論 文 の 内 容 の 要 旨

論文題目　High-speed electrical gating of single electron spin qubits with semiconductor quantum dots
（半導体量子ドットを用いた単一電子スピン量子ビットの高速電気制御）

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The field of quantum computation has gained intensive research interest in recent years due to its potential to outperform its classical counterpart in some applications. The information units in quantum computers, called quantum bits or *qubits*, follow the laws of quantum mechanics, rather than being either 0 or 1. Quantum properties of qubits such as superposition and entanglement are expected to allow for a much more computational power. In principle, any two level systems can be treated as qubits, but only few physical systems are truly useful as a quantum computational platform. The following five criteria for a viable quantum computer are the most widely recognized of their kind. (1) A scalable physical system with well characterized qubits. (2) The ability to initialize the state of the qubits to a simple pure state. (3) Decoherence times much longer than the gate operation time. (4) A universal set of quantum gates. (5) A qubit-specific measurement capability.

Requirement on scalability has made solid-state implementations exceptionally attractive in search of future quantum computing architectures. Spins in quantum dots (QDs) are regarded as one of the most promising systems among them, together with superconducting circuits, and nuclear spins in semiconductors, etc. Indeed, recent experiments have shown that spins in electrically-controlled semiconductor QDs meet many criteria for quantum computers. Qubits can be encoded by superposing the Zeeman sublevels of single electron spins confined in QDs. Initialization and readout of single spins can be performed electrically through spin-to-charge conversion, for example by Pauli spin blockade (PSB). A universal gate set can be achieved by combining arbitrary single-spin rotations via electron spin resonance (ESR) and a square-root-of-SWAP operation via exchange interaction between neighboring spins, both demonstrated experimentally with GaAs QDs. Coherence times are measured to be relatively long, with longitudinal relaxation time limited by spin-orbit interaction and, more importantly, transverse relaxation time by hyperfine interaction.

Along with all these achievements, realizing qubit manipulations on timescales much shorter than the coherence times lies at the heart of quantum computation (see the criterion (3)). In contrast to exchange-mediated SWAP operations in less than a nanosecond, single spin rotations via ESR are slow, due to technical limitation in the a.c. magnetic field amplitude that drives ESR. To improve in this aspect, several techniques have been demonstrated for generating such ESR driving fields. They include the use of an on-chip micro-coil with an a.c. current injected, and the use of spin-orbit interaction to couple a.c. electric field and spin degrees of freedom. Narrow-gap semiconductors are also used for larger spin-orbit interactions. All these efforts, however, have failed to make spin flip times (T_π) much shorter than the ensemble phase coherence time (T_2*) by the interaction with the surrounding nuclear spins in the host material.

This thesis presents high-speed manipulations of a single electron spin confined in GaAs semiconductor quantum dots. To overcome the problem of a weak ESR driving field compared with the hyperfine field, we utilized an on-chip micro-magnet (MM). The MM-induced stray field gradient couples the electron's spin degrees of freedom to an oscillating electric field or microwave (MW) and allows for electrically driven ESR. In order to achieve spin rotations faster than the dephasing, we refined the MM design and the QD device design of the preceding MM-ESR experiments. We observed above 100 MHz Rabi oscillations, the fastest in the electrically-controlled QDs, with T_π roughly 10 times shorter than T_2*. Suppressed effect of nuclear spins in the fast Rabi oscillation is evidenced from observation of no initial π/4 phase shift and a chevron interference pattern. We also established for the first time a direct control of spin phase, which serves as a single-step Z gate. Above 50 MHz phase rotation was demonstrated, providing a faster implementation of Z(π/4) and Z(π/8) than with the 100 MHz ESR. We then extended this technique to a multiple qubit system, a triple QD.

The detailed contents of the thesis are as follows. We first optimized the design of the MM and the QD device. The magnetic field components useful for spin manipulations are the slanting out-of-plane component and the Zeeman field. We clarified the required values for fast ESR experiments and simulated the MM property in a systematic manner, while successfully including the non-negligible effect of ~ 100 nm misalignment of MM with respect to QDs in the real devices. Our simulation was validated by the agreement of the simulation results and the previous experimental results. Based on the simulation, we proposed a novel MM design that produces misalignment-robust local magnetic field and employed it in all the experiments described in this thesis.

Next we fabricated a double QD device on an AlGaAs/GaAs heterostructure with a 2DEG located 57 nm below surface. An important change in the device design is that the MW was parallel-coupled to the QDs. At dilution temperatures, we tuned the DQD into (1,1)-(2,0) PSB regime, where the charge transition from (1,1) to (2,0) is only allowed when a spin flips. Here (N_L, N_R) denotes the charge configuration with the electron numbers of $N_{L(R)}$ in the left (right) QD. We detected this transition through the change in the conductance of a proximal quantum point contact. Two clear ESR peaks were observed when the MW frequency and the external magnetic field were swept, with a separation of ~ 100 mT. This large separation was attributed to the MM-induced local Zeeman field, indicating an enhanced magnetic field inhomogeneity. To measure the Rabi frequency, we then performed pump-and-probe ESR experiments and observed up to 127 MHz Rabi oscillations with a spin flip fidelity of 97 %. The observed 4 ns spin flip is the fastest ever reported in electrically-controlled QDs, and the figure of merit T_2^*/T_π was improved by an order of magnitude.

In these fast Rabi oscillations, we observed distinct effects of nuclear spins. Unlike in the previous experimental reports, the Rabi oscillation was not shifted in phase and the decay did not follow a power-law. We also observed a chevron pattern in the plane of the ESR detuning and the MW burst time. We paid careful attention to these first experimental observations and conducted analysis on the relationship between the ESR field strength and the standard deviation of the fluctuating Overhauser field. We concluded that these observations could not be explained without driving fields sufficiently larger than the nuclear field fluctuation and that we reached a novel regime of control strength.

We then thought of using the local Zeeman field for a spin manipulation, not the slanting field as in ESR. A change in the Zeeman field will result in a direct phase accumulation (extra spin precession), which provides a single-step Z gate with no overhead as with ESR implementation. The problem is then how to control the Zeeman field electrically, but thanks to the spatially inhomogeneity induced by MM, it can be changed by the QD position, which in turn is tunable by gate voltage. We evaluated this gate-induced change in the field by pumping ESR at various gate configurations. The measured ESR spectra showed that a 10 mT change is accessible, which corresponds to ~ 50 MHz phase shift. As a direct proof of its usefulness for operations, we performed the time-resolved measurement of this phase gate. To project the spin phase to the spin component that our PSB-based measurement is sensitive to, we inserted π/2 ESR pulses before and after the gate. We observed up to 50 MHz oscillations, just as expected.

Finally, we tried to extend the above MM technique to a TQD system. We employed the MM design developed for a double QD since we found it worked equally fine for a TQD in the simulation. An important difference made in this experiment is that the radio-frequency reflectometry circuit was introduced for fast measurements. We could tune the device into the regime of interest with each QD containing a single electron and sensed the flavor of PSB, but unfortunately no spin manipulations have been performed yet.

Fast spin operations demonstrated in this thesis will render all required gate-times an order-of-magnitude shorter than the coherence time of the system, which allows high-fidelity single-qubit gates in a highly scalable platform with an established fast entangler. We believe these achievements contribute to future advances in quantum information processing in the QD system e.g. state tomography by fast ESR gates, CNOT gates incorporating Z gates, and quantum error correction. The MM techniques studied here should be also applicable to other material systems with longer coherence times.