

## Characteristic of InGaN/GaN Laser Diode Grown by a Multi-Wafer MOCVD System

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InGaN/GaN multi-quantum well (MQW) laser diodes (LDs) were grown on c-plane sapphire substrates using a multi-wafer MOCVD system. The threshold current for pulsed lasing was 1.6 A for a gain-guided laser diode with a stripe of 10 x 800  $\mu\text{m}^2$ . The threshold current density was 20.3  $\text{kA cm}^{-2}$  and the threshold voltage was 16.5 V. The optical power ratio of transverse electric mode to transverse magnetic mode was found to be greater than 50. The characteristic temperature measured from the plot of threshold current versus measurement temperature was between 130 and 150K.

### 1 Introduction

Nitride semiconductor short wavelength laser diodes (LD) have attracted much attention as a light source for the optical data storage. Since Nichia Co. reported pulsed lasing in an InGaN multi-quantum well (MQW) LD in the end of 1995, [1] significant progress has been made in the development of blue LD's. Nakamura et al. has already demonstrated a blue LD with lifetime in excess of 10,000 hrs. [2] Although Nichia's conspicuous successes have stimulated the nitride research society during the last three years, until recently a limited number of research groups in the United States and Japan reported continuous wave [3] [4] [5] or pulsed lasing. [6] [7] [8] [9] In this paper, we report InGaN/GaN MQW LD operated under pulsed conditions.

### 2 Experiment

The LD structure shown in Figure 1 was grown on a c-plane sapphire substrate using a multi-wafer MOCVD system into which three 2" wafers can be loaded in a time. To our knowledge, this is the first report on InGaN/GaN MQW LD grown by a mass production scale MOCVD reactor in the open literature. TMGa, TMIIn, TMAI,  $\text{Cp}_2\text{Mg}$ ,  $\text{NH}_3$ , and  $\text{SiH}_4$  were used as material sources for the structure growth. The reactor pressure was maintained at 100 torr during the growth. In order to form gain guided LD's the structure was etched using chemically assisted ion beam etching (CAIBE) until the n-type GaN layer was exposed. A Pd/

Au contact was formed onto the p-type GaN, and a Ti/Al contact onto the n-GaN. The laser facets were formed by CAIBE. No mirror coating was employed on the facet surface. Fabricated LDs were measured under pulsed current conditions with pulse widths ranging from 100 ns to 1  $\mu\text{sec}$  at 1 kHz.

### 3 Results

Figure 2, Figure 3, Figure 4, Figure 5 show typical features proving that the diodes lased. Figure 2 shows L-I-V characteristics of one of the LDs with a stripe of 10  $\mu\text{m}$  x 800  $\mu\text{m}$ . The lowest threshold current was found to be 1.6 A, corresponding to a threshold current density of 20.3  $\text{kA cm}^{-2}$ . The threshold voltage of the device at the threshold current was 16.5 V. Figure 3 shows the polarized light output intensity as a function of current for another LD, which was measured under a pulse condition of 200 ns width at 1 kHz. It is clear that the emission was strongly polarized in transverse electric (TE) mode above the threshold current of 1.9 A, which is a good indication of lasing operation. The ratio of TE to transverse magnetic (TM) mode was found to be larger than 50. Figure 4 shows optical spectra of one of the LD's. The spectra were collected using a monochromator and a photon multiplier with a resolution of 0.1 A. Above the threshold current, strong and well-defined mode spectra were observed. They have several groups of sub-band emissions in the wavelength range of 415 to 421 nm with a peak spacing of around 0.72 nm. Figure

5 illustrates a narrow far-field pattern of the stimulated emission.

The sub-band emissions in the spectra shown in Figure 4 are known to be composed of many longitudinal modes. [5] [10] Figure 6 is a spectrum obtained at a higher resolution on the LD with a stripe of 10  $\mu\text{m}$  x 800  $\mu\text{m}$ . The sample was measured with a pulse width of 1  $\mu\text{sec}$  at 1 kHz. It is observed that each sub-band consists of several sharp peaks with a separation of 0.043 nm. Assuming that these peaks arise from the longitudinal modes of the LD, the mode separation  $\Delta\lambda$  is given by

$$\Delta\lambda = \lambda_0^2 / 2Ln$$

where  $n$  is the effective refractive index,  $\lambda_0$  is the emission wavelength, and  $L$  is the cavity length. Given the values, 0.043 nm, 416.6 nm, and 800  $\mu\text{m}$  for  $\Delta\lambda$ ,  $\lambda_0$ , and  $L$ , respectively, we obtained 2.52 as the refractive index  $n$ . This value is close to a value calculated from the optical modes of the structure and similar to a value Nakamura et al. used in their early work on the pulsed lasing. [11] However, somewhat larger effective refractive indexes of 3.3 and 3.6 have been reported in other papers. [5] [10]

Figure 7a shows L-I characteristics of one of the LD's with a stripe of 10  $\mu\text{m}$  x 1200  $\mu\text{m}$  at different temperatures ranging from 0 to 100  $^\circ\text{C}$ . The pulse width was 200 ns at 1 kHz. As shown in Figure 7a, the LD lased up to a temperature as high as 100  $^\circ\text{C}$ . However, the LD showed a degradation phenomenon at 100  $^\circ\text{C}$ . It failed at greater current than 5 A. It is certain that with increasing measurement temperature threshold current increases. The temperature dependence of threshold current is shown in Figure 7b. The calculated characteristic temperature was 155K for around room temperature operation and 133K for higher temperature operation. These values are comparable to those of other group's InGaN LDs. [5] [10] [12] Kuramata et al. has reported a similar change in the characteristic temperature. [5] It is worth noting that the LD showed a kink in the L-I plot at temperatures higher than 60 $^\circ\text{C}$  with more apparent appearance at higher temperature. Nakamura et al. suggested that such a kink in the L-I plot for their high power LD was due to the change in emission mode. [13] More work is necessary to verify the origin of the kink.

#### 4 Conclusion

We demonstrated the room temperature pulsed lasing of InGaN/GaN MQW blue LD grown by a multi-wafer

MOCVD system. Threshold current density was found to be 20.3  $\text{kA cm}^{-2}$  for 10  $\mu\text{m}$  x 800  $\mu\text{m}$  stripe LD. The operating voltage at this threshold current density was 16.5 V. Above the threshold current a strong and well-defined emission mode with a peak spacing of 0.72 nm was observed. The refractive index calculated from the spacing between longitudinal modes was 2.52. The measured characteristic temperature was between 130 and 150K.

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FIGURES

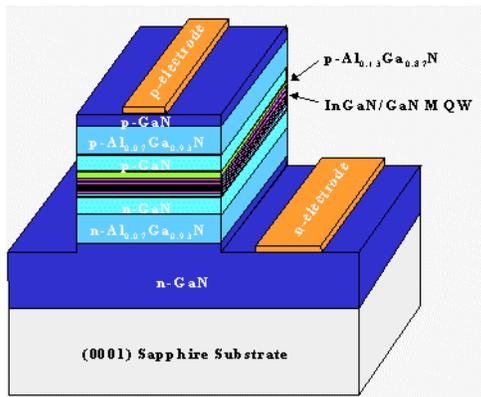


Figure 1. A schematic of the fabricated LD

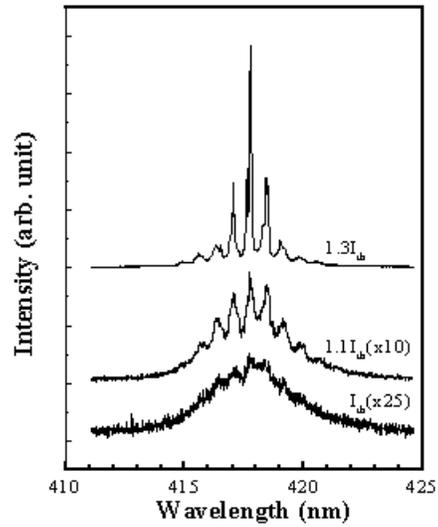


Figure 4. Spectra of the pulsed lasing

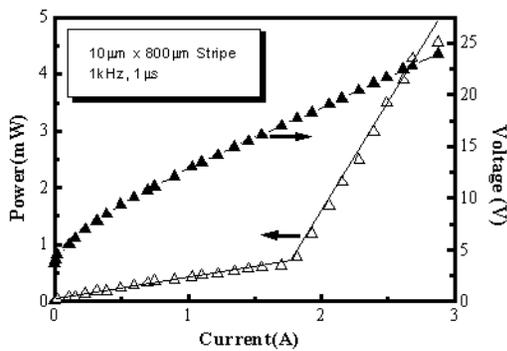


Figure 2. L-I-V characteristic of the LD

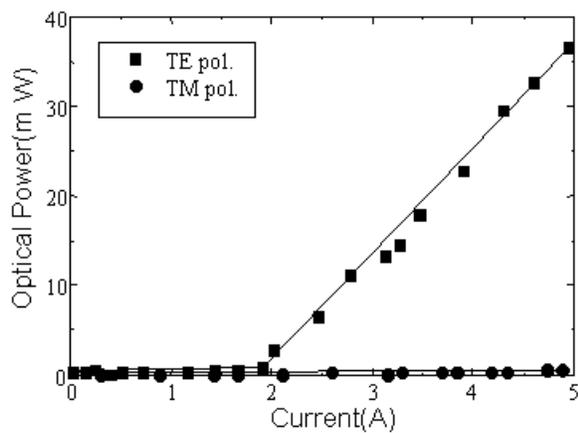


Figure 3. Polarized light output intensity of the LD.

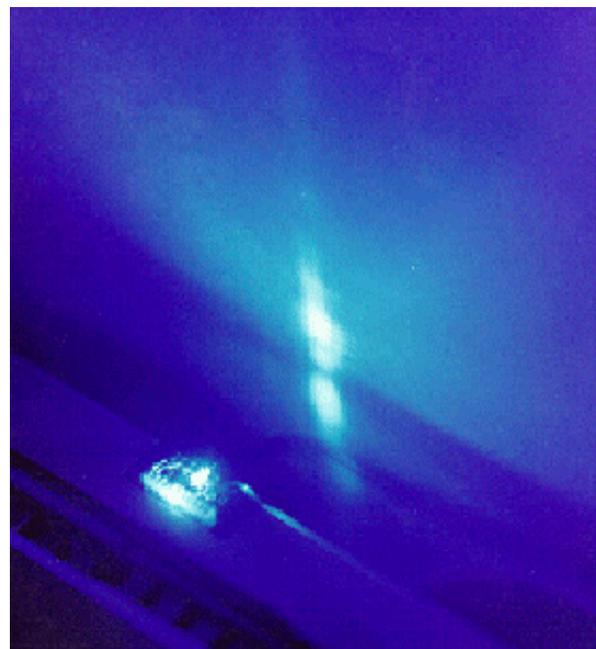


Figure 5. A far-field pattern of pulsed lasing.

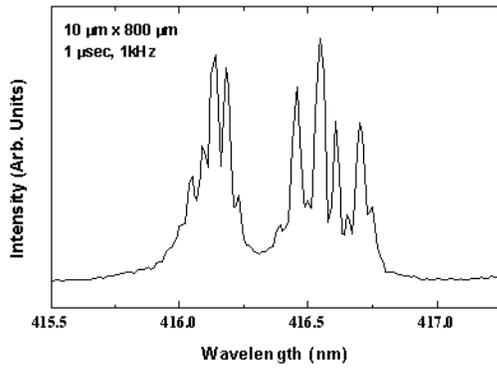


Figure 6. Subband emission consisting of sharp longitudinal modes.

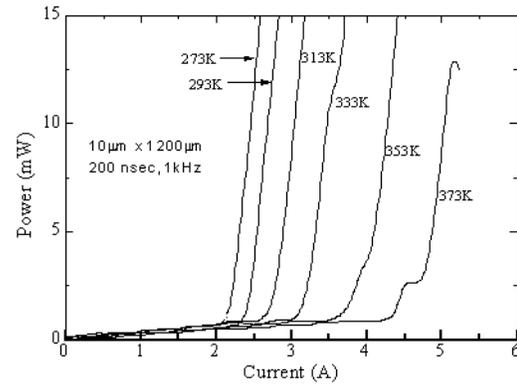


Figure 7a. Temperature dependence of L-I characteristics of the LD

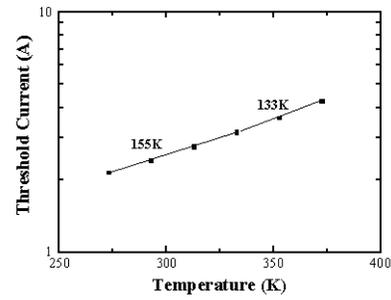


Figure 7b. Threshold current as a function of measurement temperature.