F-2-05

Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp271-272

Experimental Studies and Model Analysis on Potential Fluctuation in InGaN Quantum-Well Layers

T. Fujita[1], S. Sakai[1], Y. Ikeda[1], A. A. Yamaguchi[1], Y. Kanitani[2], and S. Tomiya[2]

[1] Kanazawa Institute of Technology, Optoelectronic Device System R&D Center
7-1, Ohgigaoka, Nonoichi, Ishikawa 921-8501, Japan
Phone: +81-76-294-6725 E-mail: b1414471@planet.kanazawa-it.ac.jp
[2] R&D Center, Sony Corporation
4-14-1 Asahi-cho, Atsugi, Kanagawa 234-0014, Japan

Abstract

Potential fluctuation in InGaN quantum wells causes carrier localization and it strongly affects the gain characteristics in blue / green lasers. In this study, the carrier localization has been experimentally investigated in InGaN quantum wells, and the results have been explained by a theoretical model.

1. Introduction

InGaN quantum-well (QW) layers have been promising for active-layers in visible-light-emitting laser diodes. It is known, however, large potential fluctuation is introduced in the InGaN QW layers, due to alloy compositional and/or QW width spatial fluctuation. The fluctuation strongly affects the gain characteristics in laser diodes, and it is important to accurately evaluate the electronic states in such fluctuated systems. In general, injected carriers in such systems relax down to the lower energy states (*i.e.* spatial potential valleys), and they are localized and cannot move freely when they are relaxed to a critical energy or lower. The energy of such localized and nonlocal boundaries are called “mobility edge” (ME), which is often used as an index to evaluate the potential fluctuation. There have been at least three methods for evaluating the ME energy by optical measurements as follows; (1) Excitation-wavelength dependence of photoluminescence (PL) peak energy, (2) Excitation- wavelength dependence of PL intensity (PLE), and (3) Emission-wavelength dependence of PL lifetime. It has been reported, however, that the estimated ME values are sometimes different depending on the method.

In this study, we have experimentally estimated the ME energy for an InGaN-QW sample by the three methods, and have confirmed that the estimated values are completely different each other although the measurements are performed for the same sample. Next, to clarify the discrepancy, we have established a new theoretical rate-equation model considering fluctuation-induced tailing in the density of states (DOS) to describe the carrier dynamics in the system. Then, we have successfully explain the origin of the discrepancy between the ME-estimation methods by theoretical analysis using the rate-equation model.

2. Experimental results

400-nm light emitting InGaN-QW sample was used in the study, and the three ME estimation methods were carried out for the same sample, and all the measurements were performed at low temperature (~ 3 K). The experimental results are summarized in Fig. 1. In the first method, ME can be estimated from the dependence of the PL peak energy on the excitation wavelength [1]. As shown in the figure, when excited with energy sufficiently larger than the band gap, the PL peak energy becomes almost constant. However, when excited with a specific energy (~3.23 eV in this case) or lower, the PL peak energy decreases with excitation energy. In this behavior, ME can be estimated as this specific energy. In the second method, ME is obtained from the PLE spectrum. As shown in Fig. 1, the PLE signal increases with increasing energy from ~3.15 eV, and its increase becomes moderate around 3.22 eV. According to the classical percolation theory [2], the ME can be estimated as the energy where the PLE signal intensity is half of the maximum value in the spectrum, and it is estimated as 3.18 eV here. In the third method, ME can be estimated from the emission-wavelength dependence of PL lifetime (τ_{PL}) measured by time-resolved PL measurement. As shown in the figure, τ_{PL} increases with decreasing emission photon energy. The ME is obtained by fitting using the following Eq. (1) [3].

$$\tau_{\mathrm{PL}} = \tau_{\mathrm{r}}/[1 + \exp(E - E_{\mathrm{m}})/\sigma] \qquad (1),$$

where, the fitting parameters are τ_{r}: radiative recombination lifetime, σ: standard deviation of bandgap fluctuation, and E_{m}: ME energy. ME is estimated to be ~ 3.06 eV in this method. These results indicate that the estimated ME values are quite different depending on the estimation method.

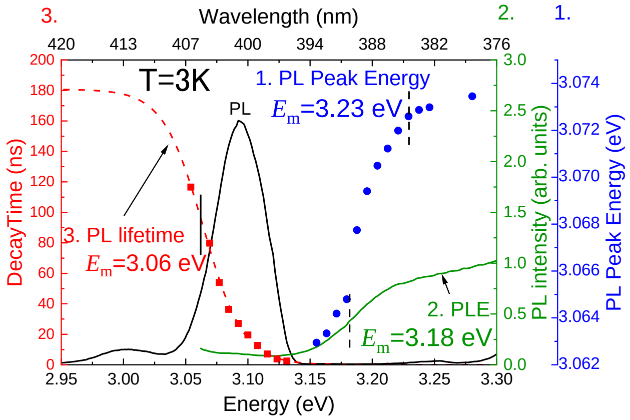

Fig.1 Measured PL spectrum, PLE spectrum, excitation-wavelength dependence of PL peak energy, and emission-wavelength dependence of PL lifetime. in an InGaN-QW sample at 3K.

3. Theoretical model analysis

A new theoretical model has been established to explain the above experimental results. Considering the DOS tailing due to the potential fluctuation, error-function-form DOS is assumed in the model. This corresponds to the DOS in the ideal QW systems (with step-function DOS) whose bandgap energy is fluctuated by Gaussian distribution. Figure 2 shows a schematic diagram of transition processes in the model. We consider finite energy spacing for convenience although the energy states are continuous in real bands, but we set the energy spacing sufficiently small. Carriers dynamics are calculated by using the following rate equations;

$$\frac{\mathrm{dn}}{\mathrm{dt}} = -\frac{\mathrm{n}}{\tau_{\mathrm{r}}} - \mathrm{Bn(E)} \sum_{\mathrm{E'<E}} [\mathrm{D} - \mathrm{n(E')}] + \mathrm{B}[\mathrm{D} - \mathrm{n(E)}] \sum_{\mathrm{E'>E}} \mathrm{n(E')} \quad (2)$$

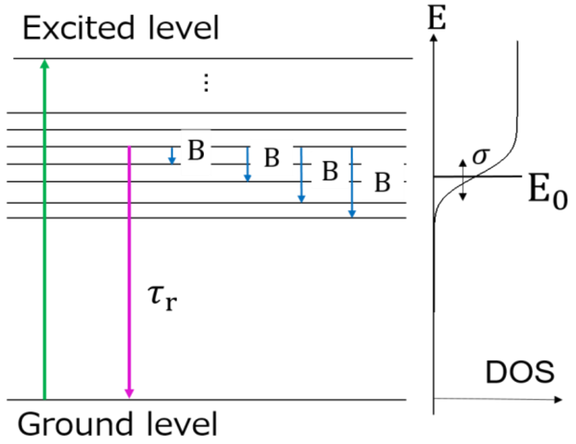

Fig.2 A schematic diagram of transition processes in the proposed theoretical model.

Here, n_i is the carrier density at i-th energy state, and τ_{r} is the radiative recombination lifetime. It is assumed that intra-band transitions take place only for energy downward direction, and that the transition rate is proportional to number of vacant states. D_i is the density of states for i-th energy state and it is set as proportional to the error-function DOS, and B is a parameter proportional to the intra-band relaxation rate. Since τ_{r} is independent of energy in this model, the PL spectrum reflects the carrier energy distribution itself. Then, we calculated time evolution of carrier distribution by using Eqs. (2), and the PL spectrum was calculated from temporal integral of carrier density at each state. The PL lifetime τ_{PL} was calculated as the time interval during the carrier density at each level decays into $1/e$ times of the maximum value. We tried to reproduce all the experimental results shown in Fig. 2 by optimizing the parameters in the theoretical model. Figure 3 shows an example of such calculated results of PL / PLE spectra, excitation-wavelength dependence of PL peak energy, and emission-wavelength dependence of PL lifetime. In this calculation, we set maximum density of state as 4.7×10^{20} $1/(\mathrm{eV \cdot cm^3})$, τ_{r} as 18 ns, B as 2.4×10^{-7} $\mathrm{cm^3/s}$, and excited carrier density as 3.7×10^{17} $1/\mathrm{cm}^3$, respectively, and set the standard deviation of the error-function DOS, the degree of fluctuation, as 40 meV.

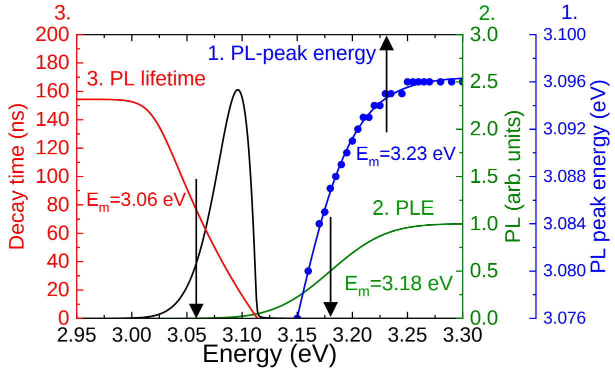

Fig.3 Calculated PL spectrum, PLE spectrum, excitation-wavelength dependence of PL peak energy, and emission-wavelength dependence of PL lifetime.

It is shown that the calculated results shown in Fig. 3 agree quite well with the experimental results shown in Fig. 1, and that estimated ME values by the three methods (shown by arrows in the figure) also agree qualitatively between the experimental and theoretical results. Furthermore, it can be seen that the dependences are quite similar between the excitation-wavelength dependence of PL peak energy and the PLE spectrum in the two figures. This can be explained as follows. When the excitation wavelength is longer than a certain value, light absorption is reduced by the DOS reduction. That causes signal decrease in the PLE spectrum. At that time, excited carrier density also decreases and it causes the red-shift of PL peak because the state-filling induced blue-shift is reduced. Thus, it is shown that the ME estimated from the excitation-wavelength dependence of PL peak energy is not accurate. Moreover, it is found that the emission-wavelength dependence of PL lifetime cannot provide accurate values because the calculated results strongly depend on the ratio of τ_{r} and τ_{tr}. Thus, it is suggested that the method using the PLE spectrum can be the most suitable way to estimate the ME values.

4. Conclusion

In this study, we have performed the three methods to estimate the ME for the same InGaN-QW, and have confirmed that these methods cannot provide the same value. These results have been successfully reproduced by the proposed theoretical model considering the DOS tailing due to the potential fluctuation. Based on the calculation results, it is suggested that the method using the PLE spectrum can be the most suitable way to estimate the ME values. This work was partially supported by JSPS KAKENHI (JP19H04553).

References

[1] A. Satake *et al*, Phys. Rev. B**57,** R2041 (1998).
[2] M. Oueslati *et al*, Phys. Rev. B**37,** 3037 (1988).
[3] J. Hegarty *et al*, Phys. Rev. B**32,** 1354 (1985).