Intrinsic limitations of p-doped and undoped 1.3 μm InAs/GaAs quantum dot lasers

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The temperature dependencies of the recombination and gain processes reveal intrinsic limitations on the performances of quantum dot lasers. Controlling the transport of the carriers using the inhomogeneous broadening makes temperature stable threshold current possible.

The demand for fast and temperature stable lasers emitting in the telecom wavelengths drives the research on quantum dot lasers. While low and temperature insensitive threshold current densities are expected, InAs/GaAs quantum dot lasers emitting around 1.3 μm have not yet fulfilled their expectations. From the literature, one can observe that although high temperature stability can be achieved, this is usually at the expense of a high threshold current. P-doped devices are anticipated to achieve higher gain and bandwidth [1]. High temperature stabilities and bandwidth have been experimentally measured [2] but, to date, there is no clear measurement of the gain of devices with temperature stable threshold currents around room temperature. In this paper, we present a comparative study of the temperature dependence of both undoped and p-doped InAs/GaAs quantum dot lasers. We investigate the temperature dependence of the different radiative and non-radiative recombination mechanisms in order to understand the behavior of the devices. The conclusions allow us to explain our gain measurements carried at various temperatures on both device types.

The lasers investigated are as cleaved and the cavity lengths used are 1 mm for the temperature measurements, and 300 and 500 μm for the gain measurements. Their active region consist of 10 stacked dots-in-a-well layers with p-doped or intrinsic GaAs barriers within GaAs separate confinement layers surrounded by AlGaAs cladding layers.

The temperature dependence of the recombination mechanisms is studied assuming that the threshold current (I_{th}) can be written as the sum of a radiative current (I_{rad}) and a non-radiative current (I_{nonrad}) with I_{rad} being proportional to the integrated pure spontaneous emission which is measured through a

window milled on the contact of the device. The results are shown on Figure 1. The radiative currents are normalized to the measured threshold currents at low temperatures.

Figure 1: Variation of the threshold and radiative currents with temperature in undoped and p-doped InAs/GaAs QD lasers

Below 200 K, the non-radiative component of the undoped devices is negligible and both I_{th} and I_{rad} decrease with increasing temperature due to an improvement in the carrier transport among the inhomogeneously broadened dots. Above 200 K, the devices reach thermal equilibrium and the radiative current remains almost constant with temperature, however, the onset of Auger recombination contributes to the threshold current and determines its temperature sensitivity around room temperature [3, 4].

In the p-doped devices non-radiative Auger recombination is present even at low temperatures, and the temperature at which the radiative current decreases is shifted toward higher temperatures. This is attributed to the increased potential well for the electrons due to the electrostatic attraction of the trapped holes. The combination of decreasing radiative current together with the increase in the non-

radiative current explains the stability of the threshold current around room temperature [4]. At higher temperatures, the radiative current stabilizes and the temperature dependence of the p-doped devices is similar to that of the undoped lasers due to the dominating Auger recombination current.

The effect of the carrier transport on the gain is studied using the method described by Hakki and Paoli in [5]. Gain spectra are measured at various currents and at two temperatures: At 290K where only the undoped devices are at thermal equilibrium and at 350K, where, according to Figure 1, both devices seem to be at thermal equilibrium.

Figure 2: Variation of the peak net gain with the injected current density at 290K

Figure 2 shows the variation of the peak net gain as a function of the injected current density at 290K. In the undoped devices, the ground state (GS) saturates at a value of $\sim 25 \text{ cm}^{-1}$ leading to an important contribution of the first excited state. In the p-doped devices the GS does not strongly saturate in the range studied here which shows that p-doping is effective in reducing the effect of gain saturation and in achieving higher gain from the GS. It is interesting to notice that transparency is reached at higher injection in the p-doped devices compared to the undoped lasers. Although calculations in the literature suggest that p-doped devices should achieve higher gain and lower transparency current [1], our results do not show this trend. We believe that this is a consequence of the non-thermal distribution of the carriers which broadens the gain spectra and together with non radiative Auger recombination lowers the peak gain for a given current.

The results obtained at 350 K are shown in Figure 3. At this temperature, both device types tend

toward a more similar behavior, however, the transparency point is still achieved at higher injection in the p-doped lasers. This may be a sign that the carriers are still not yet fully thermalised. It is also interesting to note that the devices saturate at a lower gain value. This can result from the increasing importance played by homogeneous broadening as the temperature is increased. This could also explain why the radiative current increases at high temperatures as seen on Figure 1.

Figure 3: Variation of the peak net gain with the injected current density at 350K

To conclude, this study of the temperature dependencies of the recombination and gain mechanisms allows us to understand the physics underpinning the attractive properties of these devices. We find that Auger recombination and homogeneous broadening may intrinsically limit the performances of the lasers. However, by carefully understanding and controlling the improvement in the carrier redistribution relative to the inhomogeneous broadening, these effects can be controlled and a stable threshold current can be achieved around room temperature in the p-doped QD lasers. The remaining challenge is to achieve this whilst preserving a low threshold current density.

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