Wavelength dependence of efficiency limiting mechanisms in Type I GaInAsSb/GaSb lasers emitting in the mid-infrared

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Abstract: *Type-I GaInAsSb lasers, emitting between 2-3 µm are investigated using temperature and high pressure characterization techniques. A model of the Auger processes is used to fit the non-radiative component of the threshold current at room temperature, identifying the dominance of different Auger losses across the wavelength range of operation.*

Keywords: *Mid-infrared, Type-I Lasers, Auger recombination, spin orbit split-off resonance, quantum well, diode laser*

1. INTRODUCTION

The pursuit of semiconductor lasers in the mid-infrared, operating at ambient temperature with low temperature sensitivity, is motivated by a variety of applications which include environmental monitoring, non-invasive medical diagnosis and industrial processing [1]. Type-I quantum well (QW) laser designs, based on the GaInAsSb/GaSb material system, have received significant attention for this purpose and have reported continuous wave (CW) and room temperature (RT) operation up to 3.73 µm [2]. However, despite these advances the threshold current and external differential efficiency of these devices remain subject to a high degree of temperature sensitivity, confounding the requirement for stability over the operational temperature range. Performance stability of type I infrared inter-band lasers is fundamentally limited by the effects of non-radiative Auger recombination, inter-valence band absorption (IVBA) and carrier leakage. As the spectral range of type-I QW lasers has expanded, these limitations have become more apparent [3]. In this work we report a systematic study of the loss and non-radiative recombination mechanisms affecting the operating characteristics of type-I GaInAsSb based lasers covering the wide spectral range between 2 and 3 µm as well as the extent to which these influence device performance [4].

2. TECHNICAL WORK

The temperature (T) dependence of the threshold current density (J_{th}) of the devices were measured in a temperature range of 80-350 K. The temperature dependence of the characteristic temperature was determined from these measurements and plotted in Fig. 1a for the three wavelength devices with lasing peak at 2.3 µm, 2.6 µm and 2.9 µm at 295 K. The characteristic temperature (T_0) of J_{th} is a measure of the temperature sensitivity of the threshold current density. The same behaviour of T_0 was observed in all devices. Initially, at low T, $T_0 \approx T$ as expected if radiative recombination is dominant. At higher T (>150 K), T_0 decreases rapidly (i.e. decreasing temperature stability), approaching $T_0 = T/3$, as expected for a device dominated by Auger recombination, and then decreases further with increasing temperature. To fully account for the observed behaviour of T_0, additional processes such as inter valence band absorption (IVBA), carrier leakage, etc. are possible candidates that may play a role.

To investigate this further, high hydrostatic pressure techniques were used. Hydrostatic pressure reversibly increases the fundamental bandgap (E_g) of semiconductors providing a useful method to investigate bandgap dependent recombination mechanisms such as the Auger processes, independently of temperature, in fully-functioning devices. In the 2-3 µm wavelength range the two most important Auger processes are the CHCC and CHSH processes. In the CHCC process a **C**onduction band electron recombines with a **H**eavy hole, exciting a second **C**onduction band electron into a higher **C**onduction band state. The CHCC process is expected to decrease exponentially with increasing E_g (increasing pressure). The CHSH process involves the recombination of a **C**onduction band electron and a **H**eavy hole causing the excitation of an electron in the Spin-orbit **S**plit-off band to a state in the **H**eavy hole band. The CHSH process increases exponentially with increasing E_g, as it approaches resonance with the spin-orbit splitting energy (Δ_{SO}). If either of these processes is a dominant recombination pathway then the bandgap dependent behaviour will be evident from the pressure dependence of J_{th}.

High pressure measurements were undertaken using a helium gas pressure system at room temperature for the devices shown in Fig. 1a as well as three additional GaInAsSb lasers [5]. Under high pressures of up to 8 kbar, these lasers can be tuned to cover a wavelength range from 2.9-1.85 µm. This offers a unique opportunity to understand the contributions from both the CHCC and CHSH processes towards longer wavelengths and approaching the $E_g = \Delta_{SO}$ resonance. Through T dependent spontaneous emission measurements [4], the radiative contribution to J_{th} was estimated and removed from the J_{th} of each device, leaving the non-radiative component. The non-radiative component of the threshold current density of each device is shown in Fig. 1b where the data has been normalised.

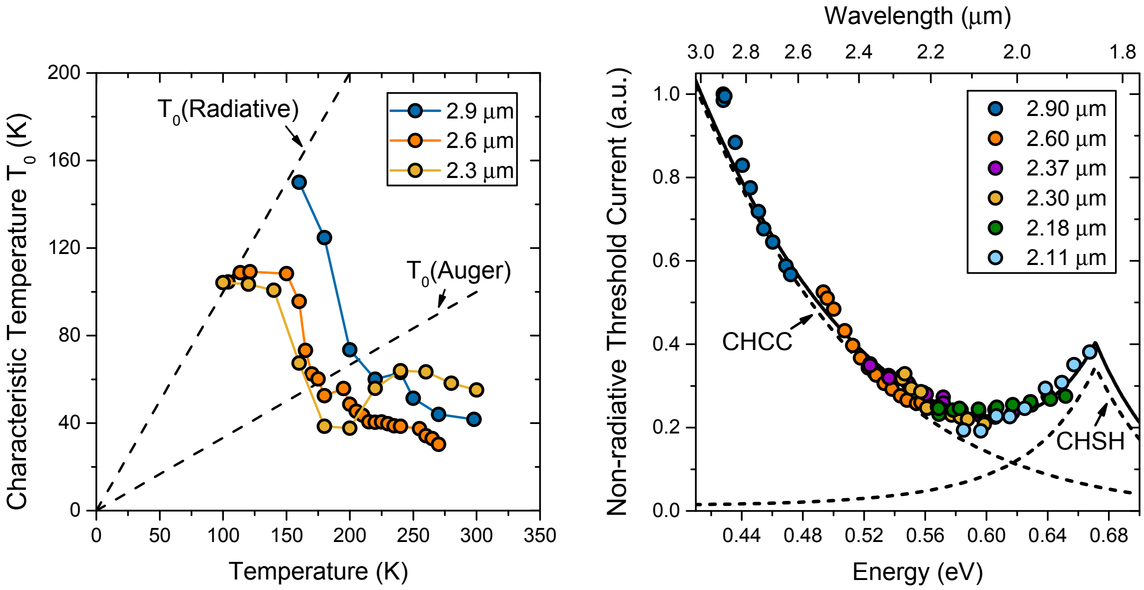

Fig. 1. a) T_0 as a function of temperature for the three different devices. The dashed lines show the theoretical dependencies for radiative and Auger T_0 recombination. b) The normalised non-radiative component of J_{th} and its fit using a simple model for CHCC and CHSH processes.

Above 0.4 eV (<3.1 µm), the non-radiative current density decays approximately exponentially with lasing photon energy, reaching a minimum around 0.6 eV (2.07 µm). The non-radiative current density then increases exponentially with increasing E_g up to 0.67 eV (1.85 µm). This two-termed exponential behaviour is indicative of two Auger processes. To demonstrate this, the non-radiative current density is fitted with a simple model for the CHCC and CHSH Auger processes. Two important regimes are evident from the fit. At wavelengths longer than 2 µm the CHCC process is the dominant recombination pathway and the CHSH process is effectively suppressed as $E_g < \Delta_{SO}$. Below 2 µm the CHSH process begins to dominate as the bandgap begins to approach resonance with the split-off band. The relative importance of these two current paths is critical to device optimization and illustrates the important of the spin split-off band which is sensitive to the Sb fraction in the QW. An increase in the CHSH process is also accompanied by an increase in IVBA which reduces the external differential efficiency. Studies such as these offer a method of optimization of device performance based on a robust understanding of the underlying device physics.

3. CONCLUSION

At room temperature the temperature sensitivity of type-I GaInAsSb diode lasers, emitting at 2-3 µm, is shown to be due to a thermally activated non-radiative/carrier loss pathways, accounting for more than 80% of J_{th}. The analyses indicated that Auger recombination contributed most significantly to the high temperature sensitivity of these devices. Additional processes such as IVBA and carrier leakage are necessary to fully account for the observed behaviour in T_0 at high temperature. High hydrostatic pressure measurements were used to determine the dominant non-radiative pathway in GaInAsSb/GaSb devices in the mid-infrared. The non-monotonic variation of J_{th} with the bandgap is shown to be due to the effects of two Auger processes and provides clear evidence of the spin-orbit split-off resonance for the CHSH process at shorter wavelengths and the dominance of the CHCC process at longer wavelengths. The importance of these processes will be discussed in further detail along with potential routes for their mitigation.

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