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Exciton Rabi Oscillation in InAs/GaAs Coupled Quantum Dot

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1. Introduction

In recent years, optoelectronic devices using self-assembled semiconductor quantum dots (QDs) have been developed into one of the most important fields in nanostructure research. QDs possess not only optical properties similar to those of atoms, but also those of a high quality active medium with a high optical gain and a high nonlinearly. The realization of two fundamental quantum logic gates of a rotation gate (1-qubit) and a controlled rotation gate (2-qubit) using coupled QDs are required for a successful implementation of quantum information processing.[1-2] The rotation gate (1-qubit) using exciton Rabi oscillation in Single QD have been demonstrated.[3] The controlled rotation gate require the two essential techniques; one is the formation of the interaction between two QDs in coupled QD [4] and the other is the controlling of the population using the Rabi oscillation at the coupled QD. We have proposed the quantum logic gate using excitons in the coupled quantum dots, where we prepared a quantum mechanically coupled QD in Fig 1. We adopt an InAs/GaAs self-assembled QDs with strong quantum confinement and long dephasing time.

In this study, we observed the Rabi oscillation in coupled QD and a transition dipole moment was obtained 72 Debye, which is twice as large as that of a single QD. This result shows that it is possible to realize the quantum logic gate using the coupled QD.

2. Experiments

The vertically aligned coupled QD were grown by the molecular beam epitaxy (MBE) with an Indium-flush method. The coupled QDs sample consists of two InAs QDs layers separated by a GaAs barrier layer with thickness of 5 nm. The detail of fabrication was mentioned elsewhere. [5] The in-plane density of the QDs is about 15pcs/μm^2. After the growth, a metal-mask with diameter of 0.2μm is fabricated on the sample surface.

Micro photoluminescence (μPL) and Micro photoluminescence excitation (μPLE) characteristic of coupled QD was investigated by means of micro-spectroscopy. A QD sample was mounted on a 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 1m-long double monochrometer and a charge coupled device (CCD) detector. Ti:Sapphire laser providing 5 ps long pulses at a repetition rate of 76MHz was used for the pulse area excitation control of exciton state in the QD.

3. Results and Discussion

First, we investigated the electronic states in the coupled QD. PL spectra from the coupled QD are presented in Fig 2 upper. We observed that the coupled QD have two PL groups at higher energy side and lower energy side consisting of the two peaks. Two peaks (Xa and Xb) are attributed to the ground states of exciton because the sample was so weakly excited that the biexciton state was not occupied. The Xa and Xb peaks are originated from the bonding state and anti-bonding state, respectively [6]. Right curves of Fig. 2 shows PLE spectra of the two peaks (Xa, Xb).

Rabi oscillations are the sinusoidal time evolution of the population difference in a two-level system that occurs at the Rabi frequency. When the laser pulse width is fixed while the intensity is varied over several orders magnitude, the Rabi oscillation describing the population of excited state undergoes as a function of the input pulse area,

$$\theta = \left(\mu / \hbar \right) \int_{-\infty}^{\infty} E(t) dt$$

,which is proportional to the square root of average laser intensity. Here, μ is the transition dipole moment and $E(t)$ is the electric field envelope.

Figure 3 shows the PL intensity versus the average power of laser pulse for a single and the coupled QD, where the excitation laser wavelength is tuned at the first excited state (E_1) of the Xa (ΔE=24.2meV).

We observed that the PL intensity oscillate with an increase in the square root of the pump power, i.e., the pulse area. The PL intensity versus the square root of the average power can be fitted to the sinusoidal solid curve. For these experimental results, we have succeeded in the observation of Rabi oscillation by controlling of input pulse area. The dipole moment calculated from experimental result was 72 Debye which is larger than that of single QD (40 Debye) [3]. The large oscillator strength of the excitons in coupled QD has been already reported [7]. Large coherent volume of excitons in the coupled QD is expected by assuming that the exciton wave function is expanded over the coupled QD. This causes the large transition dipole moment and the large oscillator strength in the coupled QD compared to that in the single QD.

4. Summary

We have developed the method of controlling of the exciton population using the Rabi oscillation in the coupled QD. And we succeed in the experimental observation of the pulse area control of the Rabi oscillation in the InAs coupled QD. The transition dipole moment estimated from experiments was about 72 Debye, which is twice as larger as that of the single QD.

References

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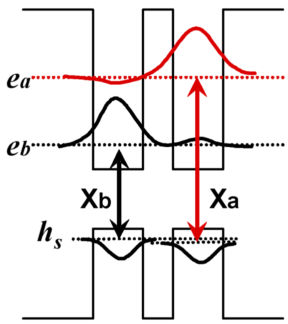

FIG. 1. Schematic drawing of the formation of bonding (Xb) and anti-bonding (Xa) states in coupled QDs

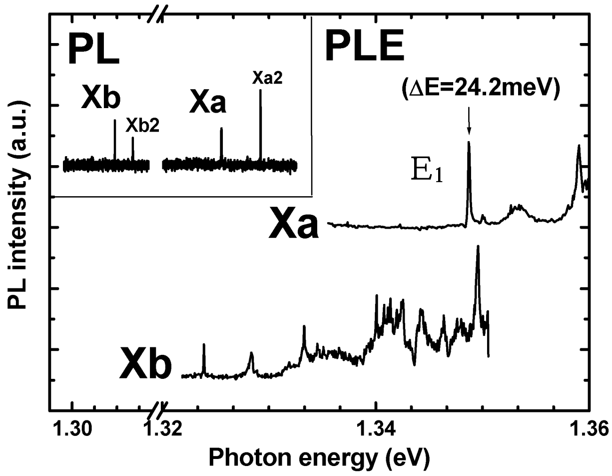

FIG.2. PL and PLE spectra of a single pair of coupled QDs. Xa and Xb indicate bonding and anti-bonding PL groups, the inset shows the PL spectrum. The E_1 peak (ΔE=24.2meV) of Xa in PLE spectrum is a first excited state of a hole.

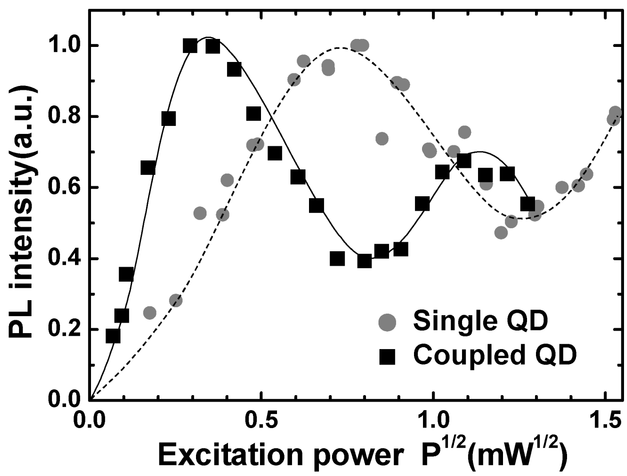

FIG.3. Rabi oscillations of the coupled QD and single QD. The PL intensity from the ground state was recorded while the average total input laser intensity was varied for pulse area at the sample surface. The solid and dotted lines are a fit to the data. The transition dipole moments of the coupled and the single QD are 72 and 40 Debye, respectively.