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Effect of inhomogeneous broadening on threshold current of GaN-based green laser diodes

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Abstract: The inhomogeneous broadening parameter and the internal loss of green LDs are determined by experiments and theoretical fitting. It is found that the inhomogeneous broadening plays an important role on the threshold current density of green LDs. The green LD with large inhomogeneous broadening even cannot lase. Therefore, reducing inhomogeneous broadening is a key issue to improve the performance of green LDs.

Key words: GaN; green laser diode; inhomogeneous broadening; threshold current density

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1. Introduction

InGaN-based green laser diodes (LDs) are highly demanded for laser display applications and therefore have attracted intensive concern[1], but laser display requires high wall plug efficiency (WPE) and optical power for each LD. At present, the wall plug efficiencies of GaAs-based red and GaN-based blue laser diodes can reach 70% and 40%[2, 3], respectively. However, the WPE of green LDs are less than 20%. Improving the performance of GaN-based green LDs is crucial for red, green and blue (RGB) LDs based displays.

One of the key issue to fabricate high performance LDs is to ensure the high peak gain of the active region. However, the active region of green LDs contains higher In mole fraction than that of blue LDs, which makes the growth of active region material of the green LDs more difficult to control[4]. This factor also results in a larger inhomogeneous broadening of the gain spectrum which reduces the peak gain and differential gain of the quantum well material[5, 6]. Inhomogeneous broadening is usually caused by the fluctuation of the In mole fraction[7] and the thickness uniformity[8] of quantum wells. Therefore, it is important to study the effect of inhomogeneous broadening on the threshold current of the green LDs.

2. Experimental

Here we measured the net modal gain spectra of green LDs and used the inhomogeneous broadening characterization model[9] to fit the net modal gain spectra. The epitaxial growth of samples in this experiment was carried out on a commercial Aixtron 6 × 2 in. Close coupled showerhead (CCS) metal-organic chemical vapor deposition (MOCVD) reactor. The green LD structures consist of a 2 μm n-GaN layer, an n-AlGaN cladding layer, an InGaN lower waveguide (WG) layer, 2 pairs of InGaN/GaN QWs as the active region, an upper WG layer, a p-AlGaN electron blocking layer (EBL), a p-AlGaN/GaN (superlattices) SLs cladding layer, and a heavily doped p^+-GaN contact layer. The LD structures were then fabricated as ridge waveguide LD chips. Ridge-guided lasers with stripes of 10 μm width and 800 μm length were fabricated by conventional lithography and lift-off technique.

The inhomogeneous broadening characterization model is based on Ref. [9], but Eq. (11) was corrected. The net modal gain spectra and the internal loss of LDs was extracted from the high resolution electroluminescence (EL) spectra by employing the Hakki-Paoli method[10, 11] since the net modal gain spectrum converges to the internal loss at long wavelength. The LD chip was driven with direct current (DC) by Keithley Sourcemeter 4ZA4. We measured the EL spectrum with a spectrometer (Horiba 1250M series) and the resolution of our systems is as high as 0.006 nm (grating: 1800 groves/mm). All the measurements were performed at room temperature.

3. Characterization model and results

The band model of GaN materials reacts to the dispersion relationship of electrons and holes. In the simulation calculation, the $k{\cdot}p$ approximation theory[12, 13] is usually used to solve the Schrödinger equation to obtain the band model of GaN materials. This calculation method is complicated, but the purpose of the material gain model in this paper is to obtain an inhomogeneous broadening value of the materials, and a simplified model is adopted as described in the following.

This inhomogeneous broadening characterization model[9]

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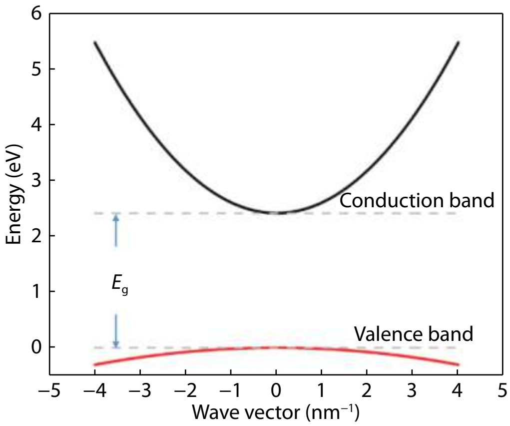

Fig. 1. (Color online) Band modal (Valence band and Conduction band).

starts with a simple parabolic band model. The band structure is shown in Fig. 1. The valence band and the conduction band are given by

$$E_{\rm v} = \frac{\hbar^2 k^2}{2m_{\rm v}}, \tag{1}$$

$$E_{\rm c} = \frac{\hbar^2 k^2}{2m_{\rm c}}, \tag{2}$$

where $E_{\rm v}$ is energy of hole, $E_{\rm c}$ is energy of electron, $\hbar$ is reduced Planck constant, k is wave vector, $E_{\rm g}$ is energy gap. The hole effective mass[14] is $m_{\rm v} = 2m_0$ and electron effective mass is $m_{\rm c} = 0.2m_0$. m_0 is mass of free electron. Electrons and holes follow the Fermi-Dirac distribution. The formula is as follows

$$f_{\rm v} = \frac{1}{1+\exp\left(\frac{E_{\rm v}-F_{\rm v}}{k_{\rm b}T}\right)}, \tag{3}$$

$$f_{\rm c} = \frac{1}{1+\exp\left(\frac{E_{\rm c}-F_{\rm c}}{k_{\rm b}T}\right)}, \tag{4}$$

where $k_{\rm b}$ is the Boltzmann constant, T is the Kelvin temperature, $F_{\rm c}$ and $F_{\rm v}$ are the quasi-Fermi level of the conduction band and the valence band, respectively. In InGaN quantum well, the density of states of electron is given by Eq. (5) and the density of states of hole is given by Eq. (6).

$$\rho_{\rm c} = \frac{m_{\rm c}}{\pi\hbar^2}, \tag{5}$$

$$\rho_{\rm v} = \frac{m_{\rm v}}{\pi\hbar^2}. \tag{6}$$

If the carrier concentration n is known condition, according to Eqs. (3)–(6) the quasi-Fermi level is determined by the following formula

$$F_{\rm c} = k_{\rm b}T\cdot\log\left[\exp\left(\frac{n}{\rho_{\rm c}k_{\rm b}}\right)-1\right], \tag{7}$$

$$F_{\rm v} = k_{\rm b}T\cdot\log\left[\exp\left(\frac{n}{\rho_{\rm v}k_{\rm b}}\right)-1\right]. \tag{8}$$

After calculating the quasi-Fermi level of the electron and hole, the distribution probability of the electron and hole can be obtained. Photon energy ($E_{\rm c}(k)$–$E_{\rm v}(k)$) is determined by energy of hole and electron. According to the band model, since the carrier distribution pattern has been obtained, the gain of the material can be given as follow

$$G_{\rm hom}(\omega) = \frac{C}{\pi\gamma_{\rm hom}}\int_{E_{\rm g}}^{\infty}(f_{\rm c}+f_{\rm v}-1){\rm Sech}\left(\frac{\omega'-\omega}{\gamma_{\rm hom}}\right){\rm d}w', \tag{9}$$

$$C = \frac{\pi e^2}{n_{\rm ref}c_{\rm vac}\varepsilon_0 m_0^2}\frac{m_{\rm r}}{\pi\hbar^2}M_{\rm b}^2, \tag{10}$$

where $\gamma_{\rm hom}$ is homogeneous broadening parameter, ω is photon angular frequency, $n_{\rm ref}$ is effective refractive index of quantum well, $c_{\rm vac}$ is velocity of light in vacuum, ε_0 is permittivity of vacuum, $L_{\rm d}$ is the width of quantum well, $M_{\rm b}$ is matrix element. Matrix element is affected by many factors[15]. In this paper, we consider matrix element as a constant and parameters are selected based on references[12, 16]. The reduced mass is $m_{\rm r} = m_{\rm c}m_{\rm v}/(m_{\rm c} + m_{\rm v})$. When the electron and hole pairs are all in the same state and are indistinguishable, there are four factors[17, 18] that cause the transition energy to be different and thus the homogeneous broadening of the gain spectrum. Homogeneous broadening is usually calculated by many-body approach and the homogeneous broadening uses the Sech function in this model.

Since inhomogeneous broadening is severe in InGaN QW active region, its effect on the gain must be considered, which can be described as Eq. (11)

$$G_{\rm ihom}(\omega) = \frac{C}{\sqrt{2\pi}\gamma_{\rm ihom}}\int G_{\rm hom}(\omega')\exp\left[-\left(\frac{\omega'-\omega}{\gamma_{\rm ihom}}\right)^2\right]{\rm d}\omega', \tag{11}$$

where $\gamma_{\rm ihom}$ is inhomogeneous broadening parameter and the inhomogeneous broadening is caused by electron–hole pairs being in different states[17, 18]. The difference in electron–hole pair state results in a Doppler frequency shift of the transition frequency, which ultimately causes the gain spectrum to produce a broadening of the Gaussian peak shape[19, 20]. The relationship between net modal gain and material gain of quantum well is expressed as

$$g = \Gamma G_{\rm ihom} - \alpha_{\rm i}, \tag{12}$$

where g is net modal gain of LD, $G_{\rm ihom}$ is material gain of quantum well, Γ is confinement factor and $\alpha_{\rm i}$ is internal loss of LD.

Figs. 2(a) and 2(b) show the net modal gain spectra of LD1 and LD2 and the fitting curves, respectively. The net modal gain spectra of both LD1 and LD2 shows large modulations at long wavelength, which is caused by the interference[21, 22] between the leakage mode and the waveguide mode of the green LDs. The modulations are absent for LDs without mode leakage according to our experiments. The interference modulation phenomenon only occurs in the long wavelength for two reasons. First, the substrate has no amplification effect of the gain material, so the intensity of the leakage mode is weak, and the intensity of the waveguide mode far from the peak gain is also weak. Second, the optical confinement of the

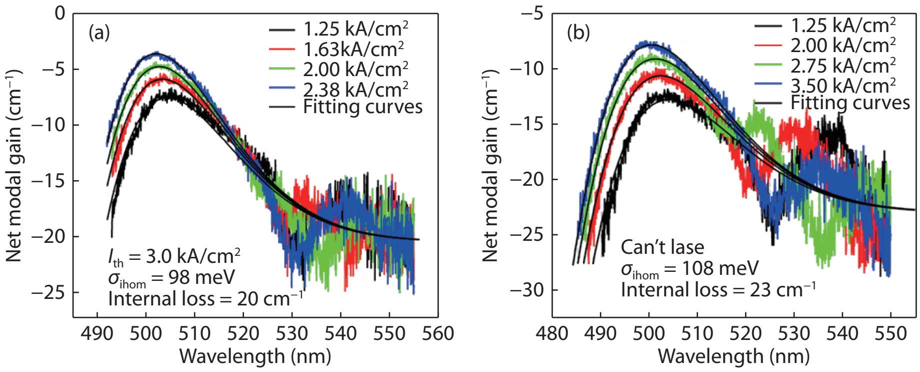

Fig. 2. (Color online) Net modal gain spectra and fitting curves of (a) LD1 and (b) LD2.

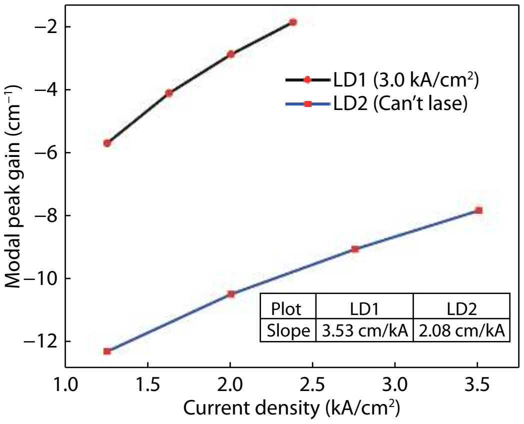

Fig. 3. (Color online) The relationship between modal peak gain and current density.

cladding layer is weaker at long wavelengths, this phenomena in turn lead to more serious mode leakage at long wavelengths[23, 24]. The internal loss is obtained first by the average of net modal gain at long wavelength tail, and is then used as fitting parameters in the fitting process. By doing so, the inhomogeneous broadening and the internal loss of LD1 are determined to be 98 meV and 20.0 cm^{-1}, respectively. The inhomogeneous broadening and the internal loss of LD2 are determined to be 108 meV and 23.0 cm^{-1}, respectively.

Fig. 3 shows the relationship between the mode peak gain (ΓG_{ihom}) and the current density. The spots are experimental data of mode peak gain, which are obtained by excluding the internal loss from the net mode gain shown in Fig. 2. The modal peak gain of LD1 is larger than LD2, which can be explained by the smaller inhomogeneous broadening of LD1. The lines are linear fitting of the experimental data of mode peak gain, which gives the differential gain of the LDs. The differential gain of LD1 and LD2 are 3.53 and 2.08 cm/kA, respectively. Therefore, higher inhomogeneous broadening of LD2 results into that its differential gain is 40% lower. For LD1 and LD2, the difference of internal loss is always 3.0 cm^{-1} at different currents density, but the modal peak gain difference increases as the current density increases. When the current density increases from 1.25 to 3.00 kA/cm^2, the mode peak gain difference of the LD1 and the LD2 increases from 3.9 to 8.2 cm^{-1}. So we believe that inhomogeneous broadening is the main reason why LD2 cannot lase.

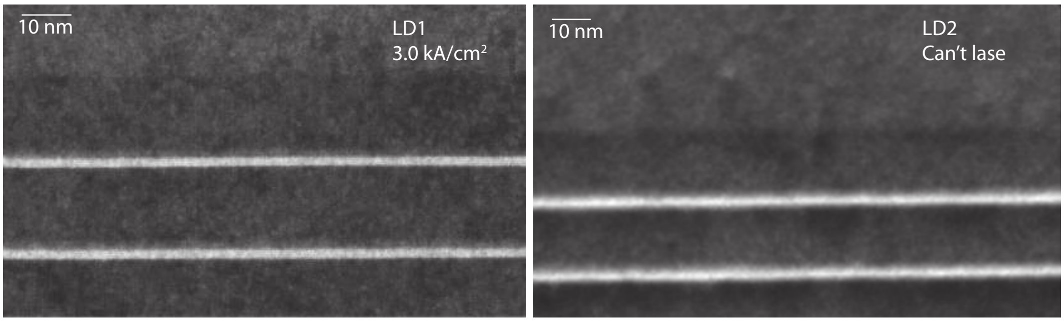

Fig. 4. STEM images of LD1 and LD2.

Fig. 4 shows the scanning transmission electron microscopy (STEM) images of LD1 and LD2. From the STEM images, the interface of the QWs (quantum wells) and QBs (quantum barriers) of LD2 is rougher than that of LD1, which might be the reason for the 10 meV inhomogeneous broadening of LD2 obtained by gain spectra measurement and fitting.

4. Conclusion

In conclusion, the inhomogeneous broadening parameter and the internal loss of green LDs are determined by experiments and theoretical fitting. It is found that the inhomogeneous broadening plays an important role on the threshold current density of green LDs. The green LD with large inhomogeneous broadening even cannot lase. Therefore, reducing inhomogeneous broadening is a key issue to improve the performance of green LDs.

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