Low-threshold 1317-nm InGaAsN quantum-well lasers with GaAsN barriers

Nelson Tansu[a)]
Center for Optical Technologies, Department of Electrical and Computer Engineering, Lehigh University, Sinclair Laboratory, 7 Asa Drive, Bethlehem, Pennsylvania 18015

Jeng-Ya Yeh and Luke J. Mawst
Reed Center for Photonics, Department of Electrical and Computer Engineering, University of Wisconsin-Madison, 1415 Engineering Drive, Madison, Wisconsin 53706

(Received 7 February 2003; accepted 1 August 2003)

Very low threshold-current-density InGaAsN quantum-well lasers with GaAsN barriers, grown using metalorganic chemical vapor deposition, have been realized with a room-temperature emission wavelength of 1317 nm. The GaAsN barriers are employed to extend the wavelength, to strain compensate the quantum well, and to improve the hole confinement inside the quantum well. RT threshold current densities of only 210–270 A/cm^2 are measured for InGaAsN quantum-well lasers (L_{cav}=1000–2000 μm) with an emission wavelength of 1317 nm. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1613998]

Conventional choices of active region for 1300-nm diode lasers are based on the InGaAsP or InGaAlAs quantum-well (QW) material systems on InP substrates.[1,2] The poor temperature characteristic of these conventional approaches[1,2] has led to increasing effort in pursuing InGaAsN QWs,[3–15] as well as other active regions, to realize high-performance 1300-nm diode lasers on GaAs for high-temperature operation. Kondow and co-workers[3] introduced the InGaAsN material system as a material system with enormous potential for realizing light emitters on GaAs in the wavelength regime of interest for optical communications, namely, 1300–1550 nm. Recent promising results[4,6,7,9,11–14] have shown tremendous potential for InGaAsN QW lasers as an alternative material system to replace the conventional technology in the wavelength regime of 1300 nm. InGaAsN QW lasers have demonstrated impressive results for devices with emission wavelength slightly below or at 1300 nm.[3–15] Only two results of 1300-nm InGaAsN QW lasers with GaAsN barriers from Stanford University[10] and Tampere University of Technology,[13] both utilizing molecular-beam epitaxy (MBE), have been realized with reasonably good lasing performance at emission wavelengths beyond 1315 nm. The utilization of GaAsN barriers surrounding the InGaAsN QW has been pursued previously by several other groups utilizing MBE technology.[11–13] Most of these pursuits have the intention of achieving slightly longer emission wavelengths beyond 1300 nm, by reducing the quantum confinement effect. An additional benefit from the utilization of tensile-strained GaAsN barriers is the strain compensation of the highly compressively strained InGaAsN QW.

The method that we pursue here is to utilize an InGaAsN QW lasers with GaAsN barriers grown by metalorganic chemical vapor deposition (MOCVD). In addition to a reduction in the quantum confinement effect, we also find improvements in the lasing characteristics at elevated temperatures, presumably as a result of stronger hole confinement.

All the laser structures reported here are realized by low-pressure MOCVD. The group-III precursors are the trimethyl sources of Ga, Al, and In. The group-V precursors are AsH_3 and PH_3. The n- and p-dopants are SiH_4 (2% in H_2) and diethylzinc, respectively. The N precursor is unsymmetrical-dimethylhydrazine. The design of the laser structure is shown in Fig. 1, with the active region composed of a 60-Å $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW surrounded by 35-Å $GaAs_{0.97}N_{0.03}$ tensile-strained barriers on each side. The composition of the InGaAsN QW and GaAsN barriers was determined using high-resolution x-ray diffraction and secondary ion-mass spectroscopy. The active region and GaAsN barrier regions are embedded symmetrically inside a 3000-Å undoped-GaAs optical confinement region, resulting in an optical confinement factor of 1.7%. The QW, barrier regions and optical confinement regions are grown at a temperature of 530 °C. The bottom and top cladding layers are composed of n- and p-$Al_{0.74}Ga_{0.26}As$ layers, respectively, with a doping level of 1×10^{18} cm^{-3}. The growth temperatures for the bottom and top cladding layers are 775 and 640 °C, respectively. Both the top and lower cladding layers have thicknesses of 1.1 μm. Thermal annealing of the InGaAsN QW is conducted during the growth of the top cladding layer for duration of 27 min. A tensile-strained buffer layer consisting

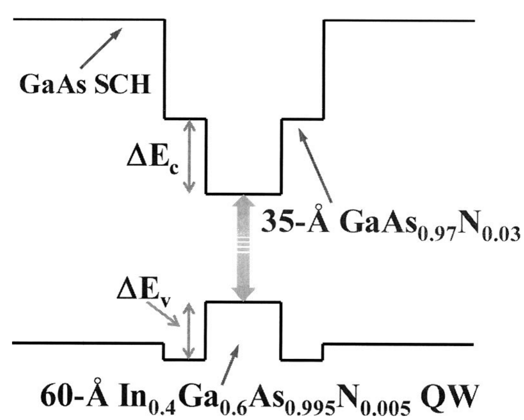

FIG. 1. Schematic band diagram of the $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW active region with $GaAs_{0.97}N_{0.03}$ barriers.

[a)]Electronic mail: tansu@lehigh.edu

0003-6951/2003/83(13)/2512/3/$20.00

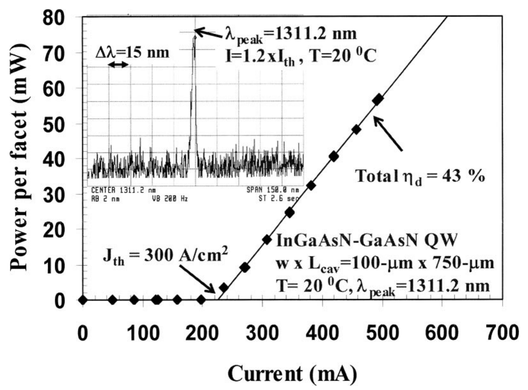

FIG. 2. The relation of output power per facet (P) and the total injected current (I) for $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW lasers with $GaAs_{0.97}N_{0.03}$ barriers ($L_{cav}=1500$ μm) at a temperature of 20 °C. The inset shows the lasing spectrum at 20 °C.

of 30-Å $GaAs_{0.67}P_{0.33}$, as described in Ref. 7, is also inserted between the n-AlGaAs lower cladding layer and the undoped-GaAs optical confinement layer. The contact layer consists of a 250-nm-thick p^+-GaAs layer with doping level of approximately 1×10^{20} cm^{-3} (carbon-doped).

Broad area lasers are fabricated with a stripe width of 100 μm, which is defined from etching a SiO_2 layer deposited on top of the p^+-GaAs layer. The metal contacts are realized with 250-Å Ti/500-Å Pt/1500-Å Au and 200-Å Ge/1000-Å GeAu/500-Å Ni/3000-Å Au for p- and n-contacts, respectively. The annealing of the metal contacts is accomplished under forming gas (10% H_2+90% N_2) at a temperature of 370 °C for duration of 30 s.

As-cleaved laser devices are characterized under pulsed conditions, with a pulse width of 5 μs and duty cycle of 1%, for various cavity lengths ranging from 750 to 2000 μm at room temperature ($T=20$ °C). The RT threshold current density and near-threshold lasing spectrum of an InGaAsN-GaAsN QW laser with a cavity length of 750 μm are measured as 300 A/cm^2 and 1311 nm, respectively, as shown in Fig. 2. A redshift of approximately 20–25 nm in emission wavelength was observed for the InGaAsN-GaAsN QW lasers compared to those of our previously reported InGaAsN-GaAs structures,[8] resulting in an emission wavelength of 1317 nm for devices with a cavity length of 1500 μm. Threshold current densities (J_{th}) of only 270, 230, and 210 A/cm^2 are measured for devices with cavity lengths of 1000, 1500, and 2000 μm, respectively. Total external differential quantum efficiency as high as 43–46% (420%–430 mW/A) was also obtained for devices with a cavity length of 750 μm. The internal loss and the above-threshold current injection efficiency of the InGaAsN-GaAsN QW lasers are measured as approximately 9 cm^{-1} and 70%, respectively.

The gain characteristics (g) of the InGaAsN QW lasers in these studies are assumed to follow the conventional semilogarithmic relation of $g_{th}=g_{oJ}\ln(\eta_{inj}J_{th}/J_{tr})$, with g_{oJ} defined as the material gain parameter. From measurements of devices with various cavity lengths, g_{oJ} and the transparency current density (J_{tr}) have been determined to be approximately 1320±50 cm^{-1} and 75±5 A/cm^2, respectively. The measured g_{oJ} and J_{tr} of the InGaAsN-GaAsN QW lasers reported here are comparable to those of InGaAsN QW lasers with GaAs barriers ($g_{oJ}\sim1150$–1200 cm^{-1} and J_{tr}

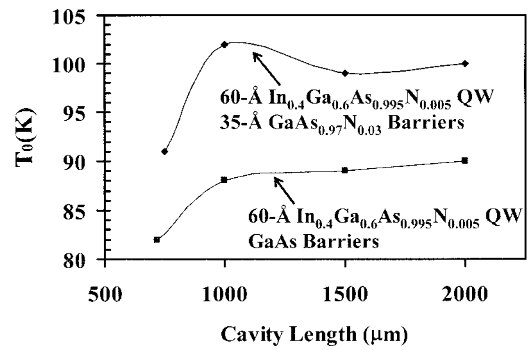

FIG. 3. The comparison of T_0 values, measured from temperature of 10 to 50 °C, for $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ QW lasers with $GaAs_{0.97}N_{0.03}$ barriers and GaAs barriers, for various cavity lengths.

$\sim$75–80 A/cm^2).[8] We find that the choice of the barrier material surrounding the InGaAsN QW is very important, affecting primarily the threshold characteristics of the lasers at elevated temperatures.

The characteristics of the InGaAsN-GaAsN QW lasers are measured from temperatures of 10 to 100 °C, with temperature steps of 5 °C. In the temperature range from 10 to 50 °C, the T_0 values $[1/T_0=(1/J_{th})dJ_{th}/dT]$ of these lasers are measured as high as 100 K for devices with cavity lengths of 1000 and 2000 μm, as shown in Fig. 3. From our measurements on devices with various cavity lengths, the threshold characteristic of these 1311–1317-nm InGaAsN-GaAsN QW lasers is less temperature sensitive by comparison to the 1290–1295-nm InGaAsN QW lasers with GaAs barriers.[8] The increase in T_0 values for the InGaAsN-GaAsN QW lasers, in comparison to those of InGaAsN-GaAs QW lasers, is not accompanied by any increase in threshold current, as shown in Fig. 4. Very low threshold current densities of only 550 (and 520) A/cm^2 and 715 (and 670) A/cm^2 are also achieved for InGaAsN-GaAsN QW lasers with cavity lengths of 1500 and 750 μm, respectively, at a temperature of 90 (and 85) °C. The lasing wavelength shift with temperature is found to be a linear function with a rate ($d\lambda/dT$) of approximately 0.39 nm/K, resulting in emission wavelengths beyond 1340–1345 nm for devices with a cavity length of 1500 μm at a temperature of 90 °C.

In earlier works,[11–13] aside from strain compensation, the

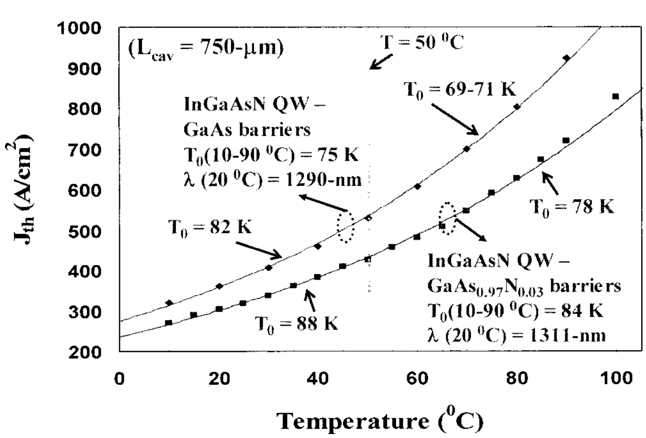

FIG. 4. Threshold current densities (J_{th}) of $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$-$GaAs_{0.97}N_{0.03}$ QW and $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$-GaAs QW lasers devices with cavity length of 1000 μm, as functions of temperature in the range of 10 to 90 °C.

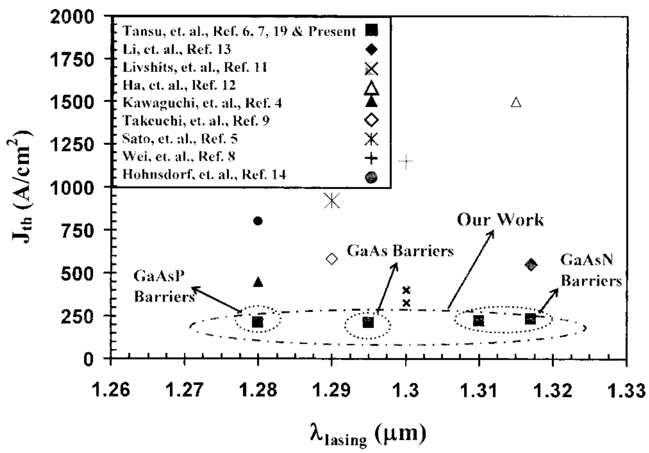

FIG. 5. Comparison of threshold current densities of InGaAsN QW lasers in the wavelength regimes of 1260–1330 nm.

motivation for using GaAsN barriers surrounding the InGaAsN QW is to reduce the quantum confinement effect, which in turn results in a redshifting of the emission from the QW. We demonstrate here that, in addition to the wavelength redshift, the utilization of GaAsN barriers surrounding the InGaAsN QW may also improve hole confinement in the QW, as is evident from the improved temperature performance. The slight type-II alignment of the GaAsN material system to the GaAs material system has been previously reported with a very small negative valence band offset (ΔE_v) of 15–20 meV/%N,[16–18] which would lead to a slight increase in the heavy-hole confinement (ΔE_v) in InGaAsN QW, as shown schematically in Fig. 1.

To place the results reported here in perspective, we plot the best-reported threshold current densities for various InGaAsN QW lasers[4,5–9,11–14,19] in Fig. 5. The previous lowest reported threshold current density of 546 A/cm^2 for InGaAsN QW lasers with a cavity length of 1600 μm at an emission wavelength of 1317 nm was realized by the group at Tampere University of Technology utilizing MBE technology.[13] Note that the threshold-current-density plots (in Fig. 5) for our various InGaAsN QW lasers are taken from devices with cavity lengths of 1000–2000 μm, which exhibit slightly lower values in comparison to the shorter cavity devices (shown in Fig. 4, for L_{cav}=750 μm).

In summary, we have realized $In_{0.4}Ga_{0.6}As_{0.995}N_{0.005}$ quantum-well lasers employing $GaAs_{0.97}N_{0.03}$ barriers, with room-temperature emission wavelength of 1311–1317 nm. Threshold current densities of approximately 300, 270, 230, and 210 A/cm^2 are measured for these devices for cavity lengths of 750, 1000, 1500, and 2000 μm, respectively. By changing only the barrier material from GaAs to GaAsN, we find improved device temperature characteristics in addition to a redshift in the emission wavelength. This improvement may be accounted for by the improved heavy-hole confinement in the GaAsN barrier structures. The weak dependency of the threshold current densities with emission wavelength for the range of 1280 to 1317 nm, also indicates potential for high-performance InGaAsN QW lasers with emission wavelengths even beyond 1320 nm.

[1] G. L. Belenky, C. L. Reynolds, Jr., D. V. Donetsky, G. E. Shtengel, M. S. Hybertsen, M. A. Alam, G. A. Baraff, R. K. Smith, R. F. Kazarinov, J. Winn, and L. E. Smith, IEEE J. Quantum Electron. **35**, 1515 (1999).
[2] P. Savolainen, M. Toivonen, P. Melanen, V. Vilokkinen, M. Saarinen, S. Orsila, T. Kuuslahti, A. Salokatve, H. Asonen, T. Panarello, R. Murison, and M. Pessa, in *Proceedings 11th IPRM 1999*, Davos, Switzerland, 1999, Paper MoP09.
[3] M. Kondow, T. Kitatani, S. Nakatsuka, M. C. Larson, K. Nakahara, Y. Yazawa, M. Okai, and K. Uomi, IEEE J. Sel. Top. Quantum Electron. **3**, 719 (1997).
[4] M. Kawaguchi, T. Miyamoto, E. Gouardes, D. Schlenker, T. Kondo, F. Koyama, and K. Iga, Jpn. J. Appl. Phys. **40**, L744 (2001).
[5] S. Sato, Jpn. J. Appl. Phys. **39**, 3403 (2000).
[6] N. Tansu and L. J. Mawst, IEEE Photonics Technol. Lett. **14**, 444 (2002).
[7] N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. Lett. **81**, 2523 (2002).
[8] J. Wei, F. Xia, C. Li, and S. R. Forrest, IEEE Photonics Technol. Lett. **14**, 597 (2002).
[9] T. Takeuchi, Y.-L. Chang, M. Leary, A. Tandon, H.-C. Luan, D. Bour, S. Corzine, R. Twist, and M. Tan, Electron. Lett. **38**, 1438 (2002).
[10] K. D. Choquette, J. F. Klem, A. J. Fischer, O. Blum, A. A. Allerman, I. J. Fritz, S. R. Kurtz, W. G. Breiland, R. Sieg, K. M. Geib, J. W. Scott, and R. L. Naone, Electron. Lett. **36**, 1388 (2000).
[11] D. A. Livshits, A. Yu. Egorov, and H. Riechert, Electron. Lett. **36**, 1381 (2000).
[12] W. Ha, V. Gambin, M. Wistey, S. Bank, S. Kim, and J. S. Harris, Jr., IEEE Photonics Technol. Lett. **14**, 591 (2002).
[13] W. Li, T. Jouhti, C. S. Peng, J. Konttinen, P. Laukkanen, E.-M. Pavelescu, and M. Pessa, Appl. Phys. Lett. **79**, 3386 (2001).
[14] F. Hohnsdorf, J. Koch, S. Leu, W. Stolz, B. Borchert, and M. Druminski, Electron. Lett. **35**, 571 (1999).
[15] N. Tansu and L. J. Mawst, IEEE Photonics Technol. Lett. **13**, 179 (2001).
[16] J. Wu, W. Shan, W. Walukiewicz, K. M. Yu, J. W. Ager III, E. E. Haller, H. P. Xin, and C. W. Tu, Phys. Rev. B **64**, 085320 (2001).
[17] B. Q. Sun, D. S. Jiang, X. D. Luo, Z. Y. Xu, Z. Pan, L. H. Li, and R. H. Wu, Appl. Phys. Lett. **76**, 2862 (2000).
[18] T. Kitatani, M. Kondow, T. Kikawa, Y. Yazawa, M. Okai, and K. Uomi, Jpn. J. Appl. Phys. **38**, 5003 (1999).
[19] N. Tansu, J. Y. Yeh, and L. J. Mawst, Appl. Phys. Lett. **83**, 2112 (2003).