論文の内容の要旨

論文題目　Control and detection of electron spin states in triple quantum dots
（3重量子ドットにおける電子スピン状態の操作と検出）

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Quantum computing enables parallel computing using quantum mechanical phenomena such as superposition and entanglement to perform data processing, which boosts the computing speed compared to classical computing. Recently, electron and nuclear spins in semiconductor solid state systems have been attracting a lot of interest in their applications to quantum computing hardware devices with potential scalability. In this context a quantum dot (QD), an artificial atom which confines an electron three-dimensionally, has been used to electrically and precisely control the electron spin states. Based on such a unique property of QDs, a quantum computing platform consisting of a QD array has been proposed. Especially, electron spin is a well-defined two-level system (spin up and down) and shows a long coherence time when confined to a QD, which means a superposition of spin-1/2 is used to make spin quantum bit (qubit). Indeed fundamental qubit operations, single-qubit rotation gates, or two-qubit entanglement gates, have been demonstrated using single spin qubits, or two spin qubits respectively. The next step is therefore to implement practical quantum algorithms by combining the fundamental qubit operations. Especially, some important algorithms such as quantum teleportation and quantum error correction are only feasible with three or more spin qubits. To perform these algorithms a technique to precisely control and detect three spins is necessary, however, it has never been realized.

Most of the previous experiments focused on one or two spins in double QDs (DQDs) to implement one or two spin-1/2 qubits. In up to two spin systems, initialization and readout is possible using Pauli spin blockade (PSB). Arbitrary single-qubit operation is realized by electron spin resonance (ESR). Two-qubit entanglement gates are implemented using nearest-neighbor exchange coupling. On the other hand, it is yet challenging to implement three or more qubits mainly because of difficulty in controlling and detecting the electron spin states.

Based on the above background, I have aimed at developing a technique to precisely control and detect the three-spin states in GaAs based triple QDs (TQDs) in my PhD thesis. Throughout the PhD work I have conducted several experiments and finally achieved four main results. First, I have established a new way to realize spin initialization and readout using PSB with a three-terminal TQD. Secondly I have realized coherent ESR control of individual three electron spins. Thirdly I have improved qubit dephasing or control fidelity by a fast measurement technique. Finally I have demonstrated a single spin and Singlet-Triplet (ST) qubit hybrid system.

Spin state detection is realized by combining techniques for spin-to-charge conversion and charge sensing. PSB enables the spin-to-charge conversion because electron tunneling from one QD to the other is forbidden when the two spins in the two dots are parallel due to Pauli exclusion while the tunneling is possible for anti-parallel spins. In addition, spin initialization is possible using PSB since electron transport in the two dots is blocked for parallel spins. Therefore, PSB has often been used for spin initialization and readout in previous spin qubit experiments with DQDs. However, PSB cannot simply be applied to three spins in TQDs. To study the three electron states in TQDs and find the necessary conditions to use PSB, I have designed and fabricated a three-terminal TQD which can be operated as a combination of two two-terminal DQDs consisting of the left two dots and right two dots with a common center dot. By applying a source-drain bias between the reservoir of the center QD and the reservoir of the left or right QD, I can observe PSB in both DQDs simultaneously. This result clarifies that we can realize PSB even in a TQD by operating it as a combination of two DQDs.

Next, I have realized individual control of three single spins by ESR. ESR requires a static d.c. magnetic field and an a.c. magnetic field perpendicular to the d.c. field. There are several ways to apply the a.c. magnetic field with QDs. I use a micro-magnet (MM) ESR scheme. Here, an electron wave function electrically oscillates driven by an a.c. voltage under a local magnetic field gradient created by the MM. The ESR condition in each QD depends on the local magnetic field at the respective dots. This enables frequency selective ESR for the three spins. Therefore, we can realize rotation or Rabi oscillation of individual spins. I have designed and fabricated a TQD with MM to implement three single spin qubits. I operate two of the three dots to prepare a coupled QD using dot-to-dot detuning pulses - a key technique for spin initialization and readout. We observe three ESR lines corresponding to resonance of the spin in each QD. Importantly, the ESR lines are well separated from each other, indicating that ESR is addressable for the respective three spins. Then, we use a pump and probe technique to measure the time dependence of ESR or Rabi oscillation for each QD. We successfully observe three Rabi oscillations coming from each QD. This is the first demonstration of three single spin qubits. This result can be extended to realize universal three-spin state control by combining an existing technique of exchange-based three-spin state manipulation.

Although fundamental qubit operation is demonstrated with three single spins, I find the gate fidelity is significantly limited by quantum dephasing due to the fluctuating nuclear spin bath. In III-V semiconductor systems, an electron spin in a QD interacts with many (~ 10^6 for GaAs) nuclear spins via the hyperfine interaction. This causes fluctuations of the Overhauser field to influence the ESR condition. Note the Overhauser field fluctuates because nuclear spins thermally fluctuate even at dilution temperature (~ 10 mK) and under a strong external field (~ T). The Overhauser field fluctuation occurs during the measurement, and therefore causes reduction of the measured dephasing time. Indeed it has recently been demonstrated that the dephasing effect on the gate fidelity can be reduced by reducing the data acquisition time. In these studies the dephasing time measured for ST qubits shows a monotonic increase just by shortening the total data acquisition time. The reduced dephasing by the fast measurement means that the system of interest is in the "non-ergodic" regime. We perform a similar experiment with a single spin qubit (the time dependent nuclear field fluctuation σ can be measured using the Ramsey fringe) and also observe monotonic suppression of dephasing as the data acquisition time is reduced. Interestingly, unlike previous experiments on ST qubits, we observe strong saturation of the nuclear field fluctuation σ in the long data acquisition time ($>$ several tens of seconds). This indicates that the system of interest is in the "ergodic regime". This is the first observation of transition from the "non-ergodic" to the "ergodic" regime. We find the transition time of several tens of seconds may arise from the nuclear spin diffusion rate and the QD size. Then, we study how the nuclear field fluctuation affects the single spin qubit control by ESR. It is established that there are two different regimes of Rabi oscillations: strong drive and weak drive depending on the ratio of the Rabi frequency f_{Rabi} and σ. In the strong drive where $f_{\mathrm{Rabi}} / \sigma \gg 1$, Rabi oscillations are well approximated by a Gaussian envelope with a decay time T_2^{Rabi}, $A\exp(-(t_{\mathrm{MW}}/T_2^{\mathrm{Rabi}})^2)\cos(2\pi f_{\mathrm{Rabi}} t_{\mathrm{MW}}) + B$. On the other hand, in the weak drive where $f_{\mathrm{Rabi}} / \sigma \leq 1$ they are well approximated by a power-law envelope with an initial phase shift, $At_{\mathrm{MW}}^{-0.5}\cos(2\pi f_{\mathrm{Rabi}} t_{\mathrm{MW}} + \pi/4) + B$. The strong drive is necessary to achieve a high fidelity spin rotation. To date the strong drive has only been achieved by increasing f_{Rabi} up to ~ 100 MHz. On the other hand, we show for the first time that the strong drive can be achieved even for a slow $f_{\mathrm{Rabi}} \sim 10$ MHz by reducing the data acquisition time. This result indicates that the fast measurement can improve the qubit dephasing and also the qubit gate fidelity.

Thanks to the highly controllable electron spin state in QDs, three different types of semiconductor QD-based spin qubit have been theoretically proposed and experimentally demonstrated, namely, single spin qubit (superposition of single spin states ↑ and ↓ in single QDs), ST qubit (superposition of two-spin states ↑↓ and ↓↑ in DQDs) and exchange only qubit (superposition of three-spin state in TQDs). The different types of qubits have different advantages, however, coupling between any two of them has never been demonstrated although efficient quantum gate operations may be possible. Here, we realize a hybrid operation of a single spin qubit and an ST qubit with a TQD for the first time. We operate the left QD as a single spin qubit and the center-right DQD as an ST qubit. When the local Zeeman energy difference $\Delta B_{\mathrm{Z,CR}}$ between the center and right QD is much larger than the exchange coupling J_{CR} between the center and right QD, the ST qubit starts to precess between S and T_0 with a precession frequency $f_{\mathrm{ST}} = |g|\mu_{\mathrm{B}}\Delta B_{\mathrm{Z,CR}}/h$. In addition to this, under a finite exchange coupling J_{LC} between the left and center QD, f_{ST} shifts by J_{LC} depending on the left QD spin projection ↑ (↓), $f_{\mathrm{ST},\uparrow(\downarrow)} = |g|\mu_{\mathrm{B}}\Delta B_{\mathrm{Z,CR}}/h \mp J_{\mathrm{LC}}/2$. This means we can perform a projection measurement of the single spin qubit by measuring f_{ST}. Furthermore, this projection measurement is a quantum non-demolition (QND) measurement because the ST precession measurement does not affect the single spin qubit projection. By using this scheme, we demonstrate the QND readout of the single spin qubit for the first time. In addition, when J_{LC} is rapidly turned on and off by a voltage pulse operation to induce interaction between the two qubits for a finite time $t_{\mathrm{interaction}}$, a relative phase between the S and T_0 in the ST qubit is accumulated by $2\pi J_{\mathrm{LC}} t_{\mathrm{interaction}}$. If we choose $J_{\mathrm{LC}} t_{\mathrm{interaction}} = 1/2 + \mathrm{m}$ ($\mathrm{m} = 0, 1, 2, \cdots$), then this operation provides CPHASE gate (conditional phase gate) where the single spin qubit works as a control qubit on the ST qubit. We can successfully demonstrate the CPHASE gate for the first time. This result implies that hybridization of spin qubits of different kinds may pave the way for realizing efficient gate operations by using different advantages of both qubits.