Effect of Droop Phenomenon in InGaN/GaN Blue Laser Diodes on Threshold Current *

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Electroluminescence (EL) and temperature-dependent photoluminescence measurements are performed to study the internal quantum efficiency droop phenomenon of blue laser diodes (LDs) before lasing. Based on the ABC mode, the EL result demonstrates that non-radiative recombination rates of LDs with threshold current densities of 4 and 6 kA/cm^2 are similar, while LD with threshold current density of 4 kA/cm^2 exhibits a smaller auger-like recombination rate compared with the one of 6 kA/cm^2. The internal quantum efficiency droop is more serious for LD with higher threshold current density. The internal quantum efficiency value estimated from temperature-dependent photoluminescence is consistent with EL measurements.

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Group Ⅲ-nitride semiconductors have attracted a great deal of attention in the past several decades due to their great potential in optical applications such as light-emitting diodes (LEDs), laser diodes (LDs) and solar cells.[1,2] Although great progress has been achieved in GaN-based LEDs, efficiency droop is still a serious problem when injection increases. Many groups have tried to investigate the mechanism of the droop in LEDs and some interpretations, such as device self-heating, carrier delocalization, carrier leakage and Auger recombination, have been proposed.[3−6] For GaN based LDs, the typical threshold current density can be as high as 1 kA/cm^2, where there should exist a droop phenomenon below threshold current. However, the droop phenomenon is rarely studied in blue LDs. In this study, the relationship between efficiency droop and threshold current density of blue LDs is investigated. By adopting the typical ABC model, the recombination rates and the internal quantum efficiency are obtained from electroluminescence (EL) measurement. Temperature dependent photoluminescence (TDPL) is also taken to verify the internal quantum efficiency estimation.

The blue laser diodes are grown on commercial c-plane GaN substrates by metal organic chemical vapor deposition (MOCVD). The LD structure consists of an n-AlGaN cladding layer, an n-InGaN waveguiding layer, two periods of GaN/InGaN multiple quantum wells, a p-InGaN waveguiding layer, a p-AlGaN cladding layer and a p^{++}-GaN contact layer. The laser chips are packaged in the TO can. For this experiment, two samples named as LDs I and Ⅱ are chosen with threshold current densities of 4 and 6 kA/cm^2, respectively. These two samples come from one epi-wafer, which means that their structure details are nominally the same.

Firstly, light-current curves of LDs I and Ⅱ are measured below threshold, and the output power is acquired by the power meter. As shown in Fig. 1, at the same current density, LD I with lower threshold behaves at a higher output power, indicating that LD I has a higher external quantum efficiency.

The well-known ABC model[7] is used to evaluate the internal quantum efficiency and recombination coefficients,

$$G=\frac{\eta_{\rm j}J}{qd}=An+Bn^2+Cn^3, \quad (1)$$

where G is the generation rate, $\eta_{\rm j}$ is the injection efficiency, J is the current density, q is the elementary charge, d is the quantum well thickness, n is the carrier density, and A, B and C correspond to Shockley–Read–Hall (SRH) non-radiative recombination, bimolecular radiative recombination, and Auger-like recombination, respectively.

The measured power P is proportional to radiative recombination

$$P=kBn^2, \quad (2)$$

where k is a constant related to the light collection efficiency. From Eqs. (1) and (2), and assuming $\eta_{\rm j}=1$, the current density J can be expressed as[8]

$$J=\alpha P^{1/2}+\beta P+\gamma P^{3/2}, \quad (3)$$

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where α, β and γ are the fitting parameters,

$$\alpha = \frac{qdA}{(kB)^{1/2}}, \quad \beta = \frac{qd}{k}, \quad \gamma = \frac{qdC}{(kB)^{3/2}}. \tag{4}$$

The internal quantum efficiency η_i and the carrier density n have the following relationship

$$\eta_i = \frac{Bn^2}{An + Bn^2 + Cn^3}. \tag{5}$$

From the above equations, η_i can be given by

$$\eta_i = \beta \frac{P}{J}. \tag{6}$$

Thus with the fitting parameter β and the measured values of P and J, η_i can be obtained at arbitrary current density. In Fig. 2, both of the LDs achieve their maximum values at relatively low current density and suffer from a serious efficiency droop when the current density increases further. The internal quantum efficiencies drop around 63% compared with the maximum value in LD I and 71% in LD II at 2.5 kA/cm^2.

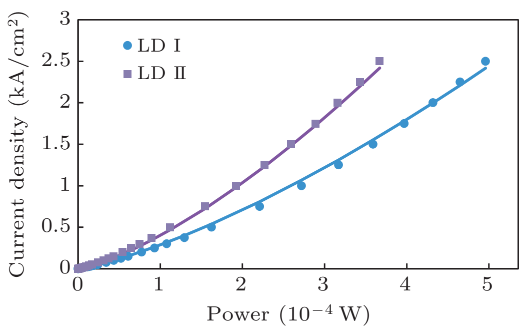

Fig. 1. Plot of the experimental data (solid dot) and fittings (line) of LDs I and II according to Eq. (4).

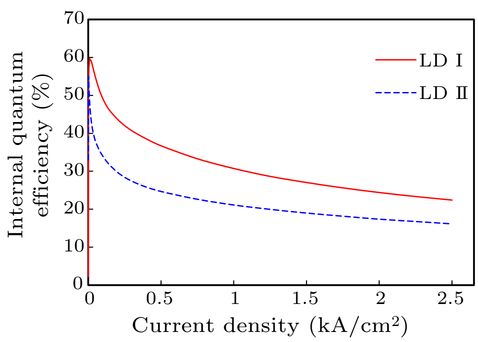

Fig. 2. Dependence of the internal quantum efficiencies of LDs I and II on current density as described in Eq. (6).

In the J–η_i curve, η_i achieves its maximum value η_{max} when $d\eta/dJ = 0$ at $J = J_{max}$. Then, J_{max} and η_{max} can be expressed as[9]

$$\eta_{max} = \frac{B}{B + 2\sqrt{AC}}, \quad J_{max} = \frac{qdA}{C}(B + \sqrt{AC}). \tag{7}$$

The recombination coefficients A, B and C are correlated to each other though J_{max} and η_{max},

$$A = \frac{(1-\eta_{max})\sqrt{BJ_{max}}}{2\sqrt{qd\eta_{max}}}, \quad C = \frac{4A^3q^2d^2}{J_{max}^2(1-\eta_{max})^2}. \tag{8}$$

It is assumed here that B is 2.0×10^{-11} cm^{3}s^{-1} for InGaN quantum wells at room temperature,[10] then A and C can be calculated from J_{max} and η_{max}. As listed in Table 1, the non-radiative recombination coefficient A of the two samples only differ slightly, which means that the material quality is nearly the same. However, this C coefficient value is one order of magnitude larger compared with the experimental value,[11–13] which may be due to the fact that the electron blocking layer (EBL) in LD structure is far away from the quantum well so that carrier leakage might be more severe than that in LEDs. What is more, it is assumed in the analysis that the injection efficiency is 100%, but it may be lower especially at high injection current. This assumption can lead to a higher C value. In addition, the auger-like recombination coefficient C differs by 1.8 times. Although the LDs are from the same epi-wafer, the widths of quantum wells can be different due to the temperature uniformity caused by wafer bending. This can also result in the difference of C.

Table 1. Non-recombination and auger-like recombination coefficient value of LDs I and II.

Sample	A (s^{-1})	C (cm^{6}s^{-1})	η_{max}	Threshold (kA/cm^2)
LD I	1.69×10^7	2.71×10^{-30}	59.66%	4
LD II	1.38×10^7	4.83×10^{-30}	55.05%	6

As shown in Fig. 2, similar coefficient A results in the similar value of η_{max}. However, the large difference in coefficient C leads to different droop phenomena in LDs I and II. At high current density before lasing, LD I with smaller auger-like recombination rate has much higher IQE, which thus results in a smaller threshold current. Therefore, suppressing this auger-like recombination rate is a good way to lower threshold current density for GaN-based LDs.

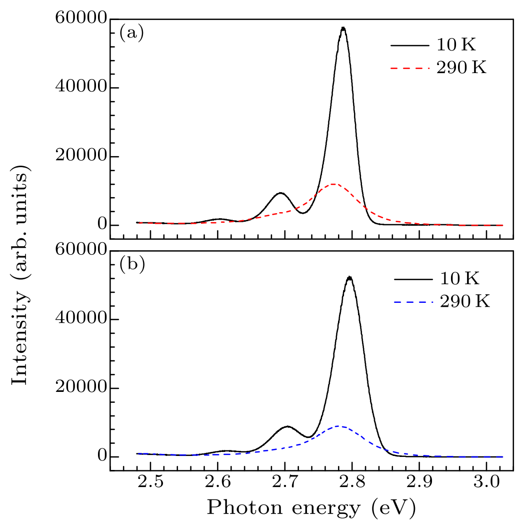

Fig. 3. TDPL spectra of LDs I and II.

To examine our result, temperature-dependent photoluminescence is employed to estimate the internal quantum efficiency. It is considered that the non-radiative recombination is frozen and the internal quantum efficiency η_i can be considered to be 100% at low temperature around 10 K. Then the non-radiative recombination center is active when the temperature increases. Here η_i can be obtained from the ratio of the intensity at room temperature I_{RT} and at low temperature I_{10K},[14]

$$\eta_i = \frac{I_{RT}}{I_{10K}}. \quad (9)$$

The metal of the laser chips was stripped by acidic solutions, and the TDPL is measured by the Montana Instrument® Cryostation. A 405 nm laser diode is adopted as excitation source which is only able to generate carriers in the quantum wells. Figure 3 shows the PL spectra at 10 K and 290 K. The internal quantum efficiencies obtained from Eq. (9) are 42.2% for LD I and 28.9% for LD II, respectively. The absorbed excitation power density J_1 by quantum wells can be expressed though excitation power density J_0, quantum well thickness d, reflectance R at the sample's surface and absorption coefficient α,

$$J_1 = J_0(1-R)(1-e^{-\alpha d}). \quad (10)$$

In this case, as $d \ll \alpha^{-1}$, Eq. (10) can be simplified to

$$J_1 = J_0(1-R)\alpha d. \quad (11)$$

In our experiment, the excitation power density is 200 μW with a beam diameter of 2 μm, and the reflectivity R is 18%. For the 405 nm photon, the absorption coefficient α of the InGaN quantum well is 5.4 μm^{-1}.[15] Calculation demonstrates that the absorbed power density is 26 A/cm^2. As shown in Fig. 2, the internal quantum efficiencies estimated by EL measurement of LDs I and II at 26 A/cm^2 are 58.2% and 41.8%, respectively, both are around 40% higher than those of the TDPL measurement. This deviation may be due to the uncertainty of the injection level calculation. As J_{max} is around 6 A/cm^2 for LD I and 2.5 A/cm^2 for LD II, both the LDs are suffering from the auger-like recombination process at 26 A/cm^2. It can be expected that at relatively low injection the internal quantum efficiencies obtained from TDPL should be the same.

In conclusion, the droop phenomenon of blue LDs below threshold has been investigated. EL and TDPL are employed to estimate internal quantum efficiency and recombination coefficients. The auger-like recombination rate is smaller for LD I with a threshold current density of 4 kA/cm^2 compared with LD II with a threshold current density of 6 kA/cm^2. The auger-like recombination is considered as the origin of the droop and suppressing this auger-like recombination can help to achieve a lower threshold for LDs.

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