Usage Report for Fiscal Year 2017

Project Title:

Spin transport in complex spin-orbit fields in mesoscopic structures

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1. Background and purpose of the project

The research project focused on spin-interferometry in low-dimensional mesoscopic semiconductor structures under the influence of spin-orbit fields. In contrast to many other interferometric methods in physics spin-interferometry in mesoscopic systems is not a high-precision measurement method. Instead it aims to directly reveal and measure dynamic and geometric Berry phases of electron spin. These phases are otherwise difficult to observe and give only indirect effects in measurements. Spin-interferometry has been employed to measure adiabatic and nonadiabatic spin geometric and spin dynamic phases via Aharonov-Casher effect where the spin is manipulated via the spin-orbit fields. Especially the Rashba type of spin-orbit interaction may be very strong in semiconductor-based quantum wells. Moreover, its strength can be modulated via external electric gate electrodes.

Spin interferometers are commonly realized using large arrays of quantum rings consisting of hundreds or thousands of rings. Kinetic and ring specific interference effects in conductance are then averaged out and conductance through the system reflects only the spin-dependent phases. Phase coherence length in these structures is of the same order as the size of the structures making spin interference possible. In experiments on large mesoscopic InGaAs-based ring arrays nonadiabatic (Aharonov-Anandan) geometric phases have been extracted and observed directly in conductance through the array (F. Nagasawa, J. Takagi, Y. Kunihashi, M. Kohda, and J. Nitta, Phys. Rev. Lett. 108, 086801 (2012)).

The present project focuses on the effect of anisotropic spin-orbit fields on spin-interference. The spin-orbit field is generally a combination of Rashba and Dresselhaus type of spin-orbit interactions. The Dresselhaus spin-orbit interaction in typical semiconductor structures results from bulk inversion asymmetry of the underlying semiconductor material. The total spin-orbit field becomes then anisotropic and can be probed using an in-plane magnetic field. The degree of anisotropy reflects then the relative importance of each spin-orbit interaction component. Anisotropy measurements reveal also signs of spin-rotation topology.

The PI of the project has collaborated with the research group of prof. Diego Frustaglia at University of Seville, Spain. While the PI perfomed large-scale 2D quantum transport simulations of semiconductor ring arrays the group of prof. Frustaglia is focusing on complementary perturbation analysis as well as physical interpretation of anisotropy. Experimental aspects of this work has been discussed intensively with prof. Junsaku Nitta at Tohoku University.

2. Specific usage status of the system and the calculation method

The PI of the project performed 2D quantum transport simulations in anisotropic spin-orbit fields using the Kwant software package (www.kwant-project.org). This is a free-to-use python programming language based code that uses highly efficient sparse matrix solvers to obtain solution of the transport problem. In realistic simulations of large mesoscopic arrays disorder is modeled using Ando type of random lattice disorder. Conductance is then obtained via averaging over large random distributions of disorder configurations. To simulate realistic ring arrays a large number of transport calculations is then needed. This consumes lots of computing power. Moreover, real-space modeling of 2D ring arrays requires large memory capacity of several Gb.

During the past fiscal year 12.6M core-hours has been used at Hokusai supercomputer (status on 13th of Feb). Moreover, additional 1.4M core-hours was used in the BigWaterFall system. The calculations resulted in high-quality data and was used to prepare manuscripts.

3. Results

The simulations were used to obtain signatures of anisotropic spin-orbit fields in spin transport under Rashba and Dresselhaus spin-orbit fields and an in-plane magnetic field. Moreover, the results established that spin-rotation topology can be determined from the pattern of anisotropy phase (see Fig. 1 and H. Saarikoski et al., Phys. Rev. B 91, 241406(R) (2015)). These results were used to prepare a manuscript

https://arxiv.org/abs/1710.07810

The manuscript has been under review in Physical Review B since October 2017.

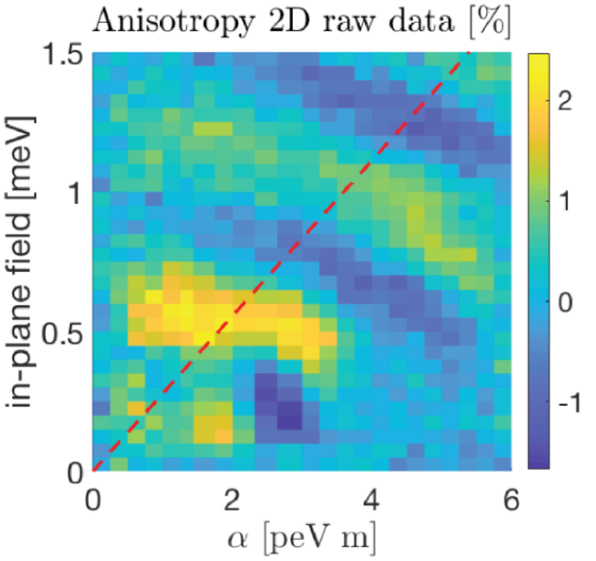

Figure 1 Anisotropy in quantum transport simulations of a large ring array showing a topological transition (shift in the interference pattern) around the dashed critical line. Calculated using the Hokusai supercomputer. From preprint arXiv:1710.07810 (2017).

In addition to these results calculations were performed to simulate measurements conducted at the Nitta group at Tohoku University. Excellent correspondence with the measurements was obtained with some intriguing unexpected signals showing emergence of possible new physical phenomena. Manuscript of these results is under preparation. The next project would involve square-shaped quantum ring interferometers and simulations were also undertaken in preparation of a manuscript. These projects are projected to continue to the next fiscal year.

4. Conclusion

The ACCC supercomputers were heavily used in the quantum transport simulation work. The method was found to adequately capture the physical characteristics of the spin-interferometers in anisotropic spin-orbit fields. Large-scale simulations were used in the preparation of manuscript on spin-interference physics.

5. Schedule and prospects for the future

Measurements of spin-orbit anisotropy in a ring array has been performed in the Nitta group at Tohoku university and results will be published shortly. Simulations of large quantum ring interferometers were undertaken and these results will be compared to the experimental data (see Fig. 2). Data indicates that gate voltage can be used to control spin-interference anisotropy in a mesoscopic ring array.

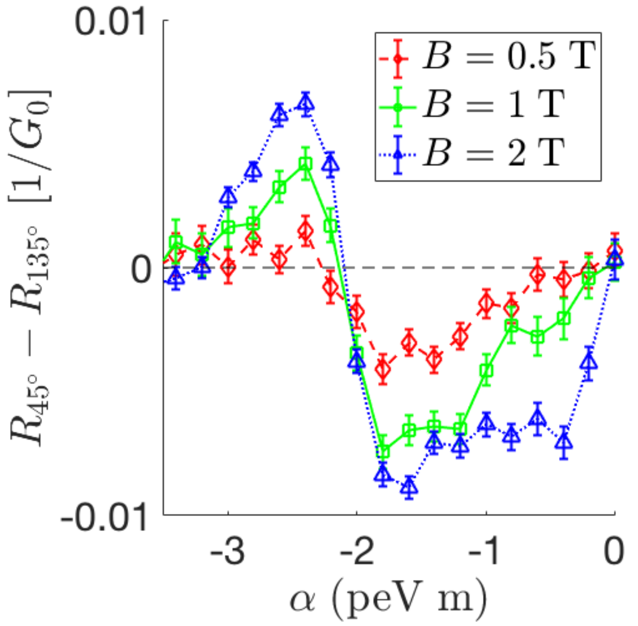

Figure 2 Degree of resistance anisotropy in a semiconductor quantum ring array as a function of Rashba spin-orbit interaction **α** under in-plane magnetic fields of 0.5T, 1T, and 2T. The Dresselhaus interaction strength **β** is constant at 0.3 peV m. Anisotropy phase switches at about **α =-2 peV m.** Preliminary results calculated using the Hokusai supercomputer.

Prospects for the future include transport simulations in square and polygonal shaped ring interferometers. Square shaped quantum rings has been fabricated in the Nitta group at Tohoku University.

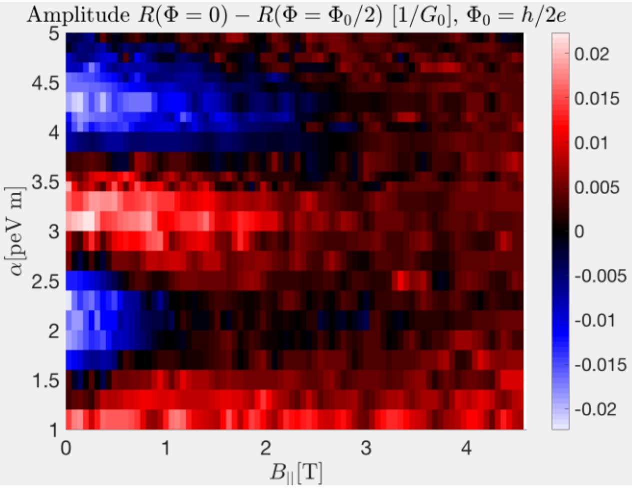

Figure 3 Aharonov-Casher oscillation amplitude calculated for a square quantum ring as a function of in-plane magnetic field $\mathrm{B}_{||}$ and Rashba spin-orbit interaction **α**. Preliminary results calculated using the Hokusai system.

Discontinuous electron propagation direction in a square-shaped quantum ring gives rise to nonadiabatic effects as the spin begins to precess after crossing the vertex point. This precessio gives rise to large geometric phases where the rotation topology becomes important. Preliminary calculations and measurements have been performed on these systems.

Figure 3 shows calculated Aharonov-Casher amplitude oscillations in a square quantum ring array. Interestingly the amplitude shows reversal from negative to positive as the magnetic field increases. This suggests a topological transition for the spin rotation trajectories in a round-trip around the square.

In addition to InGaAs-based semiconductor interferometers a collaboration between the PI and Dr. Minoru Kawamura at RIKEN CEMS has been initiated. Dr. Kawamura is focused on realizing polygonal ring interference devices using a BiSbTe topological insulator system (see Fig. 4). The Hamiltonian of the system is k-linear to lowest order approximation and interference effects are expected to arise despite higher disorder densities. Simulations to model the system are under way and should provide high-quality predictions of the physics that emerges.

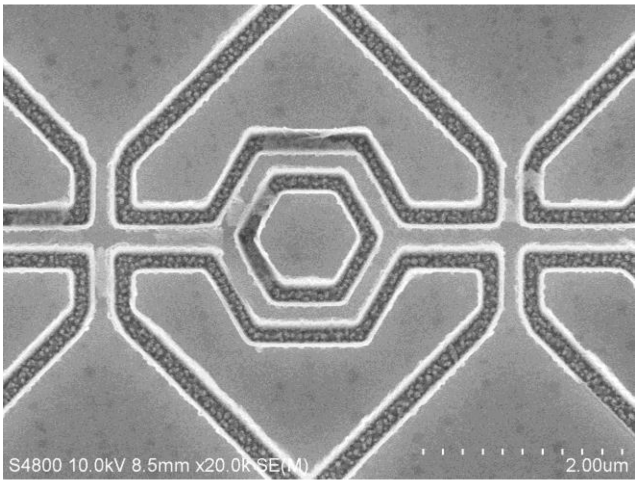

Figure 4 Micrograph of a polygonal quantum ring on a topological insulator. Hokusai system will be employed to calculate transport in these systems. Courtesy of Dr. Kawamura at RIKEN CEMS.

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Fiscal Year 2017 List of Publications Resulting from the Use of the supercomputer

Some of the research results have been submitted to Physical Review B in October 2017. The manuscript is available as a pre-print :

Henri Saarikoski, Andrés Reynoso, José Pablo Baltanás, Diego Frustaglia, Junsaku Nitta, *Spin-interferometry in anisotropic spin-orbit fields*, arXiv:1710.07810 (2017).

ACCC is knowledged in this work. The preprint is attached here.