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Quantum media conversion from a photon to an electron spin

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1. Introduction

Spin is a fundamental property of electrons and plays an important role in information storage. For spin-based quantum information technology, write (preparation) and read-out (measurement) processes of the electron spin state should be coherent. However, both the traditional write and read-out processes were projections to up/down spin states, which do not preserve spin coherence. We have recently demonstrated that we can transfer the polarization coherence of light to the spin coherence of electrons in a semiconductor quantum nanostructure [1], and we can also read out the prepared coherence of the electron spin optically by the developed tomographic Kerr rotation (TKR) method [2,3]. In these demonstrations, it was important to set the g-factor of an electron to be nearly zero. We have also demonstrated that the spin coherence of a single electron trapped in a gate-defined quantum dot, where the g-factor of electrons is tuned to nearly zero, can be electrically manipulated with a microwave applied to the gate utilizing electric-dipole spin resonance (EDSR) [4]. The fabricated quantum dot with a point contact as a charge sensor evidenced that a single electron is actually created by the absorbed photon in the dot [5]. We have also theoretically shown that two-electron coherence can be manipulated and measured via spin-flip tunneling with the help of the spin-orbit interaction [6]. Furthermore, we have shown that the full Bell-state measurement needed for the quantum repeater can even be achieved with help of g-factor engineering and g-factor switching [7].

2. Principle of quantum media conversion

Figure 1 shows the operating principles of the spin coherence transfer (write) and the TKR (read). The principle of TKR is the exchange interaction (singlet state selection) between the target electron and the probe electron created virtually by the probe light. The electron spin state tomography is based on the reverse mapping of the electron spin states onto the photon states, or partial state swapping, through the virtual excitation of a charged exciton. The polarization state tomography of the scattered light thus results in the spin state tomography of the electron interacting with the photon (Fig. 2a). In other words, we can exchange the quantum information between the electron and the photon through elastic scattering. These demonstrations were also carried out in a condition where the up/down spin basis states of electrons remained degenerated under an in-plain magnetic field. As this condition ensures the energy conservation between photons and electrons, the entire Poincare sphere representing the polarization states of photons can be mapped onto a Bloch sphere representing spin polarization states of electrons. The developed tomographic Kerr rotation method enables the density matrix tomography of coherent spin states of electrons, even when the spin does not precess around the applied magnetic field, i.e., the spin is frozen. The frozen spin faithfully maintains the coherence transferred from photons encoded in their polarization.

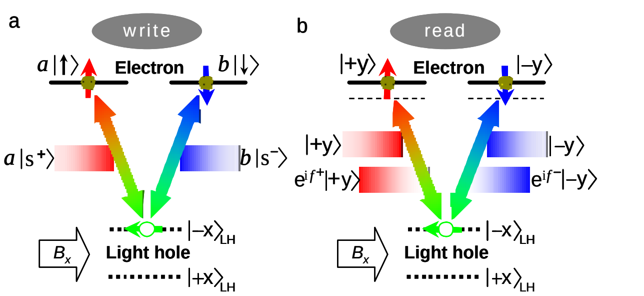

Fig. 1: Operating principles of spin coherence transfer (a: write) and tomographic Kerr rotation (b: read), based on the three-level V-shaped system.

3. Experimental demonstration of spin state transfer and spin state tomography

Figure 2a shows the time trace of the Bloch vector of electrons whose spin state is transferred from photons in the superposition state of D^+. The reconstructed density matrix of the electron spin state with and without calibration

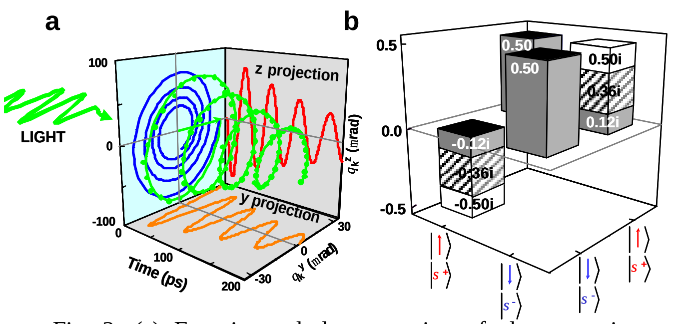

Fig. 2: (a) Experimental demonstration of electron spin state transfer and tomography showing dynamic spin precession under an in-plain magnetic field B_x. (b) A reconstructed density matrix of the optically injected electron spin state.

(shaded and dark bars) together with that of the pump light state as a reference (white bars) are shown in Fig. 2b. We assumed that the initial degree of polarization of the electron spin created by a circularly polarized light is unity owing to the optical selection rule of the well-defined LH excitons. By comparing those two density matrices (shaded and white bars), we estimate that the fidelity of the spin coherence transfer from photons to electrons in the maximally superposed case is 0.86±0.03, which is close to unity. The fidelity degradation is due to spin decoherence after the initial preparation originating in the electron-hole exchange interaction.

We can understand the fundamental quantum operations in one scheme based on the resonant scattering in a degenerate Λ system mediated by a light-hole trion under an in-plane magnetic field. We also show that spontaneous entanglement generation and quantum state swapping between a photon and an electron can be achieved based on the degenerate spin-flip Raman process in the light-hole-trion-mediated Λ system by including the spontaneous emission with the help of light field quantization in a photonic crystal.

3. Single photon - electron conversion in a quantum dot

We demonstrated that a single photon creates a single electron in a semiconductor and detected by the charge [5]. We fabricated a gate-defined single quantum dot consisting of a GaAs quantum well with multiple gates on the top surface to trap an electron (Fig. 3a). The negatively biased gates confine only the negatively charged electron created by a single photon with removing the positively charged hole. The exceptional feature of this device is that the electron g-factor is designed to be zero, which enables the ideal spin state transfer from a photon to an electron. Another important feature is that a quantum point contact serves as an electron counter is implemented in the vicinity of the dot to count the number of electrons in the dot. This electron counter ensures the fidelity of the quantum media conversion by the post-selection of the conversion event. We succeeded to demonstrate that the device serves as a single photon to single electron converter with the conversion efficiency of 27%, excluding the coupling efficiency estimated by the area and the well thickness. The anti-bunching nature of the 1st captured electron and the 2nd captured electron (Fig. 3b) and polarization selectivity (not shown) indicate that the photon polarization of a single electron is successfully transferred to the spin polarization of an single electron.

3. 4. Coherent spin manipulation with microwave

Using a similar device with two coupled double quantum dots (Fig. 4a), we succeeded in demonstrating single-electron spin manipulation by observing the Rabi oscillation in the dot current leaking through the dots as a function of microwave burst length (Fig. 4b). The importance of this demonstration is that even an electron with nearly zero g-factor can be manipulated by microwaves using the electric-field component instead of the commonly used magnetic-field component through the spin-orbit interaction, and two-spin coherence is measured by the singlet detection through the Pauli spin blockade. The frozen spin can never be manipulated by a microwave via the magnetic field component. Instead, the electrical field component enables the spin manipulation through the modulation of the wavefunction of the electrons in the dot device. [4]

4. Conclusions

The spin coherence transfer and the spin state tomography demonstrated here will be applicable to the transfer of a single-particle quantum state and a two-particle entangled state, which is the kind of transfer needed for quantum information technology. The developed scheme offers a tool for performing basis-independent preparation and readout of a spin quantum state in a solid-state device for quantum cryptography and quantum distributed computing.

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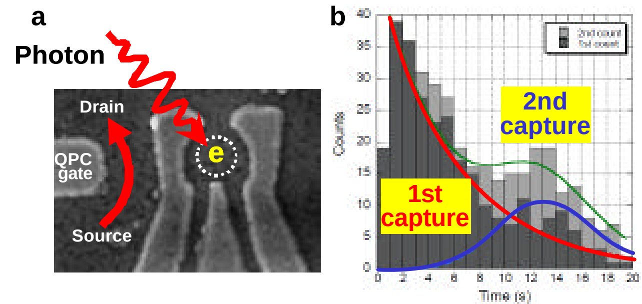

Fig. 3, Experimental demonstration of single photon to single electron conversion. (a) SEM image of the device. QPC: quantum point contact. (b) Histogram of the electron-capture events detected by the QPC as a function of light exposure time.

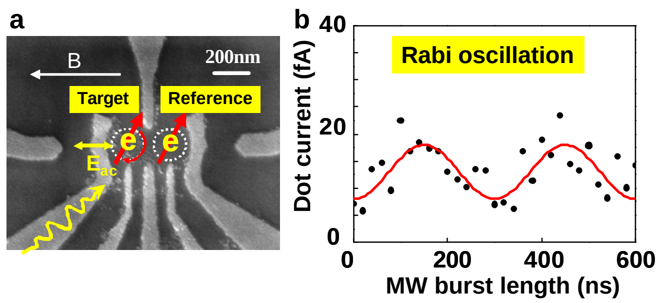

Fig. 4, Experimental demonstration of coherent spin manipulation of a single electron trapped in one of the coupled double quantum dots by the electric field of microwaves via the gate. (a) SEM image of the coupled double quantum dots. (b) Measured Rabi oscillation.