論文の内容の要旨

論文題目　Observation and control of electron states in lateral multiple quantum dots for realization of spin qubits

（量子計算の実現に向けた横型多重量子ドットにおける電子状態の観測と制御の研究）

氏　名　　高倉　樹

Recently quantum information processing, which is not based on classical computing but quantum mechanics, has been attracting a lot of interest. Solid state quantum systems are assumed to be advantageous to realize scalable quantum computers because of their device similarity to classical ones. With recent developments in semiconductor fabrication techniques, quantum particles such as electron spins and nuclear spins in solids have seen more and more attempts to be utilized as quantum bits or "qubits". Since the realization of quantum dots (QDs), artificial structures in a semiconductor to confine an electron within the size of de-Broglie wave length, various quantum phenomena related to single electron charges and spins have been observed experimentally. These observations imply that confined electrons could be coherently manipulated as qubits, which are able to implement quantum information processing.

For the realization of experimental quantum computers it has been known that at least general five criteria have to be satisfied: operation of qubits and quantum gates, initialization, state readout, sufficiently long coherence time, and scalability. In 1998, it was theoretically proposed that QDs were promising devices to satisfy these demands. Since spin is a natural two-level system, spin qubits can be implemented by superposing the up and down spin of single electrons confined to QDs. Quantum gates are decomposed into single qubit operation and correlative operations between two adjacent qubits; the former by using electron spin resonance (ESR), the latter by tuning exchange interaction J. Spin orientation is easily initialized in parallel with the external magnetic field in the sub-Kelvin temperature environment. Moreover, spin readout can be typically performed via Pauli spin blockade (PSB), which is observed as suppression of electron transport through double QDs (DQDs) governed by Pauli exclusion rule. These elements allow the implementation of quantum computers in realistic QDs.

Since the proposal of QD-based quantum computation many experimental challenges have been addressed to coherently manipulate electron spins in QDs. ESR, the fundamental tool for single-spin-based qubits, usually requires a DC and an AC magnetic field normal to each other. Several ESR experiments have been demonstrated generating such an AC field in various ways: AC current injection into an on-chip coil and conversion from AC voltage via spin-orbit interaction, for instance. However, in order to handle individual electron spins in multiple QDs or to make multi-qubit systems, it is necessary to establish the ESR conditions of both DC and AC magnetic fields local to each QD. We have recently proposed and demonstrated a new technique of electrically-driven single spin resonance (EDSR) using a micro magnet (MM) and an applied microwave (MW) or AC electric field. This technique allows us to address single spins in multiple QDs with EDSR at different resonance frequencies, and has been already demonstrated by preparing two individual electrons in double QDs.

The next step is to extend the above technique to multiple QDs (MQDs) in order to realize multi-qubit systems. However, the number of QD-based qubits is still limited to two. A three-qubit system will be an important milestone for future fault-tolerant quantum computation since quantum error correction code requires at least three qubits to correct an error of either a bit or a phase flip. As for the number of QDs, there have been just a few previous reports on fabrication and characterization of triple QDs (TQDs) as well as quadruple QDs (QQDs) especially in the few-electron regime, and no report on MQDs designed for multiple spin qubits.

In this thesis we design, fabricate, and characterize MQDs and MMs to give a guide for multiplying the number of QD-based qubits. Our road map for implementing multiple spin qubits is as follows: 1. Realize few-electron TQDs. 2. Extend the number of QDs. 3. Examine the charge sensing sensitivity in MQDs. 4. Design MMs applicable to multiple qubits. 5. Consider new design of MQDs which enable easy initialization and readout for qubit states. Below we show the summary of each component that we have achieved to date.

First, we characterized TQDs by electron transport through them and charge sensing measurements utilizing nearby quantum point contacts (QPCs) for two different types of TQD devices. The first device was designed to have similar gate electrodes as conventional DQDs. Formation of three QDs was confirmed in the charge stability diagrams, which show the equilibrium charge states in two-dimensional space as a function of gate voltages. In the few-electron regime we controlled the three dot states independently with gate voltages. In addition we fabricated another device, which consists of parallel plunger gates and a T-shaped global gate opposite to them. This design was more practical to perform ESR measurements than the previous one, as we achieved the charge state in which each dot held single electron. This (1, 1, 1) charge state is fundamental to implement spin qubits. However, it was impossible to observe

PSB and ESR signals because of the difficulty in tuning both the electron number in each dot and the tunnel coupling between neighboring dots simultaneously. This problem is improved to some extent in the newest TQD device, which is shown in the last paragraph.

Next, we demonstrated a tunable QQD device to indicate the scalability of the number of QDs. Only a few experiments on QQDs have been reported to date, most of them consisting of two capacitive-coupled DQDs. In our device dots were located in a row and tunnel-coupled to the neighbors. We first tried to form various configurations of DQDs by negatively biasing corresponding gate electrodes. From the charge stability diagrams measured by electron transport, we estimated the charging energy and thus the capacitance of each dot. The obtained QD capacitance, which should be roughly proportional to the size of each dot, varied consistently. Next, we formed single, double, triple, and quadruple QDs by tuning inter-dot tunnel couplings. For each configuration charge sensing stability diagrams were measured and found to exhibit characteristic charging lines. In the QQD configurations we could form different conditions of QQDs with increasing or decreasing inter-dot couplings between arbitrary adjacent dots. These results support the extensibility of QD arrays from three to four.

We discussed the sensitivity of charge sensors by analyzing the data of charge stability diagrams for the TQD and QQD devices. Charge sensing has been used as a powerful technique to read out quantum information in QD-based qubits. Both sensitivity and scalability of the charge sensors are of importance in QD-array devices, because they may offer a path towards implementing a multiple-qubit system. We derived a simple model of QPC or QD charge sensors under measurement conditions. Applying the model we estimated the potential modulations at the electrometer caused by charging events in the MQDs. The obtained one-electron potentials are suppressed compared to the Coulomb potential by screening effects, which reflect the gate geometry. Comparing the data in different devices with different geometries implies that one of the main origins of screening is side-gate lying between QDs and sensors. Even though charging events as far as 1 μm from the sensor could be detected, especially in the QQD, it might be difficult to distinguish charging events in adjacent QDs by just comparing signal amplitudes when they are too far from the electrometer. This finding predicts that more charge sensors will be preferable for laterally gated MQD devices integrating more than four or five QDs. In designing QD-array systems which can be applied to scalable quantum computers it will be essential to optimize the geometry of charge sensors in order to readout the qubit states.

Following the above discussion, we designed split-type MMs placed above the surface gates to enable multi-spin qubits in these MQDs. A stray magnetic field is produced by the MMs in the out-of-plane and in-plane directions when the external static magnetic field B_{ext} is applied. An AC magnetic field is effectively generated by electrical oscillation of an electron inside a QD under a gradient of the out-of-plane stray field. Note that the electrical oscillation is driven by MW application. The MM also brings about an in-plane stray field local to each QD. The stray field distribution must satisfy two requirements: larger in-plane component difference among all the dots than the few mT of nuclear field fluctuation by GaAs nuclei and large enough slanting field along the B_{ext} direction. We first optimized by simulation the stray field distribution for the realistic TQD devices. As a result, we obtained comparable field components to the preceding measurements in DQDs. This design of MMs permits 50nm of misalignment from the dots, which is within the accuracy of alignment in real device processing. Moreover, extending the size of the MMs we found that the proposed design is suitable for addressing up to 25 single electron spins.

Finally we characterized a three-terminal TQD device in which each dot was connected to a corresponding reservoir. The gate electrodes are designed referring the tunable devices reported by other groups. Although our conventional TQDs are two-terminal, we modify the design to make the center dot connected to the reservoir. This configuration will enable us to initialize the center dot since electrons can be directly exchanged between the center dot and the reservoir. This type of TQD can be regarded as a set of two DQDs consisting of center and left (right) dots. Therefore, we can form the PSB states in both DQDs independently, which will help the state readout in the three qubit systems. The relevant device was measured to observe PSB in the vicinity of (1, 1, 1) charge state. We observed two different conditions of PSB: strong and weak inter-dot tunnel couplings. In the strong coupling case, leak current through the TQD observed at the edge of bias triangles was maximized at higher magnetic field. In the weak coupling case, on the other hand, the leakage was observed only at small external field and it vanished around 1T. The latter can be utilized for the ESR detection since ESR lifts the PSB, generating a leak current or change of electron distribution.