Temperature Sensitivity of 1300-nm InGaAsN Quantum-Well Lasers

Nelson Tansu and Luke J. Mawst, *Senior Member, IEEE*

***Abstract*—The temperature sensitivity of metal–organic chemical vapor deposition (MOCVD)-grown highly strained ($\Delta a/a \sim$ 2.7%) $\mathrm{In_{0.4}Ga_{0.6}As}$- and $\mathrm{In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}}$ quantum-well (QW) active lasers, with lasing wavelength of 1.185 and 1.295 μm, respectively, is analyzed in terms of measured fundamental device parameters. From our analysis, the lower T_0 values for the InGaAsN QW lasers can be explained in terms of the temperature dependence of the current injection efficiency, presumably due to increased carrier leakage in the InGaAsN QW lasers.**

***Index Terms*—Diode lasers, InGaAs–GaAs QW, InGaAsN–GaAs QW, long-wavelength lasers, quantum-well lasers, strain, temperature analysis.**

I. INTRODUCTION

THE POOR temperature characteristics of 1.3-μm InP-based semiconductor lasers [1] have led to enormous efforts in exploring GaAs-based active regions for 1.3-μm wavelength emission, due to the larger band offset between the quantum well (QW) and the barrier layers, which potentially will lead to strong suppression of carrier leakage. There have been several experimental results that have demonstrated low temperature sensitive InGaAs and InGaAsN QW lasers in the wavelength regime of 1.17–1.3 μm [2]–[11]. Although high values for the characteristic temperature coefficient of threshold current density ($T_0 = (1/J_{\mathrm{th}})\cdot dJ_{\mathrm{th}}/dT$) of threshold current density (J_{th}) have been demonstrated by several groups [2]–[11], there has been no consensus on how to interpret the T_0 values in terms of fundamental device performance. In addition, T_0 values of lasers with high J_{th}, due to large defect-induced monomolecular recombination, can be anomalously high [11].

Our present work is aimed to elucidate the physics of temperature sensitivity, based on our analysis [11] of low-J_{th} strain-compensated $\mathrm{In_{0.4}Ga_{0.6}As}$-QW ($J_{\mathrm{th}} =$ 100–130 A/cm^2, $L =$ 1000–2000 μm) and $\mathrm{In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}}$-QW ($J_{\mathrm{th}} =$ 290–400 A/cm^2, $L =$ 750–1500 μm) lasers [4], with emission wavelength of 1.185- and 1.295-μm, respectively.

II. METHOD OF TEMPERATURE CHARACTERIZATION

All the temperature characterizations of our lasers are performed on 100-μm-stripe-width broad-area diode lasers, within the temperature range 20 °C–60 °C. The laser structures utilize either a 60-Å $\mathrm{In_{0.4}Ga_{0.6}As}$ (Laser A) or 60-Å $\mathrm{In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}}$ (Laser B) QW, grown by metal–organic chemical vapor deposition (MOCVD), employing strain compensating $\mathrm{GaAs_{0.85}P_{0.15}}$ barriers and n-InGaP–GaAsP tensile-buffer layer. The bottom and top cladding layers for both lasers are based on n- and p-type $\mathrm{Al_{0.74}Ga_{0.26}As}$ layers, respectively, with doping levels of 1×10^{18} cm^{-3}. The details on the structure and lasing characteristics of these lasers have been presented in [4].

The temperature dependence of the threshold current density (J_{th}) and external differential quantum efficiency (η_d) can be expressed as functions of the temperature dependence of the physical device parameters, which include transparency current density (J_{tr}), current injection efficiency (η_{inj}), material gain parameters (g_o), and internal loss (α_i) [11]. The J_{th} and η_d of semiconductor lasers can be expressed as functions of the physical parameters as follows

$$J_{\mathrm{th}} = \frac{J_{\mathrm{tr}}}{\eta_{\mathrm{inj}}} \cdot \exp\left(\frac{\alpha_i + (1/L)\ln(1/R)}{\Gamma g_o}\right) \tag{1}$$

$$\eta_d = \eta_{\mathrm{inj}} \cdot \frac{\alpha_m(L)}{\alpha_i + \alpha_m(L)}. \tag{2}$$

By taking the temperature derivative of (1) and (2), the temperature characteristics of the J_{th} and η_d can be expressed as in equations (3) and (4), as follows:

$$\frac{1}{T_o(L)} = \frac{1}{T_{\mathrm{tr}}} + \frac{1}{T_{\eta_{\mathrm{inj}}}} + \frac{\alpha_i + \alpha_m(L)}{\Gamma \cdot g_o} \cdot \frac{1}{T_{g_o}} + \frac{\alpha_i}{\Gamma \cdot g_o} \cdot \frac{1}{T_{\alpha i}} \tag{3}$$

$$\frac{1}{T_1(L)} = \frac{1}{T_{\eta_{\mathrm{inj}}}} + \frac{\alpha_i}{\alpha_i + \alpha_m(L)} \cdot \frac{1}{T_{\alpha i}} \tag{4}$$

where $\alpha_m(L)$ and Γ corresponds to the length-dependent mirror loss, and the optical confinement factor of the QW, respectively. The temperature dependence of J_{th}, η_d, J_{tr}, η_{inj}, g_o, and α_i, are quantified by defining characteristic temperature coefficients T_o, T_1, T_{tr}, $T_{\eta\mathrm{inj}}$, T_{go}, and $T_{\alpha i}$, respectively. The J_{th}, J_{tr}, and α_i can be expressed as monotonically increasing exponential function with respect to temperature, which can be expressed as $1/T_X = (1/X)\cdot(dX/dT)$. In contrast, the temperature dependence of η_d, η_{inj}, and g_o can be expressed as functions which follow $1/T_X = -(1/X)\cdot(dX/dT)$.

All the parameters, including J_{tr}, η_{inj}, α_i, g_o, are extracted from the conventional multilength measurements of the as-cleaved devices under low duty-cycle pulsed operation (6 μs, 1 kHz). The characteristic temperature coefficients for each device parameter are determined from the measured device performance as a function of cavity length and temperature. By analyzing the measured values of T_{tr}, $T_{\eta\mathrm{inj}}$, T_{go}, and $T_{\alpha i}$, important insights into the temperature behavior of the lasers can be achieved.

Manuscript received January 2, 2002; revised April 11, 2002.

The authors are with the Reed Center for Photonics, Department of Electrical Computer Engineering, University of Wisconsin-Madison, Madison, WI 53706-1691 USA (e-mail: tansu@cae.wisc.edu).

Publisher Item Identifier S 1041-1135(02)06012-3.

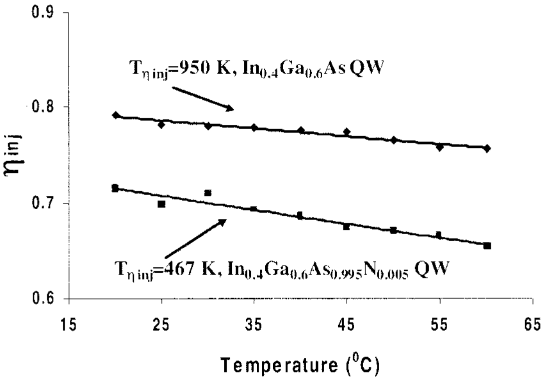

Fig. 1. The current injection efficiency of $In_{0.4}Ga_{0.6}As$ QW and $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW lasers, as functions of temperature.

III. RECOMBINATION MECHANISMS IN InGaAs(N) QW LASERS

The measurements of the T_{tr} value can give insight into whether Auger recombination is the dominant process in the recombination mechanisms at transparency [11]. For near room temperature measurements, T_{tr} values of 50 K–80 K indicate Auger recombination to be the dominant recombination in the QW. A very large T_{tr} value (350 K–400 K or higher) indicates that defect-induced monomolecular recombination, which is less temperature sensitive, is a dominant recombination process in the laser. While values of T_{tr} between these two extremes is consistent with radiative recombination being the dominant process. The extracted T_{tr} values for both lasers A and B are 285 K and 280 K, respectively. From these measurements, we can conclude that Auger recombination is *not* the *dominant* recombination process at transparency for both the $In_{0.4}Ga_{0.6}As$- and $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW lasers. However, from large value of T_{tr} alone, it is not possible to rule out the Auger recombination process in these lasers, since the presence of large monomolecular recombination may mask an underlying Auger process. Thus, the T_{tr} measurements are analogous to the z-parameters measurements [1] in identifying the *dominant* recombination mechanisms in QW lasers. Minimal Auger recombination in InGaAsN QW lasers, has been predicted by Fehse, *et al.* [12] by using pressure-dependence measurements. Further studies are needed to definitively determine the extent of the Auger process in InGaAsN QW lasers by extracting the Auger recombination coefficient.

IV. TEMPERATURE CHARACTERISTICS OF J_{th} and η_d

The threshold current density of laser A is relatively temperature insensitive, with T_0 values in excess of 175 K for $L =$ 500-, 1000-, and 2000-μm cavity length. Unlike laser A, the T_o values for laser B are reduced significantly to 110 K and 126 K, for $L =$ 750-, and 1500-μm cavity length devices. Our analysis, using (1), indicates that this reduction in the T_o values for the InGaAsN QW lasers is primarily due to a strong thermally induced carrier leakage mechanism, which is reflected in a lower $T_{\eta\mathrm{inj}}$ value, as shown in Fig. 1. The large $T_{\alpha i}$ values for both laser A ($T_{\alpha i} \sim$ 500 K) and B ($T_{\alpha i} \sim$ 1160 K), indicate very weak temperature dependence of the internal loss ($d\alpha_i/dT \sim$ 0.6–1 $\times$ 10^{-2} cm^{-1}/K) for both lasers, unlike that of typical InP-based 1.3 μm emitting lasers with $d\alpha_i/dT$ and $T_{\alpha i}$ of 0.2 cm^{-1}/K and 100 K, respectively [1]. The measured g_0 of Laser A and B, as a function of temperature, are shown in Fig. 2. The g_o value of InGaAsN is more temperature sensitive, reflected from the lower T_{go} value. Despite the lower T_{go} value for the InGaAsN QW, the contributing term $[T_{go}g_o/g_{\mathrm{th}}(\mathrm{L})]$ to T_0 value in (3) can be as large as 1200 K for long cavity devices. From here, we conclude that the more temperature sensitive g_o in the InGaAsN QW is not the dominant reason of the lower T_0 values in the InGaAsN QW lasers. T_{go} values for InP-based lasers have not been reported, although they can be estimated from the temperature dependence of the differential gain to be approximately $T_{go} =$ 200 K [13]. As shown in Fig. 3, the calculated T_0 values for both InGaAs QW and InGaAsN QW lasers, based on (3), have a high accuracy with the experimentally measured T_0 values.

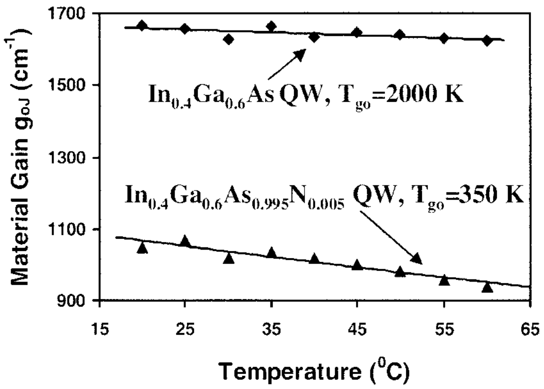

Fig. 2. The material gain parameters of $In_{0.4}Ga_{0.6}As$ QW and $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW lasers, as functions of temperature.

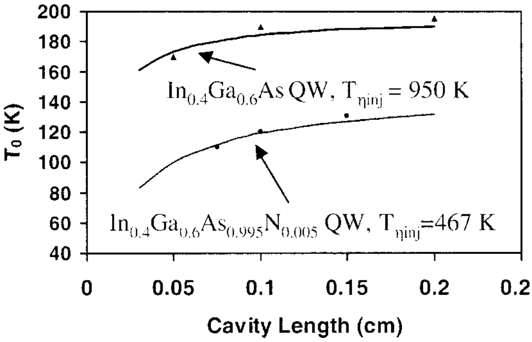

Fig. 3. The measured T_0 values of $In_{0.4}Ga_{0.6}As$ QW and $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW lasers, as functions of cavity-length, with the lines represent the predicted T_0 values from (3).

The smaller $T_{\eta\mathrm{inj}}$ ($T_{\eta\mathrm{inj}} =$ 470 K) of laser B, compared to that ($T_{\eta\mathrm{inj}} =$ 940 K) of laser A, indicates that there is a larger thermal-induced degradation of the η_{inj} of laser B. From (1), the large reduction in the η_{inj} at extended temperature, in the InGaAsN QW system, is the dominant mechanism that contributes to the increase in the threshold current density of laser B at higher temperature. The increase in the thermionic carrier leakages rate in the InGaAsN QW is somewhat puzzling, due to the fact that the $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW should have a larger band offset (ΔE_g = 470 eV) between the QW and the barriers, compared to that (ΔE_g = 378 eV) of the $In_{0.4}Ga_{0.6}As$ QW systems. In InGaAsN QW systems, significantly larger relative conduction band offset ($\Delta E_c/\Delta E_g$) will be obtained due

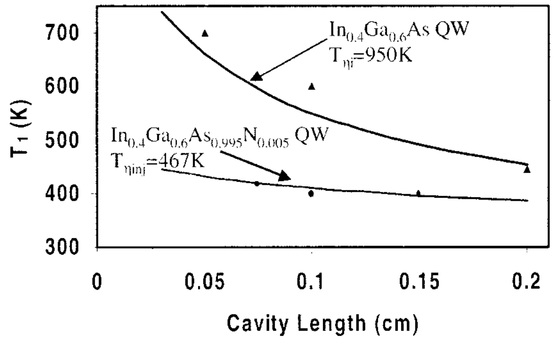

Fig. 4. The measured T_1 values of $In_{0.4}Ga_{0.6}As$ QW and $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW lasers, as functions of cavity-length, with the lines represent the predicted T_1 values from (4).

to stronger bowing parameter in the conduction band (E_c) compared to that in the valence band (E_v) [5]. The significantly higher threshold carrier density of InGaAsN QW, due to the lower material gain parameter of InGaAsN QW [14] , and the poor hole-confinement may lead to an increase in the carrier overflow in the SCH region, which in turn will lead to a reduction in the η_{inj}. The increased carrier leakage is also consistent with previously published data, showing a reduction in the η_{inj} [10] and the T_0 values [7], [10] as emission wavelength increases due to the higher N content in InGaAsN QW. Further studies are still required to understand further the mechanisms of the carrier leakage in the InGaAsN QW, which leads to a reduction in the η_{inj} and $T_{\eta\text{inj}}$.

We also observe that 1300-nm InGaAsN QW lasers with higher J_{tr}, presumably due to an increase in the monomolecular recombination, exhibit very large T_0 values of 230 K, compared to that ($T_0 = 120$ K) of lasers with lower J_{tr}. This large disparity in the T_0 values are consistent with our prediction [11] that lasers with large monomolecular recombination, should result in larger T_0 values, due to larger T_{tr} values.

From (4), the T_1 values depend on the temperature dependence η_{inj} and α_i. Similar to the T_o values, the cavity-length dependent value of T_1, as shown in Fig. 4 for both lasers A and B, are due to the differences in the modal threshold gain for different cavity lengths. As the modal threshold gain decreases in longer-cavity devices, the values of T_1 values will also decrease, which is explicitly shown in (4) and Fig. 4. Due to the large $T_{\eta\text{inj}}$ ($T_{\eta\text{inj}} = 940$ K) in the $In_{0.4}Ga_{0.6}As$ QW lasers, the T_1 values change strongly with cavity length due to the stronger contribution of the $((\alpha_m(L) + \alpha_i)/(d\alpha_i/dT))$ term. T_1 values, as high as 700 K and 600 K have been measured, and agreed close with the prediction from (4) for the 500-μm and 1000-μm cavity length devices of laser A, respectively.

For the InGaAsN QW lasers, the $T_{\eta\text{inj}}$ is significantly lower compared to that of the InGaAs QW. As a result, the T_1 values of the InGaAsN QW are less sensitive to the effect of differences in the modal threshold gain, which is reflected in the T_1 values that decrease very slowly with increasing cavity length. Despite the increased carrier leakage, the T_1 values of the InGaAsN QW lasers, with $\lambda = 1.295$ μm are still very high, 420 K and 400 K for 750- and 1500-μm cavity-length InGaAsN QW devices, respectively.

V. CONCLUSION

The dominant mechanism, responsible for the lower T_0 and T_1 values of the 1300-nm InGaAsN QW lasers compared to those of 1200-nm InGaAs QW, is a highly temperature sensitive injection efficiency, presumably the result of temperature-induced carrier leakage. The T_{tr} measurements indicate the Auger recombination not to be the *dominant* recombination at the transparency on the $In_{0.4}Ga_{0.6}As$ QW and $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW, with monomolecular recombination being the dominant process.

ACKNOWLEDGMENT

The authors would like to acknowledge helpful technical discussions by Prof. D. Botez, of the University of Wisconsin-Madison, and Prof. P. Blood of Cardiff University. The authors would also like to acknowledge careful, insightful, and constructive comments from the referee.

REFERENCES

[1] A. F. Phillips, A. F. Sweeney, A. R. Adams, and P. J. A. Thijs, "Temperature dependence of 1.3- and 1.5-μm compressively strained InGaAs(P) MQW semiconductor lasers," *IEEE J. Select. Topics Quantum Electron.*, vol. 5, pp. 401–412, May–June 1999.

[2] N. Tansu and L. J. Mawst, "High-performance, strain compensated InGaAs–GaAsP–GaAs ($\lambda = 1.17 \mu$m) quantum well diode lasers," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 179–181, Mar. 2001.

[3] W. Choi, P. D. Dapkus, and J. J. Jewell, "1.2-μm GaAsP/InGaAs strain compensated single-quantum well diode laser on GaAs using metal–organic chemical vapor deposition," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1572–1574, 1999.

[4] N. Tansu and L. J. Mawst, "Low-threshold strain-compensated InGaAs(N) (λ = 1.19–1.3μm) quantum well lasers," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 444–446, Apr. 2002.

[5] M. Kondow, T. Kitatani, S. Nakatsuka, M. C. Larson, K. Nakahara, Y. Yazawa, M. Okai, and K. Uomi, "GaInNAs: A novel material for long wavelength semiconductor lasers," *IEEE J. Select. Topic Quantum Electron.*, vol. 3, pp. 719–730, June 1997.

[6] S. Sato, "Low threshold and high characteristics temperature 1.3 μm range GaInNA's lasers frown by metalorganic chemical vapor deposition," *Jpn. J. Appl. Phys.*, vol. 39, pp. 3403–3405, June 2000.

[7] M. Kawaguchi, T. Miyamoto, E. Gouardes, D. Schlenker, T. Kondo, F. Koyama, and K. Iga, "Lasing characteristics of low-threshold GaInNA's lasers grown by metalorganic chemical vapor deposition," *Jpn. J. Appl. Phys.*, vol. 40, pp. L744–L746, July 2001.

[8] F. Hohnsdorf, J. Koch, S. Leu, W. Stolz, B. Borchert, and M. Druminski, "Reduced threshold current densities of (GaIn)(Nas)/GaAs single quantum well lasers for emission wavelengths in the range 1.28–1.38 μm," *Electron. Lett.*, vol. 35, no. 7, pp. 571–572, 1999.

[9] B. Borchert, A. Y. Egorov, S. Illek, and H. Riechert, "Static and dynamics characteristics of 1.29 μm GaInNA's ridge-waveguide laser diodes," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 597–599, June 2000.

[10] M. R. Gokhale, P. V. Studenkov, J. Wei, and S. R. Forrest, "Low-threshold current, high efficiency 1.3-μm wavelength aluminum-free InGaAsN-based quantum-well lasers," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 131–133, Feb. 2000.

[11] N. Tansu, Y. L. Chang, T. Takeuchi, D. P. Bour, S. W. Corzine, M. R. T. Tan, and L. J. Mawst, "Temperature analysis and characteristics of highly-strained InGaAs(N)–GaAsP–GaAs ($\lambda > 1.17$ μm) quantum well lasers," *IEEE J. Quantum Electron.*, vol. 38, pp. 640–651, June 2002.

[12] R. Fehse, S. J. Sweeney, A. R. Adams, E. P. O'Reilly, A. Y. Egorov, H. Riechert, and S. Illek, "Insights into carrier recombination processes in 1.3 μm GaInNAs-based semiconductor lasers attained using high pressure," *Electron. Lett.*, vol. 37, no. 2, pp. 92–93, 2000.

[13] D. A. Ackerman, P. A. Morton, G. E. Shtengel, M. S. Hybertsen, R. F. Kazarinov, T. Tanbun-Ek, and R. A. Logan, "Analysis of T_o in 1.3 μm multi-quantum-well and bulk active lasers," *Appl. Phys. Lett.*, vol. 66, no. 20, pp. 2613–2615, 1995.

[14] S. Tomic, E. P. O'Reilly, A. R. Adams, and R. Fehse, "A theoretical analysis of the radiative current and its dependence on pressure in GaInNA's 1.3 μm lasers," in *LEOS 2001*, San Diego, CA, Nov., pp. 328–329.