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A novel method for direct evaluation of nuclear spin fluctuation by using nuclear spin switch in quantum nanostructures

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Abstract

The nuclear spin fluctuation is a hot topic currently in the studies of quantum information processing. In this work, the convenient method for the direct evaluation of the nuclear spin fluctuation is demonstrated in single InAlAs quantum dots by using the nuclear spin switch. Further, the method can be used to determine the sign and magnitude of electron and hole g factors.

1. Introduction

The carrier spin dynamics in low-dimensional semiconductor structures has attracted considerable interest because of the possibilities of spin storage and manipulation in future semiconductor electro-optic devices and quantum information processing. In the applications, the effect of the nuclear spin fluctuation, which induces a severe relaxation of the localized electron spins, is one of the hot issues. Here, we demonstrate the convenient and easy method to evaluate the nuclear spin fluctuation.

2. Evaluation method for nuclear spin fluctuation

Self-assembled $In_{0.75}Al_{0.25}As/Al_{0.3}Ga_{0.7}As$ quantum dots (QDs) grown on an undoped (100)-GaAs substrate were used in this work. After the fabrication of small mesa structures, the micro-photoluminescence (μ-PL) measurements were performed at 6 K under longitudinal magnetic fields B_z up to 5 T. The excitation energy was tuned to the transitions to the wetting layers. Figure 1(a) shows the polarization-resolved PL spectra (π_x, π_y) of a typical single InAlAs QD at 6 K and 0 T under the nonpolarized excitation. The spectra indicate the emissions of the neutral biexciton (XX^0), neutral exciton (X^0), and positive trion (X^+) from the low energy side. The fact that these PL peaks originate from the same single QD can be confirmed with observing the response to the nuclear field $\boldsymbol{B}_n$ generated by the σ^+ excitation.

The ground state of X^+ consists of two holes with spin-singlet and one electron, and thus, the polarization of PL spectra is essentially determined only by the electron spin polarization $\langle S_z \rangle$. The degree of circular polarization (DCP) is given as $\rho_c = (I^+ - I^-)/(I^+ + I^-)$, where $I^{+(-)}$ is the PL intensity of $\sigma^{+(-)}$ component. Consequently, a high (low) value of $|\rho_c|$ indicates a large (small) degree of $|\langle S_z \rangle|$ according to the relation $\langle S_z \rangle = -\rho_c/2$, and the change in DCP can be used as a direct measure of $\langle S_z \rangle$.

First, the electron g factor (g_z^e), which is one of the key parameters describing the coupled electron-nuclear spin system, is evaluated for single InAlAs QDs. This procedure is necessary for evaluating $\boldsymbol{B}_n$ from the observed Overhauser shift (OHS), which is the energy shift of electron spin state induced by $\boldsymbol{B}_n$. Figure 1(b) shows the density plot of the X^+ PL spectra with increasing B_z under the σ^+ excitation. The Zeeman splitting of the X^+ PL peaks, which is defined as $\Delta E_Z = E(\sigma^-) - E(\sigma^+)$ where $E(\sigma^+)$ and $E(\sigma^-)$ are the energy of the σ^+ and σ^- PLs, changes abruptly at a critical magnetic field B_z^{HC} (=4.5515 T). The curious change of ΔE_Z depending on $\boldsymbol{B}_z$ originates from the generated $\boldsymbol{B}_n$ [1]. Since the energy cost in the flip-flop process between the electron and nuclear spins through the hyperfine interaction is reduced under the σ^+ excitation, a so-called *nuclear spin switch* (NSSW) occurs and induces the abrupt change in ΔE_Z [1,2]. ΔE_Z and DCP of the X^+ PL spectra are plotted under three different excitation powers in Fig. 1(c). Note that the electron Zeeman splitting $\Delta E_e = g_z^e \mu_B (B_z + B_n)$ (μ_B: the Bohr magneton) is exactly zero at the B_z^{HC} of each data set because of the full compensation of $\boldsymbol{B}_z$ by $\boldsymbol{B}_n$. Then, the observed ΔE_Z at the point corresponds to the hole Zeeman splitting $|g_z^h|\mu_B B_z$

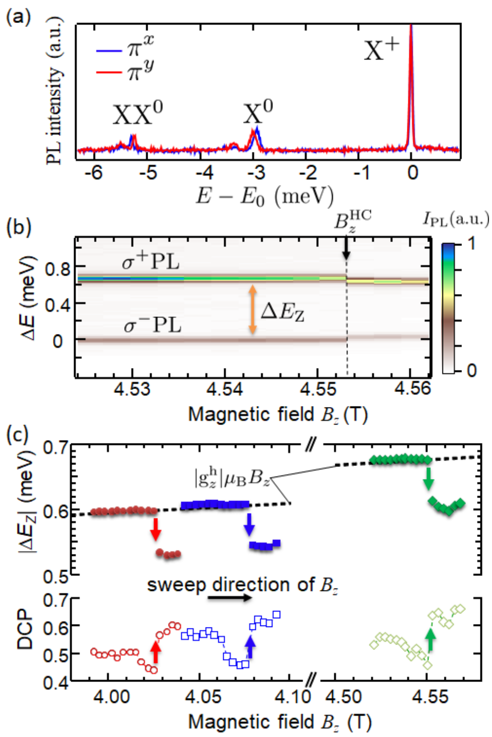

Fig. 1 (a) Polarization-resolved PL spectra of a typical single InAlAs QD at 0 T. The energy axis is replotted from the X^+ PL peak energy at 1.6449 eV. (b) The density plot of X^+ PL spectra as a function of increasing B_z. The energy axis is replotted from the lower PL peak. (c) The observed $|\Delta E_Z|$ near three different B_z^{HC}. The dashed line is the calculated hole Zeeman splitting. In the lower panel, the DCP is plotted.

indicated by a dashed line. Using the exciton g factor ($=g_z^e + g_z^h$) that can be obtained with linearly polarized excitation (i.e., B_n=0), g_z^e=+0.34±0.02 and g_z^h=–2.57±0.01 are obtained including their signs for this single InAlAs QD [3]. These magnitudes are close to those reported in the previous work [1]. In Fig. 1(c), the change in DCP depicted in the lower panel is synchronous with the changes in ΔE_Z. This property is important for the evaluation of nuclear spin fluctuation.

Next, we estimate the nuclear spin fluctuation ($\Delta \boldsymbol{B}_n$) and the resultant electron spin relaxation time (T_Δ) in a QD. According to the standard picture of spin relaxation as shown in the inserts of Fig. 2(b), the electron spin, $\boldsymbol{S}$ precesses around the effective magnetic field and loses its coherence via scattering processes. Here, the torque vector, $\boldsymbol{\Omega}_e$ is composed of the macroscopic field $\boldsymbol{B}_{eff}$ (= $\boldsymbol{B}_z$+$\boldsymbol{B}_n$) and fluctuating field $\Delta \boldsymbol{B}_n$. In the absence of $\boldsymbol{B}_{eff}$, $\boldsymbol{S}$ in a QD precesses coherently around $\Delta \boldsymbol{B}_n$ during its lifetime, which is limited by the recombination time τ_r. However, $\langle S_z \rangle$ which is an ensemble average over a large number of measurements, decreases within a characteristic time T_Δ due to the random distributions of the direction and magnitude of $\Delta \boldsymbol{B}_n$, and it converges to $S_0/3$ (S_0: the initial value of $\langle S_z \rangle$) over the long time limit (*frozen fluctuation model*) [4]. If a large $\boldsymbol{B}_{eff}$ ($\gg \Delta \boldsymbol{B}_n$) appears and $\boldsymbol{\Omega}_e$ is nearly along the *z*-axis, the reduction of $\langle S_z \rangle$ is strongly suppressed.

Figure 2(a) indicates $\langle S_z(t) \rangle / S_0$, calculated as functions of normalized magnetic field $B_{eff}/\Delta B_n$ and normalized time t/T_Δ. The right panel shows the vertical profiles of the figure, which indicates clearly that the increase in B_{eff} suppresses the oscillation and reduction of $\langle S_z(t) \rangle / S_0$. On the other hand, the lower panel is a horizontal plot at t/T_Δ= 9. In this long time region, the $\langle S_z(t) \rangle / S_0$ shows a dip structure centered at the point of zero-B_{eff}. Assuming that the orientation of $\Delta \boldsymbol{B}_n$ is randomly distributed over the accumulation time of the CCD detector (1 s), the DCP of time-integrated X$^+$ PL is given by

$$\rho_c = \frac{2}{\tau_r} \int \langle S_z(t) \rangle \exp\left(-\frac{t}{\tau_r}\right) dt. \qquad (1)$$

Note that this equation leads to a dip structure similar to the one in the lower panel of Fig. 2(a), and its width is determined by the ratio of T_Δ to τ_r.

Figure 2(b) shows the plot of DCP as a function of $|\Delta E_e|$ which can be deduced from the data set in Fig. 1(c). The absence of data points around $|\Delta E_e|$=10-50 μeV is attributed to the abrupt changes in $\boldsymbol{B}_n$ and DCP. The observed DCP has a dip structure centered at the point $|\Delta E_e|$=0, and it agrees well with the above explanation. The experimentally obtained DCP is determined by $\langle S_z(t) \rangle$ and τ_r=0.75 ns evaluated from other independent measurement. By comparing it with the solid curve obtained by Eq. (1), we can deduce the values S_0=0.31 and T_Δ=0.8 ns.

The magnitude of $\Delta \boldsymbol{B}_n$ is estimated to be 40 mT from the relation $|\Delta \boldsymbol{B}_n| = \hbar/(g^e \mu_B T_\Delta)$, assuming an isotropic electron g factor. This value is comparable to those in InAs QDs (~30 mT) [5], InGaAs QDs (~10.5 mT) [6], and InP QDs (~15 mT) [7], and it coincides with the value for a different InAlAs QD [8]. Further, the validity of the observed ΔB_n can be confirmed using the QD parameters $(g^e, \tilde{A}, \tilde{I}, N)$, where $\tilde{A}$, $\tilde{I}$, and N are the averaged hyperfine constant, averaged nuclear

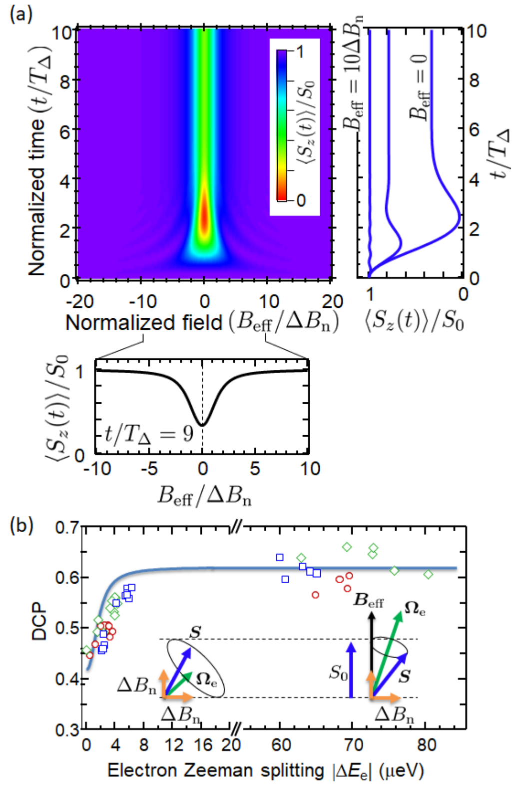

Fig. 2 (a) The calculation of $\langle S_z(t) \rangle / S_0$ as functions of normalized time and magnetic field. The vertical profiles at $B_{eff}/\Delta B_n$= 0, 2, 10 are indicated in the right panel, and the horizontal profile at t/T_Δ=9 is in the lower panel. (b) DCP versus $|\Delta E_e|$. The solid curve is a calculated one. Inserted: schematics of electron spin precession around torque vector $\boldsymbol{\Omega}_e$, which includes $\boldsymbol{B}_{eff}$ and $\Delta \boldsymbol{B}_n$, left: $\boldsymbol{B}_{eff} \sim 0$, right: $\boldsymbol{B}_{eff} \gg \Delta \boldsymbol{B}_n$.

spin, and number of nuclei, respectively. From the relation $\Delta B_n \cong \tilde{A}\tilde{I}/(\sqrt{N} g^e \mu_B)$ with the values $(g^e, \tilde{A}, \tilde{I}, N)$= (0.34, 52.6 μeV, 2.75, 3×10^4) for our InAlAs QD, ΔB_n is roughly estimated as ~42 mT, which agrees quite well with our observation.

3. Summary

A novel method to evaluate the nuclear spin fluctuation ΔB_n was demonstrated in single InAlAs QDs by using the nuclear spin switch. This evaluation method of ΔB_n is experimentally simpler and easier than the previous time-resolved observations [8] and other methods [5-7]. Further, the method can be used to determine the sign and magnitude of electron and hole g factors. In the conference, we will show also the results of InAs/GaAs quantum rings.

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