Temperature and pressure dependence of carrier recombination processes in GaAsSb/GaAs quantum well lasers

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We investigated the temperature and pressure dependence of carrier recombination processes occurring in GaAsSb edge-emitting lasers operating near 1.3 μm . Below ~ 100 K, the threshold current, I_{th} , is dominated by the radiative current, I_{rad} , and is proportional to temperature, T . However, above 100 K, non-radiative recombination increases abruptly such that by 125 K it accounts for 40% of I_{th} . From high pressure measurements at this temperature, we find that the non-radiative current decreases with increasing pressure, consistent with the presence of Auger recombination. At room temperature, non-radiative recombination accounts for $\sim 90\%$ I_{th} and gives rise to a super-linear temperature dependence of I_{th} , in spite of the fact that $I_{\text{rad}} \propto T$. At room temperature the non-radiative current increases with increasing pressure, indicating that under ambient operating conditions, the devices are also limited by carrier leakage into the Γ -minimum of the GaAs barriers and possibly also into the X-minima of the GaAsP confining layers.

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1 Introduction

Lasers emitting close to 1.3 μm are of considerable importance for the development of metro-area networks. Completing this final link will facilitate very fast data access to homes and businesses. A key requirement to achieve this aim is minimizing the cost. Vertical Cavity Surface Emitting Lasers (VCSELs) offer a potential route to achieve this aim due to the low device fabrication and packaging costs, and the fact that cooler-less operation may be possible through appropriate active region and cavity design. Unfortunately, traditional materials such as InGaAsP/InP which have been used to make 1.3 μm lasers are unsuitable for VCSELs since InGaAsP/InP offers a poor refractive index contrast and hence the very high reflectivity Distributed Bragg Reflectors (DBRs) required to make VCSELs cannot easily be fabricated. In contrast, GaAs/Al(Ga)As is an excellent material system for making DBRs and hence a GaAs-based active region is highly desirable. In order to manufacture VCSELs using GaAs technology there are several potential active regions such as GaInNAs/GaAs Quantum Wells (QWs) and InAs/GaAs Quantum Dots. Whilst the quality and performance of these systems has been continually improving they have problems. For GaInNAs-based QW lasers it has been shown that even for the best 1.3 μm devices available, approximately 50% of the threshold current at room temperature may be attributed to defect related recombination [1]. The implications of this on long-term device stability have yet to be fully addressed. The InAs quantum dot lasers suffer due to the effects of inhomogeneous broadening and non-

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radiative recombination [2]. Achieving sufficiently high gain for the dots also inhibits their potential for use in VCSELs. Another possibility is the use of GaAsSb/GaAs QWs [3]. Lasers (edge emitting [4] and VCSELs [5]) based upon this material have been successfully produced but little, if any, research has been undertaken to assess the carrier recombination and temperature dependent processes occurring in devices based upon this material. The aim of this paper is to investigate the important recombination processes using temperature and pressure dependent measurements on edge-emitting lasers to aid in the design and optimization of GaAsSb/GaAs-based edge-emitting lasers and VCSELs.

2 Laser structures and experiments

In this study we investigated devices processed from wafers grown by Solid Source Molecular Beam Epitaxy. The active region consists of 3, 7 nm GaAs_{0.64}Sb_{0.36} QWs within 5 nm GaAs spacers and 8 nm GaAsP barriers for strain compensation. The devices were measured as-cleaved with cavity lengths of 500 μm . Further details on the growth and structures can be found in [6]. Temperature dependence measurements over the range of 60–300 K were performed with a standard closed cycle cryostat set-up. Hydrostatic pressure measurements over the range 0–10 kbar were performed using either a gas compressor or a piston-in-cylinder liquid system. The application of high hydrostatic pressure causes an increase in the direct band gap, mimicking the effect of alloying thereby allowing one to investigate wavelength dependent properties of semiconductor lasers. Furthermore, due to the different pressure coefficients of the layers it can also be used to alter the alignment between direct (Γ) and indirect (X, L) bands and to alter the band offsets between layers of differing composition [7]. It is thus, a useful means of probing carrier recombination processes which are generally band-structure sensitive. In order to quantify the different carrier recombination processes, we also measured the pure spontaneous emission from the lasers. Since the light emitted from the facets is strongly influenced by gain/loss as the optical field propagates along the cavity, we instead measure the light emitted in a perpendicular direction. To do this we milled a window in the n-side of the devices using a focused ion beam and aligned an optical fibre with the window to collect the spontaneous emission where the coupling efficiency is kept constant. This experiment was performed as a function of both temperature and pressure. Further details of this technique are described elsewhere [8].

3 Temperature dependence

The threshold current of a semiconductor laser is the point at which the gain equals all of the losses in the device and above this current efficient stimulated emission dominates. It is therefore desirable to have a low (ideally zero) and temperature independent I_{th} .

Figure 1 shows the temperature, T , dependence of the threshold current, I_{th} (circles). It can be seen that the threshold current exhibits an approximately linear dependence on temperature in the low temperature regime. This is exactly as one would expect for an ideal QW laser for which carriers recombine purely radiatively [8]. However, above ~ 100 K, I_{th} increases strongly with temperature, particularly around room temperature. This is highly undesirable and it is important that the origin of this strong temperature sensitivity is understood for the eventual device application. In Fig. 1 we also show the variation of the radiative current at threshold, I_{rad} , with temperature (squares). At threshold, the spontaneous emission from the laser window pins, due to the fact that the carrier density is clamped by the lasing process (see inset of Fig. 1). The temperature variation of I_{rad} is thus determined from the pinning level, L_{pin} , of the integrated spontaneous emission. From the threshold current measurements at low temperature we observed that I_{th} behaved ideally and thus, we may write that $I_{\text{th}} = I_{\text{rad}}$ for $T \leq 100$ K. Hence, by normalizing the value of L_{pin} at low temperature to I_{th} we may determine the absolute magnitude of I_{rad} as a function of temperature, as shown by the squares. I_{rad} exhibits a close to linear temperature variation over the entire temperature range studied from which we conclude that the strong super-linear increase of I_{th} must be due to a non-radiative process. From temperature dependence measurements (Fig. 1) we find that around room temperature, the threshold current (I_{th}) is very temperature sensitive whilst the radiative current

Fig. 1 Temperature dependence of I_{th} (circles) and I_{rad} (squares). Inset shows the integrated spontaneous emission versus current from which I_{rad} is calculated.

(I_{rad}) is relatively temperature stable. This suggests that close to room temperature the lasers are dominated by non-radiative recombination amounting to $\sim 90\%$ of I_{th} . However, from the temperature dependence measurements it is not clear which non-radiative process dominates.

4 Pressure dependence

In order to investigate the non-radiative process(es) further we subjected the lasers to high hydrostatic pressure. High pressure can help to differentiate between different non-radiative recombination processes. In high quality material, as here, the possible non-radiative processes are Auger recombination and carrier leakage. In an Auger recombination process, when an electron and hole recombine, instead of producing a photon, the energy is used to promote a third electron (hole) higher into the conduction (valence) band. This carrier then releases its energy in the form of phonons. Auger recombination tends to reduce with increasing pressure (band gap) due to the fact that it becomes increasingly difficult to conserve energy and momentum in the carrier transitions. Thus whilst Auger recombination is almost absent in short wavelength (visible) lasers, it dominates lasers in the near and mid infra-red. Pressure is therefore a useful means of probing Auger recombination processes through varying the band gap. In carrier leakage processes, given sufficient thermal energy, a carrier may escape from the QW Γ -minimum into the Γ , L or X-minima of the QW, barrier or cladding layers where they may recombine radiatively (albeit at a higher energy which is of no use to the lasing process) or non-radiatively. Carrier leakage is therefore important in structures with low band offsets. Pressure can be used to vary the splitting between the Γ , L or X-minima and can therefore be used to investigate carrier leakage currents. In most laser materials operating at $1.3\ \mu\text{m}$, Auger recombination dominates, accounting for 50, 30 and 25% of I_{th} in InGaAsP/InP, InGaAlAs/InP and GaInNAs/GaAs QW lasers at room temperature, respectively [9]. Furthermore, the room temperature threshold current of $1.3\ \mu\text{m}$ InAs/GaAs Quantum Dot lasers is dominated by Auger recombination [2].

In Fig. 2 we plot the pressure dependence of I_{th} for the GaAsSb/GaAs lasers at room temperature (circles). With increasing pressure, we find that I_{th} increases by $\sim 40\%$ over 8 kbar. Also shown is the pressure dependence of the radiative current, as determined from the integrated spontaneous emission at threshold (squares). The measured increase in I_{rad} is in reasonable agreement with the ideal QW transparency model where $I_{rad} \propto E_g^2$ dependence (dash-dot-dot line) [9], where E_g is the band gap which is assumed to be equal to the measured lasing energy. However, the pressure dependence of the threshold current is stronger, particularly above 6 kbar. This is perhaps unsurprising since, as shown earlier, I_{rad} accounts for only $\sim 10\%$ of I_{th} at room temperature and atmospheric pressure. From this we conclude that the strong increase in I_{th} with pressure is due to the non-radiative process. This is confirmed by the

Fig. 2 Room temperature pressure dependence of I_{th} (circles) and I_{rad} (squares). Also shown is the derived non-radiative current (dashes) and the pressure variations of carrier leakage into Γ_{GaAs} (dotted) and X_{GaAsP} (dot-dash) and the ideal variation of the radiative current $\propto E_g^2$ (dash-dot-dot) where E_g was taken from the measured lasing energy.

dashed line which shows the pressure variation of the non-radiative current, I_{nonrad} , calculated from the measured I_{rad}/I_{th} ratio of 0.10 at room temperature and atmospheric pressure and the measured $I_{th}(P)$ and $I_{rad}(P)$. The increase in I_{nonrad} indicates that a leakage current is present in these devices. The conduction band offset of the GaAsSb/GaAs interface (for 30% Sb) is still a matter of debate with reports in the literature of both weak type I [6] and type II alignments [10]. This indicates that the conduction band offset is close to zero. Due to the slightly larger pressure coefficient of the GaAsSb QW Γ -minimum compared to the GaAs barrier Γ -minimum (difference = +1.2 meV/kbar), occupation of electrons in the GaAs barrier states will increase with increasing pressure, as shown by the calculated dotted line in Fig. 2 (see Ref. [11] for details of the leakage model). Furthermore, due to the small or possibly negative (type II) GaAsSb/GaAs band offset, the GaAsP layers act as additional barriers. With increasing pressure the X-minima in the GaAsP layers move to lower energy and may provide an additional leakage path, as shown by the dot-dashed line in Fig. 2 [11]. This has been supported by preliminary gain calculations [12].

Whilst carrier leakage into the GaAs and/or GaAsP barrier layers offers a possible explanation for the increase of I_{th} with pressure, it is clear that this in itself is insufficient. The lower rate of increase of I_{th} with pressure dependence compared to the leakage paths may be explained if carrier leakage together with a non-radiative process that decreases with pressure are *both* present. Auger recombination decreases with increasing pressure and is known to be important in other lasers operating over this wavelength range [9]. We therefore suggest that the non-radiative recombination which dominates I_{th} at room temperature is due to a combination of carrier leakage and Auger recombination. However, based on our data, it is difficult to quantify the role of each of these non-radiative current paths.

The importance of the Auger recombination in these devices becomes apparent when the pressure dependence of the threshold current is measured at low temperature (125 K), as shown in Fig. 3 (circles). The dashed line represents the ideal E_g^2 dependence of the radiative current. Whilst the radiative current was not measured at low temperature, our room temperature measurements suggest that an E_g^2 dependence is a reasonable approximation. It can be seen that the threshold current increases at a lower rate with pressure than the ideal radiative current, this is most obvious above 4 kbar. From our earlier temperature dependent measurements we estimate that the non-radiative current accounts for 40% I_{th} at 125 K. Hence, we may deduce the pressure variation of the non-radiative current, as shown by the triangles. We observe that the non-radiative current decreases with pressure. This is consistent with the presence of Auger recombination and suggests that at this lower temperature, Auger recombination is the dominant non-radiative process. This can be understood in terms of the fact that at 125 K, the electrons have considerably lower thermal energy compared with room temperature making leakage much less likely. In spite of this, Auger recombination persists leading to a large and temperature sensitive threshold current, even at this low temperature.

Fig. 3 Pressure dependence of I_{th} (circles) at 125 K. Also shown is the ideal variation of the radiative current $\propto E_g^2$ (dash-dot-dot). The triangles represent the derived pressure variation of the non-radiative current, which is seen to decrease with pressure.

5 Conclusions

In summary, we have investigated the temperature and pressure dependence of carrier recombination processes occurring in GaAsSb edge-emitting lasers operating near 1.3 μm . Below ~ 100 K, we find that the threshold current is dominated by radiative recombination leading to ideal $I_{th} = I_{rad} \propto T$ behaviour. However, above this relatively low temperature, non-radiative recombination starts to increase swiftly such that by 125 K it accounts for 40% I_{th} . From high pressure measurements at this temperature, we find that the non-radiative current decreases with increasing pressure, consistent with the presence of Auger recombination. By room temperature, non-radiative recombination accounts for $\sim 90\%$ I_{th} and leads to a very strong temperature dependence of the threshold current, in spite of the fact that the radiative current continues to follow $I_{rad} \propto T$. Pressure measurements at room temperature reveal that the non-radiative current increases with increasing pressure, indicating that under ambient operating conditions, the devices are also limited by carrier leakage into the Γ -minimum of the GaAs barriers and possibly also into the X-minima of the GaAsP confining layers. Further work is ongoing to differentiate between these non-radiative current paths. Optimisation of 1.3 μm GaAsSb lasers will rely upon reducing both the Auger current (by decreasing the carrier density at threshold) and by careful design of the barrier layers to inhibit carrier leakage.

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