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Efficiency limiting processes in 1.55 μm InAs/InP-based quantum dots lasers

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The threshold current density, J_{th}, and its radiative component, J_{rad}, in 1.55 μm InAs/InP (100) quantum dot lasers are measured as a function of temperature and hydrostatic pressure. We find that J_{rad} is relatively temperature insensitive. However, J_{th} increases significantly with temperature leading to a characteristic temperature $T_0=72$ K over the range 220–290 K. Nonradiative recombination accounts for up to 94% of J_{th} at T=293 K. J_{th} decreases with increasing pressure by 35% over 8 kbar causing an increase in T_0 from 72 to 88 K. The results indicate that nonradiative Auger recombination determines temperature behavior of these devices and T_0 value. © *2010 American Institute of Physics*. [doi:10.1063/1.3504253]

Quantum dot (QD) lasers have generated a huge amount of interest for applications, including communication networks, due to their anticipated superior electronic and optical properties associated with three dimensional carrier confinement. For example, ideal QD lasers are predicted to be temperature insensitive.[1] Recent progress in the fabrication of 1.3 μm lasers using InAs-based self-assembled QDs has stimulated substantial interest for QD lasers operating at longer wavelengths, particularly 1.55 μm due to the minimum loss in silica-based fiber optics occurring around this wavelength.[2]

In order to operate at longer wavelength the InAs dots have to be larger than that needed for 1.3 μm operation. Using the Stranski–Krastanow method to grow 1.55 μm dots on GaAs substrates has proven difficult due to the large lattice mismatch.[3] Switching to the growth of InAs-based QDs on InP substrates, where the lattice mismatch is considerably smaller, allows the 1.55 μm wavelength range to readily be reached. Considerable improvements in the performance of 1.55 μm QD lasers grown on InP substrate have been demonstrated.[4] The use of InP substrates is also compatible with existing processes for telecommunications wavelength lasers. However, to improve performance of the QD lasers requires careful control of growth parameters. The use of InP (311)B substrates has allowed growth of highest dot density, with greater than 10×11 cm^{-2} enabling the demonstration of lasers using only a single QD layer.[5] However, fabricating lasers on (311)B substrates is more difficult than on conventional (100) substrates due to difficulties with cleaving meaning that they are less compatible with standard industrial processes. For this reason optimization of (100) substrates for dot growth is of great interest.[6] In this paper we report on a detailed experimental study of the temperature sensitivity of recombination processes that occur in 1.55 μm InAs/InP (100) QD lasers.

A set of 2 mm long 100 μm wide ridge lasers were used in this study. The active region consisted of five layers of InAs QDs deposited using a double cap procedure[7] in a lattice matched InGaAsP waveguide whose composition was adjusted to have a room temperature (RT) photoluminescence peak at 1.15 μm. At RT $J_{th}=760$ A cm^{-2}, and $T_0[=1/d \ln J_{th}/dT]$ was $\sim$72 K over the temperature range 220–290 K. In order to understand the temperature sensitivity of the QD laser devices, measurements of threshold current density (J_{th}) and its radiative component (J_{rad}) were performed as a function of temperature and hydrostatic pressure. The radiative current density at threshold was measured by integrating the pure spontaneous emission spectra obtained from a circular 100 μm diameter window milled into the n-contact of the device. This method ensures that only pure spontaneous emission is collected. A multimode silica optical fiber was used to collect the light which was analyzed using an optical spectrum analyzer. An error in measurements of J_{rad} is estimated to be ±5% at 80 K and ±2% at 295 K. To avoid self heating effects a pulsed current source (500 ns at 10 kHz) was used to drive the laser diode. A gas-exchange cryostat was used for temperature-dependent measurements from 20 to 300 K. For pressure-dependent measurements hydrostatic pressure was applied using a helium gas pressure cell (further details in Ref. 8).

Figure 1 shows a plot of J_{th} and J_{rad} as a function of temperature, with J_{rad} being normalized to J_{th} at 20 K where we assume that $J_{rad}=J_{th}$. We observe an increase in threshold current density with temperature while the radiative component of the threshold current density is relatively temperature insensitive, a behavior previously observed in 1.3 μm InAs/GaAs QD lasers.[9] At RT nonradiative (NR) recombination processes are seen to account for up to $\sim$94% of the threshold current density. In other words, radiative recombination accounts for only $\sim$6% of the total threshold current.

Identification of the dominant NR recombination processes in QD lasers has been the subject of strong debate among researchers in this field.[10,11] Rossetti *et al.*[10] suggest that the increase in threshold current with temperature is due to thermal escape of carriers followed by monomolecular (defect related) NR recombination in the wetting layer (WL)

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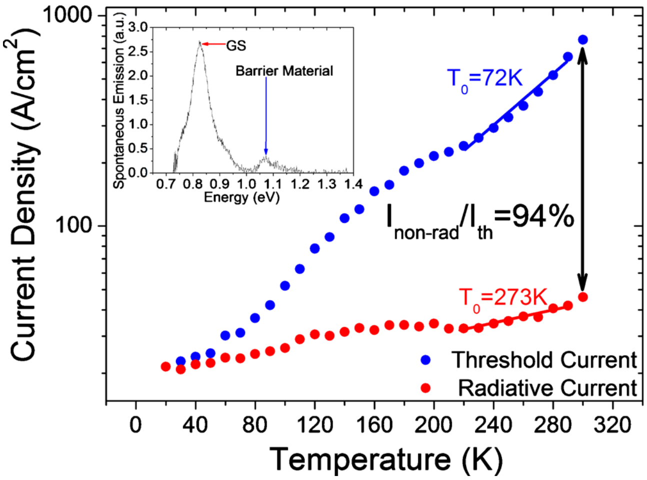

FIG. 1. (Color online) Temperature dependence of J_{th} and J_{rad} as function of temperature. Inset showing energy spectrum for GS and WL/BL.

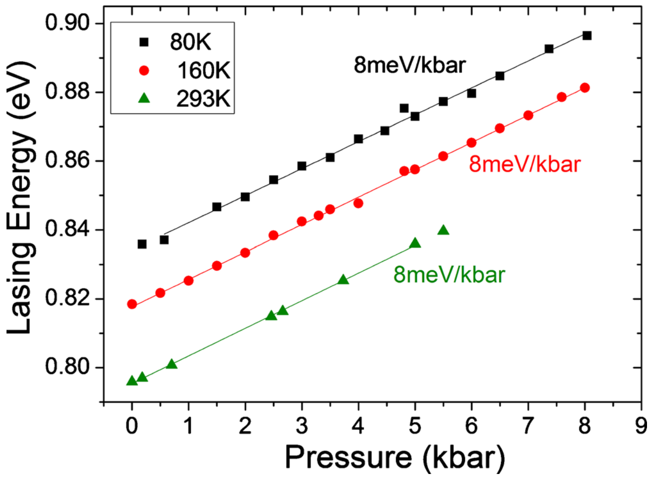

FIG. 2. (Color online) Lasing energy as a function of hydrostatic pressure at different temperatures.

and dismissed the role of Auger NR process in 1.3 μm QD lasers. Blood *et al.*[11] also suggested that the use of power laws to describe the recombination processes in QDs may not be a valid approach. Previous work by Marko *et al.*[12] on 1.3 μm InAs/GaAs QD lasers suggested that Auger recombination dominates, giving rise to a characteristic decrease in threshold current with increasing pressure. These arguments show how challenging it is to determine the dominant recombination processes in QD lasers.

Figure 1 (inset) shows that spontaneous emission spectra yielded multiple peaks. The peak at 0.815 eV corresponds to the ground state (GS) transition. The smaller peak at 1.07 eV corresponds to the WL/barrier layer (BL) transition. Due to the small WL/BL thickness, reabsorption is assumed to be negligible.[13] The presence of this peak shows that carriers occupy states in the WL/BL where they may recombine radiatively and/or nonradiatively. The total integrated emission from the WL/BL accounts for only ~5% of the total spontaneous emission at threshold, suggesting that the carrier density in the WL/BL is low around RT and that this current path makes only a small contribution to J_{th}.

To fully understand the nature of the recombination processes in these QD lasers, we employed the use of high hydrostatic pressure. Hydrostatic pressure causes a reversible change in the band gap energy of the semiconductor layers in the device by varying the interatomic spacing in the crystal.[8] The nature of the recombination processes can be identified due to their dependencies on the band gap energy.[14] The lasing energy of the QD lasers used in this study increases by ~8 meV/kbar as shown in Fig. 2, consistent with most III-V alloys.[12–15]

Owing to the fact that the different layers have similar pressure coefficients, the band offsets stay approximately constant with pressure. Hence, carrier leakage would also remain constant as a function of pressure. Radiative recombination increases with increasing pressure as previously observed in quantum well (QW) (Ref. 15) and QD lasers.[12]

Figure 3 shows the variation in J_{th} as a function of hydrostatic pressure (normalized to zero applied pressure) for different operating temperatures. It can be seen that the threshold current J_{th} decreases by ~35% (over ~8 kbar) at RT. The decrease in threshold current with increasing pressure is due to decreasing NR recombination (since radiative recombination at this temperature accounts for only 6% of the total threshold current). Rossetti *et al.*[10] argued that the decrease in threshold current as a function of pressure is due to an improvement in optical confinement, and hence a corresponding decrease in threshold gain with increasing pressure.

However, previous studies on QD lasers[12] clearly show that while the threshold current decreases with increasing pressure, the radiative component increases. The pressure variation in J_{th} therefore cannot be explained by the change in optical confinement. Other studies on QW lasers confirm this and show that the influence of the change in optical confinement factor with pressure is negligible and would still lead to an increase in threshold current with pressure.[15] Figure 3 also shows that with decreasing temperature, the rate of decrease in threshold current with pressure itself decreases. This is consistent with the temperature dependence data in Fig. 1, which shows that as temperature decreases, the nonradiative current becomes less important. Thus the relative balance between the radiative current (which increases with increasing pressure) and the Auger current (which decreases with increasing pressure) causes a weakening of the pressure dependence with decreasing temperature. Hence our experimental data indicate the presence of an

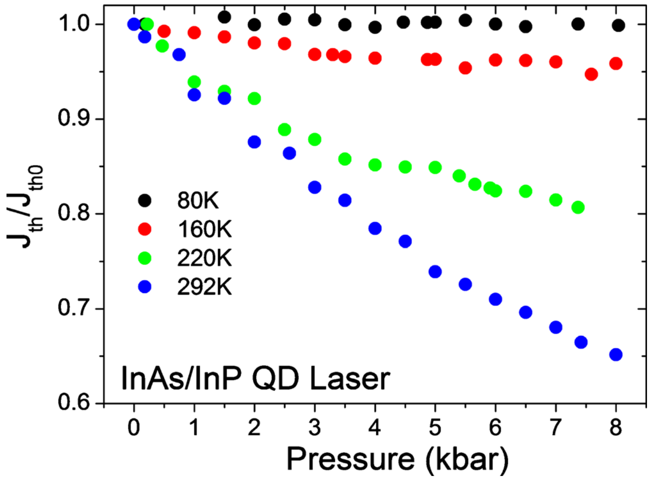

FIG. 3. (Color online) Normalized threshold current density as a function of hydrostatic pressure and temperature.

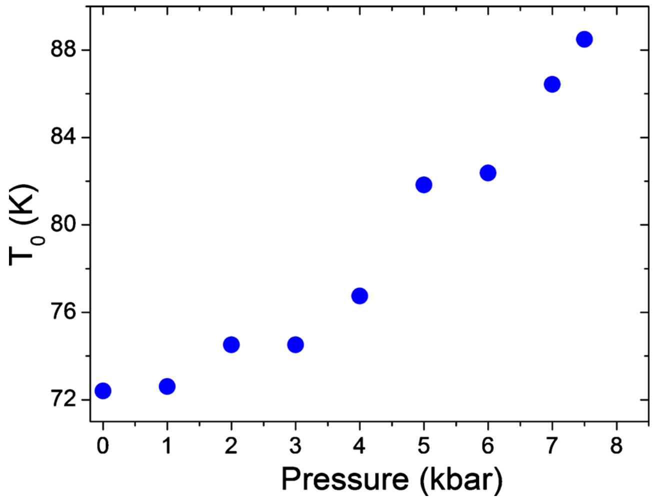

FIG. 4. (Color online) Improvement of T_0 with pressure for temperature range 220–290 K.

Auger-type process which is strongly dependent on the band gap and temperature as previously observed in (311)B 1.55 μm QD, 1.3 μm QW, and QD lasers.[8,9,12–15]

The influence of this on T_0 is further illustrated in Fig. 4 where we find that the T_0 (over the range 220–290 K) of the lasers increases from 72 K at atmospheric pressure to 88 K at 7.5 kbar, clearly showing how the decrease in Auger recombination with increasing pressure gives rise to an improvement in T_0. However, it is clear that even when Auger recombination is reduced (by approximately 30% over this pressure range), the improvement in T_0 is still relatively small (~16 K). This emphasizes the extent to which Auger recombination influences the temperature sensitivity of 1.55 μm QD lasers.

In summary, we have investigated the temperature sensitivity of 1.55 μm InAs/InP QD lasers using temperature dependent measurements of J_{th} and its radiative component J_{rad}, and hydrostatic pressure measurements to determine the role of recombination processes in the QD laser devices. These results suggest that the devices are dominated by an NR recombination process which decreases strongly with increasing pressure and decreasing temperature. Such behavior is consistent with Auger recombination, which we conclude dominates these devices under normal operating conditions.

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