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Electric-field control of coupled states in weakly coupled quantum dots

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1. Introduction

Recently, it has been energetically studied semiconductor quantum dots (QDs) for quantum logic gate devices in quantum information and computation. Fundamental elements of the quantum logic gates are one-quantum-bit (1-qubit) and interactive two-qubit-gates. The quantum computation is accomplished by arbitrary combination of 1- and 2-qubit gates.[1] The 1-qubit operation is accomplished with Rabi oscillation,[2] and Li *et al*. have demonstrated the preliminary 2-qubit operation using entanglement of excitons in a single QD (SQD).[3] However, it is difficult to extend to multi-qubit operation in such method. To overcome this problem, exciton molecule, which consists of two hetero-nuclear excitons in coupled quantum dots (CQDs), should be used. Furthermore, to construct flexible system of quantum logic gates, manipulation of the interactions in the CQD systems is necessary. One of manipulation methods is application of external electric fields. Some methods have been proposed theoretically using the dipole-dipole interaction.[4] Moreover control of the coupling condition by applying an electric field has reported by Stinaff *et al*.[5]

The purpose of our study is control of the interaction between excitons in CQD systems by applying an external electric field. We have fabricated CQD devices with a vertical electric field. In this paper, we report on control of exciton states in a CQD structure.

2. Experiment

Sample structure

Our CQD sample consisted of two self-organized InAs coupled vertically by a thick GaAs barrier layer with a thickness of 7 nm. The sample was grown by molecular beam epitaxy. The CQD layer were grown on an n-doped GaAs substrate, isolated by an non-doped 200 nm-thick GaAs buffer layer in order to fabricate an n-i-diode structure. To obtain flat interfaces, an indium-flush method was carried out after the growth of the QD layers. The detail of the sample structure and the growth procedure were described in ref. 6. After the growth, a metal mask with pinholes was fabricated on the sample surface by electron beam lithography and a lift-off method. The role of the metal mask is an optical aperture and an electrode to apply an electric field to the QDs. The diameter of the pinholes was 0.2 μm.

Experimental setup

Optical characteristics of the CQD sample were measured by conventional micro-photoluminescence (PL) and micro-photoluminescence excitation (PLE) methods. The CQD sample was held in a liquid-helium cryostat. Laser lights from a continuous wave Ti: sapphire laser were focused on the sample surface by an objective lens with a magnitude of 50, and the lights passing through the metal mask excited the CQDs. The spot size at the focal point was about 2 μm. PL signals radiated to a backward direction were collected by the objective lens, dispersed by a triple grating monochromator, and detected by a charge coupled device camera.

3. Results and Discussions

Figure 1 shows (a) PL spectra at the various electric field conditions, (b) peak positions and (c) PL peak intensities as a function of the electric field. The excitation energy was set at 1.409 eV, which is in the absorption energy band of the wetting layers underlying the QDs. At F = 0 kV/cm, two peaks were observed with an energy difference of about 3 meV. In this CQD system, quantum-mechanical coupling of the electrons in the CQD are very weak, so that the observed peaks originated from the localized excitons. The peak positions shifted with varying the electric field as shown in fig 2 (b). The shifts are well-fitted by quantum confined Stark shift characteristics:

$$E(F) = E(0) + pF + \beta F^2$$

where $E(0)$ is the transition energy of the ground state exciton without the field, p is a permanent dipole moment and β is a polarizability of the exciton. From the fitting parameter, the electron-hole separation in this CQD sample was about 0.01 nm.

In this CQD sample, correlative change in the PL intensity between the two peaks was observed, although no anti-crossing characteristic was observed. Furthermore, the total intensity of two peaks was almost constant. Such characteristic is not observed in a SQD system, so that this correlative change in the intensity is specific for the CQD. A similar phenomenon was observed in PLE experiments. Figure 2 shows PLE spectra in both X_A and X_B in various field strength conditions, and the intensity change of the first excited state, labeled X_A' and X_B', as a function of the field strength. The intensity change of X_A' and X_B' was same as that of X_A and X_B. This implies that the interaction occurs in the QDs, not in the wetting layer. In this weakly

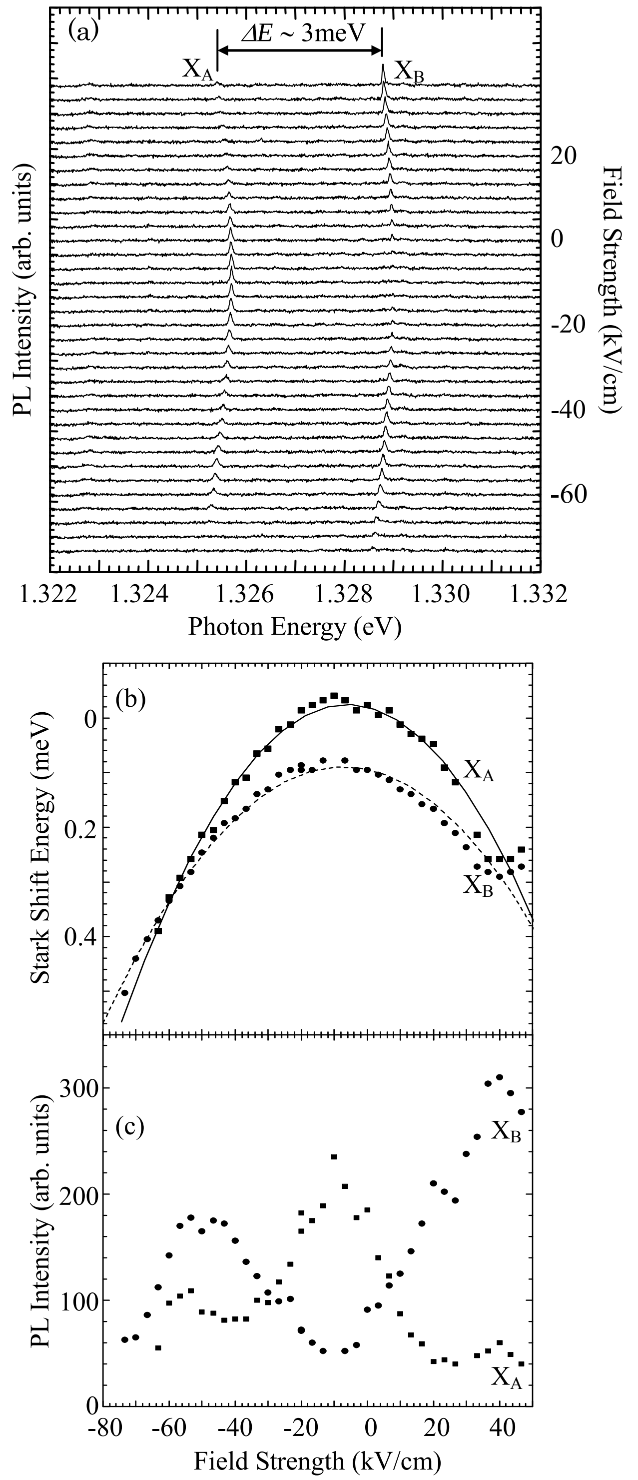

Fig. 1 (a) PL spectra in various electric field conditions (b) the peak positions and (c) the intensities of X_A and X_B as a function of the field strength.

coupled system, the dipole-dipole interaction is dominant while the quantum-mechanical coupling is weak. Thus, observed phenomena were caused by the dipole-dipole interaction, which were varied by the external electric field.

4. Conclusions

We have controlled the exciton state in a weakly coupled QD system by external electric field. PL peaks in the CQD were correlatively changed with varying the electric field. This change originated from the dipole-dipole coupling between the QDs.

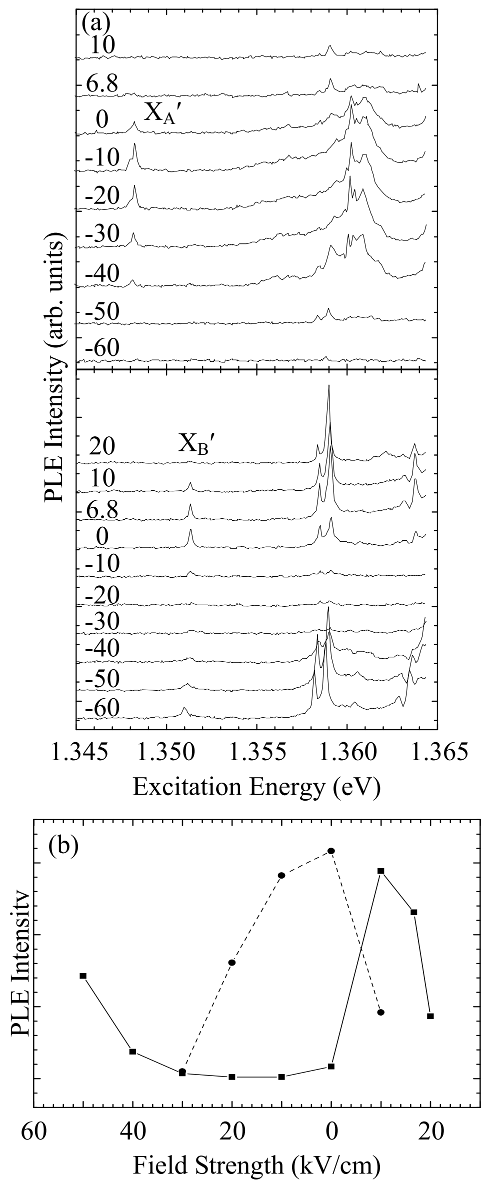

Fig. 2 (a) PLE spectra in X_A (upper) and X_B (bottom) (b) the intensity change of the X_A' and X_B'.

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