Temperature dependence of the gain in *p*-doped and intrinsic 1.3 μm InAs/GaAs quantum dot lasers

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The gain of *p*-doped and intrinsic InAs/GaAs quantum dot lasers is studied at room temperature and at 350 K. Our results show that, although one would theoretically expect a higher gain for a fixed carrier density in *p*-doped devices, due to the wider nonthermal distribution of carriers amongst the dots at T=293 K, the peak net gain of the *p*-doped lasers is actually less at low injection than that of the undoped devices. However, at higher current densities, *p* doping reduces the effect of gain saturation and therefore allows ground-state lasing in shorter cavities and at higher temperatures.
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Due to the large volume of data being readily transferred between network users, there is an increasing demand for "fiber-to-the-home" based optical fiber networks which require fast and temperature insensitive semiconductor lasers emitting at 1.3 μm. Despite significant progress in reducing the threshold current densities (J_{th}) or improving the temperature stability,[1,2] intrinsic quantum dot (QD) lasers emitting around 1.3 μm have yet to meet their full potential. This is attributed to many factors such as inhomogeneous broadening or size dispersion of the dots and dominating nonradiative recombination at room temperature (RT) which increases J_{th} and its sensitivity to temperature variations.[3,4] It has been proposed that *p*-doping the devices and thus saturating the levels in the valence band with holes would greatly improve the device performance by increasing the gain and the bandwidth.[5,6] Although the effect of *p*-doping shows major improvements on the temperature sensitivity and the bandwidth of the devices,[7] measurements do not show a clear enhancement of the gain for a given injection[8] as it is expected from theory.[5,6] Recent results reported that the superior thermal stability of InAs/GaAs *p*-doped QD lasers around room temperature arises from a combination of improving thermal distribution of the electrons, leading to a decrease in the radiative current necessary to reach the lasing threshold, and an increase in nonradiative Auger recombination with temperature, together giving rise to a constant threshold current over a limited temperature range.[4] In this work, we consider the temperature sensitivity of the gain and specifically, the effect of the nonthermal distribution of the carriers on the gain characteristics of *p*-doped devices and compare the results to those obtained with intrinsic quantum dot lasers.

The gain was measured using the method described by Hakki and Paoli[9] at both room temperature, where carriers in the intrinsic devices are in thermal equilibrium, and at 350 K, where carriers in the *p*-doped lasers are expected to be closer to thermal equilibrium.[4] The lasing wavelength of the devices was approximately 1.28 μm at room temperature. The active region consisted of ten stacked InAs dot-in-a-well layers separated by either modulation *p*-doped or intrinsic GaAs barriers sandwiched by GaAs waveguide and AlGaAs cladding layers. The chips were driven with 50 μs long pulses at a duty cycle of 50%. These pulses were long enough to avoid transient mode-hopping effects. The laser substrate temperature was kept constant using a thermoelectric heater/cooler and temperature controller. A Glan-Thompson prism polarizer was used to discriminate TE and TM modes and only a small degree of polarization cross-talk was observed. Its effect on the gain is negligible, and the error is only found to be significant for measurements made at transparency ±5 cm^{-1}.

Figure 1 shows the variation of the peak net modal gain ($g=\Gamma G-\alpha_i$) as a function of the current density for both materials at room temperature, Γ being the confinement factor and α_i the internal loss. 500 μm long cavities were used to measure the gain at low injections ($g<20$ cm^{-1}) and 300 μm long cavities ($g>13$ cm^{-1}) for both undoped and *p*-doped devices. Both cavity lengths showed excellent agreement across the same range of J as it can be seen in Fig. 1. Sandall *et al.* have recently reported in Ref. 8 that the peak modal gains of both undoped and *p*-doped devices behave in

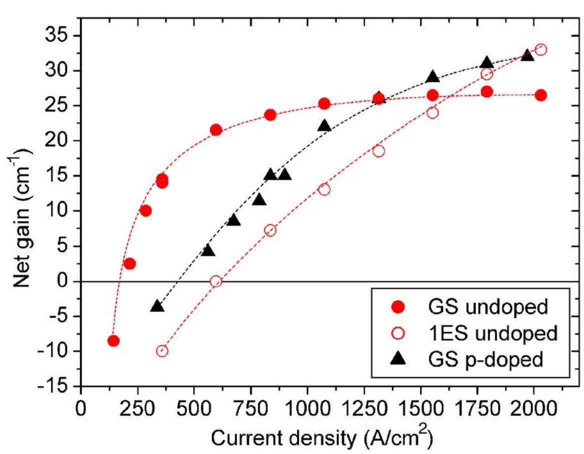

FIG. 1. (Color online) Peak net gain vs current density at room temperature.

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a similar way with increasing current densities due to a combination of increased gain and nonradiative current in the p-doped devices. As one can see in Fig. 1, the peak net gain of the p-doped device is less than that for the intrinsic device at low injection. This is clearly illustrated by the fact that device transparency (where $g=0\ \mathrm{cm}^{-1}$) is reached at current densities $J\sim200$ and $\sim450\ \mathrm{A\ cm}^{-2}$ in the intrinsic and p-doped lasers, respectively. At higher injection ($J>1300\ \mathrm{A\ cm}^{-2}$) the ground state (GS) of the p-doped devices achieves more gain than the intrinsic devices which saturates at $26\ \mathrm{cm}^{-1}$. These observations are explained by the fact that at RT, the intrinsic devices are at thermal equilibrium,[3,4] the dots are coupled, and the carriers preferentially occupy the larger dots, or lower energies. As a result, they more efficiently take part in the gain process, resulting in a high peak gain for a given current. However, the GS saturates at lower injection current and relatively low peak net gain. The excited state (ES) reaches transparency when the GS starts saturating, further demonstrating the thermal distribution of the carriers.

In the p-doped devices, due to the increased barrier height for the electrons induced by the trapped holes (liberated from the ionized acceptors), the electrons are not thermally distributed among the dots and do not necessarily occupy the ground state of the larger dots at room temperature.[4,7] This is confirmed by comparing the pinning above threshold of the total spontaneous emission (L) and GS spontaneous emission versus current. They are measured by integrating the pure spontaneous emission spectra collected through a window milled in the substrate contact of the devices.[4] At 100 K none of the L and GS emissions pin above the threshold current because of the nonthermal distribution of the electrons. At 300 K, the undoped lasers are in thermal equilibrium and hence the L and GS emissions both pin above I_{th}. However, the L and GS emissions of the p-doped laser are still not fully pinned at 370 K. The peak net gain is therefore reduced compared to the intrinsic materials due to a broader nonthermal carrier distribution. We find that the full width at half maximum of the pure spontaneous emission from the GS measured from a window milled in the substrate contact of lasers is much greater in the p-doped devices at 100 K (55 and 45 meV in the doped and undoped devices for $J\sim100\ \mathrm{A/cm}^2$) and is still slightly higher at RT (43 and 40 meV in the doped and undoped devices for $J\sim100\ \mathrm{A/cm}^2$), confirming the idea of a broader carrier distribution in the p-doped QDs. The peak net gain for the p-doped devices is therefore reduced compared to what is expected at thermal equilibrium. However, the doping increases the hole population in the dots, preventing gain saturation at low injection and allowing higher peak net gain at high currents. The emission from the first excited state in the p-doped devices is consequently reduced at low injection levels and could not be observed in our measurements. The increased carrier density required to achieve a fixed gain (prior to saturation) will tend to exacerbate Auger recombination in the p-type devices. Furthermore, the p-type doping is likely to increase the nonradiative Auger recombination present in these devices[4] at low current densities due to the increased hole concentration which would further lower the differential gain (dg/dJ).

At 350 K for both devices, the fraction of injected current going into nonradiative recombination processes is greater than at room temperature;[4] dg/dJ is therefore reduced compared to that at RT. The net modal gain was measured using a 300 μm cavity device at this temperature for both undoped and p-doped materials. As can be seen in Fig. 2, at 350 K, transparency and gain saturation are reached at lower injection in the intrinsic devices. However, three significant differences are noticeable: both materials tend toward more similar behavior at 350 K, the peak gain saturates at a lower value, and the first excited state can be observed in the p-doped devices at low peak gain. At 350 K, the peak net gain of the p-doped material is less than that of the undoped material until $J>1750\ \mathrm{A\ cm}^{-2}$; however, the difference is less than that at room temperature. This is likely to be due to the improved carrier redistribution but shows that the p-doped devices have not fully reached thermal equilibrium even at 350 K. This is further supported by the fact that the transparency carrier density remains slightly higher for the p-doped devices at 350 K, since in thermal equilibrium, the p-doped devices would have a lower transparency carrier density than the undoped devices. Furthermore, the effect of doping becomes less at higher temperatures, further reducing the difference between both device types at 350 K.[4] The lower values of the saturated net gain compared to room temperature measurements could be explained by an increase in the internal losses as we observed from efficiency measurements. This suggests that intervalence band absorption could play a significant role at high temperatures, as has previously been observed in quantum well devices at this wavelength.[10] Reports also suggest that homogeneous broadening could play a significant role when the temperature increases.[11] However, we are not yet able to determine which of these two effects dominates.

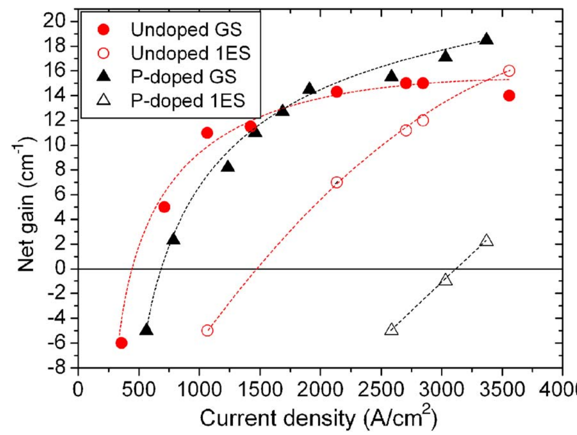

FIG. 2. (Color online) Peak net gain vs current density at 350 K.

Because the gain at which the devices saturate is lowered at 350 K, the importance played by the first excited state at higher temperatures is increased. This is clearly illustrated in the p-doped devices where the ES was absent in the RT measurements up to the very high current densities where the GS peak gain almost reaches its maximum value of $30\ \mathrm{cm}^{-1}$. However, at 350 K, the ES is observable in the gain spectra and the transparency for this state is reached at a peak gain of about $17\ \mathrm{cm}^{-1}$.

To conclude, the gain of both undoped and p-doped quantum dot lasers was studied at room temperature and high temperature (350 K). p-doping successfully reduces gain saturation. However, we find that the peak gain of the p-doped devices is less than that of the undoped devices at the temperatures studied due to the nonthermal distribution of the carriers among the dots. This coupled with Auger recombination results in a higher absolute value of current density at transparency in the *p*-doped devices and in a lower differential gain. At 350 K, the *p*-doped devices are still not completely at thermal equilibrium, but the interdot carrier transport is improved compared to RT. This results in more similar behavior of the peak net gain for both device types. We also find that at high temperatures, the peak net gain is significantly reduced, which may be due to increased homogeneous broadening and/or optical losses either of which may place an intrinsic limit on the performance of quantum dot devices at high temperatures.

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