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TEMPERATURE AND WAVELENGTH DEPENDENCE OF RECOMBINATION PROCESSES IN 1.5μm InGaAlAs/InP-BASED LASERS

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Abstract

The improved thermal stability of 1.5μm InGaAlAs- compared with InGaAs-based lasers is investigated using a combination of low temperature and high pressure techniques. The results indicate that this is due to lower non-radiative Auger recombination in the InGaAlAs devices because of the higher conduction band offset made possible with the InGaAlAs system which results in a lower hole density in the quantum wells at threshold.

I. Introduction

Semiconductor lasers operating in the 1400-1600nm band are key components of optical fibre based communications systems both as signal and pump sources. InGaAs(P)/InP is traditionally used for the production of devices at these wavelengths. However, due to the strong temperature dependence of the threshold current (I_{th}) of these devices there is ongoing activity in searching for an alternative, more thermally stable material. The development of such materials requires a detailed understanding of the thermal factors influencing device characteristics over their operating temperature range. InGaAlAs/InP-based lasers have exhibited improved thermal performance with higher T_o values compared with InGaAsP/InP devices at 1.3μm (1). It is of great interest to extend this benefit to longer wavelengths for pump and signal applications. In order to achieve this, it is vital to understand which processes limit the thermal performance of InGaAlAs/InP lasers and how these vary with wavelength and temperature.

In this paper, we describe low temperature and high pressure measurements performed on 1.5μm InGaAlAs/InP-based devices to determine the important recombination processes and their variation with wavelength and temperature. The results are compared with similar measurements performed on conventional InGaAs/InP-based 1.5μm lasers. We find that InGaAlAs lasers exhibit ideal radiative behaviour up to a much higher temperature than the InGaAs devices. Furthermore, we find that I_{th} in InGaAlAs lasers has a lower dependence on wavelength than in InGaAs devices. These results are consistent with a reduced contribution of Auger recombination to I_{th} for the InGaAlAs devices at room temperature (RT) compared with InGaAs-based 1.5μm lasers. Specifically, we find that whilst Auger recombination accounts for 80% of I_{th} in 1.5μm InGaAs devices at RT, it accounts for only ~55% of I_{th} in the 1.5μm InGaAlAs devices. We further demonstrate that this is a consequence of the increased conduction band offset offered by the InGaAlAs system, which results in a more even balance of electrons and holes in the quantum wells at threshold, thereby reducing Auger processes which depend strongly on the hole density.

II. Carrier recombination mechanisms

In long wavelength semiconductor lasers for which we can assume high quality material and therefore may neglect defect related recombination, I_{th} may be written in terms of the carrier density, n, (for equal concentrations of electrons and holes) as

$$I_{th} = eV\left(Bn^2 + Cn^3\right) + I_{leak} \qquad (1)$$

where e is the electronic charge and V is the active region volume. The Bn^2 term corresponds to the spontaneous, radiative recombination of electrons and holes giving rise to the radiative current, I_{rad}. Cn^3 is due to Auger recombination whereby the energy of a recombining electron-hole pair promotes a third electron (hole) into the conduction (valence) band, resulting in the Auger recombination current, I_{Aug}. Finally I_{leak} describes the thermal escape of carriers from the quantum wells (QWs) forming a leakage current.

For each of the current paths discussed above, the extent to which they contribute to the threshold current depends strongly on the band gap and temperature. Therefore, in order to determine their relative importance we have undertaken measurements of I_{th} as a function of temperature and used hydrostatic pressure to vary the band gap. These measurements are described in the following sections.

III. Samples

The InGaAlAs lasers studied here consist of 6, compressively strained InGaAlAs QWs within unstrained InGaAlAs barriers (λ_g=1.1μm) and separate confinement layers grown on an InP substrate. For comparison, standard InGaAs devices were measured containing 4, compressively strained QWs within unstrained InGaAsP barriers (λ_g=1.3μm) and separate confinement layers grown on an InP substrate.

IV. Temperature Dependence

In Figure 1 we plot the normalised temperature dependence of I_{th} for (a) InGaAlAs and (b) InGaAs based devices. The measurements were performed under pulsed conditions using a liquid nitrogen cryostat. At low temperatures, for both devices, we observe a linear increase in I_{th} with temperature consistent with the ideal temperature dependence $I_{rad}\propto T$ (2) as indicated by the dotted line. However, with increasing temperature, I_{th} departs from the ideal radiative line and increases super-linearly. The temperature at which this occurs is higher in the InGaAlAs lasers than in the InGaAs devices.

The Auger current has a strong temperature dependence given by $I_{Aug}\propto T^3 exp(-E_a/kT)$ (2) where k is the Boltzmann constant and E_a is the activation energy of the Auger process. The lines in Figure 1 are the fittted $I_{th}(T)$ assuming the above temperature variations of I_{rad} and I_{Aug}. Details of the fitting technique can be found in Ref. (2). From these data we observe that InGaAlAs devices have a

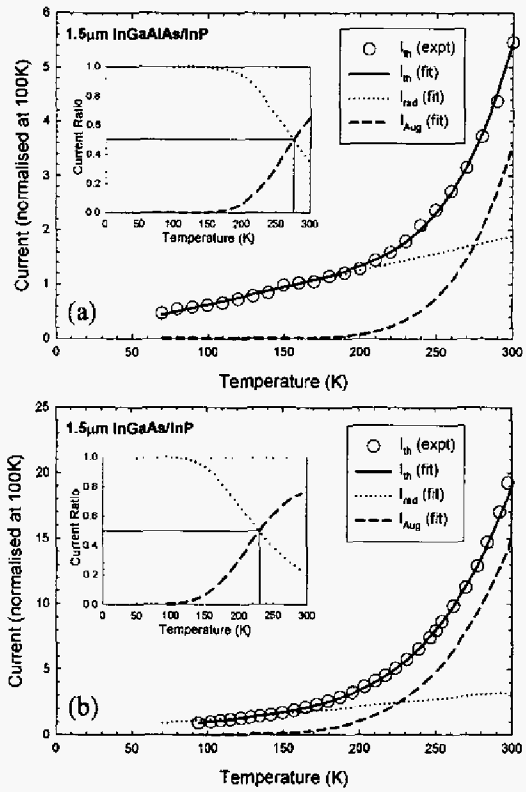

Figure 1 shows the temperature dependence of I_{th} for the InGaAlAs (a) and InGaAs (b) devices. Also shown are the fitted variations of I_{rad} and I_{Aug}. Inset shows the fraction of each current path at I_{th} as a function of temperature.

considerably lower temperature dependence of I_{th} which increases by a factor ~6 from 100K to room temperature (RT) compared with a factor ~20 for the InGaAs devices. Whilst clearly the strong temperature dependence for both devices is consistent with Auger recombination, at this stage, carrier leakage cannot be discounted although in section V we will provide further strong evidence for Auger recombination. In the inset of Figure 1 we plot the ratios I_{rad}/I_{th} (dotted line) and I_{Aug}/I_{th} (dashed line) as a function of temperature. At low temperature, I_{rad} dominates both devices but with increasing temperature, I_{Aug} becomes dominant. The temperature at which I_{rad} and I_{Aug} become equal is considerably higher for the InGaAlAs devices (276K) compared with the InGaAs devices (231K). This gives rise to a lower Auger fraction at RT for the InGaAlAs devices of ~60% compared with ~80% for the InGaAs devices.

V. Pressure (Wavelength) dependence

The application of hydrostatic pressure to semiconductor lasers is a very useful way of varying the emission wavelength because the direct band gap (E_g) of semiconductors increases with increasing pressure. High pressure affects each current path in very different ways. For an ideal QW laser, $I_{rad} \propto E_g^2$ (3), thus one would expect to observe an increase in I_{rad} with pressure. In contrast, $I_{Aug} \propto exp(-E_g/E_o)$ where E_o is approximately independent of pressure, thus I_{Aug} decreases strongly with pressure. Finally, due to the fact the pressure coefficients of the band gaps of the QW and barrier layers are approximately equal, the QW-barrier band offset is approximately independent of pressure, and hence, I_{leak} remains constant as a function of pressure. In Figure 2 we show the normalised pressure variation of I_{th} for 1.5μm InGaAs and InGaAlAs devices. For both devices I_{th} decreases with increasing pressure (decreasing wavelength). This can be understood if Auger recombination contributes strongly to the threshold current in both of the devices. The dotted line shows the expected variation of the radiative current whilst the dashed line corresponds to the theoretically predicted variation of the Auger current for the InGaAs devices. From this we deduce that, under

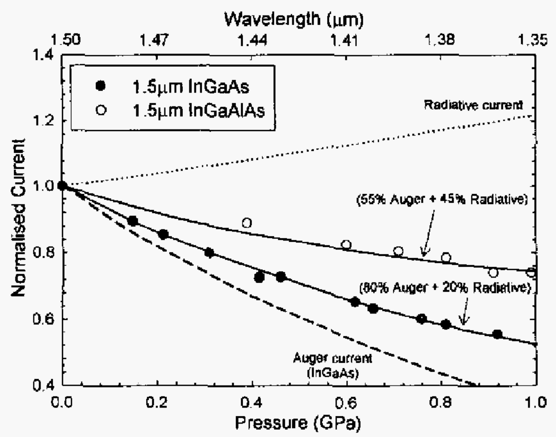

Figure 2 Measured pressure (wavelength) dependence of I_{th} for InGaAs (solid circles) and InGaAlAs (open circles) based 1.5μm lasers. These measurements indicate a smaller contribution from Auger recombination to I_{th} in the InGaAlAs devices.

ambient conditions, I_{th} consists of $80\% I_{Aug}+20\% I_{rad}$ for the InGaAs devices and, assuming the same pressure dependence of I_{Aug} for the InGaAlAs devices, we find that I_{th} is composed of $55\% I_{Aug}+45\% I_{rad}$. These values are in very good agreement with those obtained from the temperature dependence measurements in section IV.

These results indicate that non-radiative Auger recombination is important in both InGaAs and InGaAlAs devices but that it plays a smaller role in the InGaAlAs devices.

VI. Effect of Conduction Band Offset

It is of considerable interest to understand the physical origin of of the smaller role ofAuger recombination in InGaAlAs devices. In Figure 3 we plot the band alignments for the InGaAs and InGaAlAs QW structures used in the experimental studies. The InGaAlAs material offers a significantly larger band offset for electrons (ΔE_c=142meV) in the conduction band QW which would be beneficial for the suppression of electron leakage. However, measurements performed on 1.3μm InGaAlAs devices, which have a lower ΔE_c of 109meV, show significantly *less* temperature sensitivity and *reduced* non-radiative current at threshold when compared with the 1.5μm InGaAlAs devices such that, at RT, I_{rad} forms ~70% of I_{th} (*c.f.* ~40% for 1.5μm InGaAlAs). Along with the pressure dependence data this suggests that the *operating wavelength* rather than the band offset is of most importance to the non-radiative current. This is consistent with Auger recombination dominating the non-radiative current since it is a strongly wavelength dependent process (3).

With reference to equation (1), the Auger current depends upon *both* the Auger coefficient, C, and the cubed carrier density, n^3. The n^3 dependence of Auger recombination is, in fact, a generalisation where it is assumed that the QW electron density, n, is equal to the QW hole density, p.

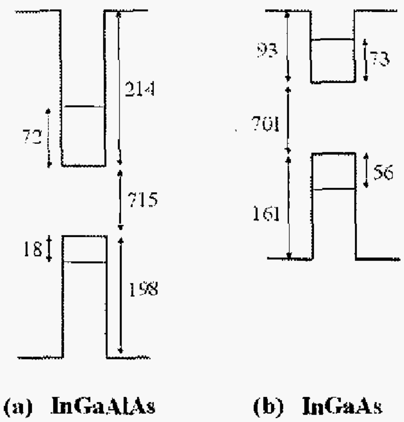

Figure 3 Calculated band alignments at RT for the (a) 1.5μm InGaAlAs and (b) 1.5μm InGaAs lasers. Energies are in meV (not to scale).

More correctly, for Auger processes which lead to the excitation of an electron, the corresponding Auger current, $I^e_{Aug} = eVC^e n^2 p$. Similarly for hole excitation, $I^h_{Aug} = eVC^h np^2$ where C^e and C^h are the electron- and hole- Auger coefficients respectively. Previously we demonstrated that for InGaAs-based devices, Auger hole excitation dominates (4) and therefore I_{th} is most strongly dependent on p. Thus, minimising p will reduce the Auger current. In Figure 4, for the structures shown above, we plot the ratio of hole to electron density, p/n, within the QW as a function of material gain. The calculations were based upon an 8x8 *k.p* theory accounting for the effects of strain together with a self-consistent solution of Schrödinger's and Poisson's equations, accounting for carrier spill-over into the barrier layers. Further details may be found in Ref. (2). These calculations show a striking difference in the electron and hole densities as a function of gain for the two materials. Over this range of material gain, $n \approx p$ for the InGaAlAs QWs, whilst $p>n$ for the InGaAs QWs. Furthermore, the *absolute* value of p is consistently higher for the InGaAs QWs, where, for a material gain of 2500cm^{-1} for example ($\approx$ threshold gain for the devices considered here), p(InGaAs)=1.13p(InGaAlAs). This will have a profound effect on the hot hole Auger process which, assuming the same value of C, will be a factor of $(1.13)^2$=1.27 (*i.e.* 27%) greater for the InGaAs devices compared with the InGaAlAs devices. This is consistent with the lower non-radiative current contribution in the InGaAlAs devices and can help to explain the improved thermal characteristics of the InGaAlAs-based 1.5μm devices.

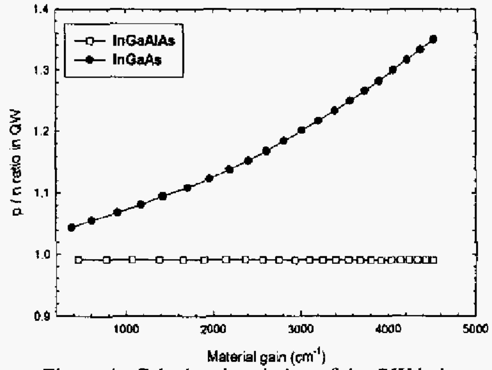

Figure 4 Calculated variation of the QW hole to electron ratio as a function of gain for 1.5μm InGaAlAs and InGaAs single QWs (at RT).

VII. Conclusions

In summary, using a combination of high pressure and low temperature techniques we find that the improved thermal stability of 1.5μm InGaAlAs-based devices is due to a reduced Auger recombination current compared with InGaAs-based devices. This is a direct consequence of the higher conduction band offset afforded by the InGaAlAs material system which suppresses Auger processes which result in the production of hot holes.

Acknowledgements

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