

# Effect of nitrogen on gain and efficiency in InGaAsN quantum-well lasers

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We compare the gain and radiative efficiency characteristics of an InGaAsN and an InGaAs laser structure where the devices are identical except for the nitrogen content and emission wavelength. We find that the inclusion of nitrogen has little impact on the gain spectra except for the required shift to longer wavelength and that the intrinsic gain-radiative current characteristics may be slightly better for the nitrogen-containing materials. The radiative efficiency is reduced by a factor of 4 in the samples containing nitrogen due to increased nonradiative recombination. © 2005 American Institute of Physics. [DOI: 10.1063/1.1868070]

Semiconductor lasers with InGaAsN quantum-well active regions grown on GaAs substrates are of much interest for near 1.3  $\mu\text{m}$  emission wavelength devices.<sup>1</sup> It is well known that the addition of nitrogen to InGaAs increases the emission wavelength but the resulting properties of the conduction band states and the effect of these upon the gain and recombination spectra have not been evaluated experimentally in any detail. In addition, either the presence of nitrogen or the growth conditions necessary for nitrogen incorporation is thought to increase the number of nonradiative centers within the material. In this work we examine the effect of the incorporation of nitrogen on the gain and recombination processes by measuring the gain spectra, optical mode loss, and spontaneous recombination rate as a function of quasi-Fermi level separation for two, single quantum well, laser structures that contain either  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$  or  $(\text{In}_{0.4}\text{Ga}_{0.6})\text{As}_{0.995}\text{N}_{0.005}$ . The structures, which are otherwise identical, were grown by low pressure MOCVD and growth details are given in Ref. 2. The approach taken for the design of these samples follows that of Sato *et al.*,<sup>3</sup> where a high indium content is used along with as small a nitrogen content as possible to push the wavelength toward 1.3  $\mu\text{m}$ . We do not expect significant differences in the samples because of strain effects since the nitrogen content is small, however both samples are highly compressively strained ( $\Delta a/a \sim 2.5\%$ ) because of the large indium content. Therefore strain compensating  $\text{GaAs}_{0.85}\text{P}_{0.15}$  barriers, offset from the quantum well by 10 nm GaAs spacer layers, are also included. The development of these structures is reported in Ref. 4. The layer structure is summarized in Fig. 1 and both samples have a calculated optical confinement factor of 1.7%. No postgrowth annealing was used.

We measured, in real units, the absorption, gain, and spontaneous emission spectra using single pass, segmented contact amplified emission measurements.<sup>5</sup> This approach allows us to separately measure transverse electric (TE) polarized and transverse magnetic (TM) polarized contributions

and we note that the TM polarized emission is negligible for both samples even at the highest injection levels indicating that, as expected, both have highly compressively strained quantum wells. The measured optical loss (absorption and internal optical mode loss) spectra are shown in Fig. 2. The absorption spectrum of the InGaAsN sample is shifted to longer wavelengths as expected (the 50 meV shift in the emission for 0.5% nitrogen agrees with the widely quoted band gap shift of 100 meV per % of nitrogen).<sup>6</sup> The internal optical mode loss,  $\alpha_i$ , was derived from the long wavelength part of both spectra where the absorption tends to zero and was found to be  $3.5 \pm 2$  and  $8 \pm 2 \text{ cm}^{-1}$  for the InGaAs and InGaAsN samples, respectively. Modal gain ( $G$ ) spectra are derived from the measured net modal gain data,  $G - \alpha_i$ , using these values of  $\alpha_i$  and are shown in Fig. 3 for both samples at three injection levels. In addition the amplitude of the peak gain versus peak gain wavelength is also plotted for these and other injection levels. Both the shape of the gain spectra and the peak modal gain versus peak modal gain wavelength data are quite similar for the two different samples although higher drive currents are required with the InGaAsN sample to achieve the same amplitude of peak modal gain as obtained with the InGaAs devices. In Fig. 4 the amplitude of the peak gain data of Fig. 3 is plotted versus the energy of the gain peak for the InGaAs sample and can be compared to a shifted version of the InGaAsN data, where the peak gain energies are shifted by 50.5 meV (the measured absorption spectra differ by 50.3 meV). In addition, the peak gain am-

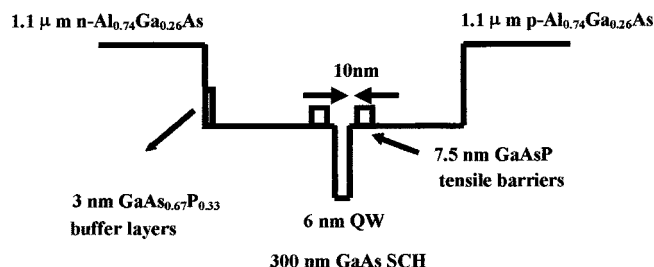


FIG. 1. Schematic diagram of structures.

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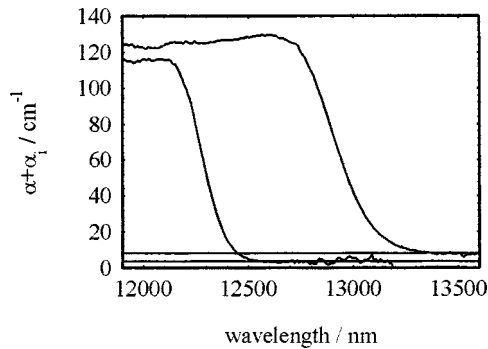


FIG. 2. TE polarized optical loss spectra.

plitude is also plotted versus the quasi-Fermi level separation, which is derived from the measured transparency point ( $G=0$ ) of each gain spectrum, for the two samples. The InGaAsN data in Fig. 4 have been shifted by 48.5 meV to make the two sets of data agree. Although the smaller shift of the transparency energy data as compared to the peak gain energy data might suggest that the InGaAsN sample has to be driven harder to achieve the same gain, the difference of 1.5 meV is within the experimental uncertainty.

The similarity of the data suggests that the addition of nitrogen, to first order at least, simply shifts the gain spectra to longer wavelengths. To evaluate this in more detail we determine the intrinsic gain-radiative current characteristics of the InGaAsN and InGaAs samples. The radiative current is obtained by using the measured spontaneous emission rate spectra in real units,<sup>5</sup> integrating and multiplying by the electronic change to find the current density associated with spontaneous radiative recombination events. The peak modal gain is plotted versus this radiative current density for the two samples in Fig. 5 and appears to be slightly better for the InGaAsN quantum well sample, albeit within the experimental uncertainty. A fit to the data using

$$G = G_0 \ln(J/J_0),$$

where  $G_0$  is the tangential gain parameter and  $J_0$  is the transparency current density, gives a value of  $G_0$  of  $29 \pm 2 \text{ cm}^{-1}$  for both the InGaAs and InGaAsN samples and  $J_0$  values of  $19 \pm 2$  and  $15 \pm 2 \text{ A cm}^{-2}$ , respectively. The superior intrinsic performance of InGaAsN has been predicted, due to the higher conduction band mass which is more similar to the valence mass in InGaAsN.<sup>7,8</sup> However, our results contained within Figs. 3–5 indicate that differences in the band struc-

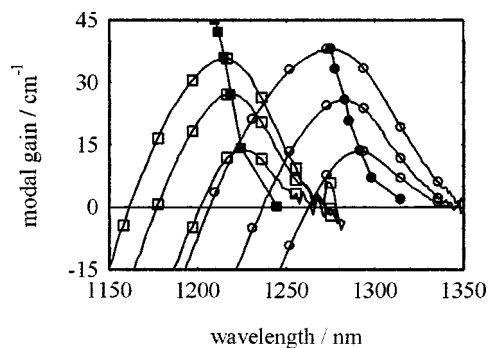


FIG. 3. TE polarized modal gain spectra for samples with (circles) and without (squares) nitrogen for three injection levels and peak gain amplitude vs wavelength of peak modal gain for other injection levels (closed symbols).

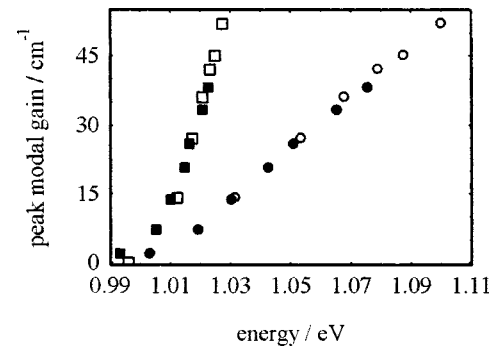


FIG. 4. InGaAs and InGaAsN peak gain vs peak gain energy (squares) and peak gain vs quasi-Fermi level separation (circles) where the InGaAsN data have been rigidly energy shifted by 50.3 and 48.5 meV, respectively, to allow comparison.

ture must be small for the low nitrogen contents used here.

Since the performance of InGaAs quantum well lasers can be excellent (e.g.,  $J_{\text{th}}=50 \text{ A/cm}^2$  at 980 nm,<sup>9</sup> and  $J_{\text{th}}=65\text{--}90 \text{ A/cm}^2$  at 1170–1233 nm,<sup>10,11</sup> an InGaAsN laser with the same performance as the InGaAs device but operating at telecom wavelengths would be an excellent outcome. However, the inclusion of nitrogen does degrade the *measured* radiative efficiency of the structures. The radiative efficiency is obtained by dividing the measured radiative current density by the total drive current density supplied to the device. We find that the measured radiative efficiency of the InGaAsN devices is reduced to about a quarter of that measured for the InGaAs samples. It is worth noting that the *measured radiative efficiency* of quantum well gain media is a multiplication of *current injection efficiency* (fraction of the injected current recombining in the quantum well) and the *radiative efficiency* of the quantum well itself. This difference in efficiency is due to an increase in the non-radiative recombination since Fig. 2 suggests that the absorption is similar for the two materials and Figs. 3–5 show that the radiative processes are similar for the two structures. A qualification to this is that the similarity of the gain versus quasi-Fermi level separation data, when the differences in the band gap of the materials are taken into account as shown in Fig. 4, or the similarity of the gain-radiative current density characteristics does *not* preclude the possibility that the carrier densities necessary to achieve the gain and radiative characteristics in the structures are different (as would be the case if the conduction band masses were different). However, such a

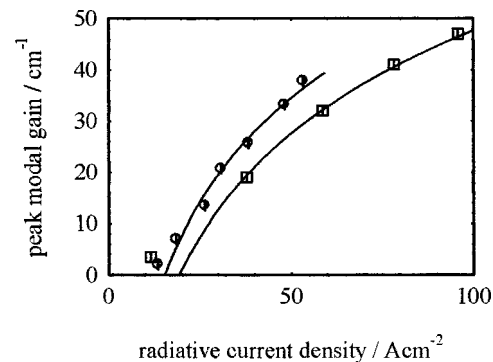


FIG. 5. Measured TE polarized peak gain vs spontaneous radiative current density for samples with (circles) and without (squares) nitrogen. The lines are the standard logarithmic function used for quantum wells fitted to the data.

difference cannot be large as the gain spectra have similar shape. The most likely origin of increased nonradiative recombination is a combination of an increased defect density in the material and reduced current injection efficiency, although we do not rule out changes in the Auger processes due to changes in the band structure at higher energies which we have not probed with these measurements.

In summary we have described the affect of nitrogen incorporation on the gain spectra and recombination processes. We found that the inclusion of nitrogen had little impact on the gain spectra except for the required shift to longer wavelength and that the intrinsic gain-radiative current characteristics may be slightly better for the nitrogen-containing materials although the differences are within the experimental uncertainties in these samples with very low nitrogen content. The radiative efficiency was reduced by a

factor of 4 in the samples containing nitrogen due to increased nonradiative recombination.

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