Localized Auger Recombination in Quantum-Dot Lasers

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***Abstract*—We have calculated radiative and Auger recombination rates due to localized recombination in individual dots, for an ensemble of 10^6 dots with carriers occupying the inhomogeneous distribution of energy states according to global Fermi–Dirac statistics. The recombination rates cannot be represented by simple power laws, though the Auger rate has a stronger dependence on the ensemble electron population than radiative recombination. Using single-dot recombination probabilities which are independent of temperature, the ensemble recombination rates and modal gain decrease with increasing temperature at fixed population. The net effect is that the threshold current density increases with increasing temperature due to the increase in threshold carrier density. The most significant consequence of these effects is that the temperature dependence of the Auger recombination rate at threshold is much weaker than in quantum wells, being characterized by a T_0 value of about 325 K. Observations of a strong temperature dependence of threshold in quantum dot lasers may have explanations other than Auger recombination, such as recombination from higher lying states, or carrier leakage.**

***Index Terms*—Auger recombination, quantum-dot lasers, recombination proceses, temperature-dependence of threshold current.**

I. Introduction

SEMICONDUCTOR quantum-dot (QD) lasers offer the prospect of devices with a low threshold current density which is insensitive to temperature due to the discrete and localized nature of the quantum states [1]. However experiments show that the threshold current of QD lasers is not necessarily temperature insensitive [2], and this may be due to some or all of several factors.

1) If there is an inhomogeneous distribution of dot energy states the intrinsic spontaneous recombination current at fixed peak gain increases with temperature due to the increasing thermally-induced spread of carriers among the dot states.
2) Auger recombination *within the dots* contributes to threshold current [3] and its temperature dependence [4].
3) Carriers may be thermally excited to the wetting layer [5], [19] where they may recombine radiatively or nonradiatively, contributing to the current.
4) Deep-state related nonradiative recombination in the dots may also contribute to the temperature dependence of threshold.

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Component (3) depends on the energy separation between the dot states and the band edge of the wetting layer, whereas processes (1) and (2) are intrinsic to any dot system. Considerable attention has focussed on Auger recombination in dot lasers and Marco *et al.* [3] suggest it is the dominant nonraditaive contribution, so we will not consider process (4) further. It has been suggested that the contribution of Auger recombination to the threshold current may decrease with increasing temperature [4], in contrast to quantum-well (QW) devices where Auger recombination is largely responsible for the strong sensitivity of threshold current in 1.55-μm lasers, contributing a threshold current component proportional to T^3.

The fundamental difference between well and dot systems is that in the latter carriers are fully localized at individual dots, but consequences of this for analysis of the threshold current components in dot lasers have not been investigated. Since QDs provide a localization potential which is many multiples of k_BT at room temperature (typically 10 k_BT for electrons) we expect the effects of localization to be apparent in laser characteristics.

The purpose of this paper is to explore the consequences of localized intrinsic radiative and Auger recombination at *individual* dots by considering recombination at a single dot then performing a computer calculation to sum over an ensemble of dots. To put this in context we first summarize the methods used to analyse the temperature dependence of threshold in QWs, and the applicability of these to dots.

II. Background

The temperature dependence of the spontaneous radiative current at threshold can be determined by measurement of the spontaneous emission itself under threshold conditions [6] and this can be extended to identify radiative recombination in barrier regions [7]. However, identification of the nonradiative currents (2) and (3) is more difficult because they cannot be observed directly. In QWs, in the Boltzmann approximation the raditive recombination rate is bimolecular, $R_{\rm spon} = B(T)n^2$ where B is the radiative recombination coefficient and n is the carrier density. The Auger rate, subject to energy and k-conservation, varies as $R_A = C_An^3$ where C_A is the Auger coefficient [8]. For a QW laser the carrier density at threshold is proportional to T so when combined with the T^{-1} dependence of the radiative recombination coefficient [9] the radiative rate at threshold is proportional to temperature. For Auger recombination the temperature dependence of C_A is often ignored so the n^3 dependence combined with $n_{th} \approx T$ contributes a temperature dependence of T^3 to the threshold current. The quadratic and cubic dependences of the radiative and Auger rates on *carrier density* are the primary origin of the characteristic temperature dependences.

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The distinctive T and T^3 dependences of the radiative and Auger recombination rates have used to identify these processes in QW lasers [10], though these models have limitations. They apply only in the Boltzmann approximation, they characterize each process by a single coefficient B and $C_{A,}$ each of which is taken to be independent of carrier density and many body interactions are neglected. This power law methodology has also been used to analyse QD systems [11], [20], [12]. Fathpour *et al.* [4] have used an Auger process described by a coefficient, derived from a power law analysis of the recombination lifetime [12] in a model which includes all the contributions listed above to obtain a description of the measured temperature dependence of QD laser threshold current. The current components were not isolated experimentally, and their individual contributions were obtained from a fit to the total current.

The power law dependences for wells derive from their plane-wave, extended state wavefunctions: overlap between initial and final states permits recombination between electrons and holes in the global population in a specific well, subject to the requirements of energy and k-selection [8]. For a fully localized system of uncoupled dots, wavefunction overlap permits recombination only between electrons and holes in the same dot: in effect this is "location selection" rather than k-selection, and the total rate for an ensemble must be obtained by summing over all dots. This is unlikely to lead to a simple quadratic or cubic dependence of the total rate on the total carrier population of the ensemble [13].

Experimentally the total nonradiative rate in dot systems can be identified as the difference between the total current and the radiative current [3], but it is not easy to identify the individual nonradiative components without making some assumptions regarding their behaviour. The identification of a wetting layer contribution usually rests on an assumed model for Auger recombination (as for example in ref [4]) and in this paper we examine localized radiative and Auger recombination, processes which are central to the analysis of threshold current components.

Our treatment is at the same level of approximation as that used to perform power law analyses of QW devices to enable direct comparisons to be made with this methodology. We recognize that representation of a recombination processes by a single parameter (in our case a lifetime) is not a full description, however if carrier localization is shown to have an effect at this level then a localized treatment should be a feature of calculations which incorporate effects such as correlations within the dot and interactions with the large population of carriers in the wetting layer.

The contribution of this work is demonstration that the radiative and Auger recombination rates of an ensemble cannot be represented by simple power law dependences on total carrier density when the recombination processes are localized at individual dots. Furthermore, this has direct consequences for the temperature dependence of these current components at threshold, and for the identification of the origins of the temperature sensitivity of threshold in QDs lasers, even in the presence of current contributions from the wetting layer.

III. Computational Model

We modelled an inhomogeneous ensemble of 10^6 InAs–GaAs dots with peak transition wavelength of 1.24 μm (1 eV) and ground state energy distribution of total width at half height of about 50 meV. In each dot there were two (e) and two (h) spin states in the ground state, and the excited state was doubly degenerate with two (e) and two (h) states of opposite spin. The wetting layer had transition energy 1.32 eV. Experimental studies suggest that a thermal carrier distribution is appropriate at room temperature though it may not apply in certain systems below about 100 K[14] The electron and hole distributions were individually described by Fermi–Dirac (FD) statistics and the electron and hole populations in dots plus wetting layer were set to be equal to determine the quasi-Fermi level positions, consequently the overall dot ensemble is not electrically neutral. The occupation probability was taken to be the *fraction of dot states with full occupancy* so each state within an individual dot was occupied (independently) by an integer number of electrons and holes. In this model the number of electrons and holes *in each dot* are not necessarily equal. From the FD occupation probability (f_e, f_h) of a pair of states at a particular transition energy E, we computed the probability of dot states being occupied with i electrons in the ground state and j in the excited state for a dot as

$$p_{i,j} = \frac{2!}{i!(2-i)!}[f_{e,gr}]^i\,[1-f_{e,gr}]^{2-i} \times \frac{4!}{j!(4-j)!}\,[f_{e,\mathrm{ex}}]^j\,[1-f_{e,\mathrm{ex}}]^{4-j}. \quad (1)$$

The numbers i and j have values of (0, 1, 2), and (0, 1, 2, 3, 4), respectively. The number of microstates with configuration $(i,j), N_i^j(E)$, is then $N_j^i(E) = p_{i,j}N_{\mathrm{dots}}(E)$ where $N_{\mathrm{dots}}(E)$ is the number of dots in the inhomogeneous distribution with an energy state separation $E; N_i^j(E)$ is the integer value. Similar quantities $p_{l,m}$ and $P_l^m(E)$ were obtained for the holes.

We assumed that ground state (e) only recombine radiatively with ground state (h) of the same spin, resulting in a maximum of two ground state transitions for a fully occupied dot. For the excited state, only transitions between (e) and (h) of the same spin and in the same quantum state were allowed, resulting in a maximum of four transitions per dot. This is consistent with the observation that the absorption strength for the excited states is twice that of the ground state [15]. The radiative rate between ground states within a *single dot* is

$$R_{\mathrm{rad}}^g(i,l) = 2\frac{1}{\tau_r}\left(\frac{i}{2}\right)\left(\frac{l}{2}\right) \quad (2)$$

where the radiative transition probability between a pair of singly occupied states is $(1/\tau_r)$ per unit time, taken to be the same for all states. (Use of a coefficient relating the rate to the total carrier population is not appropriate for a dot) The radiative rate between excited states with occupancy (j,m) is

$$R_{\mathrm{rad}}^e(j,m) = 4\frac{1}{\tau_r}\left(\frac{j}{4}\right)\left(\frac{m}{4}\right). \quad (3)$$

Electrons and holes were distributed randomly and independently amongst dots of the same size (distribution between different size dots being determined by the FD function) so the radiative rate of the ensemble was obtained by summing over all microstates

$$R_{\mathrm{rad}}^g(\mathrm{tot}) = N_{\mathrm{dots}} \sum_{i,j,l,m} p_{i,j}p_{l,m}R_{\mathrm{rad}}^{\mathrm{gs}}(i,l) \quad (4)$$

and similarly for the excited state rate.

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The role of Auger processes in carrier cooling in dots has received considerable attention, but there is little published work on Auger recombination *within* dots (see comments in ref 3). To be specific, we consider a process whereby an electron (e) recombines with a hole (h) in the same dot and excites a second electron (e') from the dot into a high-lying continuum state in the wetting layer (assumed empty). The envelope functions of the dot states involve a spread of values of k to describe the localization, consequently the recombination probability is determined primarily by energy conservation [16]. Though the (e) and (h) dot states are discrete, the final state for (e') lies in the wetting layer continuum so this can be satisfied. The Auger rate in a single dot, therefore, depends on the recombination probability and the electron and hole occupancy. Other Auger mechanisms may occur, but our intention is to identify effects of localization, and choice of any of the possible processes would be sufficient for this purpose. The probability per unit time for a single Auger event $(1/\tau_A)$ contains the matrix elements and energy conservation within a single dot. Ignoring spin, the ground state Auger rate in a single dot was taken to be

$$R^g_{\mathrm{Aug}}(i,l) = \frac{l}{\tau_A} \qquad \text{in dots with } i = 2 \text{ electrons.} \quad (5)$$

For the excited state the rate is proportional to the number of holes on the dot and the number of ways j electrons can be distributed in pairs among four states

$$R^e_{\mathrm{Aug}}(j,m) = \frac{m}{\tau_A}\frac{j!}{2!(j-2)!} \qquad j \geq .2 \quad (6)$$

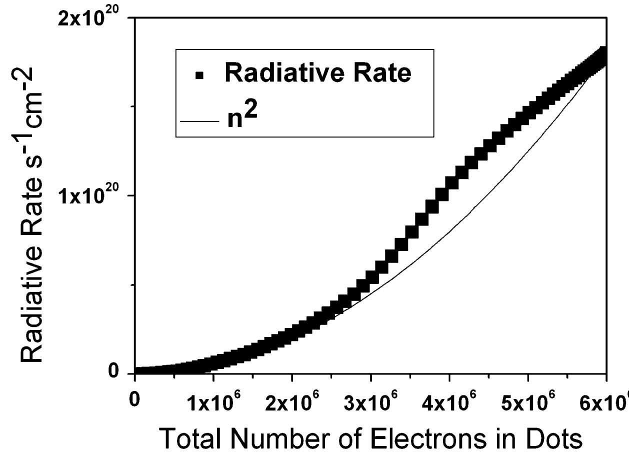
The total Auger rate for the ensemble was obtained by summing over all dots in a similar manner to (4).

IV. Results

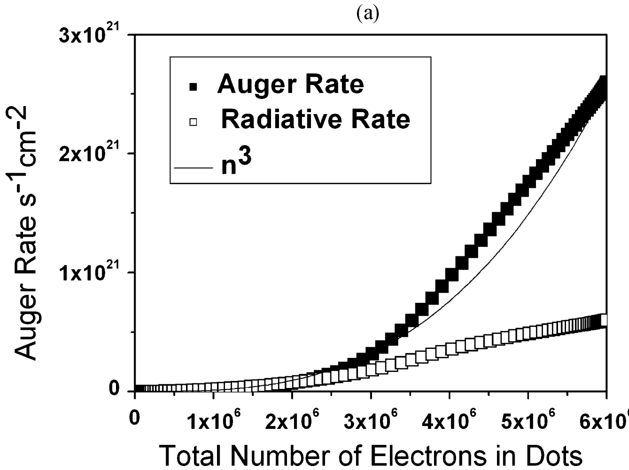
Calculations were performed for an ensemble of 10^6 dots and an area corresponding to a single layer dot density of 3×10^{10} cm^{-2}. The values chosen for the single-dot lifetimes were estimated as follows. The radiative lifetime in a single dot, averaged over the ensemble, was obtained from the measured optical absorption cross section (defined in [15]) by application of the Einstein relations. For the ground state we measure the integrated absorption cross section of dots in 1.3-μm emitters to be about 0.27×10^{-15} cm$^{-2}\cdot$ eV^{-1} which yields a lifetime of 1.7 ns. An appropriate value for the Auger lifetime in a single dot is difficult to determine, and in the absence of any reliable guidance from the literature we have chosen single dot radiative and Auger rates of $1/\tau_r = 10^9$ s^{-1} and $1/\tau_A = 3.33\times10^9$ s^{-1} [for all plots except the radiative rate in Fig. 1(b)]. We show below that these values give reasonable results for the threshold current density.

Fig. 1 shows the total (ground state plus excited state) radiative and Auger recombination rates as functions of the number of electrons (n_{dots}) occupying the ensemble at 300 K; the total number of dot states available is $(2\mathrm{gs} + 4\mathrm{es}) \times 10^6 = 6 \times 10^6$. On Fig. 1(b) we also show the radiative rate calculated using the same value for single dot radiative lifetime as for the Auger lifetime $(1/\tau_r = 3.33 \times 10^9$ s$^{-1})$. This shows that at high occupancy the Auger rate of the ensemble becomes large relative to the radiative rate due to the high degeneracy of the excited states: when all states are full (3) and (6) give $(4N_{\mathrm{dot}}/\tau_r)$ and $(24N_{\mathrm{dot}}/\tau_A)$ for excited state radiative and Auger rates respectively. Thus, localized states with high degeneracy favour Auger recombination, and localization in states with low degeneracy suppresses the strong dependence on ensemble population found in QWs. The Auger rate increases faster than the radiative rate with increasing n_{dots} because the probability of two (e) and one (h) in the same dot is more sensitive to n_{dot} than one (e) and one (h) needed for radiative recombination. However, these dependencies cannot be represented by n^2 and n^3 laws (Fig. 1), especially at high occupancies needed for population inversion where the power law dependence is suppressed by localization.

The carrier population in the wetting layer is less than 2.5% of the total population at all temperatures so the total current in our model is determined by the process of interest for this paper, namely radiative and Auger recombination. Fig. 2 shows the energy distributions of electrons at ensemble carrier populations



(a)



(b)

Fig. 1. (a) Calculated ensemble radiative and (b) Auger recombination rates for ground plus excited states as functions of electron population on the dots at 300 K (solid points). Since the excited state is doubly degenerate each dot can accommodate a maximum of three electrons of each spin: six electrons in all. The continuous lines represent n^2 and n^3 functions. The lower figure also shows the radiative rate (open symbols) calculated using the same value of carrier lifetime as used for Auger recombination $(1/\tau_r = 3.33 \times 10^9$ s$^{-1})$.

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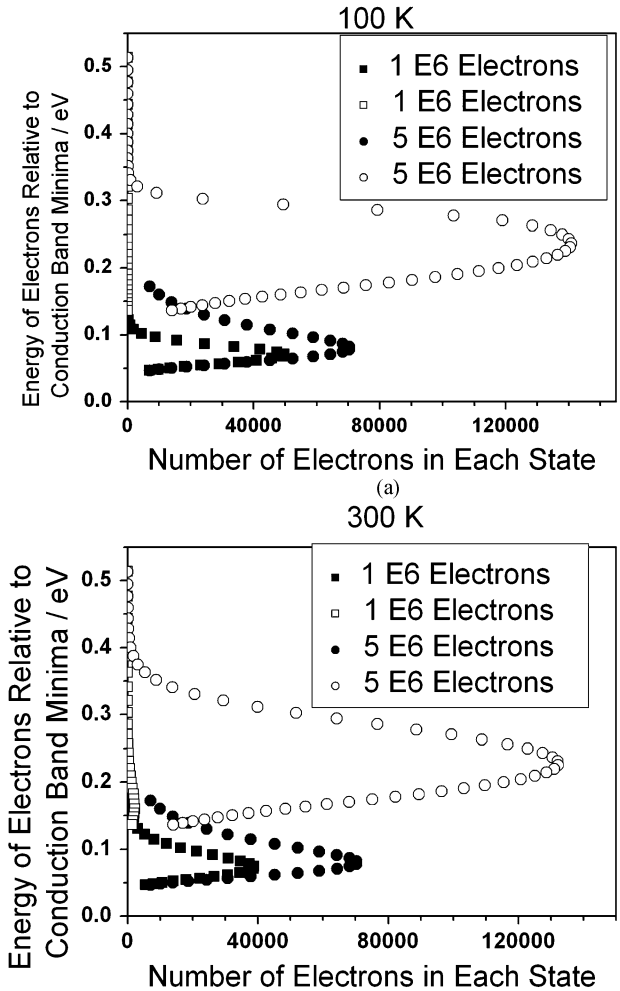

Fig. 2. Energy distributions of electrons in ground and excited states for total ensemble populations of 1×10^6 and 5×10^6 electrons. (a) 100 K. (b) 300 K.

of 1×10^6 and 5×10^6 at 100 and 300 K, showing the relative population of the ground and excited states and the wider energy spread of carriers in the excited states at higher temperatures.

Experimentally we observe that the spectrally-integrated absorption cross section of a dot does not depend on temperature so we know that the radiaitve recombination lifetime in a single dot must be temperature independent. In the absence of any other information we adopt the simplest assumption that the Auger lifetime in a single dot is also temperature independent (This is equivalent to saying that the temperature dependence of $C_A$in a QW system can be ignored, which is often assumed to be the case.) Using the values as above for $1/\tau_r$ and $1/\tau_A$ the recombination rates at fixed $n_{\rm dot}$ go down with increasing temperature. Examination of the energy distributions (Fig. 2) shows this is because carriers are distributed over a wider range of energy states at higher temperature and hence over a greater number of *localized* dots, reducing the probability of the required (e) and (h) occupancies in the same dot. We define the *average* overall lifetime of carriers in the *ensemble*

$$\tau = \frac{R_{\rm rad} + R_{\rm Auger}}{(n_{\rm dot}/{\rm area})} \tag{7}$$

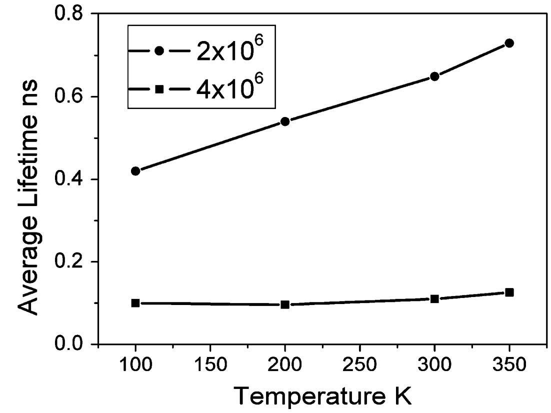

Fig. 3. Average lifetime of carriers in the ensemble due to the sum of radiative and Auger recombination as a function of temperature for electron populations of 2×10^6 and 4×10^6 (average populations of 2 and 4 electrons per dot).

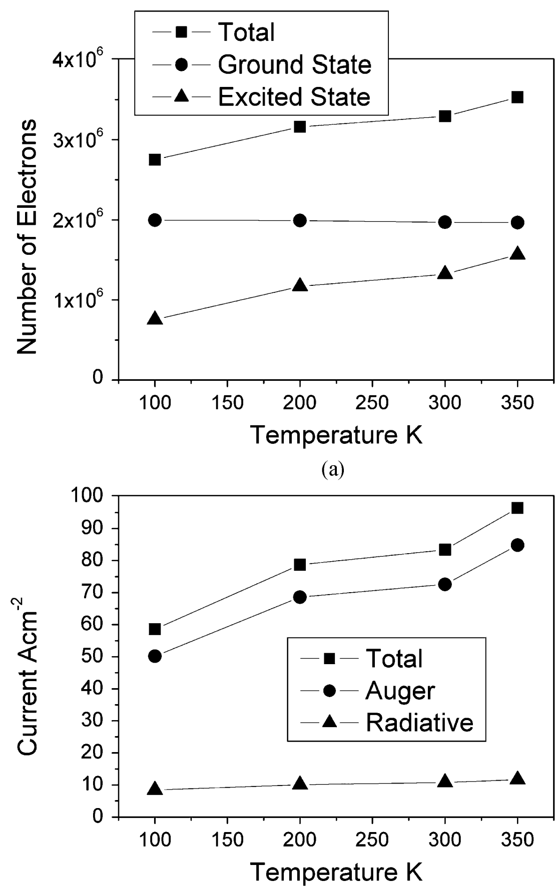

Fig. 4. (a) Temperature dependence of the electron population in ground and excited states for a peak modal gain of 4 cm^{-1} provided by the ground state. (b) Temperature dependence of the threshold radiative, Auger, and total recombination currents.

where $(n_{\rm dots}/{\rm area})$ gives the number of ensemble electrons per unit area. Fig. 3 shows that the average ensemble lifetimes, calculated for populations of 2×10^6 and 4×10^6, increase with temperature, particularly when carriers first begin to populate excited states.

We have calculated the modal gain due to *localized* stimulated recombination, with its probability obtained from $(1/\tau_r)$ by the Einstein relations. For a peak modal gain of 4 cm^{-1}, Fig. 4(a)

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shows the threshold ensemble carrier populations in the ground and excited states. At all temperatures shown the gain is provided by the ground states, which are almost fully occupied. The excited state is also populated and the total electron population at threshold $n_{\rm th}$ increases with temperature due to thermal redistribution of carriers to the excited states. Fig. 4(b) shows that the threshold current density corresponding to these threshold densities increases with temperature.

V. Limitations of the Model

We have constructed a model dot system to gain insight into the characteristics of recombination processes which are localized at individual dots and for these to be relevant the model should replicate the characteristics in real structures, while being subject to the limitations recognized in the penultimate paragraph of Section II.

We note first that the predicted threshold current for a modal gain of 4 cm^{-1} is about 100 $\text{A}\cdot\text{cm}^{-2}$ at 300 K for a single dot layer of density 3×10^{10} cm^{-2}; this is reasonable when compared with a typical experimental value of 89 $\text{A}\cdot\text{cm}^{-2}$for a 4-mm-long device having a similar threshold modal gain requirement [17]. There may also be contributions of defect recombination and leakage current to experimental results. While we represent the recombination processes by single lifetimes we are confident in the value used for the radiative lifetime since it was obtained from absorption measurements and the stimulated lifetime was obtained from the same experimental data. We, therefore, conclude that the reasonable values for threshold current density suggests the value chosen for the Auger lifetime is of the right order of magnitude.

We have assumed thermal population of the dot states which is supported by experimental evidence [14]. An alternative is the random population model (RPM) [18] wherein all dots have an equal probability of occupation with an electron–hole pair irrespective of the energy of the states within the inhomogeneous distribution. This model is regarded as being applicable at low temperatures where thermal exchange between dots and the wetting layer is suppressed. Since the RPM carrier distribution does not change with temperature, in this model there is no temperature variation of the ensemble carrier density required for a particular value of peak modal gain. Furthermore since every electron always has a hole available in the same dot the radiative recombination rate at fixed carrier density is not temperature dependent other than through any temperature dependence of the single dot lifetimes and we know that the single dot radiative lifetime does not vary with temperature. The RPM does not provide a likely basis for an explanation of the observed temperature dependence of threshold current over the range considered, 100–350 K.

VI. Discussion

A number of comments and conclusions can be made based on the results in Section IV.

- At the same level of approximation as that used for QW power law models, the radiative and Auger recombination rates in dots cannot be represented by power law dependences on ensemble carrier population (Fig. 1). This follows from the probabilities of individual dots containing the required populations of electrons and holes in a localized model and this conclusion is not influenced by the lifetime values: these determine the magnitude of the components. The specific form of the carrier density dependence depends the degeneracy of the dot states.
- Our results for the ensemble lifetime decrease with increasing temperature (Fig. 3). Laser turn-on delay provides an indication of the overall carrier lifetime [8] and *experimental measurements* on QD lasers [ref [12] Fig. 2b] show the turn-on delay in QD lasers increases with temperature in support of our results. While our work suggests that the power law *analysis* of this data [12] is not appropriate to dots, the *experimental measurements* themselves provide support for our results.
- Although the ensemble carrier lifetime increases with temperature (Fig. 3), the computed threshold current density $(J_{\rm th})$ increases with temperature. This is because the increase in n_{th} with temperature overcomes the lengthening ensemble lifetime.
- The model used to calculate the optical gain determines the quasi-Fermi level positions which are central to the calculation of the wetting layer carrier density and current. Localized stimulated recombination, therefore, affects these quantities and is, therefore, central to the validity of a comprehensive model for all three components. [4] suggests that the ensemble Auger current at threshold decreases with temperature. This is in contrast with our computed results (Fig. 4), probably as a consequence of the use in [12] of a nonlocalized model for radiative recombination and gain.
- Since the power law dependencies of the radiative and Auger recombination rates on ensemble carrier density are suppressed by localization in dots, the temperature dependence of threshold current is reduced compared with QWs. This can be quantified as follows. Over the interval 300–350 K, the temperature dependence of threshold current components due to radiative and Auger recombination have individual T_0 values of about 700 and 325 K, respectively [Fig. 4(b)], values which are significantly higher than for these processes in a QW system where T_0 is 325 and 117 K, respectively, for the T and T^3 dependences. Because T_0 is defined as a fractional change these *component* T_0 values arise from the probability statistics of localization and do not depend upon the lifetime values.
- The T_0 value of the total threshold current does depend on the relative contributions of radiative and Auger recombination, and hence upon the lifetime values. For our model, the total threshold current has T_0 of about 350 K
- The high T_0 of 325 K of the Auger contribution to threshold suggests that, in contrast to a QW, Auger recombination in dots is not synonymous with a strong temperature dependence. Furthermore, treatment of an Auger component on an assumed n^3 or T^3 behaviour may not be valid, with consequences for the identification of Auger recombination and other contributions to the temperature dependence of threshold current. Low values of T_0 observed in some dot systems may arise from other causes, such as thermal excitation to the wetting layer.

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The treatment given here in terms of single-valued single-dot carrier lifetimes with summation over all dots can be incorporated directly into device modelling calculations at this level of approximation, the essence being to allow recombination events only between carriers in the same dot. The principle can be applied with more sophisticated treatments of the recombination process, for example the energy levels in each dot may be depenendent upon the occupancy due to Coulomb interactions and the recombination lifetimes in (2), (3), and (5) similarly may depend on occupancy due to many body effects.

VII. Conclusion

We have calculated radiative and Auger recombination rates for an ensemble of dots due to localized recombination at each dot, with carriers occupying the inhomogeneous distribution of energy states according to global FD statistics. The recombination rates cannot be represented by simple power laws, though the Auger rate has a stronger dependence on the ensemble electron population than radiative recombination. Assuming the single-dot recombination probabilities are independent of temperature, the ensemble recombination rates and modal gain decrease with increasing temperature at fixed population. This is due to increasing thermal redistribution of carriers among the dot states. The net effect is that the threshold current density increases with increasing temperature due to the increase in threshold carrier density. The most significant consequence of these effects is that, due to the occupation probability statistics of a localized system, the temperature dependence of the Auger recombination rate at threshold is much weaker than in QWs, being characterized by a T_0 value of about 325 K so the presence of an Auger component is not synonymous with a strong temperature dependence. Observations of a strong temperature dependence of threshold in QD lasers may have other explanations, such as recombination from higher states, or junction leakage and our work suggests that a localized treatment of the intrinsic dot processes is necessary to quantify such processes from measurements of the total current.

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