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Measurement of electron spin states in a semiconductor quantum well using tomographic Kerr rotation

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1. Introduction

Readout of the electron spin state is an essential function for spin-based quantum information technology [1]. To measure the electron spin coherence directly, we have developed the tomographic Kerr rotation, based on the magnet-optical Kerr effect and the coherent transfer of light polarization states into electron spin states [2]. Our previous measurement, however, has required the circularly polarized probe light beam $\sigma^{\pm}$ to measure the electron spin coherence. To improve the convenience of the tomographic Kerr rotation method, we provide a new technique to measure the electron spin coherence by same polarizations of the probe light beam as the conventional Kerr rotation measurement.

2. Tomographic Kerr rotation method

Using the conventional Kerr rotation technique to measure the electron spin, it is only possible to deal with up and down spins. This is because electron spins virtually created by a probe light beam conventionally lose coherence, which is the relative phase information between spin up and down. However, we can prepare coherent superposition of up and down electron spin states using a coherent transfer scheme. By applying this scheme to the probe light beam, we can measure the electron spin coherence. Using the tomographic Kerr rotation method, we can measure the electron spin coherence through the exchange interaction $\mathbf{s}_1 \cdot \mathbf{s}_2$, which arises between the prepared electron spin $\mathbf{s}_1$ created by the pump light beam and the virtually created electron spin $\mathbf{s}_2$ created by the probe light beam on the y-axis. This interaction results in the rotation of the probe pulse polarization [3].

Table 1. Operation sheet of the tomographic Kerr rotation method

Projection basis of the electron spin		Input polarizasion of the probe light beam	Measurement basis of the Kerr rotation	Status
Sz	$\lvert\uparrow\rangle_e$	H, V	$D^+ - D^-$	○
	$\lvert\downarrow\rangle_e$	D^+, D^-	H−V	◆
Sy	$\lvert\uparrow\rangle_e + i\lvert\downarrow\rangle_e$	σ^+, σ^-	H−V	◆
	$\lvert\uparrow\rangle_e - i\lvert\downarrow\rangle_e$	H, V	$\sigma^+ - \sigma^-$	◇
Sx	$\lvert\uparrow\rangle_e + \lvert\downarrow\rangle_e$	σ^+, σ^-	$D^+ - D^-$	■
	$\lvert\uparrow\rangle_e - \lvert\downarrow\rangle_e$	D^+, D^-	$\sigma^+ - \sigma^-$	■

○The conventional Kerr rotation measurement ◆Our previous works
◇This demonstration ■Next works

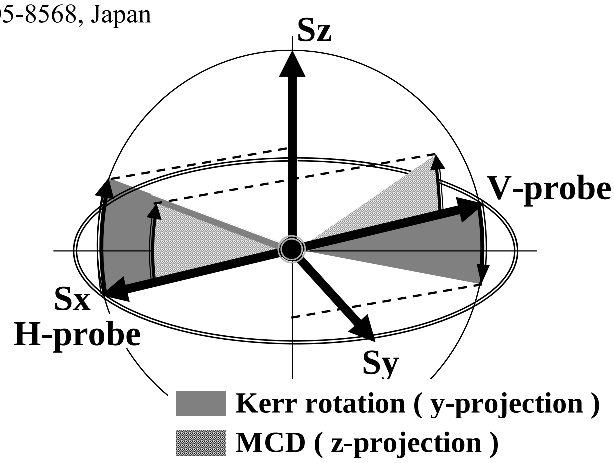

Fig. 1 The rotations of probe light beam polarization

The rotation of the probe light beam polarization tells us the electron spin state by appropriately selected measurement. **Table 1** summarizes the combination of input polarization of the probe light beam, measurement basis of the Kerr rotation, and projection basis of the electron spin state. For instance, we have already reported the y-axis projection of the electron spin state measured by the circularly polarized $\sigma^{\pm}$ probe light beam, which consists of a linear superposition of two linear polarizations $D^{\pm}$. With the coherent transfer scheme, the $D^{\pm}$ polarized light beam virtually creates the electron spin states $\lvert\pm y\rangle_e = (\lvert\uparrow\rangle_e \pm i\lvert\downarrow\rangle_e)/\sqrt{2}$, and the Kerr rotation arises from the exchange interaction $\mathbf{s}_1 \cdot \mathbf{s}_2$.

Here, we demonstrate the y-axis projection of the electron spin state with the conventionally used linear polarized beam light beams (H and V). As seen in **Table 1**, the y-axis projection of the electron spin state is indicated by measurement of the Kerr rotation on the circularly polarized $\sigma^{\pm}$ basis. It is necessary, however, to keep in mind the magnetic circular dichroism (MCD) effect [4], which is induced by the difference between the optical absorption efficiency of the two circular polarizations $\sigma^{\pm}$, and causes rotation of the probe light beam polarization as shown in **Fig. 1.** The MCD effect must be removed from the rotations to measure the y-axis projection with the tomographic Kerr rotation method.

3. Experimental setup and result

In this demonstration, we used a GaAs/AlGaAs quantum well in which g-factors are controlled so we could apply the coherent transfer scheme. The electron and light-hole (LH) g-factor under an in-plane magnetic field in this quantum well are -0.2 and -3.5, respectively. Therefore, a magnetic field B_x = 7 T causes the Zeeman splitting of the light hole, and reconfigures it into the superposed eigenstates $|\pm x\rangle_{LH} = (|\uparrow\rangle_{LH} \pm i|\downarrow\rangle_{LH})/\sqrt{2}$. When one of two light-hole states is virtually excited by the probe light, the tomographic Kerr rotation method is applicable. The pump and probe light beam are generated by spectrally filtering the same light beam from a mode-locked Ti:sapphire laser delivering 130-fs pulses at a reputation rate of 76 MHz, and a variable delay line was set in the probe path. The pump wavelength for the experiments is set to 796.7 nm, which corresponds to $|-x\rangle_{LH}$, and the probe wavelength is set to 795.0 nm, which corresponds to $|+x\rangle_{LH}$. We selected the different LH states for the pump and probe light beam to avoid their interference effect.

We prepare the electron spin state $|\uparrow\rangle_e + i|\downarrow\rangle_e$ (+y) that precess about the static magnetic field B_x by the pump light beam, and project these electron spins on two mutually-orthogonal bases (z-axis and y-axis) in the Bloch sphere. The y-axis projection is measured by the Kerr rotation on the circularly polarized $\sigma^{\pm}$ basis. Therefore, we construct an apparatus to measure the rotation of the polarization on the $\sigma^{\pm}$ basis, as shown in **Fig. 2**. Using the quarter wave plate, the rotation on the $\sigma^{\pm}$ basis is converted to the H-V basis, which is spitted by the polarization beam splitter. This apparatus also allows measurement of the $D^{\pm}$ basis by replacing the quarter wave plate with the half wave plate. **Fig. 3** shows the result of the tomographic Kerr rotation measurement of the precessing electron spins at 10 K. The result shows us that the y-axis projection is delayed by $\pi/2$ from the z-axis projection. We can recognize from this result that the projection bases are orthogonal.

To remove the MCD effect, we use two types of probe light beam polarization (H and V). In this measurement, the Kerr rotation indicates the positive and negative signals with the H probe and V probe, respectively. In contrast, the MCD effect indicates the same signed signal with each of the probe polarizations. Applying this difference between

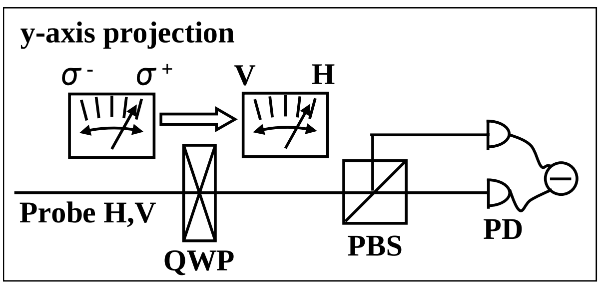

Fig. 2 Experimental setup for the y-axis projection. (QWP, quarter wave plate; PBS, polarization beam splitter; PD, photo detector). To split by the polarization beam splitter, the rotation on the $\sigma^{\pm}$ basis must be converted to the H-V basis.

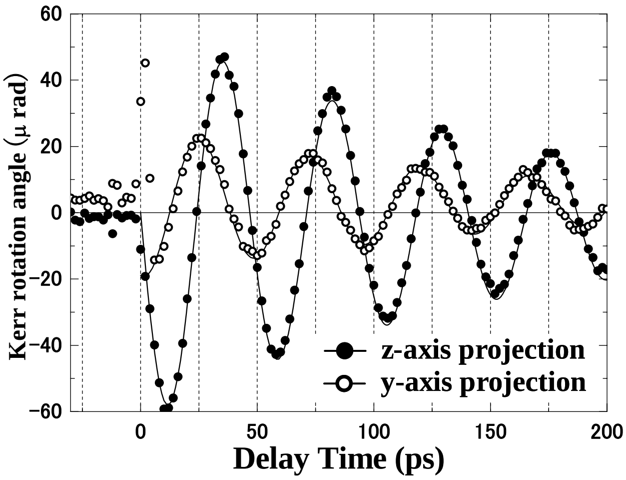

Fig. 3 The tomographic Kerr rotation measurement of the precessing electron spins with an in-plane magnetic field Bx = 7T. Each of projections is measured by two linear polarized probe light beams (H and V).

the Kerr rotation and the MCD effect, we subtract these two signals of eq. (1) and eq. (2). Accordingly, we can permit the distinction between the Kerr rotation and the MCD effect.

$$\text{Signal (H)} = \text{Signal (Kerr)} + \text{Signal (MCD)} \qquad (1)$$

$$\text{Signal (V)} = -\text{Signal (Kerr)} + \text{Signal (MCD)} \qquad (2)$$

Our pervious measurement of the y-axis projection used the circularly polarized probe light beam $\sigma^{\pm}$. Inconveniently, it was necessary to change the polarization of the probe light beam for the z-axis projection. In contrast, the new scheme provides a technique for the measurement of both the y-axis and z-axis projection by the same probe light beam polarization.

4. Conclusions

We were able to measure the y-axis projection of the electron spins with the linear polarizations (H and V). This result shows that the tomographic Kerr rotation method, except in the case of the x-axis projection, is applicable by the same probe light beam polarization. In addition, we demonstrate an effective method for distinguishing between the Kerr rotation and the MCD effect. As a consequence, the tomographic Kerr rotation method allows measurement of the y-axis and z-axis projection of the electron spin state by merely selecting the measurement basis of the Kerr rotation.

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