Recombination processes in midinfrared InGaAsSb diode lasers emitting at 2.37 μm

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The temperature dependence of the threshold current of InGaAsSb/AlGaAsSb compressively strained lasers is investigated by analyzing the spontaneous emission from working laser devices through a window formed in the substrate metallization and by applying high pressures. It is found that nonradiative recombination accounts for 80% of the threshold current at room temperature and is responsible for the high temperature sensitivity. The authors suggest that Auger recombination involving hot holes is suppressed in these devices because the spin-orbit splitting energy is larger than the band gap, but other Auger processes persist and are responsible for the low T_0 values.
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Diode lasers emitting in the midinfrared (MIR) are important for the development of highly sensitive gas detection systems. Many gases of interest have strong absorption lines in the 2–5 μm region, where the InGaAsSb material system is proving successful.[1,2] Threshold current densities as low as 58 A cm^{-2} per quantum well (QW) for devices emitting at 2.24 μm and 66 A cm^{-2} per QW at a wavelength of 2.26 μm have been achieved,[3,4] while continuous-wave maximum output powers of 500 mW near 2.3 μm have been recorded.[5]

Previously, investigations of the variation in spontaneous emission characteristics with temperature have successfully been used to examine and optimize the properties of near-infrared semiconductor lasers for optical fiber communications.[6,7] The application of these techniques to midinfrared lasers will aid the development of these particular devices and further the overall understanding of this material system. In this letter, we investigate the carrier recombination processes occurring in 2.37 μm InGaAsSb/AlGaAsSb lasers, over a wide temperature range from 80 to 300 K and using high hydrostatic pressures up to 8 kbar. From these data we identify the dominant recombination paths constituting the threshold current of the devices and the extent to which each process influences their temperature dependence.

The triple quantum well lasers under investigation were grown by solid-source molecular beam epitaxy on GaSb substrates. Two 35 nm $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$ barriers separate the 10 nm thick, 1.4% compressively strained $In_{0.35}Ga_{0.65}As_{0.11}Sb_{0.89}$ QWs, providing a type I band alignment at the QW/barrier interface. Standard photolithography techniques were used to fabricate lasers with a 100 μm-wide metal contact stripe. The *p* and *n* contacts consist of Pt/Au and a thick gold layer deposited, respectively.[8] Fabry-Pérot lasers were measured as-cleaved with a cavity length of 1 mm.

In order to collect the spontaneous emission from the device, a 100 μm diameter circular window was milled in the *n* contact, using a focused ion beam. This enables one to collect pure spontaneous emission which has been unaffected by gain or loss along the cavity. Further details of the technique can be found elsewhere.[6] The emitted spontaneous emission was collected using a chalcogenide (As_2S_3) optical fiber, which has low loss over this wavelength range. This fiber was coupled into a liquid-nitrogen-cooled InSb detector, which was also used to measure the facet emission from the devices. The lasers were operated in pulsed mode at a duty cycle of 2% with a 1 μs long pulse, to minimize Joule heating effects. The devices were mounted in a spring clip inside a static exchange gas liquid nitrogen cryostat.

The threshold current density of the triple QW device which is 126 A cm^{-2} (42 A cm^{-2}/QW) at room temperature (RT) is considerably lower than that of a typical near-infrared (NIR) device emitting at 1.5 μm, as plotted in Fig. 1(a). The optical losses are also low, at $\sim$4 cm^{-1} at RT.[8] The temperature dependence of the NIR device has been shown to be influenced primarily by Auger recombination accounting for 80% of its threshold current at RT.[6] In fact, the wavelength and temperature dependence of the threshold current in NIR devices, as shown in Fig. 1, is attributable to the band gap dependent nonradiative Auger recombination process.[9] As the band gap decreases in the MIR wavelength range, we would expect the threshold current density to increase sharply with increasing wavelength, following the Auger dominated trend of Fig. 1(b). However, the low threshold measured for the 2.37 μm device can be explained firstly by the reduction in the band gap, E_g, since the radiative current, $J_{rad} \propto E_g^2$,[10] suggests that J_{rad} of the 2.37 μm device should be 40% that of the 1.5 μm device. J_{rad} of the 1.5 μm device is known to constitute 20% of its 250 A cm^{-2} threshold current density, hence we would expect J_{rad} of the 2.37 μm device to be $\sim$20 A cm^{-2}. As J_{th} is $>$20 A cm^{-2} we must consider nonradiative processes which influence the threshold current of the device from an analysis of the spontaneous emission characteristics.

In the absence of leakage paths, the current *I* flowing through the laser may be written as

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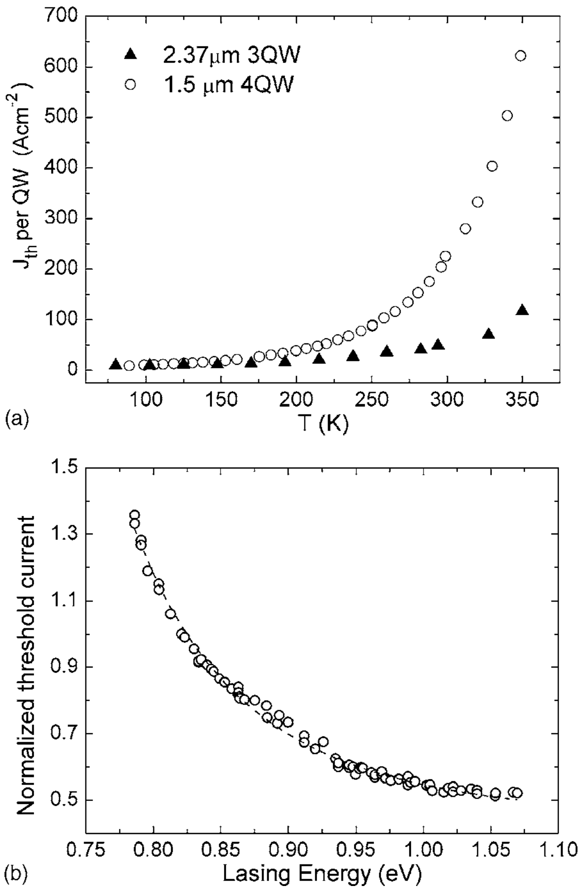

FIG. 1. (a) Temperature dependence of the threshold current density per QW for 1.5 and 2.37 μm devices and (b) variation of the normalized threshold current density with lasing energy E_{lase} using high pressure techniques to vary the band gap energy of several near-infrared lasers, as previously published by Sweeney (Ref. 9).

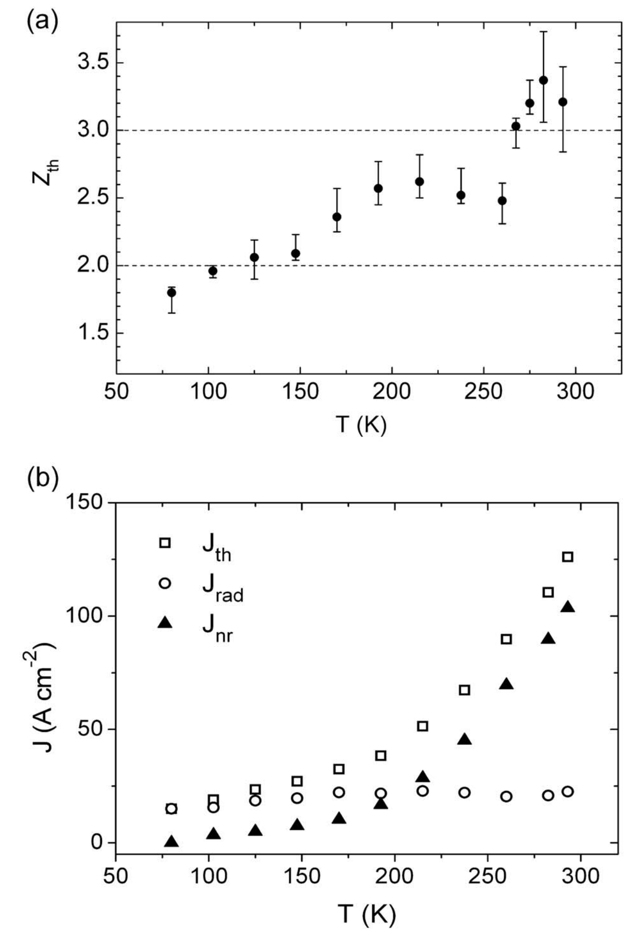

FIG. 2. (a) Z_{th} values between 80 K and RT indicating radiative dominance at low temperature and Auger recombination dominance at RT; (b) radiative (J_{rad}) and nonradiative (J_{nr}) contributions to the threshold current density vs temperature. At RT about 80% of the threshold current can be attributed to nonradiative processes.

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

where we assume that the electron and hole densities in the QWs are both equal to n. e is the electronic charge and V is the volume of the active region. A, B, and C are the coefficients referring to the three main recombination processes of monomolecular (through defects and impurities), radiative, and Auger recombination. Over a limited current range, we may write that $I \propto n^Z$ with $Z=1$, 2, or 3 corresponding to dominant monomolecular, radiative, or Auger recombination, respectively. The measured spontaneous emission L is proportional to the radiative current, thus $L \propto Bn^2$. Hence, if B is independent of n, we may write that $n \propto L^{1/2}$ from which it follows that $I \propto (L^{1/2})^Z$. Therefore, the value of Z close to threshold, Z_{th}, can be obtained by taking the slope of a plot of ln(I) against $\ln(L^{1/2})$.[6] Plotting Z_{th} as a function of temperature [Fig. 2(a)], we see that $Z_{\mathrm{th}} \sim 3$ at RT, hence if leakage is not important (as we will show later from high pressure measurements) this suggests that Auger recombination ($\propto n^3$) is the primary current path, while at low temperature Z_{th} reduces to approximately 2, indicating that radiative recombination ($\propto n^2$) is dominant. The measured spontaneous light versus current curve shows a pinning of the spontaneous emission at the lasing threshold, as additional injected carriers take part in the stimulated emission process. The pinning level L_{pin} is proportional to the radiative current J_{rad}. As there is no evidence of monomolecular recombination, which would appear as a region with $Z=1$ at low currents where n is small,[11] we can assume that the threshold current at low temperature is purely radiative and hence determine the magnitude of the radiative current over the temperature range from the variation of L_{pin}. At RT we calculate that the threshold current of these lasers consists of 20% radiative current and 80% nonradiative current, as shown in Fig. 2(b).

Interestingly, although this is large, its relative contribution is no greater than is observed in the much larger band gap GaInAs(P)/InP lasers operating at 1.5 μm.[6] This may be explained by the fact that the spin-orbit splitting energy Δ_{so} is greater than the band gap for the 2.37 μm material. Hence, the CHSH Auger process (which involves the recombination of a conduction band electron with a heavy hole and the subsequent excitation of another heavy hole into the spin-orbit split-off band), which dominates 1.5 μm lasers, is suppressed. This is also evident in the RT pressure measurements above 8 kbar, discussed below. However, other Auger recombination processes must be considered, such as CHCC, where the recombination of a conduction band electron and a heavy hole is followed by the excitation of another conduction band electron to higher energy in the conduction band and CHHL, where the recombination of a conduction band electron and a heavy hole is followed by the excitation of another heavy hole deep into the light hole band. These Auger processes persist and dominate the temperature sensitiv-

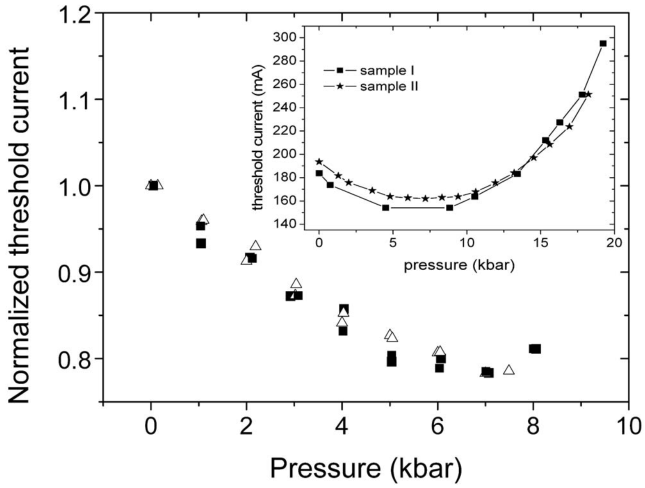

FIG. 3. Pressure dependence of threshold current at RT (squares) and 313 K (triangles) indicating Auger dominance at both temperatures and (inset) the variation in threshold current of the same devices up to 19 kbars showing an increase in threshold current as the CHSH Auger process approaches resonance. Data are from Adamiec *et al.* (Ref. 12).

ity of the device and its room temperature threshold current.

Further evidence for the importance of the Auger processes can be obtained from high pressure measurements. The application of pressure to III-V semiconductors causes an increase in the direct band gap. Thus, we can use pressure to investigate band gap dependent processes. Figure 3 shows the pressure (band gap) dependence of the threshold current of the 2.37 μm devices at RT (squares) and at 313 K (triangles). The decrease of I_{th} with pressure in both cases may be attributed to the decrease in the Auger coefficient C with increasing band gap. Additional support for this can be seen from room temperature high pressure measurements carried out by Adamiec *et al.* (inset of Fig. 3) which show a strong increase in I_{th} above 8 kbar.[12] At these higher pressures E_g approaches Δ_{so} and the CHSH process becomes resonant. An increase in inter-valence band absorption may also contribute to this strong increase in the threshold current.[13] We believe that carrier leakage plays no role since we estimate that in this structure, the conduction band offset $\Delta E_c \sim 370$ meV and the valence band offset $\Delta E_v \sim 160$ meV,[14,15] which are both large compared with kT at room temperature. Also, since the band gap pressure coefficients of the QW and barriers layers are similar and previous theoretical[16] and experimental[17] studies show that the change in ΔE_v with pressure in III-V QW systems is relatively small, changes in band offsets and hence carrier leakage could not explain the observed pressure dependence.

In conclusion, we have measured the room temperature Auger recombination contribution to the threshold current of 2.37 μm InGaAsSb/GaSb lasers to be ~80%, which is no greater than the Auger contribution in the larger band gap 1.5 μm GaInAsP/InP lasers. Significant improvements in device performance have been achieved through improved design of lasers in this material system, in fact these devices have particularly low internal losses of 4 cm^{-1} at RT. However, we identify the suppression of the CHSH Auger process as the primary reason for the low threshold current of these devices and this can be attributed to the fact that $E_g < \Delta_{\text{so}}$ in this material. In spite of this, other Auger recombination processes persist and give rise to the strong temperature sensitivity of the devices around RT.

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