Carrier recombination in InGaAs(P) Quantum Well Laser Structures: Band gap and Temperature Dependence

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Carrier recombination in InGaAs(P) Quantum Well Laser Structures: Band gap and Temperature Dependence

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Abstract. Using a combination of temperature and pressure dependence measurements, we investigate the relative importance of recombination processes in InGaAs-based QW lasers. We find that radiative and Auger recombination are important in high quality InGaAs material. At 1.5µm, Auger recombination accounts for 80% I_{th} at room temperature reducing to ~50% at 1.3µm and ~15% at 980nm. We also find that Auger recombination dominates the temperature dependence of I_{th} around room temperature over the entire operating wavelength range studied (980nm-1.5µm).

INTRODUCTION

InGaAs(P)-based quantum wells (QWs) are used in semiconductor lasers over a very wide wavelength range (~900-1700nm) by growing on either GaAs or InP substrates. It is of significant scientific and technological interest to understand carrier recombination in this material. One of the most important parameters associated with semiconductor lasers is the threshold current, I_{th}, above which stimulated emission dominates. Minimising I_{th} maximizes the electro-optic conversion efficiency. Hence it is vital to understand which carrier recombination processes dominate I_{th} and the extent to which they depend on parameters such as the operating wavelength (λ) and temperature (T). In this study, we performed measurements on 980nm InGaAs/GaAs, 1.3µm InGaAsP/InP and 1.5µm InGaAs/InP quantum well (QW) lasers. By measuring I_{th} and the spontaneous emission as a function of T, we determined the relative importance of the radiative and non-radiative recombination paths. Hydrostatic pressure measurements were used to investigate their dependence on band gap (E_g).

TEMPERATURE DEPENDENCE

Assuming equal electron and hole densities, the threshold current of semiconductor lasers can in general be written as; $I=eV(An+Bn^2+Cn^3)$ where n is the carrier density, e is the electronic charge and V is the active volume. The An term corresponds to recombination via defects and impurities, Bn^2 is due to spontaneous (radiative) emission and Cn^3 is due to

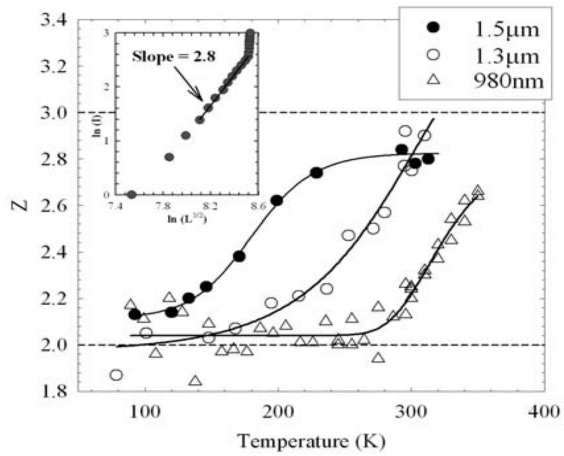

FIGURE 1. Power law dependence (Z) of the threshold current on carrier density for the 980nm, 1.3µm and 1.5µm lasers. The inset illustrates how Z is calculated.

Auger recombination whereby the energy of a recombining electron and hole excites a third electron or hole. Since the emitted spontaneous emission, L, is directly proportional to the radiative current, we may write that $L \propto n^2$ and hence, $n \propto L^{1/2}$. Thus, by plotting a graph of ln$I$ versus ln$L^{1/2}$, the slope (Z) provides a direct measure of the power dependence of I on n. L can be determined experimentally by measuring the un-amplified emission from a "window" milled into the substrate of a semiconductor laser [1]. The inset of Fig. 1 shows such a plot for the 1.5µm device at 300K where Z=2.8. This is consistent with a dominant Auger recombination process, $\propto n^3$. The results of repeating the Z measurement over a wide T range are shown in Fig. 1. From this plot we observe that at each wavelength at the lowest temperatures, Z~2 consistent

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with the current being dominated by radiative recombination. For the 1.5µm device, above ~130K, Z increases with T and stabilizes at a value of ~2.8 at room temperature. This is consistent with a transition from radiatively dominated behaviour at low T to Auger recombination dominating at and above room temperature, RT. Similar behaviour is apparent for the 1.3µm and 980nm lasers where we observe that Z increase above ~2 at a temperature of ~170K and ~280K respectively. The fact that this occurs at increasingly higher temperatures as λ decreases is consistent with the strong band gap (E_g) dependence of Auger recombination. Furthermore, given that over this T range, Z does not drop below a value of two for these devices we conclude that defect related recombination is negligible in these devices at the high carrier densities required for lasing threshold. This is in contrast to materials such as InGaAsN where defect-related recombination can account for 50% I_{th} at RT for N fractions ~2% [2].

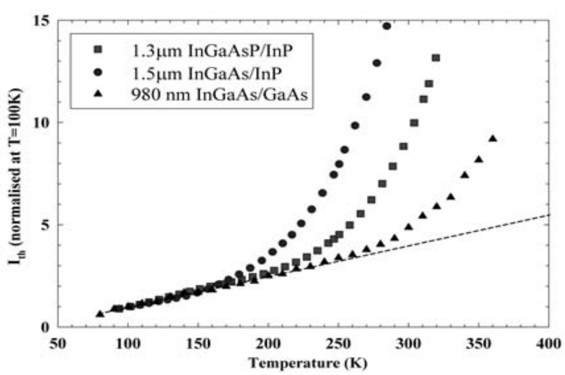

FIGURE 2. $I_{th}(T)$ for the 980nm, 1.3µm and 1.5µm lasers. The dashed line is the projected ideal $I_{rad}(T)$.

In Fig. 2 we plot the measured $I_{th}(T)$ for the three lasers (normalised at 100K). For all three devices, at low T we find that $I_{th} \propto T$ as expected for an ideal QW for which the radiative current, $I_{rad} \propto T$ [1]. Above a certain "break-point" temperature, T_B [1] I_{th} increases super-linearly. Furthermore, it can be seen that for all of the devices, at T_B, Z increases above 2 as observed in Fig. 1. Thus, at low T, both I_{th} and its temperature sensitivity are governed by radiative recombination. Above T_B, Auger recombination begins to contribute to I_{th} and gives rise to the super-linear increase in I_{th}. By extrapolating the low temperature linear variation of I_{th} we deduce that at RT, Auger recombination accounts for ~15%, ~50% and ~80% of I_{th} in the 980nm, 1.3µm and 1.5µm lasers, respectively. This is consistent with the strong E_g dependence of Auger recombination.

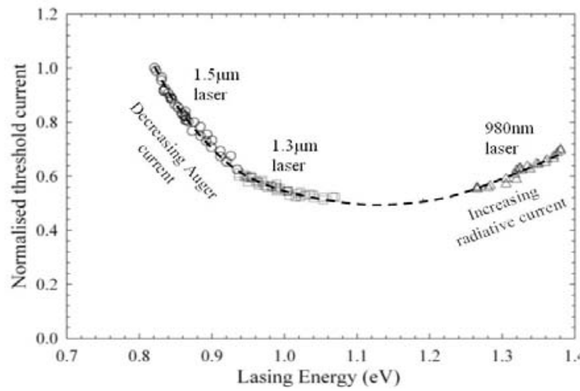

FIGURE 3. Band gap dependence of I_{th} in the nominally 980nm, 1.3µm and 1.5µm lasers. The line is a guide to the eye.

BAND GAP DEPENDENCE

Hydrostatic pressure is a useful tool to investigate the band gap, E_g, dependence of recombination processes in semiconductor lasers since E_g increases with increasing pressure. Because of the increase in E_g and electron effective mass with pressure I_{rad} increases with pressure. In contrast, due to the strong decrease in the Auger coefficient, C, with E_g, I_{Aug} decreases with pressure. In Fig. 3, we plot the normalised RT pressure dependence of I_{th} for the 980nm, 1.3µm and 1.5µm lasers, plotted versus lasing energy. From this graph it is clear that with increasing E_g, I_{th} decreases for the 1.3µm and 1.5µm devices due to the reduction in Auger recombination. In contrast, for the 980nm device where radiative recombination dominates, I_{th} increases with band gap, due to the increase in I_{rad}.

CONCLUSIONS

In summary, from a combination of temperature and pressure dependence measurements we have shown the increasingly important role that Auger recombination plays in InGaAs based lasers as the operating wavelength increases from 980nm to 1.5µm.

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