Room-temperature continuous-wave operation of InGaN multiple-quantum-well laser diodes with an asymmetric waveguide structure

Michael Kneissl,[a] David P. Bour, Chris G. Van de Walle, Linda T. Romano, John E. Northrup, Rose M. Wood, Mark Teepe, and Noble M. Johnson
Xerox Palo Alto Research Center, 3333 Coyote Hill Road, Palo Alto, California 94304

(Received 14 May 1999; accepted for publication 1 June 1999)

Room-temperature continuous-wave (cw) operation is demonstrated with InGaN multiple-quantum-well laser diodes containing an asymmetric waveguide structure. Pulsed threshold current densities as low as 5.2 kA/cm^2 have been obtained for ridge-waveguide laser diodes grown on sapphire substrates by metal-organic chemical vapor deposition. For improved thermal management, the sapphire substrate was thinned and the devices were mounted *p* side up onto a copper heatsink. Under cw conditions at 20 °C, threshold current densities were 8.3 kA/cm^2 with threshold voltages of 6.3 V. The emission wavelength was 401 nm with output powers greater than 3 mW per facet. Under cw conditions, laser oscillation was observed up to 25 °C. The room-temperature cw operation lifetimes, for a constant current, exceeded one hour. © *1999 American Institute of Physics.* [S0003-6951(99)03430-0]

Since the first demonstration of an InGaN multiple-quantum-well (MQW) laser diode[1] enormous progress has been made with several groups having now demonstrated room-temperature continuous wave (cw) operation of InGaAlN laser diodes[2–5] and the currently most advanced devices operating at lifetimes greater than 10 000 h.[6,7] Commercialization of violet laser diodes was recently announced,[8] which target a wide range of applications particularly high-density optical data storage. In all of the present approaches a separate confinement heterostructure laser diode structure has been employed with approximately 100-nm-thick doped GaN waveguiding layers on top and bottom of the active region. A 200-Å-thick *p*-doped $Al_{0.2}Ga_{0.8}N$ tunnel barrier layer (TBL) on top of the InGaN MQW active region is used to supply the necessary carrier confinement in order to suppress electron leakage or to preserve the structural quality of the InGaN MQW stack. However, the growth and, in particular, the controlled *p* doping and thickness monitoring of such a thin and high aluminum containing layer is not straightforward within the boundaries of group III-nitride growth. In our approach we therefore have employed a different device structure, which is much easier to implement, using an asymmetric waveguide structure. In this approach the *p*-doped $Al_{0.08}Ga_{0.92}N$ cladding layer is grown directly on top of the InGaN MQW active region, which leaves out the *p*-doped GaN waveguiding layer and the *p*-doped $Al_{0.2}Ga_{0.8}N$ TBL. Consequently, the upper cladding layer provides the optical confinement and serves as a barrier for electron confinement at the same time. Our dielectric waveguide calculations using (MODEIG)[9] simulation software show a negligible reduction in optical confinement factor Γ in comparison with the more conventional device structure.[10] For a five quantum well active region the total optical confinement factor for the asymmetric waveguide is about 1.06% per QW, which is only slightly lower than the confinement factor of ~1.1% per QW for a conventional structure.

The InGaAlN films were grown on a-face sapphire substrate by metal organic chemical vapor deposition. Figure 1 is a schematic of the device structure. First, a 4-μm-thick, Si-doped GaN layer was grown, followed by a 0.1-μm-thick Si-doped $In_{0.03}Ga_{0.97}N$ defect reducing layer, a 0.5-μm-thick Si-doped $Al_{0.08}Ga_{0.92}N$ cladding layer and a 0.1-μm-thick Si-doped GaN waveguiding layer. The active region was formed with five $In_{0.1}Ga_{0.9}N/In_{0.02}Ga_{0.98}N$ quantum wells with a well width of 35 Å and a barrier width of 60 Å. The upper 0.5-μm-thick Mg-doped $Al_{0.08}Ga_{0.92}N$ cladding layer was then grown directly on top of the active region, followed by a 0.1-μm-thick, Mg-doped GaN contact layer. After metal-organic chemical vapor deposition (MOCVD) growth, a ridge waveguide was formed by etching into the $Al_{0.08}Ga_{0.92}N$ cladding layer with chemically assisted ion beam etching (CAIBE). Subsequently, mesas and mirrors for the edge-emitting laser diodes were fabricated also by using CAIBE.[11,12] Then metal contacts were deposited on the exposed *n*-type GaN layer for the lateral electrical connection and on the top *p*-type GaN layer (through openings in a silicon oxynitride overlayer). In order to reduce the mirror

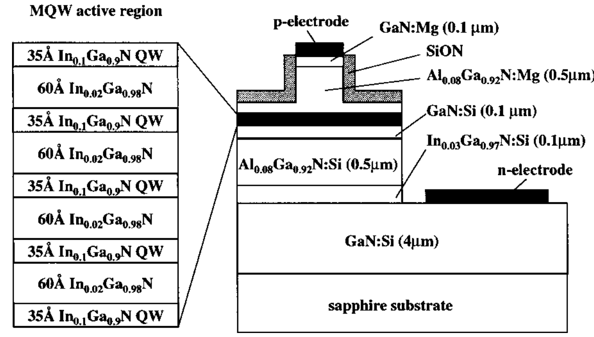

FIG. 1. Schematic diagram of the InGaN MQW laser diode with an asymmetric waveguide structure.

[a]Electronic mail: kneissl@parc.xerox.com

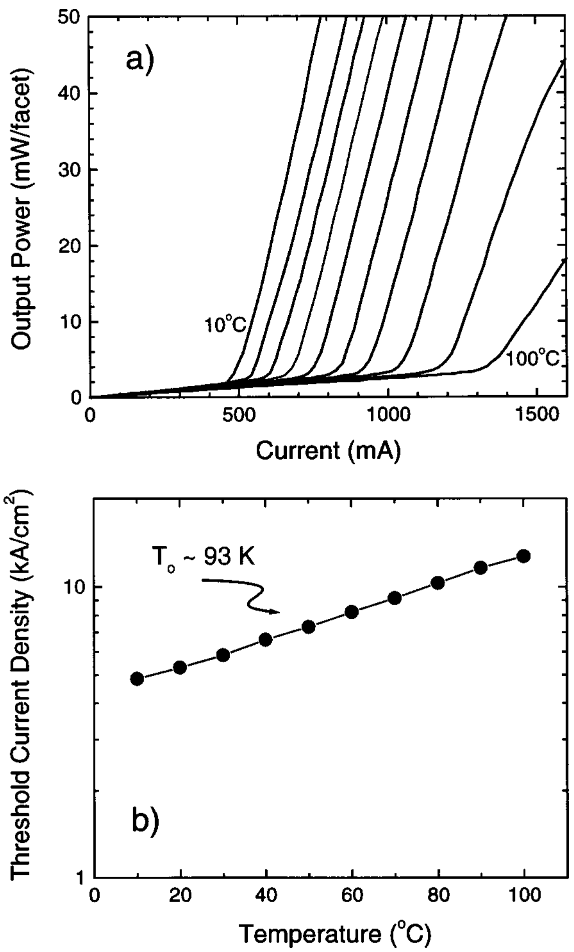

FIG. 2. (a) $L-I$ characteristic of a 10 μm$\times$1000 μm ridge waveguide laser diode under pulsed operation (pulse width 500 ns, repetition frequency 1 kHz) for a temperature range between 10 and 100 °C measured in increments of 10 °C. (b) Temperature dependence of the threshold current density. From the slope of the curve a characteristic temperature T_0 of 93 K is obtained.

loss, a high reflective dielectric coating was deposited on both mirrors. Finally, in order to evaluate the performance under cw conditions the sapphire substrate was thinned to about 100 μm and then the laser diodes were mounted *p* side up onto a copper heatsink.

Figure 2(a) shows the light output power versus current characteristics of a 10 μm$\times$1000 μm ridge-waveguide laser diode device operating under pulsed conditions (500 ns pulse width, 1 kHz repetition frequency). The temperature of the laser diode was controlled by adjusting the temperature of the heatsink in increments of 10 °C. Threshold current densities were as low as 5.2 kA/cm^2 at room-temperature under pulsed conditions. As can be seen laser operation was possible up to a device temperature of 100 °C. From the temperature dependence of the threshold current density, as shown in Fig. 2(b), a characteristic temperature T_0 of 93 K could be extracted in the vicinity of room temperature. This is slightly lower than the values we obtained in symmetric structures[13] or that have been reported by other groups,[4,14] which can be explained by the smaller barrier height of the Mg-doped $Al_{0.08}Ga_{0.92}N$ cladding layer compared to the barrier height provided by the *p*-doped $Al_{0.2}Ga_{0.8}N$ TBL. Nevertheless, T_0 was clearly high enough to allow room-temperature cw operation.

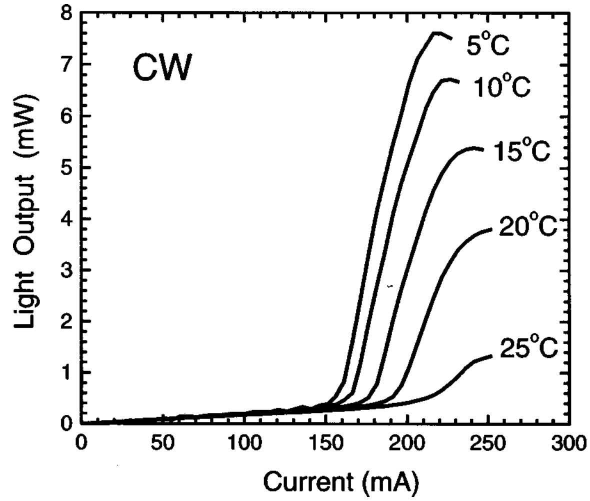

FIG. 3. $L-I$ characteristic of a 3 μm$\times$750 μm ridge waveguide laser diode under cw conditions for different temperatures.

Figure 3 shows the light output versus current characteristics of a 3 μm$\times$750 μm ridge-waveguide laser diode device operating under cw conditions for different heatsink temperatures. As can be seen cw laser operation was observed up to 25 °C. The cw threshold current at room temperature was 187 mA, corresponding to a threshold current density of 8.3 kA/cm^2. For the above T_0 this increase in threshold current density corresponds to a *pn*-junction temperature of about 65 °C. Figure 4 shows that light output power values greater than 3 mW per facet were obtained, which correspond to a differential quantum efficiency of 5.7% taking into account the combined output of both facets. The threshold voltages were ~6.3 V. Evaluation of the total power dissipation within the devices at threshold yielded a value of ~40 K/W for the thermal resistivity. This is also consistent with the thermal rollover point observed in the $L-I$ curves, which occurs when the *pn*-junction temperature reaches about 100 °C.

Figure 5 shows the room-temperature cw emission spectrum of the same laser diode device slightly above threshold. The full width at half maximum (FWHM) of the emission peak is about 0.2 Å, which is the limit of resolution of our spectrometer. Longitudinal Fabry–Perot modes are clearly resolved in the spectrum with a mode spacing of 0.30 Å.

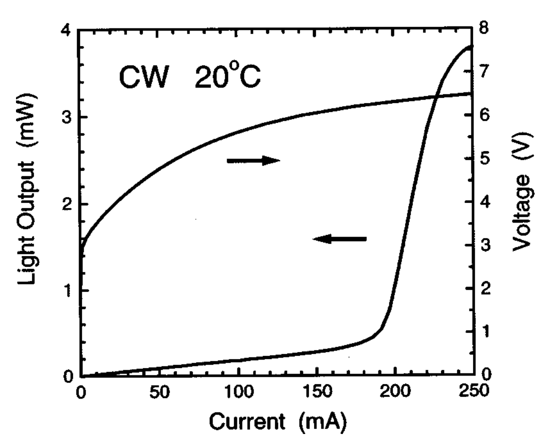

FIG. 4. $V-I$ and $L-I$ characteristic of a 3 μm$\times$750 μm ridge waveguide laser diode under cw operation at 20 °C.

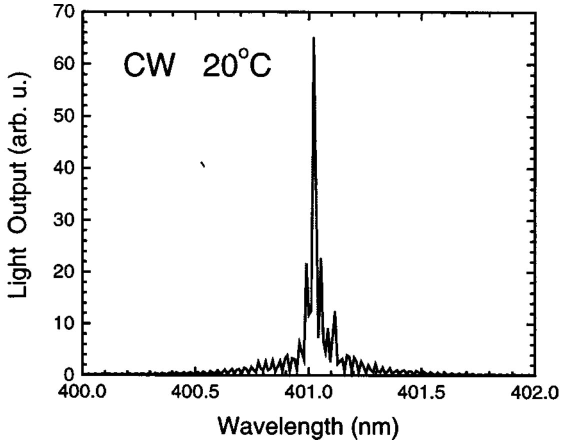

FIG. 5. Room-temperature cw emission spectrum of a 3 μm×750 μm ridge waveguide laser diode measured at a dc forward current of 190 mA.

This mode spacing yields an effective refractive index of 3.53. This value is somewhat larger than the refractive index for InGaN material but can be explained to be the strong dispersion near the band edge, the change in refractive index due to the high carrier density in this material, and increased device temperature at threshold.[15]

Figure 6 shows a lifetime measurement on a 3 μm×750 μm ridge-waveguide laser diode device with asymmetric waveguide structure operating under cw conditions at 20 °C. During the measurement the dc forward current was kept constant at 201 mA and the light output of the laser diode was recorded. Upon application of the dc forward bias the output power decayed rapidly (within 20–30 s) from about 0.9 mW to near 0.5 mW and then continued to degrade further at a much slower rate. We can attribute this initial drop in intensity to diode heating until the laser chip and the setup reach a steady state temperature. We were able to recover the device performance after stopping at the early stage of the lifetime test. However, the degradation of the device performance in the later stage of testing was irreversible, but no sudden failure or significant change in the current–voltage ($I-V$) characteristic was observed. The degradation mechanism is being investigated. Measurement of the emission spectrum and the $L-I$ characteristic showed that the device was still lasing after more than one hour of operation, however, the threshold current had increased and the differential quantum efficiency was reduced.

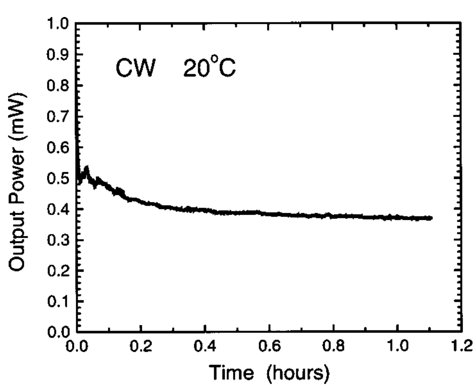

FIG. 6. Measured lifetime of a 3 μm×750 μm ridge waveguide laser diode under cw operation at 20 °C and a constant current of 201 mA.

In summary, we have demonstrated room-temperature cw operation of InGaN MQW laser diodes employing an asymmetric waveguide structure without a *p*-doped $Al_{0.2}Ga_{0.8}N$ TBL or a *p*-doped GaN waveguiding layer. The 3-μm-wide ridge-waveguide laser diodes with CAIBE etched facets exhibited cw threshold current densities of 8.3 kA/cm^2 and threshold voltages of 6.3 V. The emission wavelength was 401 nm with output powers greater than 3 mW per facet. The laser diode lifetimes exceeded one hour, a respectable number for entry-level cw operation.

The authors gratefully acknowledge technical assistance from Eva Taggart, Tanya Schmidt, and Fred Endicott. This work was partially supported by the Defense Advanced Research Projects Agency (DARPA) under Contract No. MDA972-96-0014.

[1] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, Jpn. J. Appl. Phys., Part 2 **35**, L74 (1996).
[2] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto, and H. Kiyoku, Appl. Phys. Lett. **69**, 4056 (1996).
[3] T. Kobayashi, F. Nakamura, K. Naganuma, T. Tojyo, H. Nakajima, T. Asatsuma, H. Kawai, and M. Ikeda, Electron. Lett. **34**, 1494 (1998).
[4] A. Kuramata, S. Kubota, R. Soejima, K. Domen, K. Horino, and T. Tanahashi, Jpn. J. Appl. Phys., Part 2 **37**, L1373 (1998).
[5] M. Kuramato, C. Sasaoka, Y. Hisanaga, A. Kimura, A. A. Yamaguchi, H. Sunakawa, N. Kureda, M. Nido, A. Usui, and M. Mizuta, Jpn. J. Appl. Phys., Part 2 **38**, L184 (1999).
[6] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, Appl. Phys. Lett. **72**, 211 (1998).
[7] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, Appl. Phys. Lett. **73**, 832 (1998).
[8] See, for example, article in The Nikkei Industrial Daily Tuesday Edition, 12 January 1999.
[9] PC and Macintosh versions of MODEIG may be downloaded from the website: http://www.seas.smu.edu/modeig.
[10] D. P. Bour *et al.* (unpublished).
[11] M. Kneissl, D. Hofstetter, D. P. Bour, R. Donaldson, J. Walker, and N. M. Johnson, J. Cryst. Growth **189/190**, 846 (1998).
[12] M. Kneissl, D. P. Bour, N. M. Johnson, L. Romano, B. Krusor, R. Donaldson, J. Walker, and C. Dunnrowicz, Appl. Phys. Lett. **72**, 1539 (1998).
[13] cw operation was also achieved with conventional symmetric waveguide structures, which displayed comparable performance characteristics with $T_0 \cong 116$ K and lifetimes greater than one hour, measured at a constant current.
[14] S. Nakamura and G. Fasol, *The Blue Laser Diode—GaN Based Light Emitters and Lasers*, 1st ed. (Springer, Berlin, 1997).
[15] H. X. Jiang and J. Y. Lin, Appl. Phys. Lett. **74**, 1066 (1999).