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The oscillations of excitonic and nuclear spin polarizations in an optically pumped single self-assembled In0.8Al0.2As/Al0.35Ga0.65As quantum dot (QD) were clearly observed under the excitation of a wetting layer edge at \( B = 5 \) T. This indicates that an exciton pair with opposite spins is alternatively created via the half-localized state only by changing the delay time between cross-linearly polarized pulse pair. Furthermore, periodic modulation of Zeeman energy synchronizes the degree of circular polarization of photoluminescence from a single QD, indicating that the Overhauser field follows the optically created electron spin polarization in half-localized states of a QD, and the half-localized state in a QD consists of a confined electron in a discrete state and hole in the continuum state. © 2008 American Institute of Physics. [DOI: 10.1063/1.2927448]

I. INTRODUCTION

Manipulations of a nuclei-electron spin system in a semiconductor quantum dot (QD) are currently of great interest because they have many potential applications, such as memory with ultralong coherence,1 the use of a local magnet in quantum computation,2 and media conversion between photon qubits and electron spin qubits3 for quantum information processing. It is difficult to manipulate nuclear spins in a QD by the standard nuclear spin resonance technique due to the small amount of nuclei \((-10^5)\) that are extremely well isolated. Therefore, electron-nuclear spin interaction \((\text{hyperfine interaction})\) has recently been used as a driving force for nuclear spin polarization because it is emphasized by the strong confinement of the electron wave function in QDs. In fact, a high rate of nuclear spin polarization was recently observed in interface GaAs QDs4-6 self-assembled InAlAs QDs7,8 and InGaAs QDs.9-11 In the case of optical pumping, a highly polarized electron spin should be generated in the ground state to obtain a high nuclear spin polarization.12 In general, the electron spin generated in a continuum state such as bulk material is instantaneously depolarized. Even in a QD, the observed nuclear spin polarization is small when electron-hole pairs are optically created with an excitation light having the barrier band gap energy.7 On the other hand, when electron (hole) spin is generated in “half-localized” states13-17 that consist of electron and hole states, one of which is confined to the ground state of the QD, the observed Overhauser field is of a few tesla,8 because one of the carriers (possibly an electron) confined in a QD preserves the spin state with high possibility.18 The half-localized states are significantly important to understand the practical QD physics. These states appear as a wing of the wetting layer energy band in the photoluminescence excitation (PLE) spectra. The half-localized states are one of the characteristics of the real QDs which are not observed in the ideal “artificial atoms.”

In this study, we investigate the effect of the half-localized state on the excitation process in a single InAlAs QD under a magnetic field, wherein copropagating coherent visible light pulses are used. The in-phase and antiphase coherent polarization oscillations of exciton spins in a single QD are clearly observed by changing the interpulse delay time. In addition, the optically created Overhauser field in a QD is observed using orthogonally polarized optical pulses. Although it is not mainstream for spin manipulation in a QD, the half-localized state can act as an intermediate state for the \( A \) transition19-21 between remote localized states, such as the stimulated Raman adiabatic passage. Moreover, the half-localized state can relax the selection rules of optical transitions between localized states in a single QD. Therefore, if the laboratory pulses have sufficient power to excite half-localized states, it will be a great advantage.

II. EXPERIMENTAL DETAILS

In0.8Al0.2As QDs were grown on an Al0.35 Ga0.65As(120 nm)/GaAs(300 nm) buffer layer on an undoped (100) GaAs substrate by molecular beam epitaxy using a RIBER-MBE32 system. The growth temperature was 620 °C for the buffer layer and 500 °C for the InAlAs QDs. The substrate temperature was lowered gradually during the growth of the buffer layers. The InAlAs QDs were grown at a low growth rate of \( 1.5 \times 10^{-13} \) monolayers/s. For stabilizing these QDs, postannealing was performed for 90 s. Then, the substrate temperature was gradually increased to 590 °C when an AlGaAs capping layer (100 nm) was grown. For

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A continuous-wave Ti:sapphire (TIS) laser was used as an excitation source with a linearly polarized laser field up to 5 T at 4.2 K. The magnetic field was aligned parallel to the growth direction, and the sample was excited in a Faraday configuration. A continuous-wave Ti:sapphire laser was tuned to 1.6253 eV for the excitation of the half-localized states determined by the PLE measurements [Fig. 1(b)]. The detection energy of the PLE spectrum was adjusted to the emission energy of 1.6253 eV. The sharp features above 1.7 eV are not due to bound states and may indicate some type of resonance of a multimonophoton or a mere detector noise. Note that a PL peak is located on the low-energy tails of the half-localized states, as shown in the PLE spectra. Previous studies\textsuperscript{13–17} suggested that these continuum-like tails were due to transitions between one of the carriers in a QD and the other carrier in the wetting layer, which is a quantum well with about 1 ML thickness beneath the QD.

Figure 1 shows the 3D plots of the excitonic Zeeman spectra as a function of the interpulse delay time. The excitation field at 4.2 K was applied along the growth direction. The pump-pulse pair can have either cross-linear or colinear polarization by adjusting two half-wave plates (HWPs) placed after the SLMs.

### III. RESULTS AND DISCUSSION

Figure 3 shows the 3D plots of the excitonic Zeeman spectra as a function of the interpulse delay time. The excitation field at 4.2 K was applied along the growth direction. The pump-pulse pair can have either cross-linear or colinear polarization by adjusting two half-wave plates (HWPs) placed after the SLMs.

A schematic of the experimental setup is shown in Fig. 2. A mode-locked TIS laser with a pulse repetition rate of 76 MHz was used as the light source. A sequence of pump pulses was produced by passing them through a Mach-Zehnder interferometer. A 100 fs laser pulse was divided into two pump pulses with a controlled time delay using a piezoelectric stage with a resolution of 5 nm. The pump-pulse pair was spectrally shaped by removing the tail of the laser spectra using two dispersion-free 4-f optical systems in conjunction with spatial light modulators (SLMs), which have a resolution of 350 μeV. Then, two pump pulses were combined coaxially and focused onto the sample surface by a microscope objective lens. The single QD emissions collected by the same objective lens were dispersed by a triple grating spectrometer and detected with a liquid N\textsubscript{2}-cooled Si-charge-coupled device (CCD) camera, which has a resolution of 12 μeV. Next, the energies of the emission peaks were determined to be on the order of 3 μeV by spectral fitting. The mode-locked TIS laser was tuned to ~1.7 eV for the excitation of the half-localized states determined by the PLE measurements [Fig. 1(b)]. The sample was held in a liquid He-flow cryostat and maintained at 4.2 K. A magnetic field of 5 T was applied along the growth direction. The pump-pulse pair can have either cross-linear or colinear polarization by adjusting two half-wave plates (HWPs) placed after the SLMs.
colinear polarization with the same frequency are clearly observed in the case of colinearly polarized excitation. Two excitation pulses can have either colinear (a) or cross-linear (b) polarization by changing the HWP angle (Fig. 2). In both cases (a) and (b), PL intensities are normalized by maximum intensity.

![Fig. 3](image)

**FIG. 3.** (Color online) 3D image (CCD image) of a Zeeman pair as a function of the pulse delay time. Two excitation pulses can have either colinear (a) or cross-linear (b) polarization by changing the HWP angle (Fig. 2). In both cases (a) and (b), PL intensities are normalized by maximum intensity.

Exciton ground states in a single QD is observed. As shown in Fig. 3(a), the time-integrated PL spectra of the Zeeman-split exciton pair oscillate in phase as a function of the interpulse delay time ($\tau$) with a period ($\sim 2.4$ fs) corresponding to the energy of the pump pulses ($\sim 1.7$ eV). This oscillation of the Zeeman pair can be explained by the amplitude interference between first ($E_1$) and second ($E_2$) pulses, $\sim \cos(\omega \tau) e_{1 \cdot e_{2 \cdot}}$, where $\omega$ and $e_{1 \cdot e_{2 \cdot}}$ are the center frequency and polarization vector of the pump pulses, respectively. In this experiment, since the half-localized state is excited by the optical pulses, the observed PL oscillation decays within the overlapping time of the pump-pulse pair, unlike the use of the discrete excited state in the previous studies such as wavepacket interferometry.\(^{22-24}\)

In the case of a pump pair with cross-linear polarizations, the amplitude interference becomes zero because the polarization of the pump pair is orthogonal, $e_{1 \cdot e_{2 \cdot}}=0$. In addition, the *antiphase* oscillations of the Zeeman split pair with the same frequency are clearly observed in the case of colinear polarization ($e_{1 \cdot e_{2 \cdot}}=1$),\(^{25}\) as shown in Fig. 3(b). The polarizations formed by the orthogonally polarized pulse pair are modulated by the delay time between the first and second pulses. When $\tau$ is swept, the right ($\sigma^+$) and left ($\sigma^-$) circular polarization appear alternately with the period $\omega \tau = \pi$; $\text{Re}(E_1 + E_2) \sigma^\pm \sim \cos(\omega \tau \pm \pi/2)$. The $\tau$-dependence of the degree of circular polarization is expressed as $\sim -\sin(\omega \tau)$. Therefore, the antiphase oscillations caused by the phase difference between the first and second pulses indicate that an exciton pair with opposite spins is created through the half-localized state in the QD.

The upper panel of Fig. 4 shows the degree of amplitude interference, which is determined from the total PL intensity of the Zeeman pair divided by the delay time average of PL intensity, $\text{DAI}=(I_+ + I_-)/(I_+ + I_-) - 1$, where $I_+$ and $I_-$ indicate the integrated PL intensity of the corresponding peak of Zeeman pair ($\sigma^\pm$), and the delay time average of $I_+ + I_-$. In fact, amplitude interference is observed only in the case of the colinearly polarized excitation, indicating that the amounts of optically created exciton are modulated by the delay time between the pump pulse pair. The middle and lower panels of Fig. 4 highlight the degree of the circular polarization, $\text{DCP}=(I_+ - I_-)/(I_+ + I_-)$, with cross-linear polarizations and the energy difference between the Zeeman energies of cross-linearly and colinearly polarized excitation setup, $\Delta E=E_{Z2}^{\text{cross}} - E_{Z2}^{\text{colinear}}$, where $E_{Z2}$ is the delay time average of the Zeeman energy of colinearly polarized excitation. For the sake of comparison, the delay time average of DCP in a colinearly polarized setup is shown by the dashed line in

![Fig. 4](image)

**FIG. 4.** (Color online) Amplitude interference effects of a Zeeman pair in colinearly (solid triangles) and cross-linearly (open boxes) polarized excitations. Solid and open circles indicate $\Delta E=E_{Z2}^{\text{cross}} - E_{Z2}^{\text{colinear}}$ and DCP=$(I_+ - I_-)/(I_+ + I_-)$ as a function of the pulse delay in the cross-linear polarization setup. The DAI profile with colinear polarization and DCP $(\Delta E)$ with cross-linear polarization (open (solid) circles) are fitted with a cosine (red line) and sine (blue lines) function. Dashed (blue) line indicates the average values of exciton polarization rate in the colinearly polarized excitation.
the middle panel of Fig. 4. Note that the average value could not be estimated with a high degree of accuracy because the PL spectra of the Zeeman-split exciton pair becomes zero in phase, which implies that indeterminate forms are presented in DCP.

$\Delta \varepsilon$ is varied up to $\sim 30$ $\mu$eV by changing the interpulse delay only in the case of cross-linearly polarized excitation. This variation from the colinearly polarized excitation can be explained by the “Overhauser field,”

$$B_N = A(I_z) / \mu_B g_z,$$

where $A, (I_z), \mu_B,$ and $g_z$ are the hyperfine constant, averaged nuclear spin polarizations, Bohr magneton, and electron $g$-factor, respectively. The Overhauser field is induced by the hyperfine interaction between the electron and nuclear spins,

$$\mathcal{H}_{ZD} = A'F(S+\mathcal{F}S^T)/2 + A'S_z,$$

where $T^\mathcal{F}(S^T)$ and $S_z$ are nuclear (electron) raising and lowering operators and electron spin polarization, respectively.

The nuclear spins are polarized by the first flip-flop term with an optically created electron spin. The electron Zeeman splitting is modulated by this optically created Overhauser field via $A'S_z$. The change of the Zeeman splitting energy from the linearly polarized excitation is known as the Overhauser shift $A'$.

Therefore, it is a good indicator of the electron spin polarization. The excitation is known as the Overhauser shift $A'$.

Although the DCP of the emissions originating from the ground state is reflected in the exciton polarization $<S>$ in a single QD. As shown in Fig. 4, the amplitude and direction of the Overhauser field synchronize the variation of DCP modulated by changing the delay time between the cross-linearly polarized pump pulses, $B_N \propto \text{DCP}$. Although the DCP of the emissions originating from the ground states is precisely lower than $2<S>$ in the ground state due to the flip-flop process between electron and nuclear spins, the $\Delta \varepsilon$ associated with the observed DCP is clearly observed, implying that observed DCP is reflected in $<S>$. Therefore, the observed DCP indicates the polarization of the electron spin generated in a discrete state of a QD, because the DCP in the ground state is reflected in the exciton polarization produced in the half-localized state when the coherence of half-localized states is destroyed by energy relaxation with the depolarization of hole generated in continuum state.

To verify the above-mentioned scenario, we compare the DCP dependence of $\Delta \varepsilon$ with the calculated $<S>$ dependence of OHS. The steady state OHS is expressed as

$$A(I_z) = A(\mathcal{F}) <S> - S_0 \frac{T_{ND}}{T_{NF} + T_{ND}}.$$  \hspace{1cm} (1)

The flip-flop rate $1/T_{NF}$ between the electron and nuclear spins is expressed as follows:

$$\frac{1}{T_{NF}} = \tau_f \left[ \frac{A}{\hbar} \right]^2 \left[ 1 + \left( \frac{\tau_e}{\hbar} \right)^2 (g_z \mu_B (B_z - B_N))^2 \right],$$  \hspace{1cm} (2)

where $Q(=|I(I+1)|/|S(S+1)|)$, $\tau_e, N, T_{ND}, S_0,$ and $f$ indicate the momentum conversion coefficient from electron spin to nuclear spin system, correlation time of the coupled electron-nuclei system with broadening $\hbar / \tau_e$, number of nuclei in a QD, nuclear spin depolarization rate, thermal electron spin polarization, and the degree of electron existence in a QD, respectively. Note that $B_N$ modulates only the electron Zeeman splitting energy, because the probability of a hole with a $p$-like wave function at the nucleus site is negligible. In Fig. 5, we show the OHS curves calculated using Eqs. (1) and (2).

In addition, the following parameters are used: $A = 52.38$ $\mu$eV, $T_{ND} = 5$ ms, $I(I+1) = 12.65$, $N = 23,000$, $g_z = -0.3$, $\tau_e = 10.6$ ps, and $f = 0.1$–1.0 (solid curves), where $A$ and $I(I+1)$ are weighted values for an In$_{0.8}$Al$_{0.2}$As QD. The asymmetrical OHS is caused by the increase in $1/T_{NF}$ due to the decrease in $\left| g_z \mu_B (B_z - B_N) \right|$ when $B_z$ is eliminated by $B_N$. The DCP dependence of $\Delta \varepsilon$ is fitted by the $<S>$ dependence of OHS using $f \sim 0.2$, as shown in Fig. 5, suggesting that the observed DCP is approximately $2<S>$. To confirm this compatibility, we also show the reference data obtained in cw excitation measurements with the excitation energy $\sim 1.7$ eV (measurement method is shown in Ref. 7). The excitation power was set enough to saturate the PL intensity. In comparison to the reference data, the observed $\Delta \varepsilon$ is small. This difference can be explained by the well-known excitation power dependence of nuclear spin polarization. In the cw excitation measurement, the effective excitation rate of the electron is roughly limited by the exciton lifetime in the ground state, $\sim 1.5$ ns. On the other hand, a pulse occurs only once in $\sim 13$ ns because of a repetition rate of 76 MHz. Therefore, the effective excitation rate in cross-linear polarized excitation is about one-ninth that in cw excitation. In fact, the calculation curve with $f \sim 0.9$ is fitted to the experimental data in the cw excitation. Furthermore, this compatibility suggests that the observed DCP of the optically created exciton via the half-localized states in a QD is attributed not to hole spin polarization but $2<S>$, because the OHS is not observed when electron spin polarization is created in the continuum state with instantaneous depolarization. Therefore, the optically created exciton in the half-localized state proved to consist of an electron with a long coherence in a discrete QD state and hole in the continuum state.
**IV. SUMMARY**

The antiphase polarization oscillations of exciton spins in a single QD are clearly observed by changing the inter-pulse delay time, which suggests that the half-localized state has a large oscillator strength for the optical transition between the Zeeman-split exciton states with opposite spins, in which the direct transition between the Zeeman-split exciton states is optically inactive. The optically created Overhauser states is optically inactive. The optically created Overhauser field in a QD was monitored through the modulated OHS by changing the delay time between the orthogonally polarized field in a QD was monitored through the modulated OHS by changing the delay time between the orthogonally polarized optical pulses, which signifies that the confined electron and hole created in continuum state constitute the half-localized state in a QD.

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25. The beat frequency slightly differs by ~3% for (a) colinear and (b) cross-linear excitation. However, this difference is within the delay stage repeatability, and therefore we can conclude that the beat frequencies are the same for both the cases.