Mode spacing ''anomaly'' in InGaN blue lasers

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An important experimental observation in InGaN laser diodes (LDs), which is not yet fully understood, is that the measured mode spacing of the lasing spectra could be one order of magnitude larger than that ''calculated'' from the known cavity length. The aim of this letter is to shed light on the nature of the mode spacing ''anomaly'' in InGaN LDs. We have derived a formula which accurately determines the mode spacing in InGaN LDs. Our analysis has shown that the discrepancy between the ''expected'' and observed mode spacing is due to the effect of carrier-induced reduction of the refractive index under lasing conditions and this discrepancy decreases and naturally disappears as the threshold carrier density required for lasing decreases. Since the carrier-induced reduction of the refractive index is expected only from an electron–hole plasma state, our results naturally imply that electron–hole plasma recombination provides the optical gain in InGaN LDs, like in all other conventional III–V semiconductor lasers. The implications of our results on the design of nitride optoelectronic devices are also discussed. © *1999 American Institute of Physics.* [S0003-6951(99)03008-9]

Over the past several years, we have witnessed rapid advances in the development of III–V nitride-based devices such as blue and UV light-emitting diodes (LEDs) (Ref. 1) and continuous-wave (cw) operation of InGaN multiple quantum well (MQW) laser diodes (LDs).[2,3] With continued progress in fabrication and optimization of InGaN LDs, it becomes increasingly important to understand the fundamental properties of this class of LDs. One of the key issues is of course the lasing mechanism in InGaN LDs, namely, the nature of the optical recombination that supplies the optical gain within the InGaN MQW active medium. Several lasing mechanisms for the III–V nitride lasers have been proposed recently, which include (a) localized exciton recombination in the In-rich regions (or the so-called ''quantum dot'' regions)[4,5] and (b) conventional electron–hole plasma (EHP) recombination.[6–8] The optical gain origin in the III–V nitride lasers has also been theoretically studied.[9,10] Calculation results have suggested that an interacting EHP recombination provides the optical gain in InGaN LDs. The optical gain spectra of Nichia's InGaN MQW blue LDs have been measured and it was suggested that EHP recombination is responsible for the gain mechanism.[11] Another puzzle involved in the development of InGaN LDs, which still remains unresolved, is that the measured mode spacing of the lasing spectra is larger (could be one order of magnitude larger) than that ''calculated'' from the known cavity length.[12,13] The discrepancy between the measured and the ''calculated'' mode spacing has been universally observed in the lasing spectra of GaN epilayer cleaved cavities by optical pumping[14,15] and pulsed InGaN LDs.[12,13] It has been proposed that the small cavity mirrors formed by cracks led to the observed large mode spacing.[14,15] However, these cracks have not been seen in InGaN LDs.[12,13]

In this letter, we have derived a formula which accurately determines the mode spacing in InGaN LDs. Our analysis has shown that the discrepancy between the ''expected'' and observed mode spacing is due to the effect of carrier-induced reduction of the refractive index under lasing conditions and this discrepancy between the ''expected'' and observed mode spacing decreases and naturally disappears as the threshold carrier density required for lasing decreases. Since the carrier-induced reduction of the refractive index is expected only from an electron–hole plasma state, our results thus imply that electron–hole plasma recombination provides the optical gain in InGaN LDs, like in all other conventional III–V semiconductor lasers. The implications of our findings on the design of the nitride LDs and other optoelectronic devices are also discussed.

Different mathematical formulas for the mode spacing in semiconductor lasers can be derived for the Fabry–Perot modes with different degrees of accuracy. In the following, we will discuss each case separately:

(i) In the simplest case, one assumes that the refractive index is a constant, $n=\text{constant}$. In this case, the resonant conditions are

$$2nL=m\lambda, \tag{1}$$

where L and λ are the laser cavity length and emission wavelength, respectively, and m is the order of modes within the Fabry–Perot cavity. It gives, by differentiating both sides of Eq. (1), $m\Delta\lambda+\lambda\Delta m=0$ and the mode spacing

$$\Delta\lambda=|-\lambda/m|=\lambda^2/2nL. \tag{2}$$

Equation (2) is the most crude formula for calculating the mode spacing of the lasing spectra of a semiconductor laser.

(ii) A more vigorous formula would include the dispersion relation of the refractive index, $n=n(\lambda)$. By doing so, we obtain from Eq. (1) that $2L(dn/d\lambda)\Delta\lambda=m\Delta\lambda+\lambda\Delta m$ and the mode spacing to be

$$\Delta\lambda(\lambda)=\frac{\lambda}{2L(dn/d\lambda)-m}=\frac{\lambda/2L}{(dn/d\lambda)-(n/\lambda)}. \tag{3}$$

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Equation (3) thus provides a more accurate description for the mode spacing than Eq. (2). As shown in all published literature so far, the mode spacing in III–V nitride lasers either by electrical or optical carrier injection have been estimated by using either Eq. (2) or Eq. (3). Thus, any discrepancy between the measured and the ''calculated'' (or ''expected'') mode spacing cannot be simply explained by Eq. (2) or Eq. (3).

(iii) Although the dispersion of the refractive index has been included in deriving Eq. (3), another crucial factor, namely, the effect of carrier-induced reduction of the refractive index under lasing conditions, must be included in order to explain the mode spacing ''anomaly'' in InGaN LDs. Such an effect is less critical in other semiconductor LDs, but it is very important for InGaN LDs, especially for relatively less superior pulsed LDs in which high threshold current densities or threshold carrier densities are required for lasing. Under lasing conditions, the high free-carrier density will alter the refractive index n. Thus, n is not only a function of λ, but is also a function of n_e, the free-carrier density. By writing $n=n(\lambda,n_e)$, the mode spacing must be recalculated. From Eq. (1), we have $2L(\partial n/\partial\lambda)_{n_e}\Delta\lambda+2L(\partial n/\partial n_e)_\lambda\Delta n_e=\lambda\Delta m+m\Delta\lambda$, which leads to

$$\begin{aligned}\Delta\lambda(\lambda,n_e)&=\frac{\lambda-2L(\partial n/\partial n_e)_\lambda\Delta n_e}{2L(\partial n/\partial\lambda)_{n_e}-m}\\&=\frac{\lambda-2L(\partial n/\partial n_e)_\lambda\Delta n_e}{2L(\partial n/\partial\lambda)_{n_e}-(2nL/\lambda)}\\&\approx(\Delta\lambda)_{n_e=0}[1-2(L/\lambda)(dn/dn_e)\Delta n_e],\end{aligned}\qquad(4)$$

where $(\Delta\lambda)_{n_e=0}$ is the mode spacing with neglecting the carrier effect and is just $\Delta\lambda(\lambda)$ of Eq. (3). In obtaining Eq. (4), we have used the approximation of $(\partial n/\partial\lambda)_{n_e}\approx(\partial n/\partial\lambda)_{n_e=0}\approx(dn/d\lambda)$. In most cases, the refractive index n decreases linearly with the free-carrier concentration,[6,16,17]

$$n=n_0-(2\pi n_e e^2/n_0 m^*\omega^2),\qquad(5)$$

where m^* and ω are the effective mass of carriers and frequency of laser emission, respectively, and n_0 is the refractive index of InGaN in the absence of free carriers. From Eqs. (4) and (5), we thus have

$$\begin{aligned}\Delta\lambda(\lambda,n_e)&=\Delta\lambda_{n_e=0}[1+(2L/\lambda)(2\pi e^2/n_0m^*\omega^2)\Delta n_e]\\&=\Delta\lambda_{n_e=0}[1+(2L/\lambda)(2\pi e^2/n_0m^*\omega^2)n_e].\end{aligned}\qquad(6)$$

Instead of Eq. (3), Eq. (6) provides a much more accurate description for the mode spacing of the lasing spectra, $\Delta\lambda$, in a semiconductor laser. Equation (6) includes the effect of free-carrier-induced refractive index reduction, which to the best of our knowledge has never been derived previously for semiconductor LDs but is the key for resolving the previously reported discrepancy between the observed and the ''calculated'' mode spacing in InGaN LDs. This will become quite transparent after we perform the following simple calculations.

The amount of reduction of the refractive index n due to the presence of the free carriers of density n_e is determined by Eq. (5). Using $n_0=2.6$, $m^*=0.2\,m_0$ (m_0 being the free-electron mass),[18] and $\hbar\omega=3.0\,\text{eV}$, we have

$$\Delta n=n-n_0=-(2\pi e^2/n_0m^*\omega^2)n_e=-3.2\times10^{-22}n_e(\text{cm}^3).\qquad(7)$$

Using the transparency density for less superior pulsed LDs of about $10^{19}/\text{cm}^3$ (Refs. 9 and 10) the refractive index change due to the free carriers is only about 3×10^{-3}, which is a small reduction. However, by including the variation of the refractive index with the carrier density in the mode spacing formula, a small reduction in the refractive index due to the carrier effect will result in a large change in the mode spacing because of the prefactor $(2L/\lambda)$ in the second term of Eq. (6). For a typical InGaN laser with a cavity length $L=500\,\mu\text{m}$ and emission wavelength $\lambda=0.40\,\mu\text{m}$, we would have the prefactor in the second term of Eq. (6) $2L/\lambda\approx2500$. Thus, Eq. (6) becomes

$$\Delta\lambda(\lambda,n_e)=\Delta\lambda_{ne=0}[1+8\times10^{-19}\ (\text{cm}^3)n_e].\qquad(8)$$

Assuming again the transparency density for less superior pulsed LDs of $10^{19}/\text{cm}^3$, by using Eq. (6) or Eq. (8), we obtain the mode spacing to be

$$\Delta\lambda(\lambda,n_e)=\Delta\lambda_{n_e=0}[1+8]=9(\Delta\lambda_{n_e=0}).\qquad(9)$$

We see that at a carrier density of $10^{19}\,\text{cm}^{-3}$ the mode spacing calculated by our formula of Eq. (6) is a factor 9 larger than that ''calculated'' by using Eq. (3) (or $\Delta\lambda_{n_e=0}$). Thus, Eq. (6) can easily explain why the observed mode spacing is about one order of magnitude larger than that ''calculated'' from the known cavity length by using Eq. (3) in relatively less superior LDs, in which high threshold carrier densities ($>10^{19}\,\text{cm}^{-3}$) are required to achieve lasing. Examples include the earlier Nichia's pulsed InGaN LDs,[12,13] pulsed InGaN LDs fabricated by a few other groups, and the optically pumped GaN epilayer cleaved cavities.[14,15,19]

In addition to providing a satisfactory explanation for the mode spacing ''anomaly,'' our formula also clearly illustrates that the discrepancy between the observed mode spacing and that ''calculated'' from the known cavity length by using Eq. (3) decreases linearly with the injected carrier density. As a natural consequence, in Nichia's later cw InGaN MQWs LDs in which the threshold current density was significantly reduced, the discrepancy between the measured and the ''calculated'' mode spacing by Eq. (3) became less noticable.[2,3,20]

More importantly, since the carrier-induced refractive index reduction is expected only from an EHP state, our analysis thus provides additional evidence that EHP recombination provides the optical gain in InGaN LDs. The formation of an electron–hole plasma state and the effect of reduced refractive index with increasing carrier density have been observed in InGaN epilayers under strong optical excitation.[6] It has also been suggested that under a high carrier injection rate, a local change in refractive index could result due to an increase in local temperature and excess carrier density.[14] Carrier-induced refractive index changes have been observed in other semiconductors.[21,22] Thus, in many cases, the variation of the index of refraction with the injection carrier density must be included in order to interpret the lasing spectra and the mode spacing. It is anticipated that the effect of reduction of the refraction index in the EHP state becomes more pronounced in lasers with shorter optical cavity lengths, especially the vertical cavity surface emitting lasers. Therefore, such an effect has to be taken into consideration in the design of optoelectronic devices using III–V nitrides.

In conclusion, we have shown through a mode spacing analysis that the lasing mechanism in InGaN MQW (LDs) is conventional, i.e., electron–hole plasma recombination provides the optical gain, like in all other III–V semiconductor lasers. An accurate formula describing the mode spacing in InGaN LDs has been derived. The discrepancy between the observed mode spacing and that ''expected'' from the known cavity length in the lasing spectra of the InGaN LDs and GaN epilayer cleaved cavities has been resolved. Our analysis has shown that the mode spacing ''anomaly'' in this class of LDs is due to the effect of the refractive index reduction in the electron–hole plasma state under lasing conditions. The implications of our finding on optoelectronic devices based on III–V nitrides have also been discussed.

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