High-Pressure Studies of Recombination Mechanisms in 1.3-\( \mu \)m GaInNAs Quantum-Well Lasers

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Abstract—The pressure dependence of the components of the recombination current at threshold in 1.3-\( \mu \)m GaInNAs single quantum-well lasers is presented using for the first time high-pressure spontaneous emission measurements up to 13 kbar. It is shown that, above 6 kbar, the rapid increase of the threshold current with increasing pressure is associated with the unusual increase of the Auger-related nonradiative recombination current, while the defect-related monomolecular nonradiative recombination current is almost constant. Theoretical calculations show that the increase of the Auger current can be attributed to a large increase in the threshold carrier density with pressure, which is mainly due to the increase in the electron effective mass arising from the enhanced level-anticrossing between the GaInNAs conduction band and the nitrogen level.

Index Terms—Optical measurement, quantum-well lasers, semiconductor device measurement, semiconductor lasers, spontaneous emission.

I. INTRODUCTION

THE GaInNAs–GaAs system has been extensively studied in recent years due to its promising applications in optical fiber communication systems. It has large band offsets, particularly in the electron confinement energy \( \Delta E_c \), in comparison with the conventional InGaAsP/InP, which is expected to suppress electron overflow [1]. GaInNAs is also suitable for monolithic growth with GaAs–AlAs distributed Bragg reflectors (DBRs) in vertical-cavity surface-emitting lasers (VCSELs) based on GaAs. As far as the formation mechanism of the narrow bandgap in Ga(In)NAs is concerned, the origin of the dramatic reduction of the bandgap with the participation of dilute nitrogen atoms in this material is still under debate. Different models have been suggested to explain the experimental data in this regard [2]–[9]. For example, it is attributed to the band anticrossing between the Ga(In)As band edge and resonant N level [2], or results from the band-like impurity states arising from isolated N-centers [3], [4], N-clusters [5], or N-induced bound states [6]. In fact, the distinct optical properties of N atoms as isoelectronic centers in Ga(In)As, which form a resonant state a few hundred meV above the Ga(In)As conduction-band edge, have been observed experimentally [10]–[12], consistent with theoretical predictions [13]. The observation of the luminescence from nitrogen complexes such as N–N pairs [14]–[16] and of the photomodulated reflectance spectra from the disordered N-cations [17] further shows the complex nature of the electronic band structure in this material system.

It is well known that, hydrostatic pressure increases the direct band gap of III–V semiconductors in a way very similar to changing alloy compositions, but it has very little influence on the valence band. This contrasts with in-built strain in quantum-well structures which primarily affects the valence-band. Further, the application of high-pressure enables continuous tuning of the electronic band structure of semiconductors under test in a very convenient way. Since most important recombination mechanisms, such as the band-to-band radiative recombination and nonradiative Auger recombination, exhibit a strong bandgap dependence, high-pressure is therefore powerful diagnostic tool to provide deep insights into the optical and electrical properties of semiconductors. It also allows testing of ideas about how properties such as the radiative and nonradiative recombination rates should depend on the bandgap and configuration of electronic states. This technique enables a better understanding of the basic physical processes to be obtained and allows the design of optimum structures. For these reasons, the high-pressure as well as temperature characteristics of GaInNAs devices have been extensively carried out in recent years [2], [11], [18], [19], and compared with InP-based systems such as InGaAsP and AlGaInAs with the same operating wavelength [20]–[25]. It is found that the variation of the threshold current with temperature and pressure in these lasers are strongly dependent on the relative importance of the respective radiative and nonradiative recombination pathways. For example, it was shown that Auger recombination plays an important role and causes a high sensitivity in the temperature characteristics of InGaAsP devices [26]–[29]. Also, the large Auger recombination current at threshold leads to a reduction of the threshold current with increasing pressure [29], [30]. For GaInNAs, however, both the Auger-like and defect-related nonradiative recombination play important roles in the recombination mechanisms of carriers at room temperature [31]. It is therefore important to determine the variation of the respective recombination current components with pressure in order to better understand the recombination processes constituting the threshold current in GaInNAs lasers at ambient pressure. In this paper, we present a systematic experimental investigation on the pressure dependence of the threshold current in 1.3-\( \mu \)m GaInNAs lasers. Both stimulated emission from the facet and spontaneous emission through a window in the substrate electrode of the devices...
were measured. The results are compared with theoretical calculations and also with the measured results on InGaAsP and AlGaInAs lasers with the same operating wavelength.

II. SAMPLES AND EXPERIMENT

The GaInNAs lasers were grown by solid source molecular beam epitaxy (MBE) on \( \eta^+\)-(001) GaAs substrates. An RF-coupled plasma source was used to generate reactive nitrogen from \( \text{N}_2 \). A GaInNAs single quantum-well (SQW) of 6 nm thickness is symmetrically sandwiched 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. Broad-area lasers with a nominal stripe width of 50 \( \mu \)m and a cavity length of 700 \( \mu \)m were used in this study.

The InGaAsP and AlGaInAs lasers, which used for comparison with GaInNAs lasers, have a typical separate confinement heterostructure (SCH) multiple QW structure, grown by low-pressure metal-organic vapor phase epitaxy (MOVPE) on \( \eta^-\)-InP substrates. The InGaAsP lasers consist of 8 compressively strained InGaAsP QWs, separated by unstrained InGaAsP barriers (\( \lambda_g = 1.1 \mu \)m). The devices are buried heterostructures with a stripe width of 1.85 \( \mu \)m and a nominal cavity length of 1500 \( \mu \)m. The AlGaInAs lasers comprise 8 compressively strained AlGaInAs wells with unstrained AlGaInAs barriers (\( \lambda_g = 1.1 \mu \)m). They have ridge waveguide mesa structures with a stripe width of 3.5 \( \mu \)m and a nominal cavity length of 600 \( \mu \)m. All of these lasers were designed to operate close to 1.3-\( \mu \)m at room temperature (RT). The growth procedures of GaInNAs, InGaAsP, and AlGaInAs lasers can be found elsewhere [20], [26], [28].

All lasers investigated had as-cleaved facets and the measurements were performed at RT and under pulsed operation (10 kHz, 0.5% duty cycle) in order to reduce current heating effects. The lasers were mounted in a piston-in-cylinder high-pressure system capable of generating pressures up to 15 kbar. Essence-F was used for the pressure medium. An optical fiber going through the piston acts as a high-pressure window and is used to collect the light from the lasers inside the pressure cell and to transmit the signal directly into a high-resolution optical spectrum analyzer (HP 70950A) and optical multimeter (Ando AQ2140).

III. RESULTS AND DISCUSSION

In Fig. 1, we show the measured variation of the lasing energy shift, \( \Delta E_{\text{laser}} \), as a function of pressure in GaInNAs, InGaAsP, and AlGaInAs lasers at RT. The linear pressure coefficients of \( d(\Delta E_{\text{laser}})/dP \) are found to be 9.2 (±0.1), 8.4 (±0.2), and 7.7(±0.1) meV/kbar for AlGaInAs, InGaAsP, and GaInNAs, respectively. With increasing pressure, \( E_{\text{laser}} \) increases nearly linearly in AlGaInAs and InGaAsP. By contrast, a sublinear increase of \( E_{\text{laser}} \) is observed in GaInNAs. In order to understand this sublinear behavior, we plot in Fig. 2 the measured pressure dependence of \( E_{\text{laser}} \) together with the theoretically expected variation of the \( \Gamma \) minimum in GaInAs, and the nitrogen level. The GaInAs has the same In content as GaInNAs studied. It is shown that, as pressure increases, the \( \Gamma \) minimum increases more rapidly while the N level increases slowly. As a result, the repulsive interaction between the GaInAs conduction band and N level is enhanced with pressure [2]. This causes the sub-linear pressure dependence of \( E_{\text{laser}} \) and also a large increase in both the nonparabolicity of the conduction band and electron effective mass.

Fig. 3 compares the pressure dependence of the total threshold current, \( I_{\text{th}} \), in GaInNAs, with the non-nitrogen systems such as InGaAsP and AlGaInAs for 1.3-\( \mu \)m operation at RT. Also shown is the variation of \( E_{\text{g}}^2 \) (the dashed line) with pressure, which is determined from \( E_{\text{g}}^2 \) in the GaInNAs devices. \( E_{\text{g}}^2 \) describes the variation of the ideally expected radiative current with pressure for a QW laser [29]. Since pressure increases \( E_{\text{g}}^2 \), in most semiconductors the...
ideal radiative current is expected to increase with increasing pressure. For the GaInNAs devices, we have also compared the pressure dependence of the threshold current in GaInNAs with nearly the same In and N contents in the well but different structures and quantum-well number [31], which show nearly the same pressure behavior. It is shown that, in InGaAsP and AlGaInAs lasers [23], [26], the mixed contributions of the radiative and Auger recombination currents can explain the pressure behavior of \( I_{\text{th}} \). Such analyzes suggest that the Auger current (\( \sim 50\% \)) is severe in InGaAsP while the radiative current (70\%–80\%) dominates \( I_{\text{th}} \) in AlGaInAs. In GaInNAs, \( I_{\text{th}} \) appears to follow \( E^2_{\text{g}} \) up to about 6 kbar. However, above 6 kbar, \( I_{\text{th}} \) increases more strongly than \( E^2_{\text{g}} \). This pressure behavior in GaInNAs lasers is likely to be strongly related to the complicated variation of the band structure with pressure in this material.

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

\[
I = I_{\text{mono}} + I_{\text{rad}} + I_{\text{Aug}} = eV(A_n + Bn^2 + Cn^3)
\]

where \( I_{\text{mono}} \) is the nonradiative current corresponding to recombination via defects, \( I_{\text{rad}} \) is due to the radiative recombination of electrons and holes, while \( I_{\text{Aug}} \) is the nonradiative Auger-like recombination current. The carrier density effects on the coefficients of \( A, B, \) and \( C \) are neglected in this study [22]. Carrier leakage is generally expected to be negligible due to the large conduction band offset in the GaInNAs devices [1]. The pressure dependence of the total threshold current, normalized at ambient pressure, using (1), can be rewritten as

\[
\frac{I_{\text{th}}(P)}{I_{\text{th}}(0)} = r_{\text{mono}}(0)\frac{I_{\text{mono}}(P)}{I_{\text{mono}}(0)} + r_{\text{rad}}(0)\frac{I_{\text{rad}}(P)}{I_{\text{rad}}(0)} + r_{\text{Aug}}(0)\frac{I_{\text{Aug}}(P)}{I_{\text{Aug}}(0)}
\]

where \( r_i(0) = I_i(0)/I_{\text{th}}(0) \) represents the relative contribution of each recombination current to the total threshold current at ambient pressure (hence \( \sum_i r_i(0) = 1 \)). \( I_i(P)/I_i(0) \) represents the pressure factor of each recombination mechanism. For example, the pressure factor of the band-to-band radiative recombination is given by [29]

\[
\frac{I_{\text{rad}}(P)}{I_{\text{rad}}(0)} \propto B(P)n_{\text{th}}^2(P) \sim E_{\text{g}}^2(P)
\]

The pressure factor of the band-to-band Auger process in the nondegenerate approximation is given by [29], [32]

\[
\frac{I_{\text{Aug}}(P)}{I_{\text{Aug}}(0)} = C(P)n_{\text{th}}^3(P) = \left[\frac{\eta_{\text{th}}(P)}{\eta_{\text{th}}(0)}\right]^3 \times \exp\left(-\frac{\gamma\Delta E}{k_BT}\right)
\]

where \( C \approx \exp(-\gamma E_{\text{g}}/k_BT) \) is the Auger coefficient, \( T \) is the absolute temperature, and \( k_B \) is the Boltzmann constant, \( \gamma \) depends on the Auger process [29], [32] and is pressure dependent due to the pressure induced electron effective mass change,

\[
\Delta E = E_{\text{g}}(P) - E_{\text{g}}(0),
\]

is the energy shift with increasing pressure. Since hydrostatic pressure increases \( \Delta E \), this leads to the reduction of \( C \) with pressure. Furthermore, if the pressure-induced change of \( n_{\text{th}} \) is negligible, the Auger current will decrease with increasing pressure as observed in InP-based devices [23], [26], [29], [30].

It is important to determine the relative contribution of each recombination pathway involved in order to understand the pressure dependence of \( I_{\text{th}} \) in a device. Because the integrated spontaneous emission intensity, \( I_{\text{spont}} \), is proportional to the radiative recombination rate \( Bn^2 \), we have

\[
n \propto I_{\text{spont}}^{1/2}.
\]

From (5), (1) can be rewritten as

\[
I \propto P_1\sqrt{I_{\text{spont}}} + P_2L_{\text{spont}} + P_3\sqrt{I_{\text{spont}}^3}
\]

where \( P_1, P_2, \) and \( P_3 \) are unknown parameters. Based on this simple model [29], [26], [28], [31], the monomolecular nonradiative current \( I_{\text{mono}}(\propto P_1\sqrt{I_{\text{spont}}}) \) at threshold can be determined directly from a linear extrapolation of \( I \propto n \) at low current to laser threshold from a plot of \( \ln(I) \) versus \( \ln(I_{\text{spont}}) \). In a similar way, the relative values of the radiative current \( I_{\text{rad}}(\propto P_2L_{\text{spont}}) \) and then the Auger-related current \( I_{\text{Aug}}(\propto P_3\sqrt{I_{\text{spont}}^3}) \) at threshold can be determined using (6).

We measured for the first time the high-pressure spontaneous emission from a window milled into the substrate of the GaInNAs SQW laser. Fig. 4 shows the strong blue shift of spontaneous emission spectra with increasing pressure at threshold, which is consistent with the increase in bandgap with pressure. From these measurements we determined the variation of the important current paths present in the devices with pressure, as shown in Fig. 5. At ambient pressure, upon inserting the GaInNAs devices into the pressure medium (Essence-F), we measured an increase in the threshold current of 690 mA compared with 460 mA in air. This is due to the reduction in facet reflectivity in the liquid and the consequent increase in \( n_{\text{th}} \). This, therefore, gives rise to a relative increase in the Auger current with respect to the radiative and mono-molecular current paths such that, the relative ratios of the
Fig. 5. Measured variation of the total threshold current $I_{th}$ and each recombination current component, i.e., the monomolecular nonradiative current $I_{mono}$, radiative current $I_{rad}$, and Auger current $I_{Aug}$, as a function of pressure in GaInNAs SQW lasers at RT. The dashed line describes the variation of the ideal radiative current with pressure. The solid lines are guides to the eye.

Fig. 6. Measured spontaneous emission efficiency versus carrier density below threshold in GaInNAs SQW lasers under pressures of 0 and 13 kbar. Arrows mark the positions corresponding to the maximum spontaneous emission efficiency.

If Auger recombination is negligible, e.g., at low carrier density, we have

$$\eta_{\text{spont}} \propto \frac{B n}{A + B n}. \quad (8)$$

In this case, we find that $\eta_{\text{spont}}$ increases with increasing $n$, indicating improved spontaneous emission efficiency due to the reduction of the relative importance of the monomolecular recombination with $n$. However, when Auger recombination becomes severe, usually at high carrier density, we have

$$\eta_{\text{spont}} \propto \frac{B}{B + C n}. \quad (9)$$

This suggests that $\eta_{\text{spont}}$ decreases with increasing $n$. In the simple model described by (7), the peak position of $\eta_{\text{spont}}$ is determined by the current components at threshold as follows:

$$n_{\text{th}} \left| \eta_{\text{spont}} \right| \approx \sqrt{\frac{I_{\text{mono}}}{I_{\text{Aug}}}}. \quad (10)$$

Therefore, we can determine if the strong pressure dependence of $I_{th}$ is due to the increase of the monomolecular current or Auger current by measuring the $\eta_{\text{spont}}$ variation at the maximum $\eta_{\text{spont}}$ with pressure. Fig. 6 shows the measured $\eta_{\text{spont}}$ as a function of $n/n_{\text{th}}$ below threshold in GaInNAs lasers at pressures of 0 and 13 kbar. The normalized $n$ to $n_{\text{th}}$ is determined directly by $n/n_{\text{th}} \approx \sqrt{I_{\text{spont}}/I_{\text{th}}}$ using (5), where $I_{\text{th}}$ represents the value of $I_{\text{spont}}$ at threshold. We find that the maximum of $\eta_{\text{spont}}$ shifts to a smaller value of $n/n_{\text{th}}$ as pressure increases, indicating that the Auger current is increasing more strongly than the defect-related monomolecular current and is, thus, responsible for the strong pressure dependence of $I_{\text{th}}$ in the GaInNAs devices.

Fig. 7 shows the calculated threshold carrier density $n_{\text{th}}$ as a function of pressure in a 7-nm GaInNAs single QW laser and a conventional InGaAsP laser. The calculations are based upon a 10-band $\bm{k} \cdot \bm{p}$ Hamiltonian within the band anticrossing model [33]. It shows that the threshold carrier density increases by 14% when pressure increases from 0 to 10 kbar, which is a three times larger increase than the increase in InGaAsP. This is attributed to the interaction between the GaInAs conduction band edge and the N resonant level, which strongly increases with increasing pressure and leads to a large increase in both the nonparabolicity and electron effective mass in GaInNAs, as schematically
In summary, the pressure dependence of threshold current in 1.3-μm GaInNAs lasers has been presented and compared with InGaAsP and AlGaInAs lasers with the same operation wavelengths. In GaInNAs, the pressure-induced influence of the unusual band structure on the threshold carrier density must be taken into account. It is found that, the defect-related nonradiative current is almost constant in the pressure range studied. However, the strong increase of Auger current with increasing pressure above 6 kbar in this material, which is opposite to InGaAsP and AlGaInAs devices, is associated with a large increase of the threshold carrier density with pressure as predicted by theoretical calculations. Within the band anticrossing model, the increase in the Auger current component with pressure in GaInNAs is primarily the consequence of the enhanced level repulsion between the GaInAs conduction band and the N level. Though nitrogen atoms play a crucial role in reducing the bandgap of Ga(In)NAs, the high density of nitrogen-related defects due to the difficulty in growing high-quality material is a problem for low-threshold device applications. Furthermore, it is well known that, the increase of the nitrogen content in Ga(In)NAs also increases the repulsive interaction between the Ga(In)As conduction band and the N level. Our pressure results therefore imply that, further reducing Ga(In)NAs bandgap by increasing the N content is at the cost of larger Auger effects and, therefore, larger threshold current caused by the higher threshold carrier density due to the increased electron effective mass with increasing nitrogen content.

IV. CONCLUSION

ACKNOWLEDGMENT

The authors would like to thank Dr. C. N. Ahmad for his technical help and Dr. G. Knowles for his assistance with this work.

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JIN et al.: HIGH-PRESSURE STUDIES OF RECOMBINATION MECHANISMS 1201


