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Radiative and Auger recombination in 1.3 μm InGaAsP and 1.5 μm InGaAs quantum-well lasers measured under high pressure at low and room temperatures

S. R. Jin,^{a)} S. J. Sweeney, C. N. Ahmad, A. R. Adams, and B. N. Murdin

Advanced Technology Institute, School of Electronics and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom

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We report on the pressure dependence of the threshold current in 1.3 μm InGaAsP and 1.5 μm InGaAs quantum-well lasers measured at low temperatures ~ 100 K. It was found that the threshold current of both devices slowly increases with increasing pressure (i.e., increasing band gap) at ~ 100 K consistent with the calculated variation of the radiative current. In contrast, at room temperature we observed a reduction of the threshold current with increasing pressure. Our low-temperature, high-pressure data confirm the results of previous atmospheric pressure measurements on the same devices which indicated a transition in the dominant recombination mechanism from radiative to Auger as the device temperature is increased from ~ 100 to 300 K. © 2004 American Institute of Physics. [DOI: 10.1063/1.1772871]

1.3 and 1.5 μm semiconductor quantum-well lasers are the key devices for optical communication applications. Much work has been focused on the fundamental optical processes and the limiting factors in these laser systems.^{1–12} Such knowledge enables us to investigate the scope for further device optimization by means of band structure engineering in low-dimensional heterostructure systems such as quantum-wells (QWs), quantum barriers, quantum wires, and quantum dots. In general, the threshold current, I_{th} , of semiconductor lasers may be considered to consist of four carrier density, n , dependent recombination channels,^{13,14} namely, monomolecular recombination ($\propto n$) which describes recombination via traps and defects, band-to-band radiative recombination ($\propto n^2$), Auger recombination ($\propto n^3$), and carrier leakage. It has been shown⁵ that the monomolecular recombination current is negligible in 1.3 and 1.5 μm InGaAs(P) devices at the high carrier densities required to reach lasing threshold. The carrier leakage current is also assumed to be insignificant in the above-noted material systems,¹⁵ which has previously been confirmed by room temperature (RT) hydrostatic pressure studies.¹⁶ The contributions of the different recombination mechanisms as a function of temperature have been extensively investigated in our previous work using both facet- and spontaneous-emission measurements.¹⁵ It was shown that, below a certain temperature [170 K for 1.3 μm InGaAs(P) and 130 K for 1.5 μm InGaAs], the radiative current dominates I_{th} . With increasing temperature, the Auger recombination current increases and becomes the dominant contribution to I_{th} at RT. The significant Auger recombination in 1.3 and 1.5 μm InGaAsP devices at RT is also confirmed by RT high-pressure measurements.^{15,16} Therefore, one might expect completely different pressure behavior of the threshold current in the above-noted devices at low temperatures.

High pressure is a very useful diagnostic tool, because it allows a controllable and continuous change in the band gap. Because the above-mentioned processes all depend on band

gap in different ways, the pressure dependence can be used to discriminate between them. Furthermore, since most important nonradiative mechanisms including Auger recombination and thermal leakage currents are strongly temperature dependent, becoming significant at high temperature, by performing the high pressure measurements at cryogenic temperatures we may consider the intrinsic properties of the radiative recombination in the absence of nonradiative current paths.

In this letter we report *low-temperature*, high-pressure measurements on 1.3 μm InGaAsP and 1.5 μm InGaAs lasers. It was found that I_{th} of both devices slowly increased with increasing pressure at a temperature of ~ 100 K. These results contrast strongly with the reduction of I_{th} with pressure at RT in both devices.

The devices studied here were buried-heterostructure multi-quantum-well (MQW) lasers, grown using low-pressure metalorganic vapor-phase epitaxy on n -type InP substrates. The 1.3 μm lasers consist of eight compressively strained InGaAsP QWs within unstrained InGaAsP barriers and separate confinement heterostructure layers. The 1.5 μm lasers comprise four compressively strained InGaAs QWs within lattice-matched InGaAsP barriers. The detailed growth procedures of these devices can be found elsewhere.¹⁰ All of the lasers were as-cleaved with a cavity length of 500 μm and were investigated in unmounted chip form. The optical pressure cell, mounted inside a liquid nitrogen bath cryostat was used in conjunction with Unipress U11 helium gas compressor capable of generating pressures up to 15 kbar. The temperature was measured using a buried thermocouple inside the pressure cell. The measurements were performed under pulsed operation (500 ns pulse width at a repetition frequency of 10 kHz) at RT to avoid current heating effects. At low temperatures the threshold currents were ~ 1 mA ($J_{\text{th}} < 100$ A cm^{-2}), and hence, cw operation was used to improve the measurement accuracy. At such low currents, Ohmic heating was found to have a negligible effect on the measured values of I_{th} or the measured emission wavelengths.

^{a)}Electronic mail: s.jin@surrey.ac.uk

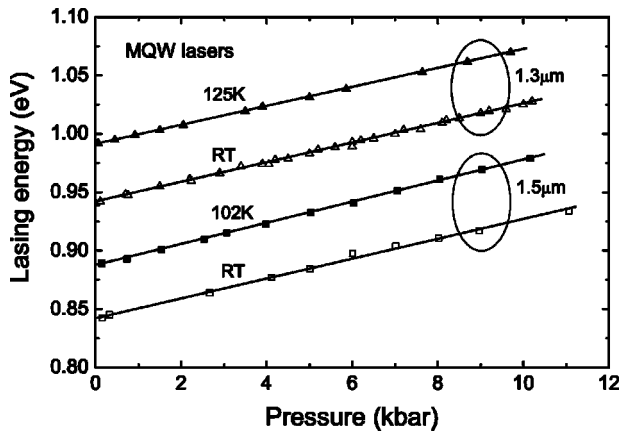


FIG. 1. Lasing energy, E_{lase} , as a function of pressure in 1.3 μm InGaAsP and 1.5 μm InGaAs lasers measured at low temperature ~ 100 K and room temperature. The solid lines are guides to the eye.

Figure 1 shows the pressure dependence of the lasing energy in 1.3 μm InGaAsP and 1.5 μm InGaAs lasers measured at a current $\sim 20\%$ above threshold at both low temperature and RT. It can be seen that the lasing energy, E_{lase} , of both devices varies approximately linearly with increasing pressure, P , in the pressure range of 0–10 kbar. The values of dE_{lase}/dP are $8.1(\pm 0.1)$ meV/kbar for the 1.3 μm device at 125 K and $9.0(\pm 0.1)$ meV/kbar for the 1.5 μm device at 102 K, which are close to their RT values of $8.3(\pm 0.1)$ meV/kbar and $8.4(\pm 0.2)$ meV/kbar, respectively. The rate of lasing energy shift of both devices is close to that of the InP cladding layer (8.4 meV/kbar). This implies that carrier leakage would cause no change in I_{th} with pressure in either 1.3 or 1.5 μm InGaAs(P) lasers, which is not what is observed.

Figure 2 shows the variation of I_{th} with pressure in the 1.3 μm InGaAsP laser at 125 K and RT. A reduction of 12%

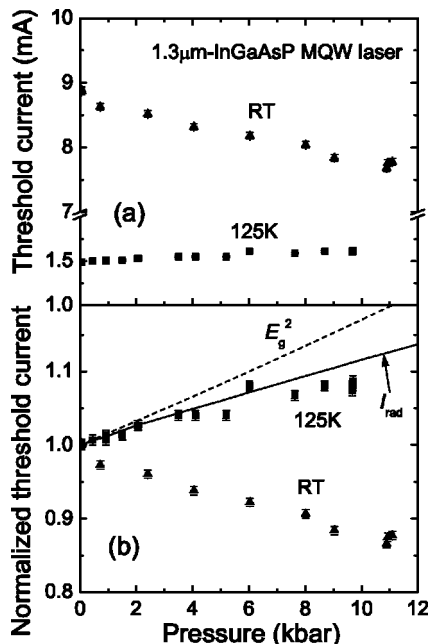


FIG. 2. The pressure dependence of (a) the threshold current and (b) normalized threshold current in a 1.3 μm InGaAsP laser measured at 125 K and room temperature. Also shown are the calculated variation of the radiative recombination current (solid line) and measured E_g^2 (dashed line) at 125 K.

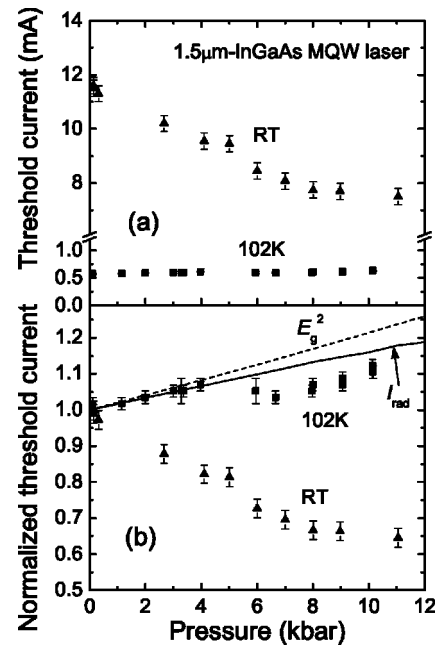


FIG. 3. The pressure dependence of (a) the threshold current and (b) normalized threshold current in a 1.5 μm InGaAs laser measured at 102 K and room temperature. The solid line and dashed line describe the variation of the calculated radiative recombination current and measured E_g^2 vs pressure, respectively, at 102 K.

in I_{th} was observed over a 10 kbar pressure range at RT, which is consistent with our previous work.^{15,17} This suggests a significant contribution from Auger recombination current rather than radiative current in I_{th} at RT. When the temperature was decreased from RT to 125 K, I_{th} dropped from 9 to 1.5 mA, a reduction of 83%. At 125 K, however, it was found that I_{th} increased slowly by $\sim 9\%$ over a 10 kbar pressure range. The solid line in Fig. 2 indicates the calculated variation of the radiative current as a function of pressure for the 1.3 μm InGaAsP laser at 125 K. For this calculation, the QW band structure was calculated using a three-band $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian including contributions from the heavy-hole, light-hole, and spin split-off valence bands. The conduction and valence bands were calculated by solving Poisson's and Schrödinger's equations self-consistently. The gain and radiative current (I_{rad}) were calculated for single QWs using the density matrix formulation including Lorentzian broadening. The optical confinement factor, Γ , was calculated using the effective index method for the complete MQW structure. The refractive index of the pressure medium (helium) was taken to be unity and pressure invariant from which the threshold gain was calculated for a fixed internal loss of 10 cm^{-1} . Further details of the calculation can be found in Ref. 15. From Fig. 2 it is clear that the calculated variation of I_{rad} fits closely with the pressure variation of I_{th} . From considerations of the gain of the active region above, one would expect I_{rad} to increase as E_g^2 where E_g is the band gap. The lower than E_g^2 increase of calculated I_{rad} is caused by the increase in Γ due to the decreasing lasing wavelength. Together, these data confirm that radiative recombination dominates I_{th} at 125 K, rather than Auger recombination, in agreement with our earlier studies.¹⁵

Figure 3 displays the pressure dependence of I_{th} in the 1.5 μm InGaAs laser at 102 K and RT. As in our previous reports,^{15,17} a reduction of I_{th} by 36% was observed over a 10 kbar pressure range at RT, which is a three times greater

decrease than for the 1.3 μm InGaAsP lasers. When the temperature was decreased from RT to 102 K, I_{th} decreased from 12 to 0.58 mA, a reduction of 95%. This implies a larger Auger nonradiative recombination rate and therefore larger contribution from Auger recombination in 1.5 μm InGaAs ($\sim 80\%$ of I_{th}) than in 1.3 μm InGaAsP lasers ($\sim 50\%$ of I_{th}) at RT. At 102 K, it was found that I_{th} increased by 9% over a 10 kbar pressure range, which is the same as in 1.3 μm InGaAsP devices. This also indicates that in 1.5 μm InGaAs devices at 102 K I_{th} is dominated by radiative recombination. This is confirmed by the calculated pressure variation of I_{rad} for these devices at 102 K (solid line) from which we find that the calculated I_{rad} and measured I_{th} have similar pressure dependencies.

The above-mentioned pressure results at low temperatures are consistent with previous temperature dependence measurements for the same devices.¹⁵ From the temperature dependence of the characteristic temperature T_0 and power factor Z (defined by $I \propto n^Z$)^{14,15} it was found that below a certain “break-point”¹⁵ temperature (170 K for 1.3 μm InGaAsP and 130 K for 1.5 μm InGaAs), $T_0 \propto T$ with the value of Z close to 2, suggesting a significant contribution from radiative recombination for both devices. In contrast, above these temperatures, Auger recombination dominates the temperature dependence. At RT, the value of $Z \approx 3$ and a small value of T_0 near $T/3$ is observed. This strongly suggests that the dominant contribution to I_{th} at RT is due to Auger recombination. Since the temperatures used for the present study (125 K for the 1.3 μm InGaAsP devices and 102 K for the 1.5 μm InGaAs devices) are well below the break-point temperature for both the 1.3 and 1.5 μm lasers, our low-temperature high-pressure results provide strong evidence which shows a transition from radiative to Auger dominated behavior as the device temperature is increased from ~ 100 K to RT.

In conclusion, low-temperature, high-pressure measurements in 1.3 μm InGaAsP and 1.5 μm InGaAs lasers are presented. At low temperature ~ 100 K, it was found that I_{th} increased with increasing pressure by 9% over a 10 kbar pressure range. This behavior corresponds well to the calculated pressure dependence of the radiative current for both devices and contrasts strongly with the reduction of I_{th} (by 12% for the 1.3 μm InGaAsP devices and 36% for the

1.5 μm InGaAs devices, respectively) over 10 kbar at RT. This confirms our previous temperature dependence measurements, indicating the transition from the laser threshold being dominated by the radiative current to one where Auger recombination dominates as the device temperature is increased from ~ 100 K to RT.

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