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High-Power InGaN-Based Violet Laser Diodes with a Fundamental Transverse Mode

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1. Introduction

Major developments in wide-gap III-V nitride semiconductors have recently led to the commercial production of high-powe uv/blue/green/amber/white light-emitting diodes and to the demonstration of room-temperature (RT) violet laser light emission in InGaN/GaN/AlGaN-based separate confinement heterostructures (SCH) under continuous-wave (CW) operations [1-3]. The lifetime of the InGaN multi-quantum-well (MQW)-structure laser diodes (LDs) has been improved to more than 10,000 h under RT-CW operation using epitaxially laterally overgrown GaN (ELOG) as a substrate and AlGaN/GaN modulation-doped strained-layer superlattices (MD-SLSs) as cladding layers [4,5]. These LDs with a lifetime of more than 10,000 h had a low output power of 2-5 mW at RT. 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 collimating the laser light to a small spot. Also for the writing use of the LDs for the DVDs, high-power LDs with an output power of more than 30 mW is required. Here, high-power InGaN-based violet LDs are described.

2. Experimental

Type III-V nitride films were grown using the two-flow metalorganic chemical vapor deposition (MOCVD) method, the details of which have been previously described [1]. First, selective growth of GaN without a silicon dioxide (SiO_2) mask was performed. A 4-μm-thick GaN layer was grown on a (0001) C-face sapphire substrate with an off-angle of 0.2 degrees toward <1-100>. The off-angle sapphire substrate was used to obtain a step growth surface of GaN. After the growth, the silicon dioxide (SiO_2) mask was patterned to form 3-μm-wide stripe windows with a periodicity of 10 μm in the GaN <1-100> 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 the 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, as shown in Fig.1. This coalesced GaN is referred to as epitaxially laterally overgrown GaN (ELOG) in this paper. This ELOG without the SiO_2 mask was recently reported by Zheleva et al [6]. After obtaining a 20-μm-thick ELOG substrate, the laser structure was grown. The details of the growth conditions and laser structures are described in other papers [1-5]. 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 450 μm. The region of the ridge-geometry LD of 2 μm x 450 μm 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 {1-100} 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. A Ni/Au contact was evaporated onto the p-type GaN layer, and a Ti/Al contact was evaporated onto the n-type GaN layer. The electrical characteristics of the LDs fabricated in this way were measured under a direct current (DC).

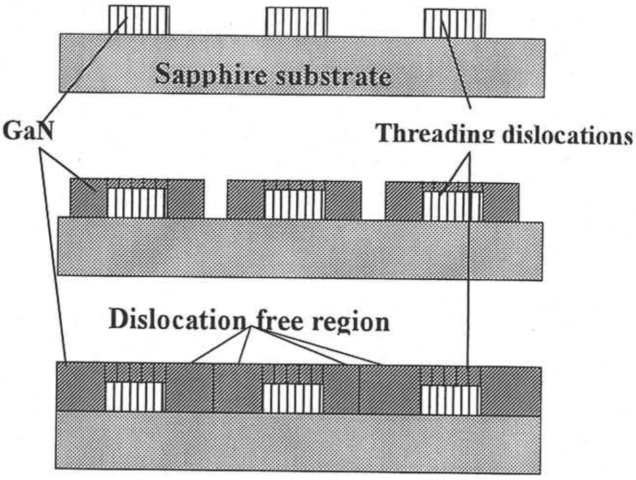

Fig.1 ELOG substrate without SiO_2 mask.

3. Results and Discussion

Figure 2 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 40 mA, which corresponds to a threshold current density of 4.4 kA/cm^2. The threshold voltage was 4.2 V. The output power of the LDs was as high as 40 mW at an operating current of 90 mA. At an output power 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.

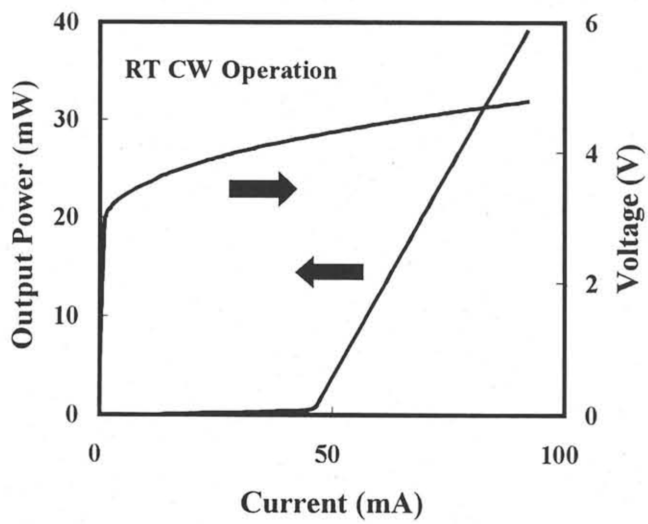

Fig. 2 L-I, V-I curves of InGaN-based violet LDs.

The measurement of the far-field patterns (FFPs) was performed. At an output power of 5 mW, the FFP in the direction parallel to the epitaxial layers collapsed to 10°; the FFP extended to 25° in the perpendicular direction. The aspect ratio was approximately 2.5. Next, the emission spectra of the LDs were measured under RT-CW operation at output powers of 10 mW, 30 mW and 50 mW. At output powers of 10 mW, 30 mW and 50 mW, single-mode emissions were observed at wavelengths of around 408.2 nm, 408.7 nm and 409.1 nm, respectively.

Figure 3 shows the results of a lifetime test of CW-operated LDs carried out at an ambient temperature of 60°C, in which the operating current is shown as a function of time under a constant output power of 30 mW controlled using an autopower controller (APC). Untill 400 h of operation, a constant degradation was observed. The degradation speed was defined to be dI/dt (mA/100 hours), where I is the operating current of the LDs and t is the 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 500 h under these high-power and high-ambient-temperature operating conditions.

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 estimated to be approximately 500 h under CW operation at an ambient temperature of 60°C. In order to lengthen the lifetime under these high-power and high-temperature conditions, the thresholod current density has to be reduced further. Also, the degradation mechanism of the InGaN-based violet LDs has to be clarified in details. Anyway, these rapid progress of InGaN-based LDs demonstrates that these LDs could be

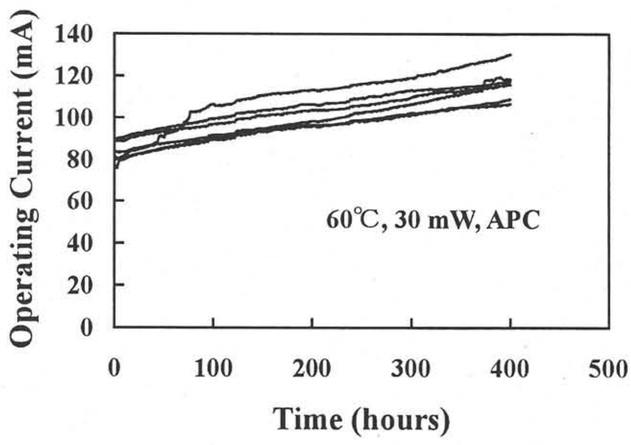

Fig.3. Operating current as a function of the time.

used for many practical applications, such as DVDs, laser printers, sensors and excitation light sources in the near future.

References

[1] S. Nakamura, M. Senoh, N. Iwasa, S. Nagahama, T. Yamada and T. Mukai: Jpn. J. Appl. Phys. **34** (1995) L1332.

[2] 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 , Appl. Phys. Lett. **72** (1998) 211.

[3] S. Nakamura and G. Fasol, The Blue Laser Diode, Springer-Verlag, Hedelberg, 1997.

[4] A. Usui, H. Sunakawa, A. Sakai, and A. Yamaguchi, Jpn. J. Appl. Phys. 36 (1997) L899.

[5] S. Nakamura, M. Senoh, S. Nagahama, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemoto, M. Sano and T. Mukai: Jpn. J. Appl. Phys. **38** (1999) L226.

[6] T. S. Zheleva, D. Thomson, S. Smith, P. Rajagopal, K. Linthicum, T. Gehrke and R. F. Davis: Ext. Abstr. (MRS Fall Meet. Boston, 1998) G3.38.