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Lasing spectra of 1.55 μm InAs/InP quantum dot lasers: theoretical analysis and comparison with the experiments

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Abstract In this paper, a theoretical model is used to investigate the lasing spectrum properties of InAs/InP (113)B quantum dot (QD) lasers emitting at 1.55 μm. The numerical model used is based on a multi-population rate equation (MPRE) analysis. It takes into account the effect of the competition between the inhomogeneous broadening (due to the QD size dispersion) and the homogenous broadening as well as a nonlinear gain variation associated to a multimode laser emission. The double laser emission and the temperature dependence of lasing spectra of self-assembled InAs/InP quantum dot lasers is studied both experimentally and theoretically.

Keywords Carrier dynamics · Quantum dots · Rate equations · Semiconductor laser

1 Introduction

Low cost, directly modulated lasers will play a major role in the next generation telecommunication links (Local and Metropolitan Area Network) for uncooled and isolator-free applications. As a consequence, semiconductor lasers based on low dimensional heterostructures such as QD laser are very promising. Indeed, QD structures have attracted a lot of attention in the last decade since they exhibit many interesting and useful properties such as low threshold current (Liu et al. 1999), temperature insensitivity (Mikhrin et al. 2005), chirpless behaviour

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(Saito et al. 2000) and optical feedback resistance (O'Brien et al. 2003). Thus, thanks to QD lasers, several steps toward cost reduction can be reached as improving the laser resistance to temperature fluctuation in order to remove temperature control elements (Peltier cooler), or designing feedback resistant laser for isolator-free transmissions and optics-free module. Most investigations reported in the literature deal with InGaAs QD grown on GaAs substrates (Grundmann et al. 2000; Hatori et al. 2000). However, it is important to stress that 1.5 μm-range laser diodes grown on metamorphic layers over a GaAs substrate have been recently reported (Karachinsky et al. 2006) which is detrimental for long-haul optical applications. In order to reach the standards of long-haul transmissions, 1.55 μm InAs QD lasers grown on InP substrate have been developed. More particularly it has been demonstrated that the use of the specific InP(113)B substrate orientation when combined with optimized growth techniques allows the growth of very small (4 nm high) and dense (up to 10^{11} cm^{-2}) QD structures (Caroff et al. 2005). Recent experimental studies conducted on these devices have shown that a second laser peak appears in the laser spectrum increasing the injection power. This double laser emission is a common property found independently by different research groups both for InGaAs/GaAs as well as for InAs/InP systems (Sugawara et al. 2005; Markus et al. 2003a; Platz et al. 2005). The experimental results in (Markus et al. 2003a) have shown a saturation and complete rollover of the first emission after the occurrence of the excited state threshold, while an increasing behaviour for both lasing wavelengths has been observed for an InAs/InP (113)B QD laser (Platz et al. 2005). The origin of the double emission has been explained by the finite ground state (GS) relaxation time using a cascade relaxation model which brings the GS emission to a constant value after the excited state (ES) threshold (Markus et al. 2003b). This approach has been also used to extract the dynamical properties of a QD laser (Gioannini et al. 2006), while the complete rollover has been attributed to an asymmetry in the thermal population redistribution (Viktorov et al. 2005). A comparison between numerical results and experimental ones has recently been conducted by using either a cascade or a direct relaxation channel model (Veselinov et al. 2007). Such a study has led to demonstrate that when a direct relaxation channel from the wetting layer to the ground state is taken into account, the numerical results match very well the measurements and lead to a qualitative understanding of InAs/InP (113)B QD lasers. If no direct relaxation channel is assumed, a good agreement with the experimental results observed in the InAs/GaAs system is obtained.

The aim of this article is to investigate the lasing spectra behaviour of InAs/InP(113)B QD lasers. As a result, a model based on the MPRE is presented. The paper is organized as follows: in Sect. 2 an accurate description of the MPRE model is proposed. More particularly, it is shown that by using the numerical analysis already reported in (Gioannini et al. 2006), many cavity longitudinal modes need to be considered for the calculation of the entire emission spectrum. In order to take into account the inhomogeneous gain broadening of the QD ensemble, it is also shown that various dot populations, each characterized by a ground state (GS) and an excited state (ES) average energy level have to be considered. Then, in Sect. 3, numerical results are presented and compared to experimental ones. At first the double laser emission experimentally observed under optical pumping in QD lasers is analyzed. More particularly, it is shown that a qualitative agreement with the MPRE model is obtained when a direct capture channel from the WL to the GS is included, as already demonstrated in reference (Veselinov et al. 2007). On the other hand, the effect on the lasing spectra characteristics of the homogeneous broadening is investigated. For instance, it is demonstrated that due to the direct channel from the WL to the GS, the GS emission continues to grow (even if the ES starts lasing) without a significant broadening of the GS line. Finally, we summarize our results and conclusions in Sect. 4. Thanks to a numerical model based on a MPRE system and also by taking into account a direct relaxation channel, these results demonstrate the possibility to predict the behaviour of InAs/InP(311B) QD lasers emitting at 1.55 µm. Good agreements with the experimental results, both for the case of the double laser emission and for the effects of the homogeneous broadening on the lasing spectra are demonstrated. This numerical investigation based on carrier dynamics is of prime importance for the optimization of low cost sources for optical telecommunications as well as for a further improvement of QD laser performances at 1.55 µm on InP substrate, as already demonstrated for InAs–GaAs QDs at 1.3 µm (Dagens et al. 2006; Gershutz et al. 2006).

2 Description of the numerical model

In the following, a numerical model is used to study carrier dynamics in the two lowest energy levels of an InAs/InP (113)B QD system. Its active region consists of a QD ensemble, where different dots are interconnected by a wetting layer (WL). For simplicity the existence of higher excited states is neglected and a common carrier reservoir is associated to both the WL and the barrier. In order to include the inhomogeneous broadening of the gain due the dot size fluctuation, the QD ensemble has been divided in n sub-groups each characterized by an average energy of the ES, E_{ESn}, and of the GS, E_{GSn}. The QD are assumed to be always neutral and electrons and holes are treated as eh-pairs and thermal effects and carrier losses in the barrier region are not taken into account. Figure 1 shows a schematic representation of the carrier dynamics in the conduction band of the n-th QD sub-group in the active region. First, an external carrier injection fills directly the WL reservoir with I being the injected current. Some of the eh-pairs are then captured on the fourfold degenerate ES of the QD ensemble with a capture time τ_{ESn}^{WL}. Once on the ES, carriers can relax on the twofold GS (τ_{GSn}^{ES}), be thermally reemitted in the WL reservoir (τ_{WLn}^{ES}) or recombine spontaneously with a spontaneous emission time τ_{ES}^{spon} or by stimulated emission of photons with ES resonance energy. The same dynamic behaviour is followed for the carrier population on the GS level with regard to the ES. This approach has been previously developed for the In(Ga)As/GaAs system (Sugawara et al. 1999; Markus et al. 2003a) but in the case of InAs/InP (113)B system it is assumed that at low injection rates, the relaxation processes are phonon-assisted while the Auger effect dominates when the injection gets larger (Miska et al. 2002). In order to

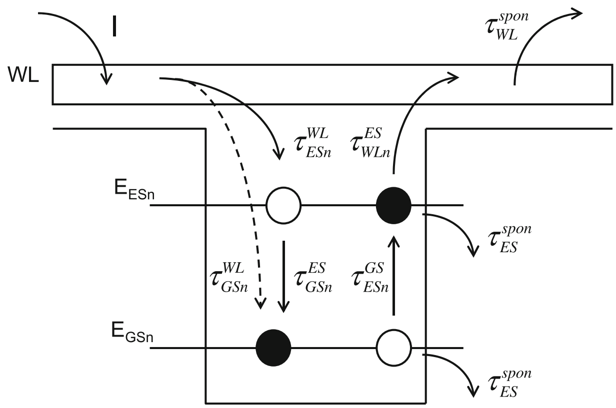

Fig. 1 Schematic representation of the carrier dynamics model with direct relaxation channel (dash line) for the n-th QD sub-group

include this effect, a modified model has been considered introducing a direct relaxation channel (τ_{GSn}^{WL}) to the standard cascade relaxation model as shown in Fig. 1 (dashed line). It is attributed to a single Auger process involving a WL electron captured directly into the GS by transferring its energy to a second WL electron (Ohnesorge et al. 1996). Carriers are either captured from the WL reservoir into the ES or directly into the GS within the same time $\tau_{GSn}^{WL} = \tau_{ESn}^{WL}$. This assumption has been made after analysis of the kinetic curves in (Miska et al. 2002) where the ES and GS populations gave raise simultaneously 10 ps after excitation. On the other hand carriers can also relax from the ES to the GS. The other transition mechanisms remain the same as in the cascade model. The capture and the relaxation times are then calculated through a phenomenological relation depending on the carrier density in the WL reservoir (Berg et al. 2001):

$$\tau_{ES0}^{WL} = \tau_{GS0}^{WL} = \frac{1}{\left(A_W + \frac{C_W N_{WL}}{V_{WL}}\right)} \quad \tau_{GS0}^{ES} = \frac{1}{\left(A_E + \frac{C_E N_{WL}}{V_{WL}}\right)} \tag{1}$$

where N_{WL} is the carrier number in the WL reservoir, V_{WL} is the WL volume and $A_W(A_E)$, $C_W(C_E)$ are the coefficients for phonon and Auger-assisted relaxation respectively, related to the WL and the ES. The final expressions for the n-th sub-group of QD, take also into account the ES and GS occupation probabilities and the fractions of QD associated to the E_{ESn} and E_{GSn} energies:

$$\tau_{ESn}^{WL} = \frac{\tau_{ES0}^{WL}}{(1 - P_{ESn})\, G_{nES}} \quad \tau_{GSn}^{ES} = \frac{\tau_{GS0}^{ES}}{(1 - P_{GSn})} \quad \tau_{GSn}^{WL} = \frac{\tau_{GS0}^{WL}}{(1 - P_{GSn})\, G_{nGS}} \tag{2}$$

P_{ESn} and P_{GSn} are the occupation probabilities of the ES and GS respectively in the n-th sub-group of dots given by:

$$P_{ESn,GSn} = \frac{N_{ESn,GSn}}{\mu_{ES,GS} N_d w L_{ca} N_l G_{nES,nGS}} \tag{3}$$

with $N_{ESn,GSn}$ being the ES and GS carrier number in the n-th sub-group, $\mu_{ES,GS}$ the degeneracy of the considered confined states, N_d the QD surface density, w and L_{ca} the width and length of the active region and N_l being the number of QD layers. A Gaussian QD size distribution has been considered with a consequent Gaussian distribution of the QD recombination energies. Thus, G_{nES} and G_{nGS} represent the fraction of QD associated to the E_{ESn} and E_{GSn} energies. The eh-pairs escape times have been derived considering a Fermi distribution for the ES and GS carriers for the system in quasi-thermal equilibrium without external excitation (Markus et al. 2003b). To ensure this, the carrier escape time is related to the carrier capture and relaxation times as follows:

$$\tau_{ESn}^{GS} = \tau_{GS0}^{ES} \frac{\mu_{GS}}{\mu_{ES}} e^{\frac{E_{ESn} - E_{GSn}}{k_B T}} \quad \tau_{WLn}^{ES} = \tau_{ES0}^{WL} \frac{\mu_{ES} N_d N_l}{\rho_{WLeff}} e^{\frac{E_{WL} - E_{ESn}}{k_B T}}$$
$$\tau_{WLn}^{GS} = \tau_{GS0}^{WL} \frac{\mu_{GS} N_d N_l}{\rho_{WLeff}} e^{\frac{E_{WL} - E_{GSn}}{k_B T}} \tag{4}$$

where ρ_{WLeff} is the effective density of states in the WL and E_{WL} is its emission energy.

The numerical model is based on the MPRE analysis already reported in (Gioannini et al. 2006). According to all those assumptions the MPRE system, describing the change in carrier number of the three electronic energy levels, can be written as:

$$\frac{dN_{WL}}{dt} = \frac{I}{e} + \sum_n \frac{N_{ESn}}{\tau_{WLn}^{ES}} + \sum_n \frac{N_{GSn}}{\tau_{WLn}^{GS}} - \frac{N_{WL}}{\overline{\tau_{ES}^{WL}}} - \frac{N_{WL}}{\tau_{WL}^{spon}} - \frac{N_{WL}}{\overline{\tau_{GS}^{WL}}}$$
$$n = 0, 1, \ldots, N-1 \tag{5}$$

$$\frac{dN_{ESn}}{dt} = \frac{N_{WL}}{\tau_{ESn}^{WL}} + \frac{N_{GSn}\left(1 - P_{ESn}\right)}{\tau_{ESn}^{GS}} - \frac{N_{ESn}}{\tau_{WLn}^{ES}} - \frac{N_{ESn}}{\tau_{GSn}^{ES}} - \frac{N_{ES}}{\tau_{ES}^{spon}} - \frac{c}{n_r}\sum_m g_{mnES} S_m$$
$$m = 0, 1, \ldots, M - 1 \quad (6)$$

$$\frac{dN_{GSn}}{dt} = \frac{N_{ESn}}{\tau_{GSn}^{ES}} + \frac{N_{WL}}{\tau_{GSn}^{WL}} - \frac{N_{GSn}\left(1 - P_{ESn}\right)}{\tau_{ESn}^{GS}} - \frac{N_{GSn}}{\tau_{WLn}^{GS}} - \frac{N_{GS}}{\tau_{GS}^{spon}} - \frac{c}{n_r}\sum_m g_{mnGS} S_m$$
$$m = 0, 1, \ldots, M - 1 \quad (7)$$

with N_{WL} being the carrier number in the wetting layer. In order to calculate the entire emission spectrum, this model has been extended by considering also the presence of many cavity longitudinal modes, hence the photon number with resonant energy of the m-th mode is depicted by S_m:

$$\frac{dS_m}{dt} = \frac{c}{n_r}\sum_n \left(g_{mnES} + g_{mnGS}\right) S_m - \frac{S_m}{\tau_p} + \beta \sum_m \left(B_{ES}\left(E_m - E_{ESn}\right)\frac{N_{ES}}{\tau_{ES}^{spon}} + B_{GS}\left(E_m - E_{GSn}\right)\frac{N_{GS}}{\tau_{GS}^{spon}}\right)\Delta E_m \quad (8)$$

The rate of photons emitted out of the cavity is S_m/τ_p, with τ_p being the photon lifetime. The contribution of the spontaneous emission to the lasing mode is calculated as the sum of the ES and GS spontaneous transitions multiplied by the spontaneous emission coupling factor β, assumed to be constant.

In Eqs. 5–7 the material gain is described by the set of equations:

$$g_{mnES} = \mu_{ES}\frac{\pi e^2 \hbar}{c n_r \varepsilon_0 m_0^2}\frac{N_d}{H}\frac{\left|P_{ES}^{\sigma}\right|^2}{E_{ESn}}\left(2P_{ESn} - 1\right) G_{nES} B_{ES}\left(E_m - E_{ESn}\right) \quad (9)$$

$$g_{mnGS} = \mu_{GS}\frac{\pi e^2 \hbar}{c n_r \varepsilon_0 m_0^2}\frac{N_d}{H}\frac{\left|P_{GS}^{\sigma}\right|^2}{E_{GSn}}\left(2P_{GSn} - 1\right) G_{nGS} B_{GS}\left(E_m - E_{GSn}\right) \quad (10)$$

here H is the average height of the QD and $\left|P_{ES,GS}^{\sigma}\right|^2$ is the transition matrix element given in (Sugawara et al. 2000). Furthermore let us emphasize that the various QD populations are coupled by the homogenous broadening of the stimulated emission process assumed to be Lorentzian.

$$B_{ES,GS}\left(E_m - E_{ESn,GSn}\right) = \frac{\Gamma_{hom}/2\pi}{\left(E_m - E_{ESn,GSn}\right)^2 + \left(\Gamma_{hom}/2\right)^2} \quad (11)$$

with Γ_{hom} being the FWHM of the homogeneous broadening and E_m being the mode energy.

All parameters used in the calculations are summarized in Table 1. In what follows, the MPREM is applied to model the behaviour of InAs/InP(311B) QD laser emitting at 1.55 μm. More particularly, the double laser emission as well as the effects of the temperature on the lasing spectra characteristics is analyzed.

3 Numerical and experimental results

In this paragraph, numerical results are presented and compared to experimental ones. The study starts with the analysis of the double laser emission while the second part is devoted to

Table 1 Parameters of the QD material and laser

QD material parameters	Laser parameters
Emission energy of the WL, $E_{WL} = 1.05\,eV$	Average QD radius, $R = 1.55 \cdot 10^{-6}\,cm$
Spontaneous emission from WL, $\tau_{WL}^{spon} = 500\,ps$	Average QD height, $H = 2 \cdot 10^{-7}\,cm$
Spontaneous emission from ES, $\tau_{ES}^{spon} = 500\,ps$	Mirror reflectivity, $R_1 = R_2 = 0.33$
Spontaneous emission from GS, $\tau_{GS}^{spon} = 1,200\,ps$	Cavity internal losses, $\alpha_i = 10\,cm^{-1}$
WL phonon assisted relaxation, $A_W = 1.35 \cdot 10^{10}\,s^{-1}$	
ES phonon assisted relaxation, $A_E = 1.5 \cdot 10^{10}\,s^{-1}$	
WL Auger coefficient, $C_W = 5 \cdot 10^{-15}\,m^3\,s^{-1}$	
ES Auger coefficient, $C_E = 9 \cdot 10^{-14}\,m^3\,s^{-1}$	

focus on the temperature dependence of lasing spectra of self-assembled InAs/InP quantum dot lasers.

3.1 On the two-state lasing

Recent experimental studies conducted on QD lasers have shown that a second laser peak appears in the laser spectrum as increasing the injection power. This double laser emission is a common property which has already been observed both for InGaAs/GaAs as well as for InAs/InP systems (Sugawara et al. 2005; Markus et al. 2003a; Platz et al. 2005). More particularly, in the case of QD lasers grown on InP substrates, it is has been shown in reference (Veselinov et al. 2007) that when a direct relaxation channel from the WL to the GS is taken into account, the impact of the double laser emission on the light current characteristic can be properly explained.

Let us consider a laser diode composed of an active region with six InAs QD stacked layers (Platz et al. 2005). The cavity length is 2.45 mm with cleaved uncoated facets while the width of the strip is 120 µm. Figure 2a shows the emission spectra as a function of the energy for different values of the pump power normalized with respect to the GS threshold value P_{th}. The optical pumped structure operates at room temperature under 1.06 µm pulsed excitation. The excitation pulse width is set at 13 ns with a repetition rate of 5 kHz. As it can be seen in Fig. 2a, only spontaneous emission is measured at low optical excitation ($0.85 P_{th}$). The peak is centred at 0.82 eV (1.51 µm) close to the peak maximum observed by conventional photoluminescence measurements. With increasing the optical excitation ($1.07 P_{th}$), laser emission occurs at 0.82 eV (1.51 µm). With increasing pumping power density the emission intensity increases. Then a second stimulated emission appears (above $1.45 P_{th}$) centred at 0.87 eV (1.43 µm). The separation between the two emissions (50 meV) corresponds to the energy difference between the GS and the ES measured by time resolved photoluminescence on similar QD (Miska et al. 2002). Figure2b exhibits now the calculated spectra for the same levels of optical pumping. In the calculations the homogenous broadening has been fixed to 10 meV. As it can be seen, numerical results show a good agreement with measurements of Fig. 2a. The GS laser emission is predicted at 0.82 eV for $1.04 P_{th}$. The calculated peak is located at 0.82 eV (1.51 µm). With increasing pumping power density the emission intensity increases. Then a second stimulated emission appears for $2.08 P_{th}$ with a laser peak centred at 0.86 eV (1.44 µm). On the other hand, simulations also show that the GS emission continues to grow (even if the ES starts lasing) without a significant broadening of the GS line. This

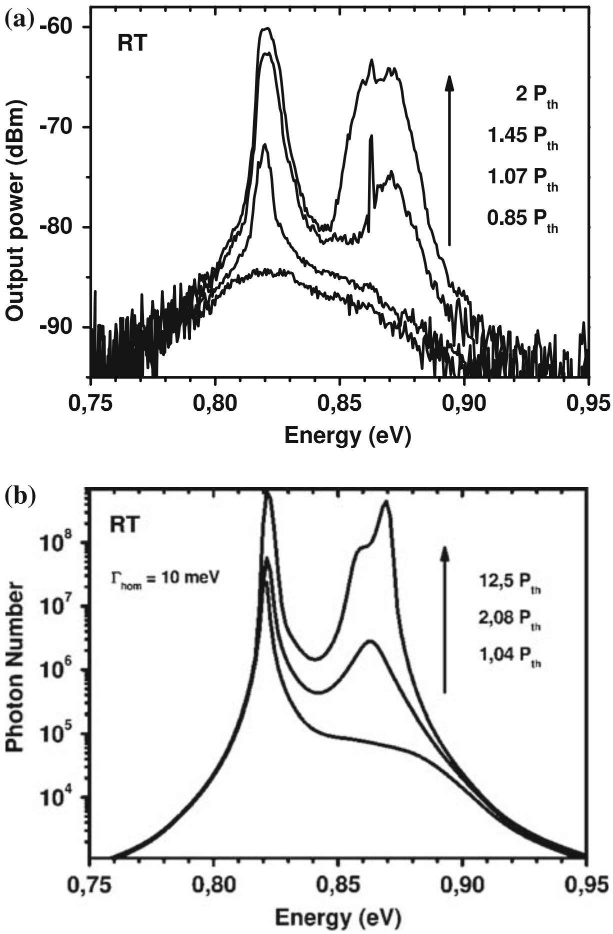

Fig. 2 Room temperature emission spectra of a QD broad area laser with six QD stacked layers (undoped structure) under a pulsed optical excitation a) and simulated laser emission spectra for the same device at $\Gamma_{hom} = 10\,\text{meV}$

effect can be attributed to the direct relaxation channel from the WL to the GS in order to describe properly the behaviour of QD lasers grown on InP has (Veselinov et al. 2007).

3.2 On the effects of the temperature on the lasing characteristic

In order to analyze the effects of the temperature on the spectrum characteristics let us consider a laser diode composed of an active region with one InAs QD layer (Homeyer et al. 2006). The laser structure consists of a waveguide structure comprising 150 nm lattice-matched GaInAsP with a band gap emission wavelength of 1.18 μm (so-called Q1.18) on both sides of the single layer of InAs QDs, self assembled through the Stranski-Krastanov growth mode. A conventional edge emitting laser with a 100 μm wide ridge structure was formed by wet chemical etching. A 5 mm long laser with uncoated as-cleaved facets with an approximate reflectivity of 33% on both sides was fabricated. In Fig. 3, lasing and electroluminescence spectra under pulsed electrical injection are shown for two different temperatures: 110 K (a), and 253 K (b).

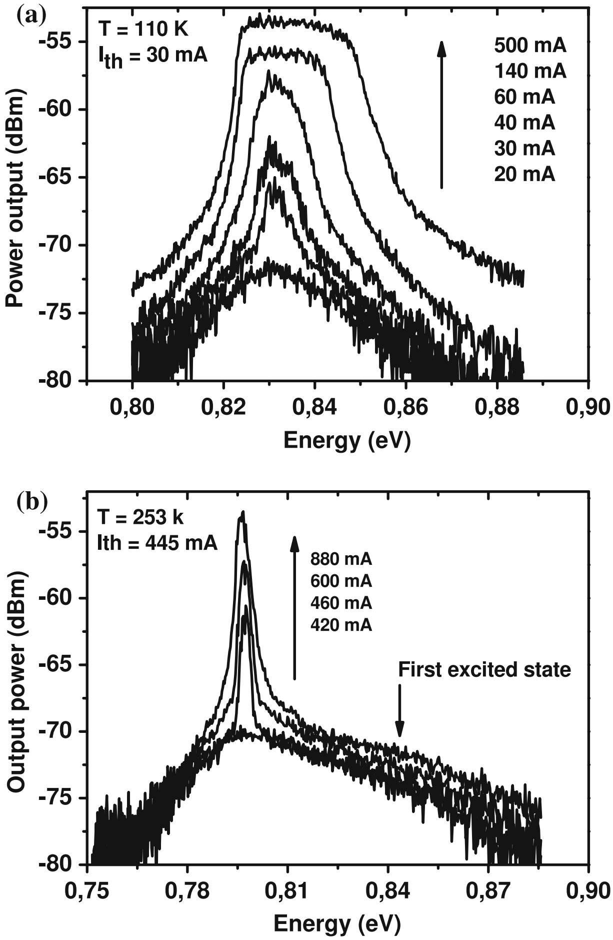

Fig. 3 Lasing and electroluminescence spectra under pulsed injection mode for two different temperatures: (**a**) 110 K and (**b**) 253 K. At each temperature, spectra at several injection currents are displayed and the threshold current (J_{th}) is given

At each temperature, spectra at several injection current are displayed and the threshold current (I_{th}) is given. As it can be seen, a drastic narrowing of the electroluminescence spectra is observed with increasing temperature. Thus, at low temperature (110 K), a very broad-band multimode lasing spectra up to 26 meV width (50 nm) at high injection current (500 mA) is observed. The laser emission progressively narrows with rising temperature, leading to spectra with a width of 2.8 meV (6 nm) at 253 K and for an injected current of 880 mA. The observed temperature dependence of lasing spectra can be explained qualitatively by taking into account the homogeneous broadening of the optical gain of a single dot. At low temperature, when the homogeneous broadening is negligible, dots with different energies have a relatively narrow individual optical gain (narrow single dot linewidth with a FWHM below 2 nm (Sugawara et al. 2000)) and since they are spatially isolated from each other, there is no correlation between the individual emissions. Then, all dots that have an optical gain above the lasing threshold start lasing independently, leading to broad-band lasing emission. On the other hand, when homogeneous broadening is comparable to inhomogeneous broadening, lasing mode photons are emitted not only from energetically resonant dots but also from other non-resonant dots within the range of the homogeneous broadening. This leads to a collective lasing emission with narrow line of a dot ensemble which explains the emission spectra observed at 253 K close to room temperature.

In Fig. 4, calculated spectra corresponding to the laser described above are presented. Case (a) is calculated for a temperature equal to 110 K while case (b) corresponds to a temperature fixed to 253 K. In both cases, a very good agreement with experimental results depicted in Fig. 3 is qualitatively observed. At low temperature, the homogeneous broadening is assumed to be equal to 3 meV in agreement with (Sugawara et al. 2000). As expected, the lasing spectrum is very broad and that corresponds to nearly individual emission of the dots as it has been experimentally observed at low temperature in (Sugawara et al. 1999) and (Homeyer et al. 2006). On the other hand Fig. 4b shows that close to room temperature, when the homogeneous broadening (30 meV in the calculations) reaches the same order of magnitude

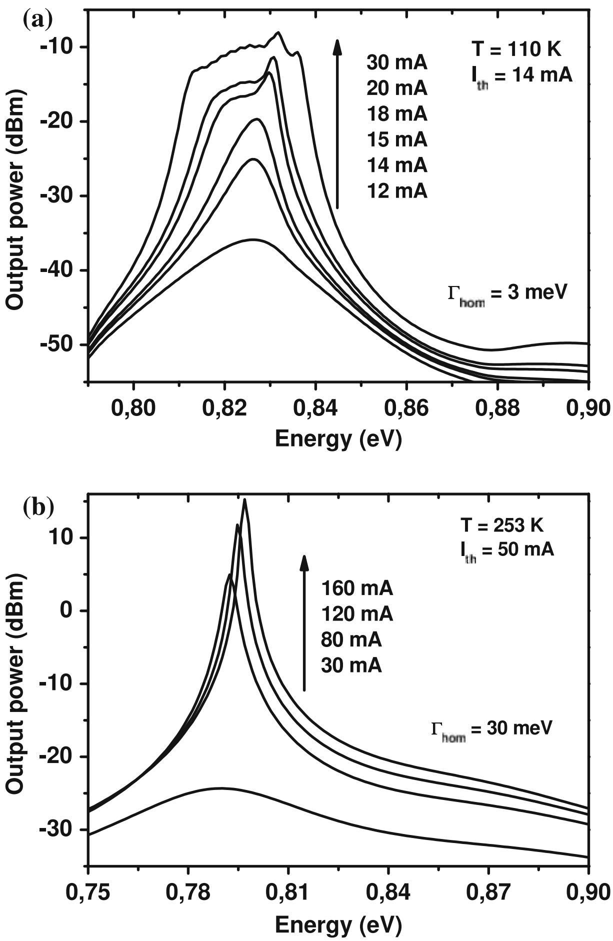

Fig. 4 Calculated emission spectra of a semiconductor laser with a single QD layer on InP(311)B substrate for two different temperatures: (**a**) 110 K and (**b**) 253 K

of the inhomogeneous broadening, it connects spatially isolated and energetically different quantum dots, leading to the collective lasing emission. These simulations demonstrate that dots with different energies start lasing independently at low temperature while at higher ones dots contribute to lasing collectively via homogeneous broadening of optical gain.

4 Conclusion

In this paper, a theoretical model is used to investigate the lasing spectrum properties of InAs/InP (113)B quantum dot (QD) lasers emitting at 1.55 μm. The numerical model is based on a multi-population rate equation (MPRE) analysis. It takes into account the effect of the competition between the inhomogeneous broadening and the homogenous broadening as well as a nonlinear gain variation associated to a multimode laser emission. The double laser emission already reported in QD lasers has been theoretically reproduced. It has been shown that a qualitative agreement with measurements is obtained when a direct relaxation channel from the WL to the GS is taken into account. Then, the temperature dependence of lasing spectra has been studied both experimentally and theoretically. While lasing occurred with a narrow line, including a few longitudinal modes close to room temperature, spectra at 110 K showed broad-band lasing emission over a range of ∼50 meV. Based on the MPRE model, it has been shown that dots with different energies start lasing independently at low temperature due to their spatial localization while at room temperature the dot ensemble contributes to a narrow line lasing collectively via the homogeneous broadening of optical gain. This is the first numerical study of those effects occurring in 1.55 μm InAs/InP(311B) quantum-dot lasers which confirm the experimental results already published in (Platz et al. 2005; Homeyer et al. 2006).

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