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Formation and control of 2-qubits exciton state in a coupled quantum dots.

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1. Introduction

In recent years, the semiconductor quantum dots (QD) have been studied extensively. As for the exciton quantum logic gate, Li et al have reported 2-qubits quantum logic gates using a single QD [1] without scalability. For the next step to realize exciton-based multi-qubits quantum logic gates, the development of the scalable device structures is very important. For this purpose, we have proposed 2-qubits logic gates of excitons in a coupled quantum dots (CQDs) [2]. For the exciton entanglement in the CQDs, creation of the correlated 2-qubits exciton states (|00>, |10>, |01>, |11>) is primarily required. We have already reported the creation of the exciton-molecule states (|11>) consisting of a bonding-like exciton and an anti-bonding like exciton [2]. However, it was not clear enough whether these states are the correlated exciton states or not. In this paper, we report the formation and control of the correlated 2-qubits exciton states by means of the selective optical excitation of both one-exciton states and two-exciton states.

Band diagram of electron and hole states (exciton states) in a CQDs and the transition energy diagram of correlated 2-qubits exciton states in a CQDs are shown in Fig.1 (b) ,(c) and (d), respectively. The transition energy between the crystal ground state (|00>) and one-exciton state (|10>) is X2b, and that between one-exciton state (|10>) and exciton-molecule state (|11>) is X2b-□E (X2b'), where □E is the energy shift due to the formation of the exciton molecule. The transition energies of other excitation processes of |00> → |01> and |01> →|11> correspond to X2a and X2a-□E(X2a'), respectively. In the correlated exciton four level system, the energy shift (□E) of X2a' should be the same as that of X2b'.

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. [3] The in-plane density of the QDs is about 15pcs/μm2. 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.

3. Results and Discussion

In the previous works, we have been observed four PL peaks (Xa, X2a, Xb, X2b) of ground exciton states in a CQDs. The higher energy peaks (Xa, X2a) and the lower energy peaks (Xb, X2b) were arising from anti-bonding-like and bonding-like states, respectively [2]. Figure 2 exhibits the PL spectra under strong optical excitation at the wetting layer energy, where the horizontal axis(ΔE) indicates the energy measured from X2a, and X2b, namely E-X2a and E-X2b, respectively. We observed eight PL peaks out of which four peaks (Xa, X2a, Xb, and X2b) originated from one-exciton states with linear power dependence and the other four peaks originated from two-exciton states, namely biexcitons(XXa, XXb) and exciton-molecules (X2a', X2b') with quadratic power dependence. A remarkable characteristic in the correlated exciton four level system is that the energy difference between X2a and X2a', which corresponds to exciton-molecule energy shift, should be the same as that between X2b and X2b'. In passing, we observed the same feature in other CQDs samples as shown in Fig.2. From these results, we succeeded in the formation of correlated 2-qubits exciton states in the CQDs.

Figure 3 shows the PL spectrum of CQDs under the spin-polarized selective excitation. The PL peak of exciton-molecule (X2b') only appeared with polarization-selective excitation of excited states of X2a (σ-) and those of X2b (σ+), respectively. This confirms that the exciton-molecule can be only created from two-excitons with anti-parallel spins. Thus we succeeded in the control of the correlated 2-qubits exciton states consisting of one-exciton states |01>, |10> and exciton-molecule state |11>. These results present an important step towards the realization of scalable quantum logic gates based on the exciton entanglement in a CQDs.

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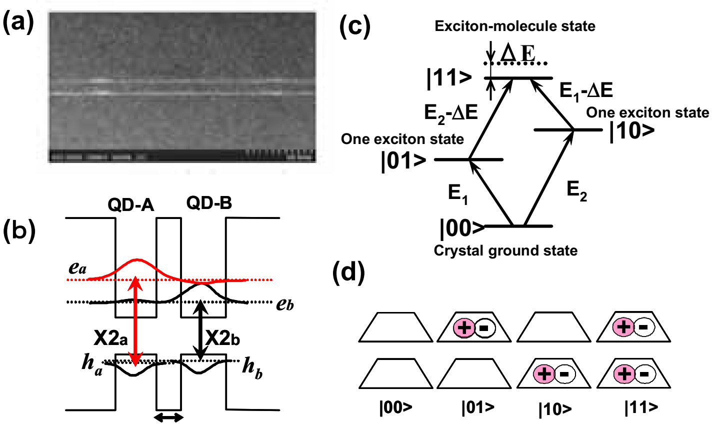


Fig. 1: (a)SEM image of a CQDs (b) Schematic drawing of the formation of bonding like (X2b) and anti-bonding like (X2a) exciton states in CQDs. (c) Correlated exciton four level system of the quantum logic gate using excitons in CQDs system. ΔE indicates the binding energy of the exciton-molecule. (d) 2-qubits exciton states |00>, |01>, |10> and |11> denote the crystal ground state, the X2b exciton state from QD-B, the X2a exciton state from QD-A and the exciton-molecule state consisting of X2a and X2b excitons, respectively.

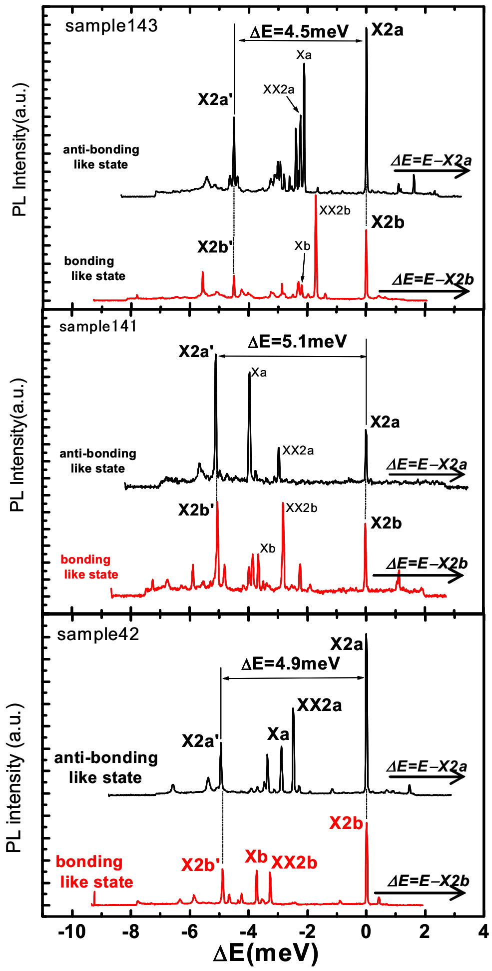
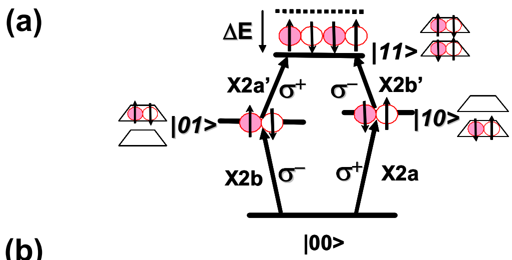


Fig.2: PL spectrum of one- and two-exciton states under the excited at 1.41 eV with strong optical excitation for the three different CQDs samples. The energy shift (ΔE) between X2a–X2a' and X2b–X2b' are almost all same value (ΔE =4.6, 5.1, 4.9 meV), respectively. X2a' and X2b' peaks are originated from exciton-molecule state.



(b)

Polarized & Selective Excitation		Biexciton or Exciton molecule	
Xa, X2a (Ea)	Xb, X2b (Eb)	Biexciton	Exciton molecule
Linear	Linear	○	○
σ+	σ+	×	×
σ−	σ+	×	○
σ+	σ−	×	○

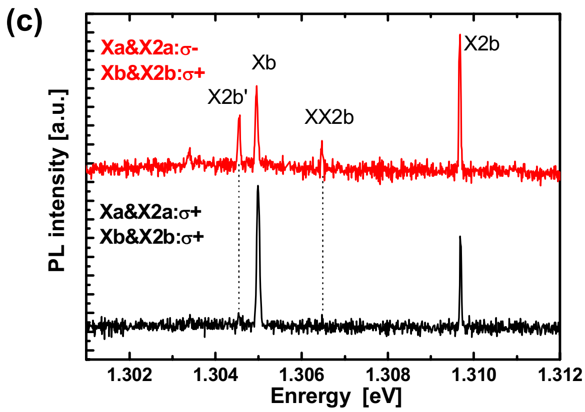


Fig.3: (a) Schematic drawing of exciton four level system including exciton spin. (b)Type of multi excitons using spin-polarized selective excitation. (c) PL spectrum of one- and two- exciton states in CQDs under both the energy (Xa,X2a and Xb,X2b) and spin-polarized selective excitation. (σ+ and σ-). Upper PL shows anti-parallel spin (Xa,X2a: σ- and Xb,X2b: σ+) excitation. Under PL shows parallel spin (Xa,X2a: σ+ and Xb,X2b: σ+) excitation.