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Single-electron spin resonance in a g-factor-controlled semiconductor quantum dot

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1. Introduction

Single-spin coherent rotation in a semiconductor quantum dot has been demonstrated by applying electron spin resonance (ESR) techniques based on on-chip coils [1], spin-orbital coupling [2] and micro-magnets [3]. These schemes are scalable methods for effectively applying an oscillating magnetic field. The spin flip event excited by applying a resonant alternative magnetic field was detected as a singlet state based on a Pauli spin blockade regime in a double quantum dot (DQD). This would enable the two-spin basis exchange needed for the full Bell-state measurement. However, the g-factor of electrons in those demonstrations is fixed at a relatively high value ($g_e \sim 0.4$). A transfer from a polarization coherence of light to a spin coherence of electrons has been demonstrated using a semiconductor quantum well [4, 5]. These demonstrations indicate that arbitrary single-electron spin states can be created in a solid-state device by single photon excitation without coherent driving of the spin. The spin degeneracy condition is ideal for the quantum state transfer from a photon to an electron spin. A degenerated spin state is also favorable to maintain the spin coherence longer because such a state is robust against the magnetic field.

Therefore, we demonstrate the electron spin resonance of a single electron in a DQD which has a nearly-zero g-factor quantum well (QW) structure. We obtained the signal of single-electron spin resonance using a double quantum dot formed on a quantum-state transfer structure to detect an electron spin state with small g-factor. The read-out scheme of a single-electron spin using a Pauli spin blockade [6, 7] is necessary for the demonstration of the transfer from a single-photon polarization state to a single electron spin state.

2. Experimental Setup

In our experiment, a g-factor-controlled quantum well structure wafer is used. The wafer is a 6-nm-thick undoped GaAs quantum well embedded in undoped $Al_{0.35}Ga_{0.65}As$ grown by molecular-beam epitaxy [4]. According to time-resolved Kerr rotation measurement, a no spin precession is observed in the QW sample without gate electrodes within the phase decoherence time, and the estimated electron g-factor is less than g_e~0.03. Electron-beam lithography and liftoff were used to create Ti/Au gates that deplete a 70-nm-deep two-dimensional electron gas with electron density 3.4×10^{11} cm^{-2} and mobility 7.0×10^{4} cm^2/Vs at T=4.2 K. We chose the method of an electric-dipole-induced spin resonance (EDSR) mediated by spin-orbit coupling which is reported by K. C. Nowack et.al [2]. We could apply a combination of fast pulses and RF bursts to the left-side gate through a bias tee. The orientation of the in-plane magnetic field is as shown in Fig. 1 (a).

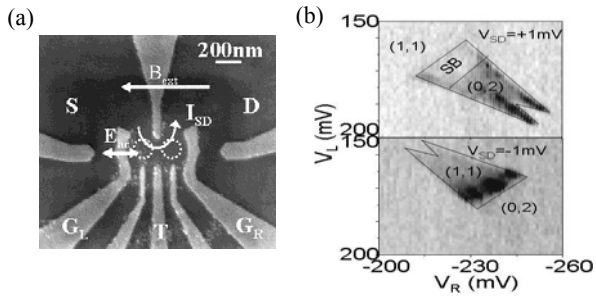

Fig. 1 (a) Scanning electron micrograph of a device with the same gate structure. The orientation of the in-plain magnetic field is as shown. (b) Color-scale plot of the current through DQD as a function of the left and right potentials. (Upper): Pauli blockade is visible (voltage bias +1 mV, B_{ext}=1.0 T). (Lower): No blockade is visible. (voltage bias -1 mV, B_{ext}=1.0 T).

We used the four steps of the control in a combination of fast pulses and RF bursts as a spin manipulation and detection scheme. The device was initialized in a spin-blockade regime where two excess electrons, one in each dot, are held fixed with parallel spins, either pointing along or opposed to the external magnetic field. Next, the two spins are isolated by a gate voltage pulse, such that electron tunneling between the dots or to the reservoirs is forbidden. Finally, the readout stage allows the left electron to tunnel to the right dot if and only if the spins are singlet state. The effective voltage of RF burst is evaluated to be 3-5 mV by measuring photon-assisted tunneling.

3. Results

The electron spin is subject to an effective nuclear field $\mathbf{B_N}$ arising from the hyperfine interaction with nuclear spins in the host material and fluctuating in time. This nuclear field modifies the electron spin resonance condition and is generally different in the left and right dots. The

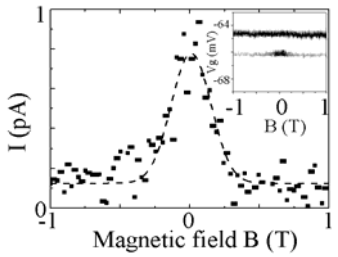

Fig. 2 Leakage current due to the mixing between single and triplet states as a function of magnetic fields B. Inset: Color-scale plot of the leakage current through DQD dependence on B in a Pauli spin blockade regime.

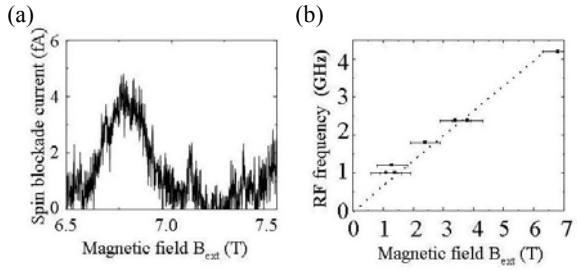

Fig. 3 (a) Current measured through the DQD in the spin blockade regime with RF field (f=4.20GHz, P=-10dBm) as a function of the magnetic field. (b) Plot of the resonance magnetic field as a function of RF frequency.

small g-factor electron spin is expected to be a large effective nuclear field. For unpolarized GaAs nuclear spins, statistical fluctuation gives rise to effective field delta $|\mathbf{B_N}|=B_N/\sqrt{n}$ ~0.15 T (Total nuclear spin n ~10^5). To evaluate the amplitude of the fluctuation of the nuclear field in a double quantum dot, we measured the leakage in the Pauli spin blockade regime, which was caused by mixing between single and triplet states. Fig. 2 shows the magnetic field dependence of the leakage current in the Pauli spin blockade regime for small tunnel coupling. At near-zero magnetic fields, the leakage current decreased with the magnetic field on a scale of about 0.3 T for resonant transport.

To demonstrate single-electron spin flips in a quantum well structure, we applied an RF burst of constant length to the right side gate and monitored the average current flow through the quantum dot as a function of an external magnetic field $\mathbf{B_{ext}}$. A finite current flow is observed around the single-electron spin resonance condition, i. e., when $|\mathbf{B_{ext}}|=hf_{ac}/g\mu_B$, with h being Planck's constant, f_{ac} the excitation frequency, and μ_B the Bohr magneton (Fig. 3 (a)). From the position of the resonant peaks measured over a wide magnetic field range as shown in Fig. 3(b), we determine a g-factor |g|=0.05, which was in agreement with the other reported values for electrons in a 6-nm GaAs/AlGaAs quantum well structure [4]. An electron g-factor in a quantum well with narrow well width can be shifted by applying the gate voltage [8].The peaks shown in Fig .3(a) are averaged over many magnetic field sweeps and have a width of about 0.3T. The width of ESR signal can be explained by the fluctuation of nuclear field [9] as shown in Fig 2.

4. Summary

We demonstrated single-electron spin resonance using a double quantum dot on small g-factor quantum well used as quantum state transfer devices. We determined the electron g-factor |g|=0.05 in a DQD on a QW with a reduced g-factor, which was in good agreement with the previously reported value. The ESR lineshapes of the g-factor controlled GaAs quantum well structure are wider than that of a typical GaAs hetero-structure. The reason is that an electron spin with small g-factor is influenced by the fluctuation of the nuclear spins.

This demonstration implies that we can coherently control the electron spin state even with a nearly-zero g-factor. This device structure introduces the possibility of achieving the full Bell-state measurement needed for building a quantum repeater.

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