Photoluminescence properties of a quantum system consisting of different size GaAs quantum wells

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Abstract

Photoluminescence properties of a quantum system consisting of four different size GaAs quantum wells (Lz=15, 7, 4.5 and 3 nm) clad by 50 nm thick $Al_{0.24}Ga_{0.76}As$ barriers have been investigated by steady-state and time-resolved (TR) photoluminescence (PL) experiments at 13-300 K. It is found that the low temperature PL emission energy distribution is not uniform over the four excitonic emission bands and different from that expected for thermalized carriers at higher temperatures above 260 K. TR-PL measurements indicate that the non-uniform PL intensity distribution observed at low temperatures is a result of non-uniform quantum capture processes of photoexcited carriers.

Keywords: semiconductor quantum well, photoluminescence, carrier capture, GaAs/AlGaAs

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1. Introduction

In a quantum system consisting of different size quantum wells (QWs) separated by thick enough barriers, confined electron states in each well are considered to be independent and the photoluminescence (PL) properties should exhibit their own characteristics with no correlation each other. However, recent PL studies in the quantum systems [1-3] show complicated emission behaviors, which cannot be explained by taking exciton states in the QWs independent with respect to radiative recombination processes. For example, the efficient exciton energy Stokes and anti-Stokes transfer between widely separated asymmetric double quantum wells was reported by Tomita et al. [1] and interpreted by dipole-dipole interaction of excitons. Kim et al. [2] also observed the large interwell transfer through sufficiently thick barriers in double-well systems, but their results were explained by parcolation of carriers through low potential channels within the barriers. In a system of triple quantum wells separated by thick barriers [3], unusual emission properties have also been reported where the high energy emission is dominating over the low energy emission, suggesting that the composite wells are by no means independent with respect to exciton recombinations, radiative fields and carriers capture processes.

In this paper, photoluminescence properties of a quantum system consisting of four different size GaAs quantum wells clad by sufficiently thick $Al_{0.24}Ga_{0.76}As$ barriers have been investigated by steady-state and time-resolved (TR) PL experiments at 13-300 K. It is found that the emission energy distribution from the four excitonic emission bands show unusual behaviors at lower temperatures. Thus, the unusual emission energy

distribution can generally occur irrespective of the number of wells in the composite well systems and be sensitively changed by variations of the lattice temperature. From TR-PL studies, low temperature PL decay behaviors are investigated and drastic differences are observed between the four emission bands. The temperature dependent TR-PL results suggest that the non-uniform quantum capture process of photoexcited carriers plays an important role to determine the emission energy distribution in the present quantum system.

2. Experimental

A QWs sample used for the present study was grown on a GaAs (100) substrate by molecular beam epitaxy. A schematic potential diagram of the undoped QWs system consisting of four different size GaAs quantum wells is shown in Fig. 1. Nominal widths of the GaAs quantum wells are L_Z= 15.0 nm (QW1), 7.0 nm (QW2), 4.5 nm (QW3) and 3.0 nm (QW4) starting from the substrate side which are isolated by 50 nm thick $Al_{0.24}Ga_{0.76}As$ barriers. These heterostructures were grown after a GaAs/AlGaAs superlattice buffer layer and terminated with a 100 nm thick $Al_{0.24}Ga_{0.76}As$ barrier. In this sample, since the barrier thicknesses are thick enough, the ground confinement states of all the QWs are electronically isolated and considered to be independent. Calculations of the subband states according to the Kronig-Penny type model within the effective mass approximation [4] predict that the lowest confined electron (heavy-hole) energies are 15.6 (3.7) meV for QW1, 46.1 (12.7) meV for QW2, 75.5 (23.5) meV for QW3 and 107.6 (38.1) meV for QW4, respectively. From these values the transition energies are

calculated to favorably compare with the observed ones. Steady state PL spectra of the sample were measured at 15-300 K in a closed loop He cryostat using a 5 mW He-Ne laser at 632.8 nm for excitation and a Jovan-Yubon HR-320 monochromator equipped with a GaAs photomultiplier (Hamamatsu R636-10) and a computer controlled digital lock-in amplifier system for ac detection. Spectrally and time resolved PL transients were measured at 13-150 K also in a closed loop He cryostat using a 50 ps pulse diode laser at 654 nm for weak exciation (average power of 1 μ W) and a Streak camera system (Hamamatsu C4334-02) for photon counting detection.

3. Results and discussion

Figures 2 shows PL spectra of the QWs sample measured at several lattice temperatures from 15 K to 260 K. The PL intensity is normalized by the maximum peak in each PL spectrum. The base lines of the PL spectra are shifted vertically for clarity. In the lowest PL spectrum measured at 15 K, the calculated transition wavelengths (energies in the upper horizontal scale) between the first electron and heavy-hole confinement states are indicated by arrows, neglecting the excitonic effects. The PL peak positions are in general agreement with the calculated values, if we consider uncertainty of the nominal well widths determined from the GaAs growth rate without the substrate rotation. However, it is important to note that the emission energy distribution from the four excitonic bands show unusual behaviors especially at lower temperatures. That is, the highest energy emission (QW4) at 1.681eV has the highest intensity at 15 K in contrast to the case at 260 K where the lowest energy emission (QW1) at 1.538 eV is

dominating due to thermalization of photogenerated carriers. At higher temperatures above 260 K the lowest energy peak (QW1) always shows the highest intensity, while the other PL peaks monotonously decrease as the emission energy increases, reflecting a thermal population. These high temperature PL intensity distributions can easily be understood in terms of thermalized and partly ionized excitonic emissions [5], since the photogenerated electron-hole pairs mainly generated in the barrier region are quickly thermalized by efficient phonon scatterings before captured and recombined in the QW layers. The emission high energy tails above the exciton lines are then explained by free carrier recombinations. We note that, at higher temperatures above 80 K, the light-hole exciton PL peaks also appear at higher energy sides of the heavy-hole exciton lines in Fig. 2.

In the lower temperature PL spectra at 15-80 K, however, it is found that the emission energy distribution strongly depends on the lattice temperature and shows complicated behaviors, as seen in Fig. 2. For example, the PL emission from QW2 exhibits the highest intensity at 80 K. To show variations of these PL signals, the peak intensities from the four emission bands are plotted in Fig. 3 (a) as a function of temperature and in Fig. 3 (b) the PL intensity ratios normalized by the PL peak intensity of the QW1 emission at each temperature. Although the absolute PL intensities generally decrease with temperature in Fig. 3 (a) due to the non-radiative recombination channels, we note that the PL intensity from QW2 shows a distinct plateau at intermediate temperature regions. For QW3 a weak plateau is also seen around 80 K in Figs. 3 (a) and (b). These results indicate that the four quantum wells are by no means independent with respect to excitonic radiative recombination efficiencies.

Figure 4 shows two-dimensional gray-scale plots of PL streak images for the four emission bands (QW1, QW2, QW3 and QW4) as a function of time and wavelength at four temperatures of 13 K, 30 K, 50 K and 70 K. The laser excitation pulse is located at 1.27 ns in the ordinate of this figure. In the top most images at 13 K, it is evident that the QW1 emission has the shortest decay with an exponential time constant of 0.14 ns, while the highest energy QW4 emission as well as the QW2 and QW3 bands exhibit much longer decays. This result clearly indicates that the decay time behaviors are not uniform through the four excitonic emission bands. The observed short decay time for the QW1 emission from the widest well cannot be related to the radiative recombination lifetime [6]. This is because the exciton binding energy of the widest (15 nm) well must be the smallest and therefore it should lead to the longest radiative lifetime [7]. The shortest decay time for QW1 is not ascribed to the enhanced non-radiative recombination channel for the quantum well firstly grown after the alloy cladding layer [8], because the QW1 PL peak has the highest intensity in the high temperature PL spectra compared to the other PL signals. Therefore, the short decay time of the QW1 emission does reflect the radiative processes in this composite QW system. When the temperature is increased to 30 K, decay times of all the emission bands start to decrease due to activation of the non-radiative recombination channels at higher temperatures. Above 50 K, the non-radiative recombination is dominating under the weak excitation conditions and the decay behaviors become homogeneous over the four emission bands. Because the efficient non-radiative recombination masks the intrinsic behaviors of dynamics above 50 K in this sample, we plot the PL transients in a semi-logarithmic scale as a function of time at 13 K and 20 K in Fig. 5 (a) and (b), respectively. Typical two exponential decays

are seen with fast and slow components due to free and localized excitons, respectively [9]. Although the measured temperature range is limited, it is clearly seen that the decay time from QW1 becomes shorter at 20 K than at 13 K, while PL lifetimes from the other PL bands do not change significantly except for an enhancement of the initial PL increase for QW2. That is, the difference of PL transients between QW1 and QW2 is enhanced when the temperature is slightly increased. These results indicate that the non-uniform quantum capture processes of photoexcited carriers play an important role to determine the temperature-dependent PL emission energy distribution.

4. Conclusion

Photoluminescence properties of a quantum system consisting of four different size GaAs quantum wells (Lz=15, 7, 4.5 and 3 nm) clad by 50 nm thick $Al_{0.24}Ga_{0.76}As$ barriers have been investigated by steady-state and time-resolved (TR) photoluminescence (PL) experiments at lattice temperature between 13 and 300 K. It is found that the emission energy distribution from the four excitonic emission bands show unusual behaviors, that is, the highest energy emission has the highest intensity at lower temperatures in contrast to the high temperature (260-300 K) cases where the lowest energy emission is dominating due to thermalization of photogenerated carriers. The TR-PL results indicate that the decay time from the lowest energy emission is the shortest, suggesting importance of the carriers capture processes in contrast to the fact that the other three higher energy emissions show much longer decays basically determined by non-radiative processes. These results suggest that the non-uniform

quantum capture processes of photoexcited carriers are operative and play an important role to determine the emission energy distribution, competing with the temperature dependent phonon-assisted thermalization processes.

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Captions to Figures

Fig. 1 Schematic potential diagram of the QWs sample structure

Fig. 2 Normalized photoluminescence (PL) spectra at 15 K, 30 K, 50 K, 80 K, 160 and 260 K. Calculated positions of the interband transitions between the first confined electron and heavy-hole states (1e-1hh) are indicated by vertical arrows for QW1, QW2, QW3 and QW4. The spectra are vertically shifted for clarity.

Fig. 3 (a) PL peak intensity and (b) PL peak intensity ratio normalized by the QW1 PL intensity as a function of temperature

Fig. 4 PL streak images for four excitonic emission bands as a function of wavelength and decay time at 13 K, 30 K, 50 K and 70 K.

Fig. 5 Semi-logarithmic plots of PL transients as a function of time from QW1, QW2, QW3 and QW4 at (a) 13 K and (b) 20 K.