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# Invited

## Bluish-Purple InGaN Multi-Quantum Well Structure Laser Diodes

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InGaN multi-quantum well (MQW) structure laser diodes (LDs) with various different cavity lengths were fabricated on A-face sapphire substrates. The external differential quantum efficiency was obtained as a function of the cavity length. An internal quantum efficiency of 86 %, an intrinsic loss of 54 cm<sup>-1</sup> and a threshold gain of 110 cm<sup>-1</sup> were obtained. Measuring the pulse response of the LDs, a carrier lifetime of 2.5 ns was obtained. A threshold carrier density was calculated as 1.3 x  $10^{19}/\text{cm}^3$ . The emission wavelength of the LDs was around 406 nm.

Major developments in the use of wide-gap III-V nitride semiconductor quantum well structures have recently led to the commercial production of high-brightness blue/green light-emitting diodes (LEDs)<sup>1</sup>) and to the demonstration of purplishblue laser light emission in InGaN/GaN/AlGaN-based heterostructures.<sup>2-4</sup>) Now, the main focus of research is the realization of a current-injected laser diode capable of continuous-wave (CW) operation at room temperature. Previous studies have yielded optically pumped stimulated emission from GaN films,<sup>5,6</sup>) InGaN films,<sup>7,8</sup>) AlGaN/InGaN double heterostructures<sup>9</sup> and GaN/AlGaN double heterostructures.<sup>10,11</sup> However, stimulated emission has been obtained only with optical pumping, not current injection. The optical gain of GaN has also been calculated although there is as yet no precise data for the parameters necessary for determining and understanding the effect of the medium on the laser gain. Suzuki and Uenoyama reported that the transparent carrier density is as high as 1-2 x 10<sup>19</sup>/cm<sup>3</sup> for a 30-Å-thick GaN/Al<sub>0.2</sub>Ga<sub>0.8</sub>N quantum well structure.<sup>12</sup>) Recently, Chow et al.<sup>13</sup> calculated the transparent carrier density as 1 x 10<sup>19</sup>/cm<sup>3</sup> for 60-Å-thick GaN/Al<sub>0.14</sub>Ga<sub>0.86</sub>N strained quantum well LDs. However, experimental data for the optical gain and threshold carrier density of current-injection III-V nitride-based LDs have not been reported. In this work, we report the optical gain and carrier lifetime of InGaN MQW LDs experimentally.

III-V nitride films were grown by the two-flow metalorganic chemical vapor deposition (MOCVD) method. The twoflow MOCVD method has been described in detail elsewhere.<sup>14)</sup> The growth was conducted at atmospheric pressure. The substrate was A-face sapphire. The InGaN MQW LD device consisted of a 300-Å-thick GaN buffer layer grown at a low temperature of 550 °C, a 3- $\mu$ m-thick layer of n-type GaN:Si, a 0.1- $\mu$ m-thick layer of n-type In<sub>0.05</sub>Ga<sub>0.95</sub>N:Si, a 0.4- $\mu$ mthick layer of n-type Al<sub>0.07</sub>Ga<sub>0.93</sub>N:Si, a 0.1- $\mu$ m-thick layer of n-type GaN:Si, an In<sub>0.2</sub>Ga<sub>0.8</sub>N/In<sub>0.05</sub>Ga<sub>0.95</sub>N MQW structure consisting of seven 25-Å-thick undoped In<sub>0.2</sub>Ga<sub>0.8</sub>N well layers forming the gain medium, separated by 50-Åthick undoped In<sub>0.05</sub>Ga<sub>0.95</sub>N barrier layers, a 200-Å-thick layer of p-type Al<sub>0.2</sub>Ga<sub>0.8</sub>N:Mg, a 0.1- $\mu$ m-thick layer of p-type GaN:Mg, a 0.4- $\mu$ m-thick layer of p-type Al<sub>0.07</sub>Ga<sub>0.93</sub>N:Mg, and a 0.2- $\mu$ m-thick layer of p-type GaN:Mg. First, the surface of the p-type GaN layer was partially etched until the n-type GaN layer was exposed, in order to form stripe-geometry LDs. The stripe width was 10  $\mu$ m and the p-type electrode width was 5  $\mu$ m. The stripe LDs have already been described in detail elsewhere.<sup>2-4)</sup> The cavity lengths used were 0.067, 0.09, 0.12 and 0.15 cm. High-reflection facet coatings (30 %) were used to reduce the threshold current. 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 were measured under pulsed current-biased conditions (the pulse width was 0.5  $\mu$ s, the pulse period was 5 ms, and the duty ratio was 0.01 %) at room temperature. The output power from one facet was measured using a Si photodetector.

Figure 1 shows the reciprocal of the external differential quantum efficiency as a function of the cavity length. The external differential quantum efficiency decreases with increasing cavity length. The external differential quantum efficiency is given by

$$1/\eta_d = \alpha_i L/\ln(1/R)/\eta_i + 1/\eta_i$$

(1)

(2)

(3)

where  $\eta_d$  is the external differential quantum efficiency,  $\alpha_i$  is the intrinsic loss, L is the cavity length, R (30%) is the reflection coefficient of the facet, and  $\eta_i$  is the internal quantum efficiency. Therefore,  $1/\eta_d$  is proportional to L, as shown in

Fig. 1. From the figure,  $\alpha_i$  and  $\eta_i$  are calculated as 54 cm<sup>-1</sup> and 86 %, respectively. The threshold gain G<sub>th</sub> is given by

$$G_{th} = \Gamma^{-1} \alpha_{t} + \Gamma^{-1} L^{-1} \ln(1/R),$$

where  $\Gamma$  is the confinement factor.  $\Gamma$  is found to be 0.7 assuming that the light wave propagates only into the 0.2-µm-thick GaN guiding layers in the structure. Hereafter, we assume that the light propagates and is confined within the GaN guiding layers. Then,  $G_{th}$  is calculated as 110 cm<sup>-1</sup>. Kim et al.<sup>8</sup> estimated the optical gain to be 160<sup>-1</sup> cm from the stimulated emission of the GaN/Al<sub>0.1</sub>Ga<sub>0.9</sub>N structure obtained by optical pumping. Our value for the optical gain is almost the same as their value in spite of the fact that the structure includes an InGaN active layer. Next, the delay time of the laser emission was measured by pulsed current modulation of the LDs. The delay time t<sub>d</sub> is given by

$$t_{\rm d} = \tau_{\rm s} \ln(I/(I-I_{\rm th})),$$

where  $\tau_s$  is the minority carrier lifetime, I is the pumping current, and I<sub>th</sub> is the threshold current. Figure 2 shows the delay time t<sub>d</sub> of the laser emission as a function of ln(I/(I-I<sub>th</sub>)). From this figure,  $\tau_s$  is calculated as 2.5 ns. Also, the carrier density is given by

 $n_{th} = J_{th} \tau_s /(ed),$ 

(4)

where  $n_{th}$  is the carrier density at the laser threshold,  $J_{th}$  is the threshold current density, d is the thickness of the active layer, and e is the elementary charge.  $n_{th}$  is calculated as  $1.3 \times 10^{19}$ /cm<sup>3</sup>. A value of 4.6 kA/cm<sup>2</sup> was used for the threshold current density  $J_{th}$ . Suzuki and Uenoyama calculated the carrier density as  $2 \times 10^{19}$ /cm<sup>3</sup> at a gain of 110 cm<sup>-1</sup> for a 30-Åthick GaN/Al<sub>0.2</sub>Ga<sub>0.8</sub>N quantum well structure.<sup>12</sup>) Chow et al.<sup>13</sup> calculated the transparent carrier density as  $1 \times 10^{19}$ /cm<sup>3</sup> for 60-Å-thick GaN/Al<sub>0.14</sub>Ga<sub>0.86</sub>N strained quantum well LDs. Our results are quite reasonable considering that the active layer is an InGaN quantum well structure in our LDs. The effective mass of carriers in InGaN is smaller than that of GaN. Therefore, the threshold carrier density of an InGaN MQW LDs is considered to be smaller than that of GaN/AlGaN LDs.





Fig. 1. The reciprocal of the external differential quantum efficiency ,  $1/\eta_d$ , as a function of the cavity length L.

Fig. 2. The delay time  $t_d$  of the laser emission as a function of  $ln(I/(I-I_{th}))$ . I is the pumping current and  $I_{th}$  is the threshold current.

Figure 3 shows the optical spectra of typical InGaN MQW LDs under pulsed current injection at room temperature. These spectra were measured using an imaging spectrophotometer (Hamamatsu) which had a resolution of 0.03 nm. At injection currents below the threshold, spontaneous emission, which had a full width at half-maximum (FWHM) of 20 nm and a peak wavelength of 406.7 nm, occurred, as shown in Fig. 3(a). Above the threshold current, strong stimulated emissions were observed. A sharp stimulated emission at 406.2 nm with a FWHM of 0.03 nm became dominant at a current of 136 mA, as shown in Fig. 3(b). The peak of this stimulated emission shows a blue shift in comparison with that of the spontaneous emission. At a current of 145 mA, many peaks appeared with a peak separation of 0.1-0.3 nm, as shown in Fig. 3 (c). If these peaks arise from the longitudinal modes, the mode separation  $\Delta\lambda$  is given by

$$\Delta \lambda = \lambda_0^2 / 2 / L / (n - (dn/d\lambda)\lambda_0),$$

(5)

where n is the refractive index,  $(dn/d\lambda)$  is the refractive dispersion and  $\lambda_0$  is the emission wavelength (406 nm). L was 0.067 cm. A value of 4.4 was used for n- $(dn/d\lambda)\lambda_0$ .<sup>13,22</sup> Thus,  $\Delta\lambda$  is calculated as 0.03 nm. Therefore, the observed peak separation is not the longitudinal mode separation. Many small peaks with a peak separation of 0.5-0.7 nm were also observed by other groups in the stimulated emission of GaN obtained by optical pumping.<sup>6,15</sup> Zubrilov et al.<sup>6</sup> proposed that the short cavity mirrors formed by cracks with a width of 20-50 µm in the GaN layer caused these peaks. However, we did not observe any cracks in our LDs. At currents above 155 mA, another subband emission appeared at a wavelength of 407.8 nm with several small peaks with a peak separation of 0.1 nm, as shown in Figs 3(d)-(f). The energy difference between these two subband emissions was 12 meV. The same spectra with many peaks and subband emissions were described in our previous papers.<sup>2-4</sup> However, the origins of the spectra have not yet been clarified. It is clear, however, that these spectra are not due to simple Fabry -Perot modes. Further study is necessary to clarify the origin of these spectra of InGaN MQW LDs.



Fig. 3. Optical spectra for InGaN MQW LDs at currents of (a) 132 mA (b) 136 mA (c) 145 mA (d) 155 mA, (e) 165 mA and (f) 175 mA. The intensity scales for these six spectra are in arbitrary units, and each one is different.

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