Differential Gain and Linewidth-Enhancement Factor in Dilute-Nitride GaAs-Based 1.3-μm Diode Lasers

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***Abstract*—The effect of the quantum-well nitride content on the differential gain and linewidth enhancement factor of dilute-nitride GaAs-based near 1.3-μm lasers was studied. Gain-guided and ridge waveguide lasers with 0%, 0.5%, and 0.8% nitrogen content InGaAsN quantum wells were characterized. Experiment shows that the linewidth enhancement factor is independent on the nitride content, and is in the range 1.7–2.5 for $\lambda = 1.22–1.34$ μm dilute-nitride GaAs-based lasers. Differential gain and index with respect to either current or carrier concentration are reduced in dilute-nitride devices.**

***Index Terms*—Lasers, semiconductor lasers.**

I. INTRODUCTION

DILUTE-NITRIDE alloys of III–V semiconductors have been studied extensively over recent years since the discovery of a strong negative bandgap bowing effect in GaAsN [1]. Laser heterostructures with dilute-nitride InGaAsN quantum wells (QWs) can be grown on GaAs substrates while emitting light in the technologically important wavelength range 1.3–1.5 μm. It was predicted theoretically and demonstrated experimentally that the electron effective mass increases in dilute-nitride materials [2], [3]. Modification of the electron density of states can change device differential gain, threshold carrier concentration, and linewidth enhancement factor, see for instance [4]. All these parameters are important and largely determine the feasibility of the corresponding laser deployment in telecommunication applications. In this work, we compare gain, loss, differential gain, and linewidth-enhancement factor (α-factor) in 1.23-μm $In_{0.4}Ga_{0.6}As$, 1.29-μm $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$, and 1.34-$\mu$m $In_{0.4}Ga_{0.6}As_{0.992}N_{0.008}$ single-QW lasers. A brief report on the measurements of the α-factor in dilute-nitride devices was given in [5].

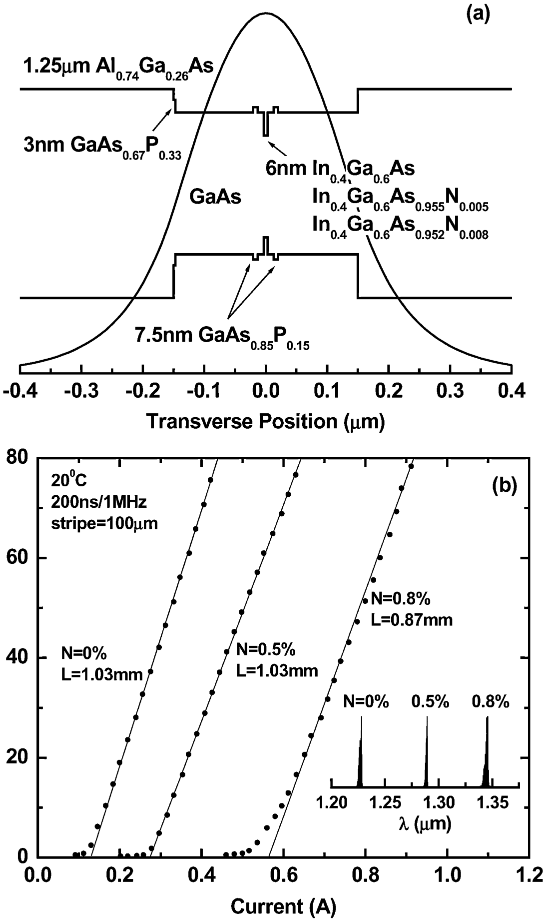

Fig. 1. (a) Schematic band diagram of single-quantum well laser heterostructures and calculated transverse near field. (b) Light-current characteristics and lasing spectra of the 100-μm-wide 1-mm-long uncoated devices with three different nitride composition in InGaAsN QW: 0%, 0.5% and 0.8%.

Lasers were grown by low-pressure metalorganic chemical vapor deposition (MOCVD) [6], [7]. With the exception of the QW composition, the laser heterostructure was kept identical for all devices studied. A 6-nm-wide single-QW active region was embedded into a 300-nm-wide GaAs waveguide region. The waveguide region was sandwiched between two 1.1-μm-wide $Al_{0.74}Ga_{0.26}$ As cladding layers. Fig. 1(a) shows schematically the energy band diagram of the laser heterostructure overlapped with the transverse near field; details of the laser design can be found in [7]. Two groups of the devices were characterized. First, 100-μm-wide multimode 1-mm-long lasers were processed and In soldered p-side down on C-blocks. Second, single spatial mode ridge lasers with ~2.6-μm aperture and 0.5-mm cavity length were processed and In soldered n-side down on C-blocks. Device characterization was performed in a pulsed current regime to minimize the effect of Joule heating on measured laser parameters.

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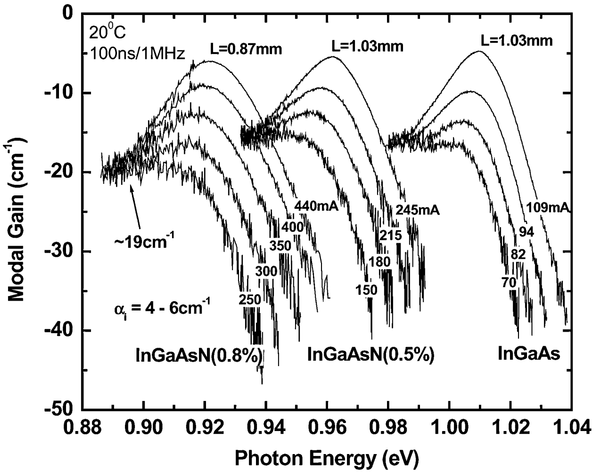

Fig. 2. Current dependences of the modal gain spectra of 100-μm-wide 1-mm-long uncoated devices with three different nitride compositions in InGaAsN QW: 0%, 0.5% and 0.8%.

In Section II, we present the results of the measurements of the modal gain spectra in broad area gain guided multimode lasers. In Section III, we describe the experiment to determine the effect of the QW nitride content on device differential gain with respect to carrier concentration. In Section IV, we present the spectral dependence of the α-factor measured in devices with different QW nitride content. Section V is our discussion and conclusion.

II. Effect of QW Nitride Content on Device Differential Gain With Respect to Current

Fig. 1(b) shows the room temperature light-current characteristics and spectra of multimode 100-μm lasers with 0%, 0.5%, and 0.8% of nitride in QW. Effect of nitrogen incorporation on the material bandgap is apparent from red shift of the laser emission line. The increase of the nitride content in the QW is also accompanied by increase of the laser threshold current.

Fig. 2 shows current dependences of the modal gain spectra for 100-μm-wide 1-mm-long uncoated lasers. Modal gain spectra were measured by Hakki–Paoli method [8] supplemented by spatial filtering optics to separate only the on-axis mode of the multimode gain guided lasers. Fig. 2 data allows for estimating several important laser parameters, namely, internal optical losses, differential gain with respect to current, and transparency current. Internal optical losses can be determined from the low energy parts of the modal gain spectra where the spectra measured at different currents converge. Since material optical gain at subbandgap energies is zero at any current the modal gain is equal to total modal losses. As indicated in Fig. 2, the modal gain in the low energy limit is equal to $\sim$19 cm^{-1} for 0.87-mm-long and $\sim$15–16 cm^{-1} for 1.03-mm-long lasers. Subtracting from these values the mirror losses, which are $\sim$13 cm^{-1} for a 0.87-mm-long and $\sim$11 cm^{-1} for 1.03-mm-long as-cleaved laser, leaves a value for internal optical losses of 4–6 cm^{-1}. Internal losses can be ascribed to free hole absorption and in single QW separate confinement heterostructure lasers are mainly controlled by the penetration of the optical field into the heavily doped cladding regions. No strong dependence of the internal optical losses on QW nitride content is observed. In contrast to optical loss, the measured differential gain with respect to current steadily decreases with increasing QW nitrogen content. The differential gain with respect to current can be characterized by the rate of the peak gain increase with current. This rate drops about three times in devices with 0.5% of nitride in QW and about five times in devices with 0.8% of nitride in QW comparing to nitride free QW lasers. Transparency currents, in turn, can be estimated from Fig. 2 data as the currents corresponding to the lowest measured peak modal gains, i.e., when peak material gain is zero. The transparency current increases with nitride content, from about 70 mA for InGaAs QW laser up to $\sim$150 and $\sim$250 mA for InGaAsN QW lasers with 0.5 and 0.8% of nitride, respectively. Reduction of the differential gain with respect to current and increase of the transparency current explain larger threshold currents of dilute nitride lasers as compared to nitride free devices [Fig. 1(b)]. Possible reasons to account for the observed reduction of the differential gain in dilute-nitride lasers include nitrogen incorporation induced modification of the QW band structure [9], enhancement of monomolecular recombination, Auger recombination [10], and carrier leakage [11]. Hakki–Paoli measurements does not allow distinguishing between reasons leading to reduction of the differential gain with respect to concentration or reduction of the carrier lifetime.

III. Effect of QW Nitride Content on Device Differential Gain With Respect to Concentration

To study the effect of QW nitride content on device differential gain with respect to carrier concentration, we performed the measurements of the relative intensity noise (RIN) in nitride-free and dilute-nitride lasers. The effective differential gain with respect to carrier concentration was determined from the experimental dependence of the electron–photon resonance frequency (f_R) on the device output power (P_0). The electron–photon resonance frequency is independent on the carrier lifetime since the QW concentration is pinned at threshold and determined by the device differential gain with respect to carrier concentration and the number of photons in the cavity; i.e., device output power. The approximate expression for the electron–photon resonance frequency is [12]

$$f_R^2 = \frac{1}{4\cdot\pi^2}\cdot\frac{1}{V}\cdot\frac{1}{h\nu}\cdot\frac{\mathrm{c}}{N_{\mathrm{eff}}}\cdot\frac{\alpha_m+\alpha_i}{\alpha_m}\cdot\Gamma\cdot\frac{\partial G}{\partial n}\cdot\left(1+\frac{\tau_{\mathrm{DC}}}{\tau_{\mathrm{E}}}\right)^{-1}\cdot P_0 \quad (1)$$

where V is an active region volume, $h\nu$ is photon energy quantum, c is the velocity of light in vacuum, N_{eff} is the modal refractive index, Γ is the optical confinement factor, *dG*/*dn*-material differential gain with respect to carrier concentration, τ_{DC} is capture time of the carrier into QW including diffusion time, and τ_{E} is escape time from QW into waveguide. The experimental dependence of f_{R} on P_0 was obtained by measuring the RIN spectra at different currents after threshold.

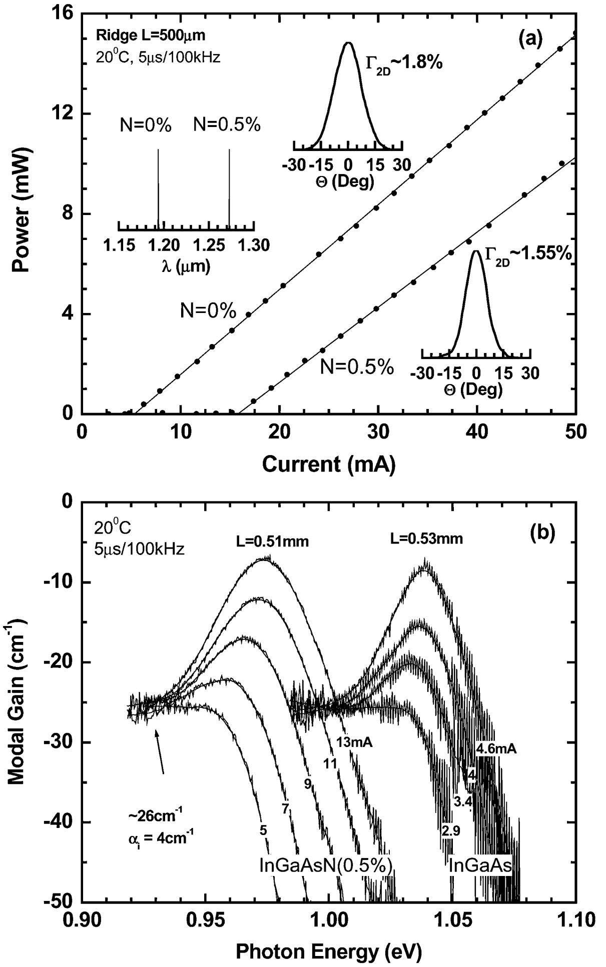

Fig. 3. (a) Light-current characteristics, laser spectra, and measured lateral far field patterns of ~2.5-μm-wide 0.5-mm-long uncoated ridge devices with two different nitride compositions in InGaAsN QW: 0%, 0.5%. (b) Corresponding current dependences of the modal gain spectra.

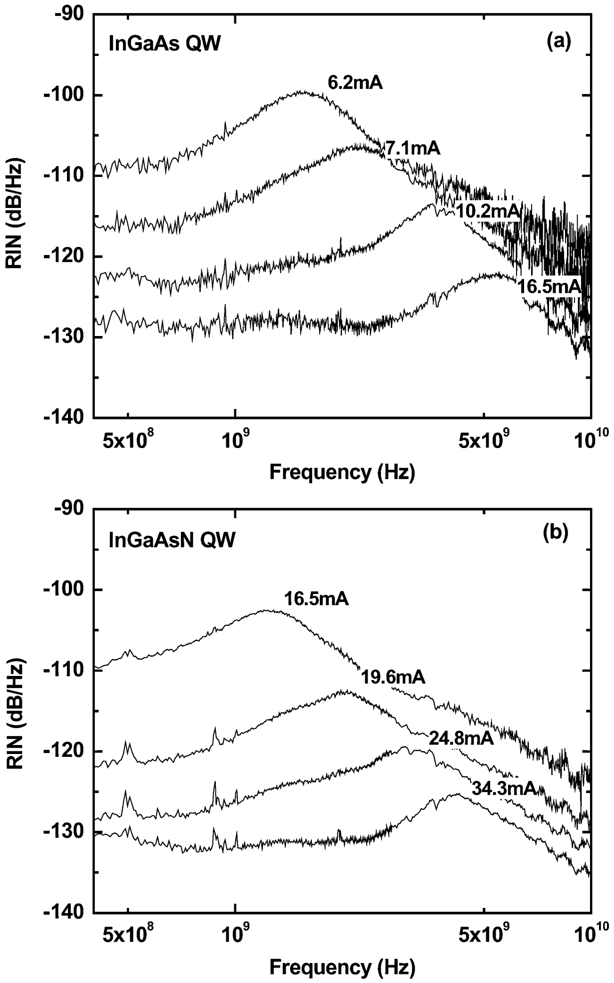

Fig. 4. Current dependences of the relative intensity noise spectra for several currents after threshold of ~2.5-μm-wide 0.5-mm-long uncoated ridge devices with two different nitride compositions in InGaAsN QW: 0%, 0.5%.

To determine the electron photon resonance frequency from experimental RIN spectra, the device emission should be spatially single mode. We used single spatial mode ridge lasers with 0% and 0.5% nitride in InGaAsN QWs. Devices were identical in heterostructure design to the one used for α-factor measurements. Wet chemical etching of the cladding material formed ridge waveguides. Scanning electron microscopy checked the output aperture size of the ridge lasers and the value found is about 2.6 μm. Fig. 3(a) shows the light-current characteristics of the single spatial mode ridge lasers. Far field patterns measured to verify the single spatial mode operation are shown in inserts. The threshold current density of the ridge devices was increased for dilute-nitride QW lasers like in broad stripe gain guided devices. Gain spectra and internal optical loss for ridge devices were measured by Hakki–Paoli technique [Fig. 3(b)]. Differential gain with respect to current was decreased about four times in dilute-nitride ridge lasers comparing to nitride-free ones. Internal optical losses are estimated as 4 cm^{-1} for both devices, which within experimental accuracy equals to internal optical losses determined for corresponding broad area lasers.

Fig. 4 shows the experimental RIN spectra for several currents above threshold for 1.19-μm nitride-free and 1.27-μm dilute-nitride laser. Electron–photon resonance frequencies at each current were determined by fitting of the RIN spectra [12], [13]. The rate of the shift of electron–photon frequency with output power characterizes the device *effective* differential gain. Fig. 5 plots the dependence of the electron–photon resonance frequency squared versus device output power. The ratio of the effective material differential gains (product of the dG/dn and $(1+\tau_{\rm DC}/\tau_{\rm E})^{-1}$) of nitride-free and dilute-nitride lasers is about 2. RIN measurements are insensitive to carrier lifetime. We conclude that the observed reduction of the differential gain in dilute-nitride devices has a fundamental contribution related to the QW band structure modification caused by nitrogen incorporation.

IV. EFFECT OF QW NITRIDE CONTENT ON ALPHA-FACTOR

Spectra of the α-factor for multimode devices with 0%, 0.5%, and 0.8% nitrogen in the QW were calculated using the spectral dependence of the modal refractive index, differential gain, and differential index with respect to current. All these spectra

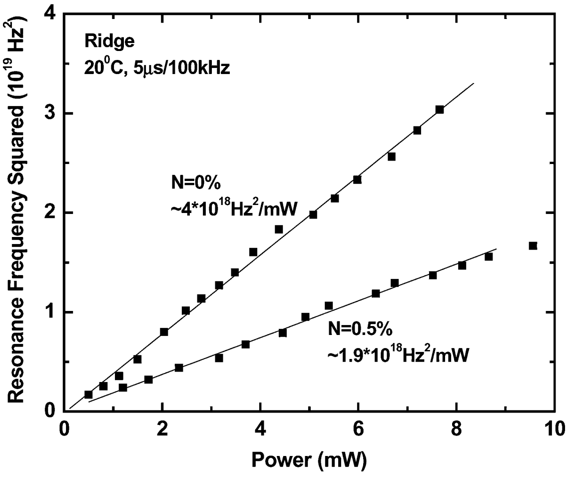

Fig. 5. Dependences of the electron–photon resonance frequency on laser output power for ~2.5-μm-wide 0.5-mm-long uncoated ridge devices with two different nitride compositions in InGaAsN QW: 0%, 0.5%.

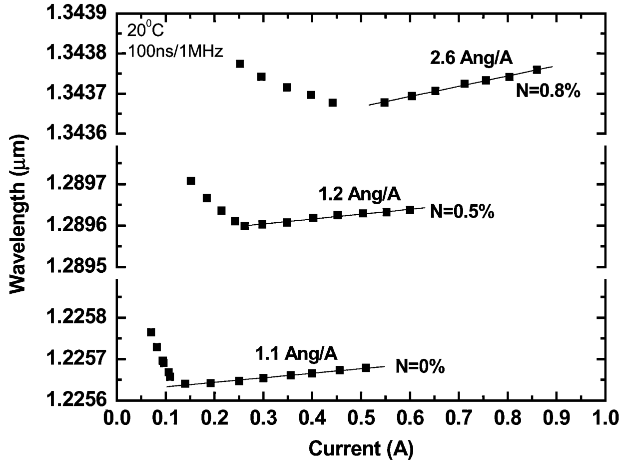

Fig. 6. Current dependences of the spectral shift of the Fabry–Perot mode below and after thresholds in 100-μm-wide 1-mm-long uncoated devices with three different nitride compositions in InGaAsN QW: 0%, 0.5%, and 0.8%.

were determined from the device amplified spontaneous emission spectra measured at several currents below threshold. The spectra of the differential gain with respect to current were obtained by subtraction of the modal gain spectra at two currents below threshold (Fig. 2). The corresponding differential index with respect to current was found through measurements of the relative shift of the Fabry–Pérot modes with injection current variations. Effect of the Joule heating was controlled by measuring the rate of the laser line shift after threshold. Fig. 6 shows the current dependence of the Fabry–Pérot fringe wavelength shift below and after threshold for devices with 0, 0.5, and 0.8% nitrogen content in the QW. The thermal contribution to the spectral shift as determined after laser threshold was linearly approximated and taken into account when α-factor was calculated.

Fig. 7 shows the spectral dependence of the α-factor for 100-μm-wide 1-mm-long uncoated lasers with 0, 0.5, and 0.8% nitrogen content in the QW. Laser spectra measured after threshold indicates values of the α-factor for each device at the laser wavelength. The threshold value of the α-factor is in the range 1.7–2.5 for all devices. The uncertainty in the determined values of the α-factor is rather large and determined mainly by limited spectral resolution of experimental apparatus (0.125 cm^{-1}). No dependence of the α-factor on nitride composition of QW can be observed within experimental error.

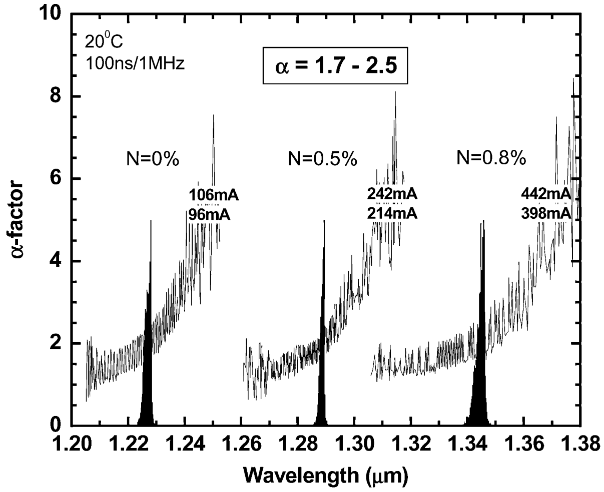

Fig. 7. Spectra of the linewidth enhancement factor of 100-μm-wide 1-mm-long uncoated devices with three different nitride compositions in InGaAsN QW: 0%, 0.5%, and 0.8%. Laser lines denote value of the α-factor near laser threshold.

V. CONCLUSION

The data in Fig. 2 data demonstrate that differential gain with respect to current is decreased several times in dilute nitride devices as compared to nitride free lasers. At the same time, the linewidth enhancement factor is independent on QW nitride content (Fig. 7). This means that the differential index changes with nitride content at the same rate as the differential gain. The decrease of the differential index with respect to current with increasing QW nitride content is illustrated in Fig. 6, which shows that the below threshold rate of the Fabry–Pérot fringe shift with current decreases with increasing QW nitride content, reflecting the fact that the device modal refractive index becomes less sensitive to current injection in dilute-nitride lasers.

One scenario explaining these experimental facts would be based on assumption that nitride incorporation introduces lattice defects. Lattice defects reduce Shockley–Reed–Hall carrier lifetime and decrease differential gain and index with respect to current. The spectra of α-factor are obtained through finding the ratio of differential modal index and differential modal gain spectra, both with respect to current. This ratio is not affected by changes of the carrier lifetime due to lattice defects and determined only by band structure of the QW material. Reduction of the carrier lifetime in the QW caused by lattice defects associated with nitride incorporation can also explain the increased threshold current in dilute-nitride lasers. This qualitative explanation does not take into account the effect of the nitride incorporation on QW band structure and, in turn, cannot explain the reduction of effective differential gain with respect to carrier concentration in dilute-nitride lasers as observed in RIN measurements (Fig. 5).

The nitride incorporation is expected to affect band structure significantly [2]. There are several experimental and theoretical reports suggesting a strong increase of the conduction band effective mass in dilute-nitride QWs and change of the valence band offset. The increased electron density of states would reduce asymmetry between conduction and valence band density of states bringing quasi-Fermi levels closer to band edges. Closeness of the quasi-Fermi levels to the band edges should reduce the energetical separation between gain and differential gain peaks; hence, α-factor at lasing wavelength can be reduced [12]. However, the reduction can be minor and not noticeable within our experimental error. Increase of the electron density of states should make the position of the electron quasi-Fermi level less sensitive to changes in electron concentration, thus decreasing device differential gain with respect to concentration. The observed reduction of the effective differential material gain with respect to concentration in dilute-nitride lasers can be explained by this consideration. Changes in the electron energy spectrum lead to modification of the refractive index and differential refractive index as well. Experiment shows that the α-factor is independent on QW nitride content, at least within experimental error. Independence of the measured α-factor on nitride content implies that reduction of differential modal gain with respect to concentration should be accompanied by nearly proportional reduction of differential modal refractive index with respect to concentration.

Carrier transport issues complicate the quantitative analysis of the effect of the QW nitride content on differential gain with respect to carrier concentration. It was shown in [7] that increase of the InGaAsN QW nitride content could reduce the valence band offset energy. Thermionic escape time (τ_E) of holes from QW into waveguide is reduced for shallower quantum wells in valence band. Reduction of the τ_E changes the value of the effective differential gain as obtained from RIN measurements (1). Thermionic escape of holes can be easily eliminated by proper adjustment of the barrier material composition directly around the QW [14]. Utilization of the $\mathrm{GaAs}_{0.85}\mathrm{P}_{0.15}$ or $\mathrm{GaAs}_{0.67}\mathrm{P}_{0.33}$ barriers directly adjacent to the QW was shown to effectively suppress carrier leakage leading to superior device temperature performance [15].

In summary, we have studied experimentally the effect of QW nitride content on gain, loss, differential gain, and α-factor in near-1.3-μm dilute-nitride GaAs-based lasers. The measured values of linewidth enhancement factor are in the range 1.7–2.5 and are independent on QW nitride content within experimental error. Relatively low value of α-factor in dilute-nitride GaAs-based near-1.3-μm lasers can be accounted for by the high quantum well compressive strain ($>2.5\%$). The differential gain and index with respect to current steadily decreases with QW nitride content while internal optical loss stays almost unchanged. Experiment shows that the increase of the threshold current density and reduction of the differential gain and index with respect to current in dilute-nitride GaAs-based lasers has a fundamental contribution and can be explained, in part, by nitride related band structure modifications.

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