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Directional phonon-assisted cascading of photoexcited carriers in stepped $In_X(Al_{0.17}Ga_{0.83})_{1-X}As/ Al_{0.17}Ga_{0.83}As$ multiple quantum wells

S. Machida[a], M. Matsuo[a], K. Fujiwara[a], J.R.Jensen[b] and J.M. Hvam[b]

[a]Kyushu Institute of Technology, Tobata, Kitakyushu 804-8550, Japan
[b]Research Center COM, Technical University of Denmark, Building 349, DK-2800 Kgs. Lyngby, Denmark

Abstract

Perpendicular motion of photoexcited electron and hole pairs assisted by phonon scattering is investigated in a novel step-graded staircase heterostructure consisting of strained $In_X(Al_{0.17}Ga_{0.83})_{1-X}As$ multiple quantum wells (QWs) with similar widths but different five x values by cw and time-resolved photoluminescence (PL) experiments. From the temperature dependence of PL spectral intensity of distinct five peaks corresponding to the QW layers, we find that, as temperature increases, the PL peaks decrease their relative intensities progressively from shorter wavelength sides after increasing the signal amplitude in the intermediate temperature range. These variations reveal that the photoexcited carriers directionally move from shallower to deeper QWs via phonon-assisted activation above the barrier band edge state. The PL dynamics directly indicate the perpendicular flowing of photoexcited carriers and the capture by the deeper QW, thus providing firm evidences for the dynamical carrier flow and capture processes.

Keywords: Semiconductor quantum well; Photoluminescence; Vertical transport; Relaxation dynamics

Corresponding author. Telefax: +81-93-884-3221;
E-mail address: fujiwara@ele.kyutech.ac.jp (K. Fujiwara)

1. Introduction

Cascading flow and/or capture of injected or photoexcited carriers in composite quantum well (QW) heterostructures are crucial for devise applications such as those utilizing inter-subband and inter-well transitions [1-3]. However, most of previous studies discussing the mechanisms of capture and relaxation processes are concerned with the vertical transport of photoexcited carriers in monoperiodic semiconductor superlattices [4-6]. Only few reports have been presented for the composite heterostructures comprised a number of dissimilar quantum wells. In this paper, perpendicular motion of photoexcited electron and hole pairs assisted by phonon scattering is investigated in a novel step-graded staircase heterostructure consisting of five-steps strained $In_X(Al_{0.17}Ga_{0.83})_{1-X}As$ multiple quantum wells by cw and time-resolved photoluminescence (PL) experiments. PL spectra of the sample reveal distinct five peaks corresponding to the QW layers, which dramatically evolve with increasing lattice temperature. We find that, as the temperature increases, some of the PL peaks first increase their relative intensities in the intermediate temperature range and then decrease the signal amplitudes progressively from shorter wavelength sides. These changes of the PL intensities as a function of temperature reflect that the photoexcited carriers directionally move from shallower to deeper QWs via phonon-assisted activation above the barrier band edge state. The PL dynamics directly evidence the perpendicular flowing of photoexcited carriers and the capture by the deeper QW.

2. Experimental

The novel step-graded staircase heterostructure consisting of strained $In_X(Al_{0.17}Ga_{0.83})_{1-X}As$ quantum wells was grown at 530 ℃ on a GaAs (100) substrate by molecular beam epitaxy [7]. In this sample nominal widths of the five wells are similar to each other with a value of about 8 nm. But x values are different to be 5.3, 8.8, 12, 15 and 18% (named QW1, 2, 3, 4 and 5, respectively) in the

heterostructure, as schematically shown in Fig. 1. The sequence of QW1, 2, 3, 4 and 5 is starting from the substrate side. These QW layers, which are electronically isolated by 30 nm thick $Al_{0.17}Ga_{0.83}As$ barriers, are further sandwiched between 200 nm $Al_{0.17}Ga_{0.83}As$ barriers. The growth is terminated by a 100 nm GaAs cap layer. The growth details of the nominally undoped sample was given and characterized in Ref. [7]. The structural parameters (well width and In mole fraction x) determined in Ref. [7] are given in Fig. 1. The steady-state PL spectra were measured between 14 and 200 K in a closed-cycle He cryostat using a He-Ne laser (632.8 nm and 1.2 mW) for excitation. A Jovan-Yubon (HR320) monochromator and a computer-controlled digital lock-in-amplifier system were used for the PL detection. Spectrally and temporally resolved PL transients were measured at 12-90 K in another closed-cycle He cryostat using a pulsed semiconductor laser with 50 ps pulses at 653 nm for weak exciation (average power of 1 μ W) and a streak camera system (Hamamatsu C 4334-02).

3. Results and discussion

Fig. 2 shows cw PL spectra of the five different QWs as a function of temperature. The PL intensity is vertically shifted for clear comparison and normalized to the highest peak intensity in each spectrum. In the lowest spectrum at 14 K, distinct five PL peaks corresponding to QW1, 2, 3, 4 and 5 are observed as assigned in the figure [7], while their relative intensity varies between the QWs. At present we do not exactly know the origin of changes of the relative PL intensity, although we may point out a possibility of the resonant capture processes [8]. However, when the temperature is increased up to 200 K, their peak intensity as well as the energy evolves significantly. At a first glance it appears they change in a complex manner. However, we note that there exists a clear trend of the variations. That is, as the temperature increases, the PL peaks decrease their relative intensities progressively from shorter wavelength sides after increasing the signal amplitude in the intermediate temperature range. For example, the QW3 PL peak shows the highest intensity at 50 K and then

decreases monotonously above 60 K. For QW4 the PL intensity is highest at 70 K and decreases above 80 K. In order to show changes of the relative PL intensities as a function of temperature, a quantitative plot of the wavelength integrated PL intensities is shown in Fig. 3. It indicates that there are some plateaus or even restorations of the PL signal in the temperature range that depends on the QW potential depth. We attribute these PL intensity variations due to the population changes of photogenerated carriers in the wells, since there are no reasons to enhance the radiative recombination rate at higher temperatures. These results mean that the photoexcited carriers directionally move from shallower (QW1 and 2) to deeper QWs (QW3, 4 and 5) via phonon-assisted thermal activation above the barrier band edge state before radiatively recombined in the wells. Once they are captured by the deeper well, they cannot go back to the shallower well, since more thermal activation energies are required to escape from that particular well at a given temperature. Thus, these experimental findings indicate that directional phonon-assisted cascading of photoexcited carriers is occurring in the novel stepped QW heterostructure.

The PL dynamics measurements directly evidence the perpendicular flowing of photoexcited carriers and the capture by the deeper QW. Fig. 4 shows PL transients at several temperatures as a function of decay time for the case of QW3 as an example. Increasing the temperature from 12 K to 40 K, the PL decay time gradually increases from 0.46 ns to 3.0 ns, accompanying the PL intensity decreases. The increases of the PL decay time can easily be understood in terms of the temperature-dependent radiative recombination rate of free excitons in QW [9], while the decreases of the PL intensity with temperature are ascribed to the thermal activation of non-radiative recombination centers. However, we stress here that a significant increase of the PL rise is clearly observed when the temperature is further increased to 50 K in Fig. 4, accompanying the drastic PL intensity enhancement. This recovery of the PL intensity and the appearance of PL rise are unique in this type of stepped QW sample and provide a firm evidence for the carrier flow and capture

processes assisted by phonon scattering. At 50 K, we note that a faster PL decay of the neighboring QW2 is observed, which indicates the carrier escape from QW2 to QW3. When the temperature is furthermore increased to 70 K, the PL decay of QW3 becomes faster as seen in Fig. 4, revealing the transfer of carriers to the deeper neighboring QW4. At 90 K the PL intensity for QW3 is very quickly quenched by completely transferring to the deeper QW4. These results of PL transients clearly and directly demonstrate the dynamical carrier flow and capture processes between the different QWs.

4. Conclusion

The temperature dependence of photoluminescence properties has been investigated of the novel step-graded staircase heterostructure consisting of strained $In_X(Al_{0.17}Ga_{0.83})_{1-X}As$ multiple quantum wells with similar widths but different five x values by cw and time-resolved photoluminescence experiments. It is found that the PL intensity as well as the dynamics of the different QWs drastically evolves with increasing the lattice temperature. The results of PL variations with temperature indicate that the photoexcited carriers directionally move from the shallower to the deeper QWs via phonon-assisted activation to the barrier band edge state. These findings suggest that a design of stepped heterostructures can be used to tailor directional motion of carriers in quantum heterostructures.

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Captions to Figures

Fig. 1 Schematic potential diagram of step-graded staircase heterostructure consisting of strained $In_X(Al_{0.17}Ga_{0.83})_{1-X}As$ multiple quantum wells with similar widths but different five x (= 5.3, 8.8, 12, 15 and 18%, named QW1, 2, 3, 4 and 5, respectively) values.

Fig. 2 Normalized PL spectra as a function of lattice temperature between 14 and 200 K.

Fig. 3 Wavelength integrated PL intensities of the emission bands for QW1, QW2, QW3, QW4 and QW5 as a function lattice temperature.

Fig. 4 Semi-logarithmic plot of PL intensity for the QW3 emission band as a function of time at seven temperatures. Note that at 50 K the PL transient shows a significant increase of the rise and the intensity, while the PL decay at 70 K is faster, determined by the escape time of carriers to QW4. The laser excitation pulse is located at 0.0 ns in the ordinate of this figure.

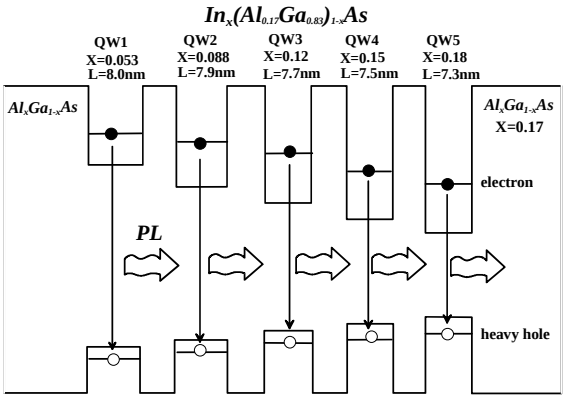

Fig. 1

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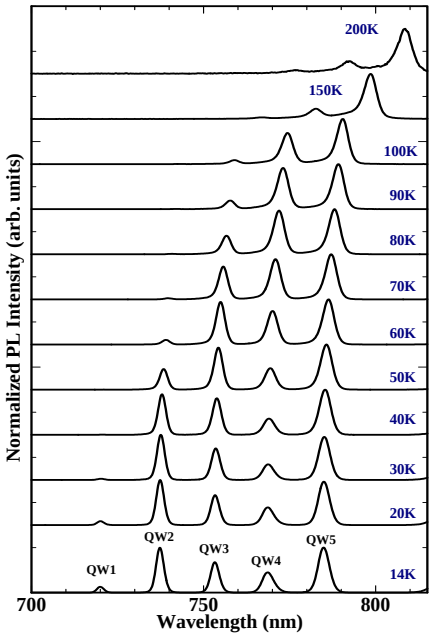

Fig. 2

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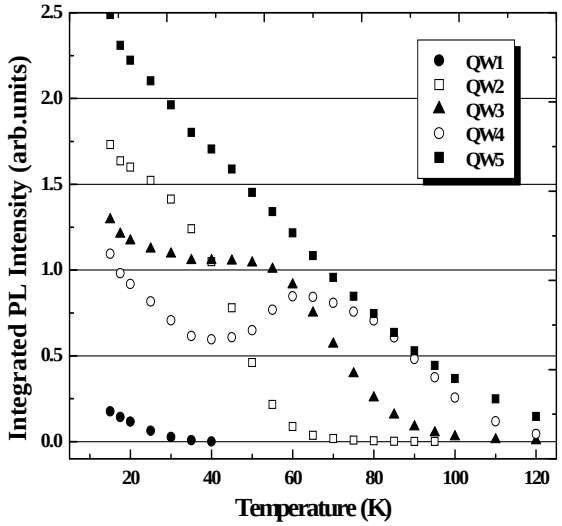

Fig. 3

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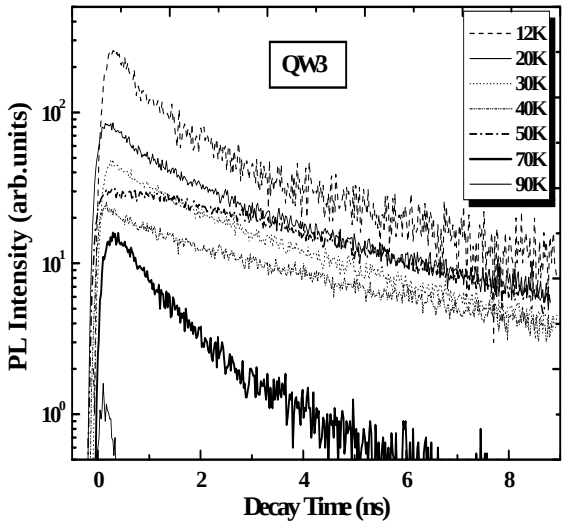

Fig. 4

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