論文の内容の要旨　　Abstract of Dissertation

Anisotropy of Spin-Orbit Interaction and *g*-factor in Single InAs Self-Assembled Quantum Dots

（単一 InAs 自己形成量子ドットにおけるスピン軌道相互作用と *g* 因子の異方性）

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Introduction

SPIN-ORBIT interaction (SOI) and *g*-factor are key parameters in spin-related physics as well as spintronics of semiconductor nanostructures. The first arises from the magnetic moment of electron spin coupling to its orbital degree of freedom and the second represents magnetic response of electron spin, both reflecting the crystal orientation, internal electric field, and quantum confinement effect [1]. Control of these parameters can provide a novel concept of spintronics and spin-based quantum information, such as Datta-Das transistor [2] and coherent spin manipulation by SOI induced electric dipole spin resonance (EDSR) [3] or *g*-tensor modulation resonance (*g*-TMR) [4].

In three-dimensional bulk systems, the SOI and *g*-factor are usually formulated using Roth’s equation which connects SOI and *g*-factor. In one- or two-dimensional systems, these spin effects suffer from anisotropy associated with the dimensional confinement, which can also be electrically tuned [5]. For quantum dots (QDs) or quasi-zero dimensional systems, the SOI and *g*-factor have recently been collecting interests and studied for various kinds of material systems, but the anisotropy as well as the relation between the SOI and g-factor has not yet been well understood. Indeed these spin effects are pretty weak in conventional semiconductor QD systems made out of GaAs, Si, C and so on. On the other hand they can be very strong in self-assembled QD (SAQD) systems made out of a narrow gap semiconductor such as InAs and InSb, and this makes such QDs promising both for the investigation of underlying physics and for the application to spin devices. Note that InAs QDs are the best grown and characterized among various kinds of SAQD systems. In addition it has recently been demonstrated that an uncapped InAs SAQD contacted by metallic electrodes shows single electron tunneling spectra reflecting the zero-dimensional states [6] with strong spin effects such as the Kondo effect and large *g*-factor [7].

In this thesis I use the single uncapped InAs SAQDs to study the anisotropic SOI and *g*-factor by measuring single electron transport through the single QDs. The dots used are laterally as large as 100 nm wide and vertically 30 nm high. Therefore, strong anisotropy may appear in the confinement potential and the same is true of the SOI and *g*-factor. This can also be the case for nanowire QDs of InAs and InSb. However, there is a big difference from them because the lateral potential of a SAQD system can be regarded as a two-dimensional harmonic type and the orbital angular momentum is well defined, which enables us to discriminate Rashba-type SOI from

Dresselhaus-type SOI by a selection rule [7]. Furthermore, the lateral QD potential or confined electron wavefunction can be modulated by lateral gating. We indeed use the lateral gating technique to electrically tune the SOI and *g*-factor anisotropy, and show that the SOI effect in the InAs QDs may be useful for making fast spin qubits.

Measurement Setups

THE devices studied are single InAs SAQDs contacted with a source and a drain electrodes with a small separation (~ 70 nm) and gated by applying voltage to a buried *n*-doped GaAs layer (Fig.1). Electron transport through the single QD was measured using these electrodes with gate voltage as a parameter to change the electron number in the QD. In the SOI and *g*-factor anisotropy measurement, ground and excited state spectroscopy was performed to evaluate the SOI energy. The sample was rotated inside a dilution refrigerator equipped with a superconducting magnet to measure the magnetic angular dependence of the SOI energy. For the *g*-factor anisotropy measurement, an extra Schottky gate, sidegate, was fabricated nearby the QD to laterally tune the electron wavefunction inside the QD. In-elastic co-tunneling spectroscopy was performed to evaluate the *g*-factor at different sidegate voltages. For measurement of three-dimensional magnetic angular dependence of the *g*-factor, a three axis vector magnet up to ±1 T was used instead of the in-situ sample rotation mechanism. Finally to study the ability of the InAs QDs for implementing spin qubits, the response to microwave (MW) induced a.c. electric field was measured. In this experiment two samples, one fabricated in the same way as above and the other with the backgate partially removed, were used in order to first check the MW power decay due to a capacitively coupled *n*-dope GaAs layer, and the effect of 20 GHz continuous wave excitation was applied to the sidegate.

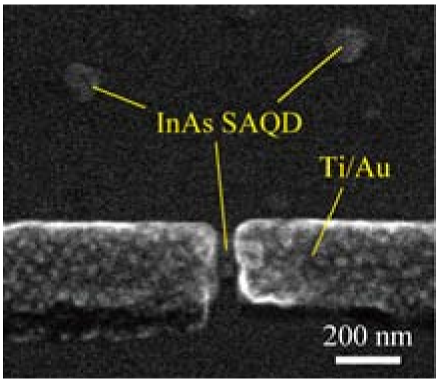

Figure 1 SEM image of the device.

Anisotropy of Spin-Orbit Interaction

FIRST we measured the magnetic field evolution of Coulomb peaks with a small source-drain bias voltage, and assigned the quantum states on each Coulomb peak assuming a two-dimensional harmonic potential confinement. Based on this assignment we were able to identify ground state transitions where only Rashba SOI hybridizes two different orbitals with opposite spin. Then, we used an excited state spectroscopy to precisely identify the transition points, observing an anti-crossing between the ground and excited states which have different orbital angular momenta with opposite spin (Fig.2). The SOI energy is directly derived from the size of the anti-crossing. The magnetic angular dependence of the SOI energy showed a quenching in a particular magnetic field direction and the absolute value of cosine function dependence for in-plane magnetic field rotation

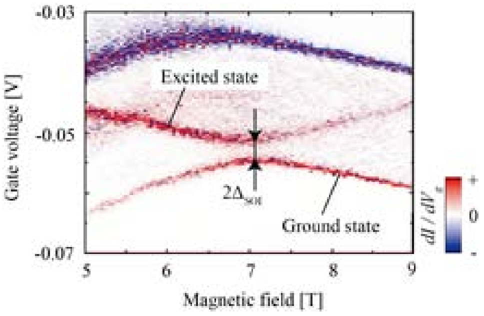

Figure 2 SOI induced anti-crossing in excited state spectroscopy.

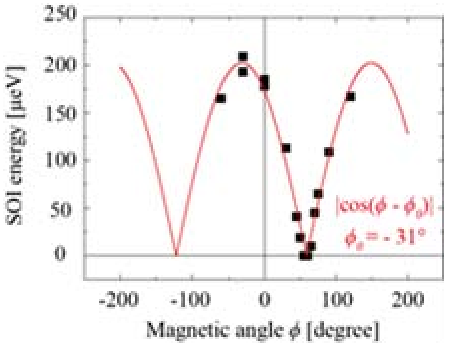

Figure 3 SOI anisotropy for in-plane magnetic field rotation.

(Fig.3). These features are first observed here and can be explained by taking into account the angle between the external magnetic field and the SOI induced effective magnetic field, which is given by the outer product of an electric field induced by the potential gradient and electron momentum in a particular state [8]. We also found that the SOI energy can be tuned electrically by a sidegate [9].

Anisotropy of *g*-factor

WE measured in-elastic co-tunneling through the single QDs in the presence of an external magnetic field in order to quantitatively evaluate the *g*-factor. Its three-dimensional anisotropy was measured using a vector magnet system for three different electron number states. While the *g*-factor is almost isotropic for one of the three states, it is apparently anisotropic for the others (Fig.4), indicating that one charge state has a symmetric *s*-like orbital whereas the other states have an asymmetric *p*-like orbital. Due to the asymmetric coupling of the QD to the source and drain electrodes for the device studied and from SEM measurement of the dot geometry, the confinement potential is assumed to be like a half of pyramid rather than a two-dimensional harmonic type. Since the *g*-factor reflects the confinement anisotropy, such an exotic potential profile may tilt the *g*-factor principle axis from the growth direction. In addition we succeeded in electrically tuning the *g*-factor anisotropy via the confinement potential modulation with sidegate voltage [10].

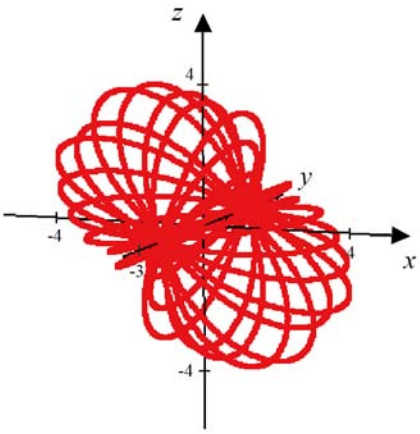

Figure 4 Three-dimensional *g*-factor anisotropy.

Microwave Application

FINALLY, we investigated MW efficiency on single QDs with application of the SOI to EDSR and *g*-TMR in mind. Note that to realize EDSR or *g*-TMR for operating spin qubits MW induced a.c. electric field has to be converted to a local a.c. magnetic field to the QD. The qubit operation speed is proportional to the strength of the a.c. electric field. A Coulomb peak observed with a small bias voltage was modified to suffer from a pumped current on application of MW to the sidegate. By analyzing the pump current in detail we found that the applied MW power was large enough to realize robust spin manipulation. Concerning the MW efficiency on the QD, no significant difference was observed for both samples with and without a *n*-doped layer. Therefore we consider that the MW power decays on the QD not due to the capacitively coupling to the backgate but probably due to the piezoelectric effect in GaAs substrate.

Conclusion

IN this thesis, I studied the anisotropic SOI and *g*-factor in single InAs SAQDs by measuring electron transport through the QDs. The genuine Rashba SOI was discriminated using the selection rule for the first time in QD systems, and quenching of the SOI energy in a particular magnetic field direction was discovered in this thesis. The measurements of three-dimensional anisotropy of *g*-factor and its electrical tunability were realized for the first time in InAs QDs. While the SOI anisotropy depends on the angle between the external magnetic field and the SOI induced effective magnetic field, the *g*-factor anisotropy depends on the confinement structure as well as the symmetry of wavefunctions, hence there was no strong relation in the anisotropy observed between the SOI and *g*-factor in QD systems. This is totally different from the case for bulk systems. MW efficiency was also firstly evaluated to be sufficient for spin manipulation in InAs SAQD systems. Combined with the MW excitation, the electric and magnetic tunability of the SOI and *g*-factor demonstrated in this thesis can pave the way to the electron spin manipulation towards spintronics and spin-based quantum information in the InAs SAQD systems.

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