Greatly suppressed potential inhomogeneity and performance improvement of c-plane InGaN green laser diodes

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High-performance green InGaN laser diodes (LDs) are highly demanded in laser display, medical instruments, and quantum technology [1–4]. However, the fabrication of green LDs is challenging, and GaN-based green LDs ($\lambda > 500$ nm) were realized by Osram Corp until 2009 [5], which was 15 years after the first violet InGaN LDs. The greatest challenge is the growth of InGaN/(In)GaN multiple-quantum-well (MQW) active regions with high potential homogeneity. The potential fluctuation becomes pronounced as the indium composition increases in InGaN quantum wells (QWs) [6] due to the composition and interface fluctuation. The complex epitaxial structure of LDs results in a large strain and severe thermal degradation of InGaN during p-AlGaIn growth [7,8], therefore further deteriorating the potential homogeneity. The potential inhomogeneity suppresses the gain [9–11]. Additionally, potential inhomogeneity results in the reduced quantum efficiency in high-composition InGaN QWs [12,13].

In this letter, we report the optical characteristics of our green LD structure and chips. Greatly suppressed potential (luminescence) inhomogeneity is indicated first by temperature-dependent photoluminescence (TDPL) and time-resolved PL (TRPL) measurement of green LD structure and then by electroluminescence (EL) measurement of LD chips. The improved LD performance is shown as a result of greatly suppressed potential inhomogeneity in the InGaN QW active region.

Green LD structures were grown through a low-pressure metalorganic chemical vapor deposition reactor on c-plane free-standing GaN substrates. Trimethyl-aluminum, trimethyl-indium, and ammonia (NH₃) were used as the precursors for Al, In, and N, respectively. Triethyl-gallium was used as the precursor for Ga for InGaN layers and GaN quantum barrier layer, whereas trimethyl-gallium was the precursor for Ga for the other layers. Nitrogen and hydrogen were used as carrier gases. Monosilane (SiH₄) and bis(cyclopentadienyl)magnesium (Cp₂Mg) were used as n- and p-type dopants, respectively. The structure of green LDs comprised the following: a regrown n-GaN layer, followed by an n-AlGaIn cladding layer, an InGaIn lower waveguide (WG) layer, two pairs of InGaIn/GaN MQW active region, an upper InGaIn (u-InGaIn) WG layer, a p-AlGaIn electron blocking layer, a p-AlGaIn/GaN superlattice (SL) cladding layer, and a heavily doped p⁺-GaN contact layer. During the InGaIn/GaN MQW growth, special attention was paid to

obtain orderly step-flow growth and sharp interface [14–16]. The p-AlGaIn/GaN SL cladding layer was grown at a low temperature of 900°C to suppress the degradation of the high In-content InGaIn/GaN MQW active region [8]. In addition, the relatively high pressure of 400 mbar (1 mbar = 100 Pa) was adopted to suppress the incorporation of carbon impurities and ensure the low resistivity of the low-temperature grown p-AlGaIn/GaN SL cladding layer [17,18]. Indium tin oxide (ITO) was deposited as an additional cladding layer to further suppress the thermal degradation of green InGaIn QWs [19]. Fig. 1 shows the schematic of the device structure, layer structure, and light distribution perpendicular to the p-n junction of green LDs.

TDPL measurement was then performed on the green LD structure. The excitation power density was 7 W cm⁻² using a 405-nm diode laser. The measured temperature range was from 10 K to room temperature. Fig. 2a shows the TDPL full-width-half maximums (FWHMs) and PL peak energy of the green LD structure. The PL FWHMs at 10 and 300 K were 47 and 108 meV, respectively. To the best of our knowledge, this PL FWHM is the narrowest one ever reported. On the other hand, the TDPL peak energy showed an “S-shape,” which is commonly observed for InGaIn MQWs and indicates the existence of potential fluctuation in the InGaIn MQW active region [20–23]. The widely used Varshni’s empirical formula (Equation (1)), which was proposed by Eliseev [6], was used to quantify the degree of potential fluctuation [20–23].

$$E_g(T) = E_g(0) - \left(\frac{\alpha T^2}{\beta + T} \right) - \frac{\sigma^2}{k_B T}, \quad (1)$$

where $E_g(0)$ is the band-gap energy at $T = 0$ K, α and β are Varshni’s thermal coefficients, σ is the standard deviation of the energy distribution width of localized states, and k_B is the Boltzmann constant. The solid red lines in Fig. 2a are the fitting curves according to Equation (1). The parameters α and β were set to 0.43 meV K⁻¹ and 650 K, respectively. The fitted σ value, which indicates the degree of localization effect and broadening of the spectra, was 18.6 meV. This σ value is notably smaller than that reported by Eliseev [6] for InGaIn QW emitting in the green range and smaller than that reported for Nichia’s green LD structure [20] (Fig. 2b). This result indicates that the homogeneity of our green LD structure has been greatly improved.

TRPL measurements were performed at 12 K with the

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Figure 1 Schematic of the (a) device structure, (b) layer structure, and (c) light distribution perpendicular to the p-n junction of green LDs.

Figure 2 (a) TDPL peak energy and FWHMs of the green LD structure. (b) Broadening parameter of InGaIn-based QWs or LD structure as a function of emission energy.

experimental setup we reported previously at an excitation power density of 3 kW cm^{-2} [24]. Fig. 3 shows the time-integrated PL spectrum and recombination lifetime of the green LD structure. The red squares indicate the measured recombination lifetime. At a low temperature of 12 K, the recombination lifetimes are considered to be the radiative lifetime. According to a weakly localized exciton model [25], the emission energy (E) dependence of the PL lifetime τ can be expressed as Equation (2):

$$\tau = \tau_{\text{rad}} / (1 + \exp((E - E_{\text{me}}) / E_0)), \quad (2)$$

where τ_{rad} is the radiative lifetime, E_{me} is the mobility edge, and E_0 is the characteristic energy describing the tail state for exciton localization. The solid red curve in Fig. 3 is the fitted data obtained using this equation. The τ_{rad} , E_{me} , and E_0 were 155 ns, 2.35 eV, and 19 meV, respectively. The E_0 value is smaller than that reported for the state-of-the-art *c*-plane green LD structure [20] and comparable to that for the state-of-the-art semipolar green LD structure [26], indicating the excellent homogeneity in the active region of our LD structure.

Hybrid green LDs with an ITO cladding layer were fabricated with a ridge width of $15 \mu\text{m}$ and a cavity length of $1200 \mu\text{m}$ by conventional lithography and lift-off technique. The cavities were formed by cleaving along the *m*-plane facets. The EL measurements of the LD chips were carried out under pulsed operation at room temperature with a pulse width of $1 \mu\text{s}$ and a repetition frequency of 10 kHz to minimize the self-heating effects. Fig. 4a shows the EL spectra of green LD at current densities of 0.02 and 0.15 kA cm^{-2} and the lasing spectrum at a threshold current density of 1.80 kA cm^{-2} . The emission peaks

Figure 3 PL spectrum and energy dependence of PL lifetime of the green LD structure at 12 K. The solid red line indicates the fit by the weak localization model.

showed a blue shift, which was caused by the screen of the polarization field as the carrier density in the QWs increased. The peak wavelengths at current densities of 0.02 and 0.15 kA cm^{-2} were 541.0 and 534.8 nm, respectively. The lasing wavelength was 511.3 nm. Fig. 4b shows the output power of LD chips as a function of the injection current (power-current (*P-I*) curve). The slope efficiency was 0.8 W A^{-1} up to 2 A, and it decreased beyond 2 A, which was possibly caused by the carrier leakage or gain saturation kicking in. The optical power was 1.7 W at an injection current of 3 A.

Fig. 5a presents the EL FWHMs of the above-mentioned LD, which were 27 (114 meV) and 28 nm, at current densities of 0.02

Figure 4 (a) EL spectra of the green LD at current densities of 0.02, 0.15, and 1.80 kA cm⁻². (b) Output power of LD device as a function of current.

Figure 5 (a) EL FWHMs of InGaN-based LEDs or LDs as a function of emission energy. The data for comparison were from Refs [12,27–29]. The data from Ref. [27] are FWHMs at an injection current density of 0.15 kA cm⁻². The data from Ref. [29] are FWHMs at an injection current density of 0.09 kA cm⁻². The data from Ref. [28,12] are FWHMs at an injection current density of 0.02 kA cm⁻². The data from this work are FWHMs at injection current densities of 0.02 kA cm⁻² (red pentagram) and 0.15 kA cm⁻² (purple triangle). (b) *P-I* curves of green LDs with different lasing wavelengths.

and 0.15 kA cm⁻², respectively. The EL FWHMs of the other two LDs with spontaneous emission wavelengths of 547.0 and 555.4 nm at a current density of 0.02 kA cm⁻² were also plotted. The EL FWHMs of polar or semipolar InGaN-based light-emitting diodes (LEDs) or LDs reported in the literature are presented for comparison [12,27–29]. The FWHM values again indicate the degree of potential homogeneity. The FWHMs increased as a function of emission energy, regardless of the manufacturer, indicating that the homogeneity in InGaN QW worsened as the In content increased. The FWHMs of our LDs were the narrowest, indicating homogeneous luminescence in the active regions, which was consistent with the measurements discussed above. The lasing wavelengths of the other two LDs were 519.0 and 524.9 nm. Fig. 5b shows the *P-I* curves of the LDs with different lasing wavelengths. The output power decreased with the increase of lasing wavelength due to the increased threshold current and reduced slope efficiency, which was attributed to the poorer homogeneity obtained as the In content in the QWs increased.

In conclusion, green LD structure and LD chips were characterized by various optical measurements. The PL FWHM at 300 K under excitation power density of 7 W cm⁻² was 108 meV, and the EL FWHM at a current density of 20 A cm⁻² was 27 nm (114 meV). Both results indicate a considerable improvement in

potential homogeneity. The high potential homogeneity was also indicated by an extremely low σ value describing the energy distribution width of the localized states obtained by TDPL and a very low E_0 value describing the tail state for exciton localization obtained by TRPL. As a result of the remarkable improvement of potential homogeneity, green LD chips with a slope efficiency of 0.8 W A⁻¹ and an output power of 1.7 W have been achieved.

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改善势能均匀性提升c面InGa_N绿光激光器性能

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摘要 激光显示、医疗设备及量子通信迫切需求高性能Ga_N基绿光激光二极管(LD)。研制绿光LD最大的挑战是生长高势能均匀性的InGa_N/Ga_N多量子阱。我们采用各种光学测量手段对绿光LD结构和芯片进行了表征。在激发功率密度为7 W cm⁻²时, 300 K下光致发光半高宽为108 meV, 电流密度为20 A cm⁻²时, 电致发光半高宽为114 meV, 这些研究结果表明势能均匀性得到了显著改善。同时, 由变温光致发光测试得到的表征局域态分布宽度的 σ 值和由时间分辨光致发光测试得到的表征激子局域带尾态的 E_0 值都很小, 进一步表明势能均匀性很好。由于势能均匀性的极大改善, 实现了斜率效率0.8 W A⁻¹, 输出光功率可以达到1.7 W的绿光LD芯片。