Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp699-700

Studies on anomalous Hanle effect observed in single self-assembled quantum dots

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Abstract

We study the formation mechanism of the in-plane nuclear field in single self-assembled quantum dots via anomalous Hanle effect measurements. The in-plane nuclear field formation is crucial to control the direction of nuclear field with optical method and the mechanisms may open up a new spin physics. We propose a formation model of the in-plane nuclear field, where the strain-induced quadrupolar interaction plays a key role.

1. Introduction

The *engineering of nuclear spin polarization* (NSP) not only leads to the potential applications such as spin storage and optical manipulation of a confined electron spin but also opens up a new spin physics. For directional control of the optically induced NSP, the generation of the in-plane nuclear field ($\boldsymbol{B}_{\mathrm{n},x}$) is crucial. Although recent works have exhibited the formation of $\boldsymbol{B}_{\mathrm{n},x}$ unambiguously [1], the associated spin dynamics and key ingredients have not been revealed entirely. We study the formation dynamics of $B_{\mathrm{n},x}$ through the observation of anomalous Hanle curves in the self-assembled InAlAs quantum dots (QDs) and model calculations.

2. Sample and Experimental procedures

The self-assembled $In_{0.75}Al_{0.25}As/Al_{0.3}Ga_{0.7}As$ QDs grown on a (100)-GaAs substrate by molecular beam epitaxy were used in this study. After the fabrication of small mesa structures, the micro-photoluminescence (μ-PL) measurements

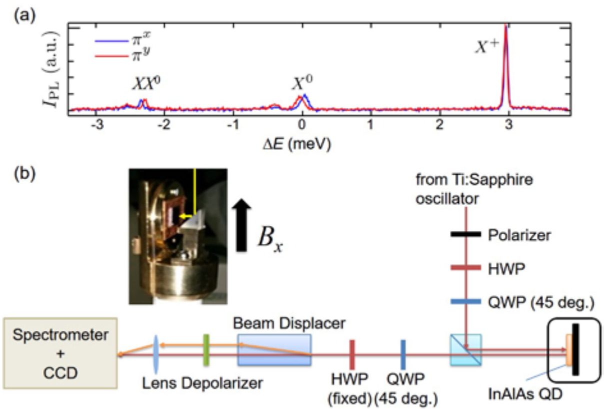

Fig. 1 (a) Polarization-resolved PL spectra under nonpolarized excitation at 6 K and 0 T. The energy axis is replotted from the mid-energy (1.6419 eV) of the fine structure of neutral exciton (X^0). (b) Experimental setup for simultaneous acquisition of the σ^+ and σ^- polarized PL components. Inset: a mounted sample and the rotation mechanism in Voigt geometry.

under the transverse magnetic fields ($\boldsymbol{B}_x$) up to 1 T were carried out at 6 K. The sweep rate of B_x was about 0.1 T/min. The QD sample was excited by a cw Ti:sapphire laser tuned to ~730 nm, which corresponds to the transition energy to the tail of the wetting layer of the QDs.

Figure 1(a) shows the polarization-resolved PL spectra of a typical single InAlAs QD under a nonpolarized excitation at 6 K and 0 T. The neutral biexciton (XX^0), neutral exciton (X^0) and positive trion (X^+) from the same single QD are observed clearly. In this work, we focus on the X^+ PL spectra since the exact relation between the observable degree of circular polarization (DCP: ρ_c) and the averaged electron spin polarization $\langle S_z \rangle$ can be established as $\langle S_z \rangle = -\rho_c/2$. This is because the X^+ consists of two holes with spin-singlet and one electron, and the polarization of PL spectra is determined only by the electron spin. Here, the DCP is defined as $\rho_c = (I^+ - I^-)/(I^+ + I^-)$ where $I^{+(-)}$ is the PL intensity of σ^+ (σ^-) component.

The optical setup is shown in Fig. 1(b). The simultaneous acquisition of the σ^+ and σ^- PL components is possible with a beam displacer, which is a contraption different from a standard polarization-resolved setup. This enables us to evaluate the DCP and the Zeeman splitting precisely and simultaneously. The Hanle curve measurement is performed in Voigt geometry as shown in the inset. The sample can rotate around the growth axis under a fixed direction of $\boldsymbol{B}_x$. To describe the Hanle curve and to evaluate $\boldsymbol{B}_{\mathrm{n},x}$, the in-plane and out-of-plane electron and hole g factors, $(\mathrm{g}_\perp^{\mathrm{e}}, \mathrm{g}_\perp^{\mathrm{h}})$ and $(\mathrm{g}_z^{\mathrm{e}}, \mathrm{g}_z^{\mathrm{h}})$ are required. From the Zeeman splitting measurements in Faraday and Voigt configurations, $\mathrm{g}_z^{\mathrm{e}}$=+0.34±0.02, $\mathrm{g}_z^{\mathrm{h}}$=-2.57±0.01, and $|\mathrm{g}_\perp^{\mathrm{e}}| \approx |\mathrm{g}_\perp^{\mathrm{h}}|$ = 0.35 ± 0.01 are obtained for this QD. Moreover, we investigated the anisotropies of the in-plane g factors by rotating the QD sample and found that the anisotropies in $|\mathrm{g}_\perp^{\mathrm{e}}|$ and $|\mathrm{g}_\perp^{\mathrm{h}}|$ are negligible. From the isotropic nature of the conduction band, $\mathrm{g}_\perp^{\mathrm{e}}$ is considered to have also a positive sign.

3. Hanle curves in classical model

The evolution of an electron spin polarization $\langle \boldsymbol{S} \rangle$ under the magnetic field can be described by the Bloch equation:

$$\frac{d\langle \boldsymbol{S} \rangle}{dt} = \frac{\tilde{\mathrm{g}}^{\mathrm{e}} \mu_B}{\hbar} \boldsymbol{B}_T^{(\mathrm{e})} \times \langle \boldsymbol{S} \rangle - \frac{\langle \boldsymbol{S} \rangle - \boldsymbol{S_0}}{T_S}, \qquad (1)$$

where $\tilde{\mathrm{g}}^{\mathrm{e}}$ is the electron g tensor, μ_{B} is a Bohr magneton (~58 μeV/T), $\boldsymbol{B}_T^{(\mathrm{e})}$ $(= \boldsymbol{B}_x + \boldsymbol{B}_{\mathrm{n}})$ is an effective magnetic field seen by a QD electron, and $\boldsymbol{S_0} = (0,0,S_0)$ is the average electron spin polarization in the absence of $\boldsymbol{B}_T^{(\mathrm{e})}$. $\boldsymbol{B}_{\mathrm{n}}$ is an optically-induced nuclear field. The first and the second

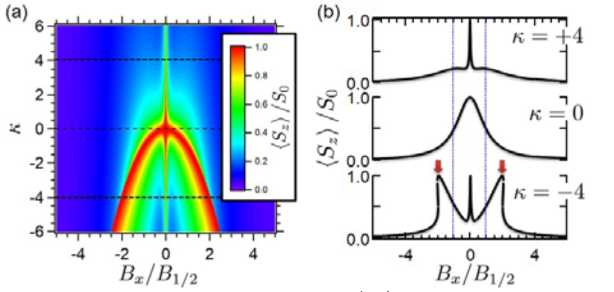

Fig. 2 (a) Calculated density plot of $\langle S_z \rangle / S_0$ as functions of a normalized magnetic field $B_x/B_{1/2}$ and κ. (b) Hanle curves with κ=+4, 0, and −4, which are sliced profiles at the dashed lines in (a).

terms in the right-hand side represent the Larmor precession and the decay of electron spin with spin lifetime T_{S}, respectively. The steady state solution of Eq. (1) gives a Hanle curve according to the relation $\rho_c = -2\langle S_z \rangle$ in the X⁺ case. Although a standard Hanle curve expected at $|\boldsymbol{B}_{\mathrm{n}}| = 0$ has a Lorentizian shape with the half width at half maximum of $B_{1/2} = \hbar / |g_\perp^{\mathrm{e}}| \mu_{\mathrm{B}} T_{\mathrm{S}}$, the curve is deformed from the Lorentzian shape by the effect of $\boldsymbol{B}_{\mathrm{n}}$. Figure 2(a) shows the calculated results by the standard theory [2]. For our single InAlAs QD, $B_{1/2}$~65 mT is expected by T_{S}~0.5 ns and $|g_\perp^{\mathrm{e}}|$= 0.35. In the theory, κ is a key parameter that represents the depth of nuclear spin cooling by a Knight field which is an effective field created by an optically-injected electron. The positive-κ (negative-κ) indicates that the $\boldsymbol{B}_{\mathrm{n},x}$ is generated parallel (antiparallel) to $\boldsymbol{B}_x$. Therefore, an electron feels a larger (smaller) field than B_x in the region of positive-κ (negative-κ) as shown in the upper (lower) panel of Fig.2 (b). Although the generated $\boldsymbol{B}_{\mathrm{n},x}$ induces the strong deviation from the Lorentzian shape ($\kappa = 0$), the deformation occurs only within a small-B_x region where the original Lorentzian curve appears as shown in the figure.

4. Anomalous Hanle effect measurements

The middle panel of Fig. 3 shows the Hanle curves measured in our single self-assembled InAlAs QD. The dashed curve is a standard Hanle curve, which is rescaled from the middle panel of Fig.2 (b). The observed curve is very different from the ones expected from the classical model (Fig.2). As clearly shown, this "anomalous" Hanle curve is distorted drastically and has the shape like a circus tent: almost symmetric with respect to the change in the sign of $\boldsymbol{B}_x$ and the abrupt change in the DCP at the critical magnetic field (B_{c}). Further, the hysteretic behaviors are seen around B_{c}. These anomalous features were observed regardless of the direction of $\boldsymbol{B}_x$. The effective field seen by an electron $|\boldsymbol{B}_x + \boldsymbol{B}_{\mathrm{n}}|$ is considered to be smaller than the applied $|\boldsymbol{B}_x|$, and thus, the Hanle curve becomes broadened. The results suggest the presence of a large $|\boldsymbol{B}_{\mathrm{n},x}|$ of up to ~0.8 T, which is generated to compensate the $\boldsymbol{B}_x$.

The whole features cannot be explained by the classical model calculations as shown in Fig. 2. From the Overhauser shift (OHS), which is the Zeeman splitting induced by $\boldsymbol{B}_{\mathrm{n}}$ and detected in the σ⁺/σ⁻ basis, the z-component of the nuclear

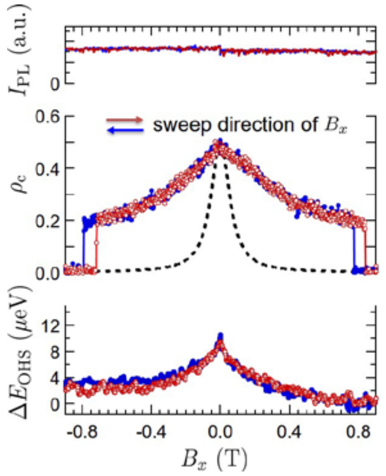

Fig. 3 Middle panel: the anomalous Hanle curve observed in a single InAlAs QD. The hysteresis behavior is detected depending on the sweep direction of B_x. Top panel: the PL intensity during the measurement. Bottom panel: the OHS detected from the spectral splitting in σ⁺/σ⁻ basis.

field $B_{\mathrm{n},z}$ can be deduced. In the bottom panel, the detected OHS, ΔE_{OHS} is indicated. The maximal value of $|B_{\mathrm{n},z}|$ appears at B_x=0, and the magnitude is about 0.5 T according to $B_{\mathrm{n},z} = \Delta E_{\mathrm{OHS}} / (g_z^{\mathrm{e}} \mu_{\mathrm{B}})$. The observed $|B_{\mathrm{n},z}|$ decreases gradually with increasing $|\boldsymbol{B}_x|$. Further, a slight asymmetry of ΔE_{OHS} was observed. It does not depend on the sweep direction of $\boldsymbol{B}_x$, and it is not due to the change of the excitation power as shown in the top panel. In addition, we observed the similar anomalous Hanle curve in InAs/GaAs quantum rings (QRs), where g_z^{e} has a negative sign [3].

To explain the anomalous Hanle curve associated with the generation of $B_{\mathrm{n},x}$, we proposed the formation model of $B_{\mathrm{n},x}$ which requires the $B_{\mathrm{n},z}$ even under a large B_x and a strong anisotropy of the nuclear g-factor [4]. In the model, the nuclear quadrupolar interaction (QI), which originates from the coupling of a nuclear spin to the electric field gradients, plays a significant role. The proposed model reproduces well the observed anomalies in Hanle curves qualitatively. In the self-assembled QDs, the impacts of QI increase due to the large residual strains. The QI may be a key clue for the formation of in-plane nuclear field; it is supported by the normal Hanle curve observed in a strain-free droplet GaAs QD [5].

5. Summary

We observed the anomalous Hanle curves in InAlAs QDs and InAs QRs. The observed curves could not be explained by the classical theory, and we proposed the formation model where the strain-induced QI plays a key role to induce a considerable $B_{\mathrm{n},x}$. The details of the model and the impacts of the quadrupolar effects will be presented in the conference.

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