (accounts for three stacks)
A_{0D} (s^{-1})	1×10^8
A_{2D} (s^{-1})	1×10^8
B_{2D} (cm^2/s)	0.0025
C_{2D} (cm^4/s)	5×10^{-16}
A_{3D} (s^{-1})	1×10^8
B_{3D} (cm^3/s)	1.5×10^{-10}
C_{3D} (cm^6/s)	5×10^{-30}
Spot size (cm)	3×10^{-4}
Refractive index at 1.1 μm (n)	3.45 (for GaAs)
Standard deviation (meV)	
σ_{holes}	20
σ_{e1} (1st electronic level)	25
σ_{e2} (2nd electronic level)	20
Degeneracies	
First electron and hole level	1
Second electron and hole level	1.5
Other hole levels	2

$$N_{\text{dots}} \times (n_{\text{dot}} - p_{\text{dot}}) + N_{\text{WL}} - P_{\text{WL}} = 0, \quad (3)$$

where N_{dots} is the dot density, n_{dot} (p_{dot}) is the number of electrons (holes) per dot, and N_{WL} (P_{WL}) is the wetting layer electron (hole) density.

The carrier density in the quantum dots was then determined from the relation³³

$$p_{\text{dot}} = 2 \sum_{\text{states}} g_{\text{state}} \int G(E) f_h(E) dE, \quad (4)$$

where the summation is over the energy states, g is the state degeneracy, $f_h = 1 - f_v$ is the hole Fermi distribution, and $G(E)$ represents the QD inhomogeneous broadening due to the large QD size distribution and was described by a Gaussian line shape,

$$G(E) = \frac{1}{\sqrt{2\pi}\sigma_{\text{holes}}} e^{-(E - E_{\text{vdot}})^2 / 2\sigma_{\text{holes}}^2}, \quad (5)$$

where E_{vdot} is the dot valence energy and σ is the standard deviation (see Table II).

The thin wetting layer was taken to contain a single subband and the carrier density per unit area determined by³⁶

$$P_{\text{WL}} = \int_{-\infty}^{E_{\text{vw}}} \frac{m_v}{\pi\hbar^2} \left(\frac{1}{1 + e^{F_v - E/kT}} \right) dE$$

$$= \frac{m_v kT}{\pi\hbar^2} \ln \left[1 + e^{-\frac{F_v - E_{\text{vw}}}{kT}} \right], \quad (6)$$

where the parabolic approximation was assumed and E_{vw} and F_v are the valence subband edge and valence quasi-Fermi level, respectively. Analogous equations can also be written for the electrons.

Once the carrier densities are known, the current density consumed within the dots, wetting layer, and GaAs barrier can be determined using

$$J_{\text{dot}} = J_{\text{spdot}} + qN_{\text{dot}}(A_{0D}P_{\text{dot}} + C_1 n_{\text{dot}} p_{\text{dot}}^2 + C_2 n_{\text{dot}} p_{\text{dot}} P_{\text{WL}}), \quad (7)$$

$$J_{\text{WL}} = q(A_{2D}P_{\text{WL}} + B_{2D}P_{\text{WL}}N_{\text{WL}} + C_{2D}N_{\text{WL}}P_{\text{WL}}^2), \quad (8)$$

$$J_b = qd(A_{3D}N_b + B_{3D}N_b^2 + C_{3D}N_b^3), \quad (9)$$

$$J_{\text{tot}} = J_{\text{dot}} + J_{\text{WL}} + J_b, \quad (10)$$

where the coefficients have their usual meanings and d is the GaAs barrier thickness. The values used for the coefficients are summarized in Table II and are typical values for (In)GaAs taken from the literature.^{33,37–41} The expression for J_{dot} includes two Auger terms. The third term is an “unmixed” Auger recombination term involving only the quantum dot carriers while the fourth term is a more complex, “mixed” Auger term corresponding to mixed transitions between the quantum dot and wetting layer states. These two terms are discussed in more detail in the next section. J_{spdot} represents the current density consumed by spontaneous recombination in the dots and was calculated according to the well known equation⁴¹

$$J_{\text{spdot}} = 2qN_{\text{dot}}R_{\text{spdot}}$$

$$= 2qN_{\text{dot}} \int \frac{q^2 n E}{\pi \epsilon_0 c^3 \hbar^2 m_0^2} |M|^2 \left[\sum_{\text{states}} g_{\text{state}} G(E) f_c f_h \right] dE, \quad (11)$$

where $|M|$ is the momentum matrix, m_0 is the free electron mass, $G(E)$ is a Gaussian distribution describing the inhomogeneous broadening of each allowed QD transition, and the envelope wave function overlap is assumed to be 1.

The gain was also determined using⁴¹

$$g(E)_{\text{dot}} = N_{\text{dot}} \frac{1}{\text{spotsize}} \frac{q^2 \pi \hbar}{c n \epsilon_0 E m_0^2} |M|^2$$

$$\times \left[\sum_{\text{states}} 2g_{\text{state}} G(E) (f_c - f_h) \right]. \quad (12)$$

Finally the Z ratio was determined from the current densities according to

$$Z = \frac{d(\ln J)}{d(\ln \sqrt{Rsp})}, \quad (13)$$

$$Z_{\text{tot}} = 2 \frac{R_{\text{sptot}}}{J_{\text{tot}}} \frac{dJ_{\text{tot}}}{dR_{\text{sptot}}}. \quad (14)$$

Z_{tot} is calculated using the combined QD/WL spontaneous emission, R_{sptot} , consistent with the experimental measurement.

V. MODELING RESULTS AND DISCUSSION

In the first pass of the model, the two QD Auger terms in Eq. (7) were not included and only the monomolecular and radiative terms were used to determine the QD current density. The model was otherwise the same as described above and the parameter values listed in Table II were used. Figures 10(a) and 10(b) show these modeled results. Figure 10(a)

FIG. 10. Modeled (a) Z ratio and (b) spontaneous emission as a function of injection current density without inclusion of the QD Auger terms and using the parameters given in Table II.

shows the modeled Z-ratio curve which reaches a maximum value of ≈ 2 . This clearly does not resemble the experimental data in Fig. 7(b), especially for the three-stack laser, where the Z ratio reaches values of 4. Figure 10(b) also shows the modeled QD, WL, and barrier spontaneous emission current densities as a function of the total injected current density. According to Fig. 10(b) a maximum injection current density of only 50 A/cm^2 is possible before the wetting layer emission becomes large, which is also in reasonable agreement with the modeled results reported in Ref. 39. However, this again does not resemble our device behavior, where little WL emission is observed at injection current densities as high as 3000 A/cm^2 [see the electroluminescence (EL) data in Fig. 8(a)]. This current density value is exaggerated by a factor of at least 5 due to the effects of current spreading and reduced injection efficiency (due to poorer quality cladding layers). However, this still means that the model should reproduce current densities on the order of 500 A/cm^2 .

The fact that the quantum dot spontaneous emission saturates in the experiment (see the inset to Fig. 8(a), while the wetting layer emission does not increase rapidly, is clear evidence of a fast, nonradiative, recombination channel. Therefore various nonradiative recombination terms were considered. As shown by Fig. 11(a), one method of achieving high Z-ratio values close to 4 is through a larger nonradiative recombination rate in the wetting layer. However, this requires an unrealistically high monomolecular term $A_{2D} \approx 10^{11} \text{ s}^{-1}$, which is orders of magnitude greater than the typical value of 10^8 s^{-1} assumed for good quality material.^{38,39} The experimental data to date suggest that the QD active region is of good quality. The QDs show strong room temperature PL, long carrier lifetimes of 1 ns, and the absence of dislocations/defects as observed by cross-sectional transmission electron microscopy. Further measurements are needed to better verify the material quality. How-

FIG. 11. Modeled Z ratio with (a) a high monomolecular nonradiative term in the wetting layer and no QD Auger terms, (b) only the unmixed Auger term, and (c) only the mixed Auger term included.

ever, at this stage, it seems unlikely that a greater monomolecular component within the wetting layer and/or barrier is the sole cause of the high Z-ratio values. Therefore other nonradiative mechanisms such as Auger recombination were also investigated.

The possibility of Auger recombination was stimulated by recent reports that a large nonradiative Augerlike component contributes to the threshold current of long wavelength quantum dot lasers.⁴² Several reports also indicate that Auger recombination in QDs can be fast, on the same time scale and competitive with radiative recombination.^{43–46} Two Auger processes, referred to as unmixed and mixed Auger, were considered and are represented by the third and fourth terms, respectively, in the J_{dot} expression [see Eq. (7)]. As discussed below, both Auger terms are able to account for high Z-ratio values. Figure 12 shows schematics of the two processes. In each process an electron and hole in the dot recombine non-radiatively by transferring their energy to a third carrier. In the unmixed case, the third carrier is also within the dot and is excited into the wetting layer continuum. In the mixed case the third carrier is in the wetting layer and excited to a higher energy level. In each of the examples in Fig. 12, holes are shown as the scattered particle. However, the equivalent processes involving electrons may also be possible.

Auger processes in self-assembled QDs are relatively

FIG. 12. Schematics of the two Auger processes considered. The equivalent processes with scattered electrons instead of holes are also possible.

unexplored, which means that the form of the Auger terms and the magnitude of their coefficients are largely unknown. Most reports deal with Auger processes for carrier capture into self-assembled QDs and intradot carrier relaxation.^{45–47} The Auger processes considered here are quite different and are only considered by a few papers.^{37,43,44} Hence each Auger term was considered separately and its coefficient varied to determine whether there was some range over which it might explain the experimental Z-ratio results.

In the case of the unmixed term, the selection rules and number of “extra” hole states not involved in radiative transitions, and their degeneracy, had a considerable impact on the Z-ratio value. Essentially, as the quasi-Fermi level increases, so does the carrier population of these extra hole states. While these extra hole states do not partake in radiative recombination, they do contribute to the nonradiative current via the Auger processes. Therefore, according to the model, a much larger increase in injection current is needed for a small increase in quantum dot spontaneous emission once these extra hole states become populated. This leads to a saturation of the spontaneous emission as seen in the experiments (see inset to Fig. 8) and pushes the Z ratio to higher values as shown in Fig. 11(b). If no extra hole levels are present, then the unmixed Auger term can only account for Z ratios up to 3.5.

The mixed Auger term operates in a similar manner as the unmixed term, except that it does not rely on the presence of extra hole states to achieve high Z ratio values because the wetting layer states are involved. The most significant Auger process for quantum wells tends to be the CHHS process, where a conduction electron (C) and heavy hole (H) recombine to excite a second heavy hole (H) to spin split off band (S). Therefore a linear dependence on the wetting layer hole density was assumed for the QD mixed Auger term. For this term, a value of the coefficient C_2 was estimated by considering the rate equations and Auger coefficient calculations presented in Ref. 48. According to this reference, the capture of holes into the dots is dominated by a term $B_{he}P_{WL}f_e(1-f_h)N_{dot}$, where f_h and f_e are the hole and electron occupation probabilities in the dot, respectively. Since in this study the radiative recombination component is small, it is assumed that most of these captured carriers recombine via Auger recombination. The calculated coefficient B_{he} in Ref. 48 therefore gives an indication of the magnitude of C_2 .

Incorporating a mixed Auger term with coefficient $C_2 = 0.5 \text{ cm}^2/\text{s}$ (of similar magnitude to B_{he} given in Ref. 48) allows good agreement between the model and experiment as seen by the modeled Z-ratio curve in Fig. 11(c). As with the unmixed Auger term, once the Fermi level passes the first conduction state, the carrier population of the excited and wetting layer states increases. The mixed nonradiative Auger transitions then quickly dominate so that a large increase in injection current is again needed for a small increase in quantum dot spontaneous emission, leading to high Z-ratio values. Figure 8(b) shows modeled spontaneous emission spectra with the mixed Auger term included. The modeled spectra are in qualitative agreement with the experiment. With in-

creasing injection currents the excited state spontaneous emission increases relative to that of the ground state without significant wetting layer emission.

Clearly, this model with the nonradiative Auger and wetting layer monomolecular terms is able to account for the high Z-ratio values measured for the three-stack QD devices. It is also consistent with the lower Z-ratio values measured for the five-stack lasers which operate from the ground state. For ground state lasing, population of the excited and wetting layer states should be minimal so that the various nonradiative recombination pathways mentioned above are insignificant. However, as expected of such a simple model, there are some discrepancies between the modeled results and experiment. Most importantly, at lower injection currents the modeled Z ratio increases much more rapidly than in the experiment. For example, in Figs. 11(b) and 11(c) the modeled Z ratio reaches values of 2–3 at an injection current density of only $\approx 10 \text{ A/cm}^2$. This is clearly not consistent with the experimental measurements for the three- and five-stack lasers and indicates that the model is not capturing some of the important carrier dynamics and that further refinement of the Auger terms is likely needed.

VI. SUMMARY

In summary, the lasing characteristics of three- and five-stack InAs/GaAs QD lasers grown using MOCVD have been investigated. By increasing the number of stacked dot layers to 5, lasing was achieved from the ground state for device lengths as short as 1.5 mm. These five-stack lasers showed superior performance compared to the three-stack lasers with threshold currents reduced by half as well as lower optical losses. The threshold current densities for the five-stack lasers are still high, 1 kA/cm^2 . This is attributed to current spreading effects and the low growth temperature used for the upper *p*-cladding layers of the structure. These two effects scale the threshold current by a factor of at least 5.

The Z-ratio dependence on injection current was compared for the three- and five-stack QD lasers. The three-stack lasers exhibited very high Z ratios of 4 and above and this is believed to be linked to the excited state lasing of these devices. A simple model was developed and indicated that high Z-ratios can be generated by three different nonradiative recombination mechanisms: (i) high monomolecular recombination within the wetting layer, (ii) Auger recombination involving carriers within the QDs (unmixed Auger), and (iii) Auger recombination involving both the QD and wetting layer states (mixed Auger). In all three cases, the nonradiative recombination process dominates once the excited and wetting layer states become populated. This leads to a rapid saturation of the QD spontaneous emission with increasing injection current and pushes the Z ratio to values above 4. This suggests that by avoiding excited state lasing, which corresponds to high carrier densities and population of the wetting layer, these three nonradiative processes can be avoided. This is certainly supported by the lower Z-ratio values measured for the five-stack devices which lase from the ground state.

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