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Carrier correlations in single pair of coupled quantum dots

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1. Introduction

The semiconductor quantum dot (QD) draws attention as a medium for quantum computing because it has long carrier coherence time due to discrete energy levels come from strong quantum confinement [1]. Li *et al.* had already demonstrated the quantum logic gate using exciton-biexciton correlation in single QD [2]. But single QD does not have scalability for realizing large number of bit. Accordingly, the carrier correlation in coupled QDs is necessary for realizing large number of bit. Although there were a few studies of single pair of coupled QDs [3], the carrier correlations in single QD pair has not been reported yet.

In this paper, we report the carrier correlations in single pair of coupled InAs/GaAs self-organized QDs. We measured micro photoluminescence (μ-PL) and two colors photoluminescence excitation (PLE) of single QD pair and observed the correlations between excitons in coupled QDs.

2. Experiments

The samples are InAs QDs stacked on (100) GaAs substrate grown by molecular beam epitaxy (MBE) with Indium-Flush method [4]. Each sample contains two InAs QDs layers separated by a GaAs barrier layer, where the thickness of barrier between QDs is 3, 5, 7nm respectively. The amount of indium supplied for 2nd QDs layer was smaller than that for 1st layer in order to make the QDs of upper and lower as same size. The in-plane density of QDs is 10~50pcs/μm^2. The detail of growth producer was mentioned elsewhere [5]. Moreover, the metal mask aperture (0.2~0.5μmϕ) was fabricated on the sample surface, and make it possible for us to measure single QD pair. In macro PL spectra, the luminescence peak from QDs ensemble was from 940 to 950nm due to size distribution of QDs.

The micro PL and PLE measurements were performed under the micro spectroscopy system with 1m length double monochromator and CCD detector, where spectrum resolution is 20μeV. The samples were cool down to 6K in liquid helium cryostat and two cw Ti:sapphire lasers were used as excitation sources in two colors PLE measurement.

3. Results and Discussions

Fig. 1 shows typical μ-PL spectra from single QD and single pair of coupled QDs excited at wetting layer energy. The spectra of coupled QDs have two groups of PL peaks at higher and lower energy side, where each group contains 2~4 peaks which are mainly separated by 2~5meV. The origin of multiple peaks among a group may be due to anisotropy of QD shape or hole states in our QD [6]. The notable feature of coupled QDs is that energy separation between the two groups increases with decrease of barrier thickness as described by ΔE in Fig. 1. On the contrary, the spectrum of single QD has only one group of peaks. We observed same features at several QD pairs, though peak energy are different each other in a reflection of inhomogeneity of QDs size. From these results, we attribute this energy splitting between two PL groups to wave function coupling, and interpret that these groups constitute bonding (X^+), anti-bonding (X^-) state respectively. In addition, we observed several common peaks to PLE spectra of both X^+ and X^- state. This phenomenon seems due to the coupling stats in coupled QDs. We will mention this phenomenon of PLE elsewhere.

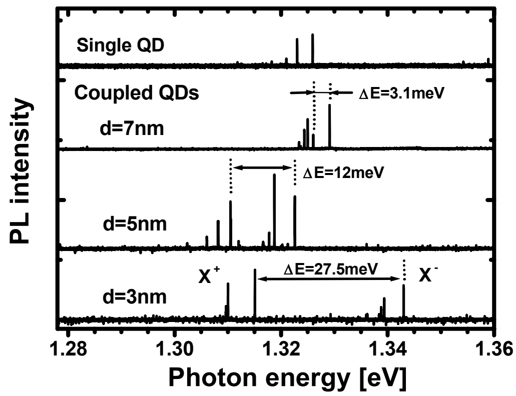

Fig. 1 μ-PL spectra of single pair of coupled QDs and single QD. Figure shows three different samples of coupled QDs, where thickness "d" of barrier between QDs is 3, 5, 7nm respectively.

Next, we tried to observe the carrier correlations, namely correlations between excitons, in coupled QDs. If we can create carriers in both X^+ and X^- state, we will observe the carrier correlations by measuring the change of X^- state due to the X^+ state carriers. Therefore, we measured differential PLE (DPLE) by two colors PLE measurement. Fig. 2 shows the measurement concept of X^+ and X^- system in coupled QDs by two colors PLE. The measurement procedure of Fig. 2 is as follows. To begin with, we select the peak in X^+ PLE spectrum whose energy does not respond to X^- state as described "Pump" in figure after measurement of one color PLE spectra of both X^+ and X^- state. Tuning wavelength of pump light source at this energy makes it possible for us to create carriers constantly in only X^+ state. And then, we measure PLE spectrum of X^- state by probe light source with or without pumping X^+. Finally, we can obtain the DPLE spectrum of X^- state modulated by the carriers of X^+ state from subtraction between two PLE spectra.

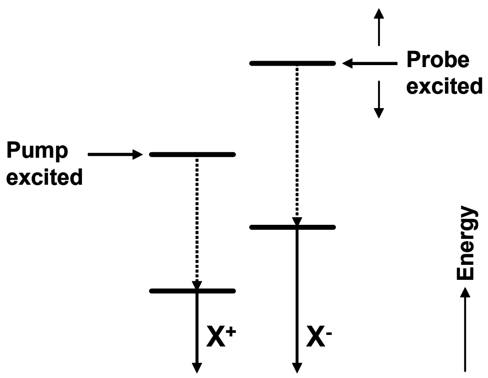

Fig. 2 The measurement concept of X^+ and X^- system by two colors PLE.

In Fig. 3(a), we show DPLE spectrum of coupled QDs whose barrier thickness is 3nm. The remarkable feature of DPLE spectrum is the existence of decrease of luminescence (absorption) excited at a particular energy as described by # arrow. In order to confirm this feature more clearly, we measured the change of the PL intensity with the pump injection intensity. As shown Fig. 3(b), the PL intensity of X^- decreases linearly with increase of X^+ state intensity. The state filling effect cannot explain this observations, because the PL intensity of X^- state increase due to interruption of carrier transfer from X^- to X^+ state when the state filling effect occur [7]. We, therefore, think this observation due to the results from the correlation between excitons in coupled QDs. And we guess that this correlation comes from the quantum interference effect at the intermediate common level to both X^+ and X^- state as Ref.8, which reflects the existence of the exciton coherence between X^- and X^+ state.

4. Conclusions

We studied the carrier correlations in single pair of coupled InAs/GaAs self-organized QDs. We observed the energy splitting due to wave function coupling by PL and PLE measurement of single QD pair. We measured DPLE by two colors PLE measurement and found the phenomena related to the correlation between excitons in coupled QDs. These results largely contribute to understanding of coupled QDs system for applications of the quantum information.

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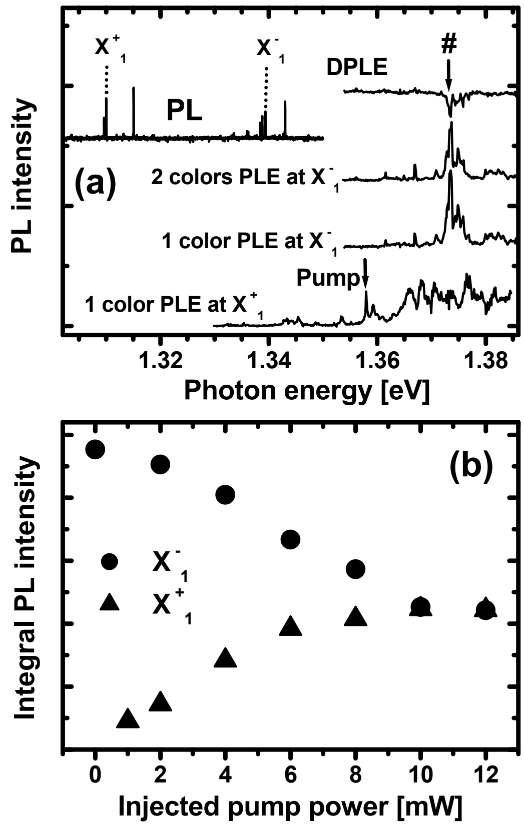

Fig. 3 (a) PLE and DPLE spectra of coupled QDs, where the thickness of barrier is 3nm. Two colors PLE means PLE with pump of X^+ state. (b) The change of the PL intensity with the pump injection. The X^- state was weakly excited at # arrow energy in figure (a) excepting when the X^+ state was measured.

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