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Coherent Control of Exciton in a Single Quantum Dot Using High-Resolution Michelson Interferometer

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We developed a high-resolution Michelson interferometer with a He–Ne two-frequency laser positioning system, and measured the coherent carrier dynamics of a single InAs self-assembled quantum dot (SAQD) using a micro-spectroscopy system. The phase-locked double pulses were stabilized, with the maximum deviation being below 10 nm during the long measurement time of 1 h. Using this system, coherent control of an exciton in an InAs SAQD with very fine phase stabilization was demonstrated. The dephasing time of the single quantum dots was 9.5 ps which is close to that estimated from the homogeneous linewidth in the photoluminescence excitation (PLE) spectrum. [DOI: 10.1143/JJAP.43.6093]

KEYWORDS: coherent control, Michelson interferometer, quantum dot, InAs, photoluminescence, photoluminescence excitation

1. Introduction

The ultrafast carrier dynamics in semiconductor quantum nanostructures, such as quantum wells (QWs), quantum wires (QWRs) and quantum dots (QDs) have been intensively investigated in recent years.[1–11)] In particular, QDs have unique properties such as a strong quantum confinement of carriers[12,13)] and a long dephasing time of exciton polarization.[14)] QDs are expected to be applicable to nonlinear devices such as ultrafast all-optical switches and qubits for quantum computing devises. A coherent control technique using a phase-locked ultrashort pulse pair is a powerful tool for investigating the carrier dynamics in a QD. Bonadeo *et al.* observed a long dephasing time in a GaAs QD,[6)] and Kamada *et al.* reported the exciton dephasing time in a disk-shaped InGaAs QD,[7)] using the phase-locked pulse pair generated by an optical interferometer. The exciton in a self-assembled InAs QD is a promising candidate for a quantum logic device due to its larger quantum confinement and long dephasing time. However, the photoluminescence (PL) wavelength of InAs QDs is longer than that of GaAs QDs or InGaAs QDs and it is more difficult to observe the carrier dynamics of single dots using a silicon photodetector. Therefore, a low-sensitivity silicon detector at longer wavelengths (more than 900 nm) requires a long exposure time of the charge-coupled device (CCD) detector and a long measurement time in order to obtain a weak PL spectrum from a single InAs QD. For this reason, a stable phase-locked pulse pair with an extremely long stabilization time is necessary for observing the weak luminescence from a single QD in a coherent control experiment. However, it is very difficult to stabilize the relative phase between two pulses for a long period of time due to thermal drift or fluctuation of the experimental setup in a conventional optical interferometer. Therefore, for this purpose, we have developed a Michelson interferometer with an extremely long phase stabilization time.

For detecting the luminescence from a single QD, either a microscope objective system or a scanning near-field microscope (SNOM) system is required in order to avoid the large inhomogeneous broadening of QD ensembles. Toda *et al.* demonstrated a coherent control experiment using a SNOM.[8)] Although the spatial resolution of the SNOM system is better than that of a conventional microscope objective system, it is difficult to observe the same QD multiple times. We performed conventional micro-spectroscopy using a microscope objective system for a metal mask with a 0.2 μm hole. This method provided a high degree of experimental reproducibility.

In this experiment, we developed a high-resolution Michelson interferometer in order to stabilize the relative phase of the double pulses. The extremely long phase stabilization time of more than several minutes and ultra-high-resolution control of the relative phase were realized by combining a He–Ne two-frequency laser positioning system and the high-resolution Michelson interferometer. The coherent carrier dynamics of a single InAs self-assembled quantum dot (SAQD) was then investigated using a micro-spectroscopy system.

2. Experimental Setup

Figure 1 shows a schematic illustration of the high-resolution Michelson interferometer with a He–Ne two-frequency laser positioning system. A solid line shows the optical path from a mode-locked Ti:sapphire laser. A dotted line shows the optical path from a He–Ne two-frequency laser positioning system. A beam from the He–Ne laser was introduced into the interferometer parallel to the beam from the mode-locked laser. The mode-locked laser with a pulse duration of 2.7 ps and repetition rate of 76 MHz was used for the incident pulse. After the incident pulse was divided by a half mirror, each pulse was reflected at each retro-reflector fixed by a pulse motor stage and a piezoelectric actuator stage, respectively. The reflected pulses was overlapped on the half mirror again, and the pulse pair was created. The arm length difference between the pulse motor stage and the piezoelectric actuator stage causes a relative pulse delay. The resolution of the pulse motor stage was 0.05 μm/step and that of the piezoelectric actuator stage was 0.69 nm/step. This Michelson interferometer was placed in a soundproof

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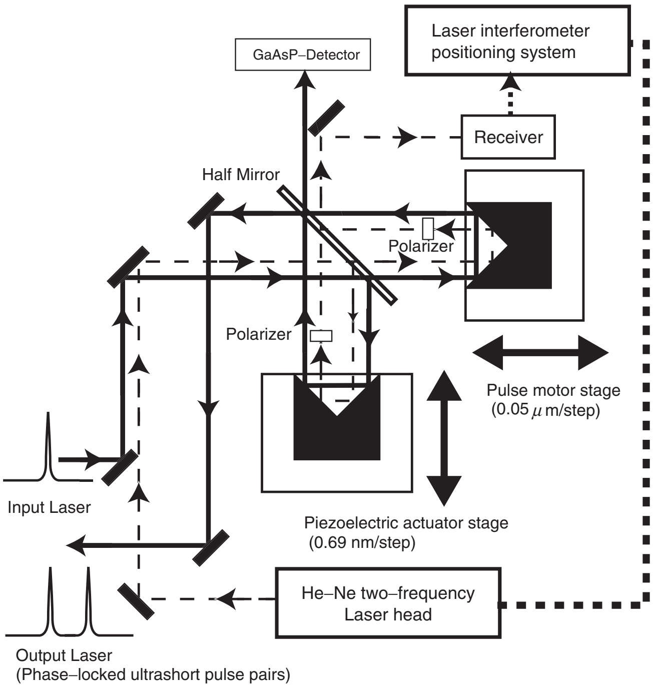

Fig. 1. High-resolution Michelson interferometer with He–Ne laser positioning system.

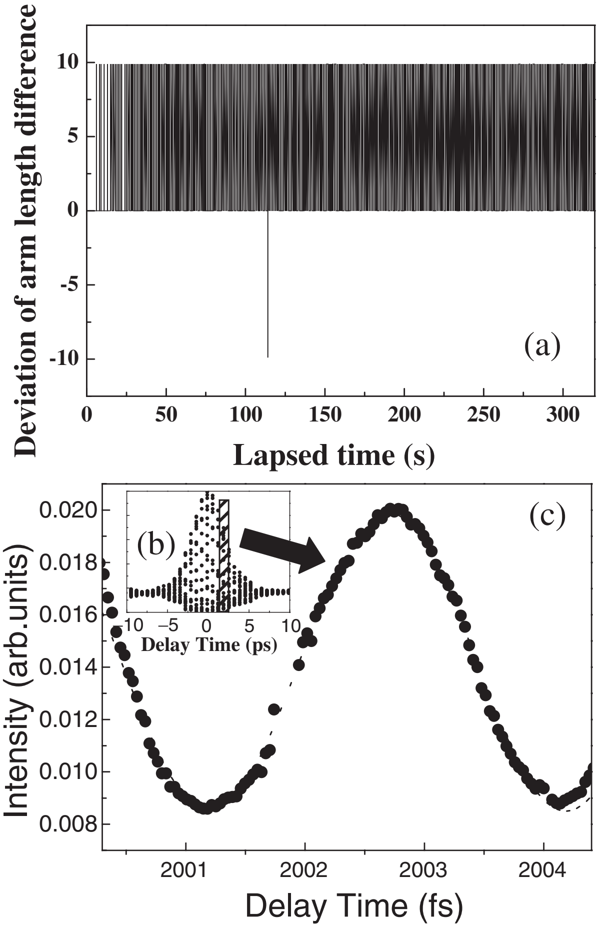

Fig. 2. (a) Deviation of arm length difference in Michelson interferometer. (b) Intensity autocorrelation. (c) Expanded view of the autocorrelation at 2 ps.

box, in order to reduce the effect of air movement and sound. The output pulse pair was reflected at a half mirror and focused by an object lens onto a sample. The beam diameter on the sample was 1.7 μm. The sample was cooled with a He-gas refrigerator to approximately 5 K.

PL signals from the sample were spectrally resolved using a monochromator and detected using a liquid-nitrogen-cooled CCD camera. In the coherent control experiment, the PL intensity was recorded as a function of the temporal interval between two pulses. Since the PL from a single QD is very weak, the relative phase should be stabilized for at least several minutes in order to obtain a sufficient signal intensity.

The samples used here were InAs SAQDs,[15,16] which were grown by molecular beam epitaxy (MBE). The density of the SAQDs was approximately $100/\mu m^2$. A metal mask with a 0.2 μm hole was formed on the sample surface by the electron-beam lithography and lift-off technique, so that the sharp PL spectra from a single dot could be detected. The outside of the mask (0.2 μm in diameter) was etched to form a pillar shape with a height of 240 nm.

3. Results and Discussion

To stabilize the relative phase of the pulse pair in this Michelson interferometer, we monitored the arm length difference by using the laser positioning system with the He–Ne two-frequency laser, and controlled the movement of the piezoelectric actuator stage by computer in intervals of 20 ms. The beat frequency of the He–Ne two-frequency laser was changed with the relative motion of the retro-reflector, due to a Doppler effect. The frequency shift was measured using the receiver and converted to a relative displacement of the light path using the controller of the interferometer. The information on the position fluctuation was sent to a computer controlling the system for feedback to the piezoelectric stage. Figure 2(a) shows the deviation of arm length difference in the Michelson interferometer. The arm length was stabilized for more than several minutes with the feedback, which ensured detection of the phase-locked pulse pair. The maximum deviation was 10 nm, and this was limited by the resolution of our He–Ne laser positioning system. Figure 2(b) shows the second-order autocorrelation of the laser pulse. An expanded view of the autocorrelation at 2 ps is shown in Fig. 2(c). The correlation waveform which closely matched the theoretical curve was measured by using the high-resolution Michelson interferometer and the He–Ne two-frequency laser positioning system. It became possible to generate a stable phase locked pulse pair with the pulse width as needed.

Figure 3(a) shows the micro-photoluminescence (μPL) spectra of the SAQDs. The excitation energy is 1.368 eV. The pulse energy is $200\,\mu J/cm^2$ and the exposure time of the CCD camera is 10 s. In this experiment, we focused the PL peak of $E_{PL} = 1.325$ eV from a single QD. Figure 3(b) shows the micro-photoluminescence excitation (μPLE) spectrum of a single InAs SAQD. This μPLE spectrum was detected at $E_{DET} = 1.325$ eV which corresponds to the fundamental sub-band level of the SAQD. The μPLE spectrum was plotted as a function of detuning between the ground state PL energy (E_{DET}) and excitation energy (E_{EX}). As shown in Fig. 3(b), we observed a peak around

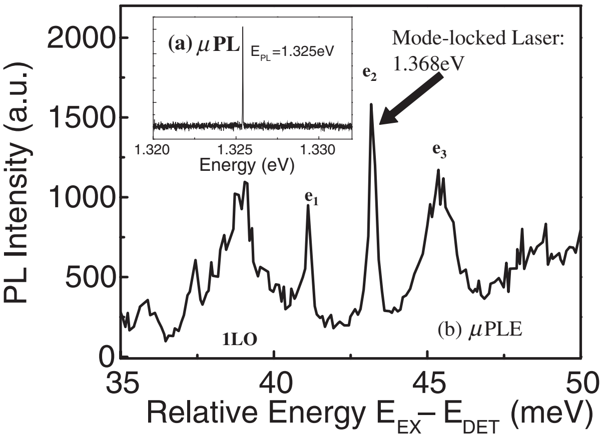

Fig. 3. (a) Micro-photoluminescence (μPL) spectrum of InAs SAQDs. (b) Micro-photoluminescence excitation (μPLE) spectra of a single InAs SAQD. (c) Expanded view of μPLE at $E_{EX} - E_{DET} = 35$–55 meV.

$E_{EX} - E_{DET} = 36$ meV related to the 1LO level,[17] and also around e1, e2, and e3 which are related to the electronic state.[18] In this study, we focused on the μPLE peak of around $E_{EX} - E_{DET} = 43$ meV, because the width of this peak was very sharp and it had a strong intensity. The linewidth was approximately 200 µeV. The dephasing time of the QD was calculated to be $T_2 > 6.6$ ps from the PLE linewidth. Since the spectral resolution for the μPLE measurements was approximately 200 µeV, we cannot estimate the dephasing time by the μPLE spectra. In the coherent control experiment, the laser wavelength of the phase-locked pulse pair was tuned to the electronic state at 1.368 eV.

Coherent control of an InAs SAQD was demonstrated using the micro-spectroscopy system with the high-resolution Michelson interferometer. Figure 4(a) shows the oscillation behavior of the integrated PL intensity as a function of relative time delay. An expanded view of the oscillation at 2 ps is shown in Fig. 4(b). In this coherent control, the first pulse creates an exciton polarization which oscillates at the frequency of the pulse field. When the second pulse is in phase, the exciton population increases, and the PL intensity is enhanced. On the other hand, when the second pulse is out of phase, the exciton population is cancelled, and the PL intensity decreases. When the pulse interval is sufficiently longer than the dephasing time of the exciton (T_2), the coherence of the exciton polarization is lost. In this case, the PL intensity is constant, because it is not influenced by the changing of the pulse interval. The resulting quantum mechanical interference gives a fast oscillating fringe in a period of the driving frequency, and its amplitude decays due to the decoherence. As shown in Fig. 4(a), the exponential fit yields the dephasing time of the polarization of approximately $T_2 = 9.5$ ps, which is close to that estimated on the basis of the homogeneous linewidth of the PLE spectrum. As shown in Fig. 4(b), a sinusoidal behavior of PL intensity was clearly observed with a temporal division of 33 as. This precise temporal control makes it possible to measure the quantum phase information by a coherent control technique using the high-resolution Michelson interferometer with the He–Ne laser positioning system and a micro-spectroscopy system.

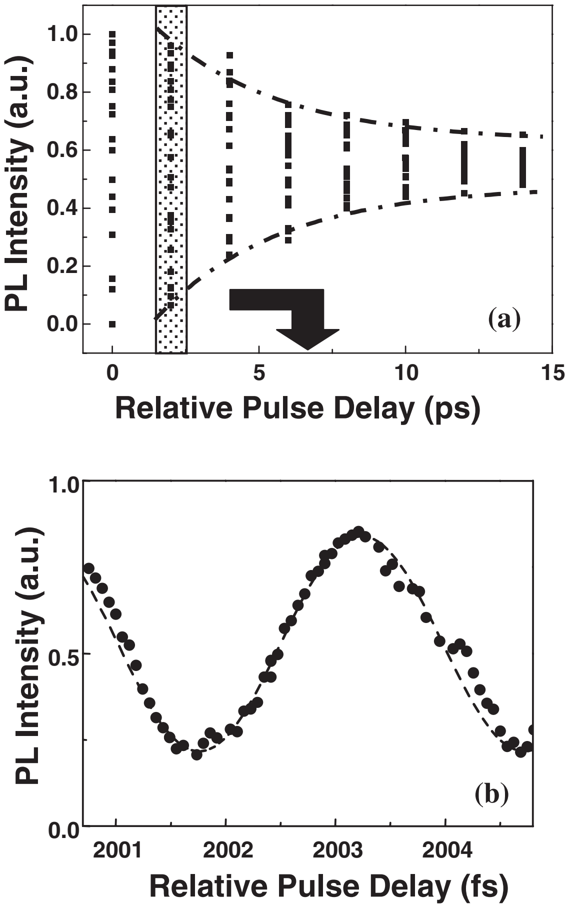

Fig. 4. (a) Amplitude of oscillation in integrated PL as a function of relative pulse delay. (b) Expanded view of the oscillation at 2 ps.

4. Conclusions

We developed a high-resolution Michelson interferometer in order to stabilize the relative phase of double pulses. The extremely long phase stabilization time of approximately 1 h and the ultra-high resolution control of the relative phase were realized by combining a He–Ne two-frequency laser positioning system and the high-resolution Michelson interferometer. The coherent carrier dynamics of a single InAs SAQD were then measured using the micro-spectroscopy system. Stabilization of a phase-locked pulse pair was realized with the maximum deviation of below 10 nm. The phase deviation of the double pulse is only 4 degrees at 900 nm. The oscillating behavior of the integrated PL intensity as a function of relative pulse delay was observed. The exponential fit yields the decay time of resonance to be approximately 9.5 ps, which is close to that estimated on the basis of the homogeneous linewidth in the PLE spectrum. This characteristic has such high precision that it is unprecedented. In quantum computing, accumulation with error can be reduced by the stable control of phases.

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