Characteristics of InGaN–AlGaN Multiple-Quantum-Well Laser Diodes

David P. Bour, *Senior Member, IEEE,* Michael Kneissl, *Member, IEEE,* Linda T. Romano,
Matthew D. McCluskey, Chris G. Van deWalle, Brent S. Krusor, Rose M. Donaldson,
Jack Walker, Clarence J. Dunnrowicz, and Noble M. Johnson, *Senior Member, IEEE*

(Invited Paper)

***Abstract*—We demonstrate room-temperature pulsed current-injected operation of InGaAlN heterostructure laser diodes with mirrors fabricated by chemically assisted ion beam etching. The multiple-quantum-well devices were grown by organometallic vapor phase epitaxy on c-face sapphire substrates. The emission wavelengths of the gain-guided laser diodes were in the range from 419 to 432 nm. The lowest threshold current density obtained was 20 kA/cm^2 with maximum output powers of 50 mW. Longitudinal Fabry–Perot modes are clearly resolved in the high-resolution optical spectrum of the lasers, with a spacing consistent with the cavity length. Cavity length studies on a set of samples indicate that the distributed losses in the structure are on the order of 30–40 cm^{-1}.**

***Index Terms*—CVD, nitrogen compounds, quantum well lasers, semiconductor epitaxial layers, semiconductor heterojunctions, semiconductor lasers, semiconductor materials.**

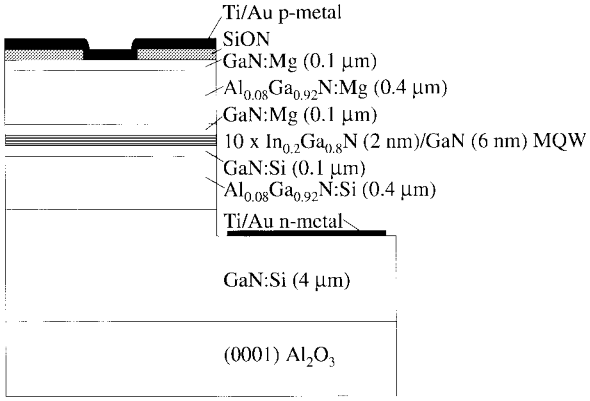


Fig. 1. Schematic diagram of the gain-guided InGaAlN laser diode heterostructure.

I. INTRODUCTION

THE RAPID development of efficient, visible light-emitting diodes (LED's) from nitride semiconductors has had a tremendous impact on many important systems technologies [1], [2]. For example, blue and green nitride LED's are now the basis of bright, full-color displays, when combined with existing red LED's. In this application, the efficiency and color purity of the LED's permit a very broad range of colors to be mixed, spanning a substantial portion of all perceived colors. Moreover, since white light can be generated through such color mixing, LED's are now also being considered for general illumination. Similarly, lasers of these primary colors may also be incorporated in full-color film printers and projection displays. Still another primary motivation for developing cheap, compact nitride semiconductor laser diodes is optical data storage, where a short wavelength translates into a small focussed spot size, as required for maximizing the density and transfer rate of stored data. Currently available DVD-ROM systems use red (650 nm) semiconductor lasers to increase the storage density compared to traditional near-infrared (780 nm) systems. Converting these systems to violet lasers ($\lambda \sim 400$ nm) would dramatically enhance performance, leading to capacity >10 Gbyte for a single DVD disk. High-resolution printing enjoys a similar advantage from short-wavelength lasers.

Over the past two to three years, blue semiconductor lasers have undergone tremendously rapid development at Nichia Chemical Industries [3]–[15]. Lifetimes exceeding 10 000 h have been projected for low-power (2 mW) single-mode self-pulsing lasers. These performance characteristics are suitable for incorporation in DVD-ROM systems; but higher powers are still required for DVD-recordable systems and for high-speed high-resolution laser printers. Accordingly, this paper is a description of our epitaxial growth, characterization, and processing of nitride materials and heterostructures, from which we have obtained room temperature, pulsed operation of nitride laser diodes.

II. OMVPE GROWTH AND NITRIDE MATERIAL CHARACTERIZATION

Nitride semiconductor films were grown by organometallic vapor phase epitaxy (OMVPE). Precursors included trimethyl-gallium, trimethyl-indium, and trimethyl-aluminum, triethyl-gallium (used for quantum-well growth), biscyclopentadienyl-

---

Manuscript received January 26, 1998; revised April 14, 1998. This work was supported in part by the Defense Advanced Research Projects Agency under Contract MDA972-96-0014 (Blue BAND II) and in part by the U.S. Department of Commerce under Contract 70NANB2H1241.

The authors are with the Electronic Materials Laboratory, Xerox Palo Alto Research Center, Palo Alto, CA 94304 USA.

Publisher Item Identifier S 1077-260X(98)05446-X.

1077–260X/98$10.00 © 1998 IEEE

magnesium, dilute (10 ppm) silane, and purified ammonia. Growth was performed over c-face (0001) sapphire substrates, beginning with a thin (30 nm) low-temperature (550 °C) GaN nucleation layer, as is typically described in the literature [1], [3], [6], [8]. The device structure, shown in Fig. 1, includes a 4-μm GaN:Si lateral n-contact layer, 0.4-μm $Al_{0.08}Ga_{0.92}N$ cladding layers, a $10 \times In_{0.2}Ga_{0.8}N$–GaN (2 nm/6 nm) multiple-quantum-well (MQW) active region surrounded by 0.1-μm GaN:Si, Mg waveguide layers, and a 0.1-μm GaN:Mg p-contact layer. To activate the p-type conductivity in the Mg-doped layers, an 850 °C, 5-min anneal was conducted, in a N_2 ambient [16].

Adequate levels of p-type doping are essential for successful operation of the device structure depicted in Fig. 1. We have performed a comprehensive theoretical investigation of acceptor doping in GaN, using first-principles calculations based on density-functional theory and *ab initio* pseudopotentials [17]. Incorporation of Mg on interstitial or substitutional nitrogen sites has often been invoked to explain limited hole concentrations; however, the calculations show that this type of incorporation is energetically unfavorable [18]. We found that the determining factor is the *solubility* of Mg in GaN, which is limited by competition between incorporation of Mg acceptors and formation of Mg_3N_2.

We have also performed an extensive computational investigation of other acceptor impurities in GaN [19]. None of the candidate impurities (Na, Li, Be, Ca, Zn, and C) exhibit characteristics superior to Mg. Only Be has a comparable solubility and potentially lower ionization energy. Be doping is likely to be severely hampered, however, by incorporation of Be donors on interstitial sites. A certain degree of compensation by native defects does occur in p-type GaN, in particular by nitrogen vacancies; however, such compensation is significantly suppressed in the presence of hydrogen [20]. Compensation by nitrogen vacancies becomes increasingly severe with increasing Al content in AlGaN alloys [21]. In addition, we calculate an increase in the ionization energy of the Mg acceptor with increasing Al content. These factors explain the increased difficulty in p-type doping of AlGaN.

In addition to p-type doping, the structural and optoelectronic quality of the InGaN MQW active region is critically important in achieving nitride laser operation. The structural quality of the InGaN QW's of a laser diode structure is apparent in the transmission electron microscope (TEM) image shown in Fig. 2. The layer thicknesses are uniform, with sharp interfaces between the InGaN QW's and GaN barriers. From this micrograph, the layer thicknesses are determined to be 2 nm for the InGaN well layers, and 6 nm for the GaN barriers. From the TEM image, there is no evidence of InGaN phase segregation, although the existence of minor composition fluctuations cannot be ruled out [22]–[27].

Likewise, X-ray diffraction from InGaN MQW's also suggests that for these compositions and thicknesses used for laser diodes, alloy segregation is not significant. Fig. 3 shows the X-ray diffraction spectrum of an MQW active region, like that which has been incorporated into InGaN laser diodes (but with no AlGaN cladding layers). This structure contains ten 20-Å $In_{0.2}Ga_{0.8}N$ QW's, separated by 50-Å GaN barriers. Evidence of the layer uniformity is indicated by coherent reflections from the periodic multilayers comprising the active region, which give rise to visible ($\pm$)first, ($-$)second, and ($-$)third-order satellite peaks in the XRD spectrum. The presence of these peaks in the XRD spectrum demands that the layer compositions and thicknesses be uniform and periodic, which would not be the case if the InGaN were highly segregated. The spacing of the satellite peaks indicates the period of the superlattice active region to be about 70 Å. Likewise, the absolute position of the 0th-order peak indicates the average InGaN composition to be $\sim In_{0.05}Ga_{0.95}N$.

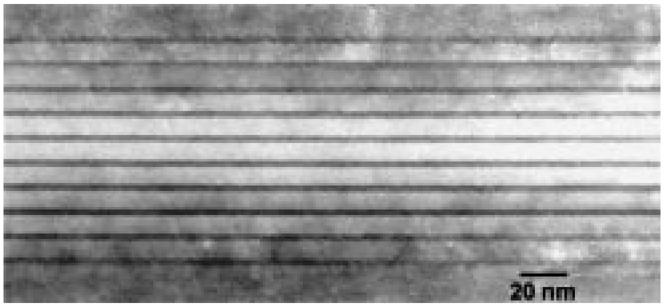


Fig. 2. Transmission electron microscope image showing the MQW active region of an InGaN–GaN laser diode structure.

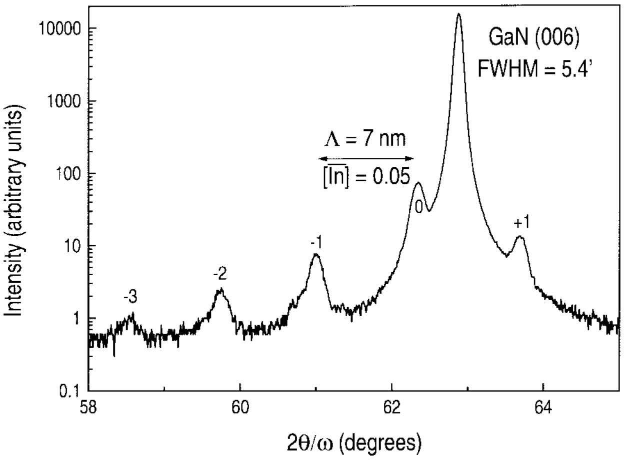


Fig. 3. (006) X-ray diffraction pattern of a InGaN–GaN MQW structure.

III. LED CHARACTERISTICS

The spectral purity and brightness of laser diode wafers, measured below threshold as LED's, is a useful diagnostic tool for rapidly assessing the quality of materials and heterostructures, with a structure that is much simpler to fabricate than a laser diode. Accordingly, simple, 250-μm dot LED's were fabricated from laser diode heterostructures by depositing Ti–Au p-contact metal, and dry-etching down to the 4-μm n-type GaN layer underlying the heterostructure, thereby defining 250-μm dots. Contact to the n-type semiconductor was made simply with a probe tip touching the exposed GaN:Si (no n-metal was deposited). The LED wafers were then probed and operated while lying on a quartz wafer, so that the emission through the substrate could be detected and analyzed. The pulsed power output (spontaneous emission) of a working

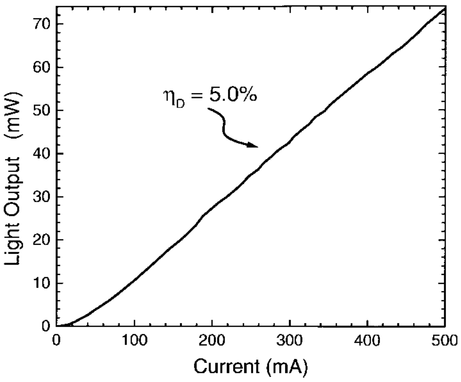


Fig. 4. *L–I* characteristic of a InGaN–GaN MQW laser diode structure tested as LED.

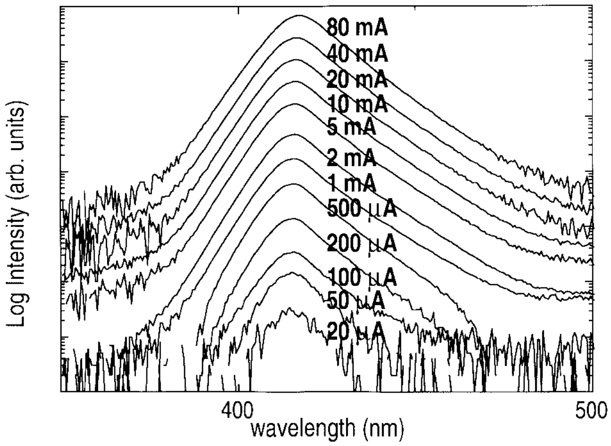


Fig. 5. Emission spectra of InGaN–AlGaN MQW LED at various injection currents from $20\,\mu\text{A} < I < 80$ mA.

InGaN–AlGaN 10-QW laser diode heterostructure, measured for this geometry where only the light emitted through the bottom of the wafer is detected, is shown in Fig. 4 as a function of the injection current. The bottom-emitted power exceeds 70 mW at 500 mA, with a differential quantum efficiency of 5%. This value indicates that the internal quantum efficiency of the InGaN MQW's is reasonably high.

The structural quality of the InGaN MQW's is also evident in the spectral purity of the spontaneous emission from a working laser diode heterostructure (this sample has a structure like that in Fig. 1, and contains ten 20-Å $In_{0.2}Ga_{0.8}N$–GaN QW's and $Al_{0.08}Ga_{0.92}N$ cladding layers). As shown in Fig. 5 for several values of dc bias, the spectrum is centered at 422 nm, and the full-width at half-maximum (FWHM) of the spectrum is ~16 nm. Most significantly, over more than three decades of dc injection current ($20\,\mu\text{A} < I < 80$ mA, corresponding to a current density $0.04 < J < 160$ A/cm^2), it is apparent that no large spectral shifts occur. Instead, only a gradual shift toward longer wavelength occurs at high currents, consistent with heating. This spectral purity with respect to injected carrier density indicates that the InGaN alloy active region composition is relatively uniform. In contrast, some structural deterioration (possibly, but not necessarily alloy segregation [27]) is evident when the QW's are made either thicker, with higher indium content, or more numerous. In these cases, structural defects are reflected in spectrally broad emission, which also undergoes large (sometimes discontinuous) shifts to shorter wavelengths as the injection current is increased. Thus, taken together with the TEM image (Fig. 2) and the X-ray diffraction (Fig. 3), the spectral purity of the spontaneous emission from these InGaN–AlGaN MQW laser diode samples indicates that InGaN alloy segregation has largely been avoided for the chosen QW composition, thickness and number of QW's.

IV. LASER DIODE CHARACTERISTICS

While there is no evidence that the InGaN comprising our MQW active region is segregated, we cannot eliminate the possibility of slight alloy segregation. Indeed, the spectra of Fig. 5 are still measurably broader (16-nm FWHM) than the emission from MQW's of lower indium content (8–10-nm FWHM for emission wavelengths 390–400 nm). This spectral broadening of long-wavelength (high-indium-content) nitride light emitters could indicate that the InGaN alloy active region is slightly nonuniform. Any alloy phase-separation may be significant for nitride laser operation, however, since it has been suggested that even very subtle InGaN segregation may play a critical role in the mechanism by which optical gain is produced in the nitrides [22]–[26]. In this situation, when the structural instability of the InGaN alloy leads to its segregation into regions of different compositions, the domains of high-indium-content material tend to confine injected carriers (quantum dots), as a consequence of their lower bandgap energy. Furthermore, unlike in red or IR lasers where excitons cannot survive at room temperature and under the high injected carrier densities associated with lasing, the optical gain in the nitrides may arise from exciton recombination [23]–[26]. Alternatively, the gain may be Coulomb-enhanced, where the attractive interaction between the electron and hole enhances both the optical gain and the rate of spontaneous emission [28], [29]. This situation represents a somewhat intermediate case between free carrier gain and pure excitonic gain. If the gain is excitonic, even slight InGaN composition variations could be significant, as they would induce weak potential fluctuations in the QW plane, leading to exciton localization [24]–[26]. At the opposite extreme, alloy segregation would also be influential even if the gain mechanism does not involve excitons, because these same potential fluctuations would similarly enhance the confinement of injected free carriers. Concerning the existence of InGaN segregation and quantum dots, and the influence of Coulomb-enhancement, excitons, and exciton localization, the understanding of nitride lasers is still immature.

In red and near-IR laser diodes, lowest threshold current is usually obtained with single-QW active regions. On the other hand, most nitride laser diodes incorporate a multiple QW active region in order to produce sufficient optical gain to reach threshold [3]–[6], [9]–[14]. This might be so for several reasons. First, InGaN QW's must be made very thin in order to maintain their structural quality [27]. Therefore, multiple QW's may be necessary to achieve the required spatial overlap (Γ) between the QW gain and the optical mode. Second, the highly dislocated nature of these epitaxial nitride films may give rise to high scattering loss [30], which must be overcome with additional optical gain. Finally, further losses may also arise from the inability to realize nitride waveguide heterostructures which completely contain either the injected carriers [31], [32] or the optical mode [15]. In this case, because the AlGaN cladding layers experience biaxial tension when grown over GaN or InGaN, they tend to crack. As a result, the cladding layer aluminum content and thickness are limited to values which may not completely contain the evanescent tail of the optical mode. Instead, some of the light is able to leak out of the guide, thereby contributing to outcoupling or absorption losses. In particular, light may be outcoupled from the waveguide, into the thick GaN underlying the heterostructure; or the optical mode may penetrate into the p-metal contact, where it is strongly absorbed. Consequently, producing sufficient optical gain to overcome these loss mechanisms, while still maintaining the InGaN's excellent structural integrity, has required multiple, thin QW's.

With respect to optical confinement, a cladding layer with high aluminum content is essential for maximizing the spatial overlap between the optical mode and the QW gain. This requirement, however must be traded off against the p-doping difficulties and the tendency to crack, both of which are problems associated with high-aluminum-content AlGaN films [15]. These difficulties could be avoided by eliminating the AlGaN cladding layers; and instead creating a waveguide with a large number of high-indium-content InGaN QW's in the active region. However, for a large number of QW's, it may become difficult to achieve good spatial overlap between the injected electron and hole distributions, since they are injected from opposite sides of the QW stack. Likewise, confinement of injected carriers would also suffer [31], [32]. Overall, there exist a multitude of tradeoffs that must be considered in the design of nitride laser structures.

We have observed pulsed laser oscillation at room temperature, with an InGaN–AlGaN multiple QW injection laser heterostructures, of the structure shown in Fig. 1. Gain-guided devices were fabricated using silicon oxy-nitride dielectric insulating layers, with stripe openings of 4, 10, or 20 μm. Both n- and p-contact metallizations were made using Ti–Au. Mirrors were etched using CAIBE (chemically assisted ion beam etching), to define cavity lengths of 300, 500, 800, or 1000 μm. In the CAIBE technique, the mechanical etching component (Ar–ion milling current and acceleration voltage) and the chemical etching component (Cl_2–BCl_3 reactive gas flows and wafer temperature) are independently adjustable. By optimizing these parameters, combined with the proper wafer tilt angle, vertical and smooth laser mirrors can be realized [14], [33]. Surface profiles of CAIBE-etched mirrors, measured using atomic force microscopy, reveal an root-mean-squared roughness of 4–5 nm. Based on optical pumping experiments, the reflectivity of these mirrors is estimated to be about 70% of the ideal value [14]. Presumably, some fraction of the incident light is scattered by the slight surface roughness, which is currently limited by the photoresist mask. In principle, more sophisticated, multilayer etch masks could be used to produce even smoother mirrors using CAIBE.

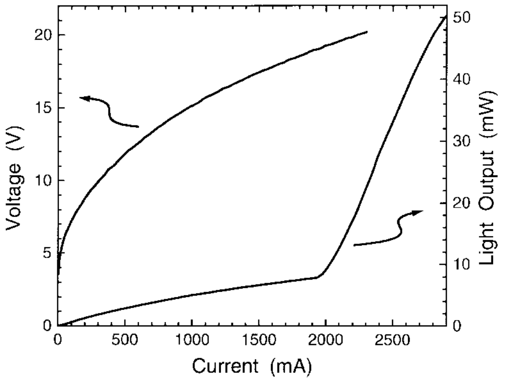


Fig. 6. Measured I–V and L–I output power for a 10×800 μm^2 laser diode (uncoated mirrors).

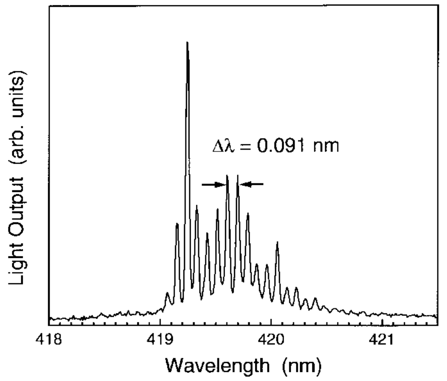


Fig. 7. High-resolution optical spectrum for a $4 \times 300 \mu m^2$ diode operating above threshold (I = 740 mA).

The light-output intensity (L) is shown as a function of the injection current (I) in Fig. 6, for a $10 \mu m \times 800 \mu m$ diode operated pulsed at room temperature (pulse width = 500 ns, repetition rate = 1 kHz), with uncoated mirrors. The L–I characteristic exhibits a threshold current of about 1.9 A, corresponding to a threshold current density of ~24 kA/cm^2. Using a calibrated silicon p-i-n diode detector, the peak power was measured to be 50 mW. This value probably represents a conservative estimate of the emitted power, because of the difficulty associated with collecting all the emitted light from an etched-mirror laser, where part of the beam is intercepted by the substrate. The emission was TE-polarized; and at threshold, the far-field emission pattern collapsed into a beam characteristic of an etched-facet laser. The beam was elliptical, with a divergence angle narrower in the junction plane than in the vertical direction. The transverse beam divergence was difficult to measure, however, because the transverse far-field pattern exhibited a strong modulation, arising from interference between the directly emitted beam and the component of the beam, which was reflected from the etched surface. The far-field was therefore very similar to that of the first nitride laser diode demonstrated by Nakamura *et al.*, which also had etched facets [3]. The voltage versus current (V–I) characteristic is also shown in Fig. 6. The threshold voltage is approximately 19 V.

An emission spectrum is shown in Fig. 7, for a $4 \mu m \times 300 \mu m$ device operated at 740 mA. The longitudinal Fabry–Perot mode spacing of 0.091 nm is consistent with the cavity length of 300 μm (giving a reasonable value of 3.22 for

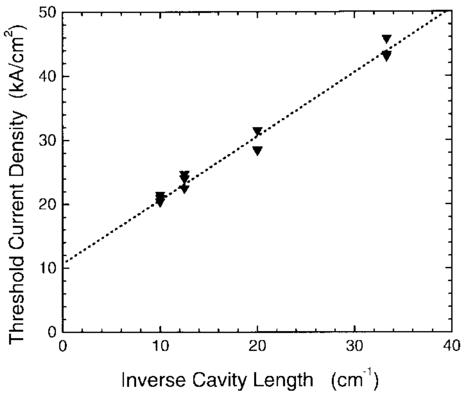


Fig. 8. Measured threshold current density for gain-guided InGaN–AlGaN laser diodes versus the inverse cavity length. The p-metal stripe width of the broad area test structures was 20 μm; mirrors are uncoated.

the dispersion-corrected index). Below threshold, the spectral width of the spontaneous emission was typically 15–20 nm.

The threshold current density was found to have a strong dependence on the cavity length (L). This is shown in Fig. 8 as a function of the inverse cavity length (since the mirror loss component of the total loss is proportional to L^{-1}), for lasers with 20-μm stripe width and uncoated mirrors. The threshold current density varies from 20 kA/cm^2 for $L^{-1} = 10$ cm^{-1} ($L = 1000\,\mu$m), to 44 kA/cm^2 for $L^{-1} = 33$ cm^{-1} ($L = 300\,\mu$m). This strong variation suggests that the distributed loss (α) is not so high as to overwhelm the mirror loss ($= L^{-1}\ln(R^{-1})$, where R is the mirror reflectivity); otherwise, the threshold current density would not exhibit a dependence on the cavity length. Since the mirror loss is approximately known, the distributed loss may be roughly estimated from the threshold current density measurements by assuming that the optical gain is simply proportional to the injection current. This assumption produces a straight-line fit to the threshold data (shown), from which the distributed loss is estimated to be $\alpha \sim$ 30–40 cm^{-1}. The lasers represented in Figs. 5–8 represent our lowest-threshold devices, with wavelength $\lambda \sim$ 420 nm. Among several laser wafers tested, however, lasing wavelengths as long as 432 nm were achieved, although with higher thresholds.

V. SUMMARY

We have achieved room-temperature pulsed operation of InGaAlN heterostructure laser diodes with mirrors fabricated by chemically assisted ion beam etching. The devices were grown by organometallic vapor phase epitaxy (OMVPE) on c-face sapphire substrates. The device structure contains ten 20-Å $In_{0.2}Ga_{0.8}N$–GaN QW's and $Al_{0.08}Ga_{0.92}N$ cladding layers. The structural quality of the InGaN MQW active region is evident in transmission electron micrographs, spectrally pure spontaneous emission, and satellite peaks appearing in the X-ray diffraction spectrum. The emission wavelengths of the gain-guided laser diodes were in the range from 419 to 432 nm. The lowest threshold current density obtained was 20 kA/cm^2 with maximum pulsed output powers of 50 mW. Longitudinal Fabry–Perot modes are clearly resolved in the high-resolution optical spectrum of the lasers, with a spacing consistent with the cavity length. Cavity length studies on a set of samples indicate that the distributed losses in the structure are in the order of 30–40 cm^{-1}.

ACKNOWLEDGMENT

The authors are pleased to acknowledge helpful discussions with R. D. Bringans and D. Hofstetter; and to thank F. Endicott and E. Taggart for technical support.

REFERENCES

[1] S. Nakamura, M. Senoh, N. Iwasa, and S. Nagahama, "High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes," *Appl. Phys. Lett.*, vol. 67, pp. 1868–1870, Sept. 1995.

[2] S. Nakamura, "A bright future for blue/green LED's," *IEEE Circuits Devices*, pp. 19–23, May 1995.

[3] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, "InGaN-based MQW-structure laser diodes," *Jpn. J. Appl. Phys.*, vol. 35, pp. L74–L76, 1996.

[4] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto, and H. Kiyoku, "Room-temperature cw operation of InGaN MQW structure laser diodes," *Appl. Phys. Lett.*, vol. 69, pp. 4056–4058, 1996.

[5] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto, and H. Kiyoku, "Ridge-geometry InGaN MQW structure laser diodes," *Appl. Phys. Lett.*, vol. 69, pp. 1477–1479, 1996.

[6] S. Nakamura, "InGaN-based blue laser diodes," *IEEE J. Select. Topics Quantum Electron.*, vol. 3, pp. 712–718, 1996.

[7] I. Akasaki, H. Amano, S. Sota, H. Sakai, T. Tanaka, and M. Koike, "Stimulated emission by current injection from an AlGaN/GaN/GaInN quantum well device," *Jpn. J. Appl. Phys.*, vol. 34, pp. L1517–L1519, 1995.

[8] I. Akasaki and H. Amano, "Widegap column-III nitride semiconductors for UV/blue light emitting devices," *J. Electrochem. Soc.*, vol. 141, pp. 2266–2271, 1994.

[9] K. Itaya, M. Onomura, J. Nishio, L. Sugiura, S. Saito, M. Suzuki, J. Rennie, S. Nunoue, M. Yamamoto, H. Fujimoto, Y. Kokobun, Y. Ohba, G. Hatakoshi, and M. Ishikawa, "Room temperature pulsed operation of nitride-based MQW laser diodes with cleaved facets on conventional C-face sapphire substrates," *Jpn. J. Appl. Phys.*, vol. 35, pp. L1315–L1317, 1996.

[10] A. Kuramata, K. Domen, R. Soejima, K. Horino, S. Kubota, and T. Tanahashi, "InGaN laser diode grown on 6H-SiC using low pressure MOVPE," in *Proc. Int. Conf. Nitride Semiconductors (ICNS-97)*, 1997, pp. 450–451.

[11] J. Edmond, G. Bulman, H. S. Kong, M. Leonard, K. Doverspike, W. Weeks, J. Niccum, S. Sheppard, G. Negley, and D. Slater, "Nitride-based emitters on SiC substrates," in *Proc. Int. Conf. Nitride Semiconductors (ICNS-97)*, 1997, pp. 448–449.

[12] M. P. Mack, A. C. Abare, M. Aizcorbe, P. Kozodoy, S. Keller, U. Mishra, L. A. Coldren, and S. P. DenBaars, "Room temperature pulsed operation of blue nitride based laser diodes," in *Proc. Int. Conf. Nitride Semiconductors (ICNS-97)*, 1997, p. 458.

[13] F. Nakamura, T. Kobayashi, T. Asatsuma, K. Funato, K. Yanashima, S. Hashimoto, K. Naganuma, S. Tomioka, T. Miyajima, E. Morita, H. Kawai, and M. Ikeda, "Room temperature pulsed operation of a GaInN MQW laser diode with an optimized well number," in *Proc. Int. Conf. Nitride Semiconductors (ICNS-97)*, 1997, p. 460.

[14] M. Kneissl, D. Hofstetter, D. P. Bour, R. Donaldson, J. Walker, and N. M. Johnson, "Dry-etching and characterization of mirrors on III-nitride laser diodes from chemically assisted ion beam etching," in *Proc. Int. Conf. Nitride Semiconductors (ICNS-97)*, 1997, pp. 462–463.

[15] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemoto, M. Sano, and K. Chocho, "Present status of InGaN/GaN/AlGaN-based laser diodes," in *Proc. Int. Conf. Nitride Semiconductors (ICNS-97)*, 1997, pp. 444–445.

[16] W. Götz, N. M. Johnson, J. Walker, D. P. Bour, and R. A. Street, "Activation of acceptors in Mg-doped GaN grown by MOCVD," *Appl. Phys. Lett.*, vol. 68, pp. 667–669, 1996.

[17] J. Neugebauer and C. G. Van de Walle, "Atomic geometry and electronic structure of native defects in GaN," *Phys. Rev. B*, vol. 50, p. 8067, 1994.

[18] ———, "Theory of point defects and complexes in GaN," in *Proc. Materials Research Soc. Symp.*, 1996, vol. 395, p. 645.

[19] ———, "Defects and doping in GaN," in *Proc. ICPS-23*. Singapore: World Scientific, 1996, p. 2849.

[20] ———, "Role of hydrogen in doping of GaN," *Appl. Phys. Lett.*, vol. 68, pp. 1829–1831, 1996.

[21] C. Stampfl and C. G. Van de Walle, "Doping of Al$_x$Ga$_{1-x}$N," *Appl. Phys. Lett.*, vol. 72, no. 4, Jan. 26, 1998.

[22] A. Wakahara, T. Tokuda, X. Dang, and S. Noda, "Compositional inhomogeneity and immiscibility of a GaInN ternary alloy," *Appl. Phys. Lett.*, vol. 71, pp. 906–908, Aug. 1997.

[23] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto, and H. Kiyoku, "Subband emissions of InGaN multi-quantum-well laser diodes under room-temperature continuous wave operation," *Appl. Phys. Lett.*, vol. 70, pp. 2753–2755, May 1997.

[24] S. Chichubu, T. Azuhata, T. Sota, and S. Nakamura, "Luminescences from localized states in InGaN epilayers," *Appl. Phys. Lett.*, vol. 70, pp. 2822–2824, May 1997.

[25] Y. Narukawa, Y. Kawakami, M. Funato, S. Fujita, S. Fujita, and S. Nakamura, "Role of self-formed InGaN quantum dots for exciton localization in the purple laser diode emitting at 420 nm," *Appl. Phys. Lett.*, vol. 70, pp. 981–983, Feb. 1997.

[26] M. Kuball, E. Jeon, Y. Song, A. Nurmikko, P. Kozodoy, A. Abare, S. Keller, L. Coldren, U. Mishra, S. DenBaars, and D. Steigerwald, "Gain spectroscopy of InGaN/GaN quantum well diodes," *Appl. Phys. Lett.*, vol. 70, pp. 2580–2582, May 1997.

[27] K. Hiramatsu, Y. Kawaguchi, M. Shimizu, N. Sawaki, T. Zheleva, R. Davis, H. Tsuda, W. Taki, N. Kuwano, and K. Oki, "The composition pulling effect in MOVPE grown InGaN on GaN and AlGaN and its TEM characterization," *MRS Internet J. Nitride Res.*, vol. 2, article 6, 1997.

[28] P. Rees, C. Cooper, P. Smowton, P. Blood, and J. Hegarty, "Calculated threshold currents of nitride- and phosphide-based quantum-well lasers," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 197–199, Feb. 1996.

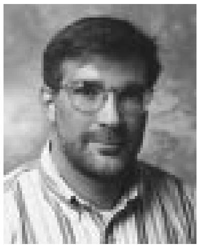
[29] W. Chow, A. Knorr, and S. Koch, "Theory of laser gain in group-III nitrides," *Appl. Phys. Lett.*, vol. 67, pp. 754–756, Aug. 1995.

[30] Z. Liau, R. L. Aggarwal, P. Maki, R. Molnar, J. Walpole, R. Williamson, and I. Melngailis, "Light scattering in high-dislocation-density GaN," *Appl. Phys. Lett.*, vol. 69, pp. 1665–1667, Sept. 1996.

[31] G. Hatakoshi, K. Itaya, M. Ishikawa, M. Okajima, and Y. Uematsu, "Short-wavelength InGaAlP laser diodes," *IEEE J. Quantum Electron.*, vol. 27, pp. 1476–1482, June 1991.

[32] A. Ishibashi, "II-VI blue-green laser diodes," *IEEE J. Select. Topics Quantum Electron.*, vol. 1, pp. 741–748, June 1995.

[33] M. Kneissl, D. P. Bour, N. M. Johnson, L. Romano, B. Krusor, R. Donaldson, J. Walker, C. Dunnrowicz, and R. Bringans, "Characterization of AlGaInN diode lasers with mirrors from chemically assisted ion beam etching," *Appl. Phys. Lett.*, vol. 72, pp. 1539–1541, Mar. 1998.



David P. Bour (S'84–M'85–SM'97) was born on May 2, 1961, in Pittsburgh, PA. He received the B.S. degree in physics from the Massachusetts Institute of Technology, Cambridge, in 1983, and the Ph.D. degree in electrical engineering from Cornell University, Ithaca, NY, in 1987, where he worked on OMVPE growth of AlGaInP red semiconductor lasers.

From 1987 to 1991, he worked on infrared AlGaAs and InGaAsP laser diodes as a member of research staff at the David Sarnoff Research Center (formerly RCA Laboratories, Princeton, NJ). Since 1991 he has been with Xerox PARC, working first on red laser diodes and arrays for printing; and more recently he established a nitride semiconductor film growth capability at Xerox, for deposition of material for blue semiconductor lasers. He is currently a Principal Scientist in the Electronic Materials Laboratory of the Xerox Palo Alto Research Center (PARC), Palo Alto, CA.

Michael Kneissl (M'98) was born in Schneckenlohe, Germany, in 1966. He received the Dipl.-Phys. degree and the Dr. rer. nat. degree, both in physics, from the University of Erlangen-Nürnberg, Germany, in 1992 and 1996, respectively. His graduate research work involved in the design, MBE growth and characterization of (In)GaAs–AlGaAs electrooptic modulator devices.

During his graduate studies, he was also a Visiting Scholar at the University of California, Berkeley, in 1993. At present he is a Member of Research Staff at the Xerox Palo Alto Research Center, Palo Alto, CA, where he is working on MOCVD growth, fabrication, and in particular dry-etching of III-nitrides using CAIBE, and characterization of AlGaInN laser diodes.

Linda T. Romano was born in New York, NY. Her undergraduate study started at Purdue University in West Lafayette, IN, in a cooperative Materials Engineering work program with Caterpillar Tractor Company, Peoria, IL. She received the B.S. degree in 1980 and the Ph.D. degree in 1987 from the University of Illinois, Urbana-Champaign, in materials science. Her Ph.D. dissertation involved the growth and characterization of sputter deposited metastable (III–V)$_{1-x}$ (IV$_2$)$_x$ alloys.

From 1987 to 1992, she was at Oxford University, Oxford, U.K., involved in structural studies of high-temperature oxide superconductors by transmission electron microscopy (TEM) in connection with the growth and electrical properties. At Oxford University, she also helped develop novel ways to use the techniques of Rutherford backscattering (RBS) and proton induced X-ray emisson (PIXE) for materials characterization. Since 1992, she has been at Xerox Corporation's Palo Alto Research Center working on materials for printing and laser applications. Currently, she is responsible for the structural characterization of nitride lasers with a major emphasis on transmission electron microscopy studies.

Matthew D. McCluskey received the B.S. degree in physics from the Massachusetts Institute of Technology, Cambridge, MA, in 1991 and the Ph.D. degree in physics from the University of California, Berkeley, in 1997. His Ph.D. research involved local vibrational mode spectroscopy of defects in semiconductors.

Since January of 1997, he has been a Research Associate at Xerox Palo Alto Research Center, where he is investigating the optical and structural properties of GaN-based heterostructures.

Chris G. Van de Walle received the degree of Engineer from the University of Ghent, Belgium, in 1982, and the Ph.D. degree from Stanford University, Palo Alto, CA, in 1986.

He is a Member of Research Staff at the Xerox Palo Alto Research Center, Palo Alto, CA. After a Post-Doctoral Fellowship at the IBM T. J. Watson Research Center, Yorktown Heights, NY (1986–1988), he was with Philips Laboratories in Briarcliff Manor, NY (1988–1991). His research activities address a wide variety of problems in materials physics using first-principles computations. He has performed extensive studies of semiconductor interfaces, including the development of a widely used model for band offsets. He also investigates defects and impurities in semiconductors, with particular emphasis on doping problems and on the role of hydrogen. Recently, he has been focusing on the III–V nitrides. He has authored over 120 scientific publications and holds two U.S. patents. He is a Divisional Associate Editor for *Physical Review Letters*.

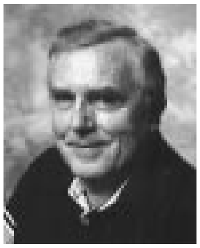
Dr. Van de Walle was a Fellow of the Belgian American Educational Foundation in 1982–1983. He chaired the 7th Trieste Semiconductor Symposium on Wide-Bandgap Semiconductors in 1992, the 23rd Conference on Physics and Chemistry of Semiconductor Interfaces in 1996, and is chairing the Gordon Research Conference on Point and Line Defects in Semiconductors in 1998. He is a Fellow of the American Physical Society.

Brent S. Krusor was born on May 4, 1951, in Lincoln, NE. He received the B.S. degree in chemistry from the Massachusetts Institute of Technology, Cambridge, MA, in 1973 and the M.S. degree in chemistry from the University of California, Berkeley, in 1977.

Since 1978, he has been with Xerox Palo Alto Research Center, Palo Alto, CA, where he is currently involved in the characterization of epitaxial thin films by high-resolution X-ray diffraction.

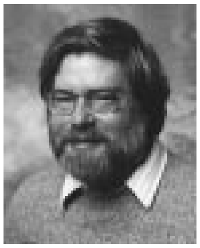
Rose M. Donaldson was born in Phoenix, Arizona, on January 7, 1954. She attended Mission College, Santa Clara, CA.

She began working at Data General, Sunnyvale, CA working on single crystal epitaxy, and the fabrication of semiconductors and integrated circuits. Since 1985, she has been with Xerox Palo Alto Research Center, Palo Alto, CA, where she has worked on a variety of novel device architectures, including independently addressable array lasers, heterojunction bipolar transistors, and vertical-cavity surface-emitting lasers.



Jack Walker received the B.A. degree in chemistry from Southwestern College, Winfield, KS, in 1957, and the M.S. degree in chemistry from Wichita State University, Wichita, KS, in 1960.

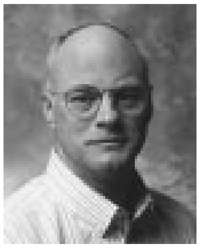
He began working at Texas Instruments Incorporated, Dallas, TX, in 1966 and was involved with vapor phase epitaxial growth of GaAs and GaAsP and liquid phase epitaxial growth of GaAs and GaP. In 1973, he joined Monsanto in Cupertino, CA, and was involved in all phases of liquid and vapor phase epitaxy of III–V materials and also in substrate growth and preparation of GaAs and GaP, and also in all phases of III-V LED fabrication. In 1981, he joined Xerox Palo Alto Research Center, Palo Alto, CA, where he has processed and characterized material for red laser diodes and is presently processing and characterizing materials for III–N laser diodes and LED's.



Clarence J. Dunnrowicz received the B.S. degree in physics from Worcester Polytechnic Institute, Worcester, MA, in 1973. His senior project involved the design and construction of a argon–ion laser and pulse-forming network.

From 1973 to 1980, he was employed at Raytheon Research where his primary focus involved the fabrication of surface-acoustic-wave (SAW) pulse compression devices and low-phase-noise oscillators for advanced radar systems. He is co-inventor of the "all-quartz package" concept for low aging, vibration insensitive SAW resonator-oscillators. From 1982 to 1996, he has been associated with various companies dealing with GaAs- and InP-based semiconductor devices for communications, sensing, and electronic warfare. Since joining Xerox Palo Alto Research Center (PARC), Palo Alto, CA, in 1996, he has been involved with edge emitters, vertical cavity surface emitting lasers, and novel high density interconnection schemes. He holds five patents, and has published in the areas of SAW and millimeter-wave devices.

Dr. Dunnrowicz is a member of SPIE/AVS.



Noble M. Johnson (S'66–M'73–SM'86) received the Ph.D. degree from Princeton University, Princeton, NJ, in 1974 under a National Defense graduate Fellowship.

From 1974 to 1976, he worked at SRI International, Menlo Park, CA, in the Radiation Physics Group of the Physical Sciences Division. In 1976, he joined the Xerox Palo Alto Research Center, Palo Alto, CA, as a Member of the Research Staff in the Electronic Materials Laboratory, where he is currently a Principal Scientist. He has conducted experimental research in the general areas of electronic materials and devices and particularly on the following: electronic defects in semiconductors (crystalline and amorphous), metal–insulator–semiconductor structures, deep-level transient spectroscopy, hydrogen in semiconductors, plasma-assisted synthesis of materials, and the development of InGaAlN materials for optoelectronic device applications. In 1986 (spring semester), he was a visiting lecturer at Princeton University.

In 1987, Dr. Johnson received a Distinguished U.S. Scientist Award from the Alexander von Humboldt Foundation, Germany, and in 1988, under the auspices of the Humboldt Foundation, he was in residence at the Institute for Applied Physics, University of Erlangen-Nürnberg, Germany. He is a Fellow of the American Physical Society and a member of the Materials Research Society (an elected member of the Advisory Council, 1986–1988).