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Present Status of InGaN-Based Laser Diodes

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A violet InGaN multi-quantum-well (MQW)/GaN/AlGaN separate-confinement-heterostructure laser diode (LD) was grown on epitaxially laterally overgrown GaN on sapphire. The LDs with cleaved mirror facets showed an output power as high as 40 mW under room-temperature continuous-wave (CW) operation. The stable fundamental transverse mode was observed at an output power of up to 40 mW. The smallest aspect ratio of the far-field pattern was 1.6. The wavelength drift caused by the temperature change was estimated to be 0.06 nm/K. The lifetime of the LDs at a constant output power of 5 mW was more than 1900 h under CW operation at an ambient temperature of 50 °C. That at a constant output power of 30 mW was more than 400 h under CW operation at an ambient temperature of 60 °C.

1. Introduction

Major developments in wide-gap III–V nitride semiconductors have recently led to the commercial production of high-efficiency uv/blue/green/amber/white light-emitting diodes [1 to 3] and violet laser diodes (LDs) with a structure of InGaN multi-quantum-well (MQW)/GaN/AlGaN separate confinement-heterostructure (SCH) [4]. The lifetime of the violet LDs has been improved to more than 10000 h under RT-CW operation using epitaxially laterally overgrown GaN (ELOG) [5, 6] as a substrate and AlGaN/GaN modulation-doped strained-layer superlattices (MD-SLSs) as cladding layers [7]. These LDs with a lifetime of more than 10000 h had a low output power of 2 mW at RT and a higher order transverse mode in the near-field patterns (NFPs). For applications such as read/write laser light sources of digital versatile disks (DVDs), the fundamental transverse mode is indispensable, under a variable operating current, for collecting the laser light to a small spot. Recently, we succeeded in producing commercially available violet LDs with an output power of 5 mW, a fundamental transverse mode and an emission wavelength of around 400 nm [4]. Here, present performance of those LDs is described.

2. Experimental

III-nitride films were grown using the two-flow metal-organic chemical vapor deposition (MOCVD) method, the details of which have been previously described [3]. First, ELOG was grown without a silicon dioxide (SiO_2) mask. A 4 μm thick GaN layer was grown on a (0001) C-face sapphire substrate with an off-angle of 0.2° toward $\langle 1\bar{1}00 \rangle$ [4]. The off-angle sapphire substrate was used to obtain a step growth surface of GaN. After the growth, the SiO_2 mask was patterned to form 4 μm wide stripe windows with a periodicity of 12 μm in the GaN $\langle 1\bar{1}00\rangle$ direction. Next, a 4 μm thick GaN layer of the window region was etched out by dry etching until the sapphire substrate appeared. After removing the SiO_2 mask, the GaN growth was performed again on these rectangular GaN films. In this growth process, the growth rate of GaN initiated from the etched surface of both sides was much faster than that from the top surface of each rectangular GaN film. Thus, following 20 μm thick GaN growth, the coalescence of the GaN from both sides of the rectangular GaN made it possible to achieve a flat GaN surface over the entire substrate. The defect density of the epitaxially laterally overgrown region, as determined by plan-view transmission electron microscopy (TEM), on the etched region of the underlayer GaN with a width of 8 μm, was lower than $1 \times 10^6\ \text{cm}^{-2}$. The defect density on the un-etched region was on the order of $1 \times 10^{10}\ \text{cm}^{-2}$. This coalesced GaN is referred to as epitaxially laterally overgrown GaN (ELOG) in this paper. This ELOG without the SiO_2 mask was previously reported by Zheleva et al. [8] and by author's group [4]. After obtaining a 20 μm thick ELOG substrate, the laser structure was grown. The details of the InGaN-MQW/GaN/AlGaN SCH laser structure are described in other papers [3, 4]. The surface of the p-type GaN layer was partially etched until the n-type GaN layer and p-type $Al_{0.15}Ga_{0.85}N$/GaN MD-SLS cladding layer were exposed to form the ridge-geometry LDs. The stripe width was 2 μm. The cavity length was 600 μm. The region of the ridge-geometry LD of $2 \times 600\ \mu\text{m}^2$ was formed on the laterally overgrown region of the GaN on the etched region of the underlying GaN. A laser cavity was formed by cleaving the facets along the $\{1\bar{1}00\}$ face of the LD grown on the ELOG. A facet coating consisting of two pairs of quarter-wave TiO_2/SiO_2 dielectric multilayers was formed on one side of the facets. The output power of the LD was measured from an uncoated facet. The electrical characteristics of the LDs fabricated in this way were measured under a direct current (dc).

3. Results and Discussion

Figure 1 shows the voltage–current (V–I) characteristics and the light output power per uncoated cleaved facet of the LD as a function of the forward dc current (L–I) at RT. No stimulated emission was observed up to a threshold current of 43 mA, which corresponds to a threshold current density of 3.6 kA/cm^2. The threshold voltage was 4.3 V. The output power of the LDs was as high as 40 mW at an operating current of 90 mA. At an output power of up to 40 mW, no kink was observed in the L–I curve because the transverse mode was stable at a fundamental transverse mode with a small ridge width of 2 μm [9]. The slope efficiency was as high as 1.0 W/A. The temperature dependence of the L–I curves of the LDs was measured under CW operation at temperatures between 20 and 60 °C. The threshold current increased gradually with increasing temperature. The characteristic temperature T_0, which was used to express the temperature dependence of the threshold current in the form $I_{th}(T) = I_0 \exp(T/T_0)$, was estimated to be 213 K as shown in Fig. 2. Here, I_0 is a constant, T is the absolute temperature and $I_{th}(T)$ is the threshold current. The value of this characteristics temperature was the highest one ever obtained in our group. The typical value of the characteristic temperature was around 150 K.

The measurement of the far-field patterns (FFPs) was performed, as shown in Fig. 3. At an output power of 30 mW, the FFP in the direction parallel (X) to the epitaxial

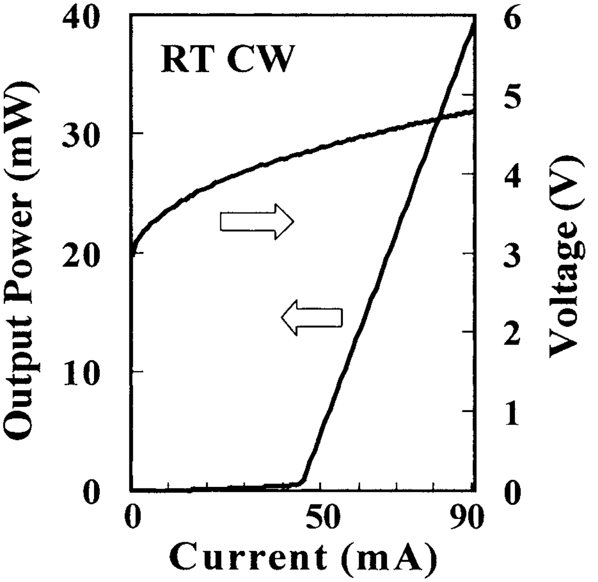

Fig. 1. Typical L–I and V–I characteristics of InGaN-MQW/GaN/AlGaN SCH LDs measured under CW operation at RT

layers collapsed to 16.2°; the FFP extended to 23.8° in the perpendicular direction (Y). The aspect ratio was 1.6, which value is relatively small and is desirable for practical applications to condense a laser beam to a small spot size efficiently using collecting lens. This small aspect ratio was obtained by etching the p-type AlGaN/GaN MD-SLS to a thickness of 0.05 μm in order to improve the transverse optical confinement.

Next, the emission spectra of the LDs were measured under RT-CW, as shown in Fig. 4. An optical spectrum analyzer (ADVANTEST Q8347), which utilizes a Fourier

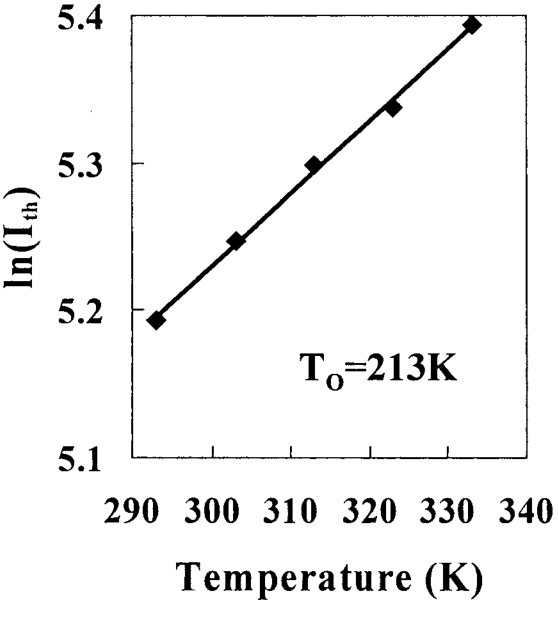

Fig. 2. Threshold current of $I_{th}(T)$ as a function of the ambient temperature

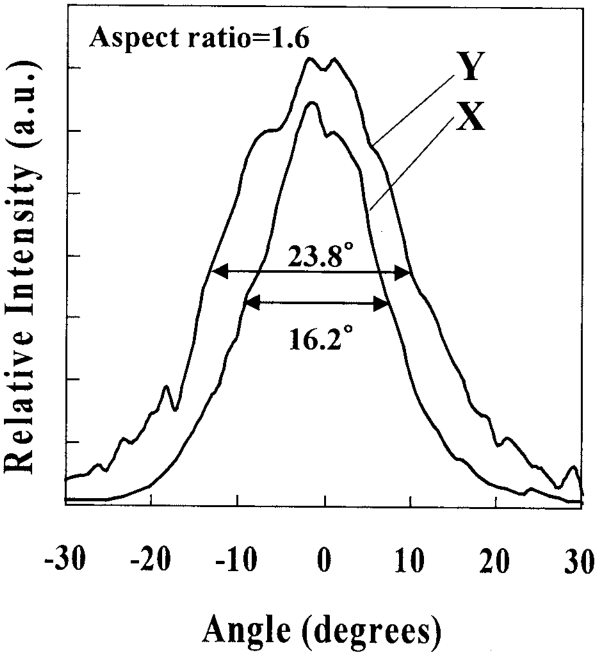

Fig. 3. FFP of InGaN-MQW/GaN/AlGaN SCH LDs in the planes parallel (*X*) and perpendicular (*Y*) to the junction at an output power of 30 mW under RT-CW operation

transform spectrometer with a Michelson interferometer, was used to measure the spectra of the LDs with a resolution of 0.001 nm. At output powers of 3 and 10 mW, single-mode laser emissions were observed at wavelengths of 408.1 and 408.2 nm. At output

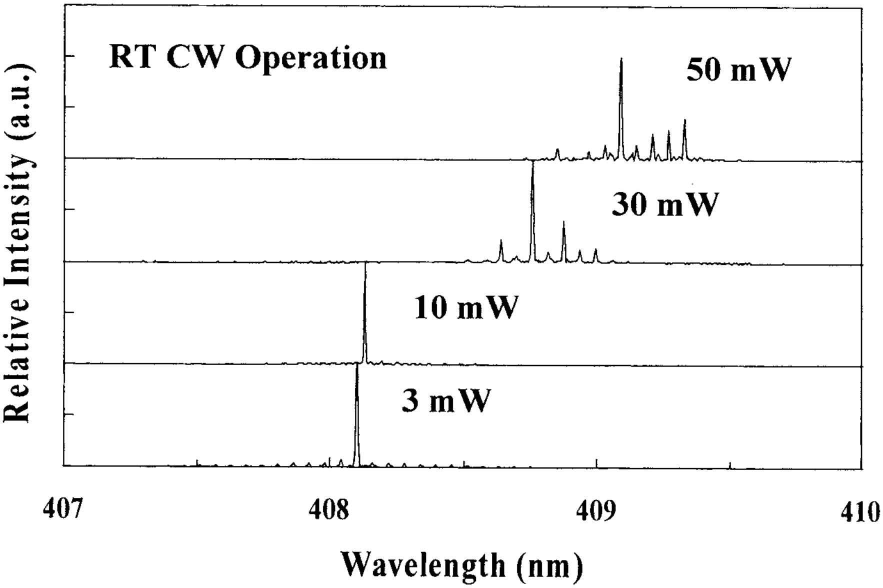

Fig. 4. Laser emission spectra measured under RT-CW operation at output powers of 3, 10, 30 and 50 mW

powers of 30 and 50 mW, multimode laser emissions were observed at wavelengths of 408.7 and 409.1 nm. Figure 5 shows the temperature dependence of the peak emission wavelength of three LDs under CW operation at an output power of 5 mW. During this measurement, the LDs were placed on a Peltier-type cooler to maintain the temperatures of the LDs between 10 and 70 °C. The average wavelength drift caused by the temperature change was estimated to be 0.06 nm/K from this figure. Assuming that the wavelength drift of the longitudinal mode is determined by the temperature dependence of band gap energy of the active layer, the wavelength drift is determined as

$$\mathrm{d}\lambda_\mathrm{p}/\mathrm{d}T = (\mathrm{d}\lambda_\mathrm{p}/\mathrm{d}E_\mathrm{g})\,(\mathrm{d}E_\mathrm{g}/\mathrm{d}T)\,, \tag{1}$$

$$\lambda_\mathrm{p} = 1240/E_\mathrm{g}. \tag{2}$$

Taking the derivative of eq. (2), we obtain

$$\mathrm{d}\lambda_\mathrm{p}/\mathrm{d}E_\mathrm{p} = -1240/E_\mathrm{g}^2\,. \tag{3}$$

Therefore, eq. (1) becomes

$$\mathrm{d}\lambda_\mathrm{p}/\mathrm{d}T = -(1240/E_\mathrm{g}^2)\,(\mathrm{d}E_\mathrm{g}/\mathrm{d}T)\,, \tag{4}$$

where λ_p (in nm) is the emission wavelength of the LD, E_g (in eV) is the band gap energy of the active layer and T (in K) is the absolute temperature. Other groups have already estimated the temperature coefficient $\mathrm{d}E_\mathrm{g}/\mathrm{d}T = -6.0 \times 10^{-4}$ eV/K around RT from the temperature dependence of the principle emission peak of GaN [10, 11]. Using this value for GaN and eq. (4), we were able to estimate a value of 0.06 nm/K for the wavelength drift. This value agrees well with the experimentally obtained one of 0.06 nm/K, even though the actual active layer is an InGaN MQW layer.

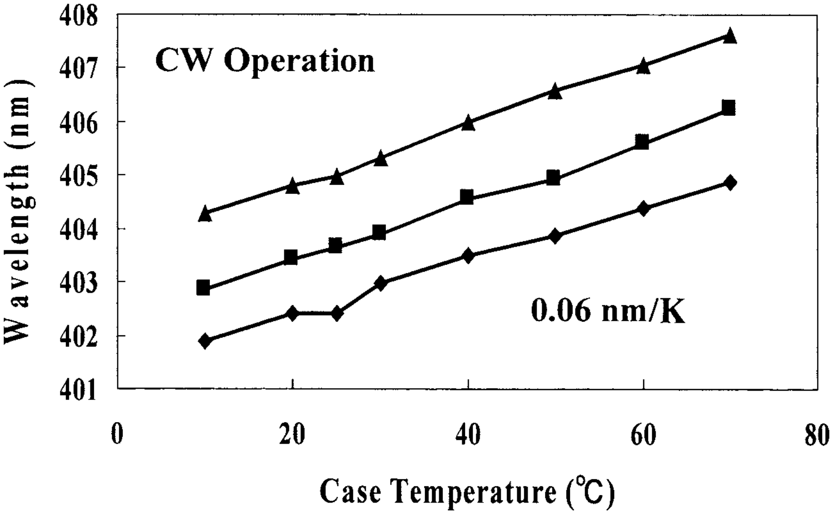

Fig. 5. Temperature dependence of the peak emission wavelength of LDs under CW operation at an output power of 5 mW

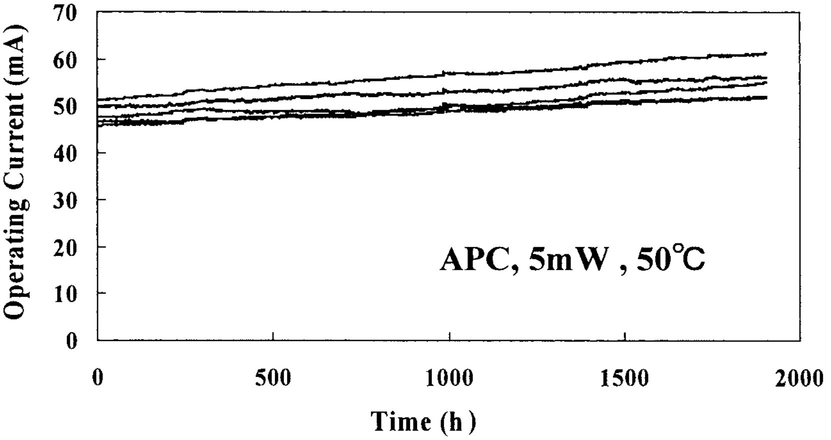

Fig. 6. Operating current of InGaN-MQW/GaN/AlGaN SCH LDs as a function of time under a constant output power of 5 mW at an ambient temperature of 50 °C controlled using an autopower controller

Figure 6 shows the results of a lifetime test of five CW-operated LDs carried out at an ambient temperature of 50 °C, in which the operating current is shown as a function of time under a constant output power of 5 mW controlled using an autopower controller (APC). After 1900 h of operation, only small degradation was observed. For the application of writing use of DVDs and hard disk drives (HDDs), a high power of 30 mW is required. Figure 7 shows the results of a lifetime test of CW-operated LDs carried out at an ambient temperature of 60 °C under a constant output power of 30 mW. In this case, the degradation speed is relatively large. The degradation speed was defined to be d*I*/d*t* (mA/100 h), where *I* is the operating current of the LDs and *t* is the

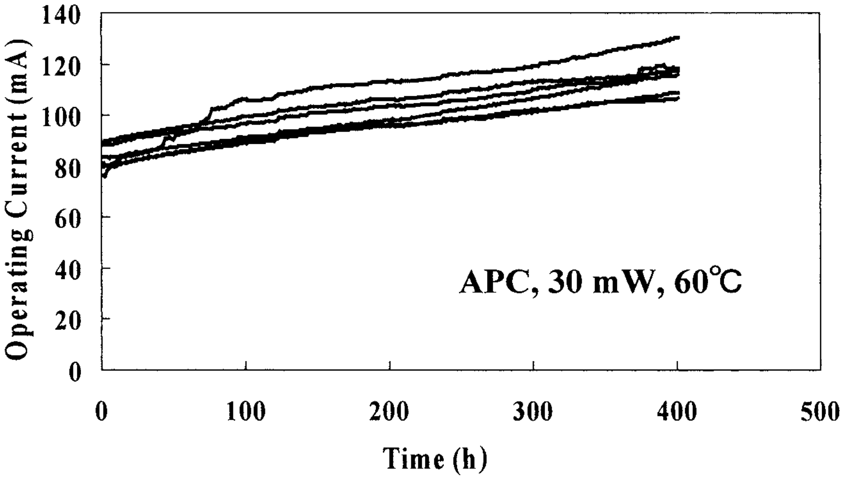

Fig. 7. Operating current of InGaN-MQW/GaN/AlGaN SCH LDs as a function of time under a constant output power of 30 mW at an ambient temperature of 60 °C controlled using an autopower controller

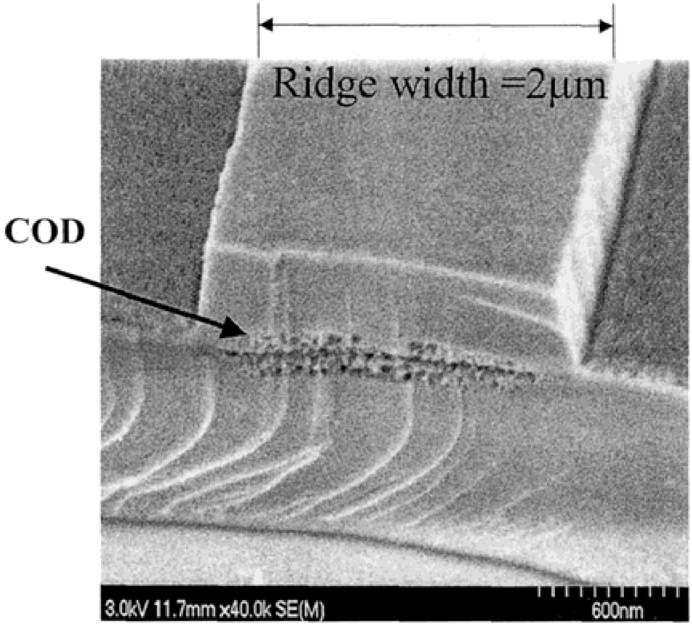

Fig. 8. Cross-sectional secondary electron microscope image of one of the degraded LDs after 400 h operation at an output power of 30 mW and an ambient temperature of 60 °C

time. Using this degradation speed, the estimated lifetime was determined to be the time when the operating current became 1.5 times the initial operating current of the LDs. The lifetime was estimated to be approximately 400 to 500 h under these high-power of 30 mW and high ambient temperature of 60 °C. Figure 8 shows the cross-sectional secondary electron microscope (SEM) image of one of the degraded LDs after 400 h operation at an output power of 30 mW and an ambient temperature of 60 °C. Before the SEM measurement, the mirror facet was etched using aqua regia to expose the damaged surface clearly. The mirror facet, where output laser beam was obtained, showed a damaged surface like a catastrophic optical damage (COD). Probably, the LDs were degraded due to this damage. Further studies are required to clarify the origin of the COD.

4. Conclusion

InGaN-MQW/GaN/AlGaN SCH LDs were fabricated on the ELOG substrate grown by MOCVD. The LDs with cleaved mirror facets showed an output power as high as 40 mW under RT-CW operation with a stable fundamental transverse mode. The lifetime of the LDs at a constant output power of 30 mW was 400 to 500 h under CW operation at an ambient temperature of 60 °C. The mirror facet of the degraded LDs showed a damaged surface like a COD.

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