Strategic International Collaborative Research Program (SICORP)

Japan-Germany Joint Research Project on Nanoelectronics

JST Project End term Report

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Project term: 1/3/2010-31/3/2013

Project Description

1 The research description during the funding period

研究の背景とねらい

現代のエレクトロニクスは、半世紀にわたり、電子デバイスの小型化と集積化を進めることで性能の向上を図ってきた。しかし、デバイス原理としては、古典的なトランジスタから踏み出すことはなく、そのため、デバイス寸法が電子の波長に近づくにつれて発展の限界も見えてきた。やがて近いうちに集積度の飽和、そして計算処理に必要なエネルギー消費の不可避的な増大に対処できなくなることが予想されている。この問題に対応すべく、スピンエレクトロニクス、マルチフェロイクスといった、非電荷の自由度を扱うエレクトロニクスが研究され始めている。しかし、その動作概念は依然として古典的自由度に立脚しており、従ってエネルギー散逸が避けられない。一方で、完全に量子的な原理を利用する計算処理として、ここ数年、量子情報が注目されている。量子状態のコヒーレント操作によれば、究極の計算速度の上昇とエネルギー消費の削減が可能になるとされている。しかしながら、その実現には、数 10 年かかると予想されている。とくに、集積化の期待が掛かる固体系量子情報に関しては、量子力学の基本概念である、コヒーレンスとエンタングルメントの制御が当面の課題となっている。本共同研究では、新しい量子力学的自由度（幾何学位相、トポロジカル絶縁体、非局所所エンタングルメント）を利用する新しいパラダイムのエレクトロニクスとして、“トポロジカルエレクトロニクス”を提案する。この研究の狙いは、原理的にエネルギー散逸のないエレクトロニクスの構築と、固体系量子情報に技術革新をもたらすことにある。

着眼点とコンセプト

トポロジーは、本来、位相幾何学を意味するが、“トポロジカルエレクトロニクス”は、「幾何学的に量子性が保証される現象の電気的制御を原理とするエレクトロニクス」と定義する。具体的には、その典型的な量子現象である、(A)スピン軌道相互作用、(B)トポロジカル絶縁体、(C)非局所的なエンタングルメント生成（非局所エンタングラー）に注目する。(A)－(C)のいずれにおいても半導体低次元電子系の幾何学的量子性と相互作用が本質的な役割を担う。(A)は、相対論的効果が量子論的効果と組み合わさって固体中電子に現れるというものであり、(B)はやはり量子力学的波動関数の位相が持つ位相幾何学的性質がもたらす新しい量子状態で、両者とも従来エレクトロニクスでは利用されて来なかった画期的な体系である。 (C)は空間的に分離した量子もつれ電子対の独立な量子操作を可能にする概念で、量子もつれ操作による固体系量子情報技術に大きなブレークスルーをもたらすことが期待される、純粋に量子論的な現象である。

近年、低次元電子系のスピンに関する研究が急増しているが、上記、幾何学的量子性の電気的制御に関する研究は依然として少なく、その本質もまだ解き明かされていると言い難い。本共同研究では、日独のグループが協同して、“トポロジカルエレクトロニクス”を支える基本の物理を明らかにするとともに、量子制御のための技術開発を目指す。（A)スピン軌道相互作用に関しては、新田 G と永長 G、Weiss G を中心に重要なパラメータである、ベリー位相と Rashba、Dresselhaus 効果の強さを電圧制御することにより、原理的にエネルギー散逸のないスピントロニクス、高性能のスピン量子情報素子の実現を目指す。ここでの実験結果は、永長 G、Richter G による数値計算、スピン軌道相互作用理論と厳密に対比する。また、大野 G は新田 G と連携して、量子井戸構造を用いたベリー位相の制御、樽茶 G はスピン軌道相互作用の強い InAs ドットを用いた高速スピン共鳴の実現を目指す。（B)トポロジカル絶縁体の研究の中心は、永長 G と大野 G、Molenkamp G で、HgTe と InAs/GaSb のトポロジカル絶縁体と散逸のない伝導に注目する。トポロジカル絶縁体のエッジ状態ではスピンによって互いに反対向きに伝播するモードが対となっており、これらが散逸のないカレントを運ぶ。この非散逸性と、伝導チャンネルの非局所性故に、これらの物質群はスピンエレクトロニクスのデバイス応用に大変有望であると考えられているが、未だ、実験は皆無である。また、樽茶 G と永長 G がナノ細線/超伝導体接合で予測されているマヨラナフェルミオンの検証に取り組む。以上の項目では、理論と実験のグループがタイアップして実証と応用の研究を進める。（C)非局所エンタングラーに関しては、樽茶 G と Molenkamp G が

中心的役割を果たし、理論の永長 G、Trauzettel G の協力を得て、超伝導電極と InAs ドット、グラフェンの接合の交差アンドレーフ反射を利用した、クーパー対電子の分離と分離電子のエンタングルメント操作の実現を目指す。これにより固体量子情報系にエンタングルメント操作の概念を提供する。また、樽茶 G は、新たなテーマとして、表面弾性波を利用した非局所もつれの検証実験と 2 経路干渉計を用いた量子もつれ状態（近藤雲）の検出に取り組む。

将来展望
本共同研究の成果を発展させることにより、幾何学的量子性を中心概念とする新しいエレクトロニクスの世界が開けると期待される。

スピン軌道相互作用に関する研究に関連して、スピンコヒーレンスとベリー位相の電場操作を基本原理とする、超低消費エネルギーのエレクトロニクス、量子計算の構築が期待される

トポロジカル絶縁体に関しては、まず実証実験からスタートするが、最終的には、散逸のない量子スピンホールエッジチャネル伝導と Rashba スピン軌道相互作用による電子スピンの操作を組み合わせることにより、新しいスピン依存電子デバイス概念の誕生、トポロジカル絶縁体の幾何学的安定性を利用した新しい量子情報技術の誕生が期待できる。

非局所エンタングラーに関しては、その制御、検出技術を発展させることにより、現在進められている固体量子情報技術の研究進捗を著しく加速させること、また、量子もつれ操作やテレポーテーションを原理とする、固体系の新しい量子情報概念を構築することが期待できる。

2 The work done during the funding period

Our Japan-Germany joint research project is aimed at building a concept of “topological electronics” and applying it for new schemes of quantum electronics and quantum information technology. In this project, we particularly focus on such representative quantum phenomena in low-dimensional electronic systems. The effort is divided into three pillars: (A) spin-orbit interaction (SOI), (B) topological insulators (TIs), and (C) control of non-local entanglement. Each pillar’s efforts are led by the relevant groups. Prof. Nitta, Prof. Weiss and Prof. Ganichev focused on pillar (A) in close collaboration to characterize and control the spin dynamics in low-dimensions and in new materials with strong SOI. The experimental activity has been complemented by theory and numerical simulations of Prof. Richter. Prof. Tarucha and Prof. Nagaosa have worked particularly on SOI mediated quantum control of electron spin in quantum dots. Prof. Ohno has used an optical technique to probe SOI induced electron spin relaxation and dynamic coupling to nuclear spin. Prof. Nagaosa, Prof. Tarucha, Prof. Molenkamp and Prof. Trauzettel work on extensively on pillar (B) in three- to one-dimensional TIs including HgTe and InSb nanowires to explore topologically non-trivial phenomena including Majorana fermions. Prof. Tarucha and Prof. Nagaosa directed pillar (C) to probe and manipulate the split electron pairs in solid state systems.

The Japan-Germany collaboration has led to quite a few significant results already and many of these seem promising to extend towards new physics in the second funding period. Electrical control of persistent spin helix is a major realization of pillar (A). This technique will be utilized to explore spin devices which are robust against scattering. Collaborative research on Majorana fermion has been well promoted in pillar (B) and finally predicted that there appears a robust Majorana state at the end state of a quantum wire placed on an anisotropic superconductor. This collaboration work will be advanced in further applications to topological quantum computing. New systems to manipulate non-local entanglement have been proposed by Japan groups in pillar (C). The concept and technology are now linked to those in pillars (A) and (B) and therefore they will be further advanced through collaboration with the groups in (A) and (B) to develop a new scheme of entanglement-based quantum information.

2.1 Pillar A: Spin-Orbit Interactions

Electrical control of geometrically protected quantum phenomena is a key milestone for topological electronics. Spin-orbit interaction (SOI) plays an important role in realizing a topological insulator Berry phase and persistent spin helix (PSH), which are robust against spin independent scatterings. In the first funding period, gate control and detection of PSH was demonstrated in a 2DEG InGaAs/InAlAs QW with strong SOI as a result of collaboration between the Weiss/Ganichev, Nitta, and Richter-Gs. Weiss- and Richter-Gs applied the local tuning of the Zeeman splitting to realize a new spin-transistor concept based on Landau-Zener transitions between spin-split bands. Nitta-G performed an Aharonov-Casher spin-interference experiment with top gated InGaAs/InAlAs mesoscopic rings. The quantitatively evaluated geometric phases of the spin were in good agreement with theoretical prediction by the Richter-G, demonstrating a precise control of the spin. For quantum information technologies, it is also important to manipulate and detect nuclear spins. The Ohno-G investigated the effects of quadrupole interaction on the NMR spectra in n-doped GaAs/AlGaAs (110) QWs by the optical time-resolved Faraday rotation technique. Nagaosa-G theoretically applied the time-dependent SOI to the spin pumping and also to the control of qubits in the double quantum dot. A novel concept of spin-orbit echo was proposed by the Nagaosa-G. The SOI in semiconductor nanostructures strongly depends on various device parameters such as dimensionality, confining potential, and materials. In InAs QDs, Tarucha-G observed angle dependence of the SOI energy due to the Rashba SOI and demonstrated that the SOI strength can be electrically tuned while maintaining the charge state.
The research outcome through the first funding period will be applied to quantum information technologies.

2.1.1 A1: Two- and one-dimensional electron gas systems

Persistent spin helix (PSH) based on spin-orbit interaction (SOI) requires that the Rashba SOI parameter α equals the Dresselhaus SOI parameter β. The PSH state is robust against all forms of spin-independent scattering. Within the project Nitta-, Weiss/Ganichev- and Richter gate showed control and detection of the PSH in a two-dimensional electron gas (2DEG) consisting of a InGaAs/InAlAs quantum wells (QWs) with strong SOI, and this including terms cubic in momentum [A1].
Another type of spin-helix with U(1) symmetry was realized by combining a 2DEG with exchange enhanced giant spin splitting (in CdMnTe QWs) with a spatially periodic magnetic stray field. This resulted in an artificial spin helix in which – in the presence of a homogeneous magnetic field – the giant Zeeman splitting E_Z varies along the spin-superlattice. The local tuning of the Zeeman splitting allows for the realizing of a new spin-transistor concept which is based on Landau-Zener transitions between spin-split bands [A2]. This result was published in Science in a collaborative effort between Weiss- and Richter-Gs.
The geometric (Berry) phase of the electron spin, defined by the solid angle on the Bloch sphere, is a promising candidate for robust spin control. The Nitta group performed an Aharonov-Casher spin-interference experiment with top gated InGaAs/InAlAs mesoscopic rings having five different radii. They quantitatively evaluated the spins' geometric phase, and found it to be in good agreement with theoretical prediction by Richter's group, demonstrating that they have achieved precise spin control. The result constitutes the first convincing observation of the geometric phase of spin in solid state devices [A3], [A4].
Berry-phase effects for systems with complex band topologies were studied by Richter's group using the well-established Kohn-Luttinger 4-band model. As a main result they could demonstrate

both analytically and numerically that the coupling between heavy hole and light hole states gives rise to subtle additional Berry phases that affect coherent backscattering [A5].

Exchange enhanced photocurrents in 2DEG:Mn structures were investigated by Weiss and Ganichev-Gs. Asymmetric scattering upon excitation of low-dimensional charge carriers in the presence of magnetic impurities (here Mn) results in pure spin-currents. Such experiments have been carried out by Ganichev-G on magnetic 2DEGs in CdMnTe QWs and within this project on InAs:Mn 2DEGs and on AlSb/InAs/ZnMnTe QW (QW) [A6]. A further joint publication between Weiss and Nitta –Gs addresses magnetic anisotropies in nanoscale (Ga,Mn)As wires [A7], which are important as spin-injectors and detectors [A8].

Ganichev-G found that CdHgTe/HgTe/CdHgTe QWs (QW) with critical thickness (~6.6 nm) at which Dirac fermions prevail, exhibit a dc-photocurrent (photogalvanic effect) under low-power terahertz (THz) radiation, and which can be greatly enhanced by a perpendicular magnetic field. They observe, under terahertz laser irradiation, transitions between the ground and first Landau levels as well as between the first and second Landau levels. The low magnetic fields, at which the cyclotron resonance occurs, as well as the strong dependence of the position of the resonance on the electron density, indicate the Dirac character of the spectrum in these QWs. It has been shown that disorder plays an important role in the formation of the spectrum of two-dimensional Dirac fermions [A9].

In order to investigate spin-related physics in semiconductors, it has become important to manipulate and detect nuclear spins. In particular, optical and electrical manipulation and detection of nuclear magnetic resonance (NMR) have been extensively studied in GaAs-based nanostructures. In those experiments, quadrupole interaction plays a crucial role in the presence of an electric field gradient (EFG)[A10], which is induced by a strain, because all the constituent nuclei of GaAs have quadrupole moment. The quadrupole interaction is dependent not only on the EFG but also on the direction of the static magnetic field. Therefore, it is necessary to examine and understand its angular dependence to establish a comprehensive picture of the nuclear spin dynamics. In this program, Ohno-G investigated the effects of quadrupole interaction on the NMR spectra in an n-doped GaAs/AlGaAs (110) quantum well by the optical time-resolved Faraday rotation technique. They evaluated the EFG and the strain by analyzing the dependence of the NMR spectra on the direction of the static magnetic field. It was also shown, by studying the line widths of the NMR spectra, that nuclear spin coherence is influenced by inhomogeneity of the EFG[A11].

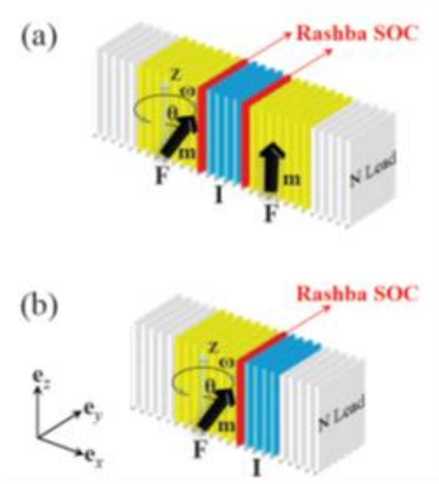

Figure A1: Configuration of quantum pumping with Rashba SOC

Nagaosa-G has studied theoretically the effects of the SOC on the quantum transport and magnetism. The time-dependent spin-orbit coupling (SOC) has been applied to the spin pumping [A12] and also to the control the qubits in the double quantum dot [A13]. By applying the voltages on the gates, one can control the Dzyaloshinsky-Moriya SOC acting on the two spins on the double quantum dot. By manipulating the time-dependence of the SOC, one can achieve the spin rotations with the same and opposite directions of the two spins, and hence all the unitary operations. The discussion with Tarucha-G was essential to achieve this work.

The theoretical framework to treat the quantum pumping has been developed in terms of the Keldysh formalism including the relativistic spin-orbit interaction, and has been applied to the magnetic tunnel junctions (MTJ) with Rashba interfacial spin-orbit coupling (SOC) and the bulk

extrinsic SOC [A14]. This formalism can treat the non-equilibrium situation with finite voltage. The situations considered are indicated in Fig. A1, where the Rashba SOC occurs at the interface between the ferromagnet (F) and the insulator. Various unique properties due to the SOC have been clarified.
This study has been also extended to replace the insulator by topological insulator (TI). In this case the surface Dirac fermion appearing at the interface plays the crucial role for the charge pumping. When the Fermi energy is within or near the gap opening by the exchange coupling, the charge and spin pumping is tremendously enhanced since the gap is modulated by the precession of the magnetization. Spin transfer torque in the situation of Fig. A1(b) replacing I by TI, and the charge current being flowing through the junctions has been also studied. The torque T acting on the ferromagnetic moment m is found to have a useful property compared with the Rashba SOC case and F/I/F MJ case since it remains finite in most of the situations.
Nagaosa-G studied the fundamental issue, i.e., the (non)conservation of spin, which is due to the elastic scattering by disorder in the presence of the spin-orbit interaction. They express the SOC in terms of the non-Abelian gauge field, which leads to the deformation quantization and twisted conservation law. This twisted spin preserves the information of spin because it is an adiabatic invariant with respect to change in the SOC. As a consequence, spin-orbit echo, is predicted, i.e., the spin is recovered when the spin-orbit interaction is reduced adiabatically even after spin relaxation due to disorder scatterings has occurred [A15]. They are now communicating with Richter-G on the numerical simulation of this spin-echo phenomena sending Dr. Sugimoto to Germany. The close discussion with Nitta-G on the Rashba-Dresselhaus SOC was essential to achieve this work.
In order to study the dynamical magneto-electric effect, Nagaosa-G have studied the electrons in the two atoms with multi-orbitals [A16]. The main question here is "What is the most basic mechanism of the dynamical magneto-electric coupling without the SOC ?". They employ the perturbation theory in the transfer of electrons t, and reexamine the derivation of the super-exchange interaction. They have derived the effective action of the spin system, and have found that the electric field *E* is coupled to the internal electric field coming from the Berry phase. This enables the electric field manipulation of the spin textures in insulating systems. Several candidate materials (La,Sr)MnO_3, $BiMnO_3$, La_2NiMnO_6 etc.) are proposed to show this coupling.

2.1.2 A2: Zero-dimensional electron system

Self-assembled uncapped InAs quantum dots (QDs) are relatively large and has a doom-like or pyramid-like shape. Electrons confined to the dots have wave functions strongly depending on the electron number and orbital type. So does the SOI. Tarucha-G developed two techniques to evaluate the SOI energy and Landé g-factor both of which are essential parameters to characterize SOI and control them both magnetically and electrically.
Tarucha-G used an excitation spectroscopy technique to derive the SOI energy in the InAs QDs with angle of in-plane magnetic field angle (θ) as a parameter. They have observed |cos(θ)| dependence of the SOI energy, and assigned it to Rashba effect [A18]. This is the first direct evidence of Rashba effect as given by ($\boldsymbol{E} \times \boldsymbol{p}$)·$\boldsymbol{\sigma}$ in QDs with angular dependence of $\boldsymbol{B}_{\mathrm{ext}}$ (//$\boldsymbol{\sigma}$) and since then the same technique has been widely used to verify and control the Rashba type SOI in QDs and nanowires.
A strong spin-orbit interaction allows fast spin manipulation as recently demonstrated in InAs nanowire QDs. Tarucha-G demonstrated that the SOI strength can be electrically tuned while maintaining the charge state of single InAs QDs [A19].

In experiments single InAs QDs with two different gates to globally (back gate) and locally (side gate) tune the electrostatic potential of the dot were fabricated. Use of these gates enables to tune the electron wave function confined to the dot while maintaining the QD charge state. The SOI induced hybridization of twofold degenerate states with different orbital and opposite spin is observed as a peak splitting (=4Δ where Δ is the SOI energy) of the high magnetic field Kondo effect (Fig. A3). The magnitude of the Kondo splitting or SOI energy is varied as a function of side gate voltage. This is the first demonstration of electrical control of SOI in QDs without changing the charge state. The tunability of the spin-orbit hybridization significantly depends on the QD charge state because it is strongly linked to the orbit state whose wave function can be shifted by the local gating. This result offers ingredients for SOI driven spin qubits.

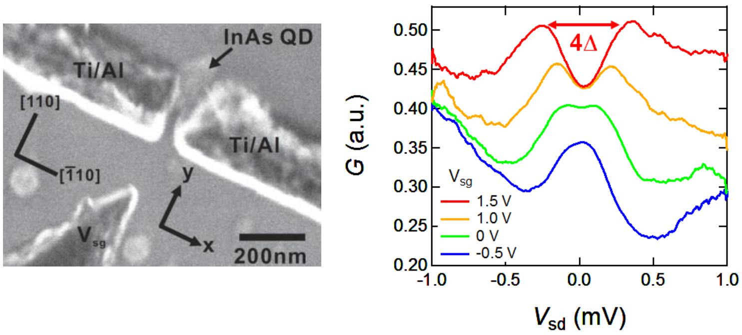

Fig.A3: (left) SEM image of the InAs QD device. (right) Splitting of Kondo zero-bias anomalies, indicating the electrical tuning of spin-orbit interaction energy Δ.

The g-tensor modulation resonance (g-TMR) is potentially suitable for scalable quantum computing. This technique, however, has not been realized in QDs. Tarucha-G used the InAs QDs to electrically tune the anisotropic g-tensor in single uncapped self-assembled and InAs QDs showed the feasibility of g-TMR in the QDs. The g-factor was evaluated from measurement of the spin-half Kondo splitting associated with Zeeman energy in the vicinity of zero magnetic field. The anisotropy of the g-factor was characterized by changing the angle of magnetic field. In the same way as described above the g-factor was significantly changed by more than 50 % by side gating [A20]. This is the largest change in any QD systems reported to date. From the obtained result Rabi frequency of 2 MHz in the g-TMR was estimated [A20,A21].

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2.2 Pillar B: Topological Insulators

Over the past years topological insulators (TI) have become a subject of massive research interest. The search for new TI materials was strongly inspired by the experimental success in the demonstration of the quantum spin Hall effect in a two-dimensional (2D) TI [B1] and the subsequent observation of Dirac-like surface states in many bismuth (Bi) based compounds [B2,B3]. While more and more TI materials have been identified, the number of materials where the topologically protected surface states are accessible in transport experiments is very limited. The reason for this is mainly the crystalline quality of the samples available. Due to defect doping most materials are highly bulk-conducting and even with extreme gating techniques obtaining an insulating bulk remains elusive.
Up to today, the only TI material where Dirac-like surface states are readily accessible in transport measurements is mercury-telluride (HgTe). After the original discovery of the 2D TI state in HgTe quantum well (QW) structure, which is characterized by two counter-propagating one-dimensional (1D) helical edge channels, recently the 2D Dirac-surface states have been identified in thick three-dimensional (3D) layers of strained HgTe [B4]. Since these HgTe layers are grown by molecular beam epitaxy (MBE), samples of high crystalline quality are available and therefore this material offers the unique opportunity to investigate 2D and 3D topological properties equally in transport experiments.

2.2.1 B1: Dirac Band structures

One of the underlying themes in this part of the project is an investigation of the similarities and differences between the Dirac band structure as encountered in Tis and the zero gap Dirac structure in graphene. On the TI side, Molenkamp-G succeeded in growing HgTe QWs at the critical thickness (6.3 nm) separating topologically trivial and non-trivial band structure [B5]. At this thickness, the QW exhibits a zero gap band structure, with the carriers residing in a single (spin degenerate) Dirac cone. This is the simplest possible realization of a Dirac system in to-dimensions, and basically establishes the relation between HgTe and graphene. This research also allowed Molenkamp-G to investigate the backscattering of Dirac fermions in the presence of a Dirac mass [B6]; currently the quantum interference behavior in these structures is under investigation. On the graphene side, the Molenkamp-G has fabricated narrow graphene wires and multi-terminal structures, and studied the edge channel transport in these devices [B7], [B8]. Moreover, the Molenkamp-G has successfully fabricated ferromagnetic contacts on graphene, and is now in a position to investigate the spin-polarized edge transport advocated by the Richter-G. Additionally, the team also has superconducting contacts on graphene working, allowing them to interface with Tarucha-G's effort towards a spin-entangler in part C of this project.

2.2.2 B2: Two dimensional topological insulators

At present, a major challenge for our 2D HgTe-based TIs is to make the topologically protect states accessible in advanced transport experiments. So far, quantized transport can be observed only in devices of a few micrometers. The main reason for this is related to potential fluctuations in the narrow gap of HgTe, which is expected to introduce random metallic conducting parts within the regime of the 1D edge channels. Nonetheless, the Molenkamp-G was able to demonstrate the quantized conductance [B1] and the non-locality [B9] of the transport through the helical edge channels. More recently, it was also shown by the Molenkamp-G (within the framework of the present consortium) that the edge states of a 2D TI system exhibit the predicted distinct spin-polarization [B10]. In this experiment the spin-polarizing properties of the intrinsic spin Hall effect in n- or p-conducting HgTe QWs has been used to inject in or detect the spin polarized carriers of helical edge states. A schematic picture of the device is illustrated in Fig. B1. The possibilities of spin manipulation in spin-orbit coupled systems is explored experimentally in Part-A by Nitta-G and

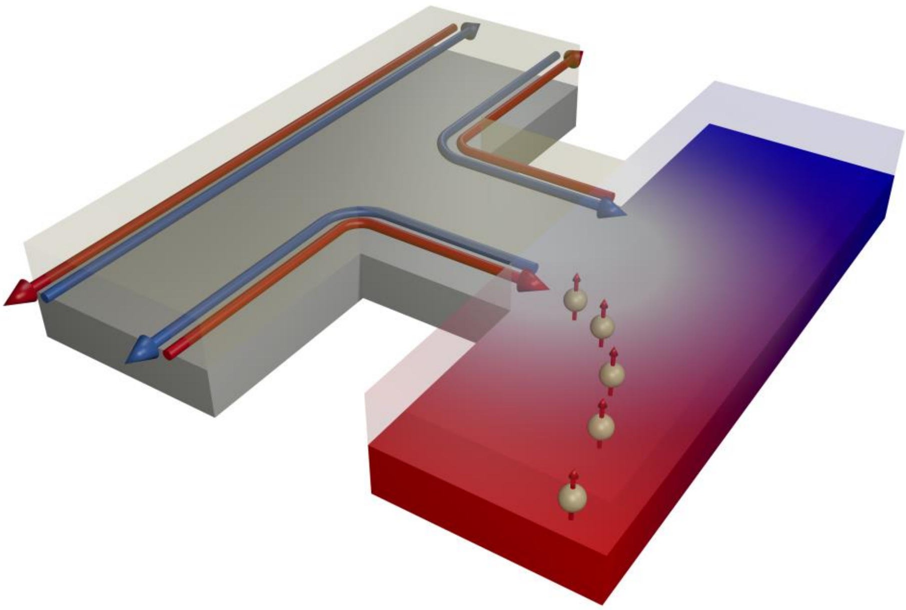

Fig. B1: Schematic illustration of a four-terminal device used for injection and detection of helical edge state, as performed in Ref. [B10]. The edge states are indicated by red and blue arrows symbolizing the transport direction and the spin polarization. The spin polarized carriers in the metallic part are symbolized by bullets. The created or applied voltage is indicated by a blue (positively charged) and red (negatively charge) areas. (Drawing by Luis Maier).

Weiss-G. In addition to the work which is part of that pillar, Weiss-G extended the work on Rashba- and Dresselhaus effect to HgTe QW wire structures. These investigations will be important for the ongoing work on TI-SHE hybrid structures.

Another important question is whether these helical states can be used directly for the development of novel electronic devices where the interaction between edge channels or the electron-electron interactions of parallel channel lead to controllable and well distinguishable electronic states. This work connects to theoretical concepts for edge channel transport developed by Nagaosa-G and Trauzettel-G. While Molenkamp-G has succeeded in fabricating structures that are small enough to observe the above interaction effects, we have also discovered that the heat load seen by the samples during fabrication has thoroughly reduced the carrier mobility. Molenkamp-G is currently developing zero heat-load lithography to avoid these problems.

2.2.3 B3: Three-dimensional topological insulators

3D TI exhibit 2D surface states, whose energy dispersion is characterized by a single Dirac cone on all surfaces. Thus transport of 3D TI surface states is comparable with that of graphene. Graphene however has 4 Dirac cones (due to spin and valley degeneracy), while a TI surface only has a single one. This leads to distinct differences and electromagnetic and quantum mechanical behavior. One example is the occurrence of a specific electromagnetic response (“axion electrodynamics [B8]) and another is the proximity effect with superconducting contacts which is expected to give rise to p-wave superconductivity and Majorana bound states.

This variety of exotic transport properties of Dirac fermions guides the experimental research in the field of 3D topological insulators. With the discovery of strained HgTe [B4] a new 3D TI has become available, which exhibits clean Dirac fermion transport physics without any complications from bulk doping. Strained HgTe layers can be grown with a very high crystal quality, so that Dirac surfaces dominate transport even in regimes where bulk transport is expected to be present. Additionally, Molenkamp-G has shown recently that proximity-induced superconductivity is observable in strained HgTe layer with niobium (Nb) contacts. This is a very promising development, and the group now plans to devote much of their effort to further investigate the exotic superconductivity occurring in these structures. The experiments will be supported by the theoretical work of Nagaosa-G and Trauzettel-G.

2.2.4 B4: Topological superconductivity and Majorana Fermions in nanowires

During the first funding period of this consortium, theorists realized [B12] that a similar topological superconductivity as discussed in section B3 can also be realized in 1-dimensional nanowires with a strong Rashba coupling. This finding resulted in a strong experimental activity, culminating a recent report by the Delft group [B13] of a zero bias anomaly in

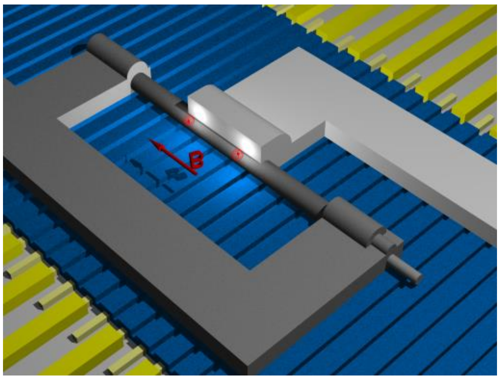

Fig. B2: Envisioned device layout of a device for the creation and detection of Majorana Fermions

superconducting InSb wires, that can be tentatively interpreted as an observation of Majorana fermions(MFs). Because of the large overlap of this type of research with the other activities in this consortium, we have decided to add this line of work to our coming work program.
Much of the work in the first funding period focused on the development of transparent superconducting contacts made of TiNb to the InSb/InAs wires. Recently, Tarucha-G was able to observe signatures of multiple Andreev reflection in InSb-QD-TiNb devices and induced superconductivity in TiNb-InSb-TiNb structures. Supercurrent characteristics in these devices can be tuned by means of local back-gates. Further, by applying a magnetic field, the supercurrent shows characteristic suppression and recovery which is interpreted in terms of the influence of the Zeeman effect.

2.2.5 B5: Topological insulator theory

During the first funding period, the contributions from the three theory groups within the research unit were innovative, diverse, and helpful for a better understanding of experimental measurements. The Nagaosa-G developed ideas on spin pumping by time-dependent spin-orbit coupling (SOC) which can be used as building block for spintronics devices [B14]. Furthermore, the members of the Nagaosa-G looked at various aspects of magneto-transport, such as magneto-transport in the presence of strong SOC, the dynamical magneto-electric effect, and magneto-transport of edge channels of topological insulators [B15]. Similarly, the research of the Richter-G was very much motivated by the physics of SOC, particularly the interplay of Rashba and Dresselhaus SOC. The members of the Richter-G carefully analyzed how the so-called persistent spin helix which appears at equal strength of linear Rashba and Dresselhaus SOC is affected by the cubic Dresselhaus term. These calculations agreed well with weak localization measurements performed in the Nitta group. Additionally, the Richter-G analyzed how a topological insulator constriction can work as a spin transistor in four-terminal geometry [B16] and the physics of Bloch-Zener transitions in topological insulators [B17]. Moreover, the Richter-G showed that the band topology of HgTe can be probed by weak localization and antilocalization measurements [B18]. In the Trauzettel-G, the main focus was on inelastic backscattering of the helical edge states at the boundary of a quantum spin Hall insulator, for instance, based on electron-phonon interaction [B19] or electron-electron interaction [B20]. Interestingly, it was found that the helical edge states are more robust against inelastic backscattering as initially believed [B19]. The members of the Trauzettel-G also showed that the helical edge states at the two opposite edges of the quantum spin Hall sample form an ideal system to analyze spin properties of interacting one-dimensional systems and predicted a new kind of charge-spin duality [B21].

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2.3 Pillar C: Non-local entangler

Non-locality of entanglement can expand the ability of quantum information technology. However, it is difficult to make it in solid state systems because of strong interaction with environment. In this program we have challenged to develop technologies for generating, detecting and manipulating non-local entangled electrons. In the first period Tarucha-G proposed several new systems for generating non-local entangled electrons: QD Josephson junctions (JJs), “moving QD” and two-path interferometer, and Nagaosa-G newly proposed a candidate using Majorana fermion in topological insulator. The research outcome through the first funding period should be upgraded for applications to quantum information by sharing the expertise with the groups in progam (A) and (B).
Cooper pair in s-wave superconductor is an ideal spin singlet state or entangled electron state. The paired electrons can split into two QDs due to the Coulomb blockade effect if the two dots are parallel coupled and contacted to the superconductor. Just before this project started the Cooper pair splitting was reported for a carbon nanotube and an InAs nanowire in a Y-junction with two independent normal leads coupled to a superconductor through two QDs. The charge measurement through the normal leads however does not provide evidence of the non-local entanglement. In addition the device setup cannot be used to handle the non-local entanglement. On the other hand, the parallel double QD (DQD) JJs and “moving QD” driven by a surface acoustic wave (SAW) Tarucha-G proposed to sort out this problem. Self-assembled uncapped InAs QDs used for making DQD JJs are more suitable than nanotubes and nanowires, because two closely coupled QDs can be grown epitaxially. In addition, “moving QD” provides a new concept of non-local entangler applicable to quantum information because the two-electron ground state is a singlet pair state and because the paired electrons can be split into two paths and manipulated based on the concept of qubits.
Theoretically, the possible realization of Majorana fermions has been studied in terms of the topological insulator, Rashba spin-orbit interaction, and unconventional superconductors. The physical phenomena associated with these Majorana fermions were also explored.

2.3.1 C1: InAs double QD JJs

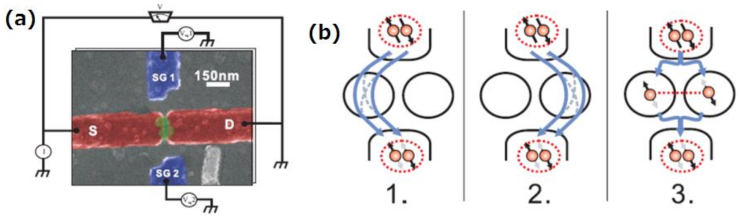

Fig. C1: (a) Photo of DQD JJ. (b) Local and non-local tunneling processes.

Before starting the project Tarucha-G had developed a technique of making single InAs QDs contacted to Al superconductors to observe supercurrent and Andreev reflection. They first used these devices to clarify the physics of spin entanglement specific to QD JJs. Cooper pair states and Kondo singlet states are typical entangled states. Strength and symmetry of dot-lead tunnel couplings and interaction effects are both important parameters to control the super-Kondo interplay. They newly developed single InAs QDs having a local gate (side gate) and a global gate (back gate) and used the side gate to change “in-situ” the strength of dot-lead coupling as well as the QD orbital degeneracy to control the super-Kondo interplay. Then the quantum phase transition between the magnetic doublet and Kondo ground states could be characterized in an odd electron occupation region and singlet-triplet degeneracy region. This result is a great step toward realization of non-local entangler, because the efficient Cooper pair splitting and the detection of the non-local entanglement requires fine tuning of both QD and interface parameters.

Tarucha-G extended the single QD JJs techniques to fabricate DQD JJs having two InAs QDs in very close proximity (~10 nm separation) contacted to two Ti/Al electrodes (Fig. C1). In this system the supercurrent may flow by splitting the Cooper pair into two quasi-particles which tunnel through the system and recombine in a 4th-order cotunnelling event. The non-dissipative supercurrent is only comprised of processes which maintain the coherence of the Cooper pair and so may provide conclusive proof of non-local processes. Resonance of the two dots were independently turned ON and OFF with side gating to detect influence of the non-local processes. In the normal state when both QDs are ON resonance, the conductance was reduced by ~30% from the sum of the OFF resonance conductances indicating that the proximity of the QDs results in selective transport through QD1 or QD2. In the superconducting state in contrast the switching current was enhanced when both QDs were ON resonance indicating the influence of the non-local processes [C1].

2.3.2 C2: Graphene JJs

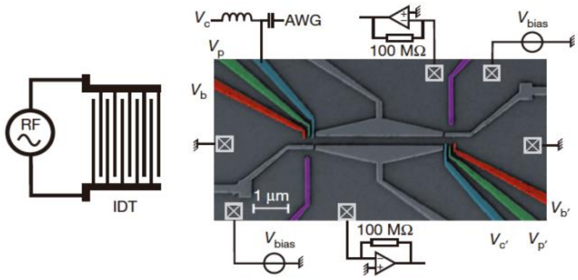

Fig. C3: Single electron transfer device with two QDs bridged by a 3 µm long 1D channel, two QPC charge sensors and inter digital transducer for generating SAWs.

Graphene is such a clean 2D sheet that Cooper pair electrons split into graphene ribbons may coherently travel over a long distance. The ingredients in such devices are good electrical graphene-super contact and high quality of graphene. Tarucha-G previously used Pd as an adhesive layer to make the good contacts but the transport through the graphene was typically diffusive. Therefore they first developed a technique to transfer single layer graphene flakes onto hexagonal Boron Nitride (h-BN) crystals. After annealing the sample, the mobility exceeded 30,000 cm2/Vs. However, we found that annealing usually breaks the electrical contact between graphene and superconductor contacts. So we are now developing a technique to deposit superconductor contacts without contaminating graphene in which graphene is sandwiched between two h-BN flakes but have not established it yet.

2.3.3 C3: Electron transfer with SAW device

"Moving QD" is formed by each period of SAW propagating through a gate-defined depleted quantum wire. The two-electron ground state in the moving QD is a singlet state, so non-local entanglement can be generated by splitting the two electrons. Tarucha-G first developed the SAW technique for transferring one or two electrons in each SAW period, and extended it to transfer just an electron between distant static QDs [C4]. A SAW burst to a QD holding two electrons to pick up one of them, transfer it over 3 µm and finally place it on the other QD. This operation could be performed with a high efficiency of 87 %. The electron transfer time is ≈1 nsec much shorter than the dephasing time.

2.3.4 C4: Two-path interferometer

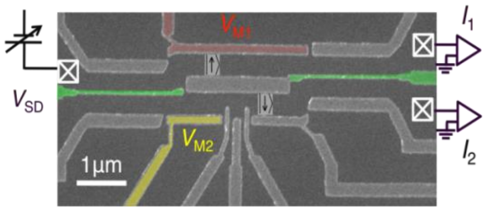

Fig. C4: Photo of the interferometer used for detecting the Kondo cloud.

In parallel to the SAW experiment Tarucha-G developed a singlet pair splitter or an electron beam splitter through which electrons transfer coherently. As one of the most robust ways to see the coherent transport, they proposed a two-path interferometer consisting of tunnel coupled wires and an Aharonov-Bohm ring [C5]. The electron transport through it provides a concept of a flying qubit whose |0> and |1> states are defined by the presence of propagating electron in either of the two paths. It was confirmed the coherent electron transport through the interferometer by measuring the output currents as a function of inter-wire tunnel coupling and phase difference between the two paths. Both inter-wire tunnel coupling and the phase difference were electrically tuned, but the phase difference was magnetically tuned as well.

2.3.5 C5: Theory of superconducting spintronics and non-local entangler

Nagaosa-G has studied the possibilities and physical properties of topological superconductors and associated Majorana fermions theoretically. The behavior of the chiral Majorana edge channel appearing in the superlattice of F/N/S (F:ferromagnet, N:normal metal with Rashba SOC, S: s-wave superconductor) has been studied especially near the topological phase transition to reveal the two different types [C6]. The possible helical superconducting state has been investigaed in the interacting double layer Rashba system. It is found that the attractive intralayer and repulsive inter-layer interactions leads to the helical superconductor and helical Majorana edge channels [C7]. A 2D model of chiral superconductors including the Kitaev model in 1D and p+ip chiral superconductor as the two limiting cases has been studied. 9 types of phases are obtained classified by the strong and weak topological invariants. The Majorana bound states have been studied for the dislocation and vortex in this model [C8]. Thermal transport properties due to the surface Majorana fermion of the chiral topological supercondcutors/superfluids were studied, and the quantization of the response was predicted [C9]. Furthermore, Majorana bound states caused by the proximity effect of a quantum wire with an unconventional superconductor, and their application to the quantum entanglement have been explored theoretically [C10].

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3 Project participants

3.1 Japanese Team

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Naoto Nagaosa	Univeristy of Tokyo	Prof.	Condensed matter theory	Leading the theoretical activities
Junsaku, NItta	Tohoku University, Matrial Science	Porf.	Spintronics	Group Leader
Yuzo Ohno	University of Tsukuba	Prof.	Semiconductor Spintronics	Experimental study of spin-orbit interaction and nuclear

				spin dynamics

3.2 German Team

Name	Organization, Division	Title	Specialty	Role in Project
Laurens W. Molenkamp	Würzburg University, EP3	Prof.	TI, novel electronics phenomena, solid state physics	German Principal Investigator
Björn Trauzettel	Würzburg University, TP4	Prof.	Theory of TI, graphene, transport, novel devices	Reserach group leader
Dieter Weiss	Regensburg University	Prof.	Spintronics, Nanostructures, Solid state phsyics	Focus on transport experiments
Sergey Ganichev	Regensburg University	Prof.	Spin current, laser physics, Solid state physics	Focus on microwave, terahelz experiments
Klaus Richter	Regensburg University, Institute of Theoretical Physics	Porf.	Quantum transport, mesoscopic physics	Reserach group leader

4 Project Deliverables of Japanese side

4.1 Publications

The number of Japanese side publications in FY 2012

The number of coauthored publication in FY2012	3 publications
The number of Japanese publication in FY2012	22 publications

4.1.1 Coauthored Jointly by Japanese and German Teams

(1) J. Shiogai, D. Schuh, W. Wegscheider, M. Kohda, J. Nitta, and D. Weiss, "Magnitude and sign control of lithography-induced uniaxial anisotropy in ultra-thin (Ga,Mn)As wires", Appl. Phys. Lett. **98**, 083101 (2011).

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4.1.2 Authored by Japanese Team Only

Tarucha-G

(1) S. Takahashi, R. S. Deacon, K. Yoshida, A. Oiwa, S. Tarucha, K. Shibata, K. Hirakawa and Y. Tokura, „Anisotropy of the Spin-orbit interaction in a Single InAs Self-Assembled Quantum Dot", Solid State Physics **45**, 457 (2010).

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SICORP GERMANY NANOELECTRONICS FINAL SUMMARY

Project title : Topological Electronics
Coordinator of the Germany part of the project : Laurens W.Molenkamp, Professor, Physik EP3, Universitat Wurzburg, Experimentelle
Coordinator of the Japanese part of the project : Seigo Tarucha, Professor, Applied Physics, The Universty of Tokyo
Project period : 1 Jan 2010 – 31 March 2015

CONSOLIDATED PUBLIC SUMMARY IN ENGLISH

We explore the fundamental science of "Topological electronics" whose operating principle is electrical control of geometrically protected quantum phenomena with the aim of establishing a concept for dissipationless electronics and providing technical breakthroughs for solid state quantum information technology.

Method and models:
We explore the physics and technology of three fundamental concepts i.e., spin-orbit interaction, topological insulators, and non-local generation of entanglement which are the basis of geometrically protected quantum phenomena and may bring novel quantum technologies and breakthroughs in solid state quantum information.

Paragraph1
We develop novel methods of electrically controlling quantum mechanical effects arising from three fundamental concepts of (A) Spin-orbit interaction, (B) Topological insulators, and (C) Non-local generation of entanglement, which may bring a new paradigm of quantum electronics and quantum information technology. Our Japan-Germany team promotes this project in an integrated and complementary manner. Nitta-G, Weiss/Ganichev-G and Richter-G as the main players and in addition Ohno-G, Nagaosa-G and Tarucha-G study subject (A) in zero- to two-dimensional electron gases (2DEG). Nagaosa-G and Trauzettel-G theoretically and Tarucha-G and Molenkamp-G experimentally deal with transport properties of 2D and 3D topological insulators in (B). Tarucha-G with technological assistance of Molenkamp-G experimentally and Nagaosa-G in collaboration with Trauzettel-G theoretically develop novel techniques non-local operation of entanglement.

A. Spin-orbit interaction and spin control
Spin-orbit interaction (SOI) is indispensable for electrical manipulation of spins. On the contrary, the SOI gives rise to spin relaxation because the spin precession axis is randomized after scattering events. To utilize the spin degree of freedom as an information bit, both electrical manipulation and long spin coherence are necessary. In this program, we will pursue these four topics.
(1) Nitta-G will pursue gate controlled Berry's phase and its application for topological electronics. The detection of Berry phase effects from spin interference experiments will be tried by Nitta-G in collaboration with Regensburg University. The objective of this project is to make novel spintronics devices protected from scattering events by using the persistent spin helix (PSH) state and the Berry phase.

(2) Ohno-G will investigate the nuclear spin dynamics coupled with electrical spins via the hyperfine interaction. Furthermore, the spin dynamics of 2DEG in a gated modulation-doped GaAs/AlGaAs quantum well (QW) structure will be investigated to manifest the effective magnetic field induced by the spin-orbit interaction.
(3) Tarucha-G will try to make/control entangled electron pairs in quantum dots and bits based on electrically controlled SOI.
(4) Nagaosa-G will try to establish theoretical concept of electron control based on gauge field caused by SOI, and will explore new aspects of SOI such as quantum pump, giant Rashba effect, and spin structure in ferromagnets.

B. Topological insulators
We aim to demonstrate the usefulness of the Majorana fermions, which are the quantum state with protected coherence, and the dissipationless surface/edge current. Both subjects are rapidly attracting world-wide interests. For the former, Tarucha-G focuses on the experimental verification and perform experiments on the helical states in nanowires, the AC Josephson effect in 3D topological insulator HgTe Josephson junctions in collaboration with Molenkamp-G and also in nanowire Josephson junctions. For the latter Nagaosa-G theoretically studies the spin-orbit interaction, topological insulators (TIs), and topological superconductors (TSCs) from the viewpoint of gauge field, and explore the principles of electron manipulation based on it. New phenomena such as quantum pumping, giant Rashba effect, spin textures in magnets, electron fractionalization on the surface of TI, and also the theoretical design of TSCs and Majorana fermions are explored.

C. Nonlocal entangler
We aim to generate and detect "nonlocal quantum entanglement" in which multiple particles have quantum correlation irrespective of the distance between them. While various methods have been proposed to investigate the nonlocal entanglement, we take the following original methods: (1) Splitting Cooper pairs of s-wave superconductors utilizing the charging energy of quantum dots made of InAs or graphene, and detecting spin coherence after the splitting, (2) Splitting electron pairs of a spin singlet ground state in a quantum dot using surface acoustic waves (SAW) or two-path interferometers, and (3) Exploring novel phenomena originating from nonlocal entanglement of Majorana fermions and investigating emergence mechanism of topological superconductors and Majorana fermions.

Method and models:

paragraph2

We proposed and developed a number of new methods and technologies useful for electrical control of spins, topological particles, and non-locally entangled pairs. These are control and characterization of spin-orbit interaction using quantum interference, development of HgTe surface states and nanowires contacted to superconductors and derivation of the topological functions, and development of novel technologies for generating non-local quantum entanglement as typical examples.

A. Spin-orbit interaction and spin control
Nitta-G proposed a novel method to detect the ratio between α and β by utilizing wire structures and in-plane magnetic field in collaboration with Richter-G. α and β are the Rashba and Dresselhaus SOI parameters, respectively. They have realized the PSH state by using this proposed method and gate controlled Rashba SOI α [66]. Nitta-G has also investigated the gate

voltage dependence of AC spin interference with different radius of interference rings [62]. The group has tried to control the spin geometric phase by in-plane magnetic fields [64]. Theoretical support has been given by K. Richter group.

Ohno-G has employed nuclear electric resonance (NER) to manipulate nuclear spins with quadrupole moments and detect them by optical means [39]. The group has fabricated gate electrode on top of the sample and control the ratio of α/β and realize the PSH state by spatiotemporal Kerr rotation microscopy [50].

Tarucha-G has developed a novel method to control the confinement potential of InAs quantum dots through side gate electrodes [18,19,80] for the electrical manipulation of SOI and g-factor [5,6,17-19,47].

Nagaosa-G has employed the non-equilibrium Keldysh formalism, the first-principles band structure calculations, exact diagonalization of tight-binding Hamiltonians, numerical solutions of the Landau-Lifshitz-Gilbert (LLG) equation, and perturbative renormalization group method, depending on the problems of interest.

B. Topological insulators

Tarucha-G has fabricated high quality nanowires with strong spin-orbit interaction and their Josephson junctions, and constructed high frequency measurement systems in a dilution refrigerator to study the AC Jospehson effect. They have carried out high frequency response measurements in HgTe Josephson junctions fabricated by Molenkamp-G to obtain experimental verification of Majorana fermions [79].

Nagaosa-G has employed the exact diagonalization of tight-binding Hamiltonians to reveal the electronic structure of topological insulators with surfaces and interfaces.

C. Nonlocal entangler

Tarucha-G has developed a technology to transfer electrons in a single electron unit as a tool to split an electron pair in a quantum dot [84,92,94,95]. The group has also developed an original two-path interferometer [91,97,99] and has proposed a new scheme to generate and detect nonlocal entanglement combining the interferometer with the single electron transfer by SAW.

In addition Tarucha-G has developed the microfabrication technologies using a high-precision electron-beam lithography and have fabricated the devices and characterized the superconducting property (InAs quantum dot Josephson junctions [80,87,88,90], parallel double InAs dot Josephson junctions [101], superconductor-Y-shape double quantum dot junctions, etc.) for separating the electron pairs consisting of superconductors and for detecting these electrons using the technologies. They have also developed a layer-by-layer transfer technique of atomic layer materials to fabricate clean graphene devices and proposed a Cooper pair splitter using valley effects in graphene [102]. They have characterized the structural and electrical properties of graphene [82,93,98] and developed a double gate structure of graphene [83,93].

Main results :

A. Spin-orbit interaction and spin control

The gate controlled persistent spin helix (PSH) states in an InGaAs based quantum well was realized by Nitta-G in collaboration with Weiss/Ganichev-G and Richter-G [63]. Nitta-G and Richter-G have established a novel concept to evaluate Rashba and Dresselhaus SOI parameters without any fittings. Nitta-G and Richter-G have successfully observed the spin geometric phase and they have controlled the spin geometric phase by in-plane magnetic field [66]. Ohno-G has demonstrated electrically controlled nuclear spin coherence[39]. Tarucha-G has observed magnetic field angle dependence of Rashba SOI energy [5,6,17,47] and demonstrated the gate control of SOI energy [18,19]. Nagaosa-G has established the theory for quantum pump in ferromagnet/SOI junctions [7], and has clarified the electronic states in BiTeI with giant Rashba SOI together with the experimental group [34]. Furthermore, the group has clarified the dynamics of skyrmions in chiral ferromagnets [44,52].

B. Topological Insulators

In collaboration with the German group, Tarucha-G has succeeded for the first time in the world to observe the anomalous Shapiro steps in the Josephson junction made out of a topological insulator HgTe, which implies the Majorana fermion [79]. Nagaosa-G has developed a theory of quantized anomalous Hall effect in the ferromagnet on a three dimensional topological insulator [71], and have revealed that the domain wall there can be manipulated by an electric field.

C. Nonlocal entangler

Tarucha G has worked on the experiments for the separation of entangled electrons, and they have observed the non-local supercurrent components due to the coherent tunnelling of two electrons separated from a Cooper pair through the two individual dots in parallel double quantum dot Josephson junctions [101].

The group has also realized Cooper pair splitting in a superconductor-graphene double dot "Y" shaped junction. In addition, Tarucha-G has proposed Cooper pair splitting using valley degree of freedom of graphene, and has observed valley Hall effect in bilayer graphene [102]. The group has also succeeded in splitting an entangled electron pair in a quantum dot into distant quantum dots with high efficiency using surface acoustic wave [84,92,94,95].

In collaboration with Trauzettel-G, Nagaos-G has theoretically found that the Majorana fermion states with spins have a non-local entanglement [103] and has elucidated the behaviors of the Andreev reflection and the Josephson effect related to the Majorana fermion states [104].

Added Value from International collaborative work :

Much of the research has been carried out on the basis of the Japan-Germany collaboration by sharing the experience as well as the scientific and technical ability in an integrated and complementary manner. For subject (A) the Japanese and German teams having past successful record of collaboration could use this Japan-Germany project most efficiently to raise the research productivity. Subject (B) has been promoted by Japanese and German teams with the highest, complementary potentials. They have been able to substantially share their expertise to demonstrate pioneering accomplishments. (C) is a subject of new direction and has been tackled by able Japan teams of experiment and theory. They have succeeded in developing novel techniques and theories with technical support from German teams.

・Nitta-G had a Ph. D student from Richter-G as a JSPS fellow in 2007, and had jointly proposed a theory in Phys. Rev. Lett. (2008). In 2009, we made an agreement on academic exchange between the Graduate School of Engineering, Tohoku University and the School of Physics, University of Regensburg. Then, the collaborative research started between the two universities, and a Ph. D student from Nitta-G had stayed in Weiss-G for one year. From 2011, the Strategic Japanese-German Joint Research Program supported by JST-DFG started and promoted international collaborations. One of the goals for this program was to realize the theoretical proposal jointly predicted in 2008. We were able to experimentally demonstrate it using support from this program.
We could extend the new horizon of spintronics based on spin-orbit interaction by transport study mainly done by the Japanese group and by optical measurements and theory mainly done by German group. Furthermore, we could make a shot noise measurement of spin current in collaboration with Osaka University [68]. This is an extended collaborative work in this program.

・Nagaosa-G has collaborated with Trauzettel-G to study theoretically the topological superconductivity and Majorana fermions [103], and associated quantum transport phenomena (Andreev reflection and Josephson effect) [104]. This was enabled only when the knowledge of the two nations has been unified, i.e., long term experience of Japanese group on the interfaces of superconductors and accumulation of experimental researches on quantum wires and dots, and the German researches on quantum many-body systems in one-dimension.

・Molenkamp-G is the only group making quality 3D TI HgTe in the world but had no good expertise for low-temperature high frequency measurement to study the AC Josephson effect. On the other hand Tarucha-G had a skilful technique for such measurement. They have shared the expertise through this project to perfume the experiments of Majorana fermions with the HgTe Josephson junctions and finally succeeded in observing the anomalous Shapiro steps in topological insulators [79].

・To fabricate the parallel double quantum dot Josephson junctions with Nb eletcrodes, Tarucha-G was offered a technology from Molenkamp-G of evaporating quality Nb to form superconducting contacts to quantum dots and indeed applied it to improve transport properties of InAs QD Josephson junctions.

Factual information :

"Toplological Electronics" project is a fundamental science project and organized by Prof. S. Tarucha of Tokyo Univ., and Prof. L.W. Molenkamp of Würzburg Univ. as leaders of the Japanese and German teams respectively and Prof. Nagaosa of Tokyo Univ., Prof. Nitta of Tohoku Univ., Prof. Ohno of Tsukuba Univ., Prof. Trauzettel (Würzburg Univ.), and Prof. Weiss and Prof. Richter of Regensburg Univ. as principal investigators. The project lasted five years and three months, starting in January, 2010 and ending in March, 2015. The total grant from JST was 263,634,000 yen.

SICORP 独 情報通信技術（ナノエレクトロニクス） 終了報告書（概要）

題名 : トポロジカルエレクトロニクス
ドイツ側代表者名・所属 : 代表：ヴュルツブルク大学実験物理学部 EP3 教授 LAURENS W.MOLENKAMP
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期間 : 2010 年 1 月 1 日 ～ 2015 年 3 月 31 日

CONSOLIDATED PUBLIC SUMMARY IN JAPANESE
要約：現代エレクトロニクスにおける電力消費の問題を解消し、また革新的な情報処理技術を提供する新概念の構築を目指して、「幾何学的な量子性の制御」を動作原理とするエレクトロニクスの基礎科学を探究する。

プロジェクトの目的と課題
幾何学的な量子現象を与える3つの基本概念、「スピン軌道相互作用」、「トポロジカル絶縁体」、「非局所的な量子もつれ」の物理と電気制御法を開拓し、その応用として新奇な量子技術の創出と固体系量子情報の技術革新を目指す。

パラグラフ1：
3つの基本概念、(A)スピン軌道相互作用とスピン制御、(B)トポロジカル絶縁体、(C)非局所量子もつれ、によって発現する量子力学的性質を電気的に制御、評価する方法を日独の専門家が共同開発することにより、量子エレクトロニクス、量子情報の将来技術に貢献する。(A) は新田 G、Weiss/Ganichev-G、Richter-G を中心に大野 G、樽茶 G、永長 G を含めて、低次元電子系のスピン軌道相互作用の電圧制御と評価を行う。(B)では永長 G、Trauzettel-G が理論、樽茶 G、Molenkamp-G が実験を担当し、トポロジカル絶縁体の電子伝導を解明する。(C)では樽茶 G が Molenkamp-G の技術協力を得て実験的に、永長 G が Trauzettel-G と協同して非局所的な量子もつれ操作の理論研究を行う。

A. スピン軌道相互作用とスピン制御
電子スピンを電場で制御するにはスピン軌道相互作用が不可欠である。一方、スピン軌道相互作用はスピン緩和をもたらす原因となり、スピンを情報の担体として用いるには、スピンの電場制御とスピン緩和抑制を同時に満たす必要がある。この問題に対処するため、具体的には以下の４つをテーマとして取り上げた。
（１）散乱に対してもスピン緩和の抑制された永久スピン旋回状態の電場制御と電場により制御されたベリー位相をスピンの干渉効果により検出する。
（２）電場制御による核スピンコヒーレンスの操作実証と高移動度2次元電子系におけるスピン軌道相互作用を調べる。
（３）量子ドットにおいてスピン軌道相互作用の異方性の電気的制御を実現し、高速なスピン操作、量子ドットを利用したもつれ電子対の制御に有用であることを示す。
（４）スピン軌道相互作用をゲージ場として捉え、それを用いた電子制御の学理を理論的に開拓する。量子ポンプ、巨大ラシュバ効果の起源と物性、磁性体のスピンテクスチャーなど、スピン軌道相互作用の新しい側面を理論的に開拓する。

B. トポロジカル絶縁体
コヒーレンスが保護された量子状態であるマヨラナフェルミオン、非散逸性カレントの有用性を示す。これらの研究は、いずれも最近急速に注目されている。本プロジェクトでは、前者では実証実験を優先し、ナノ細線によるヘリカル状態の伝導特性、ナノ細線ジョセフソン接合の AC 効果、及び Molenkamp-G と共同してトポロジカル絶縁体 HgTe のジョセフソン接合の AC 効果を解明する。後者では、理論提案により、トポロジカル（TI）の機能を開拓する。特に、表面やエッジに存在する電子

分裂を起こしたチャンネルの運ぶ非散逸性カレントを理論的に研究し、デバイスの設計学理を確立する。

C. 非局所量子もつれ
2粒子が離れているにも関わらず量子もつれを保持する“非局所量子もつれ状態”の生成と検出を目的とする。非局所性に関しては各国で様々な提案がなされているが、独自の試みとして、(1)量子ドット(InAs、グラフェン)のクーロン相互作用などを利用した、s波超伝導体のクーパー対の空間分離と分離後のスピンコヒーレンスの確認、(2)表面弾性波や2経路干渉計を利用した、量子ドット中でスピン一重項状態にある電子対の空間分離、などを目指す。(3)理論によるアプローチとして、トポロジカル超伝導体とマヨラナフェルミオンの発現機構を明らかにし、マヨラナフェルミオンの示す非局所的もつれに起因する現象を探究する。

見出し2：用いた技術、手法
スピン、トポロジカル粒子、量子もつれ対の電気的制御に適合した手法・技術を独自に提案、開発した。量子干渉を利用したスピン軌道相互作用の制御と評価、HgTe 表面、ナノ細線の超伝導接合の開発とトポロジカル性の抽出、新規の非局所量子もつれ生成技術の開発などがその代表例である。

パラグラフ2
A. スピン軌道相互作用とスピン制御
・量子干渉効果の面内磁場の角度依存性から、干渉効果が最大となるとなる角度から直接α/β比を求めることが出来ることを実験的に検証した。さらに、ゲート電圧によりαを制御し、電場により制御された永久スピン旋回状態の実現に成功した[66]。また、スピン干渉効果のリング径依存性を調べることによりスピン幾何学位相の効果を抽出し[62]、面内磁場によりスピン位相を直接制御する手法を開発した。また実験結果は、Richter-Gによる理論解析により比較した[62]。
・核電気共鳴により核四重極相互作用を振動電界で制御した[39]。また、ゲート電極付き高移動度2 次元電子系において時空間分解 Kerr 測定法を用いた[50]。
・量子ドットのスピン軌道相互作用やg因子の電気的制御[5,6,17-19,47]のため、自己形成 InAs ドットに横方向から結合したサイドゲート電極により閉じ込めポテンシャルを制御する手法を開発した[18,19,80]。
・ 量子ポンプに関しては、非平衡 Keldysh グリーン関数法を用いてスピン密度、スピン流密度、電荷密度、電流密度を計算した。巨大ラシュバ効果に関しては、第一原理電子状態計算結果をダウンフォールディング法によりタイトバインディング模型に帰着し、それに対してモデル計算を行った。磁性体のスピンテクスチャーに対しては、Landau-Lifshitz-Gilbert (LLG)方程式の数値積分を行い、そのダイナミクスを調べた。

B. トポロジカル絶縁体
・実験ではスピン軌道相互作用の大きな高品質ナノ細線、ナノ細線ジョセフソン接合を作製し、また交流ジョセフソン効果の測定に適した希釈冷凍機高周波測定系を構築した。マヨラナフェルミオンの検証に繋がる実験手法として、Molenkamp グループが作製した HgTe ジョセフソン接合試料を共同で測定し、新たな実験結果を得た[79]。
・理論では3次元 TI の有限サイズタイトバインディング模型を数値的に対角化し、その結果を連続体近似の場の理論を用いて解析した。電子間相互作用については、量子電磁気学で発展した摂動的くりこみ群の手法を用いて解析した。

C. 非局所量子もつれ
・高精度電子描画による微細化技術を開発、それを用いて超伝導体を構成する電子対を分離し、検出するための試料の作製と超伝導特性の評価(InAs 量子ドットジョセフソン接合[80,87,88,90]、並列２重量子ドットジョセフソン接合[101]、超伝導体-Y 字型２重量子ドット接合など)を行った。

・原子層物質の転写技術を開発してグラフェン試料の清浄度を高めるとともに、バレーを用いたクーパー対分離を提案した[102]。また、グラフェンの特性評価[82,93,98]、ゲート構造[83,93]の開発を行った。
・量子ドット中の2個の電子（＝もつれ電子対）を分離する手法として、表面弾性波を用いて電子を1個単位で伝送する技術を開発した[84,92,94,95]。また、2経路干渉計を開発し[91,94,97,99]、表面弾性波との組み合わせによる非局所もつれ検出を新たな課題に加えた。
・理論ではグリーン関数法を用いて、粒子浴を積分し、着目する系のスペクトルを求めてゼロエネルギー状態を解析した。数値的な厳密解と低エネルギーの有効模型の結果を比較検討した。

主なプロジェクトの成果

A. スピン軌道相互作用とスピン制御

新田 G、Weiss/Ganichev-G、Richter-G は InGaAs 系二次元電子ガスのラシュバスピン軌道相互作用をゲート電場により制御し、永久スピン旋回状態を実現した[63]。新田 G と Richter-G は細線構造を用いて直接ラシュバとドレッセルハウススピン軌道相互作用の比を求める概念を確立することに成功した。また、両グループは、スピン幾何学的位相を観測することに成功するとともに[64]、面内磁場により幾何学的位相を制御することに成功した[66]。大野 G は、電界制御による四重極核スピンコヒーレンスを実証した。またゲート電極付き高移動度 2 次元電子系においてスピン永久旋回状態を実証した。樽茶 G は InAs 量子ドットにおいてラシュバ効果に特徴的な SOI エネルギーの磁場角度依存性を観測するとともに[5,6,17,47]、その電気的制御に成功した[18,19]。永長 G はスピン軌道相互系と強磁性体との接合系における量子ポンプの理論を構築した。巨大ラシュバ物質 BiTeI の電子状態と光学応答、磁気応答、輸送現象などの物性を実験グループとの共同研究でほぼ完全に解明した[15]。カイラル磁性体のスキルミオンの電流駆動運動、熱揺らぎ、などの動的性質を明らかにした[44,56]。

B. トポロジカル絶縁体

MolenkampG と樽茶 G は共同で HgTe のジョセフソン接合の実験を行い、マヨラナフェルミオンの存在を示唆する異常なシャピロステップを観測した[79]。これはトポロジカル絶縁体ジョセフソン接合としては初めての結果である。理論では、永長 G が局在効果を取り入れた3次元 TI 表面の強磁性体における量子化異常ホール効果の理論を構築した[71]。また、この系では磁壁が電場によって制御できることを見出した。さらに進んで磁場中 TI の新しい量子ホール状態のエッジチャンネルを調べ、非局所伝導などの現象を説明した。

C. 非局所量子もつれ

樽茶 G が主にもつれ電子対分離の実験を担当し、多くの新手法を開発した。並列2重量子ドットジョセフソン接合の超伝導電流を測定し、クーパー対の2電子が2つのドットに分離してコヒーレントに流れる非局所電流成分を抽出した[101]。これにより分離電子対のコヒーレンスを初めて確認した。また、グラフェン2重量子ドット-超伝導 Y 字接合でも、クーパー対の分離実験に成功した。グラフェンのバレーを用いたクーパー対分離に向けた実験では、2層グラフェンでバレーホールの測定に成功した[102]。表面弾性波を用いた実験では、量子ドット中の量子もつれ電子対を遠く離れた別々の量子ドットへと高効率で分離することに成功した[84,92,94,95]。
　永長 G は、Trauzettel-G との共同研究で、スピンを持ったマヨラナフェルオン状態が非局所的な量子もつれを持つことを理論的に見出し[103]、それが関与するアンドレーフ反射やジョセフソン効果の振る舞いを明らかにした[104]。

国際共同研究により得られた付加価値

本国際共同は、3つの基本概念を日独の専門家が集中して発展させることを狙ったもので、研究の多くは、国内、国際の研究交流（人的交流を含む）、技術共有の基に進められた。テーマ A は、日独の担当者間に当初から十分な交流実績があり、本国際共同により相補的な研究開発が大きく加速した。テーマ B には、世界トップの日独の実験、理論グループが参画し、国際共同の方針に沿っ

てアイデア、実験技術を共有することで、世界を主導する成果があげられた。テーマ C は新しい方向性テーマであり、同分野で実力のある日本の実験、理論グループが、ドイツのグループと技術提携、アイデア交換を行うことにより、先駆的な手法、技術の開発、理論提案に成功した。

・2007 年 Regensburg 大学の Richter 教授のグループから博士課程学生 M. Scheid を JSPS フェローとして新田 G(東北大学)に受け入れ、その研究成果を 2008 年共同で PRL に理論提案した。2009 年東北大学工学研究科と Regensburg 大学物理学科と学術協定を締結し、塩貝君が 1 年間、Weiss 教授のグループに滞在し、両大学の共同研究が始まった。2011 年より DFG-JST による戦略的国際共同研究プロジェクトが開始され、国際共同研究が一層活性化した。国際共同研究プロジェクトでは 2008 年の理論的な提案が 1 つの柱になっており、本プロジェクトの中で実験的に検証することに成功した。

スピン軌道相互作用はスピントロニクス分野の重要なキーワードであるがドイツ側は主に光学測定、理論、日本側は伝導測定を行いより深い理解と研究の進展をもたらした。また、当初の計画になかった大阪大学によるスピン流のショット雑音測定への展開に繋がった[68]。

・永長 G は Trauzettel-G との共同研究を通じて、トポロジカル超伝導体とマヨラナフェルミオン[103]、およびそれに関連した量子輸送現象(アンドレーフ反射やジョセフソン効果)の理論的研究を進展させた[104]。これは、日本側の超伝導接合理論および量子細線・量子ドットの実験に関する長年の経験と、ドイツ側の1次元量子多体系に関する研究蓄積を組み合わせて初めて可能になった成果である。

・Molenkamp-G は、3D トポロジカル絶縁体である HgTe の結晶成長では世界トップだが、極低温での交流ジョセフソン効果測定の技術を持っていなかった。一方、樽茶 G は低温超伝導測定、高周波測定で世界的実績をあげてきた。両 G が本プロジェクトで共同して HgTe の交流ジョセフソン効果の実験を遂行することにより、世界初の成果(シャピロステップ異常の観測)をあげることができた[79]。

・Nb 電極を持つ並列 2 重量子ドットジョセフソン接合の作製のため、樽茶 G は Nb 蒸着につい Molenkamp-G から技術提供を受け、目的を達成できた。

・プロジェクト期間中、毎年共同の研究会(日本、ドイツ交互に5回)を開催し、これにはドイツ、日本の学生、若手研究者が数多く参加した。これらの合同研究会、共同研究などを通して、当該プロジェクトは、研究の進展のみならず、若手研究者、学生の研究、教育にも貢献した。その度合は、プロジェクト参加者のポスト獲得の実績に数値として現れている。(日本側データ:教授2、准教授3, 講師1, 助教3、博士研究員7(特任教員含む)、会社就職10)

事実情報

「トポロジカル エレクトロニクス」プロジェクトは基礎研究プロジェクトである。ドイツの Molenkamp 教授(Wuerzburg 大)と日本の樽茶教授(東京大)を研究代表者とし、永長教授(東京大)、新田教授(東北大)、大野教授(筑波大)、Trauzettel 教授(Wuerzburg 大)、Weiss 教授、Ganichev 教授、Richter 教授(Regensburg 大)を研究分担者として組織された。プロジェクトは平成22年1月に開始され平成26年3月に終了するまで5年3ヶ月間続いた。JSTからの補助金は263, 634千円であった。