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Invited

Long Lifetime InGaN/GaN/AlGaN-Based Laser Diodes Grown on GaN Substrates

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1. Introduction

Major developments in wide-gap III-V nitride semiconductors have recently led to the commercial production of high-brightness blue/green light-emitting diodes (LEDs) and to the demonstration of room-temperature (RT) violet laser light emission in InGaN/GaN/AlGaN-based heterostructures under continuous-wave (CW) operations [1]. The estimated lifetimes of the InGaN multi-quantum-well (MQW)-structure laser diodes (LDs) have been improved to longer than 10,000 hours under RT-CW operation using AlGaN/GaN modulation-doped strained-layer superlattices (MD-SLSs) and an epitaxially laterally overgrown GaN (ELOG) on sapphire as a substrate [2]. However, further improvements of the LD characteristics, including mode control, higher output power and longer lifetime at a high ambient temperature, are required to enable commercialization of short-wavelength LDs. In the structures, sapphire substrates are used. Using a sapphire substrate, it is difficult to obtain cleaved mirror facets which are used for the cavities of conventional LDs. Also, the thermal conductivity of the sapphire is relatively small in order to dissipate the heat generated by the LDs. Here, the LDs grown on GaN substrates which are easily cleaved and have a high thermal conductivity, are described.

2. Experimental

The III-V nitride films were grown using the two-flow metal-organic chemical vapor deposition (MOCVD) method [1]. First, selective growth of GaN was performed on a 2-μm-thick GaN layer grown on a (0001) C-face sapphire substrate. The 0.1-μm-thick silicon dioxide (SiO_2) mask was patterned to form 4-μm-wide stripe windows with a periodicity of 11 μm in the GaN <1-100> direction. Following the 10-μm-thick GaN growth on the SiO_2 mask pattern, the coalescence of the selectively grown GaN made it possible to achieve a flat GaN surface over the entire substrate. This coalesced GaN was designated the ELOG. After obtaining 10-μm-thick ELOG substrate, the GaN growth was continued up to 100 μm thickness. After 100-μm-thick GaN growth, the sapphire substrate was removed by polishing in order to obtain pure GaN substrate with a thickness of approximately 80 μm. Then, the InGaN MQW LD structure was grown on the surface of the 80-μm-thick GaN substrate. The InGaN MQW LD structure consisted of a 3-μm-thick layer of n-type GaN:Si, a 0.1-μm-thick layer of n-type $In_{0.1}Ga_{0.9}N$:Si, a $Al_{0.14}Ga_{0.86}N$/GaN MD-SLS cladding layer consisting of 240 25-Å-thick Si-doped GaN separated by 25-Å-thick undoped $Al_{0.14}Ga_{0.86}N$ layers, a 0.1-μm-thick layer of Si-doped GaN, an $In_{0.15}Ga_{0.85}N/In_{0.02}Ga_{0.98}N$ MQW structure consisting of four 20-Å-thick Si-doped $In_{0.15}Ga_{0.85}N$ well layers forming a gain medium separated by 50-Å-thick Si-doped $In_{0.02}Ga_{0.98}N$ barrier layers, a 200-Å-thick layer of p-type $Al_{0.2}Ga_{0.8}N$:Mg, a 0.1-μm-thick layer of Mg-doped GaN, a $Al_{0.14}Ga_{0.86}N$/GaN MD-SLS cladding layer consisting of 120 25-Å-thick Mg-doped GaN separated by 25-Å-thick undoped $Al_{0.14}Ga_{0.86}N$ layers, and a 0.05-μm-thick layer of p-type GaN:Mg. The area of the ridge-geometry LD was 3 μm x 450 μm. A mirror facet was formed by dry etching. High-reflection facet coatings (50 %) consisting of 2 pairs of quarter-wave TiO_2/SiO_2 dielectric multilayers were used to reduce the threshold current.

3. Results and Discussion

The voltage-current (V-I) characteristics and the light output power per coated facet of the LD grown on the GaN substrate as a function of the forward DC current (L-I) at RT were measured. No stimulated emission was observed up to a threshold current of 70 mA, which corresponded to a threshold current density of 5 kA/cm^2. The operating voltage at the threshold current was 6 V. The operating voltage and threshold current density were relatively large due to a lack in the optimized growth condition when using the GaN substrate resulting from the reduced thickness of 80 μm. Figure 1 shows the results of a lifetime test of CW-operated LDs carried out at RT, in which the operating current is shown as a function of time under a constant output power of 3 mW per facet controlled using an autopower controller. After 2,700 hours operation, the operating current increased dramatically. This short lifetime is probably due to the high threshold current density of the LD.

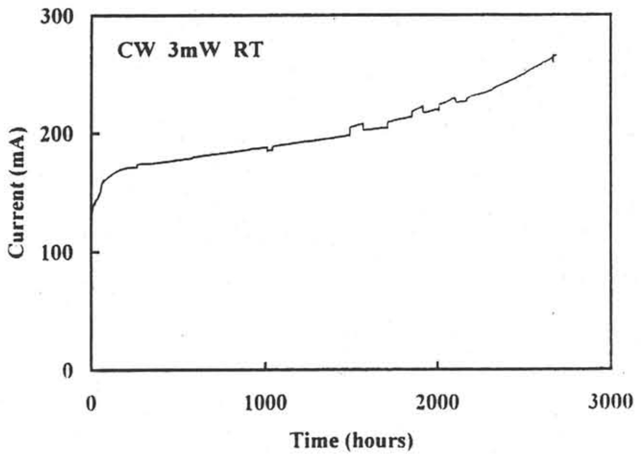

Fig. 1. Operating currents as a function of the time under a constant output power of 3 mW per facet controlled using an autopower controller.

The emission spectra of the LDs were measured under RT CW operation at an output power of 0.5 mW, 1 mW and 7 mW. At an output power of 0.5 mW and 1 mW, longitudinal modes with many sharp peaks due to a cavity, were observed, as shown in Figs. 2(a) and 2(b). At an output power of 7 mW, a single-mode emission was observed at a wavelength of 393.3 nm, as shown in Fig. 2(c). Previous LDs grown on sapphire substrates exhibited periodic subband emissions which were different from the cavity mode [1]. Without a sapphire substrate and with a thick n-type cladding layer, the intensity of these subband emissions became extremely small, as shown in Figs. 2(a) and 2(b). Thus, there is a possibility that these subband emissions originate from the coupling between the laser waveguide and the substrate waveguide which is transparent to the laser emission. When we cleaved the facets along <1-100> of the LDs grown on the GaN substrate, the cleaved mirror facets were obtained easily. The far-field pattern (FFP) of the LDs with the cleaved mirror facets was measured in the planes parallel and perpendicular to the junction. The FFP revealed a single mode emission without any interference effects which were observed in previous LDs due to a reflection of the laser beam by the remaining sapphire substrate [1].

4. Conclusion

InGaN MQW LDs grown on a GaN substrate were demonstrated. The LDs with an output power of 3 mW exhibited a lifetime of 2,700 hours, despite a relatively large threshold current density. If the threshold current density of the LDs grown on the GaN substrate could be reduced further, the characteristics of the LDs would be improved.

References

[1] For a review, see S. Nakamura, G. Fasol, *The Blue Laser Diode* (Springer-Verlag, Heidelberg, 1997).

[2] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemoto, M. Sano, K. Chocho, Jpn. J. Appl. Phys. **36** (1997) L1568: **37** (1998) L309.

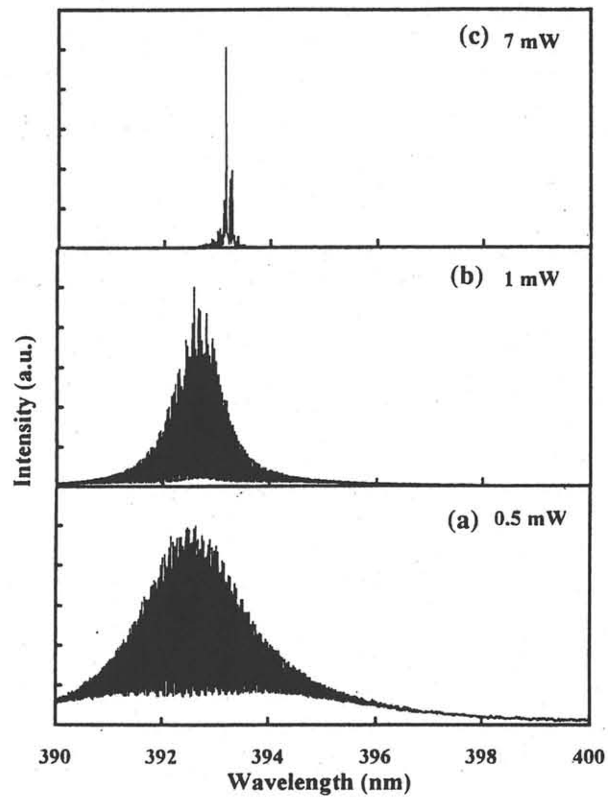

Fig. 2. Laser emission spectra measured under RT CW operation at output powers of (a) 0.5 mW, (b) 1 mW, and (c) 7 mW.