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The role of Auger recombination in the temperature-dependent output characteristics ($T_0=\infty$) of *p*-doped 1.3 μm quantum dot lasers

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Temperature invariant output slope efficiency and threshold current ($T_0=\infty$) in the temperature range of 5–75 °C have been measured for 1.3 μm *p*-doped self-organized quantum dot lasers. Similar undoped quantum dot lasers exhibit $T_0=69$ K in the same temperature range. A self-consistent model has been employed to calculate the various radiative and nonradiative current components in *p*-doped and undoped lasers and to analyze the measured data. It is observed that Auger recombination in the dots plays an important role in determining the threshold current of the *p*-doped lasers. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1829158]

The temperature dependence of the threshold current of quantum dot (QD) lasers is a subject of immense interest, in the context of applications envisaged for these devices. Techniques such as *p*-doping of the dots[1,2] and the use of tunnel injection heterostructures[3] have resulted in reduced temperature dependence of the threshold current and large values of $T_0(I_{th}(T)/I_{th}(0)=\exp(T/T_0))$. We have recently measured temperature-invariant threshold current ($T_0=\infty$) in the temperature range 5–75 °C in 1.3 μm InAs self-organized *p*-doped quantum dot lasers grown by molecular beam epitaxy (MBE).[4] While large values of T_0 have been theoretically predicted[5–7] and measured[1,2] in *p*-doped quantum dot lasers, complete temperature independence of I_{th} is unlikely, since the emission and the density of states function of self-organized quantum dots—either doped or undoped—are broadened inhomogeneously due to size fluctuations. The narrowest photoluminescence linewidth reported for an ensemble of InGaAs self-organized quantum dots is 16–29 meV.[8,9] Therefore, a recombination process, the rate of which possibly deceases with temperature, needs to be considered in order to explain the experimental observations. In the present study we have analyzed the temperature dependence of the threshold current of 1.3 μm *p*-doped self-organized quantum dot lasers by considering radiative and nonradiative recombination processes in the quantum dots, wetting layer, and the GaAs barriers and waveguide regions. It is found that Auger recombination in the quantum dots, whose rate decreases with temperature, plays a significant role in establishing the overall temperature dependence of the threshold current, which is in agreement with the conclusion drawn by Marko *et al.*[10] from hydrostatic pressure-dependent measurements. We have previously determined the temperature-dependent Auger recombination coefficients in self-organized quantum dots from large-signal modulation experiments made on 1.0 μm $In_{0.4}Ga_{0.6}As/GaAs$ quantum dot lasers.[11] Contrary to the trend in higher-dimensional systems, the Auger coefficient *decreases* with increase of temperature, which is a direct consequence of the temperature dependence of electron–hole scattering.[11–15] In this scattering process an excited state electron scatters from holes in the ground state, thereby transferring their energy to the holes and relaxing to the ground state. The energetic holes move to higher energy states, from which they thermalize rapidly by multiphonon emission due to the close proximity of the hole states. In the present study, we have incorporated the trend and very similar values of the measured Auger coefficient[11] in analyzing the threshold currents.

The laser heterostructure, grown by MBE, is shown in Fig. 1(a). The modulation doping of the dots with holes is done by delta-doping with a carbon-doped layer in the GaAs waveguide region separated from the quantum dots by 14 nm. The optimum doping level was determined by studying the luminescence of the dots and the device characteristics. The results reported here are for *p*-doped quantum dot lasers with a doping of 5×10^{11} cm^{-2}. Heterostructures with undoped dots were also grown for comparison. Mesa-shaped broad area (100 μm-wide) and single-mode ridge waveguide (3 μm ridge width) lasers were fabricated. Lasers of various lengths, in the range 400–2000 μm, were obtained by cleaving. Measurements were made on lasers with facet reflectivities of 32% and 95%.

Light–current characteristics of both single-mode and broad-area lasers were measured in a wide temperature range both in continuous wave and pulsed mode (1 μs, 10 kHz) of biasing with the devices mounted on a Cu heat-sink, whose temperature was stabilized with a Peltier cooler. To avoid any significant heating of the device, the measurements reported and analyzed here are done under pulsed mode biasing. From the light–current characteristics of the *p*-doped broad area lasers of varying cavity length, we determine the value of internal quantum efficiency $\eta_i=0.62$ and cavity loss $\gamma=6.6$ cm^{-1} by plotting the inverse of differential efficiency, η_d, against cavity length. The value of J_{th} is 380 A/cm^2 for a cavity length, l, of 1000 μm. For the undoped QD lasers, η_i,γ, and J_{th} are 0.89, 4.3 cm^{-1}, and 110 A/cm^2(l $=1000$ μm), respectively. The spectral output of a single-mode *p*-doped laser at room temperature is shown in Fig. 1(b). Plotted in Fig. 2 are the light–current (L–I) characteristics of a single-mode *p*-doped laser at room temperature. From temperature-dependent measurements it is found that

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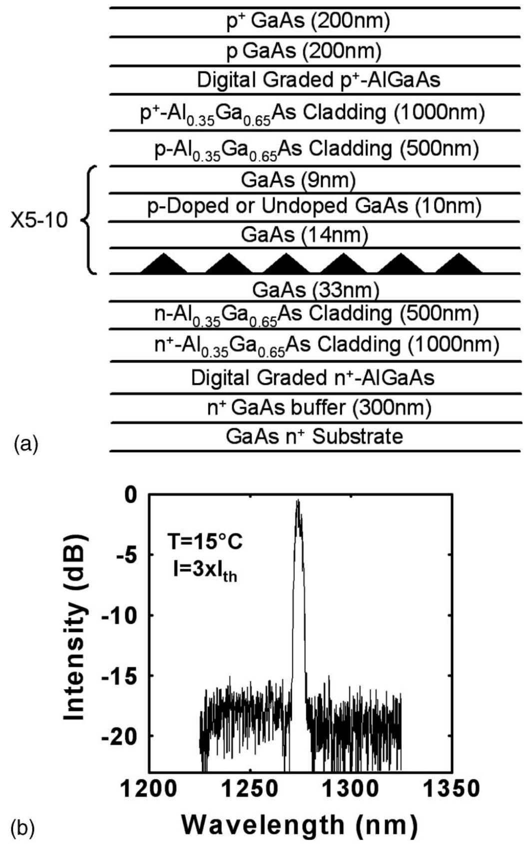

FIG. 1. (a) Heterostructure schematic of 1.3 μm *p*-doped and undoped self-organized quantum dot lasers grown by molecular beam epitaxy; (b) output spectrum of *p*-doped single-mode lasers at 15 °C obtained with pulsed biasing.

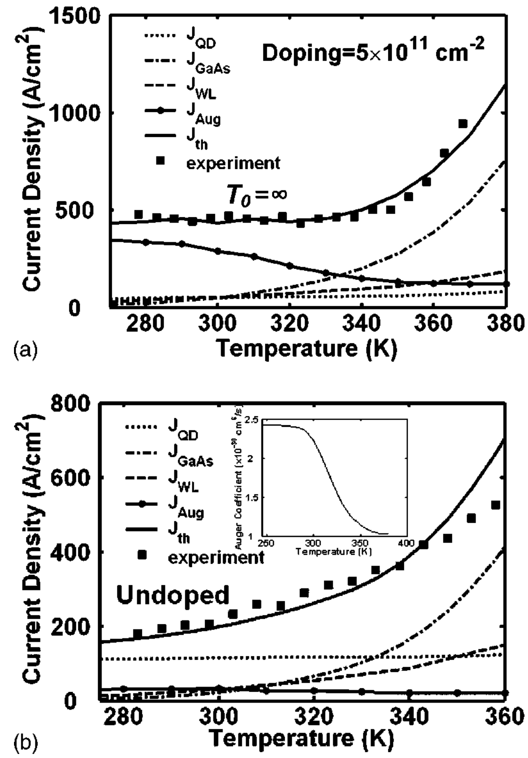

FIG. 3. Variation of calculated and measured threshold current density, J_{th}, in (a) *p*-doped, and (b) undoped self-organized quantum dot lasers. Also shown are the contributing current components resulting from radiative recombination in the dots (J_{QD}), recombination in the barrier/waveguide regions (J_{GaAs}), wetting layer (J_{WL}), and Auger recombination in the dots (J_{Aug}). The inset in (b) shows the temperature dependence of the Auger coefficients used in the calculation.

both the threshold current density, J_{th}, and the output slope efficiency of the *L–I* characteristics remain unchanged over a wide temperature range, as shown by the data points in Fig. 3(a) and the inset to Fig. 2, respectively. Similar results and trends were observed under continuous wave bias ($T_0=\infty$ in the temperature range $5 \leqslant T \leqslant 50$ °C). On the other hand, as shown in Fig. 3(b), J_{th} increases monolithically with temperature in lasers with undoped barriers ($T_0=69$ K).

In order to understand these trends, we have analyzed the measured threshold current data by taking into account radiative recombination in the quantum dots, wetting layer, and GaAs barrier/waveguide regions, and Auger recombination in the dots. Nonradiative recombination in the wetting

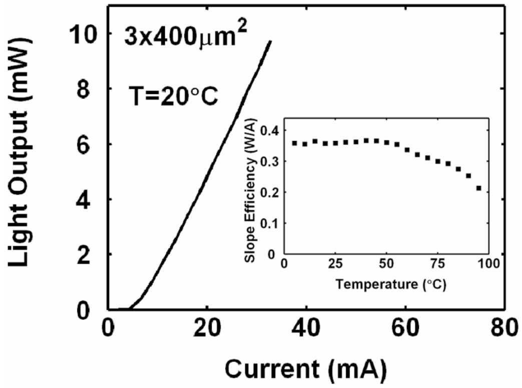

FIG. 2. Light–current characteristics of 1.3 μm single-mode *p*-doped quantum dot lasers at 20 °C with pulsed biasing. The inset shows the variation of slope efficiency with temperature.

layer, GaAs regions, and $Al_{0.35}Ga_{0.65}As$ outer cladding layers have been neglected.[10,16] Hydrostatic pressure-dependent measurement of threshold current in QD lasers shows that although carrier thermal excitation and the consequent nonradiative recombination in the GaAs barrier regions may be important in 1.0 μm lasers, it is not significant in 1.3 μm lasers and Auger recombination is the only dominant nonradiative term.[10] The modal gain in the devices was calculated by including interband transitions between the ground and first two excited states and by assuming inhomogeneously broadened Gaussian linewidth of 50 meV for the transitions. The optical confinement factor is $\Gamma=0.01$. The height, base length, and density of the dots are 7 nm, 12 nm, and 5×10^{10} cm^{-2}, respectively. The temperature-dependent band gaps are calculated with the Varshni equation. The band structure (bound states in the dots and band-offsets) are calculated with the eight-band **k.p** formulation. The wetting layer is treated as a two-dimensional electron gas,[17] and the temperature dependence of the wetting layer states in the range 5–80 °C is neglected since it is very small in the very shallow well (<1 meV). The threshold condition and the measured values of cavity loss are used to determine the carrier densities in the different regions. Fermi–Dirac statistics was employed,[6,7,16–18] with the assumption of flatband quasi-Fermi levels across the active region at threshold and complete ionization of dopants. In the case of the *p*-doped QD lasers, charge neutrality was assumed to exist between each QD layer and the immobile ionized dopants in the neighboring barrier. The values of the Auger recombination coefficient used are discussed in the next paragraph.

The results of the analysis are depicted in Figs. 3(a) and 3(b) for *p*-doped and undoped lasers, respectively, together with the measured threshold current densities of single-mode devices. The temperature dependence of the different current components and their cumulative effect are shown. It is evident from Fig. 3(b) that radiative recombination in the quantum dots is the dominant factor contributing to the threshold current at temperatures below 330 K in the undoped QD lasers. At higher temperatures, an exponential increase of recombination in the barriers increases the temperature dependence of the current. The value of T_0 is 79 K, which is close to the measured value of 69 K. These values of T_0 and the cross-over temperature of 330 K are in excellent agreement with the calculated results of Asryan and Suris.[16] On comparing the result of Figs. 3(a) and 3(b), it is also evident that the value of J_{QD}, resulting from radiative recombination in the dots, decreases upon *p*-doping. This trend agrees with the prediction of Miyamoto *et al.*[5] and subsequent calculations by other workers.[6] However, our experimental observation of an invariant J_{th} in the temperature range $5 \leqslant T \leqslant 75\,°C$ [Fig. 3(a)] and an increase in the value of J_{th}, compared to the undoped QD lasers, can only be explained by considering Auger recombination. The increase of hole population in the quantum dots due to modulation doping causes an increase in the rate of Auger recombination, particularly at low temperatures. Upon incorporating the measured temperature dependence of Auger recombination in 1.0 μm dots[11] and using slightly different values of the coefficients for the present 1.3 μm dots [inset of Fig. 3(b)], the measured temperature invariant threshold current of Fig. 3(a) can be explained. The exponential increase of recombination in the barrier/waveguide regions with temperature is compensated by the decrease of Auger recombination in the same temperature range.

In conclusion, we have analyzed the measured temperature variation of the threshold current of undoped and *p*-doped self-organized 1.3 μm quantum dot lasers. It is found that Auger recombination in the dots plays an important role in establishing temperature invariance of J_{th} in the range 5–75 °C.

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