Excitonic Rabi oscillations in semiconductor quantum dot observed by photon echo spectroscopy

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Abstract. Optical properties in single-layer InGaAlAs/GaAlAs semiconductor quantum dots were studied by two-pulse photon echo technique. From the decay time, the optical coherence time of the excitons was estimated to be 2.5 ns, which is independent of the excitation intensity. We also observed the excitonic Rabi oscillations by measuring the photon echo intensity as a function of the excitation pulse area. The observed oscillatory structure is not expected from two-level systems.

Keywords: quantum dot, exciton, Rabi oscillations, photon echo
PACS: 78.67.Hc

INTRODUCTION

Excitons in semiconductor quantum dots (QDs) have atom-like discrete energy structure due to the three-dimensional quantum confinement of electrons and holes. This discrete energy structure of the excitons gives the phonon bottleneck effect [1], which reduces the scattering rate of excitons and phonons. Therefore, an exciton in QD shows the extremely long dephasing time, compared with higher dimensional semiconductors. These energy structure and coherence properties of QDs suggest that an exciton in a single QD works as a quantum bit (qubit) based on solid state for quantum information processing.

Recent experiments of a single QD spectroscopy have already demonstrated the coherent manipulation of a single exciton in a single QD through the excitonic Rabi oscillations, as a single qubit rotation. The observed oscillations show the damping behavior with increasing the excitation power [2-4], which is usually explained by the excitation induced dephasing (EID). On the other hand, the experimental estimation of the dephasing time, which is difficult for a single QD spectroscopy, has not been performed under the strong resonant excitation. Therefore, the detail relation of the Rabi oscillations and the dephasing effect is still unclear.

Here, we report the optical coherence time of QDs under the strong excitation regime observed by photon echo (PE) technique and show the excitonic Rabi oscillations, which are not expected from two-level systems.

EXPERIMENTAL

The sample used in this work was a single layer self-assembled $In_{0.4}Ga_{0.5}Al_{0.1}As/Ga_{0.83}Al_{0.17}As$ QDs grown on (311)B GaAs substrate by molecular beam epitaxy. From the AFM image of QD layer, the density of QD is estimated to be 1.3×10^{10} /cm^2. The photoluminescence (PL) peak of QDs at 3.5 K is located at 1.565 eV with spectral width 40 meV due to the size distribution of each QD.

The experiment was performed by two-pulse PE technique in a reflection configuration at 3.5 K. The excitation light source was a mode-locked Ti: Sapphire laser with repetition rate 76 MHz. The temporal duration and spectral width of the laser pulses were 1.8 ps and 0.5 meV, respectively. The center wavelength of the laser pulses was set to 1.565 eV, which corresponded to the PL peak. The pulses from the laser were divided into two beams, which were linearly polarized along the same direction and focused on the same spot on the sample. The time-integrated PE

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signal in the direction $2\boldsymbol{k}_2$-$\boldsymbol{k}_1$ was detected as a function of the time delay of the first and second pulses τ.

RESULTS AND DISCUSSIONS

Figure 1 shows the dependence of the decay profiles of the PE signal on the excitation intensity of the first pulse. The intensity of the second pulse was set to 16.8 μJ/cm^2/pulse. After the sharp peak at zero time delay, the slowly-decaying signals are observed in each scan. These long decay components reflect the dephasing process of the excitons in QDs. It was found that the decay time constant of the PE signal is insensitive to the excitation intensity of the first pulse. Therefore, EID can be negligible in our QDs. From the decay curves, we evaluated the decay time constants of the PE intensity 610 ~ 630 ps by single-exponential fittings. The dephasing time T_2 of the excitons in QDs is calculated to be 2.5 ns, corresponding to the homogeneous line width 0.52 μeV.

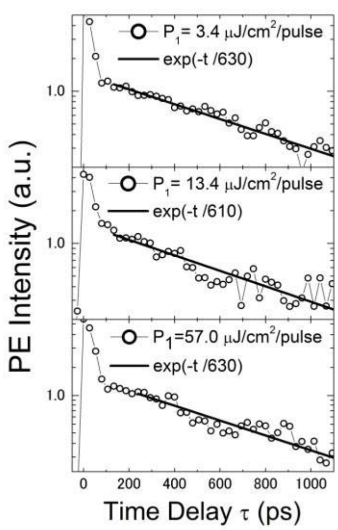

FIGURE 1. PE intensity vs. Time delay

The PE intensity as a function of the pulse area of the first pulse is shown in Fig. 2. The data was taken at the fixed intensity of the second pulse 16.8 μJ/cm^2/pulse and the time delay was set to τ = 100 ps. The oscillatory behavior of the PE intensity is clearly observed. This oscillatory behavior is due to the excitonic Rabi oscillations because the oscillation period gives the dipole moment 12.0 D, which is in good agreement with the value 10.1 D estimated by the exciton lifetime 2.0 ns measured by a pump-probe method. The observed oscillatory structure exhibits the damped oscillations with increasing the pulse area.

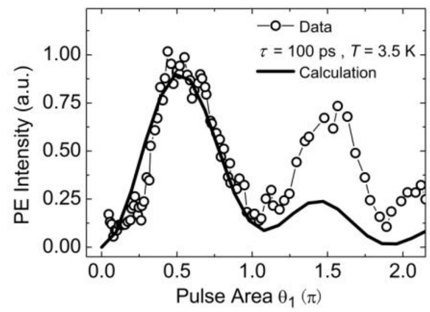

FIGURE 2. PE intensity vs. Pulse area of the first pulse

The physical origin of the damping is different from that of the previous report in a single QD experiment [2] because the dephasing time in our QDs is independent of the excitation power up to 57.0 μJ/cm^2/pulse, which corresponds to the pulse area θ_1 = 1.5 π in Fig. 2. In order to investigate the damped oscillations, we calculated the Rabi oscillations of the PE intensity in two-level systems including the macroscopic ensemble effect [5]. The calculated curve shows the much stronger damping than the observed one, as seen in Fig. 2, suggesting that the optical response of QDs is different from two-level systems, which has not been discussed in the previous experimental investigations.

CONCLUSIONS

We measured the dephasing time of QDs and observed the excitonic Rabi oscillations by the PE technique. The dephasing time is estimated to be T_2 ~ 2.5 ns and independent of the excitation intensity up to 57.0 μJ/cm^2/pulse, which corresponds to the pulse area θ = 1.5 π. The damped Rabi oscillations were also observed. The physical origin of the damping is not due to EID and the ensemble effect of two-level systems. Our experimental findings are important for the further progress of the optical study on semiconductor quantum dots.

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