Optical Gain Spectra in InGaN/GaN Quantum Wells with the Compositional Fluctuations

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The compositional fluctuations of the In content were found in InGaN/GaN quantum wells and it caused the localized states by the potential fluctuation. We have evaluated the optical gain of GaN based quantum well structures with localized states. The localized states are treated as the subband states of the quantum disk-like dots in the well. It was found that the inhomogeneous broadening played an important role in the optical gain and that it should be reduced to use the benefit of the localized states for laser oscillations.

Introduction

A short wave length is one of the essential requirements of laser diodes (LDs) for high-density storage devices. Recently, continuous-wave operation of the InGaN multi-quantum-well LDs with a life time of more than thousand hours has been achieved [1]. However, there is a key issue, such as high threshold carrier density, to lead them to commercial production. So far, we evaluated the optical gain of the wurzite GaN/AlGaN quantum well lasers and derived that the threshold current density of the GaN/AlGaN LDs would be estimated very high compared to conventional GaAs/AlGaAs quantum well LDs. It is caused by the large density of states due to the strong electronegativity and the weak spin-orbit coupling of the N atom in group-III nitrides. To overcome the problem, we proposed the strain effects [2] and the incorporation of the GaAs or GaP in the well layer to reduced the density of states.

On the other hand, the well layer of InGaN/GaN quantum wells has the compositional fluctuations of the In contents. These fluctuations would induce the localized states due to the random potentials. Since the radiative recombination attributed to the localized excitons by the alloy fluctuation in InGaN/GaN quantum wells were measured recently [3,4], it becomes important to study the relation between the localized states and the optical gain. We evaluated the optical gain coefficient, including the broadening in the spectra by the transitions between the localized states.

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Formalism

Let us describe the localized states caused by the compositional fluctuations. We assume that the potential fluctuations in the well are written by the quantum-disk like potentials and that they are randomly distributed without any correlation among them, as shown in Fig. 1. The Hamiltonians H^i for the electronic states for the electron (i=e), the heavy hole (i=hh) and the light hole (i=lh) is given by

$$H^i = h^i(z) - \frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial \mathbf{r}^2} + U(\mathbf{r}, z),$$

where

$$h^i(z) = -\frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial z^2} + V^i_{QW}(z), (\mathrm{i = e, hh, lh})$$

$$U(\mathbf{r}, z) = \begin{cases} 0 & \text{if } |z| > \frac{L}{2} \\ \sum_j v(\mathbf{r} - \mathbf{r}_j, R_j, u_j) & \text{otherwise} \end{cases}$$

$v(\mathbf{r} - \mathbf{r}_j, R_j, u_j)$ are the potentials by the compositional fluctuations at $\mathbf{r}_j$ in the two dimensional system, where R_j and u_j are the radius and the potential depth of the quantum-disk, respectively, as shown in Fig.2. Then, the eingenfunctions of the localized state can be approximated as

$$\Psi^i_{j,n,m}(\mathbf{r}, z) = \varphi^i_{j,n}(\mathbf{r})\zeta^i_m(z),$$

where

$$\left(-\frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial \mathbf{r}^2} + v(\mathbf{r} - \mathbf{r}_j, R_j, u_j)\right)\varphi^i_{j,n}(\mathbf{r}) = E^i_{j,n}\varphi^i_{j,n}(\mathbf{r}),$$

$$h^i(z)\zeta^i_m(z) = E^i_{z,m}\zeta^i_m(z).$$

$\varphi^i_{j,n}(\mathbf{r})$ and $\zeta^i_m(z)$ are the eigenfunctions in the lateral directions and *z* direction, respectively. Using the above eingenfunctions, the optical gain spectrum is given by

$$g(\omega) = \sum_{i,n,m,k}(1 - f(E^e_{n,k}) - f(E^h_{m,k}))\frac{1}{\pi}\frac{\left|\langle\zeta^e_n|\zeta^h_m\rangle\right|^2\Gamma_s}{(\omega - E^e_{n,k} - E^h_{m,k})^2 + \Gamma_s^2}$$

$$+ \sum_{i,n',m',n,m,k}(1 - f(E^e_{j,n'}) - f(E^h_{j,m'}))\frac{1}{\pi}\frac{\left|\langle\zeta^e_n|\zeta^h_m\rangle\right|^2\left|\langle\varphi^e_{n'}|\varphi^h_{m'}\rangle\right|^2\Gamma_l}{(\omega - E^e_{j,n'} - E^h_{j,m'})^2 + \Gamma_l^2}$$

where Γ_s and Γ_l are the energy widths of the broaden spectra for the continuum state transition and the localized state one, respectively. Γ_s is mainly caused by the carrier-carrier scattering and Γ_l is caused by the inhomogeneities of R_j and u_j of the potential.

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Results and Discussions

Figure 3 (a) and (b) show the potential profiles and the bound state energies by the compositional fluctuations. The energy depths are 80 meV for the electron and 50 meV for the holes. The radii of the disks are assumed to be 20_ and 50_, respectively. The effective masses are 0.2 m_0 for electron, 1.1m_0 for heavy hole and 0.17 m_0 for light hole, respectively. The quantum well length is 40_. In the case of R=20_, the number of the bound states are a few and it is almost like quantum-dots. However, the bound states become condensed, especially for the holes when the radius is more than R=50_. Then, these states become like band tailing by introducing the homogeneous or inhomogeneous broadening.

Figure 4 (a) and (b) show the carrier density dependence of the optical gain spectra of quantum wells with the random potentials in the case of Fig. 3 (a) and (b), respectively. The densities of the quantum disks are 1_10^{11} cm^{-2} in Fig. 4 (a) and Fig. 4 (b), respectively. We assumed here that the broadening energies, Γ_s and Γ_l, are same as 6 meV. It corresponds to the scattering rate of about 0.1 psec.

In the case of R=20_, there is only one peak from the localized state transition although there are two bound states in the valence band. This is due to the orthogonarity between the wavefunctions of n=1 and n=2. The gain appears from the localized state transition, increasing the carrier density. It becomes more than 1000 cm^{-1} at 4_10^{12} cm^{-2}. Note that the maximum gain is obtained at the localized state transition, which can be used for the laser oscillations.

On the other hand, in the case of R=50_, the gain appears from the localized state transitions. However, the maximum gain tends to move to the continuum state transitions, increasing the carrier density. Consequently, the advantage of using the localized states for laser oscillation becomes weak as long as the density of the localized states are around 1_10^{11} cm^{-2}.

Figure 5 shows the optical gain spectra for the case of Fig. 4 (b) at 6_10^{12} cm^{-2}, with the various broadening Γ_1 s. When the broadening becomes small as 2 meV, the gain spectrum gets sharp and large. However, when it becomes broaden as 20 meV, the gain peak gets so broaden that there are no more benefit for laser oscillations. Therefore, in order to use the localized states in terms of the quantum disks or dots, the inhomogeneity of the structures should be reduced.

Then, we have estimated the energy broadening by the carrier-carrier scattering in terms of the intraband transitions. Since the population inversion needs many carriers in the cavity, the carrier-carrier scattering would be dominant mechanism of the relaxation in the subband. The relaxation time or rate is given by the imaginary part of

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the self-energy of the electron and the hole. The localized electrons or holes are also scattered by the carriers around them in the continuum states. Then, the spectra of the transitions attributed to the localized states become broaden, as well, but this is not one by the inhomogeneity of the structures of the localized states. The relaxation times of the localized electron and the continuum one at n=2_10^{12} cm^{-2}, u=80 meV and R=50_ were 0.089 psec and 0.080 psec, respectively. They correspond to the energy broadening of 7.6 meV and 8.2 meV, respectively. The detail explanation of the calculation will be discussed elsewhere [5]. Then, the energy broadening of the localized state is comparable of the continuum one. Therefore, in order to use the quantum-dot like structures for the reduction of the threshold current density, the homogeneity of their structures are definitely necessary.

Summary

In this paper, we investigated the relation between the optical gain spectra and the localized states by the compositional fluctuation in the InGaN/GaN quantum well structures. The relation between the energy widths in the broaden spectra by the localized states and the continuum ones is important. Since the broadening by intraband transitions is manly due to the carrier-carrier scattering, we estimated them quantitatively by using the many-body approach and found that the broadening of the localized state and the continuum one are comparable. In order to use the localized states positively for laser oscillations, the reduction of the inhomogeneity of the energies is necessary.

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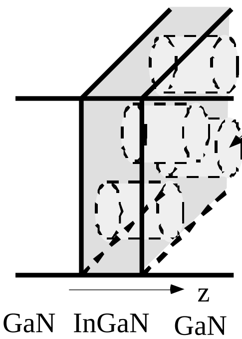

Fig. 1 InGaN/GaN quantum well structure.

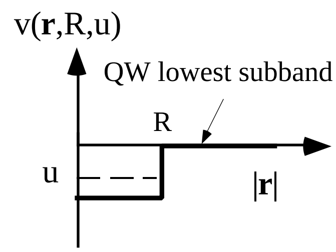

Fig. 2 Potential profiledue to the compositional fluctuations.

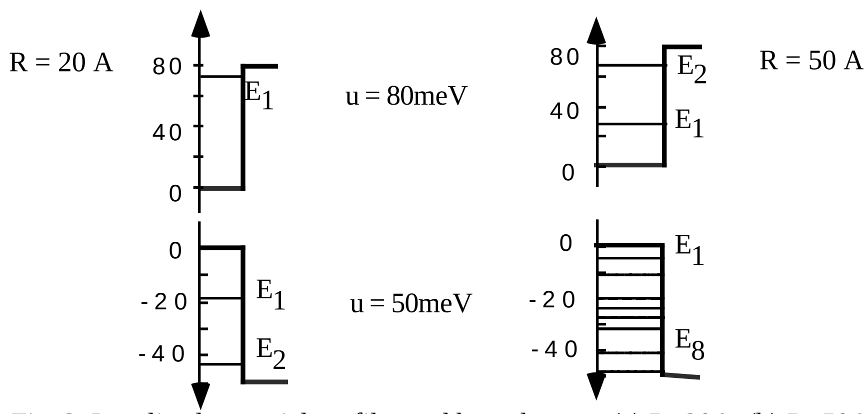

Fig. 3 Localized potential profiles and bound states. (a) R=20A, (b) R=50A.

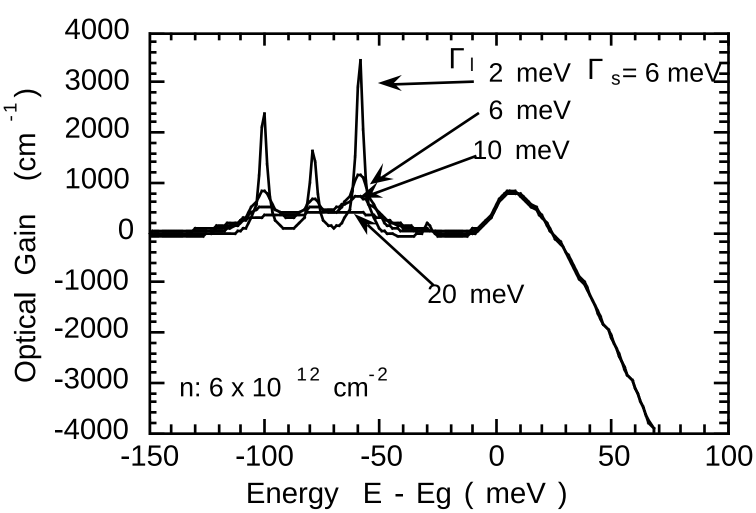

Fig.5. Optical gain spectra for the case of R=50 Å at 6_10^{12} cm^{-2}, with the various broadening Γ_l s.

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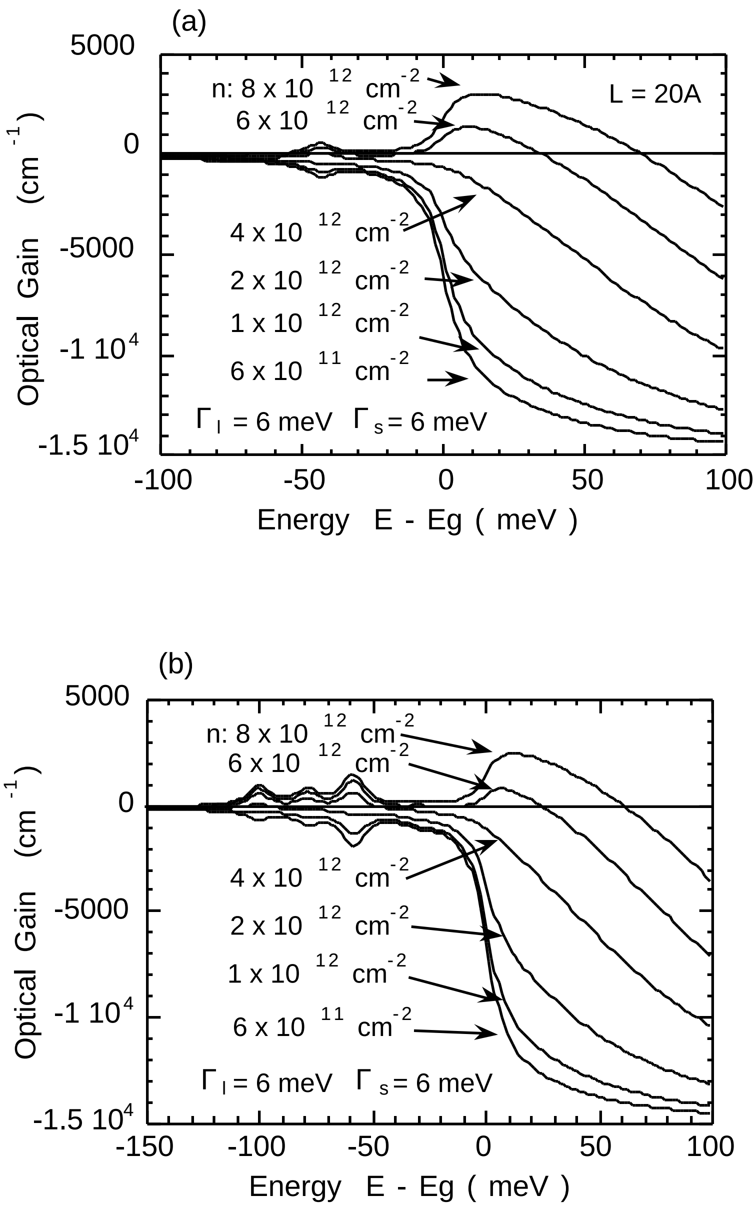

Fig. 4. Carrier density dependence of the optical gain spectra of quantum wells with the random potentials. R=20 Å (a) and R=50 Å (b)

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