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Full-dimensional analysis of coherent spin dynamics in a semiconductor

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1. Introduction

Spin is a quantum mechanical degree of freedom in particles such as electrons, holes, and nuclei. Since the spin state is represented by a state vector in a three-dimensional space called the Bloch sphere, it cannot be defined by only one parameter, which is usually obtained by a projection measurement. The conventional three-dimensional analysis of the spin state thus needs spin precession or Rabi oscillation prior to the one-dimensional projection measurement [1]. When we need to analyze the spin dynamics themselves, however, we cannot rely on the conventional method. This is why we have developed a tomographic Kerr rotation (TKR) method to directly measure the electron spin state without relying on the dynamics [2]. Using this method, we have succeeded in showing the trajectory of the spin vector in the Bloch sphere during the spin precession as shown in Fig. 1(a). In this presentation, we perform the three-dimensional analysis of the spin dynamics under a magnetic field and reveal precise information on the decoherence depending on the initial spin state in arbitrary Bloch bases.

2. TKR method

The TKR method is based on the pump and probe technique. When a probe light beam is reflected on the material, the polarization is changed under the influence of the electron spin state. This change in probe light polarization tells us the electron spin state in the material. The full-bases measurement is realized by a combination of the conventional Kerr rotation method and the coherent transfer scheme [3]. Here, the coherent transfer scheme is based on the V-shaped optical transition as shown in Fig. 1(b). In a semiconductor quantum well, an in-plane magnetic field defines the x direction, and the degenerated light-hole (LH) spin state splits into two eigenstates. When one of the two LH states is virtually excited by the probe light in the V-shaped system, it is possible to perform a coherent state transfer between photon polarization and electron spin polarization. Here, the magneto-optical Kerr effect is caused by the spin exchange interaction $\mathbf{s_1}\cdot\mathbf{s_2}$ between the electron spin $\mathbf{s_1}$ in the material and the virtually created electron spin $\mathbf{s_2}$ by the probe light. Through the coherent optical transition, the spin exchange interaction in the material is converted to the Stokes operator including the coherence terms [4], which rotates the polarization of the probe light. Table 1 summarizes the combination of the projection basis of the electron spin state, the Stokes operator responsible for the Kerr rotation, the polarization of the probe light, and the measurement basis of the change in the probe light polarization. Through the spin projection of precessing electrons on the z- and y-bases, as shown in Fig. 1(a), we confirmed that the TRK method is available for the measurement of electron spin coherence [2].

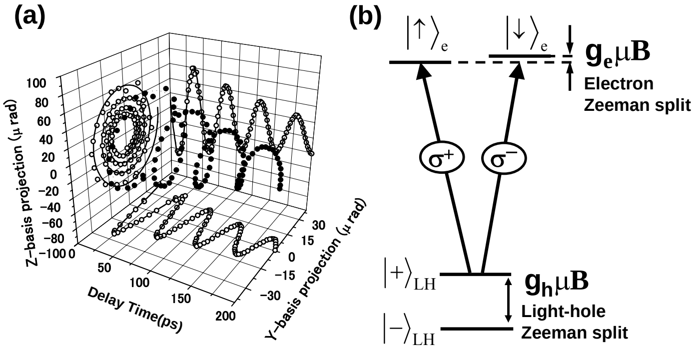

Fig. 1. (a) The trajectory of the spin vector in the Bloch sphere during the spin precession under a magnetic field. The electron spin state $|+y\rangle_e$ is prepared by the pump light $|D^+\rangle_{ph}$ and starts the Larmor precession. The z- and y-basis projections of the electron spin dynamics are obtained by the TKR method (b) Energy band diagram for the V-shaped optical transition in a GaAs/AlGaAs semiconductor quantum well.

Table 1. Operation sheet of the tomographic Kerr rotation method.

Projection basis of the electron spin		Stokes operator	Input polarization of the probe light beam	Measurement basis of the Kerr rotation
z	$\|\uparrow\rangle_e, \|\downarrow\rangle_e$	S_z^{ph}	H, V	$D^+ - D^-$
			D^+, D^-	H−V
y	$\|\uparrow\rangle_e \pm i\|\downarrow\rangle_e$	S_y^{ph}	σ^+, σ^-	H−V
			H, V	$\sigma^+ - \sigma^-$
x	$\|\uparrow\rangle_e \pm \|\downarrow\rangle_e$	S_x^{ph}	σ^+, σ^-	$D^+ - D^-$
			D^+, D^-	$\sigma^+ - \sigma^-$

3. Experimental setup and result

We used a 20-nm-thick GaAs/AlGaAs quantum well in which the electron and LH g-factors under an in-plane magnetic field are -0.37 and -2.5, respectively. The sample was cooled to 10.0 K in a superconducting magnetic cryostat. A magnetic field B_x = 7 T causes the Zeeman splitting of the light hole and reconfigures it into the superposed eigenstates $|\pm x\rangle_{LH} = (|\uparrow\rangle_{LH} \pm |\downarrow\rangle_{LH})/\sqrt{2}$. A mode-locked Ti: sapphire laser delivering 130 fs pulses at a repetition rate of 76 MHz was used to pump and probe light through a wavelength-tunable filter (full width at half maximum (FWHM) = 0.3 nm) consisting of a diffraction grating in each path. For the time-resolved measurement, a variable delay line was placed in the probe path. To avoid the influence of dynamic nuclear-spin polarization, the polarization of the pump light beam was periodically alternated by using a photoelastic modulator at a frequency of 42 kHz, which also enables lock-in detection to reveal only the pump-light-induced effect.

In this experiment, three kinds of initial spin states ($|+x\rangle_e$, $|+y\rangle_e$, and $|+z\rangle_e$) were prepared by the pump light polarizations ($|H\rangle_{ph}$, $|D^+\rangle_{ph}$, and $|\sigma^+\rangle_{ph}$). Fig. 2 shows the result of the measurement of the electron spin dynamics under an in-plane magnetic field. The prepared $|+x\rangle_e$ state remains in the same orientation without showing the Larmor precession. The TKR signal of x-basis projection therefore shows only the exponential decay. In contrast, the prepared $|+z\rangle_e$ and $|+y\rangle_e$ states exhibit spin precession about the x-axis, and their TKR signals of z-basis projection oscillate at the same frequency of 34.6 GHz and decay. The spin lifetime of these spin states are approximately equal to 600 ps without significant basis dependency. In this timescale, the spin lifetime depends on the recombination time and the electron-hole spin-exchange interaction. Although the LH state is always prepared in the x-state by any pump light polarizations with the V-shaped transition, the LH state relaxes into the heavy-hole state and the hole spin state becomes mixed state immediately. Therefore, the electron-hole exchange interaction does not depend on the prepared electron spin states.

Another interesting phenomenon is that a long lifetime component appears as decreasing the pump-power. Fig. 3 shows the pump-power dependence of the TKR dynamics

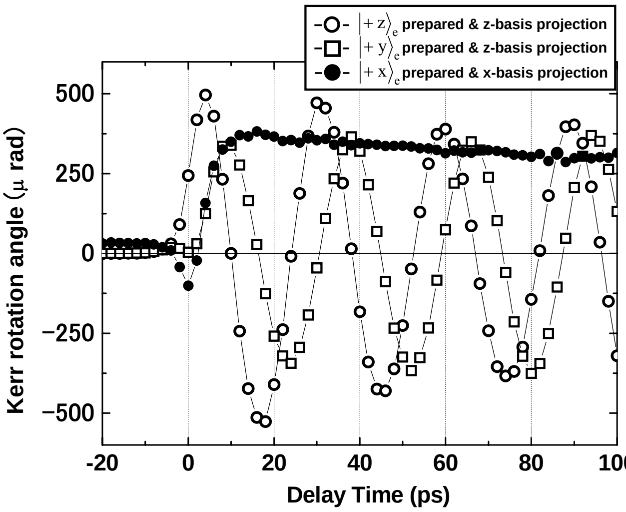

Fig. 2. The electron spin dynamics in three-dimensions with an in-plane magnetic field B_x = 7 T at 10 K. Initial spin states ($|+x\rangle_e$, $|+y\rangle_e$, and $|+z\rangle_e$) are prepared by the pump light polarizations ($|H\rangle_{ph}$, $|D^+\rangle_{ph}$, and $|\sigma^+\rangle_{ph}$). The prepared $|+x\rangle_e$ state is projected to the x-basis, and the $|+z\rangle_e$ and $|+y\rangle_e$ states are projected to the z-basis.

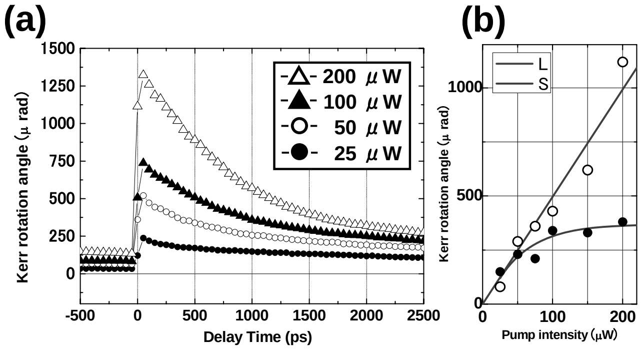

Fig. 3. (a) The pump-power dependence of the TKR dynamics. Initial spin states $|+x\rangle_e$ are prepared and projected onto the x-basis. (b) Intensity of the TKR signals decomposed into the long and short lifetime components. Their lifetimes are approximately 8 ns and 600 ps, respectively.

in the case that electron spins are prepared in $|+x\rangle_e$ state and projected onto the x-basis. The spin lifetime of the long component is over 8 ns which is longer than the general recombination time in the quantum well. That is why the spin with longer lifetime is supposed to be of an electron after the recombination of the created hole with a residual electron in the quantum well, which is free from recombination and exchange interaction with the hole. In this case, the hyperfine interaction and the inhomogeneity of the electron g-factor will be more significant. In the same way, the electron spins are prepared $|+z\rangle_e$ and $|+y\rangle_e$ states, and the long lifetime components are also observed. The obtained spin lifetimes of the long component were shorter than those of $|+x\rangle_e$ state. These observations imply that the dephasing caused by the hyperfine interaction and the inhomogeneity of the electron g-factor may depends on whether the electron spin state is parallel or perpendicular to the magnetic field (the x-basis in this case). However, more detailed experiments and theoretical work will be needed to make them clear.

4. Conclusions

We have demonstrated full-dimensional analysis of electron spin dynamics by applying the developed TKR method. The analysis clarified that the spin state $|+x\rangle_e$, which is parallel to the applied magnetic field, only decays without the Larmor precession, and the spin lifetime of any prepared spin state are approximately equal to 600 ps without significant basis dependency.

Acknowledgments

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