Principal Axis Orientation Dependence of Quadrupole Interaction in Anomalous Hanle Effect

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In self-assembled quantum dots (SAQDs), nuclear quadrupole interaction (NQI) originating from residual strain has attracted a lot of attention since the interaction plays a crucial role to describe the dynamics of electron-nuclear spin-coupled system. One example of the NQI-related phenomena is the anomalous Hanle effect: a large nuclear field B_n formation perpendicular to the photo-injected electron spin under a transverse magnetic field B_x [1, 2, 3]. As shown in Fig. 1(a), this phenomenon is detected through modification of Hanle curve (depolarization curve of photo-injected electron spin $\langle S_z \rangle$ due to the magnetic field). The fact that such the modification has not been observed in strain-free systems such as bulk [4] and droplet-grown QDs [5] strongly suggests the anomalous Hanle effect is realized by the strain-induced NQI. Therefore, studying the anomalous Hanle effect provide not only insight into the NQI but also method to utilize nuclear spins more precisely in semiconductor nanostructures.

In a single $In_{0.75}Al_{0.25}As/Al_{0.3}Ga_{0.7}As$ SAQD, we studied the anomalous Hanle effect based on time-integrated (TI) and time-resolved (TR) measurements of positively charged exciton (X^+) photoluminescence (PL). The TR-PL measurements revealed that formation of nuclear field is slowed down by increasing B_x (not shown here) and that the degree of circular polarization of X^+ PL reverses quickly following excitation helicity reversal [Fig. 1(b)]. Since the previously proposed model [3] could not explain the latter observation, we reconsidered the spin dynamics while focusing on the direction of the principal axis of NQI (q-axis). By comparing two limits of q-axis distribution [Fig. 1(c)], the alternatively proposed model succeeded in explaining both the TR-PL and TI-PL measurements. Our calculations suggest that in-plane nuclear field $B_{\mathrm{n},x}$ compensating for B_x and the out-of-plane nuclear field $B_{\mathrm{n},z}$ persisting under large B_x are independently formed under influence of NQI with different q-axis while it has been believed that $B_{\mathrm{n},x}$ is generated with a help of $B_{\mathrm{n},z}$. In particular, the formation of $B_{\mathrm{n},x}$ and $B_{\mathrm{n},z}$ originate from NQI with q-axis in the sample growth plane (xy plane) and with q-axis along the sample growth axis (z axis), respectively. These facts provide clues for studying the NQI from a microscopic perspective.

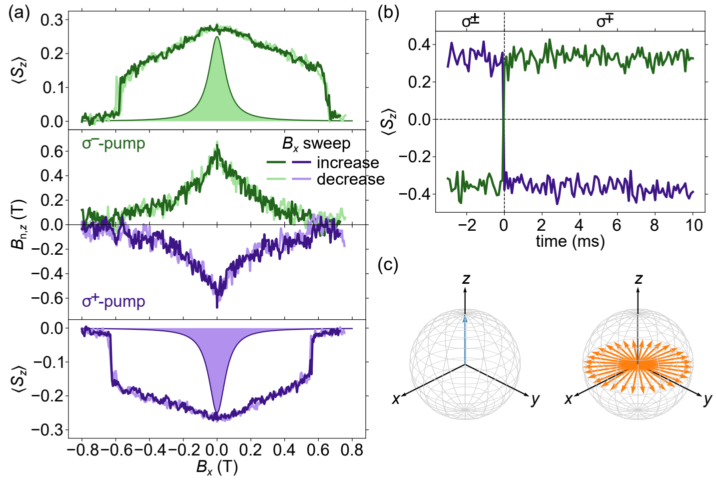

Fig. 1. (a) Upper and bottom: anomalous Hanle curves observed in InAlAs SAQD under σ^- (green) and σ^+ (purple) excitation, respectively. Hatching regions indicate the Hanle curves without B_n. Middle: out-of-plane nuclear field $B_{\mathrm{n},z}$ deduced from the Overhauser shift. (b) Temporal change in $\langle S_z \rangle$ due to the excitation helicity reversal at $t = 0$ under $B_x = 0.45$ T. Green (purple) curve indicates helicity switching from $\sigma^{+(-)}$ to $\sigma^{-(+)}$. (c) Two limits of the principal axis of NQI. Left shows all of the axes in a QD are along with the z axis, while right shows these are in the xy plane.

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