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P9-2

Observation of bonding states in single pair of coupled quantum dots using micro-spectroscopy

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1. Introduction

In recent years, self-assembled semiconductor quantum dots (QD) have developed into one of the most topical fields in nanostructure research. Especially, QD is one of the promising candidate for the materials of quantum computation. In the case of the one qubit operation using QD, it has been reported a great deal in recent reports [1, 2]. As for the preliminary nonscalable 2qubit operation, Li *et al*. has successfully demonstrated using exiton-biexciton interaction in a single QDs [3]. However, the interactions between individual dots are essential functions for scalable quantum computation.

In this paper, we investigated electron states of individual coupled QD using micro-photoluminescence (μPL) and micro-photoluminescence excitation (μPLE) measurements. We revealed electron state of individual dots in a coupled QD. Moreover, we found that the energy difference between bonding state and anti-bonding state depend on dot size in coupled QDs. And we investigate linewidth of PL peak of the single QD and the coupled QD.

2. Experiments

The single QD and vertical aligned coupled QD were grown by the molecular beam epitaxy (MBE) with indium-flush method [4]. The coupled QDs sample contains two InAs QDs layers separated by a GaAs barrier layer, where the thickness of barrier is 3nm. The in-plane density of QDs is about 100pcs/μm^2. After growth, a metal-mask with diameter of 0.2μm is fabricated on the sample surface. The detail of procedure was mentioned elsewhere [5].

The μPL and μPLE characteristics of single and coupled InAs quantum dot were investigated using micro-spectroscopy. A QD sample was mounted on liquid helium cryostat and was kept at a temperature of 5K. The sample was excited by a tunable continuous wave (CW) Ti:sapphire laser with a spot size of ~2μm. PL signals were detected by a long double monochrometer and a charge coupled device (CCD) detector.

3. Results and Discussion

We investigated the difference of electronic-states between a single QD and a coupled QD using PL and PLE measurement. Fig.1 shows PL and PLE spectra from a single QD. Ten PL peaks were observed in PL spectrum in the range from 1.27 to 1.37eV, since the sample was so weakly excited that only the ground state could be occupied and most of all peaks observed are attributed to the ground states excitons. We discuss PLE spectra for one of these PL peaks. The upper spectrum in Fig.1 is PLE spectrum monitored (detected) at "Dot1", where ΔE is the difference between the excitation and detection energies. Some peaks of Dot1 appeared at ΔE=29, 35, 40, 43 and 50meV. Peaks located at ΔE=29, 35meV is related to the InAs and GaAs LO phonon resonance states, respectively. The peaks at ΔE=40, 43 and 50 meV (e_1, e_2, e_3) originate from first, second and higher electron states, respectively. There are no PLE peak in the region of zero absorption (ΔE<29 meV) in single QD.

Next we investigated PLE spectra for the individual coupled QD. Fig.2 shows PL and PLE spectra in coupled QDs. About twenty peaks were observed in PL spectrum in the range from 1.27 to 1.365eV (Fig.2 lower), the coupled QDs have twice as many PL peaks as single QDs. The distance between QDs is enough narrow for quantum mechanically coupling, and electron state of single QD split into bonding and anti-bonding state. However, only from PL spectrum, it is difficult to identify the bonding state in a pair of coupled QDs. Therefore we measured PLE spectra about most of emission peaks observed in PL spectrum and found some pairs of PLE spectra which have similar features, where most of peaks coincide in both PLE spectra. By way of example, the upper spectrum in Fig2 is PLE spectra which were detected at peak A and peak B. The origin of the peak at ΔE=35meV is GaAs phonon resonance state. A sharp peak (e_0^- and e_1^+) appeared in the region of zero absorption (ΔE<29 meV), which can not be observed in the sample of single QD. Since the difference between the samples of single and coupled QDs in PLE spectra are e_1^+ and e_0^- states, these two peaks are attributed to the bonding state and anti-bonding state that originated from the quantum mechanically coupling of two QD.

In Figure 2, inset shows schematic band structure of a coupled QD system. The each holes (h) localized each in Dot A and Dot B and don't creates bonding states, due to their large effective mass. In constant, the electron creates easily bonding states due to the small electron effective mass.

The electrons recombine from the bonding state (e_0^+) to the hole-state appeared in peak A of PL. Similarly, peak B in PL reflects the transitions of electrons in anti-bonding state (e_0^-) to hole-state (h). The photon energy of peak B is very close to the peak e_0^- in PLE spectra detected at peak A. Therefore peak e_0^- in PLE spectra is also due to the electronic transition between anti-bonding state (e_0^-) to hole-state. In a similar way, the peak e_1^+ and peak e_1^- that appear in two PLE spectra is due to the bonding state and anti-bonding state, respectively, which is the evidence of the quantum mechanically coupling of the two QDs.

We investigated dot size dependence on the energy difference between e_0^+ state and e_0^- state. We have measured PLE spectra about sixteen peaks, which originate from bounding states (e_0^+), observed in the range from 1.29 to 1.33eV in the PL spectrum. The vertical axis in Fig.3 indicates the energy difference between e_0^+ and e_0^- absorption peak and between absorption peak of GaAs 1LO and e_0^+. The horizontal axis indicates the detected PL energy related to bonding state (e_0^+). The PL energy from e_0^+ reflected the dot size. Therefore the peaks of e_0^+ in higher energy side of PL spectra originate from smaller coupled dots. We found that the energy difference between e_0^- and e_0^+ increase as the dot size decreases, because the tunneling of electron wave function through barrier layer is enhanced in small dot. As a result, the energy difference between e_0^+ and e_0^- depend on dot size.

We investigated linewidth of PL spectra for the single QD and the coupled QD. The linewidth of single QDs were 30~40μeV, and that of coupled QDs were 50~60μeV.

4. Conclusions

We investigated the difference of electron states between a single QD and a coupled QD sample using PL and PLE measurement with a microscopic technique. In a single QDs, there were no PLE peak in the region of zero absorption (ΔE<29meV). In PLE spectra from the coupled QDs sample, the sharp peaks (e_0^- and e_1^+) appeared in the region of zero adsorption (ΔE<29 meV), which are due to the bonding state between two QDs. And we found the energy difference between bonding state and anti-bonding states in coupled QD depend on dot size. Moreover, we found that the linewidth of PL peaks in coupled QDs broader than single QDs.

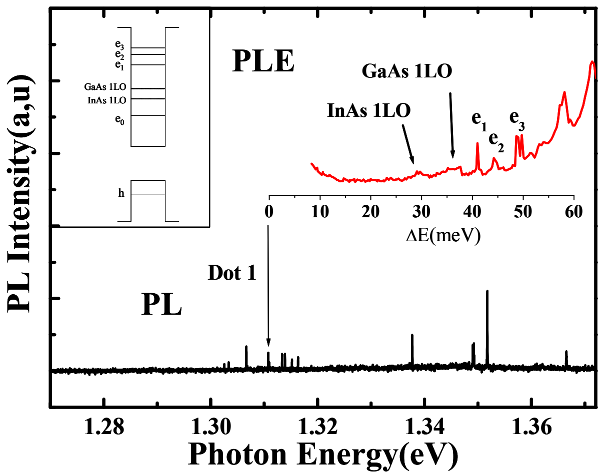

Fig.1 μ-PL and PLE spectra of a single QDs with I-F method. Upper shows PLE spectra at Dot1. ΔE is the difference between the excitation and detection energies. Inset shows schematic of single QD energy state.

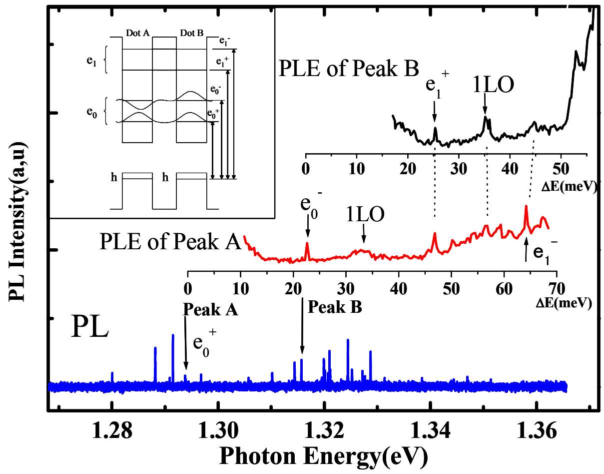

Fig.2 μ-PL and PLE spectra of coupled QDs with I-F method. Upper shows PLE spectra at Peak A and Peak B. ΔE is the difference between the excitation and detection energies. Inset shows schematic of coupled QD energy state. Inset shows schematic of coupled QD energy state.

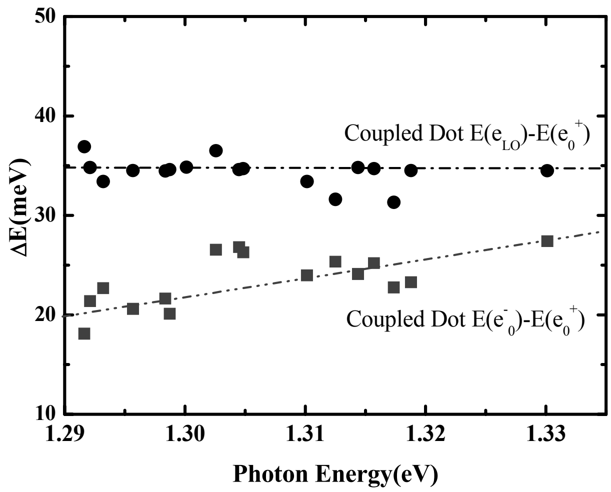

Fig.3 The dependence on the energy difference between e_0^+ state and e_0^- state in coupled QDs. The vertical axis indicates the energy difference between e_0^+ and e_0^- absorption peak and between absorption peak of GaAs 1LO(e_{LO}) and e_0^+. The horizontal axis indicates the detected PL energy related to bonding state(e_0^+). The photon energy reflected the dot size.

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