論文の内容の要旨

論文題目　Sidegate control of superconducting transport and spin-orbit interaction in InAs self-assembled quantum dots

（サイドゲートを用いた自己形成InAs量子ドットにおける超伝導輸送とスピン軌道相互作用の制御）

.

氏　名　金井　康

（本文）

Recent developments in nano-device fabrication of carbon nanotubes, semiconductor nanowires and self-assembled quantum dots (QDs) have enabled various kinds of hybrid devices such as superconductor/semiconductor and ferromagnet/semiconductor nanostructures. In particular superconductor/semiconductor QD junctions have offered research platforms for the study of proximity effect, Andreev reflections and more recently interplay between Kondo effect and superconductivity. Among such hybrid devices uncapped InAs self-assembled quantum dots (SAQDs) allow us to electrically tune the important parameters of the dots including confinement potential and tunnel coupling using a gating technique. These parameters can influence various spin effects of many-body correlation, interplay between Kondo effect and superconductivity and spin-orbit interaction, which are the main topics in this thesis.

Spin-orbit interaction (SOI), which is known as a relativistic effect, provides many intriguing effects of spin-related physics and also recently topological phenomena in semiconductors. Because the ability of SOI for the spin-based quantum processing has been demonstrated using QDs, it would be indispensable to elucidate the physical insight of SOI as well as Landé *g*-factor in QD systems with strong SOI and large *g*-factor to develop the novel spin-based qubits and to contribute to the quantum information processing. Because InAs has large SOI and *g*-factor compared with GaAs, InAs SAQDs are interesting.

QDJJs are useful tools for the study of the competition and interplay between the spin-1/2 Kondo effect and superconductivity. When the QD is occupied by an unpaired odd electron number the unpaired electron spin hinders the tunneling of Cooper pairs and suppresses the proximity effect. Under these conditions the supercurrent may still flow through a fourth order cotunnelling process which results in a reversal of the spin order of the Cooper pair and a π superconducting phase shift for the junction (resulting in a π-junction). This effect has been experimentally confirmed in measurements of QD SQUID devices. However when QD-lead coupling is strong such that Kondo temperature (T_K) is high compared with the superconducting gap energy (Δ), the QDJJ theoretically becomes a 0-junction due to the Kondo screening of the unpaired spin in the QD. Under these conditions the system ground state undergoes a Quantum phase transition between a ‘magnetic’ doublet state (π-junction) to a singlet state (0-junction) at a critical ratio of T_K to Δ. Although this 0-π phase transition has been experimentally deduced from the non-dissipative supercurrent behaviors, the phase in the Kondo regime has not been directly measured. Also superconducting transport in the two orbital states degenerate system in the QDJJs is attracting but has not been studied in detail experimentally.

For application as a spin qubit the advantages of the InAs system lies in its strong SOI, which results in efficient coupling of the spin state to local electrical gates. This allows fast spin manipulation at rates which exceed those observed in more conventional GaAs based spin qubits. For application it is of interest to control the strength of the SOI as this is also an important mechanism for spin relaxation. One method of achieving such control is the fine manipulation of the confinement potential of the QD device. Another proposal for all electrical spin manipulation requires a gate tunable Landé g-tensor which may also be achieved by controlling the confinement with local gates.

In this thesis we fabricate QDJJs utilizing the InAs SAQDs coupled with superconducting leads and gated by both global 'back' gates and local sidegates. In the first half of this thesis we discuss the superconducting transport which interplays with the Kondo effect. We focus on the odd number electron QD with the spin-1/2 Kondo regime and in regions with two orbital states degenerate to generate the spin-1 Kondo. Here we use the sidegate to tune in-situ the Kondo temperature and the state degeneracy. In the last half we discuss the control of SOI and g-tensor in the InAs QD using sidegates towards spin manipulations in QDs.

First to measure the superconducting junction phase in the Kondo regime with large T_K, we fabricate QD SQUIDs (Fig. 1(a)). Devices are characterized in the normal state by applying a magnetic field B which exceeds the critical magnetic field of superconductivity of the aluminum leads. We confirm that QDs in each junction exist and in one QD (henceforth QD2) we detect Kondo effect with T_K = 4.9 K > Δ/k_B in an odd electron region. In our study we probed the transport in this junction using the 'probe' junction (QD1) in the other arm of the SQUID ring. In the superconducting state ($B < B_c$), we detect the zero-bias conductance oscillations as a function of B which indicate superconducting interference, shown in Fig. 1(b). The observed periodicity of the oscillation well matches to the value evaluated from the ring area of the SQUID. In Fig. 1(b) we compare the phase of the oscillations between an odd region and an even region in QD1, and find that the oscillation is shifted by π in the odd region indicating the QDJJ is a π-junction. On the other hand comparing with an even region and a Kondo regime in QD2, the oscillation is not shifted indicating that the QDJJ in the Kondo regime remains a 0-junction. This is the first experimental demonstration of 0-junction in the Kondo regimes.

Next, to realize the experimentally-tunable Singlet-Triplet degeneracy we use uncapped InAs SAQD JJs with a sidegate, shown in Fig. 2(a). In this device it is possible to control the orbital degeneracy by the sidegate altering the lateral confinement potential of the QD. By observing the normal state transport (B = 250 mT) we detect the zero-bias conductance anomaly in a region with an even number of electrons. The temperature dependence of the zero-bias anomaly in this regime indicates Singlet-Triplet (ST) Kondo effect. The existence of the ST Kondo effect means that two orbital states are almost in degeneracy. We could tune both the state degeneracy and

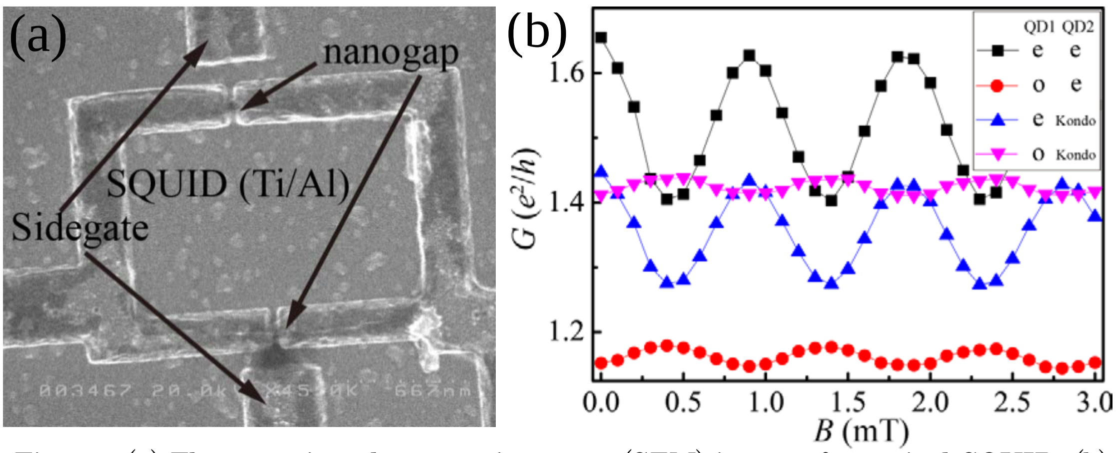
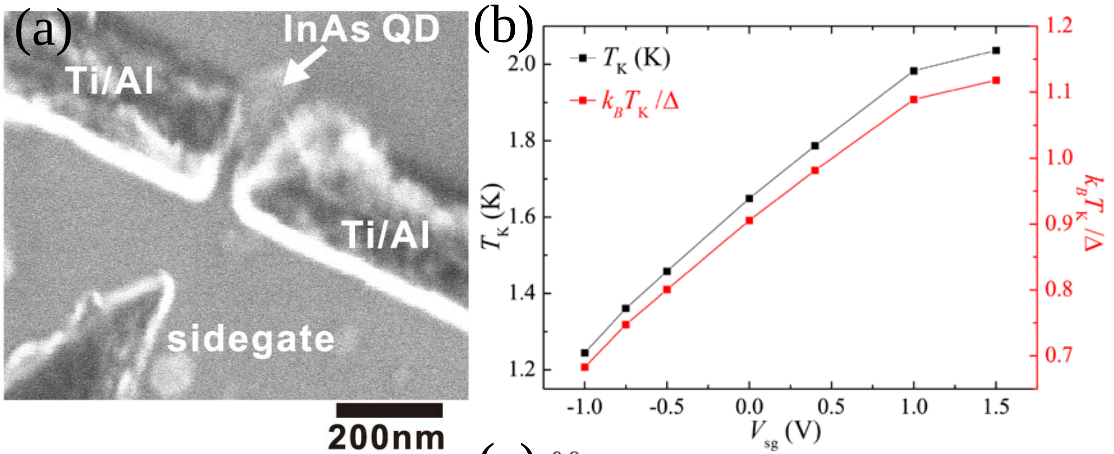


Figure1 (a) The scanning electron microscope (SEM) image of a typical SQUID. (b) Zero bias conductance as the function of perpendicular magnetic field at ■(both QDs have even occupation.), ●(QDI has odd and QD2 has even occupation), ▲(QD1 has even and QD2 has odd occupation in the Kondo regime) and ▼(QD1 and QD2 have odd occupation and QD2 is in the Kondo regime.). e, o and Kondo indicate even and odd number of electrons and Kondo regime($k_B T_K > \Delta$), respectively.

Kondo effect by changing the sidegate voltage V_{sg}. From the magnetic field evolutions of Coulomb peaks, we identified that the ground state is triplet for the negative V_{sg} while it is singlet at V_{sg} =2.0 V. For making V_{sg} negative (V_{sg} =-1.0 V) to positive (V_{sg} =1.5 V), the Kondo temperature T_K monotonically increases from 1.2 K to 2.0 K, and then suddenly drops and finally could not be measured in the singlet ground state at V_{sg} =2.0 V as shown in Fig. 3(b). This trend is well explained in terms of the ST Kondo effect. Non-dissipative supercurrent, which can be evaluated from the sharp zero-bias conductance peak shown in Fig. 3(c) in the superconducting state, is strongly affected by the ground state transition and ST Kondo effect. In the regions of singlet ground state and ST Kondo effect with large $k_B T_K/\Delta$, the supercurrent could be observed whereas in the region of ST Kondo effect with small $k_B T_K/\Delta$, where the triplet is a ground state, the supercurrent is strongly suppressed, inferring the π-junction. These results suggest that the 0-π phase transition is induced by the change of two states degeneracy and ST Kondo effect

In this paragraph we show the tuning of SOI without changing the electron charge state for the fast electron spin manipulation. Electrical tuning of SOI has not been demonstrated in the QD systems while it has been well studied in 1- and 2-dimensional systems. We use the same sample shown in Fig. 2 (a). To estimate the SOI energy Δ_{SOI} we have to detect in transport the excited states of the system. Here, we propose to use the Kondo effect in high B. At the degenerate point of two orbital states with opposite spins the Kondo effect occurs and the split zero-bias Kondo conductance anomaly appears, indicating the separation of ground and excited states. From the splitting we can evaluate Δ_{SOI} in QDs. Furthermore, as shown in Fig. 3(a) applying V_{sg} gives rise to a change in the splitting of the zero-bias Kondo anomaly. This suggests that Δ_{SOI} can be tuned using the sidegate, which is the first demonstration for any kinds of QD systems. We also measure the in-plane anisotropy of the split zero-bias Kondo anomaly. To ensure that split



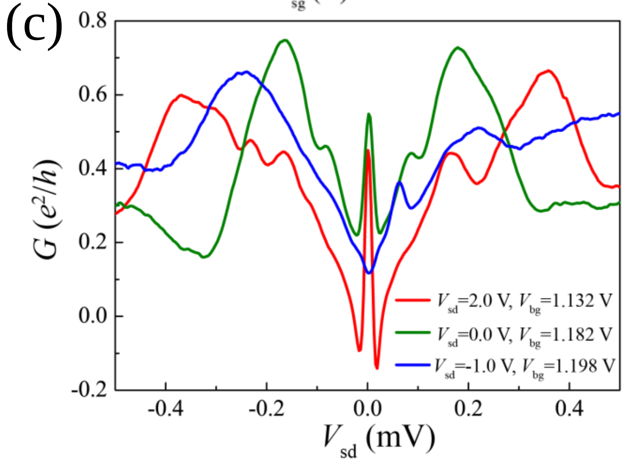


Figure2 (a) The SEM image of an uncapped InAs SAQD coupled with superconducting leads (Ti/Al) with a sidegate. (b) T_K and $k_B T_K/\Delta$ (red) as the function of V_{sg}. (c) The superconducting transport at Singlet (red, V_{sg} = 2.0 V and V_{bg} = 1.132 V), ST Kondo (Green, V_{sg} = 0.0 V and V_{bg} = 1.182 V) and Triplet states (Blue, V_{sg} = -1.0 V and V_{bg} = 1.198 V).

zero-bias Kondo anomaly comes from SOI, we measure the in-plane anisotropy of the split zero-bias Kondo anomaly shown in Fig. 3(b). Overall trend shows a cosine-like anisotropy and Δ_{SOI} almost quenches at an in-plane angle of $\theta = 30°$. These are consistent with our previous studies for InAs QDs and also with theoretical explanation. From this result we confirm that the SOI energy Δ_{SOI} can be measured by the splitting of Kondo zero-bias anomaly.

Finally we show the electrical tuning of the g-tensor by the sidegate in the device shown in Fig. 2(a). As initially demonstrated in parabolic quantum wells, it is possible to cause the electron spin resonance by electrically modulating g-tensor anisotropy, which is g-tensor modulation resonance (g-TMR). g-TMR has not been however realized in QD system. Figure 4(a) shows the in-plane angle dependence of the g-factor at V_{sg} = -2.0 V, -1.0 V and 0.9 V. This clearly shows that the g-tensor components are tuned by the sidegate. From this result we evaluate the spin precession vector Ω_0, which the electron spin processes about, to see a change in the g-tensor anisotropy due to the sidegate voltage. Figure 4(b) shows that the precession vector angle ϕ can be changed by the sidegate, indicating that the g-TMR is feasible in the InAs QDs. Taking the QD parameters into account the maximum Rabi frequency is expected to be 10 MHz .

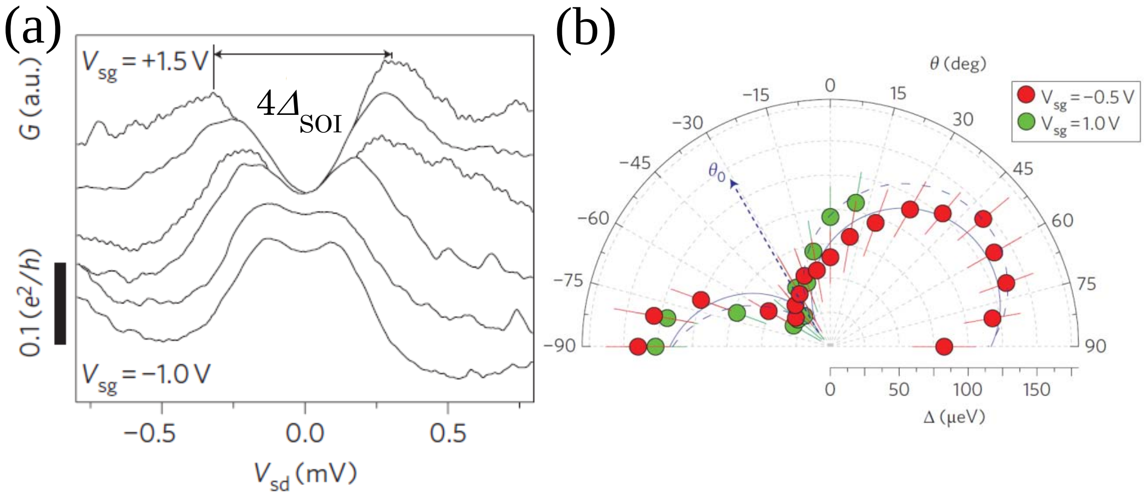


Figure3 (a) The differential conductance as the function of V_{sd} at the different V_{sg} from 1.5 V to -1.0 V in the center of the degenerate point. (b) The SOI energy as the function of in-plane B angle θ at ●(V_{sg} = 1.0 V) and ●(V_{sg} = -0.5 V).

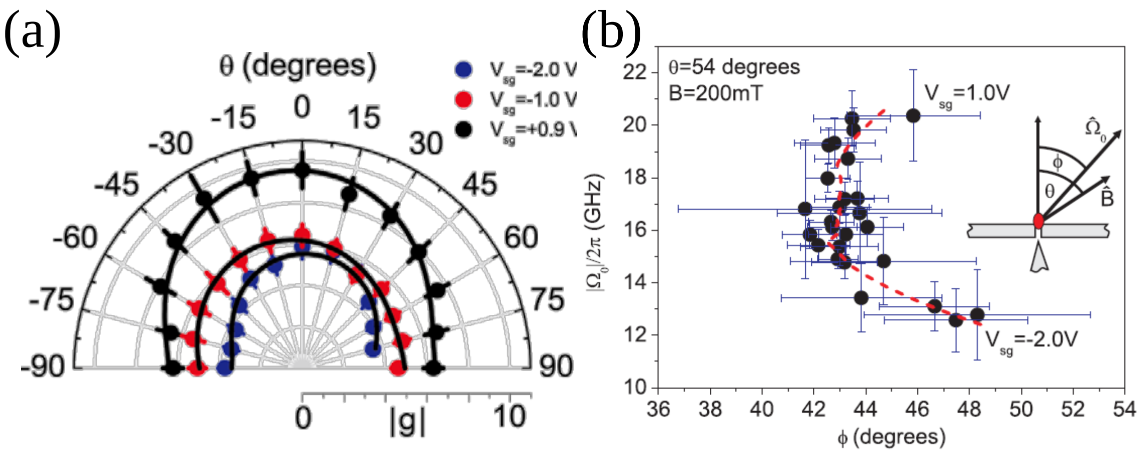


Figure4 (a) The in-plane angle dependence of the g-factor at ●(V_{sg} = -2.0 V), ●(V_{sg} = -1.0 V) and ●(V_{sg} = 0.9 V). (b) V_{sg} dependence of the Lamer frequency $\Omega_0/2\pi$ and the angle of the Ω_0 ϕ at $\theta = 54°$.