Free carrier screening of quantum confined Stark effect affecting on luminescence energy shift and carrier lifetime in $In_{0.12}Ga_{0.88}N$/ $In_{0.03}Ga_{0.97}N$ quantum wells

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In InGaN quantum wells (QWs), the large internal polarization field[1] is known to cause a luminescence energy shift and a reduction of the oscillator strength. Both these behaviors were mainly investigated in relation to the quantum well thickness[2]. In this paper, we focus on free carrier screening of quantum confined Stark effect (QCSE) caused by the internal electric field. Theoretically, the free carrier screening effect is reported to explain some puzzling experimental data on nitride lasers, such as the unusually high lasing excitation thresholds and emission blue shift for increasing excitation levels[3]. To clarify the importance of this effect, we have performed a systematic study of time-resolved photoluminescence (PL) measurements of $In_{0.12}Ga_{0.88}N/In_{0.03}Ga_{0.97}N$ multiple quantum wells (MQWs) for various carrier density. We show that the energy shift for small carrier density and the change in the carrier lifetime are well explained by the free carrier screening effect which compensates the internal electric field.

The sample used in this study is a MQWs structure which has three periods of 4-nm-thick $In_{0.12}Ga_{0.88}N$ wells and 5-nm-thick $In_{0.03}Ga_{0.97}N$ barriers grown on a SiC substrate by metalorganic vapor phase epitaxy. We have measured the time-resolved PL spectrum at 10 K using a streak camera with time resolution of 20 ps. Frequency-doubled optical pulses generated from a Ti:sapphire laser are used for pumping. The pumping wavelength is 384 nm which excites only the well layers. The repetition rate of laser pulses is 100 MHz. The pump power is changed from 0.5 mW to 15 mW to change carrier densities. the carrier density of 1 mW pumping is deduced to be 2.0×10^{17} /cm^3 assuming the quantum efficiency of 1.

First, we focus on the carrier density dependence of the PL energy. The inset in Fig. 1 shows the PL spectra of low carrier density (1 mW pumping) and high carrier density (15 mW pumping). This figure typically shows a red shift with decreasing carrier density. We plotted the peak energy of the PL spectrum as a function of the carrier density in Fig. 1. Note that the change in the energy is larger for smaller carrier densities. The PL energy decreases nonlinearly with decreasing carrier density for pump power below 7.5 mW, although the PL energy shift appears to have a linear characteristic above this value.

Next, in Fig. 2, we depicted the carrier density dependence of the carrier lifetime which is evaluated at the time delay of 0.5 ns using single exponential fitting. For carrier density below the pump power of 7.5 mW, the carrier lifetime increases nonlinearly with decreasing carrier density. For carrier density above this value, the change in the carrier lifetime becomes extremely small and the carrier lifetime converges to 2.2 ns.

Most of these experimental results can be explained qualitatively by the free-carrier screening effect[3] which compensates QCSE. The internal electric field, which is spontaneous or piezoelectric, causes band bending resulting in the red shift and the spatial separation of the confined electrons and holes in the quantum well. The increase of the spatial separation between electrons and holes causes the decrease of the recombination rate. On the contrary, free carriers screen internal electric field and reduce the QCSE. Therefore, for higher carrier density, we can expect a larger luminescence energy and smaller spatial separation between electrons and holes resulting in a shorter lifetime.

To verify the quantitative agreement, we calculated the magnitude of the free carrier screening effect by solving the Poisson equation and the Schrödinger equation of the envelope function model self-consistentely. Because of the uncertainty of the effective masses of carriers in InGaN, we used an effective electron mass of $0.2m_0$ and a hole mass of $0.54m_0$, which are the same as those of carriers in GaN. In Fig. 1, we fitted the energy shift mainly for the lower carrier density region where the energy shift is large. The internal electric field is a unique fitting parameter which is optimized to be 650 kV/cm. Note that the observed dependence, especially in the case of lower carrier densities, is well explained by this model.

We calculated the recombination rate as a function of the carrier density. We approximated the recombination rate by $\langle\phi_e|\phi_h\rangle^2$, where ϕ_e and ϕ_h are the wave functions of electrons and holes, respectively. We plotted $\langle\phi_e|\phi_h\rangle^2$ by assuming that the PL decay time of 2.2 ns corresponds to $\langle\phi_e|\phi_h\rangle^2 = 1$. A good agreement is obtained for the carrier recombination rate as shown in Fig. 2. Both these quantitative agreements prove that the free carrier screening of QCSE is the most dominant mechanism which determines the carrier density dependence of the carrier lifetime and the luminescence energy. Another interesting feature is that although the dependence of the PL decay time becomes flat for pump power above 7.5 mW in Fig. 2, the PL energy in Fig. 1 still increases with leaving from the theoretical curve. This energy difference can be attributed to the band-filling effect which becomes significant after the realization of the flat band condition. Since the QW has a step-function-like density of states, the PL energy should shift linearly at low temperatures in the frame of the band filling effect.

In conclusion, we have performed a systematic study of time-resolved PL measurements for $In_{0.12}Ga_{0.88}N/In_{0.03}Ga_{0.97}N$ MQWs for various carrier densities. Carrier recombination rate and PL energy, for carrier density below the pump power of 7.5 mW, are found to decrease nonlinearly with decreasing carrier density, although the carrier recombination rate becomes constant and PL energy shift becomes linear for high carrier density. We show that the energy shift for small carrier density and the change in the carrier lifetime are well explained by the free carrier screening of the QCSE. The linear energy shift for high carrier density is attributed to the band-filling effect.

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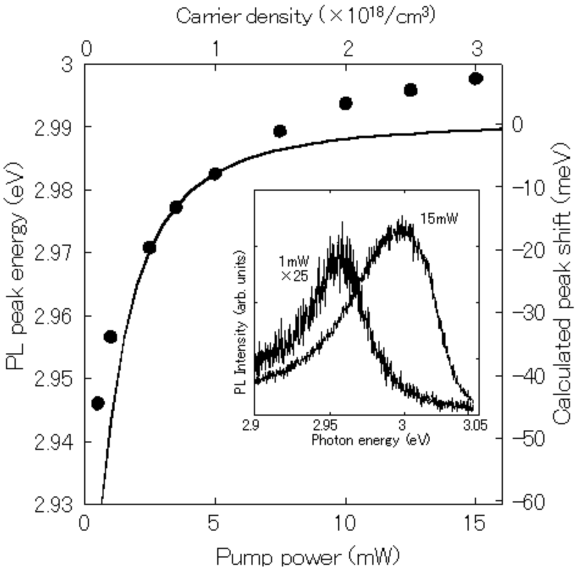

Fig. 1 Pump power dependence of PL peak energy at 10 K (solid circle). The PL peak energies are measured after 0.5 ns from optical excitation. The solid curve represents the calculated PL energy shift as a function of carrier density assuming an internal electric field of 650 kV/cm. The inset shows the measured PL spectra for 15 mW and 1 mW . Each spectrum is time-integrated between the time delay of 0.2 ns and 0.8 ns.

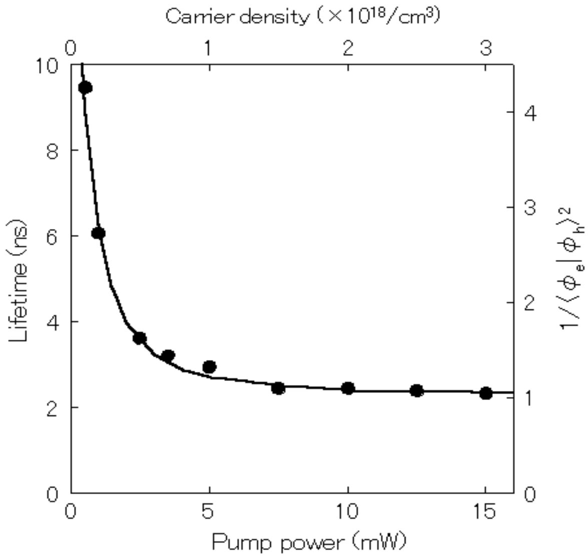

Fig.2 Pump power dependence of lifetime at 10 K (solid circle). PL decay time are measured at the times delay of 0.5 ns. The solid curve represents the calculated recombination rate as a function of carrier density assuming an internal electric field of