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Coherent spin preparation, manipulation and read-out with light and microwaves in a quantum well and dot

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Abstract. Spin is a quantum property of electrons. For spin-based quantum information technology, preparation and read-out of the electron spin state should be spin coherent. We demonstrate that the polarization coherence of light can be transferred to the spin coherence of electrons in a semiconductor quantum nanostructure [1], and the prepared coherence of the electron spin can also be read out with light by the developed tomographic Kerr rotation method [2] . We also demonstrate that a single photon is efficiently converted (~27%) into a single electron trapped in a gate-defined quantum dot, where the g-factor of electrons is tuned to zero, and the charge state is detected with an adjacent quantum point contact without destructing the spin state [3]. We further demonstrate that the spin coherence of a single electron trapped in one of double quantum dots is electrically manipulated with a microwave applied to the gate and read out via the Pauli spin blockade phenomenon [4]. These demonstrations were 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 polarization states of photons can be mapped onto the Bloch sphere representing spin polarization states of electrons. We theoretically showed that relative spin coherence of two electrons can be also measured with the help of spin-flip tunneling of electrons between the dots [5]. Full Bell state measurement is also possible by the single-spin manipulation and Pauli spin blockade [6]. All of these functions are needed to build all semiconductor quantum repeaters and distributed quantum computers.

1. Quantum media conversion

None of the physical implementations of quantum bits or qubits is suitable for all aspects of quantum information technology. Quantum information interfaces connecting those qubits are thus needed to place the right qubit at the right position. Photons are the natural messenger qubits for fast and reliable communication, whereas electron spins in a semiconductor are suitable processor qubits for stable and scalable computation. Quantum media conversion (QMC) between photons and electrons[7] will drastically extend the potential of quantum information and communication technologies. The QMC from a photon to an electron might look similar to the photo-electric effect as explained by Albert Einstein with the assumption of a light quantum (photon) ; however, the photo-electric effect utilizes only one aspect of quantum nature as the energy quantum, since only energy of a photon is converted into that of an electron through the photo absorption. The QMC , on the other hand, utilizes another aspect of quantum nature as the information quantum, which is essential for both the quantum mechanics and quantum information technology.

2. Coherent spin preparation and read out with light

As electron spin coherence originates in the quantum coherence between up ($\uparrow_e$) /down ($\downarrow_e$) spin states, light polarization coherence originates in the quantum coherence between right (σ^+_{ph})/left (σ^-_{ph}) circular polarization states. Electron spin states can be prepared by injecting circularly polarized photons or by optical pumping, and read-out can occur by measuring the Kerr (Faraday) rotation angle of reflected (transmitted) light. However, we cannot directly prepare and read out a coherent superposition of up and down electron spin states using the conventional optical spin injection and Kerr rotation schemes. Conventionally, the mixture of up spin and down spin results in a completely incoherent mixture of those spin states likewise the classical states. We have overcome this obstacle by developing new methods for coherent spin state transfer and coherent spin state tomography based on the V-shaped band structure in a semiconductor quantum well. The combination of the two spin states now results in the coherent superposition of those spin states likewise the quantum states.

Figure 1 shows operating principles of the spin coherence transfer and the tomographic Kerr rotation. By applying an in-plane magnetic field B_x to configure the V-shaped three-level system, the Kramers degeneracy of the light hole (LH) is lifted and reconfigures the eigenstates as $|\pm x\rangle_{lh} = |\downarrow\rangle_{lh} \pm |\uparrow\rangle_{lh}$ while keeping the degeneracy of the electron with the smaller g-factor **(Fig. 1a)**. Via the resonant transition between the $|-x\rangle_{lh}$ state and the degenerated electron states, the optical selection rules lead to the transition from $\alpha|\sigma^+\rangle_{ph}+\beta|\sigma^-\rangle_{ph}$ to $(\alpha|\uparrow\rangle_e+\beta|\downarrow\rangle_e)\otimes|-x\rangle_{LH}$, resulting in the coherent transfer of light polarization to electron spins [1]. The same scheme applies the tomographic Kerr rotation as a virtual excitation **(Fig. 1b)**. Provided that the prepared electron spin s_1 is in $|+y\rangle_e$, the probe light in $|+z\rangle_{ph} = (|+y\rangle_{ph}+|-y\rangle_{ph})/\sqrt{2}$ virtually creates another electron spin s_2 in $|+z\rangle_e = (|+y\rangle_e+|-y\rangle_e)/\sqrt{2}$ together with an LH in $|-x\rangle_{LH}$. Then, two components $|\pm y\rangle_{ph}$ in the scattered light experience different phase shifts $f^\pm$ due to the exchange interaction $s_1 \cdot s_2$. The Stokes vector thus rotates about s_1 by the Kerr rotation angle q_K $f^+ - f^-$ in the Poincaré-Bloch sphere. The q_K in effect measures the projection of the electron spin onto the projection basis $|\pm y\rangle_e$. The developed tomographic Kerr rotation method enables the density matrix tomography of coherent spin states of electrons (**Fig. 2**), even when the spin does not precess around the applied magnetic field, as if the spin is frozen [2]. As this condition ensures energy conservation between photons and electrons, the entire Poincare sphere representing the polarization states of photons can be ideally mapped onto a Bloch sphere representing spin polarization states of electrons. The frozen spin also faithfully maintains the

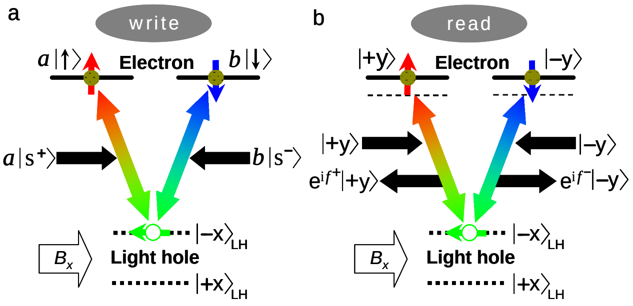

Fig. 1, Operating principles of spin coherence transfer (a: write) and tomographic Kerr rotation (b: read), based on the three-level V-shaped system.

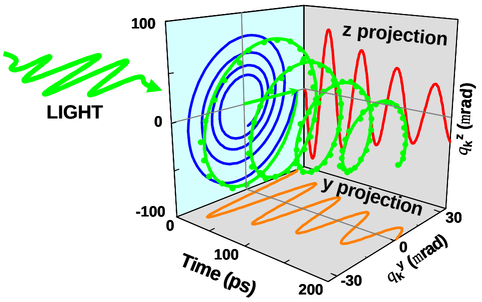

Fig. 2, Experimental demonstration of electron spin state tomography showing dynamic spin precession under an in-plain magnetic field Bx.

coherence transferred from photons encoded in their polarization.

The fundamental principle of TKR is the Pauli blockade (singlet state selection) between the target electron and the probe electron created virtually by the probe light. The TKR phenomenon is regarded as the reverse mapping of the electron spin states onto the photon states or the spin state swapping between a photon and an electron, through the resonant excitation of the spin trion with a light hole based on the degenerate Λ system. In other words, we can exchange the quantum information between the electron and the photon.

3. Single photon to single electron conversion in a single quantum dot

We demonstrated that a single photon creates a single electron in a semiconductor and detected by the charge [7,8]. We fabricated a gate-defined singe quantum dot consisting of a GaAs quantum well with multiple gates on the top surface to trap an electron (**Fig. 3**). 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. 4**) 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].

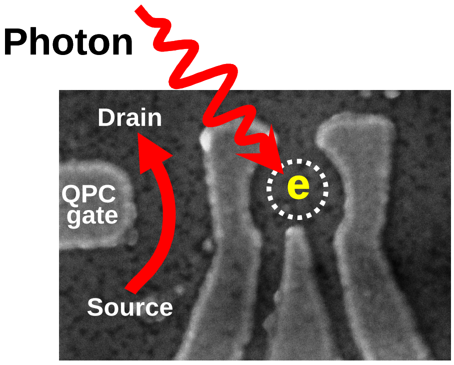

Fig. 3, SEM image of the device used for the demonstration of single photon to single electron conversion. QPC: quantum point contact.

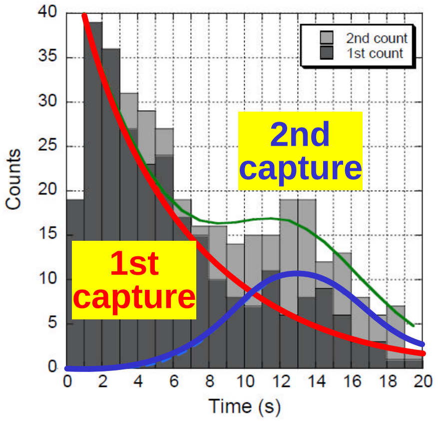

Fig. 4, Histogram of the electron-capture events detected by the quantum point contact as a function of light exposure time.

4. Coherent spin manipulation with microwave

Using a similar device with two coupled double quantum dots (**Fig. 5**), 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. 6**). 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.

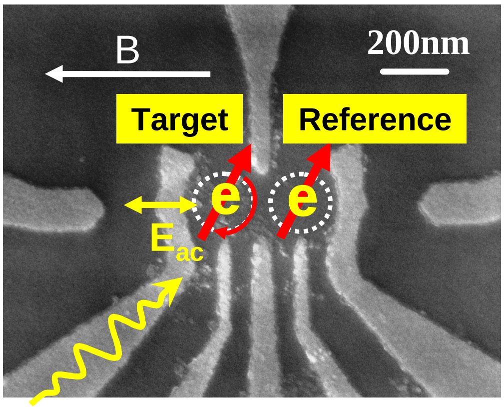

Fig. 5, SEM image of the coupled double quantum dots used for the demonstration of single electron spin manipulation.

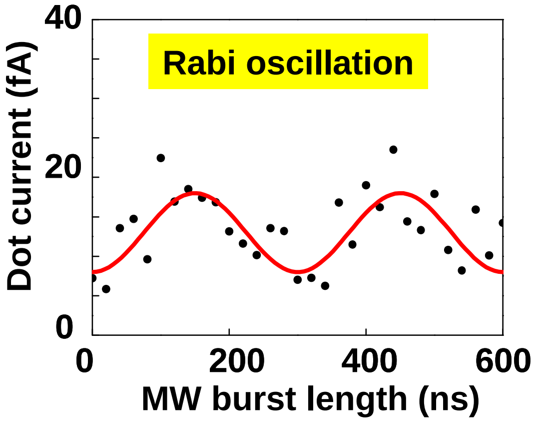

Fig. 6, Experimental demonstration of coherent spin manipulation of a single electron trapped in one of the coupled double quantum dots.

5. Full Bell state measurement

The above demonstrations of single electron spin resonance and singlet-state detection encourage us to perform the full Bell state measurement needed for the quantum repeater. Given that the g-factors of the electrons on both sides have the same magnitude but the opposite sign as shown in **Fig. 7**, we can swap any of the three triplet states for the single state and read out without disturbing the other states simply by the spin resonance in the x, y, and z directions and Pauli spin blockade, which enables full Bell state measurement [5,6].

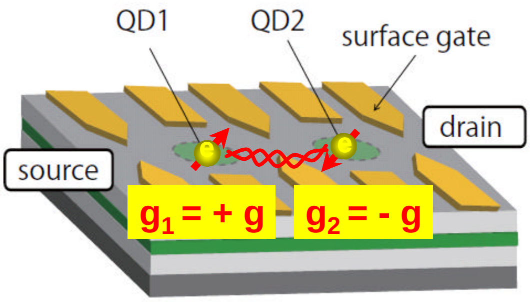

Fig. 7, Schematic structure of the proposed devise for the demonstration of full Bell state measurement.

6. Conclusions

We have demonstrated coherent spin preparation, manipulation and read-out with light and microwaves in a quantum well and dot. All of these functions are needed for building all semiconductor quantum repeaters and distributed quantum computers.

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