Analysis of the characteristic temperatures of (Ga,In)(N,As)/GaAs laser diodes

M Montes[1], A Hierro[1], J M Ulloa[1], A Guzmán[1], B Damilano[2], M Hugues[2,3] , M Al Khalfioui[2], J-Y Duboz[2] and J Massies[2]

[1] ISOM and Departamento de Ingeniería Electrónica, Universidad Politécnica de Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain
[2] CRHEA-Centre National de la Recherche Scientifique, Rue B Gregory, 06560 Valbonne, France

Abstract
The characteristic temperatures of the threshold current density, T_0, and external differential quantum efficiency, T_1, of a series of (Ga,In)(N,As)/GaAs quantum well (QW) laser diodes are measured in the wavelength range from 1 to 1.5 μm. It is found that both T_0 and T_1 strongly decrease with increasing lasing wavelength. The origin of this degradation is shown to be, in the case of T_0, mostly dominated by a decrease in the transparency current density characteristic temperature, an increase in the optical losses and a decrease in the modal gain. The degradation of T_1 is mainly due to the increase in the optical losses. The effective carrier recombination lifetime in the QW is shown to decrease from 1.2 to 0.2 ns with N content up to 2%, in good agreement with previous reports that link this low lifetime to non-radiative monomolecular recombination through defects in the QW. Carrier leakage is ruled out as the dominant process degrading T_0 and T_1 on the basis of the temperature dependence of the effective carrier recombination lifetime.

1. Introduction

The need for light emitting devices operating at optical fibre communication wavelengths of 1.3 and 1.55 μm has motivated much research on semiconductor systems such as InGaAsP/InP, (Ga,In)(N,As)/GaAs and their related alloys. However, the InP family still remains as the only technology commercially available at the longest wavelengths [1,2]. One of the key features that have made (Ga,In)(N,As) so attractive as an active material for quantum well (QW) laser diodes (LDs) is its higher conduction band offset compared with the InP family materials [3]. This should enhance electron confinement in the QW and thus improve the temperature performance of (Ga,In)(N,As)/GaAs QW LDs compared with that of the InP family [1,3,4]. Devices using this quaternary alloy would not need any extra thermoelectric cooling in order to operate, thus making packaging simpler, cheaper and more compact. However, it is well known that increasing the N content in order to reach the desired 1.3 and 1.55 μm wavelengths tends to degrade the LDs figures of merit as well as their temperature behaviour [5,6]. Nevertheless, the origin of this degradation is still under controversy, and while some groups propose hole leakage as the dominant process [6,7], others rule out this mechanism at room temperature [8,9]. In this work we aim to shed light into the problem of the temperature degradation of the figures of merit of (Ga,In)(N,As)/GaAs QW LDs and the role that hole leakage plays into it.

2. Experimental procedure

The laser structures used in this work were grown by molecular beam epitaxy and consist of a 70 to 100 Å thick (Ga,In)(N,As) single QW (SQW) with 38% In and 1.4% to 3% N surrounded by 150 nm thick GaAs barriers. The active layers were surrounded by two 2200 nm thick AlGaAs cladding layers. An additional InGaAs/GaAs SQW LD with 20% In and a 100 Å thick SQW was grown for comparison. The Fabry–Perot

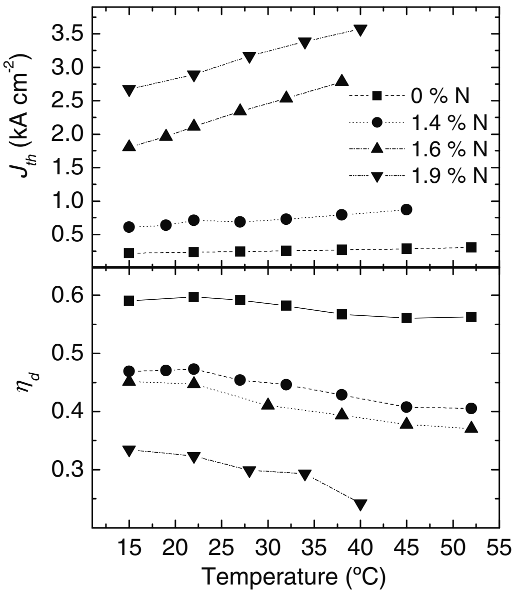

Figure 1. Dependence of J_{th} and η_{d} on temperature for 1000 μm long (Ga,In)(N,As)/GaAs LDs with N contents ranging from 0% to 1.9%.

cavities were defined by cleavage of the material, producing 15 μm wide and 500–1500 μm long stripes. More detail on the LDs growth, fabrication and performance can be found elsewhere [5, 10, 11]. The LDs were mounted p-side up on a temperature controlled copper heat sink, accessed with a fine probe and measured under pulsed conditions (1 μs long pulses and 0.1% duty cycle). This series of LDs covers the 1–1.5 μm spectral region.

3. Experimental results and discussion

The external differential quantum efficiency, η_{d}, and the threshold current density, J_{th}, of the LDs were recorded from 5 to 7 devices of each length at temperatures ranging from 15 to 45 °C (see [5] for results at 22 °C). Figure 1 shows the dependence of η_{d} and J_{th} on the temperature for 1000 μm long (Ga,In)(N,As)/GaAs LDs with N contents ranging from 0% to 1.9%. It is readily seen from the figure that the temperature dependence of these two figures of merit increases with the N content in the QW. Assuming an exponential dependence of η_{d} and J_{th} with T of the form $\eta_{\mathrm{d}} \propto \exp(-T/T_1)$ and $J_{\mathrm{th}} \propto \exp(T/T_0)$, respectively, the characteristic temperatures T_0 and T_1 of the LDs can be extracted [12]. Figure 2 shows the dependence of T_0 and T_1 on lasing wavelength for 1000 μm long (Ga,In)(N,As)/GaAs LDs. As can be seen from the figure, T_0 decreases from 107 to 37 K, whereas T_1 falls from 360 to 32 K when the wavelength increases from 1 to 1.5 μm, i.e. as the N content in the QW is increased from 0% to 3%. Similar T_0 and T_1 values have been previously reported for other (Ga,In)(N,As)-based laser structures, with a similar dependence on lasing wavelength [6, 13]. The reduction in these characteristic temperatures in (Ga,In)(N,As) compared with InGaAs has been attributed by some groups to a higher and more temperature dependent carrier leakage, particularly hole leakage, from the active region [6, 7].

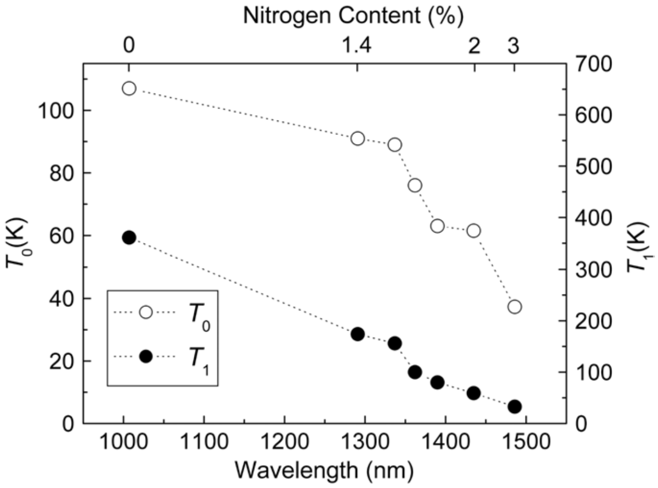

Figure 2. Dependence of T_0 and T_1 on lasing wavelength for 1000 μm long (Ga,In)(N,As)/GaAs LDs.

Since the series of (Ga,In)(N,As) LDs analysed here have higher In content than the InGaAs reference, and to rule out the relaxation of the QW as the origin of the degradation observed in figure 2, the LDs have been analysed by transmission electron microscopy (TEM). This analysis (not shown for brevity) indicates that none of the QWs are relaxed, and thus, any degradation of T_0 or T_1 must be linked to a different origin. In addition, the changes in the electron and hole effective masses [14–16], due to the increase in In content and the decrease in QW width in the (Ga,In)(N,As) LDs compared with the InGaAs LD, are such that the calculated transparency carrier density (n_{tr}), and its derivative with respect to T, are lower in the GaInNAs devices (see [5, 16]). These lower values for n_{tr} and its derivative should yield better figures of merit and higher T_0 and T_1 values in the GaInNAs LDs than in the InGaAs reference LD but, as shown in figure 2, the opposite is observed. Thus, the degradation of T_0 and T_1 should be linked to the presence of N and/or the longer emission wavelengths. Therefore, a detailed analysis of the temperature behaviour of these LDs has been performed in order to identify what mechanisms are involved in this degradation.

The InGaAs reference LD and the GaInNAs LD emitting at 1.29 μm have been analysed following the approach used by Tansu *et al* [12]. The longest wavelength devices could not be included in the analysis due to the failure of some diodes after repetitive measurements at the highest temperatures. Note that such multi-length studies assume that the internal differential quantum efficiency is constant with cavity length. Both Auger and leakage contributions will be different for different cavity lengths, i.e. different carrier densities. Thus, for this approach to be valid, Auger recombination and carrier leakage must not be the dominant processes present in the devices. We make the initial assumption that Auger is not the dominant recombination process, in agreement with the results of [17] for temperatures below 50 °C at similar wavelengths. On the other hand, there are several theoretical and experimental results, which indicate that carrier leakage, in particular hole leakage, does not increase for (Ga,In)(N,As) and that it is not the dominant process. Indeed, based on the experimental results of

Galluppi *et al*, the differences in structure between our InGaAs and GaInNAs LDs yield an increase in the valence band offset [18, 19]. Thus, the temperature dependence of the hole leakage mechanism should be smaller for the (Ga,In)(N,As) LDs than for the InGaAs LD. Moreover, Healy and O'Reilly have recently shown that the electrostatic attraction of electrons significantly increases the binding energy of heavy holes in the QW region of GaInNAs QW LDs due to the increased conduction band offset, thus reducing the hole leakage effect [9]. So, based on these initial assumptions, we apply the multi-length approach used in [12] to our set of LDs.

Based on Tansu's work, the T_0 and T_1 characteristic temperatures can be expressed in terms of the internal differential quantum efficiency (η_i), the modal gain (Γg_0), the transparency current density (J_tr), the intra-cavity optical losses (α_i) and their characteristic temperatures ($T_{\eta\mathrm{i}}$, $T_{\Gamma g0}$, T_tr and $T_{\alpha\mathrm{i}}$, respectively):

$$\frac{1}{T_0} = \frac{1}{T_\mathrm{tr}} + \frac{1}{T_{\eta\mathrm{i}}} + \frac{\alpha_\mathrm{i} + \alpha_\mathrm{m}(L)}{\Gamma g_0}\,\frac{1}{T_{\Gamma g0}} + \frac{\alpha_\mathrm{i}}{\Gamma g_0}\,\frac{1}{T_{\alpha\mathrm{i}}}, \qquad (1)$$

$$\frac{1}{T_1} = \frac{1}{T_{\eta\mathrm{i}}} + \frac{\alpha_\mathrm{i}}{\alpha_\mathrm{i} + \alpha_\mathrm{m}(L)}\,\frac{1}{T_{\alpha\mathrm{i}}}. \qquad (2)$$

Here, a temperature dependence of the form $x \propto \exp(T/T_x)$ is assumed for α_i and J_tr, whereas Γg_0 and η_i are assumed to depend on T as $x \propto \exp(-T/T_x)$. The results of this analysis are summarized in table 1 at $T = 32\,^\circ\mathrm{C}$ and for a cavity length $L = 900\,\mu\mathrm{m}$. As shown in table 1, the most significant changes take place for the cavity optical losses, α_i, which increase by a factor of 2.3 and for the modal gain, Γg_0, which decreases by a factor of 0.5. However, further insight can be obtained by looking at the partial contributions of each of the terms on the right-hand side of (1) and (2). These partial contributions are shown in table 2. The equation for T_1 comprises the terms labelled (**B**) and (**E**). The term labelled (**B**) has a significantly smaller contribution to T_1 in both N-free and N-containing samples than the term labelled (**E**), which increases by ~50% mostly due to the increase in α_i when N is incorporated. Thus, the decrease in T_1 is mainly due to the increase in α_i. The decrease in T_0 is primarily due to a decrease in T_tr (term (**A**)), which is the dominant term, and also by an increase in (**C**) and (**D**), which is in turn caused by the increase in α_i and the decrease in Γg_0 as N goes from 0% to 1.4%. Thus, it can be concluded that the prevailing phenomena in the degradation of T_0 when N is added to InGaAs are the decrease in T_tr, and, to a lesser extent, the increase in α_i and the decrease in Γg_0. Such increase in α_i when N is present could be ascribed to a larger light scattering from compositional inhomogeneities of the QW, or an enhanced intra-valence-band absorption. The causes for the decrease in Γg_0 could be related to the reported drastic reduction of peak gain for the N-containing alloy [20]. Finally, the relatively high values of T_tr indicate that Auger recombination is not the dominant recombination process on both LDs [12], in agreement with our previous assumption based on what is reported in [17] for temperatures below 50 °C. Table 2 includes the values of T_0 and T_1 calculated through (1) and (2). Note that these calculated values of T_0 and T_1 are in fair agreement with those directly measured in the devices (shown in table 1).

Table 1. Physical parameters and their characteristic temperatures for the $\lambda = 1007$ and $\lambda = 1291$ nm LDs at $T = 32\,^\circ\mathrm{C}$, for a cavity length of 900 μm. Measured values of T_0 and T_1 are included.

	$\lambda = 1007$ nm $J_\mathrm{th} = 243\ \mathrm{A\,cm^{-2}}$	$\lambda = 1291$ nm $J_\mathrm{th} = 617\ \mathrm{A\,cm^{-2}}$
$T_{\alpha\mathrm{i}}$ (K)	59 ± 24	76 ± 36
T_tr (K)	150 ± 22	125 ± 6
$T_{\eta\mathrm{i}}$ (K)	741 ± 550	794 ± 629
$T_{\Gamma g_0}$ (K)	205 ± 84	215 ± 46
α_i (cm^{-1})	2.5 ± 0.2	5.7 ± 0.8
Γg_0 (cm^{-1})	50 ± 15	34 ± 5
Measured T_0 (K)	103 ± 2	83 ± 8
Measured T_1 (K)	231 ± 32	198 ± 27

Table 2. Partial contribution to T_0 and T_1 of the individual terms of (1) and (2) for the LDs with a cavity length of 900 μm emitting at 1007 and 1291 nm. T_0 and T_1 values calculated through these two equations are included.

	$\lambda = 1007$ nm	$\lambda = 1291$ nm
(**A**) $1/T_\mathrm{tr}$ (K^{-1})	1/150	1/125
(**B**) $1/T_{\eta\mathrm{i}}$ (K^{-1})	1/741	1/794
(**C**) $\frac{\alpha_\mathrm{i} + \alpha_\mathrm{m}(L)}{\Gamma g_0} \cdot \frac{1}{T_{\Gamma g0}}$ (K^{-1})	1/636	1/398
(**D**) $\frac{\alpha_\mathrm{i}}{\Gamma g_0 T_{\alpha\mathrm{i}}}$ (K^{-1})	1/1133	1/461
(**E**) $\frac{\alpha_\mathrm{i}}{\alpha_\mathrm{i} + \alpha_\mathrm{m}(L)}\frac{1}{T_{\alpha\mathrm{i}}}$ (K^{-1})	1/365	1/249
Calculated T_0(K)	96±18	72±15
Calculated T_1(K)	245±120	190±72

On the other hand, as shown in table 2, the partial contribution of $T_{\eta\mathrm{i}}$ to T_0 and T_1 is much smaller than that of all the other terms, both in N-containing and N-free LDs. Moreover, the value of $T_{\eta\mathrm{i}}$ does not seem to change significantly when adding N. This would suggest that hole leakage does not increase for (Ga,In)(N,As) and that it is not the dominant process, as was assumed at the beginning of the analysis. However, due to the high uncertainty in the $T_{\eta\mathrm{i}}$ values (table 1) it is not possible to draw any conclusions regarding the role of hole leakage on the temperature behaviour of the LDs. Further insight into this issue can be obtained through the analysis of the effective carrier recombination lifetime in the QW, τ. In a recent work, Anton *et al* determined τ in the QW of MOCVD-grown 1.3 μm InGaAsN-GaAsP-GaAs QW LDs. They found a decrease of τ when N is added to the QW, and they concluded that this effect is mainly due to an increase in the non-radiative monomolecular recombination at defects in the GaInNAs alloy [8]. Assuming $J_\mathrm{tr} = e \cdot n_\mathrm{tr}/\tau$, the effective carrier recombination lifetime in the QW can be obtained using the measured values of J_tr and the calculated transparency carrier density, n_tr. This last calculation was carried out using the BAC model as in [16]. It should be noted that the values of J_tr used in this analysis are internal values (namely, the effect of η_i was taken into account), so τ is an effective carrier lifetime within the QW only. Figure 3 shows the calculated values of τ at 22 °C for the LDs emitting from 1007 to 1435 nm. The effective lifetime decreases from 1.2 ns in the InGaAs LD to 0.5 ns for the 1291 nm LD and

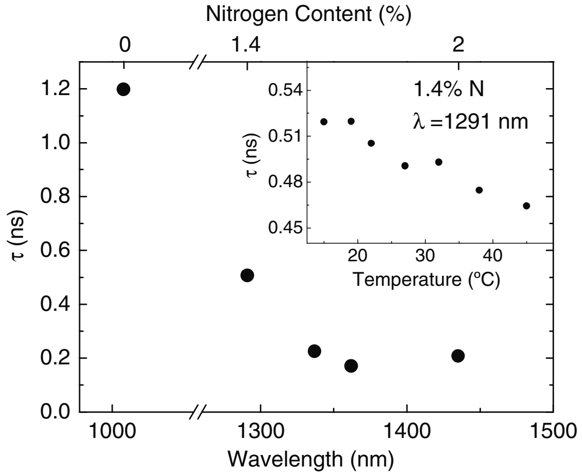

Figure 3. Calculated effective carrier recombination lifetime at transparency, τ, at 22 °C as a function of lasing wavelength for the (Ga,In)(N,As)/GaAs LDs. The inset shows the temperature dependence of τ for the $\lambda = 1291$ nm LD.

to 0.2 ns for longer wavelengths. These values are in good agreement with those reported by Anton *et al* [8] at threshold, which are of the order of 0.5 ns for a 1.3 μm LD. In addition, these values are much higher than the hole thermionic escape times of 0.1 and 0.01 ns calculated for InGaAs and GaInNAs, respectively, in the work by Tansu *et al* [7]. This suggests that hole thermionic escape is not the dominant mechanism. Moreover, if this were the case, the T-dependence for τ should be of the form $1/\tau \propto T^2 \exp(-E_{\mathrm{act}}/kT)$. To check this possibility, we have calculated $n_{\mathrm{tr}}(T)$, which together with the measured $J_{\mathrm{tr}}(T)$, yields $\tau(T)$ (inset of figure 3). This analysis produces a negative activation energy for the $\lambda = 1291$ nm LD, further ruling out the hole thermionic escape mechanism, as was assumed at the beginning of the analysis. It is worth mentioning that since none of the LDs analysed here are relaxed, the reduction in τ with N could be linked to non-radiative recombination originated at point defects, or clusters of point defects, formed by the presence of N.

4. Conclusions

In conclusion, the T_0 and T_1 characteristic temperatures of (Ga,In)(N,As)/GaAs QW LDs emitting between 1 and 1.5 μm have been studied. We have found that both figures strongly degrade with increasing lasing wavelength up to 1.51 μm. This degradation has been related to the decrease in T_{tr} and Γg_0, and the increase in α_{i} when N is present, in the case of T_0, and the increase in α_{i} in the case of T_1. In addition, the effective recombination lifetime in the QW decreases down to 0.2 ns for $\lambda = 1435$ nm, but its temperature dependence does not follow a thermionic escape model. This result, taken together with the fact that $T_{\eta\mathrm{i}}$ has a small contribution to T_0 and T_1, rules out carrier leakage from the QW as the dominant process limiting T_0 and T_1.

Acknowledgments

The authors would like to thank Achim Trampert for the TEM analysis of the LDs and Maite Pérez for her kind help in processing the LDs. This work has been supported by the Spanish Ministerio de Educacion y Ciencia, TEC2005-03694/MIC and NAN2004-09109-C04-02, and by Comunidad de Madrid, S05051ESP-0200. M Montes holds a FPU grant from the Spanish Ministerio de Educación y Ciencia.

[1] Phillips A F, Sweeney S J, Adams A R and Thijs P J A 1999 *IEEE J. Sel. Top. Quantum Electron.* **5** 401
[2] Harris J S Jr 2002 *Semicond. Sci. Technol.* **17** 880
[3] Kondow M, Kitatani T, Nakatsuka S, Larson M C, Nakahara K, Yazawa Y, Okai M and Uomi K 1997 *IEEE J. Sel. Top. Quantum. Electron.* **3** 719
[4] Chen T R, Chang B, Chiu L C, Yu K L, Margalit S and Yariv A 1983 *Appl. Phys. Lett.* **43** 217
[5] Ulloa J M, Hierro A, Montes M, Damilano B, Hugues M, Barjon J, Duboz J-Y and Massies J 2005 *Appl. Phys. Lett.* **87** 251109
[6] Tansu N and Mawst L J 2002 *IEEE Photon. Technol. Lett.* **14** 1052
[7] Tansu N and Mawst L J 2003 *Appl. Phys. Lett.* **82** 1500
[8] Anton O, Menoni C S, Yeh J Y, Mawst L J, Pikal J M and Tansu N 2005 *IEEE Photon. Technol. Lett.* **17** 953
[9] Healy S B and O'Reilly E P 2006 *IEEE J. Quantum Electron.* **42** 608
[10] Damilano B, Barjon J, Duboz J-Y, Massies J, Hierro A, Ulloa J M and Calleja E 2005 *Appl. Phys. Lett.* **86** 71105
[11] Hugues M, Damilano B, Barjon J, Duboz J Y, Massies J, Ulloa J M, Montes M and Hierro A 2005 *Electron. Lett.* **41** 595
[12] Tansu N, Chang Y L, Takeuchi T, Bour D P, Corzine S W, Tan M R T and Mawst L J 2002 *IEEE J. Quantum Electron.* **38** 640
[13] Jaschke G, Averbeck R, Geelhaar L and Riechert H 2005 *J. Cryst. Growth* **278** 224
[14] Foreman B A 1994 *Phys. Rev.* B **49** 1757
[15] Singh J 1995 *Semiconductor Optoelectronics (Physics and Technology)* (New York: McGraw-Hill)
[16] Ulloa J M, Sánchez-Rojas J L, Hierro A, Tijero J M G and Tournié E 2003 *IEEE J. Sel. Top. Quantum Electron.* **9** 716
[17] Fehse R, Tomić S, Adams A R, Sweeney S J, O'Reilly E P, Andreev A and Riechert H 2002 *IEEE J. Sel. Top. Quantum Electron.* **8** 801
[18] Galluppi M, Geelhaar L and Riechert H 2005 *Appl. Phys. Lett.* **86** 131925
[19] Galluppi M, Geelhaar L, Riechert H, Hetterich M, Grau A, Birner S and Stolz W 2005 *Phys. Rev.* B **72** 155324
[20] Thränhardt A *et al* 2006 *Appl. Phys. Lett.* **86** 201117