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研究課題名（和文）Topological Transitions in Spin Transport in Nanostructures

研究課題名（英文）Topological Transitions in Spin Transport in Nanostructures

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研究成果の概要（和文）：電子の角運動量などの理論上スピンを含む量子力学について研究を行った。スピン干渉計における幾何学的効果を計算し、外部磁場を用いてスピン位相の幾何学的寄与をオン/オフできることを示した。「オンとオフ」の間の移行は、実験で直接識別できる有効な幾何学的位相と呼ばれる新しい量を含むことが判明した。実験者達と共に例えば互いに反強磁性的になる二層金属ワイヤーにおいて、磁壁可動性が大幅に向上していることすらも明らかにした。その影響は異等方的に結合した非断熱駆動に起因すると見出された。このメカニズムは効果的磁壁デバイスの設計にも利用できる。これらの結果は微分幾何学にも関係することから学際的ともいえる。

研究成果の概要（英文）：We studied theoretically various quantum mechanical systems involving spin, i.e., electrons's internal angular momentum. We calculated geometric effects in spin interferometers and showed that the geometric contribution of spin phase can be switched on and off using an external magnetic field. The transition between 'on and 'off' states was found to involve a new quantity called an effective geometric phase that is directly observable in experiments. Together with experimentalists we further showed that domain wall mobility may be greatly enhanced in synthetic antiferromagnets, i.e., double-layer metallic wires that are antiferromagnetically coupled to each other. The effect was found to be due to nonadiabatic driving of anisotropically coupled walls. This mechanism can be used to design efficient domain-wall devices. These results are also interdisciplinary since they are connected with the mathematics of differential geometry.

研究分野：spintronics

キーワード：spintronics　geometry　interference　spin-orbit　topology　Rashba

１．研究開始当初の背景

Spin phenomena in metals and semiconductors have been among the most studied topics in spin electronics, i.e. spintronics. Especially topology of spin structures and the spin-guiding fields have been under intense research efforts. The possibility to control spin response by changing the topology of the path of transported spin gives physicists robust tools to control, transport and manipulate spin. Topology of a controlling path of the field used in the spin control may be protected against small changes brought about by noise and impurities in the system. Spin manipulation that depends on topological properties of the transport path are therefore very tolerant against imperfections.

２．研究の目的

In this research project we investigated various spin transport phenomena with focus especially on the effects of topology on field and spin structures. The project belongs to the field of spintronics with interdisciplinary aspects from the mathematical field of differential geometry. These interdisciplinary aspects arise from the studies of geometric phases that are important in spin interference.

The project followed two distinct research paths. The first path focused on domain wall dynamics in metallic synthetic antiferromagnets that are double-layer metallic nanowire antiferromagnetically coupled to each other.

The second research path focused on spin interference phenomena in semiconductor quantum devices. The studied mesoscopic devices included loop and ring shaped interferometers.

３．研究の方法

The state-of-the-art KWANT software package was used to numerically calculate spin interference in mesoscopic systems. In disordered systems these are computationally very intensive. During this project the HOKUSAI massively parallel computer system at RIKEN was extensively used to numerically solve the realistic case of multi-mode transport in mesosopic spin interferometers with Ando-type of lattice disorder. Millions of core-hours were used at the system each fiscal year.

In the case of metallic systems a 1D method to describe coupled domain wall motion in a synthetic antiferromagnet was first developed in publication number #6 below. This was subsequently used to study coupled domain wall motion. The array of differential equations was solved using Matlab software package on a desktop computer.

４．研究成果

The outstanding research results were achieved in studies of synthetic antiferromagnets. In collaboration with experimentalists we published a paper in Scientific Reports (publication #2 below) that reported an order of magnitude improvement of domain-wall threshold current density in comparison to metallic single-layer nanowires. Theoretical modelling indicated that this was due to nonadiabatic driving of anisotropically coupled walls. This mechanism can be used to design efficient domain-wall devices.

Subsequent work on domain wall dynamics included a study of domain wall stopping mechanism using Rashba interaction embedded in the wire (publication #3).

Calculations in semiconductor spin interferometers indicated that topological transitions in electronic spin transport can be achieved by a controlled manipulation of spin-guiding fields. The transitions were determined by the topology of the fields texture through an effective Berry phase. This phase was related to the winding parity of spin modes around poles in the Bloch sphere, irrespective of the actual complexity of the nonadiabatic spin dynamics (publication #5). We reported transport simulations showing a topological phase transition away from the adiabatic limit where the transition is determined by the topology of the field texture through an *effective Berry phase* related to the winding parity of the spin eigenmodes around the poles in the Bloch sphere. This contrasted with the actual complexity of the emerging dynamic phases and Aharonov-Anandan geometric phases, which exhibit a complex correlated behavior close to the transition.

Interestingly an analogous topological transition in the effective Berry phase was also found in classical systems where a magnetic moment precesses in a magnetic field texture (publication #4). This connects the results to differential geometry of the rotations. Our results have therefore a general validity and applications in diverse fields of physics such as electron spin resonance experiments as discussed in publication #1.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

The PI of the project has been marked with an underline. The coinvestigator has been marked with dashed underline.

〔雑誌論文〕（計　6　件）

1. A. A. Reynoso, J. P. Baltanás, H. Saarikoski, J. E. Vázquez-Lozano, J. Nitta, and D. Frustaglia, *Spin resonance under topological driving fields*, New Journal of Physics **19**, 063010 (2017). (refereed)
2. S. Lepadatu, H. Saarikoski, R. Beacham, M. J. Benitez, T. A. Moore, G. Burnell, S. Sugimoto, D. Yesudas, M. C. Wheeler, J. Miguel, S. S. Dhesi, D. McGrouther, S. McVitie, G. Tatara, and C. H. Marrows, *Synthetic ferrimagnet nanowires with very low critical current density for coupled domain wall motion*, Scientific Reports **7**, 1640 (2017). (refereed)
3. G. Tatara, H. Saarikoski, and C. Mitsumata, *Efficient stopping of current-driven domain wall using a local Rashba field*, Applied Physics Express **9**, 103002 (2016). (refereed)
4. H. Saarikoski, José Pablo Baltánas, J. Enrique Vázquez-Lozano, Junsaku Nitta, and Diego Frustaglia, *Effective geometric phases and topological transitions in SO(3) and SU(2) rotations*, Journal of Physics: Condensed Matter **28**, 166002 (2016). (refereed)
5. H. Saarikoski, J. Enrique Vázquez-Lozano, José Pablo Baltanás, Fumiya Nagasawa, Junsaku Nitta, and Diego Frustaglia, *Topological transitions in spin interferometers*, Physical Review B **91**, 241406(R) (2015). (refereed)
6. H. Saarikoski, H. Kohno, C. H. Marrows, and G. Tatara, *Current-driven dynamics of coupled domain walls in a synthetic antiferromagnet*, Physical Review B **90**, 094411 (2014). (refereed)

〔学会発表〕（計　15　件）

12/2017 H. Saarikoski, "Geometric phase switching in mesoscopic rings", CEMS-Tsinghua-APW Joint Workshop, RIKEN Okochi Hall, Wako, Japan. (poster)

11/2017 H. Saarikoski, “Spin interferometry in circular and polygonal mesoscopic rings”, CEMS Symposium on Trends in Condensed Matter Physics, RIKEN Wako, Japan. (poster)

11/2017 H. Saarikoski, "Geometric Phase Switching in Circular and Polygonal Mesoscopic Rings", ISNTT2017 Conference, NTT Atsugi R&D Center, Atsugi, Japan. (poster)

8/2017 H. Saarikoski, “Spin interferometry in anisotropic spin-orbit fields”, Nano-Spin Conversion workshop, Osaka University, Osaka, Japan, September 2017.

6/2017 H. Saarikoski, "Spin interference in anisotropic spin-orbit fields in mesoscopic rings", SpinTECH IX conference, Fukuoka International Congress Center, Fukuoka, Japan. (poster)

8/2016 H. Saarikoski, "Topological effects in spin interference", PASPS9 conference (9th International Conference on Physics and Applications of Spin-related Phenomena in Solids), Kobe, Japan (contributed talk)

3/2016 H. Saarikoski, "Effective geometric phases and topological transitions in SO(3) and SU(2) rotations", German Physical Society (DPG) Spring Meeting 2016, Regensburg (contributed talk)

3/2016 H. Saarikoski, "Topological transitions in spin interferometers", Japanese Physical Society (JPS) Spring Meeting 2016 (contributed talk)

1/2016 H. Saarikoski, "Reduced critical current density for motion of coupled domain walls in synthetic ferrimagnet nanowires", MMM-Intermag conference, San Diego (poster)

3/2015 H. Saarikoski, "Topological transitions in spin interferometers", APS March Meeting 2015, San Antonio (contributed talk)

3/2015 H. Saarikoski, "Topological transitions in spin interferometers", Japanese Physical Society (JPS) Spring Meeting 2015 (contributed talk)

3/2015 H. Saarikoski, "Topological transitions in spin interferometers", German Physical Society (DPG) Spring Meeting 2015, Berlin (contributed talk)

9/2014 H. Saarikoski, "Topological transition in Aharonov-Anandan geometric phase of spin in mesoscopic rings", 4th Summer School on Semiconductor/Superconducting Quantum Coherence Effects and Quantum Information, Nasu, Japan (talk)

7/2014 H. Saarikoski, "Current-driven domain-wall dynamics in a synthetic antiferromagnet", joint Tohoku-Riken workshop, Kaminoyama, Japan (talk)

3/2014 H. Saarikoski, "Geometric phase of electron spin in semiconductor quantum rings - phase manipulation and topological transitions ", joint DFG-JST workshop on Topotronics, Hakone, Japan (talk)

６．研究組織

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