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Double nuclear spin switching in single self-assembled quantum dots

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Abstract

In this work, we report the first observation of two-staged nuclear spin switching in single InAlAs self-assembled quantum dots. That implies that nuclear spin polarization indicates three stable branches, although the number of branches has been believed to be two at the maximum thus far. The states were accompanied by hysteresis loops around the boundaries of each branch with a change in the excitation condition. To explain these findings, we incorporated the electron spin relaxation caused by the nuclear spin fluctuation into the previously studied dynamic nuclear spin polarization mechanism. The model reproduces successfully the features of nuclear spin polarization and the associated strong reduction in the observed electron spin polarization. Since the developed model does not relate with specific materials or lattice structures, the observed behavior of nuclear spin polarization is general in the systems where confined electron and nuclear spins are coupled via hyperfine interaction.

1. Introduction

Hyperfine interaction (HFI) has significant importance on the spin physics especially in hybrid quantum system such as quantum dots (QDs). This is because a confined electron spin is strongly coupled to the lattice nuclei in the localized volume, and the spin flip-flop process via HFI transfers the electron spin angular momentum to the lattice nuclear spin ensemble. Then, nuclear spin polarization (NSP) can be established easily by spin-selective electron injection [1–4]. The NSP affects the electron spin states as an effective magnetic field (i.e., nuclear field) and paves the way to various applications such as quantum memory owing to the unparalleled spin coherence. Therefore, it is essential to reveal the formation and relaxation processes of NSP entirely.

One of the most interesting properties of NSP is bistability known as *nuclear spin switching* (NSSW); the NSP transits abruptly between two stable coexisting branches due to the negative and positive feedback of the spin transfer rate [2-5]. This phenomenon occurs when electron spin splitting, which determines the energy cost in spin transfer, is reduced by the compensation of the external field by a generated nuclear field $\boldsymbol{B}_{\rm n}$. Here, we show that NSP in a QD potentially has *three* stable branches in general and the impact of nuclear spin fluctuation. The $\boldsymbol{B}_{\rm n}$ consists of a static part $\boldsymbol{B}_{\rm n}^{\rm stat}$ and a fluctuating part $\boldsymbol{B}_{\rm f}$, and under specific conditions the $\boldsymbol{B}_{\rm f}$ has significant influence on both electron and nuclear spin dynamics in spite of the small magnitude (a few tens mT) [6].

2. Observation of double NSSW and model calculations

We performed the time-integrated micro-photoluminescence (PL) measurements under a longitudinal magnetic field B_z at 6 K. The sample used here is single self-assembled $In_{0.75}Al_{0.25}As/Al_{0.3}Ga_{0.7}As$ QDs grown by MBE on (100) GaAs substrate [1]. Figure 1(a) is the typical PL spectra at the wetting layer excitation (~1.6986 eV). The most intense PL peak is attributed to the positive trion X^+ consisting of one electron and spin-singlet two holes. We focus on the X^+ PL. This is because the *z* component of electron spin polarization $\langle S_z \rangle$ can be deduced from the degree of circular polarization defined as $\rho_c = (I^- - I^+)/(I^- + I^+)$ where $I^{-(+)}$ denotes the $\sigma^{-(+)}$ PL intensity through the relation, $\langle S_z \rangle = \rho_c/2$.

Figure 1(b) represents the X^+ PL spectra at B_z =+4 T. As seen clearly, the Zeeman splitting for σ^+ excitation is larger than that for σ^- excitation. This can be explained by the Overhauser shift $\Delta_{\rm OS}$ via an optically generate $\boldsymbol{B}_{\rm n}^{\rm stat}$ whose direction is dependent on the excitation polarization (i.e. photo-injected electron spin) [1-4]. For our InAlAs QDs, the compensation of B_z by $B_{\rm n}^{\rm stat}$ occurs under σ^+ excitation which generates the spin-down electron selectively.

Figure 1(c) shows the excitation power $(P_{\rm exc})$ dependencies of the $\langle S_z \rangle$ and $\Delta_{\rm OS}$. While $\Delta_{\rm OS}$ under σ^- excitation increases monotonically with increasing $P_{\rm exc}$, $|\Delta_{\rm OS}|$ under σ^+ excitation exhibits clear jumps accompanying drops of $|\langle S_z \rangle|$. Surprisingly, the NSSW occurs obviously twice; in the previous works [2-4], the NSSW has been believed to occur only once, and it indicated that only two branches of NSP are stable. To the best of our knowledge, This is the first observation in nuclear spin physics, and the observed *double NSSW* implies that the third stable branch exists.

To explain our findings, we proposed a new model of NSP formation based on the previous one [2,5]. Figure 2 (a) and (b) show the schematics of the normalized formation term (blue curve) and relaxation term (orange straight lines) of NSP formation dynamics [7]. The steady-state NSP observed in the time-integrated PLs is interpreted as their intersection.

One of the key points of our model is the incorporation of electron spin relaxation by nuclear spin fluctuation. In the previous model, the formation term of NSP has a simple Lorentzian shape, and it explains a single NSSW with two stable and one unstable branches. However, the effect of nuclear

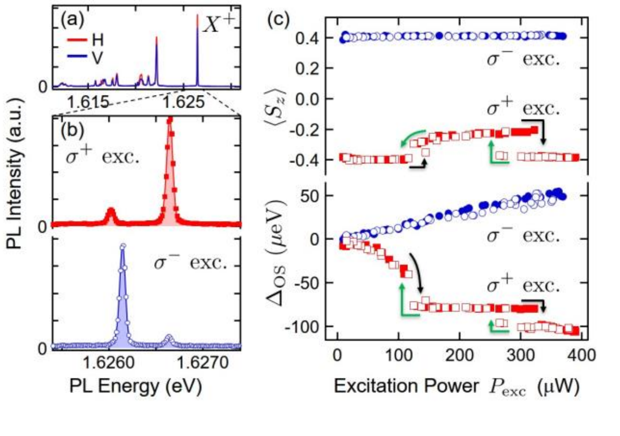

Fig. 1 (a) PL spectra detected in a linearly polarized basis under the unpolarized excitation at 0 T. (b) The Zeeman-split PL spectra under the $\sigma^{+(-)}$ excitation depicted in the upper (lower) panel at B_z =+4 T and P_{exc} =350 μW. (c) P_{exc} dependence of $\langle S_z \rangle$ and Δ_{OS} under the σ^+ and σ^- excitations at 4 T. Double NSSW is observed clearly.

spin fluctuation induces an additional narrow dip to the formation term as depicted in the figures. The dip is located at $B_{\mathrm{n,z}}^{\mathrm{stat}}/(-B_z)$=1, which indicates the complete compensation of B_z by $B_{\mathrm{n,z}}^{\mathrm{stat}}$. At this point, the residual $\boldsymbol{B}_{\mathrm{f}}$ causes a severe relaxation of electron spin polarization [6,7], and thus, the formation of NSP reduces significantly.

On the other hand, the relaxation term of NSP in the figures reflects a parameter f_{e}: it is the fraction of time when unpaired electron occupies the QD, and is controlled via P_{exc} in the experiments (i.e., $f_{\mathrm{e}} \propto P_{\mathrm{exc}}$). Then, the increase of f_{e} corresponds to the larger tilting of the relaxation term.

Let us consider the trajectory of the intersection point as f_{e} varies. Starting from the lower f_{e} where the system takes a unique solution, the intersection follows the formation curve with increasing f_{e} until point A, and it jumps to point B. Subsequently, the state moves to point C along the dip structure and finally jumps to point D as shown by a black trace. Returning from the larger f_{e}, on the other hand, the system preserves a unique intersection till point E, and the state-tracking route E → F → G → H (green trace) is obtained.

The trajectories of these intersections and accompanying $\langle S_z \rangle$ are plotted as a function of f_{e} in Fig. 2(c). The hysteresis loops ABGH and CDEF can be regarded as double loops in Fig. 1(c). From these considerations, we found that the plateau of the Mid. branch [B–C in the bottom panel of Fig. 2(c)] came from the narrow dip centered at $B_{\mathrm{n,z}}^{\mathrm{stat}}/(-B_z)$=1. Since a steep decay of $\langle S_z \rangle$ occurs at this point as shown in the top panel, it is difficult for the NSP to grow and overcome the cancellation point even under the increasing f_{e}. As a result, the saturation of $B_{\mathrm{n,z}}^{\mathrm{stat}}$ occurs, leading the appearance of the newfound Mid. branch. The observed features of NSP are general in various QD systems since the developed model is not associated with specific materials or lattice structures.

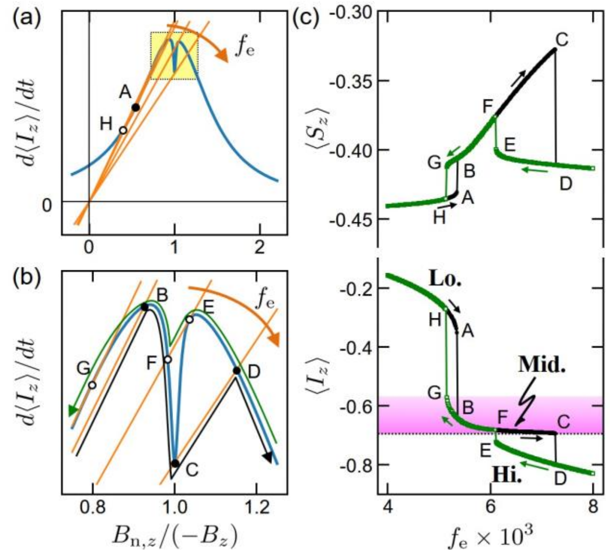

Fig.2 (a), (b) Schematics of the NSP formation (blue curve) and decay terms (orange lines). (b) is a closeup view of the square region in (a). The steady-state solutions are interpreted as the intersections of the curves, and the inclination of the decay term depends on f_{e}. Solid (open) circles represent the intersections with increasing (decreasing) f_{e}, and arrowed black (green) trace indicates the state-tracking route. (c) The f_{e} dependencies of $\langle S_z \rangle$ (top) and $\langle I_z \rangle$ (bottom) in σ^+ excitation. The labeled points correspond to those in (a) and (b).

3. Conclusions

We observed the double NSSW in single InAlAs self-assembled QDs, which indicated the presence of undiscovered third branch of NSP. From the developed model incorporating the electron spin relaxation by nuclear spin fluctuation, the third stable branch was identified to originate from the fluctuation of NSP. In addition, the model calculation revealed the following points: 1) the effect of electron spin-flip relaxation which is the counter action of the spin flip-flop process via HFI, 2) the tristability of NSP where the three stable branches coexist can be predicted. These findings will be presented in the conference.

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