# Angular momentum conversion from single photons to single electron spins in a lateral double quantum dot

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Abstract

In gate-defined quantum dots (QDs), coherent manipulation of electron spins and two-qubit gate operations have been achieved, verifying their suitability to the scalable qubits for quantum computations. If the spin states in such gate-defined QDs could couple to the photon states coherently the ability of the gate-defined QDs would be considerably extended to a long distance quantum communications. Here we demonstrate that the angular momentum of the circularly polarized single photon can be transferred to the electron spin in a double QD. This result confirms that the photon can be coupled to the spin degree of freedom in the gate-defined QDs.

## 1. Introduction

Quantum computing is one of the fascinating and challenging issues in solid state physics. Spins in semiconductor quantum dots are extensively investigated as a candidate for the building block of the quantum computer. In gate-defined quantum dots (ODs), coherent manipulation of single electron spins and two-qubit gate operations have been demonstrated, verifying their suitability to the scalable qubits for quantum computations [1,2]. In the optically active self-assembled QDs and diamond NV centers the entanglement between spin states and photon states has been achieved [3-5]. Such a coupling between photon and spin would provide a route to realize the long distance quantum communications via quantum repeaters. The coherent transfer from photon to electron spin based on the spin selective excitation has been proposed [6] and has been verified using a quantum well structure in ensemble manner [7]. The scheme of the state transfer among single quanta is strongly needed to in quantum communication. Indeed we have reported the single photoelectron detection using a gate-defined single QD [8].

In this work first we study the g-factor variation in the AlGaAs/GaAs quantum wells (QW) for different well widths to satisfy the condition of the proposed coherent state transfer [6]. Then, we fabricate the gate-defined lateral double quantum dots using the QW wafers and show dis-

crimination of photoelectron spin and the angular momentum conversion from circularly polarized single photons to electron spins in a double QD.

## 2. Experimental

Al<sub>x</sub>Ga<sub>l-x</sub>As/GaAs QWs with different well widths were grown by molecular beam epitaxy. We measured the longitudinal and transverse resistances as a function of magnetic field in a conventional lock-in technique. The electron g-factors were evaluated from the resistively detected electron spin resonance [9]. Lateral double quantum dots (DQDs) were fabricated from the QW wafers. In order to selectively irradiate single photons to one of the QDs, an optical metal mask with a center aperture was placed on the left dot. The measurements were performed in a cryogen free dilution refrigerator with an optical window. The light source used was a pulsed Ti:Sapphire laser. The photo-generated single electrons are detected in a single shot manner using a quantum point contact nearby the left QD. The average photon number on the QD was a few photons/pulse. The heavy hole states were selectively excited.



Fig. 1 (a) SEM image of double quantum dot device with a quantum point contact charge sensor. (b) Typical stability diagram measured by the charge sensor.

## 3. Results and discussion

To coherently transfer the photon polarization state, only a single light hole state of Zeeman split states has to be excited under magnetic fields applied orthogonal to the light propagation direction [6]. Therefore, the Zeeman splitting of the light states should be larger than the photon spectral width while the electron Zeeman splitting is negligibly small to excite both up and down states [6]. Therefore the QW with a small electron g-factor is suitable for the coherent state transfer. From the ESR measurements, we have found that the electron g-factor depends on the well width and becomes -0.12 at a well width 7.5 nm for the perpendicular magnetic field. In the following we study the DQD fabricated from the QW wafer.

First we discuss the single photoelectron detection using interdot tunneling in DQDs. Figure 2 shows an example trace of the repetitive interdot tunneling of a single photoelectron trapped in the DQD. Initial charge state in the DQD was set to (0,4) state and the first excited states of each dot were tuned to be aligned energetically. When a single photon is absorbed in the left QD, the generated photoelectron moves back and forth resonantly between two QDs, resulting in the repetitive charge current signal. This would give distinct single photoelectron detection because the charge signal of the interdot tunneling between (1,4) and (0,5) can easily exceed the noise level of the charge signal [10].



Fig.2 Single photon detection signal in the DQD. A repetitive current is seen when a single extra photoelectron is trapped in the DQD and tunnels between the two dots. At t=220 ms, the electron escapes from the dot and the current returns to the value corresponding to the (0,4) state[10].

Pauli spin blockade can offer a robust discrimination of single photoelectron spins when it is combined with the single photoelectron detection scheme. Before the photon irradiation, the charge state of the DQD was set to the (0,1)state and the single photoelectron detection was performed in the presence of magnetic field perpendicular to the plane. When the photoelectron trapped in the left QD has a spin anti-parallel to the right QD, the photoelectron immediately tunnels to the right dot, while it cannot when the photoelectron has a spin parallel to the right. This shown in Fig.2 the interdot tunneling time scale observed after the single photoelectron trapping gives us a distinct discrimination of parallel or anti-parallel two electron spin configuration after a single photoelectron trapping. From the detailed analysis of the ratio of the two time scales as a function of magnetic field, we find that the spin distinguishability can be tuned over 90 %. The g-factors obtained from the analysis of the spin dynamics affected by nuclear field fluctuation are consistent with the confinement effect of the QW, important for the structural requirement of coherent transfer.

Moreover, by changing the incident photon polarization

systematically, the probability of the antiparallel spin configuration smoothly changes from left-handed to right-handed circularly polarization through liner polarization. This distinctly verifies that the angular moment of single photon can be transferred to single electron spin in a QD. Although the visibility of angular momentum transfer is limited by thermal distribution in the electron Zeeman sublevels, the visibility might be improved by lowering temperature, increasing Zeeman splitting.



Fig. 3 Example traces of single-shot single photoelectron detection measured at 750 mT. Top (bottom) shows the detection of down (up) photoelectron spin, respectively.

#### **3.** Conclusions

We have demonstrated non-destructive single photoelectron trapping using the resonant interdot tunneling in a DQD. This provides a very efficient spin detection scheme by combining with Pauli spin blockade. Indeed we have achieved the spin discrimination of single photoelectron trapped in the DQD with high distinguishability. It has been found that the distinguishability is strongly governed by the (1,1) spin relaxation. Finally we have shown that the angular momentum transfer from single photons to single electron spins in the DQD. As for the future work, to verify coherent transfer from single photon to single electron spin, the spin tomography measurements for the transferred single electron spin has to be realized.

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