Temperature and pressure dependence of the recombination processes in 1.5 μm InAs/InP (311)B quantum dot lasers

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The threshold current and its radiative component in 1.5 μm InAs/InP (311)B quantum dot lasers are measured as a function of the temperature. Despite an almost temperature insensitive radiative current, the threshold current increases steeply with temperature leading to a characteristic temperature $T_0 \approx 55$ K around 290 K. Direct observation of spontaneous emission from the wetting layer shows that some leakage from the dots to the wetting layer occurs in these devices. However, a decrease in the threshold current as a function of pressure is also measured suggesting that Auger recombination dominates the nonradiative current and temperature sensitivity of these devices.
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It has been suggested that excellent temperature stability, low threshold currents, and high modulation bandwidths can be expected from 1.3 μm InAs/GaAs quantum dot (QD) lasers, in particular, if the devices are *p* doped.[1] This has stimulated interest in extending the lasing wavelengths of QD lasers toward 1.55 μm for long haul telecommunication applications. In order to reach longer wavelengths the dots have to be larger than that needed for 1.3 μm operation. Growing 1.55 μm quantum dots on GaAs is therefore difficult because of the large strain that accumulates during the Stranski-Krastanow growth.[2] A possible alternative is to grow InAs dots on InP substrates which have a much smaller lattice mismatch with InAs (3.2%) compared with GaAs (7%). Molecular beam epitaxy on (100) InP substrates has already allowed the growth of quantum dots[3] or quantum dashes,[4] which has led to the demonstration of high performance lasers.[4,5] Also, the use of the specific InP(311)B orientation has already allowed three-dimensional confined nanostructures with a QD density as high as 10^{11} cm^{-2} (Ref. 6) to be demonstrated as well as a low chirp of 2.5 Gb/s for a directly modulated single mode waveguide laser emitting at 1.6 μm.[7] Recently, an InAs/InP(311)B narrow ridge single mode waveguide laser emitting on the ground state at 1516 nm under continuous wave operation at room temperature was reported.[8]

In this letter we report on a detailed experimental study of the recombination processes that occur in 1.5 μm InAs/InP (311)B QD lasers. A set of 1.5 mm long, 100 μm wide ridge lasers were used for this study. Their active region consists of five layers of dots deposited using the double-cap procedure[9] in a $Ga_{0.2}In_{0.8}As_{0.435}P_{0.565}$ waveguide. The dot density is $\sim 10^{11}$ dots/cm^2, as determined from atomic force microscopy measurements. At room temperature the threshold current densities were typically ~500 A/cm^2 and the T_0 $[=1/(d \ln I_{th}/dT)]$ was ~55 K for temperatures ranging from 0 to 50 °C. In order to understand the recombination processes which take place in these devices, measurements of the threshold current (I_{th}) and its radiative component (I_{rad}) were performed as a function of pressure and temperature. The radiative current was determined by integrating unamplified spontaneous emission spectra obtained from a 100 μm diameter circular window milled in the substrate contact. This ensures that one is measuring the pure spontaneous emission independent of the effect of gain and loss along the cavity. A closed-cycle helium cryostat was used for the temperature-dependent measurements while a piston-in-cylinder apparatus (as described in Ref. 10) was used for high hydrostatic pressure measurements. In both setups the lasers were positioned in a spring clip and were driven by a pulsed source with 500 ns long pulses and a repetition rate of 2 kHz to minimize internal heating.

The results of the temperature measurements are shown in Fig. 1. It can be seen that the radiative current remains approximately constant over this temperature range, as origi-

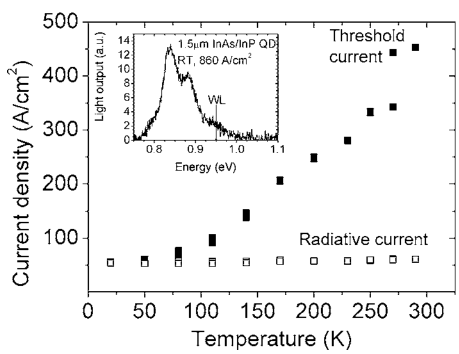

FIG. 1. Temperature dependence of the threshold and radiative current densities as a function of the temperature. The inset shows a pure spontaneous emission spectrum measured at 860 A/cm^2 at 290 K.

[a)]Electronic mail: s.sweeney@surrey.ac.uk nally predicted by Arakawa and Sakaki for an ideal quantum dot laser.[11] We previously observed that for 1.3 μm InAs/GaAs QD lasers, I_{rad} decreases with increasing temperature below 200 K because of an improvement in the interdot carrier transport via the wetting layer.[12] Above 200 K, I_{rad} was measured to be constant as a consequence of the carriers coming into thermal equilibrium. In the 1.5 μm devices studied here, the energy difference between the ground state (GS) transition of the wetting layer and the GS transition of the QD is ~110 meV for both holes and electrons, as shown in the inset of Fig. 1, compared with ~300 meV in 1.3 μm InAs/GaAs QD lasers.[13] This is a direct consequence of the smaller lattice mismatch in InAs/InP compared to InAs/GaAs, which generates a thick wetting layer compared to the dimensions of the dots.[2] Consequently, the temperature at which thermal equilibrium is reached is expected to be much less than 200 K in the 1.5 μm lasers. The thermal distribution and the atomiclike nature of the energy levels thus lead to an almost constant I_{rad} over a large temperature range. The measurements show that I_{rad} increases very weakly (~10%) from 200 to 270 K which could be an effect of either thermal broadening and/or gain saturation.[14,15]

In Fig. 1, I_{rad} was normalized to the value of I_{th} at the lowest measured temperature where we assume that $I_{rad}=I_{th}$. However, we note that the absolute value of I_{rad} might, in fact, be less than this, if, for example, another nonradiative path is present. Figure 1 shows that while I_{rad} is almost constant (and hence the gain is approximately constant), the threshold current increases steeply with increasing temperature. Clearly, this increase is due to a strong temperature dependent nonradiative recombination mechanism which accounts for at least 90% of the total threshold current at room temperature. Pure spontaneous emission spectra show light emission at 0.95 eV; the peak of which corresponds to the transition energy of the wetting layer (inset of Fig. 1). Due to its small layer thickness reabsorption is expected to be negligible. This is a sign that electrons are thermalizing into the wetting layer and, subsequently, undergoing radiative and possibly nonradiative recombination in the wetting layer. We note, however, that the integrated emission from the wetting layer accounts for only ~13% of the total spontaneous emission at threshold and at room temperature. The peak which appears to be at 0.88 eV is likely to be due to the electron first excited state, but interference effects cannot be ruled out at this stage. However, it is clear that the total radiative contribution to the threshold current is small and recombination through the first excited state makes a negligible direct contribution to the total current or its temperature sensitivity.

In order to get more information about the dominating nonradiative recombination process, high hydrostatic pressure measurements were carried out. Hydrostatic pressure increases the direct band gap of III/V semiconductors by decreasing the interatomic spacing. Since the carrier recombination processes have different band gap dependencies, this allows one to separate which process dominates at threshold.[16] In the devices studied here, the lasing energy increases by ~8.4 meV/kbars (inset of Fig. 2). The results of the lasing-energy dependence of the threshold current are shown in Fig. 2. I_{th} is found to decrease by ~40% over ~63 meV at room temperature.

Clearly, since the radiative current is less than ~10% of the total current, this shows that the nonradiative component

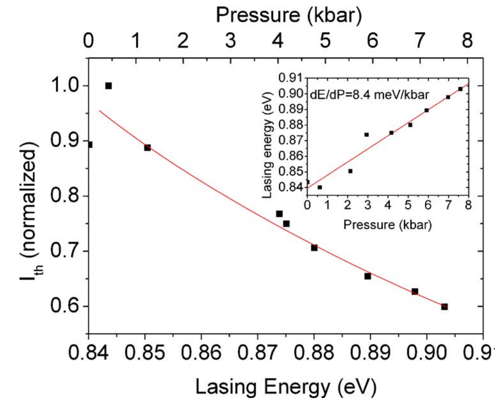

FIG. 2. (Color online) Band gap dependence of the threshold current. The pressure dependence of the lasing energy is shown in the inset.

of the current must decrease with increasing pressure. Although it has not yet been measured for this type of device, I_{rad} is expected to increase with pressure as has previously been measured in 1.5 μm InGaAs/InP quantum well lasers[17] and 1.3 μm InAs/GaAs QD lasers.[18] If I_{rad} increases while I_{th} decreases with increasing pressure, this suggests that the dominant recombination process decreases even more strongly with pressure than I_{th}. Initial photocurrent measurements carried under pressure suggest that the band offset is approximately pressure independent within experimental error. Carrier leakage into the wetting or barrier layers is thus expected to be pressure independent. Previous calculations have shown that the rate of Auger recombination decreases with pressure in quantum dots due to the decreased overlap of the electron and hole wavefunctions involved in the Auger process with increasing band gap.[16] The measured decrease in threshold current with pressure (band gap) is therefore consistent with nonradiative Auger recombination dominating the threshold current at room temperature.

In summary we have measured the temperature dependence of the radiative and threshold currents of 1.5 μm InAs/InP (311)B quantum dot lasers. The relatively small strain induces a confinement potential of about 110 meV. The results show that the interdot carrier transport via the wetting layer effectively leads to an almost temperature stable radiative current over the range of temperatures studied here. Carrier recombination in the wetting layer is directly observed suggesting that there is some carrier leakage. However, pressure measurements of the threshold current suggest that Auger recombination plays an even more dominant role in these devices than in 1.3 μm InAs/GaAs quantum dot lasers.

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