

## Effect of Auger recombination on the performance of $p$ -doped quantum dot lasers

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Experimental results on spontaneous emission rates from InGaAs quantum dot lasers that can be explained theoretically by considering the influence of nonradiative mixed state recombinations in the quantum dot-wetting layer system are presented. Our model qualitatively explains the experimental results such as an increase in the threshold current density, temperature stability, and a narrower gain spectrum due to doping the quantum dot active region with the acceptors. Our model also predicts that moderate acceptor concentrations can improve the laser performance at higher carrier injection densities; but high acceptor concentrations deteriorate the laser performance due to the nonradiative Auger recombination that counteracts the benefits of increased spontaneous emission rates. © 2006 American Institute of Physics. [DOI: 10.1063/1.2193433]

The atomlike density of states in quantum dots (QDs) leads to a narrow gain spectrum and, hence, improved lasing characteristics.<sup>1,2</sup> Following these theoretical predictions, there has been a drive to make GaAs-based QD devices for applications in the communications industry.<sup>3,4</sup> But practical devices are still not able to achieve the theoretically predicted performances.<sup>5–7</sup> It has been suggested that the performance of QD lasers can be improved by  $p$ -type doping, which provides excess hole concentration in the valence band, compensating the deterioration in the laser properties due to the thermal broadening of holes.<sup>8</sup> There have been some reports in the literature on  $p$ -doped QD lasers where some groups reported deterioration, while others reported improvement in the device performance.<sup>5,9,10</sup> Even though there has been experimental evidence that Auger recombination is an intrinsic recombination mechanism for QD lasers,<sup>11,12</sup> the theoretical models presented so far to explain the performance of lasers with a  $p$ -doped active region do not consider nonradiative recombination processes. In this letter, we propose that the nonradiative Auger recombination should be considered to explain the experimental spontaneous recombination rates from the QD sample. We present a simple model that takes into account the nonradiative mixed state recombinations, assuming complete carrier thermalization, to show that moderate  $p$  doping can improve the performance of lasers at higher carrier injection densities, but higher acceptor concentrations may degrade the laser performance.

The 4  $\mu\text{m}$  wide ridge waveguide lasers with five layers of undoped or  $C$ -doped  $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$  QDs in the active region studied in this letter were grown by low-pressure metal-organic chemical-vapor deposition (MOCVD) and tested under pulsed conditions. The unamplified spontaneous emission from the side of the lasers and the edge emission were dispersed through a 0.5 m spectrometer and detected by a cooled InGaAs detector at various injection levels.

Figure 1 shows the  $L$ - $I$  characteristics for lasers with

undoped and doped active regions at 5 and 55 °C. The differential efficiency of the lasers with a doped active region is lower than that of the lasers with an undoped active region in this temperature range. But the change in differential efficiency with temperature is smaller for the doped device (21%) than for the undoped device (31%). The characteristic temperature of the doped device is higher than that of the undoped device. The doped devices show better temperature stabilities than the undoped devices. The  $p$ -doped lasers consistently lase at higher threshold currents than the undoped lasers with similar lengths in the temperature range of 5–55 °C. Theoretical predictions<sup>8,13</sup> suggest that doping the active region of lasers should decrease the transparency carrier density, which in turn should decrease their threshold currents. But our results, which agree with some reports presented in the literature,<sup>7,13</sup> show the contrary. It is worth mentioning that in the above-mentioned temperature range, the doped devices have narrower lasing spectra than that of undoped devices (Fig. 1).

The light output (spontaneous emission rates) from the dot layers, WL, and the total light output (QDs+WL+GaAs barrier) from the doped devices are plotted against the injected current density in Fig. 2. For QDs with a large inhomogeneous broadening, the occupation of different en-

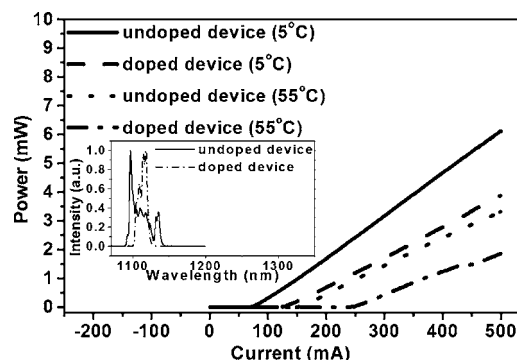


FIG. 1.  $L$ - $I$  plots showing the lasing thresholds at 5 and 55 °C for lasers with undoped and  $C$ -doped InGaAs QDs in the active region. The lengths of the two devices are 2.2 and 2.3 mm, respectively. (Inset) Lasing spectra of devices with undoped and doped active regions at 55 °C for an input current of 420 mA.

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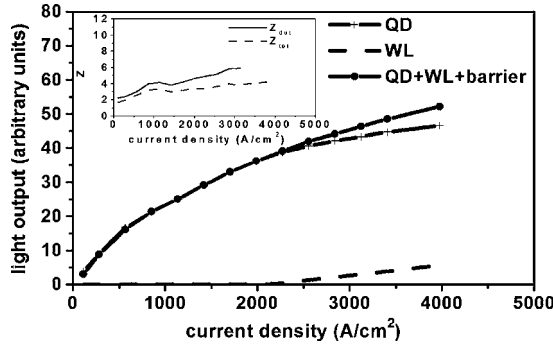


FIG. 2. Light output from the dot layer, WL, and the total light output (QD+WL+barrier) from the side of acceptor-doped QD device as a function of injected current density. The inset shows the variation of “Z” parameter with the current density.

ergy levels in the QD system can be described by a Fermi-Dirac probability distribution with a global Fermi level.<sup>14</sup> Once the electron quasi-Fermi level moves past the highest energy level in the QD, all the energy levels in the dot are occupied and hence the light output and carrier density from the dots saturate, while the contribution to light output and carrier density from the WL should increase, as the quasi-Fermi level moves closer to the WL states. Experimental results (Fig. 2) show that the light output from the WL does not increase considerably, while the light output from the dots saturates. This observation suggests the presence of the Auger recombination, due to the nonradiative mixed state (QD and WL states) transitions.<sup>15</sup> Without the Auger recombination contribution to the total current density, the radiative component from the WL should become dominant for current densities higher than 100 A/cm<sup>2</sup>,<sup>16</sup> which contradicts the experimental observations. The inset of Fig. 2 shows the variation of the experimentally obtained Z (Ref. 17) parameter as a function of the injected current density.

We modeled the light output and gain from the QDs, taking into consideration the nonradiative Auger recombination between the QD and the WL. Our model takes into consideration one electron level and five closely spaced hole levels. We use a Fermi-Dirac probability distribution function with a global Fermi level<sup>14</sup> to determine the occupation of energy levels in the QD and the WL. The quasi-Fermi energy for electron and hole distributions are determined by the level of injection and the charge neutrality condition for the QD and WL systems, respectively. The light output (spontaneous recombination rate per unit area, cm<sup>-2</sup> s<sup>-1</sup>) from the sample can be expressed as

$$\frac{J_{sp}}{q} = R_{sp} = R_{spdot} + R_{spwell} + R_{spb},$$

where  $R_{spdot}$ ,  $R_{spwell}$ , and  $R_{spb}$  are the light output from the QDs, the two-dimensional (2D) WL and the GaAs barriers, respectively. Using the parabolic band approximation for the density of states in the WL and the Boltzmann approximation for the Fermi factors in the GaAs barrier, the light output from the WL and the barrier can be expressed in terms of the 2D radiative recombination coefficient,  $B_{2D}$ <sup>22</sup> and bulk (3-dimensional) radiative recombination coefficient,  $B_{3D}$ <sup>19,20</sup> as  $B_{2D}N_wP_w$  and  $d_bB_{3D}N_b^2$ , respectively,<sup>18</sup> where  $N_w$  and  $P_w$  are the electron and hole areal densities in the WL,  $d_b$  is the thickness of the barriers, and  $N_b$  is the volume carrier density in the barrier. Considering the  $\delta$  function like density of

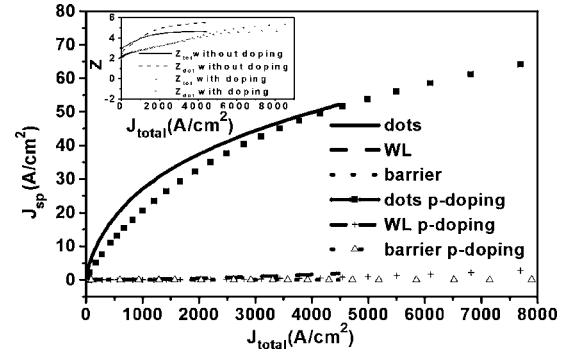


FIG. 3. Calculated radiative current densities from QDs, WL, and the barrier, as a function of total current density, with and without doping; the inset shows  $Z_{dot}$  and  $Z_{tot}$  as a function of total current density, with and without doping.

states and a Gaussian size distribution for QDs, light output from the QDs can be expressed as<sup>18</sup>

$$R_{spdot} = 2N_{dot} \int \frac{q^2 n E |M|^2}{\pi \epsilon_0 c^3 \hbar^2 m_0^2} \left( \sum_i \frac{1}{\sqrt{2\pi\sigma_i}} e^{-(E-E_i)^2/2\sigma_i^2} \right) \times \frac{1}{1 + e^{(E_{ci}-F_c)/E_t}} \cdot \frac{1}{1 + e^{-(E_{vi}-F_v)/E_t}} dE,$$

where  $N_{dot}$  is the areal dot density,  $q$  is the electronic charge,  $n$  is the refractive index,  $M$  is the momentum matrix element,  $\epsilon_0$  is the permittivity of free space,  $c$  is the velocity of light in vacuum,  $m_0$  is the mass of the electron,  $\sigma_i$  is the width of the Gaussian function describing the dot size distribution,  $F_c$  and  $F_v$  are the quasi-Fermi energies in the conduction and valence bands,  $E_t$  is the thermal energy of charge carriers, and  $E_{ci}$  and  $E_{vi}$  are the electron and hole energy levels in a QD corresponding to certain transition energy,  $E$ . The total recombination rates in the dot layer, WL, and the barrier are given by

$$\frac{J_{dot}}{q} = A_{0D}P + R_{spdot} + B_{he}N_{dot}f_c(1-f_v)P_w,$$

$$\frac{J_w}{q} = A_{2D}P_w + B_{2D}P_wN_w + C_{2D}N_wP_w^2,$$

$$\frac{J_b}{q} = d_b(A_{3D}N_b + B_{3D}N_b^2 + C_{3D}N_b^3),$$

respectively, where  $A_{0D}$ ,  $A_{2D}$ , and  $A_{3D}$  are the nonradiative monomolecular recombination coefficients for the QD, WL, and the barrier;<sup>19,21,22</sup>  $B_{he}$  is the Auger capture coefficient that accounts for nonradiative mixed state transitions;<sup>15</sup>  $f_c$ ,  $f_v$  are the Fermi occupancies for the given quasi-Fermi levels  $F_c$  and  $F_v$ , respectively;  $C_{2D}$  is the CHHS Auger coefficient for the WL (considered as a quantum well), and  $C_{3D}$  is the Auger recombination coefficient for bulk GaAs.<sup>19,20,22</sup> The CHCC Auger recombination rate in the WL has been neglected in comparison to the CHHS recombination rate.<sup>19,23</sup>

The gain from the QD layer has been computed using the expression given by Ref. 18.

Figure 3 shows the light output from QDs and WL and GaAs barriers as a function of injected current density as predicted by our model for the undoped and acceptor doped samples. For higher current densities, the spontaneous emission from the samples saturates (at  $\sim 20$ – $60$  A/cm<sup>2</sup>) and

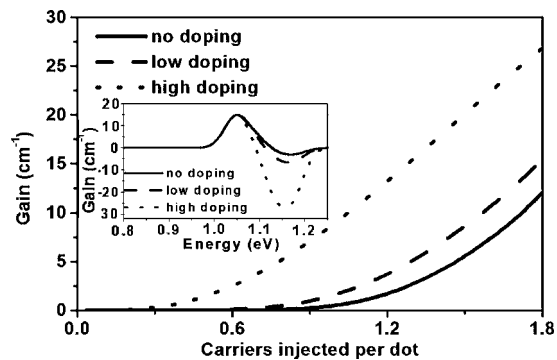


FIG. 4. Maximum gain from the QD layer as a function of the injected carrier density as predicted by the model; the inset shows the calculated gain spectra for undoped and doped QD layers.

rest of the current is consumed by nonradiative Auger recombination involving mixed states from the QD and WL.<sup>19</sup> Our model predicts much higher Auger recombination rates than the radiative recombination rates in the WL or the barrier, which agrees well with the experiment (Fig. 2). It also qualitatively reproduces the behavior of experimental  $Z$  vs  $J$  plots (inset of Figs. 2 and 3), which is not possible without considering the mixed state recombinations.

Our model predicts that with increasing dopant concentration, the spontaneous emission rate from the QDs saturates at higher radiative current densities (Fig. 3) and the QDs have higher gain (figure not shown), but at higher injection current densities. This suggests that we may have higher spontaneous recombination rates and a higher gain from acceptor doped QDs for moderate dopant concentrations, but at higher injection densities. For higher dopant concentrations, spontaneous emission rate and the maximum modal gain from doped QDs may be lower than that of the undoped dots for all practical current densities. Figure 4 shows the maximum modal gain as a function of injected carrier density and the gain spectra for QDs with no doping and with 0.3 and 1 acceptor/dot, where the maximum dopant concentration can be 8 corresponding to five hole levels with degeneracies 1, 1, 2, 2, and 2. As we increase the dopant concentration, the maximum gain that can be obtained from the QDs for a given injected carrier density increases and the gain spectrum for a given maximum modal gain narrows.

A diode laser starts to lase as soon as the maximum gain from the active region equals the losses in the cavity. Even though  $p$  doping reduces the transparency carrier density, the current density at which the maximum gain equals the total losses is higher for lasers with a  $p$ -doped active region due to higher Auger recombination rates. Thus, the behavior of maximum gain and spontaneous emission rate as a function of total injected current density predicted by our model explain higher threshold current densities of  $p$ -doped lasers. The usual explanation of the experimentally observed temperature dependence of the properties of a laser is based on the carrier occupation of higher energy WL and barrier states. The reduction of the carrier density in the barrier and the WL, and the number of injected carriers required for obtaining the same modal gain (Fig. 4) due to doping qualitatively explain the better temperature stabilities of  $p$ -doped lasers. The narrower lasing spectrum of the doped QD laser can also be qualitatively explained in terms of a narrower

gain spectrum from the doped QDs (inset of Fig. 4). In addition to explaining the experimental results on the performance of moderately doped QD lasers, our model predicts that by increasing the acceptor concentrations, the increase in nonradiative Auger recombination component counteracts the benefits of the increased spontaneous emission rate, and deteriorates the laser performance.

In summary, we have presented results on InGaAs QD lasers that show that  $p$ -type doping in the active region increases the threshold current density, improves the temperature dependant characteristics, and leads to a narrower lasing spectrum. These experimental observations can be explained in terms of a simple model that takes into consideration the nonradiative Auger recombination between QD-WL mixed states. Our model qualitatively reproduces the behavior of experimental  $Z$  vs  $J$  plots and spontaneous emission rates from QD samples and predicts that while moderate acceptor concentrations in the active region of a laser can improve its performance, high acceptor concentrations will deteriorate the laser performance.

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