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 公開

（全体計画書の研究概要）

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 公開

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].

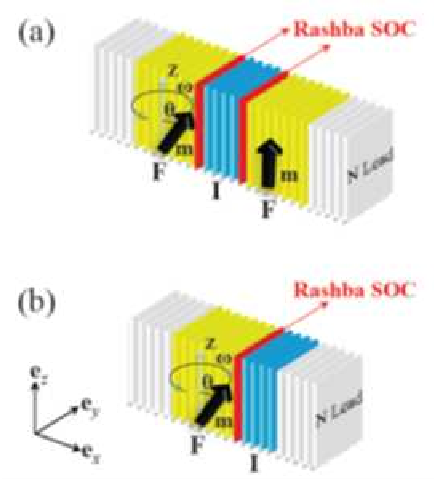

Figure A1: Configuration of quantum pumping with Rashba SOC

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 $|\cos(\theta)|$ dependence of the SOI energy, and assigned it to Rashba effect [A18]. This is the first direct evidence of Rashba effect as given by $(\boldsymbol{E}\mathbf{x}\boldsymbol{p})\cdot\boldsymbol{\sigma}$ in QDs with angular dependence of $\boldsymbol{B}_{\text{ext}}$ ($//\boldsymbol{\sigma}$) 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.

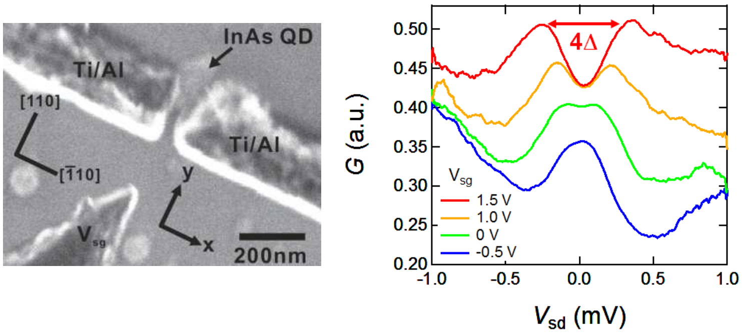

Fig.A3: (left) SEM image of the InAs QD device. (right) Splitting of Kondo zero-bias anomalies, indicating the electrical tuning of spin-orbit interaction energy Δ.

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].

References

A1 M. Kohda, V. Lechner, Y. Kunihashi, T. Dollinger, P. Olbrich, C. Schönhuber, I. Caspers, V.V. Bel'kov, L.E. Golub, D. Weiss, K. Richter, J. Nitta and S.D. Ganichev, Phys. Rev. B (Rapid Commun.) **86**, 081306 (2012).

A2 C. Betthausen, T. Dollinger, H. Saarikoski, V. Kolkovsky, G. Karczewski, T. Wojtowicz, K. Richter, D. Weiss, Science **337** 324 (2012).

A3 F. Nagasawa, J. Takagi, Y. Kunihashi, M. Kohda, and J. Nitta, Phys. Rev. Lett. **108**, 086801 (2012).

A4 K. Richter, Physics **5**, 22 (2012).

A5 V. Krueckl, M. Wimmer, I. Adagideli, J. Kuipers, and K. Richter, Phys. Rev. Lett. **106**, 146801 (2011).

A6 Ya. V. Terent'ev, C. Zoth, V.V. Bel'kov, P. Olbrich, C. Drexler, V. Lechner, P. Lutz, A.N. Semenov, V. A. Solov'ev, I.V. Sedova, G.V. Klimko, T.A. Komissarova, S.V. Ivanov, and S.D. Ganichev, Appl. Phys. Lett. **99**, 072111 (2011).

A7 J. Shiogai, D. Schuh, W. Wegscheider, M. Kohda, J. Nitta, D. Weiss, Appl. Phys. Lett. **98**, 83101 (2011)

A8 J. Shiogai, M. Ciorga, M. Utz, D. Schuh, T. Arakawa, M. Kohda, K. Kobayashi, T. Ono, W. Wegscheider, D. Weiss, and J. Nitta, "Dynamic nuclear spin polarization in an all-semiconductor spin injection device with (Ga,Mn)As / n-GaAs spin Esaki diode", Appl. Phys. Lett. **101**, 212402 (2012)

A9 Z.D. Kvon, S.N. Danilov, D.A. Kozlov, C. Zoth, N.N. Michailov, S.A. Dvoretzkii, and S.D. Ganichev, JETP Lett. **94**, 816 (2011).

A10 J. Ishihara, M. Ono, G. Sato, S. Matsuzaka, Y. Ohno, and H. Ohno, Japanese Journal of Applied Physics **50**, 04DM03 (2011).

A11 M. Ono, J. Ishihara, G. Sato, S. Matsuzaka, Y. Ohno and H. Ohno, submitted (2012)

A12 Y.Avishai, D. Cohen, and N. Nagaosa、Phys. Rev. Lett. **104**, 196601 (2010)

A13 A. Shitade, M. Ezawa, and N. Nagaosa, Phys. Rev. B **82**, 195305 (2010)

A14 F. Mahfouzi, J. Fabian, N. Nagaosa, and B. K. Nikoli´c, Phys. Rev. B **85**, 054406 (2012).

A15 N. Sugimoto and N. Nagaosa, Science **336, 1413** (2012).

A16 M. Mostovoy, K. Nomura, and N. Nagaosa, Phys. Rev. Lett. **106**, 047204 (2011)
A17 I. Adagideli, V. Lutsker, M. Scheid, Ph. Jacquod, and K. Richter, Phys. Rev. Lett. **108**, 23601 (2012).
A18 S. Takahashi, R. S. Deacon, K. Yoshida, A. Oiwa, K. Shibata, K. Hirakawa, Y. Tokura, and S. Tarucha, Phys. Rev. Lett., **104**, 246801 (2010).
A19 Y. Kanai, R. S. Deacon, S. Takahashi, A. Oiwa, K. Yoshida, K. Shibata, K. Hirakawa, Y. Tokura, and S. Tarucha, Nature Nanotechnology **6**, 511 (2011).
A20 R. S. Deacon, Y. Kanai, S. Takahashi, A. Oiwa, K. Yoshida, K. Shibata, K. Hirakawa, Y. Tokura, and S. Tarucha, Physical Review B (Rapid Commun.) **84**, 041302 (2011).
A21 S. Takahashi, R. S. Deacon, A. Oiwa, K. Shibata, K. Hirakawa, and S. Tarucha, Physical Review B (Rapid Commun.) (accepted).

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 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

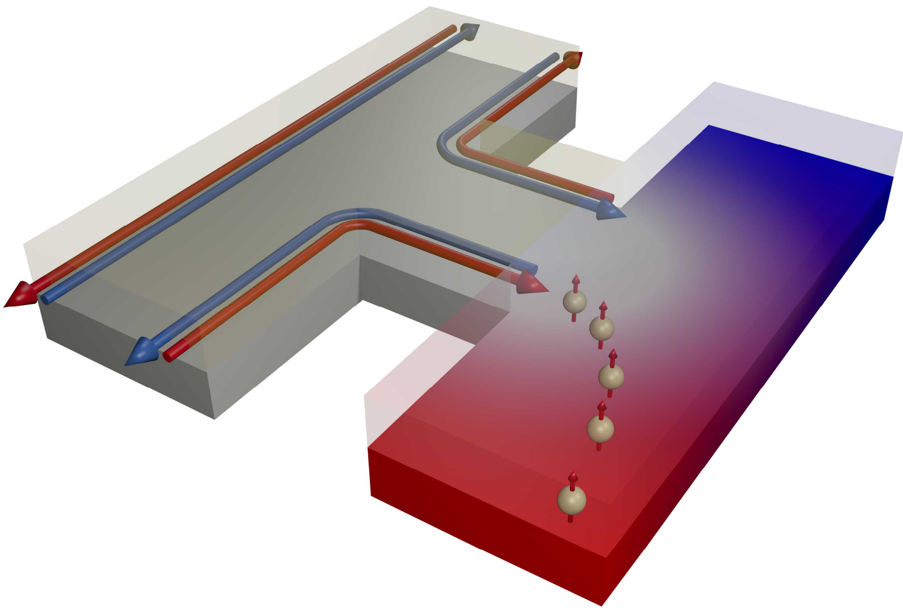

Fig. B1: Schematic illustration of a four-terminal device used for injection and detection of helical edge state, as performed in Ref. [B10]. The edge states are indicated by red and blue arrows symbolizing the transport direction and the spin polarization. The spin polarized carriers in the metallic 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).

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 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.

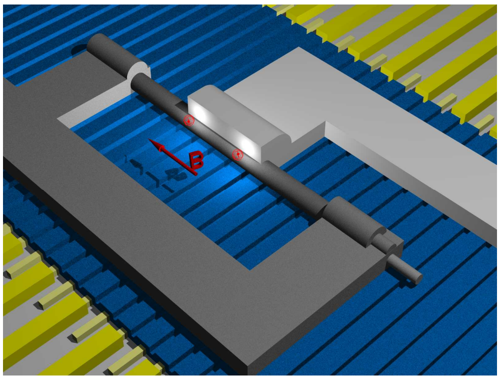

Fig. B2: Envisioned device layout of a device for the creation and detection of Majorana Fermions

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].

References

B1 König, M., S. Wiedmann, C. Brne, A. Roth, H. Buhmann, L.W. Molenkamp, X. L. Qi and S. C. Zhang, Science 318, 766 (2007).

B2 Hsieh, D., D. Qian, L. Wray, Y. Xia, Y. S. Hor, R. J. Cava, and M. Z. Hasan, Nature 452, 970 (2008).

B3 Xia, Y., D. Qian, D. Hsieh, L.Wray, A. Pal, H. Lin, A. Bansil, D. Grauer, Y. S. Hor, R. J. Cava and M. Z. Hasan, Nat. Phys. 5, 398 (2009).

B4 C. Brüne, C.X. Liu, E.G. Novik, E.M. Hankiewicz, H. Buhmann, Y.L. Chen, X.L. Qi, Z.X. Shen, S.C. Zhang and L.W. Molenkamp, Phys. Rev. Lett. 106, 126803 (2011).

B5 B. Büttner, C. X. Liu, G. Tkachov, E. G. Novik, C. Brüne, H. Buhmann, E. M. Hankiewicz, P. Recher, B. Trauzettel, S. C. Zhang, and L. W. Molenkamp, Nature Physics 7, 418 (2011).

B6 G. Tkachov, C. Thienel, V. Pinneker, B. Büttner, C. Brüne, H. Buhmann, L. W. Molenkamp, and E. M. Hankiewicz, Phys. Rev. Lett. 106, 076802 (2011).

B7 F. Dürr, J.B. Oostinga, C. Gould and L.W. Molenkamp, Phys. Rev. B 86, 081410, (2012).

B8 H. Hettmansperger, F. Dürr, J.B. Oostinga, C. Gould, B. Trauzettel, L.W. Molenkamp, Cond-mat: arXiv:1205.5144, (2012)

B9 A.Roth, C. Brüne, H. Buhmann, L.W. Molenkamp, J. Maciejko, X.-L. Qi, and S.-C. Zhang, Science 325, 294 (2009).
B10 C. Brüne, A. Roth, H. Buhmann, E.M. Hankiewicz, L.W. Molenkamp, J. Maciejko, X.L. Qi, and S.C. Zhang, Nature Physics 8, 485 (2012).
B11 X.L.Qi, R. Li, J. Zang, and S.C.Zhang, Science 323, 1184 (2009).
B12 R. M. Lutchyn, J. D. Sau, and S. Das Sarma, Phys. Rev. Lett. 105, 077001 (2010); Y. Oreg, G. Refael, F. von Oppen, Phys. Rev. Lett. 105, 177002 (2010).
B13 V. Mourik, K. Zuo, S. M. Frolov, S. R. Plissard, E. P. A. M. Bakkers, L. P. Kouwenhoven, Scienc 336, 1003 (2012).
B14 Y.Avishai, D. Cohen, and N. Nagaosa、Phys. Rev. Lett. 104, 196601 (2010)
B15 K. Nomura and N. Nagaosa, Phys. Rev. Lett. 106, 166802 (2011).
B16 V. Krueckl and K. Richter, Phys. Rev. Lett. 107, 086803 (2011).
B17 V. Krueckl and K. Richter, Phys. Rev. B 85, 115433 (2012).
B18 V. Krueckl and K. Richter, accepted for publication in Semicond. Sci. and Technol. (Topological Insulators Special Issue) (2012), arXiv:1207.1294.
B19 J.C. Budich, F. Dolcini, P. Recher, and B. Trauzettel, Phys. Rev. Lett. 108, 086602 (2012).
B20 F. Crepin, J.C. Budich, F. Dolcini, P. Recher, and B. Trauzettel, Phys. Rev. B 86, 121106(R) (2012).
B21 C.X. Liu, J.C. Budich, P. Recher, and B. Trauzettel Phys. Rev. B 83, 035407 (2011).

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

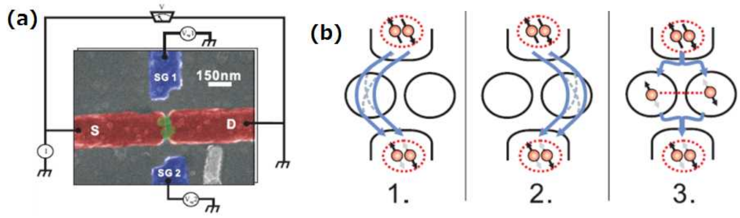

Fig. C1: (a) Photo of DQD JJ. (b) Local and non-local tunneling processes.

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

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

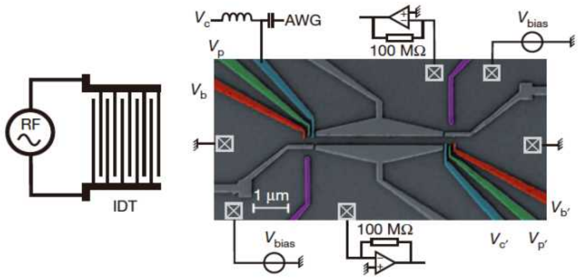

Fig. C3: Single electron transfer device with two QDs bridged by a 3 µm long 1D channel, two QPC charge sensors and inter digital transducer for generating SAWs.

"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

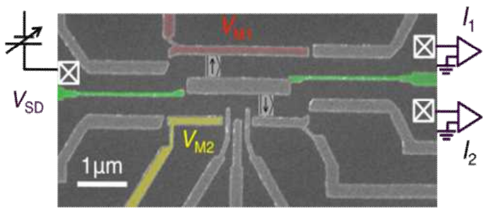

Fig. C4: Photo of the interferometer used for detecting the Kondo cloud.

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].

References

C1 R.S. Deacon, J. Sailer, S. Baba, A. Oiwa, K. Shibata, K. Hirakawa, and S. Tarucha, in preparation.
C2 Z.Wang and X. Hu, Phys. Rev. Lett 106, 037002 (2011).
C3 Y. Kanai, R. S. Deacon, S. Takahashi, A. Oiwa, K. Yoshida, K. Shibata, K. Hirakawa, Y. Tokura, and S. Tarucha, Nature Nanotechnology 6, 511 (2011)
C4 S. Hermelin, S. Takada, M. Yamamoto, S. Tarucha, A. D. Wieck, L. Saminadayar, C. Bäuerle, and T. Meunier, Nature 477, 435 (2011).
C5 M. Yamamoto, S. Takada, C. Bäuerle, K. Watanabe, A. D. Wieck and S. Tarucha, Nature Nanotechnology 7, 247 (2012).
C6 A. Yamakage, Y. Tanaka, and N. Nagaosa, Phys. Rev. Lett. 108, 087003 (2012).
C7 S. Nakosai, Y. Tanaka, and N. Nagaosa, Phys. Rev. Lett. 108, 147003 (2012).
C8 D. Asahi and N. Nagaosa, Phys. Rev. B 86, 100504 (2012).
C9 K. Nomura, S. Ryu, A. Furusaki, and N. Nagaosa, Phys. Rev. Lett. 108, 026802 (2012).
C10 Sho Nakosai, Jan Carl Budich, Yukio Tanaka, Björn Trauzettel, and Naoto Nagaosa, Phys. Rev. Lett. **110**, 117002 (2013).

3 Project participants

3.1 Japanese Team公開

Name	Organization, Division	Title	Specialty	Role in Project
Seigo Tarucha	Univeristy of Tokyo	Prof. Dr.	Low Temperature Quantum Physics	Japanese Principal Investigator
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公開

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,	Reserach

			graphene, transport, novel devices	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公開

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).

(2) M. Kohda, V. Lechner, Y. Kunihashi, T. Dollinger, P. Olbrich, C. Schönhuber, I. Caspers, V. V. Bel'kov, L. E. Golub, D. Weiss, K. Richter, J. Nitta, and S. D. Ganichev, "Gate-controlled persistent spin helix state in InGaAs quantum wells", Phys. Rev. B Rapid Comm., **86**, 081306 (2012).

(3) J. Shiogai, M. Ciorga, M. Utz, D. Schuh, T. Arakawa, M. Kohda, K. Kobayashi, T. Ono, W. Wegscheider, D. Weiss, and J. Nitta, "Dynamic nuclear spin polarization in an all-semiconductor spin injection device with (Ga,Mn)As / n-GaAs spin Esaki diode", Appl. Phys. Lett. **101**, 212402 (2012)

(4) Sho Nakosai, Jan Carl Budich, Yukio Tanaka, Björn Trauzettel, and Naoto Nagaosa,"Majorana Bound States and Nonlocal Spin Correlations in a Quantum Wire on an Unconventional Superconductor", Phys. Rev. Lett. **110**, 117002 (2013).

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).

(2) P. A. Maksym, M. Roy, M. F. Craciun, S. Russo, M. Yamamoto, S. Tarucha and H. Aoki, "Proposal for a magnetic field induced graphene dot", Journal of Physics: Conference Series **245**, 012030 (2010).

(3) M. Yamamoto, M. F. Craciun, S. Russo, A F. Morpurgo, S. Tarucha, "Charge transport and band structure of trilayer graphene", Solid State Physics **45**, 581 (2010)

(4) S. Takahashi, R. S. Deacon, K. Yoshida, A. Oiwa, K. Shibata, K. Hirakawa, Y. Tokura, S. Tarucha, Large Anisotropy of the Spin-Orbit Interaction in a Single InAs Self-Assembled Quantum Dot, Phys. Rev. Lett. **104**, 246801 (2010).

(5) R. S. Deacon, Y. Tanaka, A. Oiwa, R. Sakano, K. Yoshida, K. Shibata, K. Hirakawa, and S. Tarucha, "Tunneling Spectroscopy of Andreev Energy Levels in a Quantum Dot Coupled to a Superconductor", Phys. Revi. Lett. **104**, 076805 (2010).

(6) R. S. Deacon, Y. Tanaka, A. Oiwa, R. Sakano, K. Yoshida, K. Shibata, K. Hirakawa, and S. Tarucha," Kondo-enhanced Andreev transport in single self-assembled InAs quantum dots contacted with normal and superconducting leads", Physi. Rev. B **81**, 121308(R) (2010).

(7) Y. Kanai, R. S. Deacon, A. Oiwa, K. Yoshida, K. Shibata, K. Hirakawa, S. Tarucha, ”Electrical control of Kondo effect and superconducting transport in a side-gated InAsquantum dot Josephson junction”, Phys. Rev. B **82**, 054512 (2010).

(8) Y. Kanai, R. S. Deacon, S. Takahashi, A. Oiwa, K. Yoshida, K. Shibata, K. Hirakawa, Y. Tokura, and S. Tarucha, “Electrically tuned spin-orbit interaction in an InAs self-assembled quantum dot”, Nature Nano. **6**, 511 (2011).

(9) R.S. Deacon, Y. Kanai, S. Takahashi, A. Oiwa, K. Yoshida, K. Shibata, K. Hirakawa, Y. Tokura, and S. Tarucha, “Electrically tuned g tensor in an InAs self-assembled quantum dot” Phys. Rev. B **84**, 041302 (2011).

(10) S. H. Jhang, M. F. Craciun, S. Schmidmeier, S. Tokumitsu, S. Russo, M. Yamamoto, Y. Skourski, J. Wosnitza, S. Tarucha, J. Eroms and C. Strunk, “Stacking-order dependent transport properties of trilayer graphene”, Phys. Rev. B **84**, 161408(R) (2011).

(11) S. Hermelin, S. Takada, M. Yamamoto, S. Tarucha, A. D. Wieck, L. Saminadayar, C. Bäuerle, and T. Meunier, "Electron surfing on a sound wave as a platform for quantum optics with flying electrons”, Nature **477**, 435 (2011).

(12) M. Yamamoto,H. Takagi, M. Stopa, and S. Tarucha, “Hydrodynamic rectified drag current in a quantum wire induced by Wigner crystallization”, Phys. RevB. **85,** 041308(2012)

(13) H. Shioya, M. Yamamoto, S. Russo, M.F. Craciun, and S. Tarucha, “Gate tunable non-linear currents in bilayer graphene diodes”, Appl. Phys. Lett. **100**, 033113 (2012).

(14) M. Yamamoto, S. Takada, S. Tarucha, S. Hermelin, C. Bäuerle and T. Meunier, “Single ewlectron transfer using surface acoustic wave:towards quantum optics with flying electrons”, Solid State Physics **47**,163 (2012).

(15) M. Yamamoto, S. Takada, C. Bäuerle, K. Watanabe, A. D. Wieck and S. Tarucha, “Electrical control of a solid-state flying qubit”, Nature Nanotechnology, **7**, 247 (2012)

(16) Y. Kanai, R. S. Deacon, A. Oiwa, K. Yoshida, K. Shibata, K. Hirakawa, and S. Tarucha, “Control of supercurrent in a self-assembled InAs quantum dot Josephson junction by electrical tuning of level overlaps”, Appl. Phys. Lett. 100, 202109 1-3 (2012).

(17) T. Otsuka, Y. Sugihara, J. Yoneda, S. Katsumoto, S. Tarucha, “Detection of spin polarization utilizing singlet and triplet states in a single-lead quantum dot”, Phys. Rev. B **86**, 081308(R) (2012)

(18) R. Sakano, Y. Nishikawa, A. Oguri, AC. Hewson, S. Tarucha, “Full Counting Statistics for Orbital-Degenerate Impurity Anderson Model with Hund's Rule Exchange Coupling”, Phys. Rev. Lett. **108**, 266401 (2012).

(19) A. Oiwa, R. S. Deacon, Y. Kanai, Y. Tanaka, K, Shibata, K. Hirakawa, and S. Tarucha, “Andreev bound state spectroscopy and interplay between proximity effect and Kondo effect in hybrid InAs QD-superconductor device”, Solid State Physics **47**, 321 (2012).

Nagaosa-G

(20) Y.Avishai, D. Cohen, and N. Nagaosa、“Purely Electric Spin Pumping in One Dimension“、Phys. Rev. Lett. **104**, 196601 (2010)

(21) J.Linder, Y.Tanaka, T.Yokoyama, A.Sudbø, and N.Nagaosa、“Interplay between, superconductivity and ferromagnetism on a topological insulator“、Phys. Rev. B **81**, 184525 (2010)

(22) T. Yokoyama, J.D. Zang, and N. Nagaosa、“Theoretical study of the dynamics of magnetization on the topological surface“、Phys. Rev. B **81**, 241410(R) (2010)

(23) K.Nomura and N. Nagaosa、“Electric charging of magnetic textures on the surface of a topological insulator“、Phys. Rev. B **82**, 161401(R) (2010)

(24) Shitade, M. Ezawa, and N. Nagaosa、“Manipulation of two spin qubits in a double quantum dot using an electric field“、Phys. Rev. B **82**, 195305(2010)

(25) W. Koshibae, N. Furukawa and N. Nagaosa, “Photo-induced insulator-metal transition of a spin-electron coupled system”, EPL, **94**, 27003 (2011).

(26) K. Nomura and N. Nagaosa, “Surface-Quantized Anomalous Hall Current and the Magnetoelectric Effect in Magnetically Disordered Topological Insulators”, Phys. Rev. Lett. ,**106**, 166802 (2011).

(27) T. Yokoyama, Y. Tanaka and N. Nagaosa, “Anomalous Meissner Effect in a Normal-Metal Superconductor Junction with a Spin-Active Interface”, Phys. Rev. Lett. **106**, 246601 (2011).

(28) Y. Tanaka, M. Sato †, and N. Nagaosa, “Symmetry and Topology in Superconductors - Odd-frequency pairing and edge states –“, J. Phys. Soc. Jpn. **81** 011013 (2012).

(29) Shitade and N. Nagaosa, “Anomalous Hall Effect in Ferromagnetic Metals: Role of Phonons at Finite Temperature“, J. Phys. Soc. Jpn. **81** 083704 (2012).

(30) M. Mostovoy, K. Nomura, and N. Nagaosa, “Theory of Electric Polarization in Multiorbital Mott Insulators”, Phys. Rev. Lett. **106**, 047204 (2011)

(31) K. Nomura and N. Nagaosa, “Surface-Quantized Anomalous Hall Current and the Magnetoelectric Effect in Magnetically Disordered Topological Insulators”, Phys. Rev. Lett. **106**, 166802 (2011)

(32) J. S. Lee, G. A. H. Schober, M. S. Bahramy, H. Murakawa, Y. Onose, R. Arita, N. Nagaosa, and Y. Tokura, “Optical Response of Relativistic Electrons in the Polar BiTeI Semiconductor”, Phys. Rev. Lett. **107**, 117401 (2011)

(33) K. Nomura, S. Ryu, A. Furusaki, and N. Nagaosa, “Cross-Correlated Responses of Topological Superconductors and Superfluids”, Phys. Rev. Lett. **108**, 026802 (2012).

(34) Ai Yamakage, Yukio Tanaka, and Naoto Nagaosa, “Evolution of Edge States and Critical Phenomena in the Rashba Superconductor with Magnetization”, Phys. Rev. Lett. **108**, 087003 (2012).

(35) F. Mahfouzi, J. Fabian, N. Nagaosa, and B. K. Nikoli´c, “Charge pumping by magnetization dynamics in magnetic and semimagnetic tunnel junctions with interfacial Rashba or bulk extrinsic spin-orbit coupling”, Phys. Rev. B **85**, 054406 (2012).

(36) N. Sugimoto and N. Nagaosa, “Spin-orbit Echo”, Science, **336**, 1413 (2012).

(37) S. Nakosai, Y. Tanaka, and N. Nagaosa, “Topological Superconductivity in Bilayer Rashba System”, Phys. Rev. Lett. **108**, 147003 (2012).

(38) D.Asahi and N. Nagaosa, “Topological indices, defects, and Majorana fermions in chiral superconductors”, Phys. Rev. B **86**, 100504 (2012)

(39) M. S. Bahramy, P. D. C. King, A. de la Torre, J. Chang, M. Shi,L. Patthey, G. Balakrishnan, Ph. Hofmann, R. Arita, N. Nagaosa, and F. Baumberger, "Emergent quantum confinement at topological insulator surfaces", NATURE COMMUNICATIONS, 3(2012)

(40) L. Demkó, G. A. H. Schober, V. Kocsis, M. S. Bahramy, H. Murakawa, J. S. Lee, I. Kézsmárki, R. Arita, N. Nagaosa, and Y. Tokura, "Enhanced Infrared Magneto-Optical Response of the Nonmagnetic Semiconductor BiTeI Driven by Bulk Rashba Splitting", Phys. Rev. Lett. 109, 167401(2012)

(41) Farzad Mahfouzi, Naoto Nagaosa, and Branislav K. Nikolić, "Spin-Orbit Coupling Induced Spin-Transfer Torque and Current Polarization in Topological-Insulator/Ferromagnet Vertical Heterostructures", Phys. Rev. Lett. 109, 166602(2012)

(42) Hiroki Isobe and Naoto Nagaosa,"Theory of a quantum critical phenomenon in a topological insulator: (3+1)-dimensional quantum electrodynamics in solids", Phys. Rev. B 86, 165127(2012)

(43) G. De Filippis, V. Cataudella, E. A. Nowadnick, T. P. Devereaux, A. S. Mishchenko, and N. Nagaosa,"Quantum Dynamics of the Hubbard-Holstein Model in Equilibrium and Nonequilibrium:

Application to Pump-Probe Phenomena", Phys. Rev. Lett. 109, 176402 (2012)

(44) N. Nagaosa, X. Z. Yu and Y. Tokura,"Gauge fields in real and momentum spaces in magnets: monopoles and skyrmions",Phil. Trans. R. Soc. A 2012 370(2012)

(45) Patrick A. Lee and Naoto Nagaosa,"Proposal to use neutron scattering to access scalar spin chirality fluctuations in kagome lattices", Phys. Rev. B 87, 064423(2013)

Nitta-G

(46) J. Nitta, J. Takagi, F. Nagasawa, and M. Kohda, "Suppression of Aharonov-Casher spin interference in an InGaAs ring array", J. of Phys.: Conf. Ser., **302**, 012002 (2011).

(47) J. Nitta, S. Moulis, and M. Kohda, "Anisotropic spin transport affected by competition between spin orbit interaction and Zeeman", J. Phys. Conf. Ser., **334**, 012062 (2011).

(48) Y. Kunihashi, M. Kohda, and J. Nitta, "Semiclassical approach for spin dephasing in a quasi-one-dimensional channel", Phys. Rev. B **85**, 035321 (2012).

(49) F. Nagasawa, J. Takagi, Y. Kunihashi, M. Kohda, and J. Nitta, "Experimental Demonstration of Spin Geometric Phase: Radius Dependence of Time-Reversal Aharonov-Casher Oscillations", Phys. Rev. Lett., **108**, 086801 (2012).

(50) Y. Kunihashi, M. Kohda, H. Sanada, H. Gotoh, T. Sogawa, J. Nitta, "Proposal of spin complementary field effect transistor", Appl. Phys. Lett., **100**, 113502 (2012).

(51) S. Nonaka, Y. Kunihashi, M. Kohda, J. Nitta, "Anisotropic Weak Anti-Localization under In-Plane Magnetic Field and Control of Dimensionality via Spin Precession Length", Jpn. J. Appl. Phys., **51**, 04DM01 (2012).

(52) J. Nitta, "Spin Current" Edited by S. Maekawa Chapter 13 "Spin generation and manipulation based on spin-orbit interaction in semiconductors" , Oxford Science Publications, (2012).

Ohno-G

(53) M. Ono, H. Kobayashi, S. Matsuzaka, Y. Ohno, and H. Ohno, "Gate voltage dependence of nuclear spin relaxation in an impurity-doped semiconductor quantum well", Appl. Phys. Lett. **96**, 071907 (2010).

(54) J. Ishihara, M. Ono, G. Sato, S. Matsuzaka, Y. Ohno, and H. Ohno, "Magnetic Field Dependence of Quadrupolar Splitting and Nuclear Spin Coherence Time in a Strained (110) GaAs Quantum Well," Jpn. J. Appl. Phys. **50**, 04DM03 (2011).

(55) M. Ghali, K. Ohtani, Yuzo Ohno and Hideo Ohno, "Generation and control of polarization-entangled photons from GaAs island quantum dots by an electric field," Nature Communications **3**, 661 (2012)

(56) Eli Christopher I. Enobio, H. Sato, K. Ohtani, Y. Ohno, and H. Ohno , "Photocurrent Measurements on a Quantum Cascade Laser Device by Fourier Transform Infrared Microscope," Jpn. J. Appl. Phys. **51**, 06FE15 (2012).

(57) M. Ghali, K. Ohtani, Y. Ohno, and H. Ohno, "Vertical-Electrical-Field-Induced Control of the Exciton Fine Structure Splitting in GaAs Island Quantum Dots for the Generation of Polarization-Entangled Photons", Jpn. J. Appl. Phys. **51**, 06FE14 (2012).

(58) L. R. Fleet, K. Yoshida, H. Kobayashi, Y. Kaneko, S. Matsuzaka, Y. Ohno, H. Ohno, S. Honda, J. Inoue, and A. Hirohata, "Correlating the interface structure to spin injection in abrupt Fe/GaAs(001) flms", Physical Review B 87, 022401 (2013).

(59) M. Ono, J. Ishihara, G. Sato, Y. Ohno, and H. Ohno, "Coherent Manipulation of Nuclear Spins in Semiconductors with an Electric Field", Applied Physics Express 6, 033002 (2013).

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