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## Unusual increase of the Auger recombination current in 1.3 $\mu\text{m}$ GaInNAs quantum-well lasers under high pressure

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The pressure dependence of the total threshold current and its respective recombination components in 1.3  $\mu\text{m}$  GaInNAs single-quantum-well lasers using spontaneous emission measurements up to 13 kbar is presented. We observed an unusual increase of the nonradiative Auger recombination current with increasing pressure in this material, which is opposite to those in 1.3  $\mu\text{m}$  InP-based InGaAsP and AlGaInAs devices where the Auger current decreases with pressure. It is shown that the high-pressure-induced increase of the threshold current in GaInNAs is associated with the increase of the Auger current, while the defect-related monomolecular nonradiative current remains nearly unchanged in the pressure range studied. Theoretical calculations show that the unusual increase of the Auger current with pressure in GaInNAs is due to a large increase in the threshold carrier density. © 2003 American Institute of Physics. [DOI: 10.1063/1.1566468]

The GaInNAs material with dilute nitrogen has been extensively investigated in recent years due to its potential advantages for 1.3  $\mu\text{m}$  lasers for optical fiber communications.<sup>1-8</sup> Compared with InGaAsP lasers at the same emission wavelength, GaInNAs lasers have the smaller temperature sensitivity of threshold current, and hence, higher characteristic temperature  $T_0$  as predicted theoretically.<sup>1,9</sup> However, the recent reports show that the defect-related nonradiative recombination is still severe in this material<sup>10</sup> due to the difficulty in the growth of high-quality nitride compounds.<sup>6</sup> Meanwhile, Auger recombination also plays an important role in the recombination mechanisms of carriers. Since hydrostatic pressure increases the direct band gap of semiconductors, and hence, the lasing energy of semiconductor lasers, this enables one to study band-gap-dependent recombination mechanisms.<sup>11</sup> Under high pressures, it was observed that<sup>12</sup> the threshold current in GaInNAs lasers increases more rapidly than the ideal radiative current ( $\sim E_g^2$ ) (Ref. 11) with increasing pressure. In contrast, in 1.3  $\mu\text{m}$  non-nitrogen devices, it was reported that either the threshold current increases more slowly than the ideal radiative current [in the case of AlGaInAs (Ref. 13)] or even decreases with increasing pressure [in the case of InGaAsP (Ref. 14)]. It is, therefore, of paramount importance to identify, both experimentally and theoretically, the high-pressure-induced increase of the threshold current in GaInNAs, which may be due to the enhanced defect-related or Auger-associated nonradiative recombination. In this letter, we report the high-pressure spontaneous emission measurements of GaInNAs single-quantum-well (SQW) lasers at various injection currents. The pressure dependence of the total threshold current and its respective recombination components is quantitatively determined from the fit to the inte-

grated spontaneous emission below laser threshold. Theoretical calculations based upon a 10 band  $\mathbf{k}\cdot\mathbf{p}$  Hamiltonian are also discussed.

The GaInNAs lasers were grown by solid-source molecular beam epitaxy on  $n^+$ -(001) GaAs substrates. A 6-nm-thick GaInNAs SQW is sandwiched symmetrically between the two undoped GaAs waveguiding layers and 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.<sup>15</sup> Broad-area lasers with a nominal cavity length of 700  $\mu\text{m}$  were used in this study. The lasing wavelength at room temperature (RT) is 1270 nm. Optical windows were milled into the substrates of lasers. A sample clip was designed specially for both facet emission and window-spontaneous emission measurements at various injection currents and under different pressures. A piston-in-cylinder high-pressure system was used, which is capable of generating pressures up to 15 kbar. The light signal was collected via an optical fiber and analyzed using an optical spectrum analyzer and optical multimeter. The measurements were done with pulsed current of width 0.5  $\mu\text{s}$  at a 10 kHz repetition rate at RT in order to reduce current heating effects.

Figure 1 shows the measured pressure dependence of lasing energy,  $E_{\text{lase}}$ , in GaInNAs together with the theoretical expectation of the  $\Gamma$  minimum, in GaInAs, and the nitrogen level.<sup>2,3</sup> The GaInAs has the same In content as GaInNAs studied. It is shown that as pressure increases the  $\Gamma$  minimum increases relatively rapidly while the N level increases a bit slowly. As a result, a repulsive interaction between the conduction band and N level is enhanced with pressure.<sup>2</sup> This causes sublinear pressure dependence of  $E_{\text{lase}}$  and also a large increase in both the nonparabolicity and electron effective mass. In the inset, we display the pressure dependence of lasing energy shift,  $\Delta E_{\text{lase}}$ , in 1.3  $\mu\text{m}$  GaInNAs, InGaAsP, and AlGaInAs lasers. It is shown that the InGaAsP and AlGaInAs lasers have nearly linear pressure

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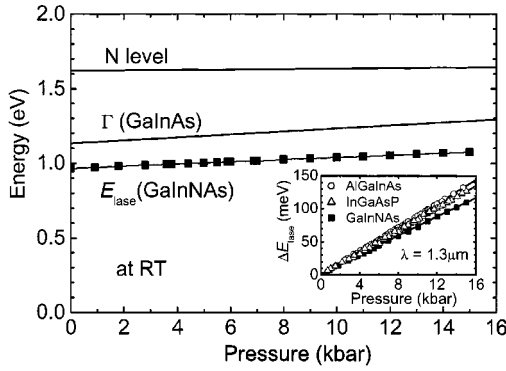


FIG. 1. Measured lasing energy,  $E_{\text{lase}}$ , as a function of pressure, in 1.3  $\mu\text{m}$  GaInNAs lasers, in comparison with the theoretical expectation of the  $\Gamma$  minimum, in GaInAs, and the nitrogen level. Inset displays energy shift,  $\Delta E_{\text{lase}}$ , in 1.3  $\mu\text{m}$  GaInNAs, InGaAsP and AlGaInAs lasers.

dependence of  $\Delta E_{\text{lase}}$  with pressure coefficients of 9.2 ( $\pm 0.1$ ) and 8.4 ( $\pm 0.2$ ) meV/kbar, respectively. In contrast,  $\Delta E_{\text{lase}}$  in the GaInNAs lasers increases sublinearly with the pressure coefficient of 7.7 ( $\pm 0.1$ ) meV/kbar.

Figure 2 shows the measured total threshold current,  $I_{\text{th}}$ , as a function of pressure in GaInNAs lasers.  $E_g^2$ , which is determined from  $E_{\text{lase}}$  of the GaInNAs lasers, describes the variation of the ideal radiative current.<sup>11</sup> Also shown are the pressure dependences of  $I_{\text{th}}$  in 1.3  $\mu\text{m}$  InGaAsP and AlGaInAs lasers. For GaInNAs, it is found that the variation of the normalized threshold current with pressure in these broad-area SQW lasers is about the same as in ridge waveguide triple-quantum-wells lasers.<sup>12</sup> It can be seen that  $I_{\text{th}}$  appears to follow this curve up to about 6 kbar. However, above 6 kbar,  $I_{\text{th}}$  increases more strongly than  $E_g^2$ . The threshold current in GaInNAs increases by about 30% over a 10 kbar pressure range, while it increases by about 7% in AlGaInAs (Ref. 13) and even reduces by about 15% in InGaAsP.<sup>14</sup> The threshold current in GaInNAs increases more rapidly at higher pressure.

In long-wavelength lasers, the total injection current,  $I$ , can be obtained by adding all the recombination current contributions<sup>16</sup>

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

where  $I_{\text{mono}} (\propto An)$  is the monomolecular nonradiative current corresponding to defects recombination,  $I_{\text{rad}} (\propto Bn^2)$

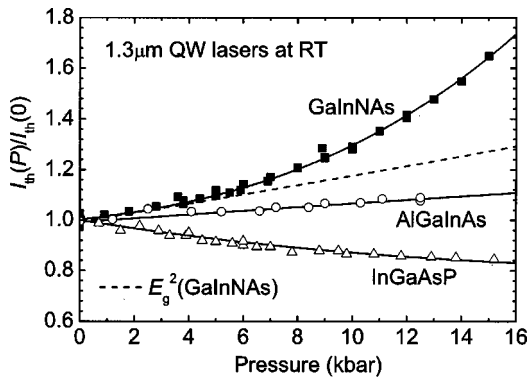


FIG. 2. Measured threshold current as a function of pressure in GaInNAs SQW lasers at RT. The pressure dependence of the threshold current in InGaAsP and AlGaInAs lasers is plotted for comparison. Also shown is  $E_g^2$  in GaInNAs, which describes the variation of ideal radiative current with pressure.

due to the radiative recombination of free electrons and holes,  $I_{\text{Aug}} (\propto Cn^3)$  the nonradiative Auger recombination current. Carrier leakage is presumably neglected due to the large conduction-band offset in GaInNAs devices.<sup>1</sup> The pressure dependence of  $I_{\text{th}}$  normalized at ambient pressure, using Eq. (1), can be rewritten as

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

where  $r_i(0) = I_i(0)/I_{\text{th}}(0)$  corresponds to the relative contribution of the respective recombination pathways in  $I_{\text{th}}$  at ambient pressure, and  $I_i(P)/I_i(0)$  represents the pressure factor of each recombination pathway. For example, the pressure factor of the ideal radiative recombination is approximately described by  $E_g^2(P)/E_g^2(0)$  for a quantum-well laser.<sup>11</sup> For the band-to-band Auger process, it is in the non-degenerate approximation given by<sup>11</sup>

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

where  $C [\propto \exp(-\gamma E_g/k_B T)]$  is the Auger coefficient,  $k_B$  the Boltzmann constant,  $T$  the absolute temperature,  $\Delta E = E_g(P) - E_g(0)$ , the band-gap energy shift at pressure  $P$ .  $\gamma$  depends on the Auger process<sup>11</sup> and varies with pressure due to the pressure-dependent electron effective mass. Since hydrostatic pressure increases  $E_g$ , this leads to the reduction of  $C$  with pressure. If the pressure-induced increase in  $n_{\text{th}}$  is neglected, the Auger current will decrease with increasing pressure as is normally observed in the InP-based devices.<sup>11,13,14</sup> Moreover, due to negligible monomolecular nonradiative recombination in InGaAsP and AlGaInAs devices, the pressure behaviors in those devices have been well explained using just two major recombination pathways, i.e., radiative and Auger recombination.<sup>13</sup> It is shown that the weak pressure dependence of  $I_{\text{th}}$  in AlGaInAs (Ref. 13) is due to the dominant radiative current ( $\sim 80\%$   $I_{\text{th}}$ ) mixed with small fraction of the Auger current ( $\sim 20\%$   $I_{\text{th}}$ ). In InGaAsP, larger Auger current ( $\sim 50\%$   $I_{\text{th}}$ ) with the radiative current ( $\sim 50\%$   $I_{\text{th}}$ ) causes the reduction of  $I_{\text{th}}$  with pressure.<sup>13,14</sup> However, due to the complicated band structures in GaInNAs, the increase of  $n_{\text{th}}$  with pressure is no longer negligible especially at high pressure. This will modify the pressure dependence of the Auger current in this material as discussed below.

It is obviously important to quantitatively determine the relative contribution of each recombination pathway involved in the total threshold current in order to understand the pressure dependence of  $I_{\text{th}}$  in the GaInNAs lasers. We measured spontaneous emission spectra from the active region of GaInNAs lasers through the window at various injection currents and different pressures at RT. From these data we determined the variation of the recombination currents of the important current pathways present in the devices with pressure,<sup>17</sup> as shown in Fig. 3. It is found that the monomolecular nonradiative current remains nearly constant in the pressure range studied. The Auger current dominates  $I_{\text{th}}$  and shows a large increase with pressure, which is oppo-

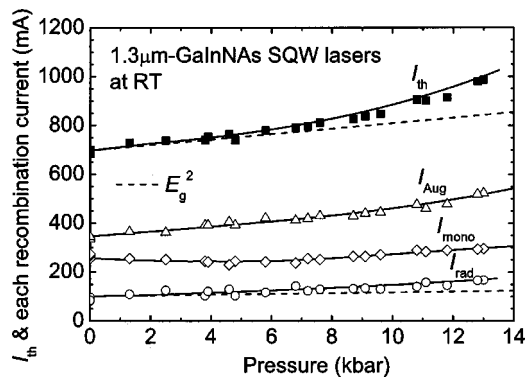


FIG. 3. Measured variation of the total threshold current  $I_{th}$  and its respective recombination components, i.e., the monomolecular nonradiative current  $I_{mono}$ , the radiative current  $I_{rad}$  and the Auger current  $I_{Aug}$ , as a function of pressure in the GaInNAs lasers.

site to the InP-based devices. The increase of the Auger current with pressure suggests that  $n_{th}$  should also increase rapidly since  $C$  decreases with pressure, as indicated by Eq. (3).

Figure 4 shows the calculated cubic threshold carrier density  $n_{th}^3$ , Auger coefficient  $C$ , and the expectations of the Auger currents ( $\propto Cn_{th}^3$ ) for the typical CHCC and CHSH band-to-band processes<sup>15</sup> as a function of pressure in a 7-nm-wide GaInNAs SQW laser at RT. Also shown is the variation of the CHSH Auger current,  $I_{CHSH}^{(InGaAsP)}$ , calculated for typical 1.3  $\mu\text{m}$  InGaAsP devices.<sup>13</sup> It is generally believed that the CHSH process dominated over the CHCC process in the long-wavelength range.<sup>11</sup> The calculations of  $n_{th}$  for the GaInNAs lasers are based upon a 10 band  $\mathbf{k}\cdot\mathbf{p}$  Hamiltonian.<sup>18</sup> The variation of the normalized Auger coefficient with pressure is determined using  $\exp(-\gamma\Delta E/k_B T)$ .  $\gamma$  is calculated for the CHCC and CHSH processes according to Ref. 11. The pressure-induced increase in electron effective mass is also considered.  $\Delta E$  is determined from  $\Delta E_{lase}$ . It is shown that  $n_{th}$  increases by 14% over a 10 kbar pressure range, which is three times larger than that in InGaAsP.<sup>18</sup> This is attributed to the interaction between the conduction-band edge and N resonant level, which strongly increases with increasing pressure and leads to a large increase in both the nonparabolicity and the electron effective mass in GaInNAs. It can be clearly seen that although  $C$  reduces with pressure, the strong N-induced increase in  $n_{th}^3$  still leads to an overall increase in  $Cn_{th}^3$  with pressure in this material for both the CHSH and CHCC processes. The CHSH current shows a stronger increase than that in the CHCC process, which is caused by the larger activation energy  $\gamma\Delta E$  associated with the CHCC process. It should be emphasized that the simplified theory above predicts the enhanced importance of the Auger recombination with increasing pressure in GaInNAs contrasting with 1.3  $\mu\text{m}$  non-nitrogen devices. Full understanding of this pressure behavior needs further theoretical investigations.

In conclusion, the pressure dependence of the total threshold current and its respective recombination components in the GaInNAs lasers is presented using spontaneous emission measurements. We observe an unusual increase of

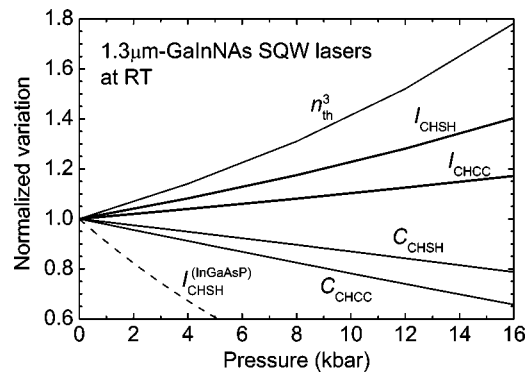


FIG. 4. Theoretically calculated Auger currents for the typical CHSH and CHCC band-to-band processes as a function of pressure in GaInNAs at RT. Also shown is the variation of the CHSH Auger current  $I_{CHSH}^{(InGaAsP)}$  calculated for typical 1.3  $\mu\text{m}$  InGaAsP devices.

the Auger current in the GaInNAs lasers with pressure, which is opposite to the InP-based InGaAsP and AlGaInAs devices. This is due to a large increase in the threshold carrier density with increasing pressure in GaInNAs as predicted by theory.

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