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Temperature dependence of 4.1 μm mid-infrared type II “W” interband cascade lasers

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The thermal properties of 5-stage “W” Interband-Cascade Lasers emitting at 4.1 μm at room temperature (RT) are investigated by measuring the lasing and spontaneous emission properties as a function of temperature and hydrostatic pressure up to 1 GPa. Experiments show that at RT more than 90% of threshold current of these devices is due to non-radiative loss processes. We also find that the threshold current density dependence on temperature can be fitted with a single exponential function over a wide temperature range with a characteristic temperature, T_0 , of 45 K. The relatively high temperature sensitivity in these devices is attributable to the large non-radiative current contribution coupled with non-pinning of the carrier density above threshold. © 2011 American Institute of Physics. [doi:10.1063/1.3606533]

Temperature stable semiconductor lasers emitting in the mid-infrared (MIR) spectral range of 3–5 μm are required for applications in environmental pollution monitoring, medical diagnostics, infrared countermeasures, laser surgery, and gas leakage detection.¹ Type-I GaSb based devices have been successfully demonstrated for room temperature (RT) operation to slightly beyond 3 μm (Ref. 2) but emission beyond this wavelength is limited by poor hole confinement.³ While MIR quantum cascade lasers (QCLs) operate in continuous wave (cw) mode at ambient temperatures for wavelengths above 4 μm (Ref. 4), shorter wavelength QCLs tend to suffer from inadequate conduction band offset and inter-valley carrier scattering, which degrade their high temperature performance.^{4,5} InAs/GaInSb type-II “W” interband cascade lasers (ICLs) using spatially indirect transitions⁶ and resonant interband carrier tunnelling⁷ as studied in this work have yielded promising results in the 2.9 μm to 4.2 μm range^{6,8} and recently operated in cw mode at ambient temperature.⁸

Generally, the dominant non-radiative recombination process in interband MIR lasers is Auger recombination.^{9,10} In an Auger process, instead of producing a photon the transition energy is gained by a third carrier that is excited to a higher energy state in the conduction band (CHCC), spin-orbit split off valence band (CHSH), or a light or heavy valence subband. Since the probability of such processes occurring is increased by reduced band gaps, because energy and momentum are more easily conserved, this poses a significant challenge for interband MIR lasers.⁹ Furthermore, the Auger recombination rate increases with increasing temperature due to the increased carrier energies and the intrinsic cubic carrier density dependence of Auger processes. Especially at lower temperatures, the threshold current is also affected by defect-related (Shockley-Read-Hall) recombination that is associated with the material quality. Another important temperature dependent property in MIR diode lasers is the optical loss, which is often attributed to inter-valence band absorption (IVBA).¹¹

The “W” ICL design has been shown to reduce the probability of Auger recombination.^{7,10,12} While the dominant processes are not yet determined, one expects that Auger events involving a hole and two electrons (CHCC) should be reduced by the lower in-plane mass for holes near the valence band maximum achieved by growing compressively strained layers. Also, the CHSH process is eliminated due to the large spin-orbit band separation obtained for the InAs/GaInSb quantum well type II band alignment.⁸ The AlSb barriers effectively confine both electrons and holes, thereby providing a two-dimensional density of states and minimising carrier leakage.¹³ While these advantages substantially lower the threshold current densities, ICLs nonetheless remain temperature sensitive with typical T_0 values of 45–50 K (Ref. 8) (where $1/T_0 = d(\ln I_{\text{th}})/dT$). The full cause had not been satisfactorily explained.³

In this letter we report studies on the temperature dependent properties of 5-stage ICLs. As-cleaved devices with cavity lengths of 1.0, 1.5, and 2.0 mm, ridge widths of 70, 90, and 110 μm , and emitting in the wavelength range of 3.5 μm at 100 K and 4.1 μm at RT were experimentally investigated. The device active regions utilise the type II broken gap alignment, where electrons and holes are confined primarily in separate quantum wells. The structures comprise a cascade of five stages, each consisting of a single GaInSb hole quantum well sandwiched by two InAs electron quantum wells yielding a “W” geometry.⁷ Through spatially indirect interband optical transitions, electrons and holes recombine to produce photons. The electrons then tunnel through the InAs quantum well to the valence band of two GaSb hole injector quantum wells, where they scatter elastically into an InAs/AlSb superlattice to be injected into the next stage of the cascade.^{6,7} This electron transfer is possible because of the InAs and GaSb energy overlap due to their type II band alignment. Details of the device structure and growth procedure are presented elsewhere.^{14,15}

Temperature and hydrostatic pressure dependence techniques have been used to study the recombination processes in

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these devices and to shed light on the cause of their high temperature sensitivity. Measurements were performed in an Oxford Instruments static gas exchange liquid nitrogen cryostat connected to an Oxford Instruments temperature controller that regulated the temperature from 80 K to 320 K (for details see Ref. 3). While the measured threshold current density is extremely low at cryogenic temperatures, with a value of 4 A/cm² at 78 K, it increases exponentially to more than 700 A/cm² at room temperature. Over this range T_0 remained constant at ≈ 45 K, as Figure 1(a) illustrates for three of the devices. It is also interesting to note that even at the lowest temperatures the temperature dependence of J_{th} is strongly super-linear, unlike conventional interband quantum well lasers. Here we show that this super-linear behaviour is associated with contributions by non-radiative current paths to the threshold current, which are significant compared to the very small radiative current even at the lowest temperatures.

The total current, I , flowing through the laser diode in the absence of carrier leakage may be approximated by

$$I = eV(An + Bn^2 + Cn^3), \quad (1)$$

where the terms proportional to A , B , and C correspond to Shockley-Read-Hall, radiative, and Auger recombination, respectively. Figure 1(b) shows that the differential quantum efficiency (slope of the light-current characteristic above threshold) decreases by a factor of 3 with increasing temperature from 80 K to 300 K, suggesting that either the optical loss increases if the carrier concentration is pinned at threshold and/or that the internal quantum efficiency decreases with increasing temperature if the carrier concentration is not pinned at threshold.

To gain further insight into the carrier distribution and loss processes in these devices, we undertook spontaneous emission measurements. This was accomplished by milling a window in the substrate of the laser chip and collecting the pure spontaneous emission out of plane from the laser cavity. Since the integrated spontaneous emission L_{spont} is propor-

tional to the radiative current density J_{rad} , by measuring L_{spont} at threshold (L_{pin}) the variation of the radiative component of J_{th} with temperature may be obtained. In this analysis, J_{rad} is assumed, at most, to be equal to J_{th} at the lowest temperature and hence J_{rad} represents the maximum contribution of radiative recombination to the threshold current as a function of temperature. From this analysis we observe that J_{rad} has much weaker temperature dependence than J_{th} , even at the lowest temperature, confirming that a non-radiative process is responsible for the strong temperature dependence of J_{th} . This is in contrast to previous measurement on type-I lasers where J_{rad} is found to remain equal to J_{th} over a significant range at low temperatures. Based on these data, we estimate that at room temperature at least 90% of J_{th} is due to non-radiative recombination, as indicated in Figure 1(a). The strongly sub-linear L_{spont} - I characteristics at higher temperatures also provide evidence for the dominance of non-radiative Auger recombination with its n^3 dependence. In an ideal laser diode, the spontaneous emission above threshold is pinned due to the lasing process. The inset in Figure 2 shows that such behaviour is found in the present ICLs at low temperature. However, the main portion of the figure indicates a lack of pinning of the spontaneous emission at temperatures above 180 K. This implies that the carrier concentration continues to increase above threshold, which will cause any n-dependent loss mechanisms to continue to increase and thereby decrease the measured differential quantum efficiency of the devices.

To further probe the recombination processes we used high pressure techniques.^{3,9,16} Applying hydrostatic pressure to a semiconductor laser causes a reversible increase of the direct band gap due to compression of the lattice. For the high pressure studies the lasers were mounted in a pressure cell,³ which was then placed in a closed cycle helium cryostat. The cell was connected to a helium gas compressor, which can generate pressures up to 1 GPa. The cryostat with a temperature controller allows the pressure dependence to be measured at temperatures from 50 to 300 K. In our experiments we measured an increase in band gap with pressure

FIG. 1. (Color online) Temperature dependence of J_{th} (a) with a $T_0 = 45$ K for three InAs/GaInSb “W” ICLs with the indicated cavity lengths, measured with 500ns, 10 kHz pulses. Radiative part J_{rad} of J_{th} of 1.5mm device vs T is also plotted. Numbers show losses due to non-radiative recombination. Temperature dependence of the slope efficiency (b) for InAs/GaInSb “W” ICLs measured with 500 ns, 10 kHz pulses.

FIG. 2. (Color online) Integrated spontaneous emission at temperatures ranging from 180 K to 293 K, and 80 K to 140 K (inset). Note the poor pinning of the curves at 180 K and above. Arrows indicate the threshold current for a given temperature.

FIG. 3. (Color online) Pressure-induced band gap dependence of J_{th} at 100 K, 200 K, and 293 K in InAs/GaInSb “W” ICLs measured in pulsed mode with 500 ns, 10 kHz pulses.

having the coefficient 87 meV/GPa. Figure 3 shows that at $T \geq 200$ K the threshold current density (J_{th}) decreases as the band gap increases. This may be related to a variation of the Auger recombination rate, although at this time it is not possible to assign a direct correspondence because the Auger coefficients extracted previously from ICL thresholds do not show strong dependencies on either temperature or bandgap.¹⁰ However, at 100 K $J_{th}(P)$ initially decreases with increasing pressure, but then reaches a minimum around 0.6 GPa before increasing at higher pressures ($E_g > 0.4$ eV). A similar effect was observed in an earlier study of ICLs emitting at somewhat shorter wavelength.³ Although it was suggested that inter-valence band Auger processes may play a role, the evidence remains inconclusive.

Figure 4 shows that at 293 K the slope efficiencies of the present ICLs increase by more than a factor of 2.5 with increasing pressure. Since above threshold the internal efficiency is known to exceed 50% at ambient pressure, the large increase in slope efficiency with pressure implies some reduction of the internal losses.¹⁷ Since free carrier absorption processes probably dominate the loss, one factor may be a reduction of the threshold carrier concentration, or suppression of the increase in carrier density above threshold (improved pinning). A shifting energy alignment of the valence sub-bands participating in IVBA may also play a role. One does not expect an appreciable shift of the conduction band confinement energies because InAs and AlSb have similar pressure coefficients of ~ 101 meV/GPa.¹⁸

In summary, we have experimentally investigated the temperature- and pressure-dependent properties of ICLs with InAs/GaInSb “W” active quantum wells. We observe that J_{th}

FIG. 4. Pressure-induced band gap dependence of slope efficiency at 293 K (b) in InAs/GaInSb “W” ICLs measured in pulsed mode with 500 ns, 10 kHz pulses.

increases super-linearly with increasing temperature while its radiative component has much weaker temperature dependence. This indicates that non-radiative recombination dominates the threshold current over a wide temperature range. With increasing pressure, the threshold decreases and the slope efficiency increases at high temperatures, while $J_{th}(P)$ dependence is non-monotonic at lower T . We have also observed a non-pinning of the carrier concentration above threshold, which may be at least partially responsible for the decrease in differential quantum efficiency with increasing temperature. Having probed these loss mechanisms, more research is planned to unravel the specific details. In particular, we will investigate the physical properties of the most recent state-of-the-art ICLs, which have demonstrated a substantial improvement in performance.¹⁹

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