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Quantifying pressure-dependent recombination currents in GaInNAs lasers using spontaneous emission measurements

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The pressure dependence of the total threshold current and its respective recombination components in 1.3 μm GaInNAs single quantum-well lasers has been determined by measuring for the first time the window-spontaneous emission under hydrostatic pressures at room temperature. It is shown that, above 6 kbar, the rapid increase of the threshold current with increasing pressure in GaInNAs lasers is related to the unusual increase of the Auger recombination current, while the monomolecular non-radiative current in the total threshold current is almost constant in the pressure range studied. Theoretical calculations show that the unusual increase of the Auger current is due to a large increase in the threshold carrier density with pressure, stronger than the reduction of the Auger coefficient leading to an overall increase in the Auger current.

Introduction It is well known that Auger recombination plays an important role in long wavelength InGaAsP devices due to their large Auger coefficients, which have an exponential relationship, $\exp(-\gamma E_g/k_B T)$, with the direct band gap energy E_g [1, 2]. Here γ is a constant, T is the absolute temperature, and k_B is the Boltzmann constant. The significant contribution from Auger recombination to the total threshold current in conventional InGaAsP devices dominates the temperature and pressure dependence above room temperature (RT) [2–4]. In addition, optical loss can strongly couple with Auger recombination, further degrading the temperature characteristics of devices [5]. Since hydrostatic pressure increases the direct band gap of semiconductors, it is expected to suppress the Auger processes and hence reduce the threshold current, as previously reported [2, 4]. For the GaInNAs system, however, the recent reports show that defect-related recombination is still significant which is related to the growth of this material [6]. It is also found that, with increasing pressure, the threshold current in GaInNAs lasers increases more rapidly than the ideal radiative current ($\propto E_g^2$) at high pressure [7], which is in contrast to the reduction of the threshold current with increasing pressure in InGaAsP lasers [5]. It is therefore important to identify such a rapid increase of the threshold current in GaInNAs, which may be due to the enhanced defect-related recombination or Auger recombination. In this paper, we report for the first time the spontaneous emission measurements of GaInNAs single quantum-well (SQW) lasers under hydrostatic pressure. From these measurements we determine quantitatively the pressure dependence of each recombination current component in these lasers. This provides vital information about the recombination processes and their band gap dependence in this important new laser material.

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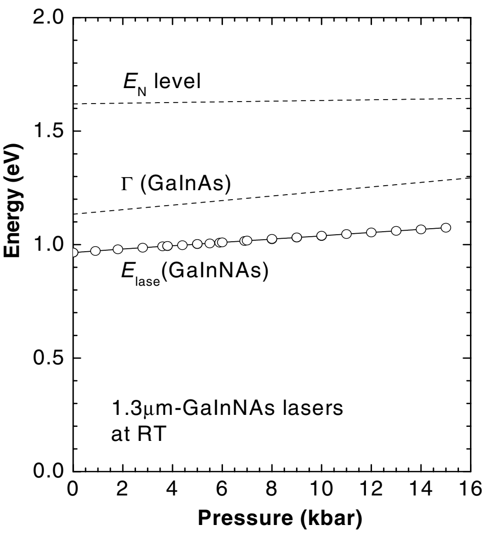

Fig. 1 Measured variation of the lasing energy, E_{lase} (open circles), as a function of pressure in GaInNAs lasers at RT. The solid line is a guide to the eye. A sub-linear pressure dependence of E_{lase} is observed due to the enhanced interaction between the conduction band and the nitrogen level with increasing pressure.

Samples and Experiment The GaInNAs lasers were grown by solid source molecular beam epitaxy (MBE) on n^+-(001) GaAs substrates. An RF-coupled plasma source was used to generate reactive nitrogen from N_2. A GaInNAs SQW of 6 nm thickness is symmetrically sandwiched between the two undoped GaAs waveguiding layers and thick AlGaAs outer cladding layers. The In- and N-contents in the well are approximately 36% and 1.7%, respectively. The detailed growth procedure of the lasers can be found elsewhere [8]. Broad-area lasers with a cavity length of about 700 μm were used in this study. The emission wavelength at RT is 1270 nm. Optical windows were milled in the n^+-substrates in some of the devices for spontaneous emission measurements. A special sample clip and holder were designed for high pressure spontaneous emission measurements. The lasers were mounted in a piston-in-cylinder high-pressure system capable of generating pressures up to 15 kbar. The light signal was collected via an optical fibre and was analysed using optical spectrum analyser and optical multimeter. The measurements were done under pulsed operation at 10 kHz and 0.5% duty cycle, to avoid current heating effects during lasing operation.

Results and Discussion In Fig. 1 we show the measured variation of the lasing energy, E_{lase}, as a function of pressure in GaInNAs lasers at RT. The theoretical energies of the Γ minimum in GaInAs with the same indium content, E_{GaInAs}, which is obtained using an interpolation scheme [9], and the nitrogen level, E_N [10], at various pressures are also plotted for comparison. We find that E_{lase} increases sub-linearly with pressure. The sub-linear pressure dependence in GaInNAs is due to the strong interaction of the N-level with the conduction band, which has been previously observed in pressure-dependent photomodulated reflectance measurements [10].

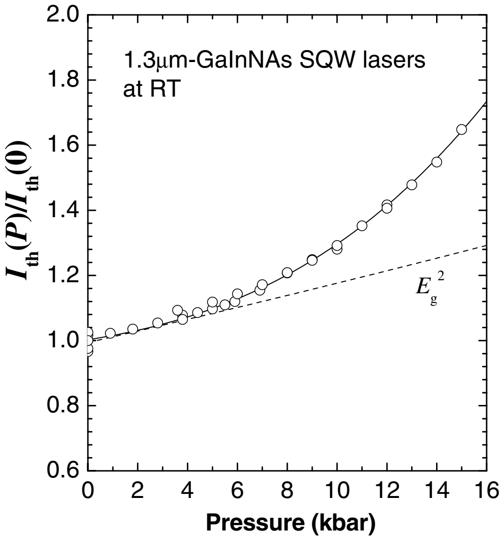

Fig.??2 Measured threshold current (open circles) as a function of pressure in GaInNAs SQW lasers at RT. The solid line is a guide to the eye. Also shown is the variation of the ideal radiative current ($\propto E_g^{\ 2}$).

Figure 2 shows the measured total threshold current, I_{th}, as a function of pressure in GaInNAs SQW lasers at RT. It is found that the variation of the normalised threshold current with pressure in these broad-area SQW lasers is about the same as in ridge waveguide triple quantum-wells lasers [7]. In Fig. 2, we also plot the pressure dependence of E_g^2, which is determined from E_{lase}. E_g^2 describes the variation of the ideal radiative current for a QW laser [2]. It can be seen that I_{th} appears to follow this curve up to about 6 kbar. However, above 6 kbar, I_{th} increases much more strongly than E_g^2.

In long wavelength lasers, the total injection current, I, can be obtained by adding all the recombination current contributions

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

where I_{mono} ($\propto An$) is the monomolecular non-radiative current corresponding to recombination via defects, I_{rad} ($\propto Bn^2$) is due to the radiative recombination of free electrons and holes, I_{Aug} ($\propto Cn^3$) is the non-radiative Auger recombination current. Carrier leakage is neglected due to the large conduction band offset in GaInNAs devices [11]. The pressure dependence of the total threshold current, normalised at ambient pressure, using Eq. (1), can be rewritten as

$$\frac{I_{th}(P)}{I_{th}(0)} = r_{mono}(0)\frac{I_{mono}(P)}{I_{mono}(0)} + r_{rad}(0)\frac{I_{rad}(P)}{I_{rad}(0)} + r_{Aug}(0)\frac{I_{Aug}(P)}{I_{Aug}(0)}\,, \tag{2}$$

where $r_i(0) = I_i(0)/I_{th}(0)$ corresponds to the relative contribution of the respective recombination current component to the total threshold current at ambient pressure. $I_i(P)/I_i(0)$ represents the pressure factor of each recombination mechanism. For example, the pressure factor of the band-to-band radiative recombination is given by [2]

$$\frac{I_{rad}(P)}{I_{rad}(0)} \propto B(P)n_{th}^2(P) \sim E_g^2(P)\,. \tag{3}$$

The pressure factor of the direct band-to-band Auger process in the nondegenerate approximation is given by [1, 2]

$$\frac{I_{Aug}(P)}{I_{Aug}(0)} = \frac{C(P)n_{th}^3(P)}{C(0)n_{th}^3(0)} = \left[\frac{n_{th}(P)}{n_{th}(0)}\right]^3 \times \exp\left(-\frac{\gamma\,\Delta E}{k_B T}\right), \tag{4}$$

where C [$\propto \exp(-\gamma E_g/k_B T)$] is the Auger coefficient, γ depends on the respective Auger process [1, 2] and also varies with pressure due to the pressure-dependent electron effective mass, $\Delta E = E_g(P) - E_g(0)$, is the energy shift with increasing pressure. Since hydrostatic pressure increases E_g, this leads to the reduction of C with pressure. Thus, if the pressure induced change of n_{th} is negligible, the Auger current will decrease with increasing pressure as is normally observed in InP-based devices [12, 13].

It is important to determine the relative contribution of each recombination pathway involved in order to understand the pressure dependence of I_{th} in GaInNAs devices. Because the integrated spontaneous emission intensity, L_{spon}, is proportional to the radiative recombination rate, Bn^2, we have

$$n \propto L_{spon}^{1/2}\,. \tag{5}$$

Equation (1) can be, after using Eq. (5), rewritten as

$$I \propto P_1 L_{spon}^{1/2} + P_2 L_{spon} + P_3\sqrt{L_{spon}^3}\,, \tag{6}$$

where P_1, P_2 and P_3 are unknown parameters. $I_{mono}(= P_1 L_{spon}^{1/2})$ can be determined directly from a plot of $\ln(I)$ versus $\ln(L_{spon}^{1/2})$, where $I \propto n$ at low current. Linearly extrapolating this to the laser threshold

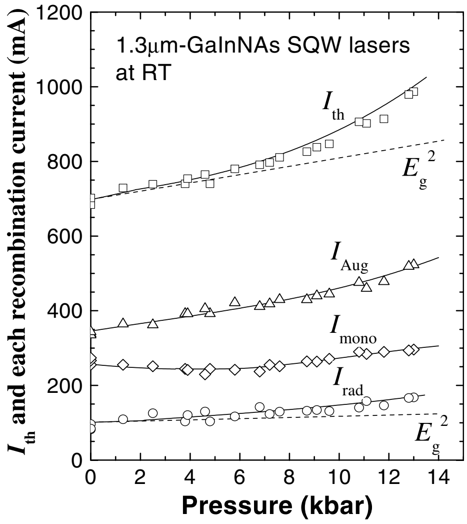

Fig. 3 Measured variation of the total threshold current I_{th} and its recombination current components, i.e., the monomolecular non-radiative current I_{mono}, radiative current I_{rad} and Auger current I_{Aug}, as a function of pressure in GaInNAs SQW lasers at RT. The solid lines are guides to the eye.

yields the value of I_{mono} at threshold [6]. Consequently the relative values of I_{rad} $(= P_2 L_{spon})$ and I_{Aug} $(= P_3 \sqrt{L_{spon}^3})$ at threshold can be determined from a fit to $\ln(I)$ versus $\ln(L_{spon}^{1/2})$ using Eq. (6).

We measured the spontaneous emission from a window milled into the laser substrates of GaInNAs SQW lasers under pressure. From these data we determined the variation of the important current pathways present in the devices with pressure, as shown in Fig. 3. It is found that the defect-related non-radiative current remains nearly constant with increasing pressure. The Auger-associated current dominates I_{th} and shows an unusual increase with increasing pressure. This increase of the Auger current with pressure suggests that n_{th} should also increase rapidly since C decreases with pressure as indicated by Eq. (4).

Figure 4 shows the calculated threshold carrier density n_{th}, Auger coefficient C, and Auger current ($\propto Cn^3$) for the typical CHCC and CHSH band-to-band Auger processes [1, 2] as a function of pressure in a 7nm thick GaInNAs SQW laser at RT. Theoretical calculations of n_{th} for GaInNAs lasers are based upon a 10 band $\boldsymbol{k} \cdot \boldsymbol{p}$ Hamiltonian [14]. The variation of the normalised Auger currents with pressure is determined using Eq. (4). γ is calculated for the respective CHCC and CHSH Auger processes according to Ref. 2. The pressure induced increase in the electron effective mass is also considered. ΔE was determined from the measured lasing energy shift with pressure. It is shown that, n_{th} increases by 14% when pressure increases from 0 kbar to 10 kbar. This is attributed to the interaction between the conduction band edge and the N resonant level, which strongly increases with increasing pressure and leads to a large increase in both the non-parabolicity and electron effective mass in GaInNAs. It can be seen that, although the Auger coefficient C reduces with pressure, the strong N-induced increase in n_{th} still leads to an overall increase

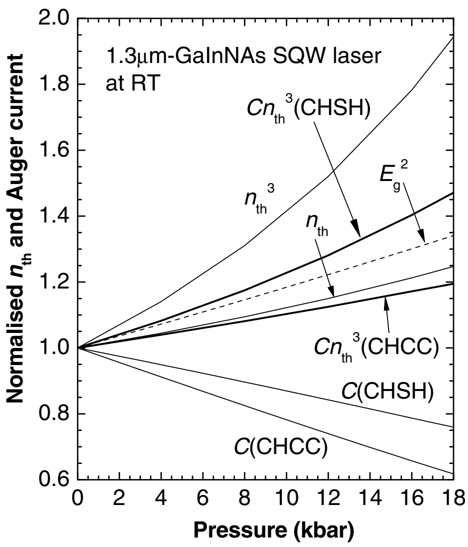

Fig. 4 Calculated threshold carrier density n_{th}, Auger coefficient C, and Auger currents Cn_{th}^3 for the band-to-band CHCC and CHSH Auger processes as a function of pressure in the GaInNAs SQW laser at RT. The CHSH Auger current shows a stronger increase than the increase of the CHCC process, which is caused by the larger activation energy associated with the CHCC process.

in Cn^3 with pressure for both the CHSH and CHCC Auger processes in GaInNAs. The CHSH Auger current shows a stronger increase than the increase in the CHCC process, which is caused by the larger activation energy $\gamma\Delta E$ associated with the CHCC process. It should be noticed that, the large increase in n_{th} is also responsible for the stronger increase in I_{rad} than E_g^2, as observed above 6 kbar in Fig. 3, though the calculated matrix elements for radiative transitions decreases with pressure.

Conclusions The pressure dependence of threshold current and its recombination components in GaInNAs lasers has been presented by measuring spontaneous emission. It is shown that the defect-related non-radiative current is almost constant in the pressure range studied. We observe an unusual increase of the Auger current with increasing pressure in GaInNAs lasers, which is associated with the stronger increase of the threshold current than E_g^2 above 6 kbar in this material. Theoretical calculations show that a large increase in the threshold carrier density with pressure is responsible for the stronger increase in both the Auger current and radiative current.

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