Temperature-Sensitivity Analysis of 1360-nm Dilute-Nitride Quantum-Well Lasers

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***Abstract*—The N-content of an InGaAsN quantum-well (QW) laser is found to dramatically affect the temperature sensitivity of the current injection efficiency ($\eta_{\rm inj}$) and material gain parameter ($g_{\rm oJ}$). The increased temperature sensitivity of $\eta_{\rm inj}$ and $g_{\rm oJ}$ of InGaAsN QW lasers with increasing N-content leads to a significant increase in their temperature sensitivity of threshold current and external differential quantum efficiency. Increasing the N-content of the InGaAsN QW potentially results in a reduction of the heavy hole confinement, which may account for the increased temperature sensitivity of the current injection efficiency.**

***Index Terms*—Current injection efficiency, InGaAsN, long wavelength quantum-well (QW) laser, material gain, temperature sensitivity, thermionic carrier leakage.**

I. INTRODUCTION

SEMICONDUCTOR lasers with emission wavelengths from 1300 to 1600 nm are crucial for the application of optical fiber communication systems. To achieve less temperature-sensitive GaAs-based quantum-well (QW) lasers in this wavelength regime, InGaAsN was proposed as a promising candidate [1]. High performance devices have now been reported by many research groups [2]–[6] in the 1300-nm wavelength range. Because of the strong electron confinement in the InGaAsN QW structures, there is a potential for achieving less device temperature sensitivity compared to conventional InP-based lasers. Recent temperature analyses of InGaAsN diode lasers in the 1300-nm wavelength region indicate that the Auger recombination [7] and hole leakage [8] may play a significant role in the observed temperature sensitivity of the threshold current density and external differential quantum efficiency. To achieve emission wavelengths beyond 1300 nm, higher N-content InGaAsN active regions have been reported by various growth techniques such as molecular beam epitaxy [9], metal–organic chemical vapor deposition (MOCVD) [10], [11], and chemical beam epitaxy [12]. In addition to higher threshold current density and lower external differential quantum efficiency than those of 1300-nm-emitting lasers, the longer wavelength devices also exhibited severe temperature sensitivity of the laser characteristics. However, no study has yet focused on the strong temperature dependence of InGaAsN QW lasers beyond 1300 nm and the underlying mechanism is still uncertain.

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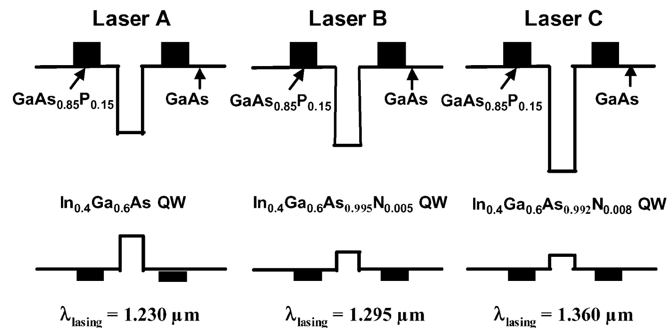

Fig. 1. Schematic band diagram of the InGaAs(N) QW laser structures with N-content of 0%, 0.5%, and 0.8% for 1230-nm $In_{0.4}Ga_{0.6}As$ (Laser A), 1295-nm $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ (Laser B), and 1360-nm $In_{0.4}Ga_{0.6}As_{0.992}N_{0.008}$ (Laser C) QW lasers, respectively.

In this work, we present a temperature analysis of InGaAs(N) QW lasers over a wide emission wavelength range from 1230 to 1360 nm by simply adjusting the nitrogen composition in the QW. It was found that incorporation of higher nitrogen content significantly deteriorated the laser characteristics *and* temperature performance. Furthermore, we conclude that this behavior can be attributed to the highly temperature-sensitive current injection efficiency and material gain parameter for InGaAsN QW lasers with higher N-content.

II. STUDIED LASER STRUCTURES AND PERFORMANCES

The InGaAs QW and InGaAsN QW laser structures were grown by low-pressure MOCVD with trimethylgallium (TMGa), trimethylaluminum (TMAl), and trimethylindium (TMIn) as the precursors for group III materials, and AsH_3, PH_3, and U-dimethylhydrazine (U-DMHy) for the group V sources. In this study, we focused on three MOCVD-grown InGaAs(N) QW lasers with lasing wavelengths of 1.230 μm (Laser A) [13], 1.295 μm (Laser B) [3], and 1.360 μm (Laser C) [11] for 2-mm-long devices, respectively, and the schematic band diagrams are shown in Fig. 1. A high In-content of 40% was utilized in the QW grown under a temperature of 530 °C for all three laser bases. The only distinction of these laser structures was the nitrogen composition x of the 60-Å-thick $In_{0.4}Ga_{0.6}As_{1-x}N_x$ QW, which was determined to be 0% and 0.5% for Lasers A and B, calibrated by secondary ion-mass spectroscopy measurements, and 0.8% for Laser C, which was estimated by extrapolating the growth parameters. The calculated strain of the InGaAs(N) QW are −2.79%, −2.69%, and −2.64%, for Lasers A–C, respectively. The similar active layer strain values of these lasers should result in no signifi-

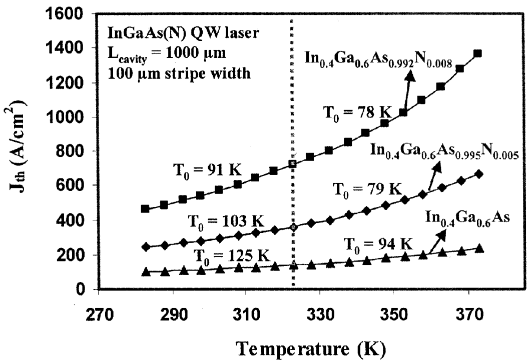

Fig. 2. $J_{\rm th}$ as a function of temperature for Lasers A–C with 1000-μm cavity length.

cant difference of the laser characteristics. The detailed laser structure was described in the previous published work [3], [11], [13]. The optical confinement factor (Γ) of 1.7% was calculated for all three structures by using the transmission matrix method.

As-cleaved broad-area lasers were fabricated with a stripe width of 100 μm and lasing characterization was conducted at a heat sink temperature range from 10 °C to 100 °C with a pulsewidth of 5 μs (1% duty cycle). No heating was observed during the optical power versus injection current measurement under the experimental condition. The threshold current density $(J_{\rm th})$ was 110, 266, and 513 and external differential quantum efficiency (η_d) was 48%, 46%, and 43% at 20 °C for 1-mm cavity length devices of Lasers A, B, and C, respectively. Fig. 2 shows the detailed temperature dependence of $J_{\rm th}$ as well as the characteristic temperature $T_0\{1/T_0 = 1/J_{\rm th}(dJ_{\rm th}/dT)\}$ at a temperature range of 10 °C–50 °C and 50 °C–100 °C. The 1230-nm $\mathrm{In_{0.4}Ga_{0.6}As}$ QW lasers (Laser A) have both the lowest $J_{\rm th}$ and the largest η_d as well as higher T_0 and T_1 values compared with the 1295-nm $\mathrm{In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}}$ (Laser B) and 1360-nm $\mathrm{In_{0.4}Ga_{0.6}As_{0.992}N_{0.008}}$ (Laser C) QW lasers. T_0 values from 20 °C to 60 °C were characterized to be 120 K, 98 K, and 88 K and T_1 are 631 K, 333 K, and 227 K for Lasers A–C, respectively, indicating a trend of a reduction in T_0 and T_1 for the lasers with higher N-content in QW. At 100 °C, the InGaAs QW lasers exhibited a very low $J_{\rm th}$ of 237 A/cm^2 and high η_d of 41%. It is concluded that with an increasing N-content InGaAsN QW, the lasers show degraded lasing characteristics and, more importantly, significantly higher temperature sensitivity, although an extension of lasing wavelength can be achieved.

III. Temperature Analysis of Lasing Characteristics

The characteristic temperature coefficients T_0 and T_1 can be expressed as (1) and (2) by assuming that $J_{\rm th}$, transparent current density $(J_{\rm tr})$, and internal loss (α_i) exponentially increase with temperature while η_d, current injection efficiency $(\eta_{\rm inj})$, and material gain parameter $(g_{\rm oJ})$ exponentially decrease. The relations can be written as [8]

$$\frac{1}{T_0(L)} = \frac{1}{T_{\rm tr}} + \frac{1}{T_{\eta_{\rm inj}}} + \frac{\alpha_i+\alpha_m(L)}{\Gamma\cdot g_{\rm oJ}}\cdot\frac{1}{T_{g_{\rm oJ}}} + \frac{\alpha_i}{\Gamma\cdot g_{\rm oJ}}\cdot\frac{1}{T_{\alpha_i}} \quad (1)$$

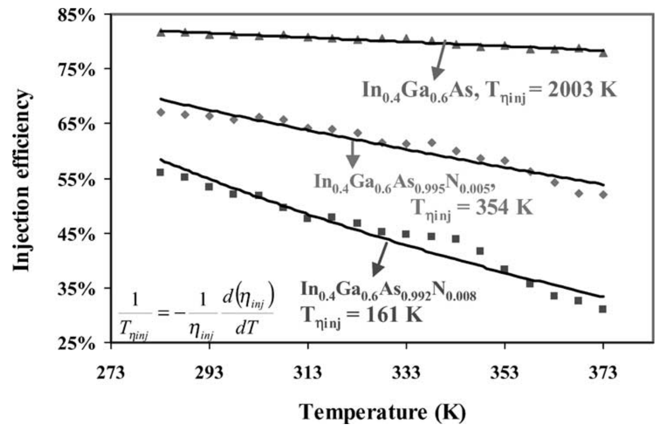

Fig. 3. Relation between current injection efficiency $\eta_{\rm inj}$ and temperature for the three laser structures. A higher $T_{\eta_{\rm inj}}$ was observed for the structure with less nitrogen in the QW.

$$\frac{1}{T_1(L)} = \frac{1}{T_{\eta_{\rm inj}}} + \frac{\alpha_i}{\alpha_i+\alpha_m(L)}\cdot\frac{1}{T_{\alpha_i}} \quad (2)$$

where $T_{\rm tr}$, $T_{\eta_{\rm inj}}$, $T_{g_{\rm oJ}}$, and T_{α_i} are the characteristic temperatures of $J_{\rm tr}$, $\eta_{\rm inj}$, $g_{\rm oJ}$, and α_i and $\alpha_m(L) = (1/L)\times\ln(1/R)$ is the mirror loss as a function of cavity length, where R is the facet reflectivity and L is the cavity length. In order to distinguish the dominant mechanism for the poor temperature performance of the long wavelength 1360-nm InGaAsN QW lasers, temperature characteristics of $J_{\rm tr}$, $\eta_{\rm inj}$, and $g_{\rm oJ}$ were obtained from a series of temperature-dependent length studies. By deducing the slope and intercept of the $1/\eta_d$ versus L data line, one can calculate the laser intrinsic parameters of α_i and $\eta_{\rm inj}$ [8].

The result of length studies for these three laser structures is shown in Fig. 3, where $\eta_{\rm inj}$ is expressed as a function of heat sink temperature from 10 °C to 100 °C. Current injection efficiency $(\eta_{\rm inj})$ values of 81%, 66%, and 53% at room temperature and $T_{\eta_{\rm inj}}$ of 2000 K, 354 K, and 161 K were observed for the InGaAs(N) QW lasers with 0%, 0.5%, and 0.8% N-content, respectively. The strong temperature dependence of the injection efficiency indicates a much stronger carrier leakage process for the high N-content InGaAsN QW lasers. At 100 °C, the $\eta_{\rm inj}$ of Laser C reduces to 31% while the $\eta_{\rm inj}$ of Laser A is still as high as 78%. The second term in (2) represents the contribution from internal loss temperature sensitivity. Values of $T_{\alpha_i}\times(\alpha_i+\alpha_m)/\alpha_i$ were measured and calculated to be 640, 1153, and 2132 for Lasers A–C, respectively, and T_{α_i} values are 260 K, 360 K, and 400 K. According to (2), we can determine that the factor which limits T_1 for InGaAs QW laser is the internal loss (the second term) since $T_{\eta_{\rm inj}}$ hardly affects T_1 due to its large value of 2000 K. On the contrary, the dominant factor resulting in the highly temperature sensitive η_d (a much lower T_1) of the 1295- and 1360-nm InGaAsN QW lasers is the current injection efficiency $\eta_{\rm inj}$ (T) [the first term]. The observed poor $\eta_{\rm inj}$ and $T_{\eta_{\rm inj}}$ values could be presumably explained by a hole leakage mechanism in InGaAsN QW lasers [8], [14], [15] with a reducing valence band offset as nitrogen composition increases [16].

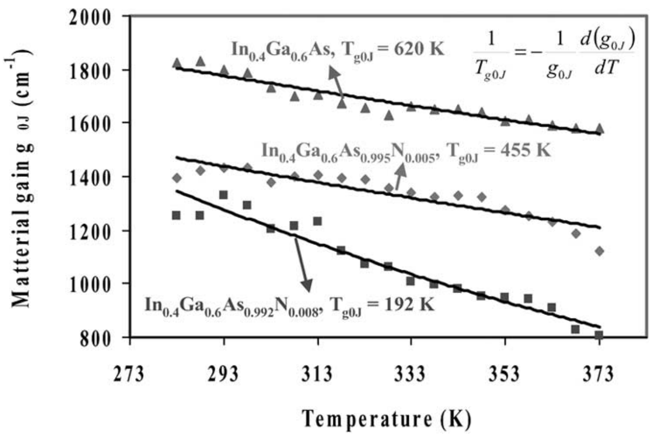

Fig. 4. Material gain parameter g_{oJ} versus temperature in a range of 10 °C–100 °C. Higher N-content results in both lower g_{oJ} and $T_{g_{\mathrm{oJ}}}$.

Unlike in (2), where $T_{\eta_{\mathrm{inj}}}$ is the dominant factor, the more complicated dependence of (1) leads to difficulty in analyzing the dominant mechanism responsible for the degraded T_0 of InGaAsN QW lasers with increasing N-content. For the analysis of T_0, the first three terms in (1) are considered important and need to be carefully examined. In Fig. 4, the measured g_{oJ} values versus temperature are shown over a range of 10 °C–100 °C. The g_{oJ} values at room temperature are measured to be 1800, 1432, and 1330 cm^{-1} and $T_{g_{\mathrm{oJ}}}$ values are 620 K, 456 K, and 192 K for Lasers A–C, respectively. The 1360-nm InGaAsN QW lasers exhibit inferior gain characteristics compared with the other two structures and with such a low $T_{g_{\mathrm{oJ}}}$, the g_{oJ} value drops rapidly as temperature elevates and reaches a very low value of 800 cm^{-1} at 100 °C. Possible mechanisms accounting for this behavior are Auger recombination, nitrogen-induced changes of the energy band structure, and temperature-sensitive carrier leakage processs below threshold. To achieve further insight, g_{oJ} and $T_{g_{\mathrm{oJ}}}$ values of $\mathrm{In_{0.35}Ga_{0.65}As_{0.992}N_{0.008}}$ QW lasers are compared with $\mathrm{In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}}$ QW lasers in which the lasing wavelengths are designed to be 1.3 μm for both cases. With identical bandgap energy, the contribution from Auger recombination are considered to be similar for these two laser structures. We find significantly lower values of g_{oJ} (1251 cm^{-1} at 20 °C) and $T_{g_{\mathrm{oJ}}}$ (330 K from 10 °C–60 °C) for the $\mathrm{In_{0.35}Ga_{0.65}As_{0.992}N_{0.008}}$ QW lasers, indicating that mechanisms other than Auger recombination play a significant role in the degradation of g_{oJ} and $T_{g_{\mathrm{oJ}}}$. From these data, it can be concluded that increasing N-content in InGaAsN QW not only significantly reduces η_{inj} and $T_{\eta_{\mathrm{inj}}}$, but also seriously deteriorates g_{oJ} and $T_{g_{\mathrm{oJ}}}$. Based on this study, it is believed that the observed low T_0 and T_1 of InGaAsN QW lasers with increasing N-content can be explained by the combination of a more severe carrier leakage process and stronger temperature dependence of g_{oJ} [8].

IV. Conclusion

This study demonstrates that the N-content in the InGaAsN QW dramatically affects the temperature sensitivity of η_{inj} and g_{oJ}. The strong temperature dependence of η_{inj} and g_{oJ} leads to low values of T_0 and T_1 for the InGaAsN QW lasers with higher N-content. The current injection efficiency of InGaAsN QW lasers with increasing N-content exhibits increasing temperature sensitivity, which could result from a reduction of the heavy hole confinement. Suppression of thermionic carrier leakage by utilizing larger bandgap material as QW barriers may allow higher performance InGaAsN QW lasers with high N-content for emission wavelength beyond 1360 nm or even up to 1550 nm.

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