Performance and degradation of continuous-wave InGaN multiple-quantum-well laser diodes on epitaxially laterally overgrown GaN substrates

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(Received 16 June 2000; accepted for publication 4 August 2000)

The performance and degradation characteristics of continuous-wave (cw) InGaN multiple-quantum-well laser diodes are reported. A cw threshold current as low as 62 mA was obtained for ridge-waveguide laser diodes on epitaxially laterally overgrown GaN on sapphire substrates grown by metalorganic chemical vapor deposition. Transmission electron microscopy reveals a defect density $<5\times10^{7}$ cm^{-2} in the active region. The emission wavelength was near 400 nm with output powers greater than 20 mW per facet. Under cw conditions, laser oscillation was observed up to 70 °C. The room-temperature cw operation lifetimes, measured at a constant output power of 2 mW, exceeded 15 h. From the temperature dependence of the laser diode lifetimes, an activation energy of 0.50 eV±0.05 eV was determined. © *2000 American Institute of Physics.* [S0003-6951(00)03339-8]

Since the first demonstration of an InGaN multiple-quantum-well (MQW) laser diode[1] enormous progress has been made with the currently most advanced devices operating under cw conditions and lifetimes greater than 10 000 h.[2,3] In the meantime a number of other groups have demonstrated room-temperature cw operation of InGaAlN laser diodes[4–7] and the commercialization of violet laser diodes was recently announced,[8] targeting a wide range of applications particularly high-density optical data storage. As Nakamura and co-workers have shown, the lifetime of group III-nitride laser diodes can be greatly improved by reducing the dislocation density in the material, for example, by employing an epitaxial lateral overgrowth technique.[2,3] Nevertheless, relatively little is known about the nature and origin of the degradation mechanism in such devices.

In this letter we report on the performance of InGaN MQW laser diodes grown on low-dislocation density epitaxially laterally overgrown (ELOG) GaN on sapphire substrates and the dependence of laser lifetime on device temperature and light output power. The laser structures were grown on sapphire substrates by metalorganic chemical vapor deposition (MOCVD). First, a 2-μm thick GaN film was deposited the (0001) c-plane sapphire substrate followed by a 100-nm-thick layer of silicon dioxide (SiO_2). The SiO_2 film was subsequently patterned to form an 8-μm-wide stripe pattern with a period of 11 μm parallel to the ⟨10-10⟩ direction of the GaN. MOCVD growth was then resumed and a 15 μm thick, Si-doped GaN layer deposited on the patterned substrate. The growth was completed with a standard laser diode heterostructure as follows:[9] a 0.1-μm-thick Si-doped InGaN defect reducing layer, a 1-μm-thick Si-doped AlGaN/GaN strained-layer-superlattice cladding layer (with an average Al composition of 8%), an active region comprised of four 35 Å thick InGaN quantum wells sandwiched between 0.1-μm-thick GaN waveguiding layers, a 20-nm-Mg-doped AlGaN tunnel barrier layer grown on top of the MQW, a 0.5-μm-thick Mg-doped AlGaN cladding layer, and finally a 0.1-μm-thick Mg-doped GaN contact layer.

Transmission electron microscopy (TEM) was used to determine the defect density of the ELOG structure. Plan-view TEM (PTEM) and cross-section TEM (XTEM) samples were prepared along the ⟨0001⟩ and ⟨10-10⟩ direction, respectively. The samples were argon ion milled to electron transparency and images were taken to reveal edge, screw, and mixed dislocations in order to accurately determine the defect density. Figure 1 shows TEM images of ELOG structures in cross section [Fig. 1(a)] and planview

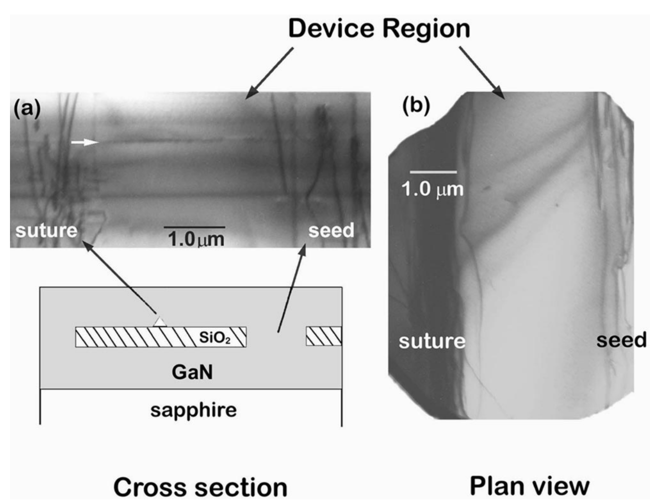

FIG. 1. (a) Cross-sectional TEM along the ⟨10-10⟩ direction and (b) plan-view TEM image along the ⟨0001⟩ direction of an ELOG film grown on sapphire. The XTEM image was taken with diffraction vector $g=11-22$ and PTEM was taken with $g=11-20$.

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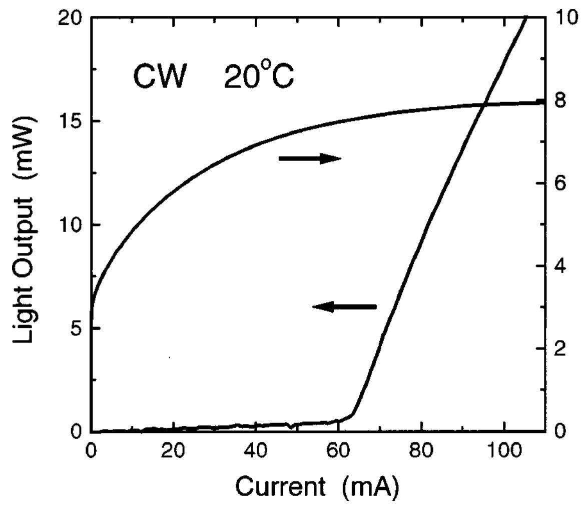

FIG. 2. Current–voltage ($V-I$) and light output–current ($L-I$) characteristic for a 2 μm ridge waveguide laser diode under cw operation at 20 °C.

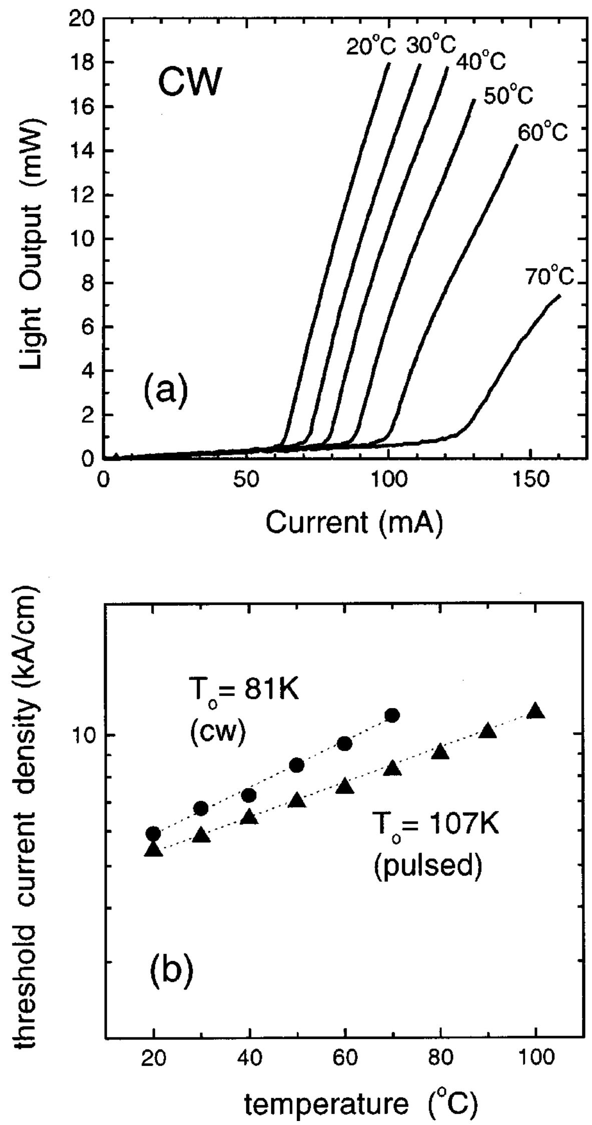

FIG. 3. (a) cw $L-I$ characteristics for a 2 μm ridge waveguide laser diode recorded over the range of heatsink temperatures from 20 to 70 °C. (b) Temperature dependence of the threshold current density for a 2 μm×800 μm ridge waveguide laser diode measured under pulsed (triangles) and cw conditions (circles).

[Fig. 1(b)]. The quantum well region is indicated by the arrow in Fig. 1(a). A higher density of basal plane dislocations are located in the suture region where the film has coalesced (located in the middle of the SiO_2 mesas) compared to the seed region (film between the SiO_2 mesas). The density of threading dislocations was determined from large area (25 μm^2) plan view images to be $<5\times10^7$ cm^{-2} in the active region compared to $\sim10^{10}$ cm^{-2} in the GaN seed region. Ridge waveguide structures were formed between the seed and the suture region by etching into the AlGaN cladding layer with chemically assisted ion beam etching (CAIBE). Subsequently mesas and mirrors for the edge-emitting laser diodes were also fabricated with CAIBE. Metal contacts were then deposited on the exposed n-type GaN layer for the lateral electrical connection and on the top p-type GaN layer. In order to reduce the mirror loss, a high reflective dielectric coating ($R\sim90\%$) was deposited on the backside mirrors. Finally, in order to evaluate the performance under cw conditions the sapphire substrate was thinned to about 120 μm and the laser diodes were mounted p-side up onto a copper heatsink.

Figure 2 shows the voltage–current and light output power–current characteristics of a 2 μm ridge-waveguide laser diode device with a cavity length of 400 μm operating cw conditions at room temperature. The cw threshold current is as low as 62 mA, which corresponds to a current density of 7.8 kA/cm^2 with a threshold voltage of about 7.5 V. The cw light output power from the front facet was greater than 20 mW, for a differential quantum efficiency of more than 0.5 W/A. The emission wavelength of the laser diode was near 400 nm. For the same device the cw light output power versus current characteristics is plotted for different heatsink temperatures. As shown in Fig. 3(a), the cw laser operation was sustainable up to a heatsink temperature of 70 °C. The temperature dependence of the threshold current density measured under pulsed and cw conditions for a 2 μm×800 μm ridge-waveguide laser diode device is shown in Fig. 3(b). The temperature dependence of the cw threshold current yields a characteristic temperature T_0 of 81 K in the vicinity of room temperature. As expected this is somewhat smaller than the characteristic temperature obtained under pulsed conditions (1 kHz repetition frequency and 1 μs pulse width), which was measured to be around 107 K.

In order to determine the actual pn-junction temperature of the device when operated under cw conditions, the change in emission wavelength and threshold current were measured and compared to the values when operated under pulsed conditions. For the above T_0 and a 2 μm×800 μm ridge-waveguide laser diode device we found that the increase in threshold current corresponds to a increase in pn-junction temperature of about 18 °C when operated under cw conditions. This is in good agreement with the temperature increase determined from the shift in emission wavelength, at our measured rate of 0.052 nm/K. For the total power dissipated under cw operation condition, this change in device temperature corresponds to a thermal resistance of 23 K/W.

The inset in Fig. 4 shows a lifetime measurement for a 2 μm×800 μm ridge-waveguide laser diode device operating under cw conditions at 20 °C. During the measurement the light output of the laser diode was kept constant at 2 mW and

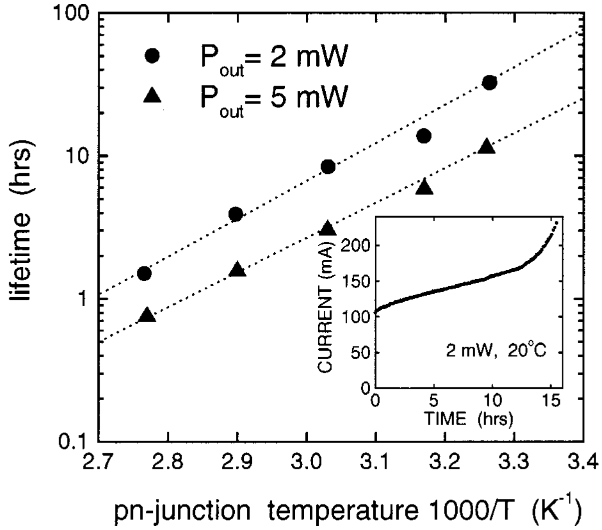

FIG. 4. Laser diode lifetimes measured at constant output powers of 2 and 5 mW vs the reciprocal *pn*-junction temperature. The dotted lines represent least-square fits to the experimental data. The inset shows the measured lifetime for a 2 μm×800 μm ridge waveguide laser diode under cw operation at a heatsink temperature of 20 °C and a constant output power of 2 mW.

the operating current of the laser diode was recorded. For the first 13 h the operating current increased almost linearly and then started to degrade at a faster rate, while continuing to lase after more than 15 h of operation. In order to study the influence of device temperature and light output power on the degradation rate of laser diodes, the lifetimes of a number of laser devices were measured for different heatsink temperatures and constant output powers of 2 and 5 mW. The lifetime in the measurement is operationally defined, as the elapsed time until the laser operating current (to maintain the constant output power) has increased by 50% from its initial value. The measured lifetimes for an output power of 2 and 5 mW and different *pn*-junction temperatures are plotted in Fig. 4. Joule heating of the device was taken into account and the actual *pn*-junction temperature was calculated from the thermal resistance, the respective operating current and voltage of the device averaged over the time of operation, and the heatsink temperature. In the case of thermally assisted defect formation, e.g., caused by thermally assisted generation of nonradiative recombination centers, the degradation rate has been found to depend exponentially on the reciprocal temperature and can be described by the following empirical relation[10]

$$L(T) \sim e^{E_A/kT},$$

where E_A is the activation energy, T is the device temperature, and k is the Boltzmann constant. As can be seen from Fig. 4 this empirical formula describes the measured temperature dependence quite well, and an activation energy of $E_A = 0.50$ eV$\pm$0.05 eV is derived (least-square fit) for 2 mW output power and $E_A = 0.46$ eV$\pm$0.04 eV is derived for an output power of 5 mW. Note that this finding is also in good agreement with previously obtained data from Nakamura[11] in which a similar activation energy was derived for long-lived laser diodes exhibiting lifetimes of several 1000 h. Although the activation energy seemed not to be strongly dependent on the light output power of the laser diodes, the overall laser diode lifetime decreased significantly with increasing light output. This reduction in laser diode lifetime when the device is operated at higher output power levels, however, cannot be merely attributed to a temperature increase. The increase in electric power dissipation, when the laser light output is changed from 2 to 5 mW, results only in a *pn*-junction temperature increase of ~1 K. This temperature increase is much too small to explain the drastic drop in lifetime for the higher output power. Therefore the light output power dependence of the laser diode lifetimes indicates that the degradation mechanism is not only thermally induced, but also photon assisted.

In summary, we have demonstrated room-temperature cw operation of InGaN MQW laser diodes grown on low-dislocation-density substrates obtained by laterally epitaxially overgrown GaN on sapphire. The ridge-waveguide laser diodes exhibited cw threshold currents as low as 62 mA and threshold voltages of 7.5 V. The emission wavelength was near 400 nm with output powers greater than 20 mW per facet. An empirical activation energy for laser diode degradation was determined from temperature-dependent lifetime measurements to be 0.50 eV$\pm$0.05 eV for an output power of 2 mW.

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