Temperature dependence of threshold current in *p*-doped quantum dot lasers

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The authors measure the temperature dependence of the components of threshold current of 1300 nm undoped and *p*-doped quantum dot lasers and show that the temperature dependence of the injection level necessary to achieve the required gain is the largest factor in producing the observed negative T_0 in *p*-doped quantum dot lasers. © *2006 American Institute of Physics*.
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p-type modulation doped In(Ga)As quantum dot lasers have attracted much interest recently, partially due to reports of an infinite or negative characteristic temperature (T_0) around room temperature.[1–3] Several authors have attributed this behavior to the temperature dependence of the Auger recombination process in doped structures,[2,4,5] although the particulars of the explanation varied in each case. In this work we report on measurements made on both intrinsic and *p*-doped quantum dot structures that emit at 1.3 μm. From studying the radiative and nonradiative components of the threshold current we show that the temperature performance of *p*-doped lasers can be described without needing to consider Auger recombination.

Two samples were grown by solid source molecular beam epitaxy on 3 in. n^+ (100) GaAs substrates. The devices were nominally identical except for the level of modulation doping. The active region consisted of five dot-in-a-well (DWELL) repeats, where each DWELL was made up of 3.0 ML of InAs grown on 2 nm of $In_{0.15}Ga_{0.85}As$ and then capped by a further 6 nm of $In_{0.15}Ga_{0.85}As$, and these were then separated by 50 nm GaAs spacers. The active region was incorporated into a $GaAs-Al_{0.4}Ga_{0.6}As$ waveguide structure. The lower *n*-contact region was doped with Si at 5×10^{18} cm^{-3} while the upper *p* contact was doped with Be at 5×10^{17} cm^{-3}, the *p* contact was finished with a 300 nm layer of GaAs doped at 1×10^{19} cm^{-3}. The growth temperature for the cladding layers was 620 °C, while the InAs layers were grown at 510 °C, the GaAs spacers were grown in two temperature steps; the first 15 nm at 510 °C and the final 35 nm at 580 °C, forming the so called high growth temperature spacer layers.[6] The doping consisted of Be atoms incorporated over a 6 nm region of GaAs situated 9 nm below each DWELL at a concentration of either 0 or 7.5 $\times10^{17}$ cm^{-3} corresponding to either 0 or 15 acceptor atoms per quantum dot. Previous work on these structures has shown that the absorption spectra, and therefore the quantum dot states, are the same for the two structures.[7]

The threshold current was measured as a function of temperature on 2000 μm long, 50 μm wide oxide stripe lasers for both structures under pulsed conditions with a pulse length of 400 ns and a repetition rate of 1 kHz to avoid any self-heating, and this is shown in Fig. 1. The undoped structure shows a monotonically increasing threshold current from low to high temperatures as is normally observed for undoped quantum dot and quantum well structures. The *p*-doped structure exhibits a threshold current density that decreases as the temperature increases from 200 K reaching a minimum threshold current density at 280 K and then increasing at higher temperatures. The initial decrease in threshold current in the *p*-doped quantum dot structures has been attributed to a decrease in the nonradiative Auger process as the temperature is increased towards room temperature. However, it is known that *p* doping can significantly reduce the temperature sensitivity of the gain and threshold current;[8] and in this letter we will show that the negative temperature dependence of threshold is almost entirely due to the temperature dependence of the gain.

To evaluate the relative radiative and nonradiative components of the threshold current, the segmented contact method[9] was used to measure the modal absorption, gain, and unamplified spontaneous emission (in real units) as a

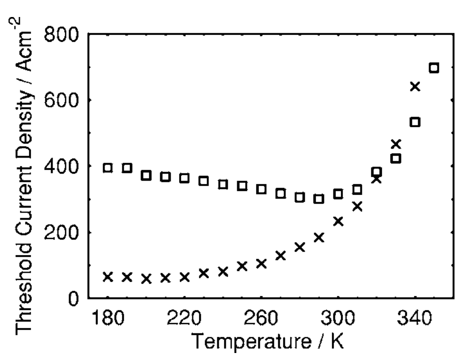

FIG. 1. Threshold current density as a function of temperature for 2000 μm long, 50 μm wide oxide stripe lasers for undoped (crosses) and *p* doped (squares).

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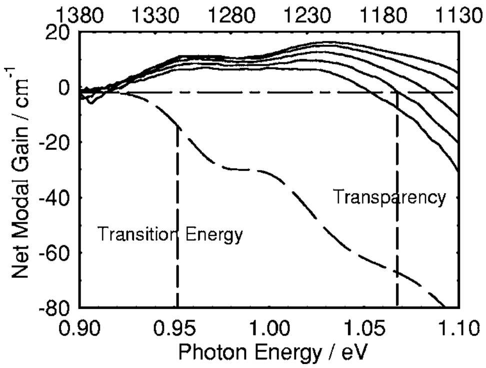

FIG. 2. Net modal gain spectra (222, 311, 444, 622, and 888 A cm^{-1}) and absorption spectrum (dashed curve) for the *p* doped sample at 300 K.

function of drive current at various temperatures under the same pulsed conditions as the laser measurements.

Figure 2 shows example net modal gain spectra for a range of drive current as well as the net modal absorption spectrum (dashed curve) at 300 K. At low energies, where the gain and absorption tend to zero, the net values yield the waveguide loss α_i, which is equal to 2 ± 2 cm^{-1} for both structures examined here. The transparency energy can be determined from the point where the modal gain spectra cross the value of α_i at high energy (low wavelength), as illustrated in Fig. 2. The difference between the transparency energy and the temperature dependent energy of the dot states can be used as a measure of the carrier injection in the sample. From the absorption spectra we have identified a transition energy given by the half height of the peak of the ground state absorption (as illustrated by the second dotted line in Fig. 2). The value of this energy at each temperature will be used to correct for the temperature dependence of the energy of the dot states in our analysis. Using the experimentally determined gain spectra we are therefore able to plot the peak value of the gain for a given drive current density or for a given carrier injection level (transparency energy minus transition energy).

To look at the temperature dependence of the gain for each of our samples we have plotted the peak net modal gain as a function of temperature for a fixed transparency energy minus transition energy in Fig. 3. The values of transparency energy minus transition energy used are 0.103 and 0.085 eV for the undoped and doped samples, respectively (being the

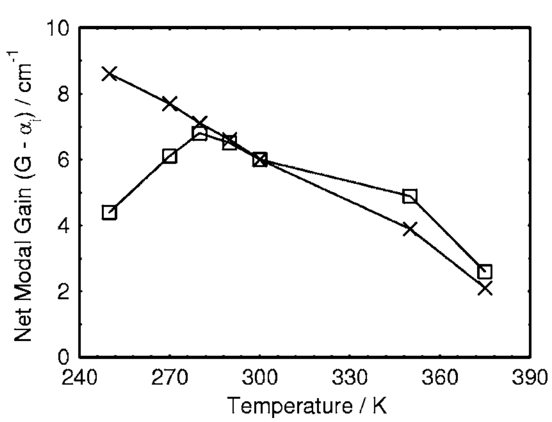

FIG. 3. Peak ground state gain vs temperature for the undoped (crosses) and the *p* doped (squares) samples for a transparency energies minus transition energies of 0.103 and 0.085 eV, respectively (which corresponds to a net modal gain of 6 cm^{-1} at 300 K).

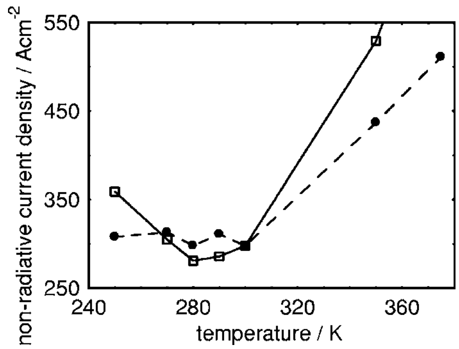

FIG. 4. Nonradiative current density as a function of temperature for the doped sample at a fixed net modal gain of 6 cm^{-1} (solid lines, squares) and at fixed transparency energy minus transition energy (dashed lines, circles) of 0.085 eV.

values necessary to achieve a net modal gain of 6 cm^{-1} at 300 K). The doped structure produces the same gain at a lower transparency energy minus transition energy (at 280 K and higher temperatures) than the undoped sample, and this is consistent with previous results that have shown an increased peak gain at fixed transparency energy with increasing levels of *p* doping at 300 K.[7] The undoped sample shows a steady decrease in the gain available from the ground state as the temperature is increased. This is the expected behavior due to the increased thermal distribution of carriers into the excited and wetting layer states as the temperature is increased.[10] The gain data of Fig. 3 (at fixed injection level) for the *p*-doped structure show a dramatically different variation with temperature. The gain initially increases reaching a maximum value of ~7 cm^{-1} at 280 K, the same temperature as the minimum in the threshold current observed in Fig. 1, before decreasing again at higher temperatures. It is this change in the gain that gives rise to the temperature dependence of the threshold current as shall now be discussed.

A 2000 μm long laser requires a net modal gain of 6 cm^{-1} for lasing to be achieved. To study the relative amounts of radiative and nonradiative recombination in these lasers, we have determined the injection current density required to obtain a peak net modal gain of 6 cm^{-1} as a function of temperature in both of our structures. The nonradiative current density is determined from the difference between this measured injection current density and the radiative current density obtained by integrating the relevant measured unamplified spontaneous emission spectrum. Note that the current density associated with stimulated emission is negligible in this single pass experiment.[9] The amount of nonradiative recombination at each temperature, at injection levels to achieve a net modal gain of 6 cm^{-1}, is plotted in Fig. 4 for the *p*-doped sample. The nonradiative recombination shows an initial decrease with increasing temperature followed by an increase at higher temperature with the minimum again occurring at 280 K. Note that for the undoped structure the nonradiative current density increases monotonically with increasing temperature over the same range. For both structures the nonradiative current makes up around 90% of the total current over the temperature range studied. The change (and particularly the reduction) in the nonradiative current density in the *p*-doped sample could be caused by two possible mechanisms. The first is that the nonradiative processes themselves are changing as a function of temperature, while the second possible cause is an indirect effect

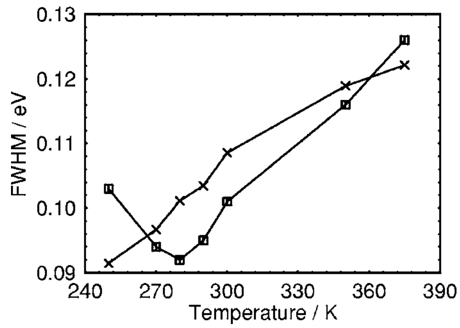

FIG. 5. FWHM of the spontaneous emission spectra at a fixed transparency energy minus transition energy of 0.103 eV for the undoped sample (crosses) and 0.085 eV for the *p*-doped sample (squares).

where the nonradiative (and radiative) recombination change due to the temperature dependence of the injection level required to obtain the required net modal gain of 6 cm^{-1}.

To ascertain the relative importance of each of these contributions we have analyzed the nonradiative current for the same injection level at each temperature for the *p*-doped structure. This was done by using the value of the transparency energy minus the transition energy required to achieve a net modal gain of 6 cm^{-1} at 300 K (0.085 eV for the doped structure). The associated nonradiative current was then determined at each temperature for this fixed injection level in the same way as before, and this is also plotted in Fig. 4 as the dashed lines. The nonradiative current from the doped structure at fixed injection level is approximately constant at temperatures below 300 K and only increases at higher temperature. The difference between the values of nonradiative recombination for constant gain and constant injection level illustrates that the structure has to be pumped to different levels at each temperature to achieve the same gain. The data also illustrate that the nonradiative process or processes themselves are not reducing with increasing temperature at fixed injection level. Note the nonradiative current density in the undoped sample for a fixed value of the transparency energy minus the transition energy (of 0.103 eV) has a similar form to that of the doped sample—being initially constant at lower temperatures and increasing at higher temperatures.

In our *p*-doped quantum dot lasers the temperature dependence of threshold current is dominated by the change in the injection level required to achieve the same gain and is not due to a temperature induced reduction in the Auger recombination process itself. It has previously been suggested that the form of the carrier distribution changes around room temperature in the *p*-doped structures[4,11] and this may be the origin of the change in the gain that we observe. We examine this in Fig. 5, where the full width half maximum (FWHM) of the spontaneous emission spectra have been plotted as a function of temperature for fixed transparency minus transition energies of 0.085 and 0.103 eV for the doped and undoped structures, respectively.

The undoped structure shows an increasing thermal broadening as the temperature is increased and higher lying states are increasingly occupied. The doped structure initially shows a narrowing in the spectra before broadening again at higher temperatures, having a minimum in the FWHM around 280 K. The initial decrease in width suggests that to begin with the dots are randomly populated and as the temperature is increased they become thermally populated, giving the narrowest distribution. The subsequent increase at temperatures above 280 K is then due to thermal broadening as observed in the undoped structure.

In summary we have measured the radiative and nonradiative contributions to the threshold current in doped and intrinsic quantum dot lasers. We have shown that the reducing threshold current with increasing temperature around room temperature in *p*-doped quantum dot lasers is primarily caused by the change in injection level required to achieve a fixed gain. We have also shown that these processes occur over the same temperature range as a narrowing of spontaneous emission spectra, which may be associated with electrons in the conduction states moving from a random to a thermal population. Such a process would occur at higher temperatures in *p*-doped quantum dots due to the increased hole population and concomitant reduction in electron population necessary to achieve a fixed value of gain.

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