New Perspectives in Spintronic and Mesoscopic Physics

SPINTRONICS

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MESOSCOPICS

ISSP international Workshop: Jun 1 (Mon) – 19 (Fri), 2015

The Institute for Solid State Physics, The University of Tokyo, Kashiwa, Japan

Symposium: Jun 10 (Wed) – 12 (Fri), 2015

Kashiwa-no-ha Conference Center, Kashiwa, Japan

The ninth of the annual ISSP International workshop/symposium on New Perspectives in Spintronic and Mesoscopic Physics (NPSMP2015) will be held in Kashiwa, Japan, from June 1 to 19, 2015.

Scope:

The workshop aims at harnessing two differently evolving but closely related sub-disciplines of condensed matter physics, i.e. mesoscopic and spintronic physics.

Mesoscopic physics has been an active research field since the 1980s, and has enabled us to elucidate the quantum mechanical nature of electrons by utilizing modern nano-fabrication technologies for semiconductors. Recent theoretical and experimental developments have deepened insight on mesoscopic systems, and also strengthened relationship with other research fields such as nonequilibrium statistical mechanics, quantum information, many-body quantum theory, fundamental theory of quantum mechanics, and so on. Physics of spintronics has also been evolving since the discovery of giant magnetoresistance in 1988. It now covers all the spin-related phenomena such as pure spin currents, spin injection, spin transfer torque, spin Hall effect, and so on. The spintronic physics is not only a basis of practical technologies, but also provides a variety of fundamental concepts relevant to mesoscopic physics such as spin diffusion, spin currents, Berry phases, and phenomena originated from spin-orbit interaction.

The goal of this workshop is to address important common future issues for both spintronic and mesoscopic physics by sharing recent theoretical and experimental developments in these research fields and to pave a way towards breakthrough in the interdisciplinary research area.

Organizers:

Takeo Kato	(Chair, ISSP, The University of Tokyo)
Yoshichika Otani	(Chair, ISSP, The University of Tokyo)
Sadamichi Maekawa	(ASRC, Japan Atomic Energy Agency)
Gerrit E. W. Bauer	(IMR, Tohoku University)
Shingo Katsumoto	(ISSP, University of Tokyo)
Yasuhiro Tokura	(University of Tsukuba)
Mikio Eto	(Keio University)
Gen Tatara	(CEMS RIKEN)
Kensuke Kobayashi	(Osaka University)

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Computational Materials Science Initiative (CMSI),
Elements Strategy Initiative Center for Magnetic Materials (ESICMM)
Tokodai Institute for Element Strategy (TIES)

PROGRAM OF WORKSHOP

The first week "Mesoscopic Physics"

Jun. 1 (Mon.)		
10:25- 10:30	Opening	
10:30- 11:30	W1-1 A. Kovalev (University of Nebraska-Lincoln)	Magnetization pumping and dynamics in a Dzyaloshinskii-Moriya magnet
14:00- 14:30	W1-2 G. Tatara (RIKEN)	Thermal vector potential theory of transport induced by temperature gradient
14:30- 15:00	W1-3 M. Kimata (The University of Tokyo)	Spin transport and relaxation mechanism in disordered organic film
Jun. 2 (Tue.)		
10:30- 11:30	W2-1 G. Zarand (Budapest University of Technology and Economics)	Failure of thermalization and the generalized Gibbs ensemble hypothesis in strongly interacting quantum systems
14:00- 14:30	W2-2 S. C. Furuya (University of Geneva)	Negative Coulomb drag in coupled quantum wires
Jun. 3 (Wed.)		
10:30- 11:30	W3-1 T. Kato (The University of Tokyo)	Kondo signature in heat transport via a local two-state system
14:00- 14:30	W3-2 Y. Tokura (Tsukuba University)	Quantum pumping in mesoscopic systems
Jun. 4 (Thu.)		
10:30- 11:30	W4-1 V. Meden (RWTH Aachen University)	Luttinger liquid universality after a quantum quench
14:00- 14:30	W4-2 A. Oguri (Osaka City University)	Some new analytical and numerical approaches to an SU(*N*) impurity Anderson model
14:30- 15:00	W4-3 C. Uchiyama (University of Yamanashi)	Nonadiabatic effect on the quantum heat flux control
Jun. 5 (Fri.)		
10:30- 11:30	W5-1 R. Egger (Heinrich Heine University Düsseldorf)	Topological Kondo effect in Majorana devices
14:00- 14:30	W5-2 R. Yoshimi (The University of Tokyo)	Quantum transport phenomena in 3D topological insulator thin films
14:30- 15:00	W5-3 K-I. Imura (Hiroshima University)	Mesoscopic topological insulator

The second week “Interdisciplinary Topics”

Jun. 8 (Mon.)		
10:30- 11:30	W8-1 T. Martin (Aix-Marseille University)	Interactions and charge fractionalization in an electronic Hong-Ou-Mandel interferometer
14:00- 14:30	W8-2 T. Arakawa (Osaka University)	Shot noise induced by spin accumulation
14:30- 15:00	W8-3 S. Katsumoto (The University of Tokyo)	Coherent transport under spin-orbit interaction
Jun. 9 (Tue.)		
10:30- 11:30	W9-1 R. Wiesendanger (University of Hamburg)	Exploring spins at surfaces by spin-polarized STM
13:30- 16:45	Related mini-workshop in ISSP “Spins at Surfaces”	

The third week "Spintronic Physics"

Jun. 15 (Mon.)		
10:30- 11:30	W15-1 I. Žutić (State University of New York at Buffalo)	Spintronics beyond magnetoresistance: putting spin in lasers
14:00- 15:00	W15-2 L. Levitov (Massachusetts Institute of Technology)	Constructing topological bands in generic materials
15:00- 16:00	W15-3 W. Belzig (University of Konstanz)	Quasiclassical circuit theory of spin transport in superconducting heterostructures
Jun. 16 (Tue.)		
10:30- 11:30	W16-1 E. Y. Tsymbal (University of Nebraska-Lincoln)	Spintronics with ferroelectrics
14:00- 14:30	W16-2 J. Ieda (Japan Atomic Energy Agency)	Perpendicular magnetic anisotropy induced by Rashba spin-orbit interaction
14:30- 15:00	W16-3 O. A. Tretiakov (Tohoku University)	Antiferromagnetic skyrmions
Jun. 17 (Wed.)		
10:30- 11:30	W17-1 H. Ebert (Ludwig Maximilians University Munich)	Transport properties calculated by means of the Kubo formalism
14:00- 14:30	W17-2 M. Koshino (Tohoku University)	Electronic transmission through the atomic domain boundary ---- from graphene to transition metal dichalcogenides
14:30- 15:00	W17-3 J. Barker (Tohoku University)	The effect of spin waves in the spin Seebeck Effect
Jun. 18 (Thu.)		
10:30- 11:30	W18-1 A. MacDonald (The University of Texas at Austin)	Quantum Hall effects for spintronics
Jun. 19 (Fri.)		
10:30- 11:30	W19-1 Y. Tserkovnyak (University of California, Los Angeles)	Spin and orbital magnetic response on the surface of a topological insulator
14:00- 14:30	W19-2 Y. Shiomi (Tohoku University)	Spin-electricity conversion induced by spin pumping into topological insulators
14:30- 14:40	Closing	

PROGRAM OF SYMPOSIUM

The first day

Jun. 10 (Wed.)		
9:20- 9:30	Opening	
9:30- 10:00	S10-1 H. Ebert (Ludwig Maximilians University Munich)	New effects in spintronics derived from the symmetry of response functions
10:00- 10:30	S10-2 Y. Niimi (Osaka University)	Detection of spin fluctuations in spin glass via spin Hall effect
	break	
11:00- 11:30	S10-3 Y. Tserkovnyak (University of California, Los Angeles)	Spin transport through antiferromagnets
11:30- 12:00	S10-4 T. Moriyama (Kyoto University)	Spin torque ferromagnetic resonance measurements in antiferromagnetic multilayers
12:00- 12:30	S10-5 D. Hou (Tohoku University)	Spin Hall angle dispersion driven anomalous Hall effect
	Lunch	
13:50- 14:20	S10-6 K. Usami (The University of Tokyo)	Bidirectional conversion between microwave and light via ferromagnetic magnons
14:20- 14:50	S10-7 A. Oiwa (Osaka University)	Conversion from single photons to single electron spin using GaAs-based double quantum dots
14:50- 15:20	S10-8 N. Mizuochi (Osaka University)	Single spin, photon, and charge manipulation of NV center in diamond
	Break	
15:50- 16:20	S10-9 I. Žutić (State University of New York at Buffalo)	Teaching nanomagnets new tricks
16:20- 16:50	S10-10 Y. Kozuka (The University of Tokyo)	Quantum Hall effects at oxide interfaces
16:50- 17:20	S10-11 E. Y. Tsymbal (University of Nebraska-Lincoln)	Local currents in a two-dimensional topological insulator
17:20- 17:50	S10-12 M. Matsuo (Japan Atomic Energy Agency)	Theory of spin mechatronics

The second day

Jun. 11 (Thu.)		
9:00- 9:30	S11-1 A. Kovalev (University of Nebraska-Lincoln)	Stability of skyrmion lattices and symmetries of Dzyaloshinskii-Moriya magnets
9:30- 10:00	S11-2 S. Seki (RIKEN)	Chirality and ferromagnetism
10:00- 10:30	S11-3 R. Wiesendanger (University of Hamburg)	Complex spin states by interfacial Dzyaloshinskii-Moriya interactions: from single atoms to thin films
	Break	
11:00- 11:30	S11-4 V. Meden (RWTH Aachen University)	Coherence by elevated temperature
11:30- 12:00	S11-5 M. Ferrier (University of Paris-Sud, and Osaka University)	Shot noise monitoring of the cross-over between SU(4) and SU(2) symmetry of the Kondo effect in a carbon nanotube quantum dot
12:00- 12:30	S11-6 G. Zarand (Budapest University of Technology and Economics)	Universal Fermi liquid crossover and quantum criticality in a mesoscopic system
12:30- 12:40	Photo Session	
	Lunch	
13:50- 14:20	S11-7 L. Levitov (Massachusetts Institute of Technology)	Topological valley currents in gapped Dirac materials
14:20- 14:50	S11-8 Y. Iwasa (The University of Tokyo)	Chiral electroluminescence from 2D material based transistors
14:50- 15:20	S11-9 T. Machida (The University of Tokyo)	Quantum transport in van der Waals heterostructures of graphene and 2D materials
15:20- 15:50	S11-10 Y. Shimazaki (The University of Tokyo)	Valley Hall effect in electrically spatial inversion symmetry broken bilayer graphene
15:50- 17:50	Poster Session	
18:00-	Banquet: Kashiwa-no-ha Conference Center Room 1 and 2	

The third day

Jun. 12 (Fri.)		
9:30- 10:00	S12-1 T. Yokoyama (Delft University of Technology)	Singularity of the spectrum of Andreev levels in multi-terminal Josephson junction
10:00- 10:30	S12-2 B. Trauzettel (University of Würzburg)	Superconducting hybrid structures based on quantum spin Hall systems
	Break	
11:00- 11:30	S12-3 N. Kumada (NTT Basic Research Laboratories)	Mode mixing in graphene *p-n* junctions investigated by shot noise measurement
11:30- 12:00	S12-4 T. Martin (Aix-Marseille University)	Josephson like effect and Cooper pair transfer in multi-terminal superconducting devices
12:00- 12:30	S12-5 M. Hashisaka (Tokyo Institute of Technology)	Fractional charge tunneling through a local fractional quantum Hall system measured using cross-correlation noise measurements
	Lunch	
13:50- 14:20	S12-6 Y. Utsumi (Mie University)	Fluctuation theorem for a small engine and magnetization switching by spin torque
14:20- 14:50	S12-7 W. Belzig (University of Konstanz)	Spin-dependent thermoelectric effects and spin-triplet-supercurrent in mesoscopic superconductors
14:50- 15:20	S12-8 K. Saito (Keio University)	Waiting for rare entropic fluctuations in mesoscopic physics
	Break	
15:50- 16:20	S12-9 K. Nomura (Tohoku University)	Coupled charge and magnetization in a Weyl semimetal
16:20- 16:50	S12-10 T. Hanaguri (RIKEN)	Imaging the wave functions of Dirac-Landau levels in the topological surface state
16:50- 17:20	S12-11 S. Murakami (Tokyo Institute of Technology)	Helical transport in helical crystals
17:20- 17:50	S12-12 Y. Ando (Kyoto University)	Conversion from a charge current into a spin polarized current in the surface state of three-dimensional topological insulator
17:50- 18:00	Closing	

PROGRAM OF POSTER SESSION

15:30- 17:30 on June 11.

PS01	T. Kikuchi (RIKEN)	Magnetization dynamics with inertia in metallic ferromagnets
PS02	M. Sato (Aoyama Gakuin University, JAEA, ERATO)	Coherent control of magnetizations and spin currents in quantum magnets with laser
PS03	K. Yamamoto (The University of Tokyo)	Thermodynamics of mesoscopic steady-state heat engine beyond linear-response regime
PS04	M. Taguchi (University of Tsukuba)	Mode engineering with a one-dimensional superconducting metamaterial
PS05	T. Kuwahara (The University of Tokyo)	Persistent metastability in periodically driven systems
PS06	J. Kim (RIKEN)	Giant spin Hall magnetoresistance in metallic bilayers
PS07	S. Kobayashi (Nagoya University)	Topological superconductivity in Dirac semimetals
PS08	N. Okuma (The University of Tokyo)	Spin Hall effect of Dirac fermions with vanishing spin current operator
PS09	X -X. Zhang (The University of Tokyo)	Electrical transport in three-dimensional cubic Skyrmion crystal
PS10	S. Tanaka (Waseda University)	Topological phase transition and sweep dynamics of a generalized cluster model in one dimension
PS11	T. Chiba (Tohoku University)	Magnetization damping in antiferromagnetically coupled spin valves
PS12	T. Ohta (Kyoto University)	Majorana fermions with spatially periodic modulation
PS13	N. Norizuki (Nagoya University)	Effect of Rashba spin-orbit coupling in diamagnetic current induced by nonuniform magnetic field
PS14	O. Sato (Kyushu University)	Cyanide-bridged Fe_{42} high-spin nanocage with S = 90/2
PS15	W. Izumida (Tohoku University)	Valley coupling, spin-orbit interaction and vernier-scale-like spectrum in finite-length metallic single-wall carbon nanotubes

PS16	H. Kawaguchi (Tokyo Metropolitan University)	Novel coupling between spin and electromagnetic field in a ferromagnetic metal with Rashba spin-orbit interaction
PS17	S. Hatanaka (Osaka University)	Detection of ferromagnetic resonance in CoFeB by tunnel anisotropic magnetoresistance
PS18	T. Hata (Osaka University)	Shot-noise of a superconductor/nanotube junction in the Kondo regime
PS19	H. Kiyama (Osaka University)	Single-shot readout of electron spins in a quantum dot using spin filtering by quantum Hall edge states
PS20	B. Gu (Japan Atomic Energy Agency)	Enhanced spin Hall effect in CuBi alloys
PS21	I. Suzuki (Tokyo Institute of Technology)	Artificial control of magnetic phase transition of B2 ordered FeRh-based thin films
PS22	R. Wakatsuki (The University of Tokyo)	Domain wall of a ferromagnet on a three-dimensional topological insulator
PS23	T. Suzuki (The University of Tokyo)	Photon-assisted current noise through a quantum dot system with an oscillating gate voltage
PS24	K. Hamamoto (The University of Tokyo)	Quantized anomalous Hall effects in skyrmion crystal
PS25	Z. Xu (Japan Atomic Energy Agency)	The Cu alloys doped with 5d elements as materials for the control of the sign of spin Hall effect
PS26	A. Osada (The University of Tokyo)	Cavity optomagnonics in a ferromagnetic sphere
PS27	K. Nakazawa (Nagoya University)	Anomalous Hall effect and persistent current due to spin chirality in a diffusive regime
PS28	K. Ohnishi (Kyushu University)	Spin current transport in a Nb/Cu/NiFe tri-layer structure
PS29	M. Ono (Japan Atomic Energy Agency)	Barnett effect in a paramagnetic state
PS30	K. Kobayashi (Sophia University)	Universal conductance distributions in disordered topological insulator nanofilms
PS31	W. Zhou (Tohoku University)	Electromotive force in a $L1_0$-FePt / $Ni_{81}Fe_{19}$ bilayer element

PS32	Y. Yoshimura (Hiroshima University)	Emergent quantum spin hall system in topological insulator nanofilms
PS33	K. Kuroyama (The University of Tokyo)	Quantum entanglement conservation in coherent quantum state transfer from a single photon polarization to an electron spin in a lateral double quantum dot
PS34	J-H. Park (RIKEN)	Quantum dot thermometry at millikelvin temperature
PS35	P. Stano (RIKEN)	How to detect helical order of a one-dimensional magnet
PS36	M. Kawano (Osaka University)	Electrical spin injection and detection across epitaxial Ge/Fe_3Si heterointerfaces
PS37	Y. Hashimoto (The University of Tokyo)	Spin injection from epitaxially grown Fe to Two-dimensional electrons in InAs quantum well
PS38	K. Yamasaki (Osaka University)	Spin-dependent Peltier effect in Co_2FeSi/Cu lateral spin-valve devices
PS39	F. Ishii (Kanazawa University)	First-principles study of spin-orbit coupling parameters and bult-in electric field in $LaAlO_3/SrTiO_3$
PS40	T. Hashimoto (Nagoya University)	Surface electronic state of topological crystalline insulator in superconducting state
PS41	T. Fukumoto (Nagoya University)	Theory of tunnel conductance in helical metal/superconductor junction
PS42	Y. Iwasaki (The University of Tokyo)	Conductance fluctuation versus in-plane magnetic field in an InAs quantum corral
PS43	M. Nakamura (The University of Tokyo)	Detection of topological states in two-dimensional Dirac systems by dynamic spin susceptibility
PS44	T. Yamaguchi (Nagoya University)	Linear response theory of spin torques due to spin waves
PS45	T. Nakamura (The University of Tokyo)	Enhancement of spin-orbit interaction in graphene due to hydrogenation
PS46	K. Harii (Japan Atomic Energy Agency)	Rotation angle dependence of NMR line structures in various nuclides
PS47	J. Fujimoto (Kyoto University)	Effects of Dirac points on Rashba spin-orbit torques

PS48	M. A. U. Absor (Kanazawa University)	Persistent spin helix on the ZnO (10-10) surface: fully relativistic study
PS49	H. Saarikoski (RIKEN)	Topological transitions in spin interferometers
PS50	M. Salehi (Sharif University of Technology)	Quantum transport through 3D Dirac materials
PS51	R. Beiranvand (Ayatollah Boroujerdi University)	Half-metallic ferromagnetism in Mn-doped zigzag AlN nanoribon from first-principles
PS52	Y. Teratani (Osaka City University)	Kondo effect in a carbon nanotube quantum dot with a finite orbital splitting and a magnetic field
PS53	G. Tatara (RIKEN)	Phasons and excitations in skyrmion lattice
PS54	T. An (Japan Advanced Institute of Science and Technology)	Application of NV-Center Spin Probe to Spintronics

Abstracts of Workshop

W1-1

Magnetization pumping and dynamics in a Dzyaloshinskii-Moriya magnet

Alexey Kovalev,[1]

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We formulate a phenomenological description of Dzyaloshinskii-Moriya magnets where the single-domain magnetic dynamics experiences magnon current-induced torques (an analog of spin-orbit torques) and leads to magnon-motive forces. We first construct a phenomenological theory based on irreversible thermodynamics, taking into account the symmetries of the system [1]. Furthermore, we confirm that these effects originate from Dzyaloshinskii-Moriya interactions from the analysis based on the stochastic Landau-Lifshitz-Gilbert equation. Our phenomenological results generalize to a general form of Dzyaloshinskii-Moriya interactions and to other systems, such as pyrochlore crystals and chiral magnets. We discuss how the magnonic analog of the spin-orbit torque can influence the motion of magnetic solitons, e.g. skyrmions. Possible applications include spin current generation, magnetization reversal and magnonic cooling (Fig.1).

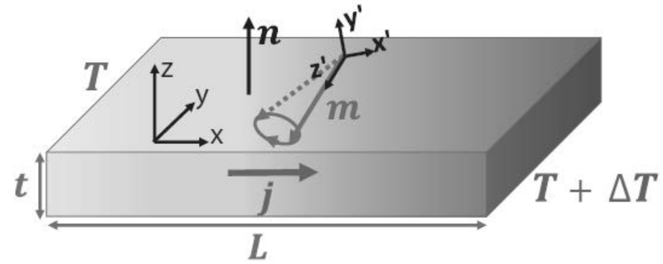

Figure 1: Single-domain magnetization dynamics induced by microwave field pumps magnon and spin currents by virtue of Dzyaloshinskii-Moriya interactions. This can develop a temperature gradient along the sample. Alternatively, a temperature gradient can result in magnon current and torque on uniform magnetization according to the Onsager reciprocity principle.

References

[1] Alexey A. Kovalev and Utkan Gungordu, EPL, 109 (2015) 67008.

W1-2

Thermal vector potential theory of transport induced by temperature gradient

Gen Tatara

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A microscopic formalism to calculate thermal transport coefficients is presented based on a thermal vector potential, whose time-derivative is related to a thermal force. The formalism is free from unphysical divergences reported to arise when Luttinger's formalism is applied naively, because the equilibrium (¥textquoteleft diamagnetic¥textquoteright) currents are treated consistently. The mathematical structure for thermal transport coefficients are shown to be identical with the electric ones if the electric charge is replaced by energy.   The results indicates that the thermal vector potential couples to energy current via the minimal coupling.

References

[1] G. Tatara, Phys. Rev. Lett., to appear (2015) (arXiv:1502.00347).

W1-3

Spin Transport and Relaxation Mechanism in Disordered Organic Film

Motoi Kimata,[1] Daisuke Nozaki[1], Yasuhiro Niimi[1],
Hiroyuki Tajima[2], and YoshiChika Otani,[1,3]

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The organic semiconductors (OSCs) are promising candidates for long-distance spin current transport. However, most of the OSCs have a strongly disordered structure, so that the spin current transport and relaxation properties of OSCs have not been fully understood compared with the usual band-like metallic materials. To resolve this problem, we have performed systematic studies of spin current transport and relaxation mechanism in a conducting polymer PEDOT: PSS, in which the PEDOT molecule is highly doped with PSS. In this study, we have carried out spin pumping, electron paramagnetic resonance, and charge transport experiments. The spin pumping experiment allows us to estimate the spin diffusion length (SDL), and the other two experiments were used to determine the spin lifetime and spin diffusion constant, respectively. The experimentally obtained spin lifetime is much shorter than that of non-doped OSCs [1]. This means that the spin relaxation is considerably enhanced in highly doped PEDOT molecules of which nano-scale grains act as trapping centers of hopping transport. Moreover, we have found a longer SDL than the average hopping length, indicating that the spins are almost conserved during the hopping process. These facts suggest the spin relaxation mainly occurs in the nano-grains of PEDOT molecules.

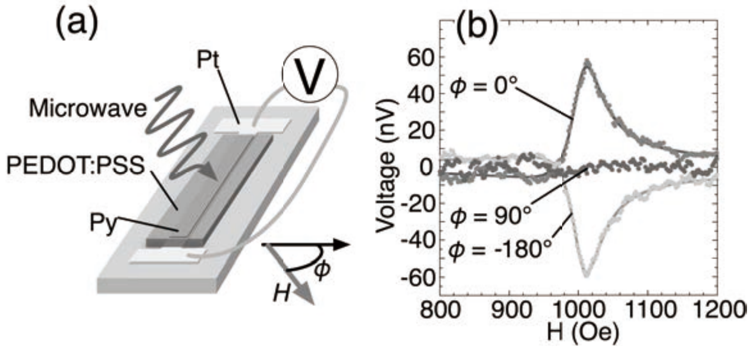

Figure 1: (a) Schematic of the sample structure used for the spin pumping experiment. (b) Magnetic field dependence of the voltage signal in Py/PEDOT:PSS/Pt trilayer for $\phi = 0^\circ$, 90°, and 180°.

References

[1] For a review, G. Szulczewski, *et.al.*, Nature Mat, **8**, 693 (2009).

W2-1

Failure of thermalization and the Generalized Gibbs Ensemble Hypothesis in strongly interacting quantum systems

G. Zarand[1], M. A. Werner[1], M. Kormos[2] , B. Pozsgay[2], M. Mestyán[2], and G. Takács[2]

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Recently, mostly triggered by the spectacular progress of experiments on cold atomic systems, considerable attention has been devoted to the equilibration of closed interacting quantum systems. I will first review some of the most basic concepts of thermalization in closed quantum systems, such as the eigenstate thermalization hypothesis (ETH) and the generalized Gibbs ensemble (GGE) hypothesis. I will then present numerical as well as analytical results for the non-equilibrium time evolution of the spin-1/2 anisotropic Heisenberg spin chain, with a choice of dimer product and Néel states as initial states [1]. We find for various short-ranged spin correlators that they deviate significantly from predictions based on the generalized Gibbs ensemble hypotheses in the long-time limit. Computing the asymptotic spin correlators within the recently proposed quench-action formalism, however, excellent agreement is found with the numerical data. These results lead us to the conclusion that the GGE cannot give a complete description of the equilibration of a closed quantum system even for local observables, while the quench-action formalism captures correctly the steady state in this case.

In the second half of my talk, I will discuss the semiclassical theory of quantum quench in the sine-Gordon model [2]. I will show that using the asymptotic S-matrix of soliton-soliton scattering, one can determine the correlation function of vertex operators analytically within the semiclassical approximation. Surprisingly, these correlations do not equilibriate, and the system exhibits a memory of the initial state. Moreover, correlations display a diffusive behavior.

References

[1] B. Pozsgay, M. Mestyán, M. A. Werner, M. Kormos, G. Zaránd, and G. Takács, Phys. Rev. Lett. **113**, 117203 (2014).

[2] M. Kormos and G. Zaránd, unpublished.

W2-2

Negative Coulomb drag in coupled quantum wires

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Coulomb drag is an induction phenomenon of the electric current by another capacitively coupled electric current, purely originating from the long-range nature of the Coulomb interaction. In coupled quantum wires (Fig. 1), positive Coulomb drag of parallel drive and drag currents was theoretically predicted. The positive drag is easily understood in view of the long-range scattering of electrons over the wires. That is, in order to avoid costing the inter-wire Coulomb potential energy generated by the drive current, the electric current is induced on the drag wire.

In 2006, Yamamoto *et al.* experimentally observed *negative* Coulomb drag of antiparallel drive and drag currents [1]. The negative drag was and is highly nontrivial in the naive picture of the long-range scattering of electrons. Initially the Wigner crystallization on the drag wire was deemed responsible for the negative drag because the negative drag was first found in the extremely low electron density region [1]. However, it was later reported that increase of the voltage of the drive and the drag wires caused alternately the positive and the negative drags [2,3]. Such an alternation in the direction of the drag current is unlikely to be explained by the Wigner crystallization on the single wire. Therefore, despite the existence of the fascinating experiments, the negative drag is yet to be clearly understood.

In this talk, we will discuss about our recent theory that explains the negative drag in a minimal setup [4]. The mechanism that we propose is simple. When the electron density of the drive wire is commensurate with the hole density of the drag wire, the particle-hole pairing over the wires occurs, resulting in the positive drag of the hole current, that is, the negative drag of the particle current.

Our simple model leads to the positive and the negative drags on equal footing. On the other hand, the negative drag occurs less easily in experiments than the positive drag does. This inequality originates from a difficulty in achieving the commensurability condition. Here the long-range nature of the Coulomb interaction plays the decisive role. We will show how the long-range Coulomb interaction conquers the difficulty and leads to the negative drag in the actual experiments.

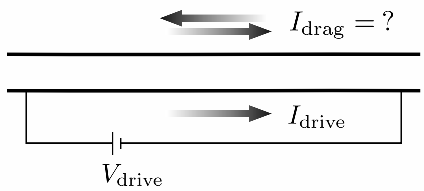

Figure 1: Coupled quantum wires

References

[1] M. Yamamoto, M. Stopa, Y. Tokura, Y. Hirayama, and S. Tarucha, Science **313**, 204 (2006).

[2] D. Laroche, G. Gervais, M. P. Lilly, and J. L. Reno, Nature Nanotech. **6**, 793 (2011).

[3] D. Laroche, G. Gervais, M. P. Lilly, and J. L. Reno, Science **343**, 631 (2014).

[4] S. C. Furuya, H. Matsuura, and M. Ogata, arXiv:1503.02499 (2015).

W3-1

Kondo signature in heat transport via a local two-state system

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Heat and electric transport have several similarities as well as dissimilarities. Fourier's law in heat transport corresponds to Ohm's law in electric transport, and these laws are commonly categorized as diffusive transport. Ballistic transport leads to the quantization of conductance in electric as well as heat transport. The conductance quantum was measured in mesoscopic electric conduction in 1988 [1], and much later, the version of heat transport was also measured [2]. Recently, the concept of thermal diode has also been discussed, and an experiment has been conducted for demonstrating this [3]. Recent progress in transport studies strongly indicates that heat transport analogue exists for many categories of electric transport.

In this talk, we present theoretical study of the Kondo effect in heat transport via a local two-state system [4]. This system is described by the spin-boson Hamiltonian with Ohmic dissipation, which can be mapped onto the Kondo model with anisotropic exchange coupling. We derive the exact formula of thermal conductance, and evaluate it by the Monte Carlo method. Thermal conductance has a scaling form indicating the universal behavior characteristic of the Kondo effect. Below the Kondo temperature, conductance follows the universal temperature dependence proportional to T^3, showing nontrivial enhancement. This is a manifestation of strong correlation between system and reservoirs, which is analogous to the Kondo effect in electric transport. We also discuss coupling dependence of heat conductance.

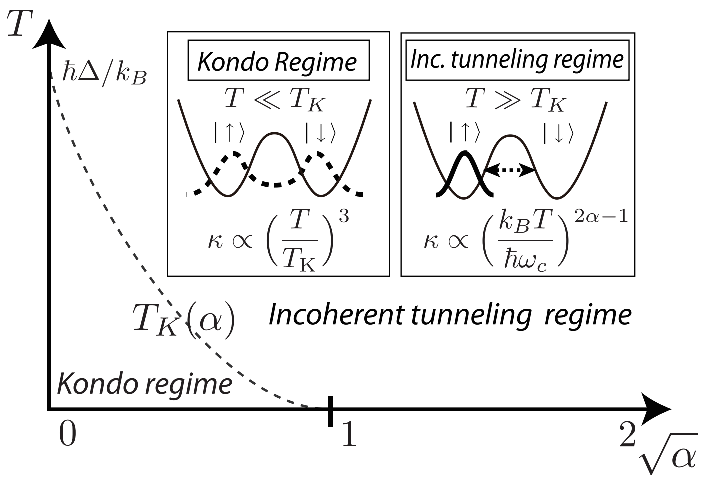

Figure 1: A schematic phase diagram of the present model.

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W3-2

Quantum pumping in mesoscopic systems

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Linear response theory often starts discussing the effect of time-dependent perturbations with frequency and then takes the zero-frequency limit to obtain intrinsic properties of many-body system, which is in principle equivalent to fluctuation-dissipation theorem. When we modulate more than one parameters, there appears a new time-dependent transport, called pumped transport.

Recently, a lot of interests are focused to the lowest-order non-adiabatic correction to the pumped transport in a static (adiabatic) limit, possibly because this can be a controlled system that can tackle the problem of non-equilibrium statistical physics. Both in classical and quantum setups, this contribution had shown to have a topological character, being expressed by a surface integral of a “Berry" curvature. In this presentation, I show our approach based on generalized quantum master equation [1] and possible extension to more non-adiabatic regimes. Finally, I explain our quantum transport results in quantum dot system coupled two leads, with time-dependent modulation of a tunneling phase and magnetic fields (Fig.1) [1, 2]. Part of this work is supported by JSPS KAKENHI (26247051).

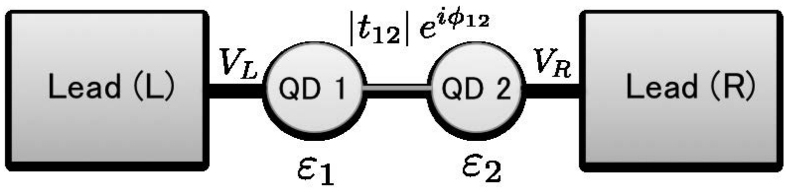

Figure 1: quantum dot coupled to two reservoirs with time-dependent modulating parameters.

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W4-1

Luttinger liquid universality after a quantum quench

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We provide strong evidence that the relaxation dynamics of one-dimensional, metallic Fermi systems resulting out of an abrupt amplitude change of the two-particle interaction has aspects which are universal in the Luttinger liquid sense: The leading long-time behavior of certain observables is described by universal functions of the equilibrium Luttinger liquid parameter and the renormalized velocity. A similar type of universality is found for static as well as dynamical correlation functions computed in the steady state reached after the quantum quench. We analytically derive those functions for the Tomonaga-Luttinger model and verify our hypothesis of universality by considering spinless lattice fermions within the framework of the density matrix renormalization group.

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W4-2

Some new analytical and numerical approaches to an SU(N) impurity Anderson model

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We discuss some exact analytical and numerical results obtained for the N-orbital Anderson impurity. Specifically, we use several different approaches to study transport and dynamical properties of quantum dots over a wide range of the energy scales:

i) The $1/(N-1)$ expansion for *low-energy* scale [1,2].
ii) Wilson numerical renormalization group (NRG) also for *low-energy* scale [3,4].
iii) Finite-U non-crossing approximation (NCA) for *intermediate-energy* scale [5].
iv) Thermal field theory with a Liouville-Fock space for *high-energy* scale [6].

The $1/(N-1)$ expansion is a large N approach based on the perturbation theory in U, and uses a scaling that keeps $(N-1)U$ a constant in the limit of $N \to \infty$. At the zeroth order, it provides the Hartree-Fock (HF) approximation. To leading order in $1/(N-1)$ it describes the Hartree-Fock random phase approximation (HF-RPA). Then, the next leading contributions of order $1/(N-1)^2$ terms capture quantum fluctuations beyond the HF-RPA. This approach correctly describes the low-energy Fermi-liquid properties, and is complementary to the NCA which is based on a power series expansion in the hybridization matrix element V with a scaling that keeps NV^2 finite for $N \to \infty$.

The thermal-field-theoretical approach is equivalent to the Keldysh formalism. However, instead of the Keldysh contour, it uses a *doubled* Hilbert space that is called the Liouville-Fock space to describe the time evolution and the statistical density matrix. With this approach, exact asymptotic form of the interacting Green's function has been obtained in the high-temperature limit of equilibrium and also in the high-bias limit of a nonequilibrium steady state.

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W4-3

Nonadiabatic effect on the quantum heat flux control

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The quantum transfer between two environments, especially the pumping phenomena of quantum particles, has been attracted intensive attentions to scientists as well as engineers. In this talk, we focus on the control of quantum heat flux between two environments by modulating environmental temperatures in cyclic and out-of-phase way. This issue has been mostly studied in the adiabatic regime where the relevant quantum system can immediately follow the external driving. In the conventional studies, the feature of quantum pumping is represented with the geometrical phase owing to the formalism of the full counting statistics, In this talk, we report a formula of quantum transfer for an anharmonic junction system with using the full counting statistics, which is generalized to include the nonadiabatic effect. Figure 1 shows the anharmonic junction system which consists of two bosonic environments and a two-level system. In the formulation, a newly added term appears to describe the non-adiabatic effect. It also shows that the quantum transfer depends on the initial condition of the anharmonic junction just before the modulation, as well as the characteristic environmental parameters such as interaction strength and cut-off frequency of spectral density. This means that we can obtain the optimum quantum flux by setting the initial condition of the anharmonic junction.

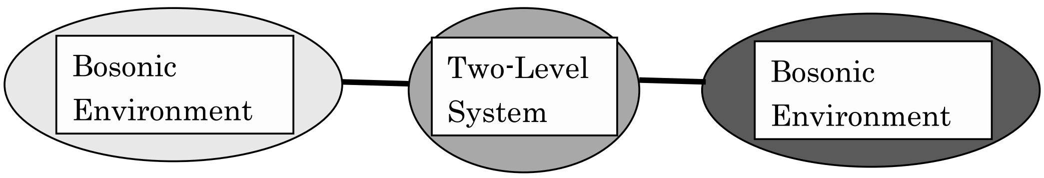

Figure 1: An anharmonic junction system

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W5-1

Topological Kondo effect in Majorana devices

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In this talk I will discuss the topological Kondo effect, which is predicted to be observable in mesoscopic superconducting hybrid devices with more than one pair of Majorana bound states. The Majorana bound states then non-locally encode an effective "spin" degree of freedom which is exchange-coupled to external (normal-conducting) leads. In a setting where Coulomb interactions are pronounced, a novel "topological" Kondo effect characterized by the orthogonal symmetry group emerges. Transport experiments in this system should be able to detect robust non-Fermi liquid behavior of multi-channel Kondo type, both in the conductance and the shot noise properties. I will also describe how to probe the competition between resonant Andreev scattering and topological Kondo physics.

Quantum transport phenomena in 3D topological insulator thin films

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The three-dimensional (3D) topological insulator (TI) is a novel state of matter as characterized by two-dimensional (2D) metallic Dirac states on its surface. Quantum transport in 3D-TI has recently been attracting much attention such as half integer quantum Hall effect (QHE) and quantum anomalous Hall effect (QAHE) in terms of breaking time reversal symmetry on surface Dirac states. These quantized phenomena in 3D TIs have been extensively studied in Bi-based chalcogenides such as Bi_2Se_3, Bi_2Te_3, Sb_2Te_3 and their combined/mixed compounds in both bulk and thin films form [1]. Here, we report the realization of the QHE and QAHE on the surface Dirac states in $(Bi_{1-x}Sb_x)_2Te_3$ films (x = 0.84 and 0.88) and its Cr-doped compound $Cr_x(Bi_{1-y}Sb_y)_{2-x}Te_3$ (x = 0.2, y = 0.78), respectively. In the pristine $(Bi_{1-x}Sb_x)_2Te_3$, with electrostatic gate-tuning of the Fermi level in the bulk band gap under magnetic field, the QH states of filling factor $\nu = \pm 1$ are resolved with quantized Hall resistance of $R_{yx} = \pm h/e^2$ and zero longitudinal resistance (Fig. 1), owing to the formation of chiral edge modes at top/bottom surface Dirac states [2]. In the magnetically doped compound, quantization of $R_{yx} = \pm h/e^2$ and transition with magnetization reversal are observed [3]. In the presentation, detail transport features of both quantization behaviors will be discussed. These observations of the quantization of Hall effects in 3D TI films may pave a way toward TI-based electronics.

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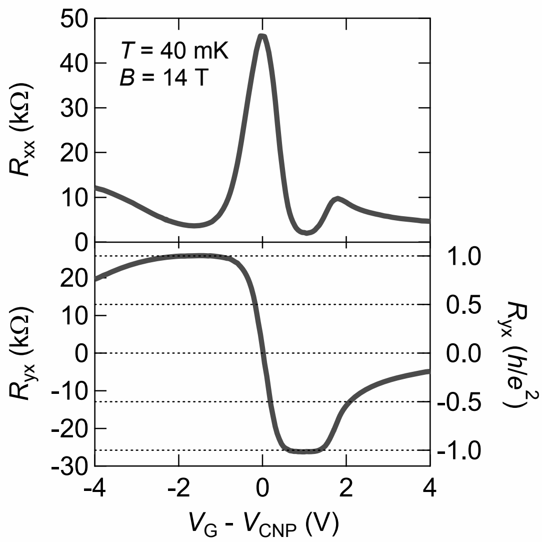

Fig.1: QHE with $\nu = \pm 1$ observed in $(Bi_{1-x}Sb_x)_2Te_3$ film (x = 0.84)

W5-3

Mesoscopic topological insulator

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Topological insulator (TI) exhibits a protected surface state, which is gapless in its dispersion, realizing an ideal auxiliary 2D system for conducting electrons. Transport characteristics of such surface states are susceptible to nanoscale formation of the sample; here we highlight the surface states of TI nanofilms [1], nanowires [2] and nanoparticles [3]. A more elaborate example of such a nanostructure is a patterned surface intended for realizing a topologically protected nanocircuit [4]. We study how the effects of finite size (associated with nanoscale formation of the sample) and of disorder determine and vary the transport characteristics of TI surface states.

As a specific example I will discuss in some detail the case of a weak TI nanofilm, which exhibits quasi-1D helical modes circulating around the periphery of the film. We focus on an even-odd feature in its transport characteristics [(de)localization properties] with respect to the number of stacked layers [1], and cast a mesoscopic viewpoint on the physics of topological insulators.

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W8-1

Interactions and Charge Fractionalization in an Electronic Hong-Ou-Mandel Interferometer

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We consider an electronic analog of the Hong-Ou-Mandel (HOM) interferometer, where two singleelectrons travel along opposite chiral edge states and collide at a quantum point contact. Studying thecurrent noise, we show that because of interactions between copropagating edge states, the degree of indistinguishability between the two electron wave packets is dramatically reduced, leading to reduced contrast for the HOM signal. This decoherence phenomenon strongly depends on the energy resolution of the packets. Insofar as interactions cause charge fractionalization, we show that charge and neutral modes interfere with each other, leading to satellite dips or peaks in the current noise. Our calculations explain recent experimental results [1] where an electronic HOM signal with reduced contrast was observed.

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W8-2

Shot noise induced by spin accumulation

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When a bias voltage is applied to a small conductor, the current fluctuates due to the partition process of electrons, reflecting the discrete nature of electric charge. This fluctuation called shot noise gives us the fundamental information of the transport process [1]. Now, as an electron possesses not only charge but also spin, one may ask how the discreteness of electron spin affects the current fluctuation. Although such spin-dependent shot noise has been discussed theoretically in various contexts [2, 3], no experimental studies have yet appeared in the literature. In particular, we focus on the effect of spin accumulation, i.e., splitting of the chemical potentials for up and down spin electrons [3].

Here, we report the experimental observation of excess shot noise induced by a nonequilibrium spin accumulation. [4]. By using a lateral all-semiconductor spin valve device (see Fig. 1)[5, 6], we applied the spin accumulation to a tunnel junction and measured the associated shot noise. Modulating the conventional bias voltage and spin accumulation independently, we successfully disentangled conventional shot noise associated with the charge current and excess shot noise connected with a spin current. In addition, we determined quantitatively the spin-injection-induced electron temperature by measuring the current fluctuation.

Given the importance of shot noise in various fields, especially in device technology and mesoscopic physics, shot noise could serve as a unique probe to explore nonequilibrium spin transport.

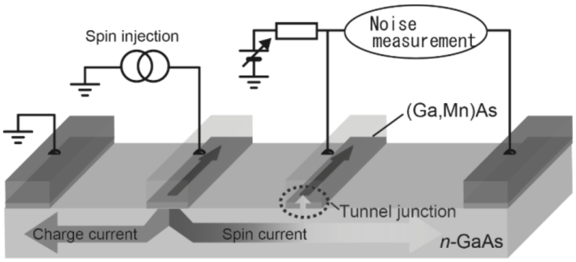

Figure 1: Schematic diagram of the measurement system.

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W8-3

Coherent Transport under Spin-Orbit Interaction

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Spin-orbit interaction (SOI) gives dramatic changes in quantum coherent transport. Particularly in the localization problem, it appears as anti-localization [1] and changes the universality class of the disorder-driven metal-insulator transition. Naive application of scaling theory to a two-dimensional (2d) system with SOI leads to an infinite conductance and apparently something goes wrong with the theory, [2] to which problem no clear solution has given yet. The SOI in 2d systems has also attracted attention as it can be controlled with external electric field and hence is applicable to manipulation of spins in spintronics.

For such manipulation of spins, we need to initialize the spin state, which means production of spin polarization. Spontaneous time-reversal-symmetry broken ferromagnets are then most useful source of the spin-polarization though at the same time they may affect the following operation process through, e.g., stray fields. Another way to polarize the spins is the use of SOI in combination with some quantum structure. Almost perfect polarization of electrons traversing through a quantum point contact (QPC) with strong Rashba-type SOI (R-SOI) has been claimed on the conductance quantized plateau at e^2/h, *i.e.*, a half of the conductance quantum $G_q=2e^2/h$. [3] However there has been no direct evidence for the polarization and every statement based on this configuration might have been a castle in the air.

In the first place we have confirmed very high spin-polarization both the conductance plateaus at $G_q/2$ and also at G_q by adopting a side-coupled quantum dot for the detector of spin-polarization. The difference between the mechanisms of polarization at these two plateaus appeared in the response to the bias voltage across the QPC.

After checking the polarization, we proceeded to experiments in spin interference circuits, in which spin polarization, manipulation and detection are predicted theoretically. [4] In the QPC+Aharonov-Bohm (AB) ring configuration, an oscillation pattern in the conductance which is characteristic to the spin interference appeared only when we emitted spin-polarized electrons into the circuit. The modulation of spin-interference amplitude is explained with dynamic nuclear polarization in the circuit. In the interpretation of the experimental results we have proposed a novel mechanism to rotate the spin direction.

Such spin interference would also affect the behavior of quantum billiard, though which the transport is dominated in part by classical paths and in part by quantum interference. The effect of SOI typically appears in the magnetoresistance for in-plane magnetic field because no AB phase shift mixes into the response. Clear reproducible conductance fluctuation appeared in superposition on ordinal weak localization like magnetoresistance. The sample configuration is, however, apparently incompatible with weak localization and requires corrections to the existing interpretations.

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W9-1

Exploring Spins at Surfaces by Spin-Polarized STM

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The understanding of magnetism at the ultimate, atomic, length scale is one of the current frontiers in solid state physics. It is a key to future applications in spin electronics and highest density data storage. Spin-polarized scanning tunneling microscopy (SP-STM) and spectroscopy (SP-STS) [1] are powerful tools to access magnetic phenomena on a scale all the way down to the individual atoms. Scanning tunneling microscopy (STM) has revolutionized surface science ever since its invention in 1982 by Gerd Binnig and Heinrich Rohrer, and it was the capability of the STM to produce atomically resolved images of conducting surfaces that fascinated people most strongly. The spin-polarized version of the STM is based on the idea to detect not only the flow of electrical charge in the tunneling current, but also to make the STM sensitive to the spin of the tunneling electrons [2], in order to combine the ultimate resolution capability of the STM with magnetic sensitivity [3,4]. During the last decade a large variety of surprising magnetic structures were discovered by SP-STM. Competing magnetic interactions effective at the atomic length scale [5,6] give rise to unexpected ordered structures of great complexity in self-assembled chains [7] and monolayers of magnetic atoms [8-12] as well as in artificially created nanostructures built up atom-by-atom [13-16]. Moreover, the application of SP-STM to magnetic molecules interacting with solid substrates has led to a detailed understanding of electrode-molecule interfaces at high spatial resolution [17-20], thereby opening up fascinating perspectives for future ultra-low power storage or logic devices.

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Spintronics Beyond Magnetoresistance: Putting Spin in Lasers

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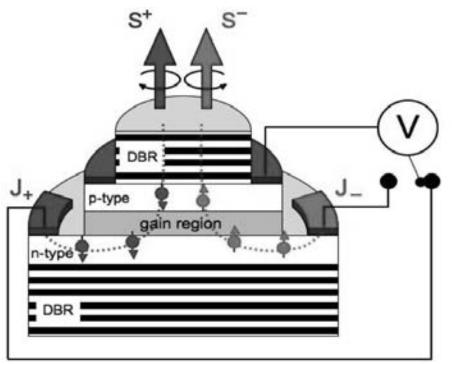
Practical paths to room-temperature spin-controlled devices are typically limited to magnetoresistive effects, successfully employed for magnetically storing and sensing information. However, spin-polarized carriers injected optically or electrically in semiconductors can also enhance the performance of lasers, for communication and signal processing [1]. Through transfer of angular momentum and spin-orbit coupling, the injection of spin-polarized carriers leads to the emission of circularly polarized light. A highly-nonlinear response of lasers provides a very efficient spin-filtering/amplification: a very small spin polarization of injected carriers leads to a fully polarized emitted light at 300K [2].



While in the steady-state such spin-lasers already demonstrate a lower threshold current for the lasing operation [2,3] as compared to their conventional (spin-unpolarized) counterparts, the most exciting opportunities come from their dynamical operation. We reveal that the spin modulation in lasers can lead to an improvement in the two key figures of merit: enhanced bandwidth [4] and reduced parasitic frequency modulation—chirp [5]. The principles of spin modulation may also enable high-performance spin interconnects exceeding by orders of magnitude the information transfer available in conventional metallic interconnects [6]. Surprisingly, we show that an optimal performance of spin-lasers can arise for short spin relaxation time [7]. Spin states in quantum dots may also enable elusive phonon lasers [8], emitting coherent phonons.

Fig. 1: *Spin-laser scheme [1]. The resonant cavity is formed by a pair of mirrors made of distributed Bragg reflectors (DBR) and the gain (active) region, typically consisting of quantum wells or dots. Electrical spin injection (J_+, J_- are unequal) is realized using two magnetic contacts. Spin-polarized carriers can also be injected optically, using circularly polarized light. The recombination of electrons and holes in the gain region, leads to the emission of coherent light of positive and negative helicity, S^+ and S^-.*

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W15-2

Constructing Topological Bands in Generic Materials

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Accessing non-trivial electron topology depends on materials in which symmetry and interactions produce topological Bloch bands. However, since good transport properties are often lacking in such materials, it is desirable to develop methods to endow a generic (vanilla) material with topological properties. Here we outline a new way to create topological bands in stacks of manifestly nontopological atomically thin materials, and illustrate it with a model system comprised of graphene stacked atop hexagonal-boron-nitride (G/hBN). We show that Berry curvature, present in the G/hBN electron Bloch bands, is highly sensitive to the stacking configuration. Commensurate stackings feature topological bands with finite valley Chern numbers, whereas incommensurate stackings (Moire superlattices) yield nontopological bands. As a result, G/hBN electron topology can be controlled by crystal axes alignment granting a practical route to designer topological materials (Chernburgers). Topological bands manifest in transport effects such as long-range valley currents and non-local electrical response, providing a clear fingerprint for distinguishing topological from non-topological bands.

Quasiclassical circuit theory of spin transport in superconducting heterostructures

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The quasiclassical theory of superconductivity provides a very successful description of transport in mesoscopic structures. By integrating out some microscopic details a very powerful and wide applicable theoretical approach for transport in superconductors is obtained.[1] In a discretized form the equations can be cast into the form of a quantum circuit theory, which provides an intuitively appealing description in terms of generalized Kirchhoff and Ohm laws.[2] Recently the combination with ferromagnetic elements has become a new paradigm including spectacular effects like a triplet proximity effect or long-range spin transport as well as novel coupling mechanisms between charge, spin and heat currents. In this talk I review some of these developments, in particular the novel prediction of giant thermoelectric effects in superconducting heterostructures due to the combined effect of intrinsic exchange fields and spin-polarized tunneling.[3] I also highlight the importance of the long-standing open problem of spin-dependent boundary conditions for the quasiclassical Greens functions and discuss its solution.[4,5]

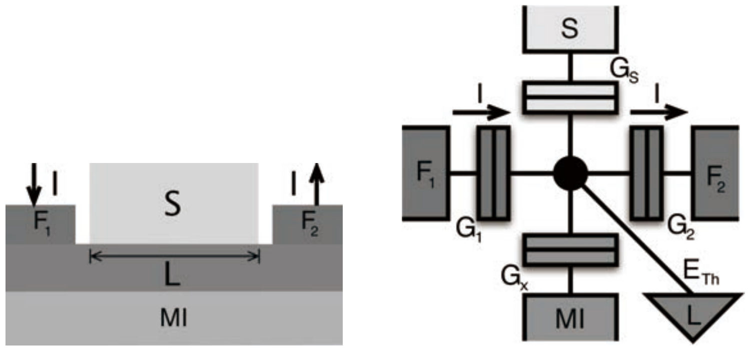

Figure 1: The left panel shows a sketch of typical experimental structuresetup to observe the predicted thermoelectric effect. The structure consists of a ferromagnetic insulating substrate (green), coupled to normal metal film (grey) covered by superconductor (yellow). Current is injected and extracted by two ferromagentic metallic contacts (blue) on top. Using the quantum circuit theorey version of the quasiclasscial Greens function theory the system is mapped on a set of dicrete elements, for which generalizations of the Ohms law can be derived and lead to a set of algebraic equations, which determine the charge, spin and energy transport.

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W16-1

Spintronics with Ferroelectrics

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Ferroelectric materials are characterized by a spontaneous electric polarization switchable by an applied electric field. If such a ferroelectric is interfaced with a metal it modifies the electronic properties of the metal near the interface through effects of charge screening and interface bonding. For thin metallic ferromagnets the effects of polarization from an adjacent ferroelectric may be sizable and involve not only electronic but also spin degrees of freedom. Thus, ferroelectric materials may be employed in spintronics to control the spin-dependent properties including the interface magnetization, the interface magnetic order, the interface magnetic anisotropy, and the spin-dependent transmission across the interface. Furthermore, ferroelectric films can now be made thin enough to allow measurable electron tunneling while maintaining a stable and switchable polarization. Modeling and experiments show that ferroelectric tunnel junctions allow the control of the spin-polarization of the tunneling current. This talk will overview our recent research efforts in this field and discuss underlying physical principles associated the effects of ferroelectricity on magnetism and spin transport.

Perpendicular magnetic anisotropy induced by Rashba spin-orbit interaction

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Thin magnetic films with a perpendicular magnetic anisotropy (PMA) are important for applications. That an interfacial internal electric field might be used to engineer such a PMA is also of great interest. Experiment [1-3] has indeed shown that such a PMA can be modified by an externally applied electric field E_{ext}.

Here we develop an analytic theory for the existence and electrical control of the PMA based on the Rashba spin-orbit (RSO) interaction [4]. Our model comprises a band Stoner model of 2D electron gases with the RSO interaction:

$$H = \frac{\hbar^2}{2m}\left(k_x^2 + k_y^2\right) - J_0 S\hat{\mathbf{m}}\cdot\boldsymbol{\sigma} + \alpha_{\mathrm{R}}\left(k_y\sigma_x - k_x\sigma_y\right),$$

where the second term is the exchange interaction between the order parameter **m** and conduction electron spin **σ**, and the last term represents the RSO interaction. We obtain the spin splitting energy eigenvalue as a function of the polar angle θ of **m** and find that the exchange splitting is enhanced due to the RSO interaction, which becomes largest in the perpendicular configuration (θ=0) since all the k-vectors contribute to the enhancement of the exchange splitting as shown in Fig. 1. Assuming $(J_0S)^2 > (\alpha_{\mathrm{R}}k_x)^2$ and retaining the θ-dependent terms in the spin splitting bands up to the order of α_{R}^2, we obtain the magnetic anisotropy energy:

$$E_{\mathrm{MA}} = E_{\mathrm{R}}\left(1 - \frac{2T}{J_0 S}\right)\cos^2\theta$$

where $E_{\mathrm{R}}=m\alpha_{\mathrm{R}}^2/(2\hbar)^2$ is the Rashba energy and $T= \hbar^2(\langle k_x^2\rangle_+ - \langle k_x^2\rangle_-)/(2m)$ denotes an increment of the exchange splitting averaged over the Fermi sea. Since α_{R} is proportional to the electric field, an E_{ext}^2 dependent PMA results if $T > J_0S/2$, which is the case for a variety of combinations of ferromagnets and nonmagnets [5,6].

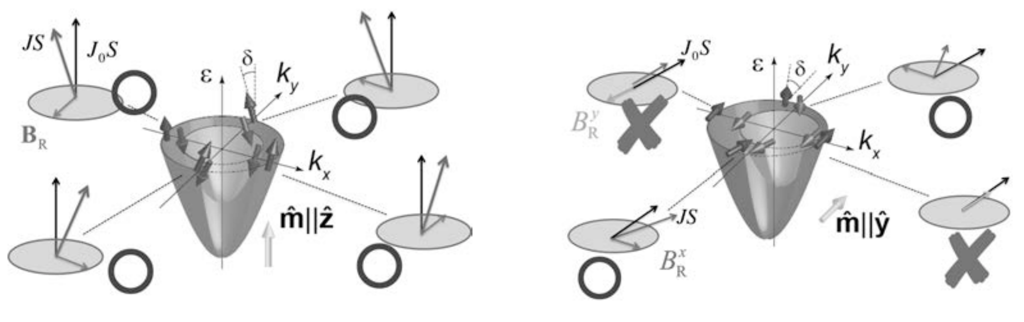

Figure 1: The spin splitting bands and contribution of the Rashba field $\mathbf{B}_{\mathrm{R}}$ to the exchange field enhancement. Left: The perpendicular configuration (θ=0). Right: The in-plane configuration (θ=π/2).

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W16-3

Antiferromagnetic Skyrmions

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Manipulating small spin textures, which can serve as bits of information, by electric current is one of the main challenges in the field of spintronics. Ferromagnetic skyrmions recently attracted a lot of attention because they are small in size and are better than domain walls at avoiding pinning while moved by electric current. Meanwhile, ferromagnetic skyrmions still have disadvantages such as the presence of stray fields and transverse dynamics, making them harder to employ for spintronic applications. In this work, we propose a novel topological object: the antiferromagnetic (AFM) skyrmion. This topological texture has no stray fields and we show that its dynamics are faster compared to its ferromagnetic analogue. We obtain the dependence of AFM skyrmion radius on the strength of Dzyaloshinskii-Moriya interaction coming from relativistic spin-orbit effects and temperature. We find that the thermal properties, e.g. such as the AFM skyrmion radius and diffusion constant, are rather different from those for ferromagnetic skyrmions. More importantly, we show that due to unusual topology the AFM skyrmions do not have a velocity component transverse to the current and thus may be perfect candidates for spintronic applications.

W17-1

Transport properties calculated by means of the Kubo formalism

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Many physical phenomena exploited in spintronics can be described by means of a corresponding linear response tensor. Kubo's response formalism provides a firm and powerful basis to determine the response of a property of a solid to a perturbation in a very general way. A first-principles approach is presented that is based on the corresponding Kubo-Bastin equation [1] and implemented within the fully relativistic KKR (Korringa-Kohn-Rostoker) formalism [2]. This approach is able to treat intrinsic and extrinsic contributions on equal footing. Both contributions from states below (*Fermi sea*) and at the Fermi level (*Fermi surface*) are treated and can be analyzed in detail. The approach is applicable to pure systems as well as metallic and semiconductor alloy systems with disorder accounted for by means of the CPA (Coherent Potential Approximation). Special emphasis is be placed on the role of the so-called vertex corrections that allow to build a bridge to the semi-classical Boltzmann transport formalism. Several examples (anomalous Hall and anomalous Nernst [3] as well as spin Hall and spin Nernst [4] conductivities) are given to illustrate this analysis in combination with numerical results obtained using the spin-polarized KKR electronic structure method. As a new feature in this type of numerical studies the inclusion of finite temperature effects as lattice vibrations and spin fluctuations will be discussed. The approach [5] is based on the alloy analogy model with thermal vibrations and spin fluctuations modeled by random atomic displacements and tilting of magnetic moments, respectively. Various models to deal with spin fluctuations, determining their impact on the temperature dependent behavior of the electrical conductivity and Gilbert damping parameter will be discussed. The corresponding results demonstrate in particular the non-additivity of the separate contributions to the conductivity.

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W17-2

Electronic transmission through the atomic domain boundary ---- from graphene to transition metal dichalcogenides

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We report the theoretical studies on the electronic transmission through domain boundary in the atomically thin two-dimensional systems, including graphene and transition metal dichalcogenides (TMDs). Two-dimensional material commonly contains an atomic-scale boundary at which one of the layers is truncated, and this kind of defect structure often gives rise to nontrivial effects on the electronic transport. In graphene monolayer-bilayer boundary, for example, it was shown that an electron is scattered to different directions depending on the valley degree of freedom (K and K')[1].

The TMDs (MX_2 with M=Mo, W and X=S, Se, Te,) attracts a significant attention as a novel family of two-dimensional material beyond graphene. A hallmark of the electronic structure of the TMD monolayer is the correlation of the spin and valley degrees of freedom. Specifically, the valence band maxima located at K and K' valleys are spin split in the opposite direction between the two valleys. This implies that, if we can split valleys using some atomic domain boundary as in graphene, it works as a spin splitter. Here we calculate the electronic transmission across a boundary between monolayer and bilayer of TMD, and demonstrate that up-spin and down-spin electrons entering the boundary are actually refracted and collimated to opposite directions.[2] The phenomenon is attributed to the strong spin-orbit interaction, the trigonally-warped Fermi surface, and the different crystal symmetries between the monolayer and bilayer systems. The spin-dependent refraction suggests a potential application for a spin splitter, which spatially sepa rates up-spin and down-spin electrons simply by passing the electric current through the boundary.

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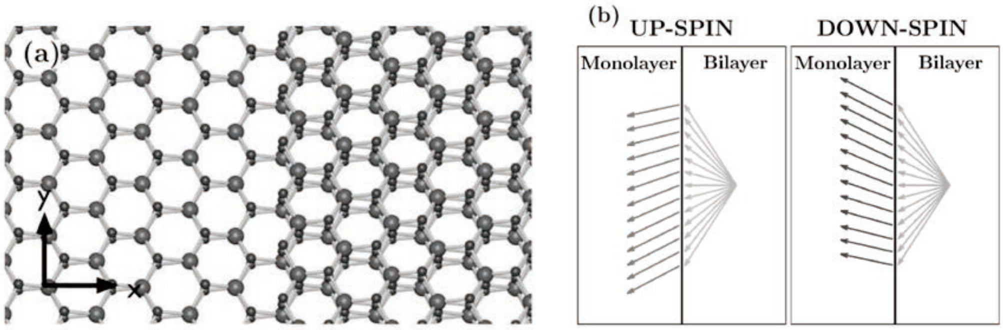

Figure 1: (a) Atomic structure of TMD monolayer and bilayer junction.
(b) Electron refraction at the atomic step between monolayer and bilayer of MoTe2 for an incident electron from the bilayer side.

W17-3

The effect of spin waves in the spin Seebeck Effect

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The spin Seebeck effect (SSE) occurs in magnetic insulators where a gradient in temperature causes a spin current to flow through the material [1, 2]. The prototypical material in which this effect has been studied is yttrium iron garnet (YIG) and recent measurements in gadolinium iron garnet (GdIG) show unusual behavior with the SSE changing sign. These materials are ferrimagnetic and analytic theories concerning SSE have often simplified the representation to a simple ferromagnet, where the magnetization is assumed to be that which is macroscopically measured. However the spin wave spectrum is radically different to that of a simple ferromagnet, containing many spin wave modes [3]. Early experiments found a strong temperature dependence of some of the spin wave modes and it was observed that high frequency modes could shift to much lower frequencies [4]. We have implemented detailed microscopic models of YIG and GdIG, incorporating temperature through atomistic spin dynamics. This many-body numerical approach is beyond analytic theories and also a significant improvement over micromagnetic approaches for such problems. We calculate spin wave spectra as a function of temperature. Our results indicate that the temperature dependent frequency shifting of spin wave modes is important in understanding the experimental observations such as the sign changes in GdIG.

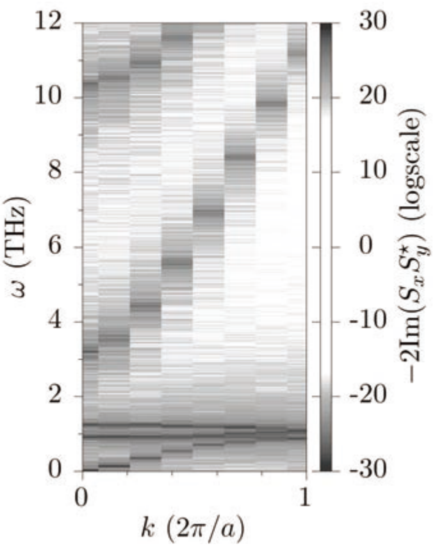

Figure 1: Low frequency part of the spin wave spectrum in GdIG.

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W18-1

Quantum Hall Effects for Spintronics

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The quantum Hall effect and the quantum spin Hall effect are closely related anomalous transport effects that are associated with topological two-dimensional states and characterized in the ideal case by dissipation free transport. I will review several experimentally demonstrated instances of the both the quantum Hall effect and the quantum spin Hall effect, emphasizing important differences between the two effects, and using ideas from Ref.[1] to discuss the conditions necessary to achieve low dissipation. I will then discuss some strategies that could potentially be used to achieve a reasonably accurate room temperature quantum Hall effects and speculate on how such an achievement could be useful for electronic technology.

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Spin and orbital magnetic response on the surface of a topological insulator

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Coupling of the spin and orbital degrees of freedom on the surface of a strong three-dimensional insulator, on the one hand, and textured magnetic configuration in an adjacent ferromagnetic film, on the other, is studied using a combination of transport and thermodynamic considerations. Expressing exchange coupling between the localized magnetic moments and Dirac electrons in terms of the electrons' out-of-plane orbital and spin magnetizations, we relate the thermodynamic properties of a general ferromagnetic spin texture to the physics in the zeroth Landau level. Persistent currents carried by Dirac electrons endow the magnetic texture with a Dzyaloshinski-Moriya interaction, which exhibits a universal scaling form as a function of electron temperature, chemical potential, and the time-reversal symmetry breaking gap. In addition, the orbital motion of electrons establishes a direct magnetoelectric coupling between the unscreened electric field and local magnetic order, which furnishes complex long-ranged interactions within the magnetic film.

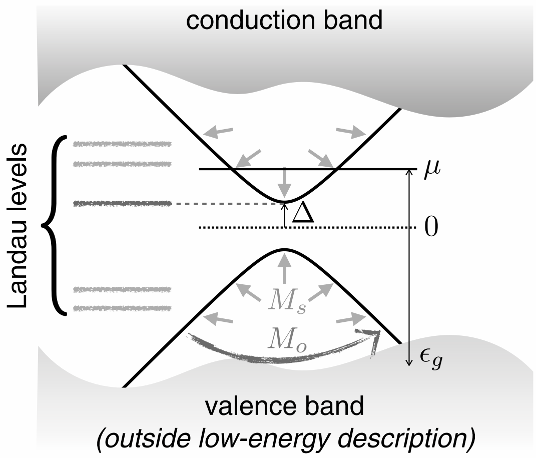

Figure 1: Schematic of the low-energy description, which captures contributions to the spin, M_S, and orbital, M_O, components of the magnetization that stem from the Dirac electrons.

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W19-2

Spin-electricity conversion induced by spin pumping into topological insulators

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A topological insulator (TI) is a new state of quantum matter that possesses a metallic surface state, while the interior is insulating. Notable is that this characteristic of TIs is the very structure commonly used in spintronics, that is, a conductor film artificially made on an insulator substrate. Moreover, conduction electrons on the surface state are helical Dirac fermions which have a novel property called the spin-momentum locking. On the surface states of TIs, the direction of the electron's motion uniquely determines its spin direction and vice versa. Hence, if a spin imbalance is induced by spin pumping, a charge current is expected to be produced along the Hall direction.

In the present paper, we have experimentally and theoretically demonstrated the spin-electricity conversion in bulk-insulating topological insulators $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ and Sn-doped Bi_2Te_2Se coupled with permalloy. On ferromagnetic resonance of permalloy, the injected spins are converted into electric voltage on the surface state of TIs despite the bulk nature of the sample. This phenomenon is caused by the spin-momentum locking on the topological surface state. The mechanism of the observed spin-electricity conversion is fundamentally different from the inverse spin Hall effect and even predicts perfect conversion between spin and electricity. The present results reveal a great advantage of topological insulators as inborn spintronics devices.

This work was done in collaboration with Prof. K. Nomura, Prof. Kouji Segawa, Prof. Yoichi Ando, Prof. E. Saitoh, Dr. K. Eto, Dr. M. Novak, and Dr. Y. Kajiwara.

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Abstracts of Symposium

S10-1

New effects in spintronics derived from the symmetry of response functions

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Kubo's linear response formalism allows to determine the response of a property of a solid to a perturbation in a very general way. A prominent example of application is the evaluation of charge, spin and heat transport coefficients of solid state systems. The scheme of Kleiner [1] to investigate the symmetry of conventional transport coefficients has been extended to describe the symmetry of various response tensors appearing in the field of spintronics. Implications for the appearance of interesting effects described by non-zero elements of these response tensors are reviewed. As a first example the occurrence of the anomalous Hall effect (AHE) in materials having nontrivial spin structures, such as non-collinear antiferromagnets, will be discussed on the basis of the shape of the conventional conductivity tensor. As observed by other authors [2,3] the AHE might even occur for a system with zero net magnetization. We revisit and extend these studies employing a combined group theoretical and first principles approach. Based exclusively on symmetry considerations the occurrence of transverse transport and related optical effects for a given magnetic order of a solid can be predicted. Numerical studies using a first principles electronic structure method in combination with Kubo's linear response formalism are performed on the Hall effect, the magnetic circular dichroism in X-ray absorption (XMCD) and magneto-optical Kerr effect (MOKE) to independently cross-check the group theoretical predictions. As a second example the symmetry properties of the spin conductivity tensor are reviewed. It is shown that only the magnetic Laue group has to be considered in this context. In this case non-vanishing transverse elements, found without making reference to the two-current model, give rise to the spin Hall effect in non-magnetic as well as magnetic solids. In the latter case non-vanishing longitudinal elements cause among others the spin-dependent Seebeck effect. For non-magnetic solids having low symmetry non-vanishing longitudinal elements are shown to exist as well. These give rise to spin-orbit induced longitudinal spin transport [4] that has not been considered before. Numerical studies confirm these findings and demonstrate that the longitudinal spin conductivity may be in the same order of magnitude as the conventional transverse one. Finally, the use of symmetry when dealing with the spin-orbit torque [5], Gilbert damping [6] as well as the Edelstein effect [7] is sketched.

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S10-2

Detection of spin fluctuations in spin glass via spin Hall effect

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Pure spin current, flow of spin angular momentum with no flow of charge, is a key physical quantity to realize low-power spintronic devices. The spin Hall effect (SHE) enables one to convert charge current into pure spin current via spin-orbit interaction. Unlike most work, that has focused primarily on the magnitude of the spin Hall angle, the conversion yield between charge and spin currents, we here demonstrate an example of employing the SHE as a probe of a fundamental response of the spin current to the random spin configurations in spin glass systems.

For this purpose, we chose CuMnBi ternary alloys [1]. When there is no Bi impurity in CuMn, it shows no SHE in the spin transport but shows a typical cusp structure at the spin glass temperature T_g in the thermo-magnetic curves. Once a small concentration of Bi was added in CuMn, a large SHE was observed as shown in our previous work on Bi-doped Cu [2]. Most remarkable is that the SHE of $Cu_{98}Mn_{1.5}Bi_{0.5}$ starts to decrease at T^* (= 40 K = $4T_g$) and becomes as little as seven times smaller at $0.5T_g$, as shown in Fig. 1(a). With decreasing the Mn concentration from 1.5% to 0, T^* is systematically shifted to the lower temperature side. A similar temperature dependence was also observed in anomalous Hall effects in the ternary alloys. These experimental results clearly show that a pure spin current induced by skew scattering at the Bi sites is strongly suppressed by fluctuating spins at the Mn sites even far above T_g (see Fig. 2), and can be qualitatively explained by the relative dynamics between the localized moment and the conduction electron spin.

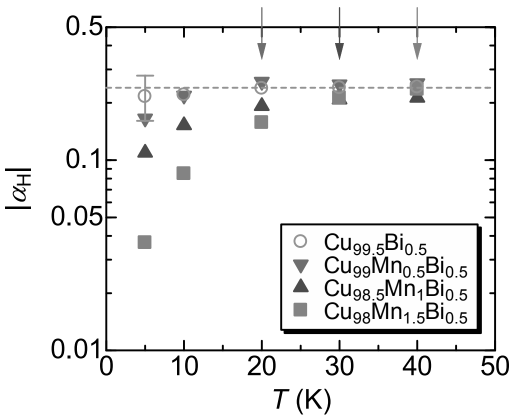

Figure 1: Spin Hall angles $|\alpha_H|$ of CuMnBi ternary alloys as a function of temperature. The arrows indicate T^* where $|\alpha_H|$ start to decrease. The broken line in the figure shows $|\alpha_H|$ of $Cu_{99.5}Bi_{0.5}$.

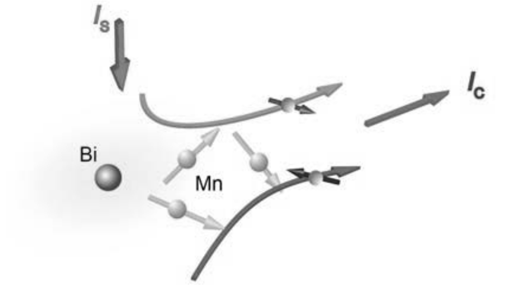

Figure 2: Illustration of inverse SHE in CuMnBi spin glass system. The pure spin current I_S is converted into the charge current I_C at the Bi site. I_S is also affected by fluctuating spins at the Mn sites. Red and blue arrows with green spheres are spins of conduction electrons (|*e*|) and the curved arrows indicate the motions of spin-up and spin-down electrons.

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Spin transport through antiferromagnets

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Antiferromagnetic insulators appear as a promising medium for low-dissipation transmission of spin currents. In the absence of charge carriers, the spin is transmitted collectively, either by thermal cloud of magnons or by a coherent precessional dynamics of the Néel order. The latter can be understood as an instance of spin superfluidity, which is operative even at absolute zero temperature. In this talk, I will discuss two experimental geometries where such spin currents can be probed: (1) Easy-plane antiferromagnet contacted by two heavy metals for injecting (detecting) spin currents by the direct (inverse) spin Hall effect. In such systems, the spin superfluidity can be manifested as a long-ranged negative drag between charge currents in the metals. (2) Easy-axis antiferromagnet sandwiched between a heavy metal and ferromagnetic insulator. The spin Hall effect at the metal/antiferromagnet interface and exchange coupling at the antiferromagnet/ferromagnet interface allow for the spin currents (carried by both coherent dynamics and thermal magnons) to be transmitted across the trilayer. This establishes reciprocal coupling between charge currents in the metal with magnetic dynamics in the ferromagnet, which can be readily accessed with the state-of-the-art experimental tools.

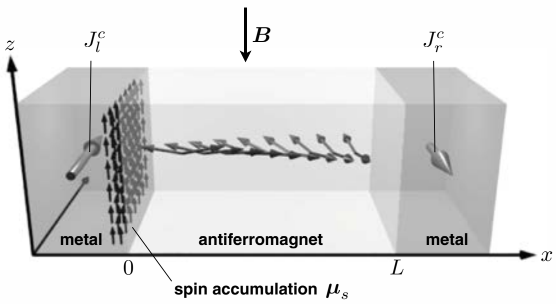

Figure 1: Antiferromagnetic spin superfluid mediating negative drag between metallic leads.

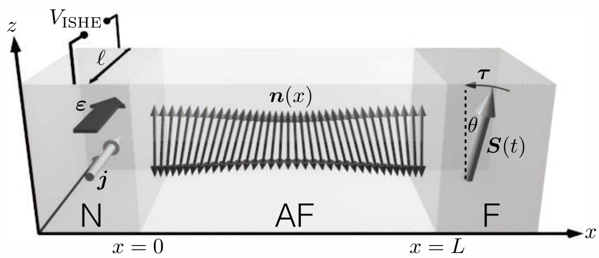

Figure 2: Antiferromagnetic spin waves (either evanescent or thermal) mediating spin-charge coupling between a heavy metal and ferromagnetic insulator.

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S10-4

Spin torque ferromagnetic resonance measurements in antiferromagnetic multilayers.

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Since antiferromagnets (AFMs) have no spontaneous magnetization unlike ferromagnetic materials, it is not easy to manipulate the magnetic moments in AFMs by external magnetic field. However, recent theoretical studies [1] suggest that it is possible to manipulate the magnetization in AFMs by spin-transfer-torque in a similar manner to ferromagnetic materials. In this study, we perform spin-toque ferromagnetic resonance (ST-FMR) measurements [2] on FeCoB/IrMn/Pt multilayers to experimentally investigate the interaction between the spin current and the magnetic moments of antiferromagnetic IrMn.

We fabricate FeCoB 4nm/IrMn t_{IrMn}=0~25 nm/Pt 4nm multilayers on thermally oxidized Si substrate by magnetron sputtering. The film is then patterned into 5~20um wide strips with a coplanar waveguide facilitating both the rf and dc current injection into the strip. The dc electric current I_{dc} flowing in Pt layer invokes spin Hall effect and injects a pure spin current into the neighboring IrMn layer. By using ST-FMR technique, we investigate the linewidth modification of the FeCoB/IrMn resonant spectra under the spin current injection from Pt. Since the spectral linewidth is a direct indication of the magnetic damping in the FeCoB/IrMn bilayer, change in the linewidth due to the spin current is a probe of how much the anti-damping torque is exerted on the FeCoB through the IrMn layer. It is found that the linewidths are varied by the spin current even with $t_{IrMn} \neq$ 0nm. Assuming that IrMn is not transparent for the electron spins [3], the results suggest that the anti-damping torque due to the spin current is exerted on the IrMn magnetic moments and it modifies the effective damping of the FeCoB layer through the interfacial magnetic coupling between FeCoB/IrMn. In the presentation, I will also discuss the recent results obtained with various antiferromagnets including NiO and FeMn.

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S10-5

Spin Hall angle dispersion driven anomalous Hall effect

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The anomalous Hall effect (AHE) is a manifestation of the breaking of the time reversal symmetry due to the magnetization. Despite decades of controversy in the microscopic mechanisms, the phenomenological explanation of the AHE is in a broad consensus: conduction electrons of up and down spins are equally deflected to opposite directions transversely, and the unbalance in their numbers causes the anomalous Hall current. Here we show that there can be another scenario of the AHE: the difference in the strength of the transverse deflections for the up and down spin electrons, which is induced by a spin accumulation, causes an anomalous Hall current with negligibly small spin polarization in normal metals(Fig. 1) [1]. Experiment results show that this spin Hall angle energy derivative governed contribution can be hundreds of times larger than that of the old AHE picture. Our findings reveal the hidden utility of the spin Hall angle dispersion in the detection of the spin accumulation and will inspire new designs for the spintronics devices.

In addition, I would like to briefly share our recent progress in the temperature dependence of the spin current transport in antiferromagnetic insultors.

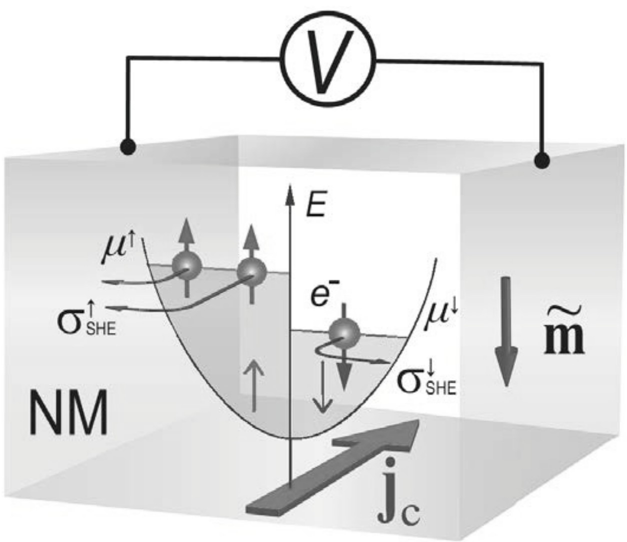

Figure 1: The anomalous Hall effect when there is a spin accumulation in a normal metal, which origins from the difference between the spin Hall conductivities of the up- and down-spin eletrons.

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Bidirectional conversion between microwave and light via ferromagnetic magnons

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Understanding and exploiting the interactions between well-controlled quantum systems can be a key to building a large-scale artificial many-body quantum system. We are pursuing the architecture where superconducting artificial atoms are connected by light via quantum transducers. The quantum transducer is a device by which an electromagnetic field in micro-wave domain and that in optical domain can be coherently converted. Here we report such conversions using ferromagnetic magnon mode, or more specifically, the uniform magnetiza-tion oscillation mode, i.e., the Kittel mode. The sample is a ferromagnetic sphere of yttrium iron garnet (YIG) crystal, which is positioned in a microwave cavity to enhance the coupling between the microwave mode and the Kittel mode. Microwave response of the coupled system can be probed by microwave reflec-tion spectroscopy [**Fig.1 (a)**] as well as by optical measurement in which the polariza-tion of a travelling optical field through the YIG crystal oscillating at the resonant fre-quency of the Kittel mode, i.e., the Faraday effect [**Fig.1 (b)**]. By driving the coupled system, on the other hand, with two optical fields at frequencies differed by the Kittel mode frequency we excite the Kittel mode. Due to the large cooperativity, the driven Kittel mode predominantly decays into the microwave cavity mode leading to the co-herent microwave generation. We thus demonstrate the bidirectional conversion between microwave and light via the Kittel mode, paving the road to use the Kittel mode as a quantum transducer.

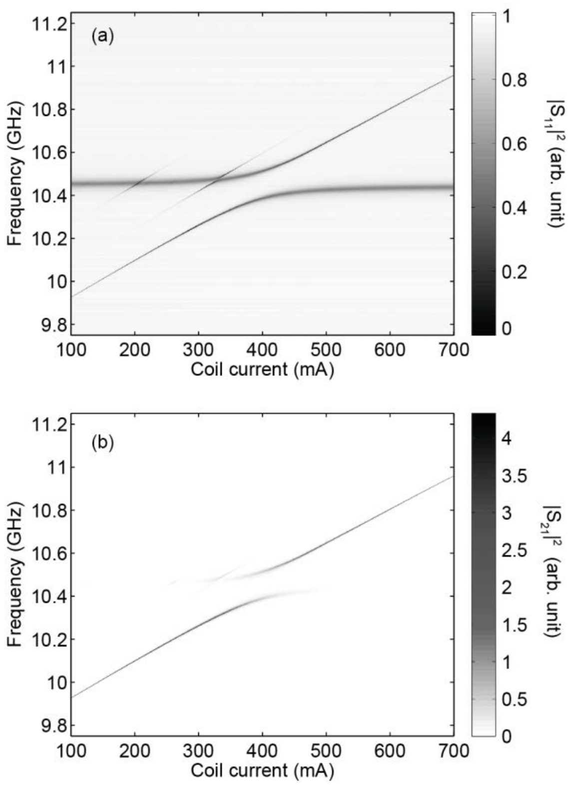

Figure 1: Spectroscopy of the coupled system consisting of the microwave cavity and the Kittel mode coupled system. (a) Spectrum probed by microwave reflection, and (b) those probed via Faraday effect.

S10-7

Conversion from single photons to single electron spins using GaAs-based double quantum dots

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Electrical controllability of gate-defined quantum dots (QDs) has brought significant developments in the coherent manipulation of electron spins and two-qubit gate operation toward scalable qubits for quantum computations. Such suitability of gate-defined QDs to quantum information technologies would be considerably enhanced if spin states in the QDs could couple to photon states coherently. Here we show that the photon polarization can couple to the spin degree of freedom in gate-defined GaAs QDs.

Double QDs were fabricated in AlGaAs/GaAs quantum wells [1]. First we show that the resonant inter-dot tunneling can offer a robust detection scheme of the single photoelectron trapping in the double QDs [2,3]. In the two-electron regime, the inter-dot tunneling of the photoelectrons strongly depends on the relative spin orientation (parallel or anti-parallel) of the two QDs. Therefore by combining the resonant inter-dot tunneling scheme with the Pauli spin effect, we have realized the detection of single photoelectron spins. Finally, we demonstrate the angular momentum conversion from single photons to single electron spins in the double QD from the dependence of the detected spins on the incident photon polarization [4].

Authors acknowledge the collaborations with K. Kuroyama, H. Kiyama, G. Allison, M. Larsson, K. Morimoto, S. Teraoka, S. Haffouz, D. G. Austing, A. Ludwig, and A. D. Wieck. This work was supported by Grants-in-Aid for Scientific Research A (No. 25246005), S (No.26220710), Innovative Area "Nano Spin Conversion Science" (No. 26103004), ImPACT Program of Council for Science, Technology and Innovation and SCOPE of MIC.

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S10-8

Single spin, photon, and charge manipulation of NV center in diamond

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NV center in diamond has been extensively interested because the single spin of it can be manipulated and detected at room temperature (RT). Furthermore, coherence time (T_2) of the NV center is very long. T_2 is the time to retain coherence (superposition state) and directly relates to the sensitivity of magnetic sensor. Therefore, the unique and excellent properties are expected to be applied for quantum computing, quantum communication and high-sensitive magnetic sensor with nano-scale resolution. By using the NV center, we previously investigated the quantum entanglement generation [1], spin coherence properties [2], and quantum coupling with a flux-qubit [3], and electrically driven single photon source at RT [4].

Recently, we realized deterministic electrical charge-state control of single NV- center [5] by using a p-i-n diode that facilitates the delivery of charge carriers to the defect for charge state switching. A homebuilt confocal microscope was used to observe the single NV centers. By developing this technique for the decoupling of nuclear spins from the NV electron spin, realization of quantum memory of nuclear spin with very long T_2 can be expected. In addition, we also realized nearly perfect alignment (more than 99 %) of the NV axis along the [111]-axis [6]. This result enables a fourfold improvement of optical detection efficiency for spin information in quantum device and a fourfold improvement in magnetic-field sensitivity. These achievements are considered to be a crucial step towards elaborated diamond-based quantum spintronics devices.

These researches are supported SCOPE program, NICT program, Kakenhi, and JST CREST program. The p-i-n diode was produced by AIST in Japan.

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Teaching Nanomagnets New Tricks

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Semiconductor nanostrcutures doped with magnetic impurities provide an intriguing playground to control magnetic ordering. An important manifestation of such ordering is the formation of a magnetic polaron (MP). It can be viewed as a cloud of localized magnetic ion spins, aligned through an exchange interaction with a confined carrier spin and is typically considered a low-temperature phenomenon in bulk semiconductors. However, recent experimental advances in colloidal nanocrystals and epitaxially grown quantum dots (QDs) show robust signatures of MPs that can persist up to room temperature and lead to effective internal fields up to 100 tesla [1]. These highly tunable semiconductor nanostructures, allowing versatile control of the number of carriers, their spin, and the effects of quantum confinement, offer novel possibilities for magnetism, inaccessible to bulk structures. We suggest how magnetic ordering can be controlled even at a fixed number of carriers [2] and enhanced by heating [3]. In a closed-shell system a pseudosinglet spin configuration is responsible for magnetic ordering [4], shown in Fig. 1. We expect that doping quantum dots with magnetic impurities (typically, Mn) may open unexplored opportunities to study the nanoscale correlations [5]. Through Mn-carrier exchange interaction, molecular-like correlations can be enhanced, imprinted on Mn spins, and thus observed. We propose experiments to verify our predictions.

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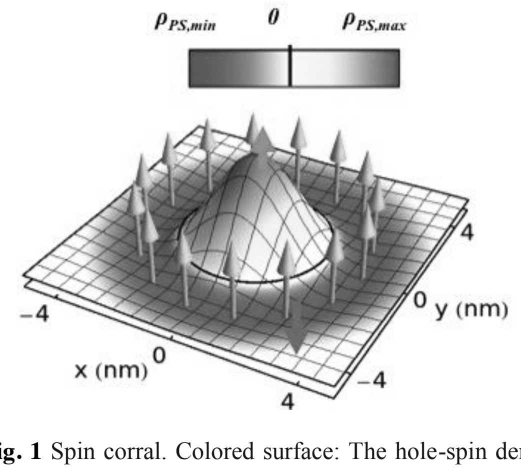

Fig. 1 Spin corral. Colored surface: The hole-spin density ρ_{PS} of the pseudosinglet. Black circle indicates vanishing $\rho_{PS.}$ Green arrows: Mn spins, placed to maximize the stability of the ferromagnetic alignment. Red and blue arrows: The more probable hole-spin projections at two positions [4].

S10-10

Quantum Hall effects at oxide interfaces

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Semiconductor interfaces have provided a variety of opportunities for physics of condensed matters particularly in mesoscopic physics as represented by the quantum Hall effect. As the physics are mostly described in terms of material-independent forms with appropriate renormalization of material parameters, the quantum Hall effect has been primarily studied in the cleanest material, i.e. GaAs. Currently, the electron mobility of the state-of-the-art GaAs heterostructure exceeds 10 million cm^2/Vs, leading to a regime where electron correlation determines its ground state.

Such high-mobility electrons are now available at oxide interfaces as well. Particularly, we have developed the growth technique of ZnO thin films [1]. While the mobility reaches one million cm^2/Vs, the quantum scattering time, which reflects total rate of the scattering, is now comparable to that of the best-quality GaAs as shown in Fig. 1. This enabled recent observation of even-denominator fractional quantum Hall state at $\nu = 3/2$ for the first time [2]. Although $\nu = 3/2$ may be understood in a similar manner to $\nu = 5/2$ state of GaAs, ZnO possesses much stronger electron interaction than that of GaAs, which would leads to a completely new ground state in this material.

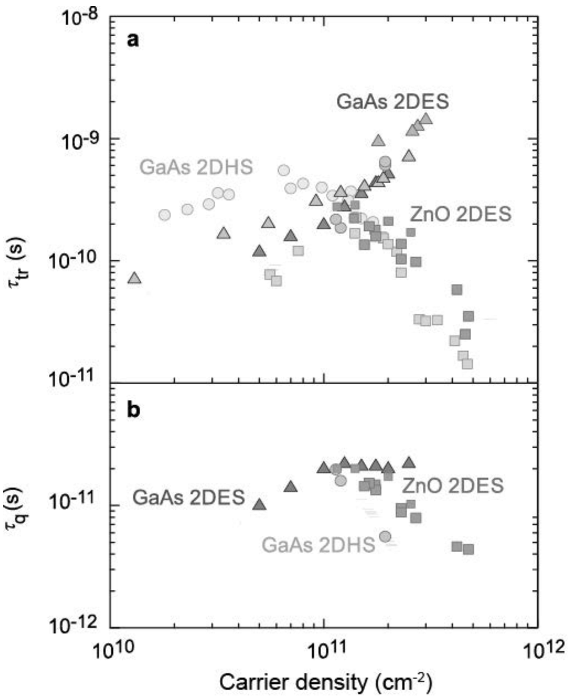

Figure 1: Transport scattering time (τ_{tr}) and quantum scattering time (τ_q) as a function of carrier density for high-mobility carriers in GaAs and ZnO

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S10-11

Local Currents in a Two-Dimensional Topological Insulator

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Symmetry protected edge states in a two-dimensional topological insulator are interesting both from the fundamental point of view as well as from the point of view of potential applications in nanoelectronics. Here using a simple tight-binding model and the Landauer-Büttiker formalism we explore local current distributions in a two-dimensional topological insulator focusing on effects of impurities as well as finite size effects. For an isolated edge state, we show that the local conductance decays into the bulk in an oscillatory fashion as explained by the complex band structure of the bulk topological insulator. We demonstrate that although the net conductance of the edge state is topologically protected, impurity scattering leads to intricate local current patterns involving vortex currents of certain chirality. For finite size strips of a topological insulator we observe the formation of an oscillatory band gap in the spectrum of the edge states, the emergence of Friedel oscillations caused by an open channel for backscattering from impurity, and antiresonances in conductance when the Fermi energy matches the energy of the localized state created by impurity.

S10-12

Theory of Spin Mechatronics

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Spin current, a flow of spins, is a key concept in the field of spintronics[1]. It is generated by using angular momentum conversion between magnetization, photon and electric current and so on. On the other hand, mechanical angular momentum due to mechanical motion has not been utilized for spin-current generation, which might be useful in nano-electromechanical systems.

In this talk, we discuss spin-current generation from mechanical motion such as rigid rotation[2], vibration[3], elastic deformations[4], and spin-manipulation by mechanical rotation[5]. Conventionally, the Pauli equation for spinor is derived from the special relativistic Dirac equation that cannot describe inertial effects induced by acceleration of a body. We use the general relativistic Dirac equation to describe spin transport phenomena with inertial effects, and show that mechanical generation of spin current and mechanical manipulation of spins stem from the inertial effects on spins that have been ignored in conventional condensed matter theory.

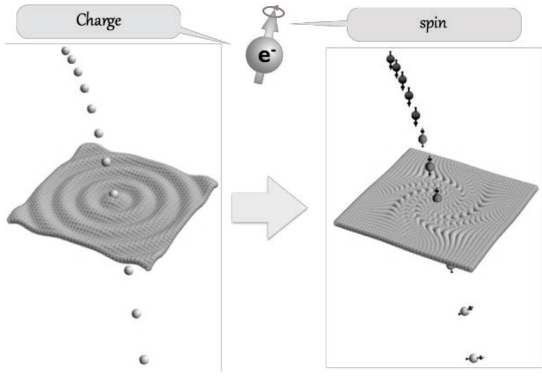

Figure 1: Concept of spin-mechatronics. *Left:* The coupling between charge current and mechanical motion has yielded electro-mechanical systems. *Right*: The coupling between spin current and mechanical motion will open up a new field of spintronics.

This work has been done in collaboration with J. Ieda and S. Maekawa.

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S11-1

Stability of skyrmion lattices and symmetries of Dzyaloshinskii-Moriya magnets

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The form of Dzyaloshinskii-Moriya interaction is defined by the symmetries of the underlying crystal, e.g. non-centrosymmetric systems or systems with structural asymmetry. By the direct Free energy minimization and Monte-Carlo simulations we study the phase diagram of Dzyaloshinskii-Moriya magnets with different symmetries of the crystal structure. We observe that the skyrmion lattice can be deformed, e.g., losing its six fold symmetry in favor of four fold symmetry. In some instances, we observe the appearance of merons – topological objects with half of the topological charge. This behavior largely depends on the balance of anisotropies and Dzyaloshinskii-Moriya interactions as well as on the form of Dzyaloshinskii-Moriya interactions. We also discuss various strategies for manipulating such magnetic textures.

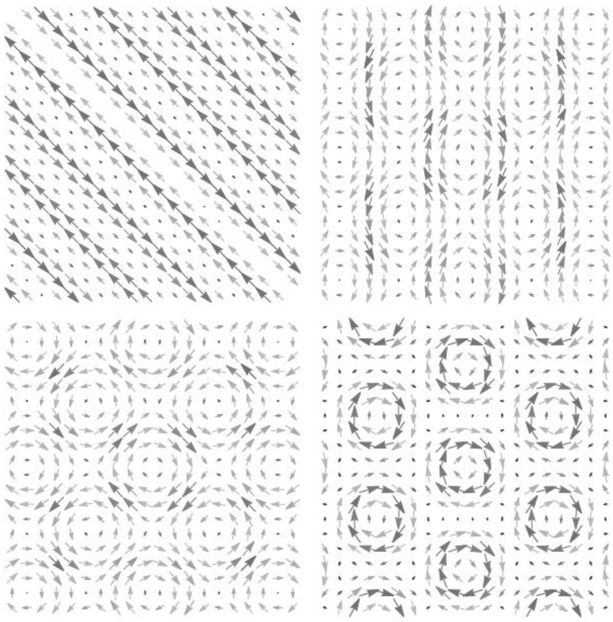

Figure 1: Possible magnetic textures in systems with DMI. Upper plots: helix state and SC1 skyrmion state with a two-fold rotational symmetry. Lower plots: SC2 skyrmion state with a four-fold rotational symmetry and SCh with a six-fold symmetry.

S11-2

Chirality and Ferromagnetism

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Recently, the interplay between the chirality and ferromagnetism has attracted much attention as the source of unique emergent phenomena.

One example is the formation of magnetic skyrmion, i.e. nanometer-scale vortex-like swirling spin texture with particle nature (Fig. 1(a)). Skyrmions in metallic materials can be manipulated by electric current through the spin-transfer torque. Such electric controllability, along with their small size and particle nature, are a promising advantage for potential spintronic device applications. Recently, we discovered that skyrmions appear also in an insulating chiral-lattice magnet Cu_2OSeO_3 [1-3]. Skyrmions in insulator can magnetically induce electric polarization through the relativistic spin-orbit interaction, which enables the manipulation of the skyrmion by external electric field without loss of joule heating.

We have also investigated the spin-dynamics in such chiral-lattice ferromagnets[4-7], and found that the propagation character of the light and spin wave in these compounds show clear nonreciprocal nature (Fig. 1(b)). In general, any (quasi-)particle flow along the magnetic field direction should hold the chiral symmetry, and the above nonreciprocal propagation character originates from the interference of chirality between the propagating entity and crystallographic lattice. The present finding indicates that the chiral-lattice ferromagnets can be utilized as the efficient diode for microwave light and spin wave.

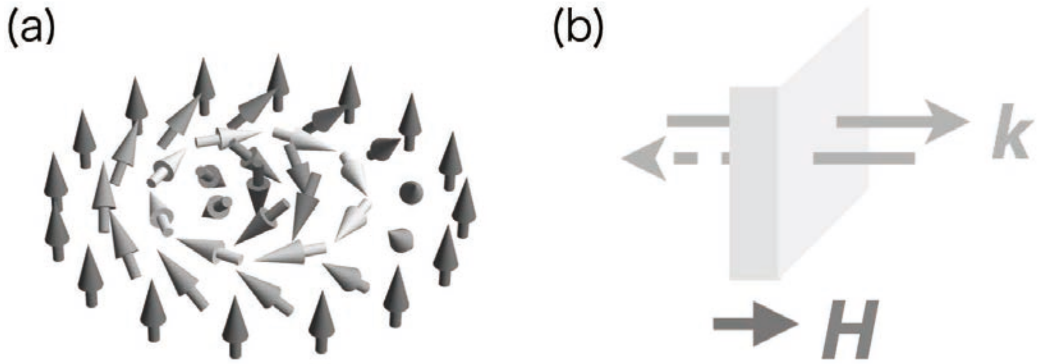

Fig. 1: Two emergent phenomena in chiral-lattice ferromagnets. (a) Formation of skyrmion spin texture, and (b) nonreciprocal propagation of (quasi)-particle flow along magnetic field direction.

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S11-3

Complex Spin States by Interfacial Dzyaloshinskii-Moriya Interactions: From Single Atoms to Thin Films

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Localized magnetic moments in a metal are coupled by indirect exchange interactions, which are mediated by the conduction electrons of the nonmagnetic host. For hosts with weak spin-orbit coupling, this exchange can be described by a Ruderman-Kittel-Kasuya-Yoshida (RKKY)-interaction. The damped oscillation of this interaction as a function of distance between ferromagnetic and antiferromagnetic coupling has already been observed in real space by spin-polarized scanning tunneling microscopy (SP-STM) [1,2]. However, for materials with strong spin-orbit coupling, such as platinum or iridium, an additional anisotropic Dzyaloshinskii-Moriya (DM) type term has to be considered [3].

Here, we report on a detailed study of the distance dependency of this DM term in pairs of an Fe-H_2 Kondo complex and an Fe atom adsorbed on Pt(111). We have built several pairs of various distances by STM-induced single-atom manipulation and performed inelastic scanning tunneling spectroscopy (ISTS) above each atom in such pairs. This reveals a splitting of the Kondo resonance, dependent on the strength of the isotropic RKKY and anisotropic DM components of the interaction for the specific distance. By comparison with theory, we were able to extract the strength of both components and find that in our system the DM term is of similar magnitude as the isotropic exchange.

The importance of these interfacial DM interactions for determining the magnetic ground state in low-dimensional systems has been revealed by observing spin spirals with a unique rotational sense in atomic Fe chains on Ir(001) [4] as well as ultrathin transition metal films on W(110) and W(001) substrates using SP-STM [5-7]. Moreover, we have discovered nanoskyrmion lattices in ultrathin layers of transition metals, such as monolayer Fe films on Ir(111) [8,9]. In this case, skyrmionic lattices with a periodicity of only one nanometer can be stabilized even in zero external field by interfacial DM interactions.

More recently, we have made use of multiple interface engineering in bilayer and multilayer systems in order to demonstrate the direct observation and manipulation of individual skyrmions of single-digit nanometer-scale size [10]. By locally injecting spin-polarized electrons from an atomically sharp SP-STM tip, we were able to write and delete individual skyrmions one-by-one, making use of spin-transfer torque exerted by the injected high-energy spin-polarized electrons. The creation and annihilation of individual magnetic skyrmions demonstrates their great potential for future nanospintronic devices making use of individual topological charges as information carriers [11].

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S11-4

Coherence by elevated temperature

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We reveal several distinct regimes of the relaxation dynamics of a small quantum system coupled to an environment within the plane of the dissipation strength and the reservoir temperature. This is achieved by discriminating between coherent dynamics with damped oscillatory behavior on all time scales, partially coherent behavior being nonmonotonic at intermediate times but monotonic at large ones, and purely monotonic incoherent decay. Surprisingly, elevated temperature can render the system "more coherent" by inducing a transition from the partially coherent to the coherent regime. This provides a refined view on the relaxation dynamics of open quantum systems.

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S11-5

Shot noise monitoring of the cross-over between SU(4) and SU(2) symmetry of the Kondo effect in a carbon nanotube quantum dot.

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In a quantum dot, Kondo effect occurs when the spin of the confined electron is entangled with the electrons of the leads forming locally a strongly correlated Fermi-liquid. Our experiments were performed in such a dot formed in a single carbon nanotube, where Kondo effect with different symmetry groups, namely SU(2) and SU(4), shows up. In the latter case, as spin and orbital degrees of freedom are degenerate, two channels contribute to transport and Kondo resonance emerges for odd and even number of electrons. With our sample it was possible to investigate both symmetries near the unitary limit.

It is predicted that, in the Kondo regime, strong interaction creates a peculiar two-particle scattering which appears as an effective charge e^* for the quasi-particles [1,2]. We have extracted the signature of this effective charge in the shot noise for both symmetry in good agreement with theory [3,4]. This result demonstrates that theory of the Kondo effect can be safely extended out of equilibrium even in the unconventional SU(4) symmetry[5].

Surprisingly, the SU(4) Kondo effect for 2 electrons persists until very high perpendicular magnetic field (13 T). We have measured this evolution in the conductance and shot noise. Our results show that only one perfect channel persists and the effective charge increases up to the SU(2) value. It suggests that the symmetry of the Kondo effect changes from SU(4) to the so called singlet-triplet SU(2) at high field.

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S11-6

Universal Fermi liquid crossover and quantum criticality in a mesoscopic system

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The microscopic origins of quantum phase transitions (QPTs) in complex materials and the fate of the Fermi liquid state at quantum criticality are often debated. Quantum dots and mesoscopic circuits provide an experimental framework for realizing known quantum impurity Hamiltonians that can feature tunable second-order QPTs. Here we investigate experimentally and theoretically in unprecedented detail the quantum phase transitions occurring in a mesoscopic system, a quantum dot coupled to a metallic grain and to lead electrodes [1,2]. We establish theoretically the complex phase diagram of this device through detailed numerical renormalization group calculations and resolve a former controversy: We show that, counter-intuitively, stable lines of non-Fermi liquid spin and charge two-channel Kondo states [3,4] emerge and coexist with SU(4) physics in this simple device [5]. We demonstrate experimentally, with support from numerical computations, a universal crossover from a quantum critical non-Fermi liquid behavior to distinct Fermi liquid ground states in a regime, where our device realizes a spin-1/2 impurity exchange-coupled equally to two independent electronic reservoirs. Arbitrarily small detuning of the exchange couplings results in conventional screening of the spin by the more strongly coupled channel for energies below a Fermi liquid scale T*. We extract a quadratic dependence of T* on gate voltage close to criticality and validate an asymptotically exact conformal field theory description of the universal crossover between strongly correlated non-Fermi liquid and Fermi liquid states [6].

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S11-7

Topological Valley Currents in Gapped Dirac Materials

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Gapped 2D Dirac materials, in which inversion symmetry is broken by a gap-opening perturbation, feature a unique valley transport regime. The system ground state hosts dissipationless persistent valley currents existing even when topologically protected edge modes are absent or when they are localized due to edge roughness. Topological valley currents in such materials are dominated by bulk currents produced by electronic states just beneath the gap rather than by edge modes. Dissipationless currents induced by an external bias are characterized by a quantized half-integer valley Hall conductivity. The under-gap currents dominate magnetization and the charge Hall effect in a light-induced valley-polarized state.

S11-8

Chiral electroluminescence from 2D material based transistors

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Layered Transition metal dichalcogenides (TMDs) are fruitful platform for electronics, spintronics, and opto-valleytronics. The monolayer TMDs have a similar crystal structure as staggered graphene and thus various physics predicted for inversion asymmetric graphene also inheres in monolayer TMDs. Especially, valley related physics are of particular importance. The broken inversion symmetry splits six Fermi pockets, locating at the first Brillouin zone edges, into two inequivalent groups (±K). The existence of valley degree of freedom is the base requirement for valleytronics. The broken inversion symmetry also lead to finite and valley-depended Berry curvature, which leads to valley-depended optical selection rule (valley circular dichroism), Zeeman-type spin splitting, and valley Hall effect [1]. After the fundamental investigation of valley circular dichroism in TMDs by polarization-resolved photoluminescence, valley-dependent spin splitting [2] and light-induced valley Hall effect [3] were experimentally observed.

We have investigated *p-n* junctions embedded in TMDs, in terms of opto-electronic applications. Taking advantage of the ambipolar transport characteristics, *p-n* junctions can be electrostatically formed in channel TMD materials using field effect transistor (FET) geometry [4]. Among various FETs, electric double layer transistor (EDLT), a FET using liquid dielectrics, have been manifested their potentials upon TMDs by field-induced superconductivity [5] or control of spin relaxation [6]. For opto-electronic devices, we observed electrically controllable helical electroluminescence from TMD *p-n* junction formed by EDLTs [7]. In a stark contrast, such a functionality is absent in junctions formed by conventional FETs [8]. The origin of this phenomenon lies in the anisotropic band dispersion (trigonal warping) that, under in-plane electric field, leads to valley-depending carrier transport and electron-hole recombination. Within the conventional FETs, the in-plane electric field is expected to be too small to induce these effects, implying the potential of EDLTs.

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S11-9

Quantum transport in van der Waals heterostructures of graphene and 2D materials

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Recent advances in transfer techniques of atomic layers have enabled one to fabricate van der Waals heterostructures of two-dimensional (2D) crystals such as graphene, hexagonal boron nitride (h-BN), and transition-metal dichalcogenides (TMDs). In this talk, we study carrier transport in high-mobility dual-gated h-BN/graphene/h-BN devices. The resistance across the npn junctions shows an oscillatory behavior, suggesing that the co-propagating p and n quantum Hall edge channels traveling along the pn interface functions as a built-in Aharanov-Bohm-type interferometer. The trajectories of peak and dip in the observed resistance oscillation are well reproduced by our numerical calculation that assumes magnetic flux quantization in the area enclosed by the co-propagating edge channels. Coherent nature of the co-propagating edge channels are confirmed by the checkerboard-like pattern in the dc-bias and magnetic-field dependences of the resistance oscillations. We will also present our recent experiments on quantum transport in various van der Waals junctions of 2D materials.

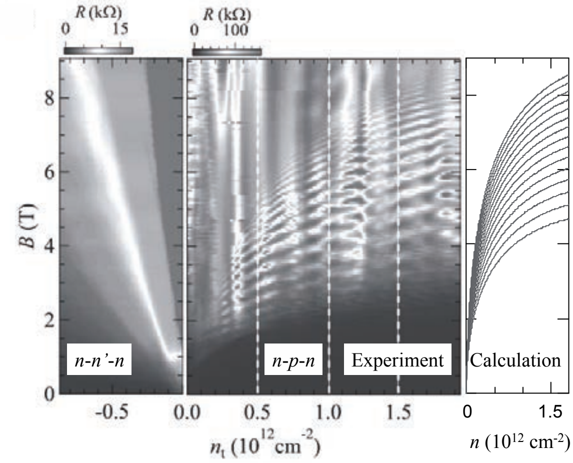

Fig. 1 Color-plot of two-terminal magnetoresistance of graphene nnn (left) and npn (center) junctions. Simulated peak positions of carrier transmission between the counter-circulating quantum Hall edge channels at the pn interface (right).

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S11-10

Valley Hall effect in electrically spatial inversion symmetry broken bilayer graphene

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We report on the observation of the valley Hall effect in electrically spatial inversion symmetry broken bilayer graphene [1, 2]. Certain specific crystal structuers result in degenerate local minima (conduction band) or maxima (valence band) called "valleys" in the band structure. "Valleytronics" is a newly developed concept for electronics utilizing the occupation degree of freedom of valleys as an information carrier. Honeycomb lattice systems such as graphene and transitional metal dichalcogenides (TMDCs) are ideal materials for valleytronics. These systems have K and K′ valleys that have opposite electron chiralities. When spatial inversion symmetry is broken in these systems, valley contrasting Berry curvature emerges. This results in valley Hall effect [3] and inverse valley Hall effect, which enable generation and detection of a pure valley current. Valley Hall effect was demonstrated in structurally spatial inversion symmetry broken systems such as monolayer MoS_2 [4] and monolayer graphene/h-BN superlattice [5]. For the case of bilayer graphene, however, a perpendicular electric field called displacement field can be used to break spatial inversion symmetry. The tunable displacement field allows for further controllability of the valley Hall effect and unambiguous detection of the pure valley current.

Here we used dual-gated bilayer graphene to break the spatial inversion symmetry electrically as well as to tune the carrier density. We employed nonlocal resistance measurement to prove existence of the valley Hall effect. Fig. 1 shows the schematic image of the nonlocal transport mediated by the pure valley current. The spatial inversion symmetry is broken by the displacement field (*D*). Pure valley current is generated at the left side via the valley Hall effect, and detected as a voltage signal at the right side after being converted via the inverse valley Hall effect. At 70K, around charge neutrality point, we found that large nonlocal resistance emerges under displacement field and it scales cubically with the local resistivity by tuning the displacement field. This is an evidence of the pure valley current mediating the nonlocal transport and the valley Hall effect in spatial inversion symmetry broken bilayer graphene. The worth noting point is the observation of valley Hall effect in insulating regime. In the ideal zero conductivity limit, energy non-dissipative conversion of an electric field to a pure valley current will be enabled.

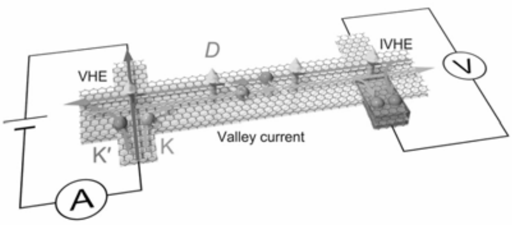

Figure 1: Schematic image of the pure valley current mediated nonlocal transport

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S12-1

Singularity of the spectrum of Andreev levels in multi-terminal Josephson junction

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We study theoretically a short multi-terminal Josephson junction. It can be realized with crossed InSb/As nanowires [1], where spin-orbit (SO) interaction is strong. In short Josephson junctions, quasiparticle Andreev bound states with discrete energy-levels are formed in the superconducting gap region, $|E| < \Delta$. The Andreev levels depend on the phase differences between superconductors. All phases have a 2π-periodicity. We consider a four-terminal junction, where three phase differences are defined and the Andreev levels form the band (like) structure, $E_n(\varphi_1, \varphi_2, \varphi_3)$. We investigate the spectrum of Andreev levels and the presence of singular points in the spectrum at $E = 0$ and $|E| = \Delta$, which are associated with the Weyl physics in a 3D solid [2].

The Andreev levels, $E_n(\varphi_1, \varphi_2, \varphi_3)$, are determined from the Beenakker's equation [3]. By the time-reversal symmetry, the change of sign of all phases results in the same energy-level, $E_n(-\varphi_1, -\varphi_2, -\varphi_3) = E_n(\varphi_1, \varphi_2, \varphi_3)$. The Andreev levels come in pair of positive and negative energy. For some junctions, accidental band touching is found at $E = 0$. In the absence of SO interaction, the Andreev levels are doubly degenerate. The conical points at $E = 0$ come in groups of four, as shown in Fig. 1(a). The SO interaction splits the conical points to upward and downward [Fig. 1(b)]. When the S-matrix is changed continuously, the conical points move but keep the groups of four. If the points meet with each other, we find a pair annihilation. These indicate topological protection of the Weyl point.

The Andreev level touches the gap edge in the absence of SO interaction. The gap edge touching point forms a 2D surface in the 3D phase space. The SO interaction generally removes the levels from $|E| = \Delta$. We establish the effective Hamiltonian from the Beenakker's equation and find the conditions of the gap edge touching in the presence of SO interaction.

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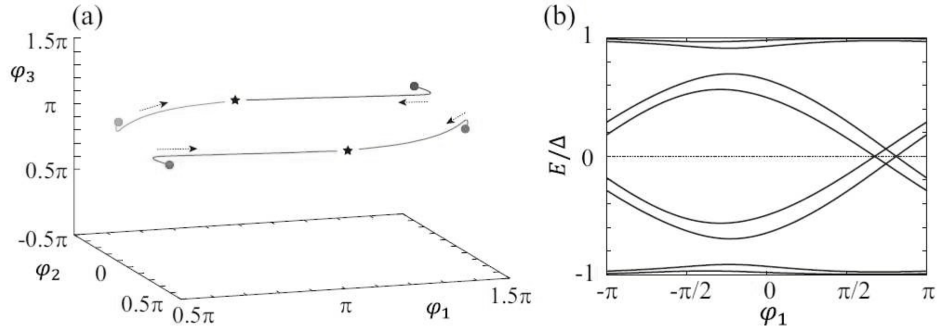

Figure 1: (a)Position of Weyl points in 3D phase space. Dots mean no SO interaction. Lines are the trajectory when the SO interaction is tuned continuously. The pair annihilation happens at star marks. (b)Andreev level with conical point, which is split by the SO interaction to upward ($E > 0$) and downward ($E < 0$).

S12-2

Superconducting hybrid structures based on quantum spin Hall systems

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We will discuss transport properties of helical edge states at the boundary of quantum spin Hall (QSH) systems in proximity to superconductors (S) and/or ferromagnets (F). For a single helical edge state, we argue that an unconventional triplet order parameter can be directly identified in an F-QSH-S setup by looking at crossed Andreev reflections [1]. In the case of two helical edge states coupled to two super-conducting electrodes in a SQUID-like geometry, we show how a Doppler shift -- due to an external magnetic field -- can significantly affect the Josephson current through the junction [2].

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S12-3

Mode Mixing in Graphene *p-n* Junctions Investigated by Shot Noise Measurement

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Because of linear and gapless band structure, graphene offers unique *p*-*n* junctions (PNJs) at which symmetric *p* and *n* regions adjoin without a gap in between. In quantum Hall effect regime, counter circulating edge modes in the *p* and *n* regions mix in the PNJ, leading to quantized conductance at unusual fractional values. In this work, we investigate the mode mixing process by shot noise measurement and suggest that the graphene PNJ can serve as a beam splitter.

We prepared graphene by thermal decomposition of SiC. We used five samples with different PNJ length between L = 5 and 100 μm. When a bias V_{sd} is applied between the edge modes in the *p* and *n* regions, the mode mixing in the PNJ leads to non-equilibrium energy distribution. Partitioning of the mixed modes at the exit of PNJ generates shot noise [Fig. 1(a)]. Since the amplitude of the noise represented by Fano factor F depends on the energy distribution in the PNJ, shot noise measurement provides information on the mode mixing process. We show that, for short PNJs, F is consistent with the value expected for quasi-elastic mode mixing. As L is increased, F becomes smaller; this is due to energy loss towards external degrees of freedom. The energy relaxation length deduced from the L dependence of F is 16 μm. We suggest that the mixing and subsequent partitioning of the modes without energy loss which are provided by a short PNJ (L << 16 μm) suggest that it can serve as a beam splitter. Since 16 μm is much larger than the typical size of mesoscopic devices, our results encourage using graphene for electron quantum optics experiment.

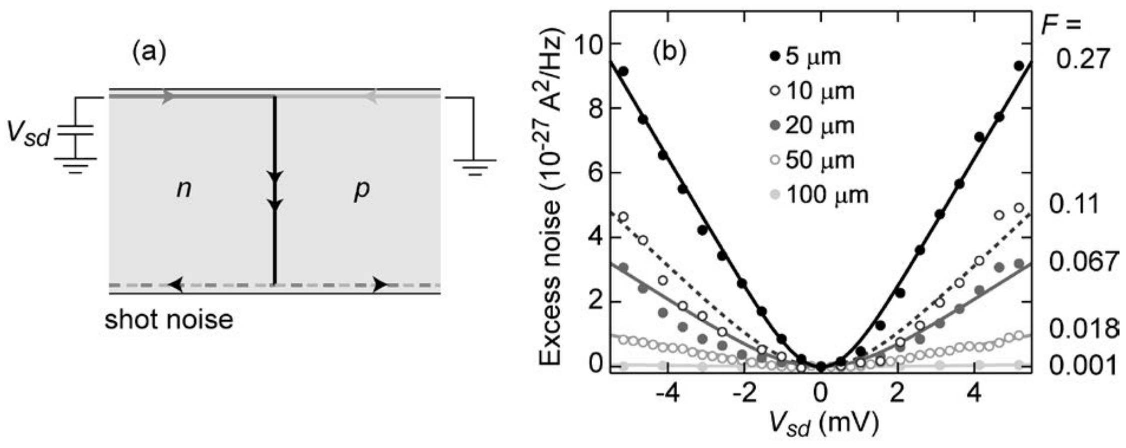

Figure 1: (a) Mode mixing and partitioning in a graphene *p*-*n* junction in quantum Hall effect regime. (b) Shot noise as a function of V_{sd} for five samples with different length of the *p*-*n* junction. The filling factors in the *p* and *n* regions are ν = -2 and 2, respectively. The magnetic field is 10 T and the temperature is 4 K.

S12-4

Josephson like effect and Cooper pair transfer in multi-terminal superconducting devices

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I will summarize the ongoing efforts of my team and my collaborators on the transfer of multiple Cooper pairs between hybrid circuits containing more than two superconductors and where non local crossed Andreev reflection operates. This can be studied with biased superconductors, where strikingly a DC Josephson signal can be obtained when the voltage biases imposed on the superconductors are commensurate. The DC current which are generated depend then on the combination of phases of the superconductors, which is unusual in non-equilibrium superconductivity. This DC signal can be optimized by tuning the energy level of the dots which separate the superconducting leads. Furthermore, we exhibit novel multiple Andreev reflection processes which depend again of these phases. Alternatively, we can also study such multiple Cooper pair resonances in an equilibrium setting in a setup containing two coupled SQUIDS (the biSQUID): a magnetic field piercing the loops of this device can be used to study its current phase response, and careful Fourier analysis reveals the signal of multiple Cooper pair transfers which are identical to those observed off equilibrium. Further extensions of this work using the circuit theory of superconductivity might be discussed.

S12-5

Fractional charge tunneling through a local fractional quantum Hall system measured using cross-correlation noise measurements

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While an electron cannot divide into fractions, a fractional quasiparticle can be exited in fractional quantum Hall (FQH) systems. Fractional quasiparticles have been investigated by measuring shot noise, which reflects charge of tunneling quasiparticles [1,2]. Here, I demonstrate a shot-noise evidence of the creation of fractional quasiparticles in a local FQH system, which is sandwiched between integer quantum Hall (IQH) systems [3]. After a brief introduction of our cross-correlation noise measurements [4], I show that a fractional quasiparticle emerges from the IQH system, when a charge tunnels through the local FQH state.

Figure 1 shows a schematic of the device and the measurement setup. The measurements were performed at 80 mK in a high magnetic field (8.0 T) perpendicular to the two dimensional electron system. The local FQH state (filling factor ν_{QPC}) is formed at the quantum point contact (QPC), which is embedded in the $\nu_B = 1$ IQH system. A dc current I_1 injected from ohmic contact Ω_1 flows along the chiral quantum Hall edge channel, and is partitioned at the QPC. We evaluated the shot noise generated at the QPC by measuring the cross correlation $S_{35} = \langle \Delta I_3 \Delta I_5 \rangle$. The charge of tunneling quasiparticles is extracted from the shot-noise power. The obtained S_{35} is plotted in Fig. 2 as a function of the transmission probability T of the QPC. The data follows the theoretical curve of $S_{35} \propto -e^* \times T(1-T)$ calculated assuming the quasiparticle charge $e^* = e/3$ (dotted line), rather than that assuming $e^* = e$ (solid line), over the wide range of T. What is important to note is that T is the transmission probability between IQH systems through the local FQH system. This indicates that the fractional quasiparticles emerge from the IQH system to tunnel through the FQH system.

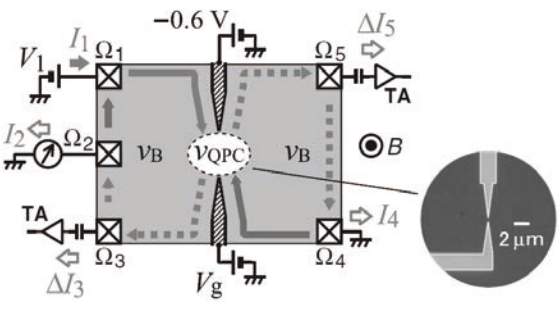

Figure 1: Schematic of a local FQH state (ν_{QPC}) sandwiched between bulk IQH systems (ν_B) and the measurement setup.

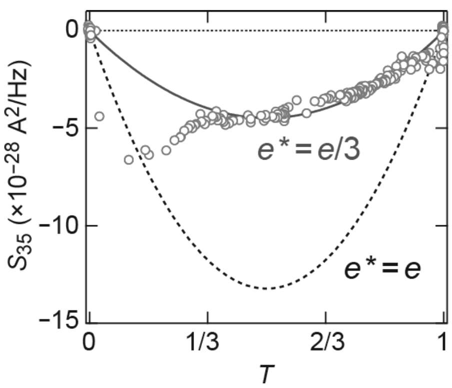

Figure 2: S_{35} measured as a function of T.

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S12-6

Fluctuation Theorem for a Small Engine and Magnetization Switching by Spin Torque

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We consider a reversal of the magnetic moment of a nano-magnet by the fluctuating spin-torque induced by a non-equilibrium current of electron spins [Fig. 1 (a)]. This is an example of the problem of the escape of a particle from a metastable state subjected to a fluctuating non-conservative force. The spin-torque is the non-conservative force and its fluctuations are beyond the description of the fluctuation-dissipation theorem. We estimate the joint probability distribution of work done by the spin torque and the Joule heat generated by the current, which satisfies the fluctuation theorem for a small engine [Fig. 1 (b)]. We predict a threshold voltage above which the spin-torque shot noise induces probabilistic switching events and below which such events are blocked. We adopt the theory of the full-counting statistics under the adiabatic pumping of spin angular momentum. This enables us to account for the back-action effect, which is crucial to maintain consistency with the fluctuation theorem.

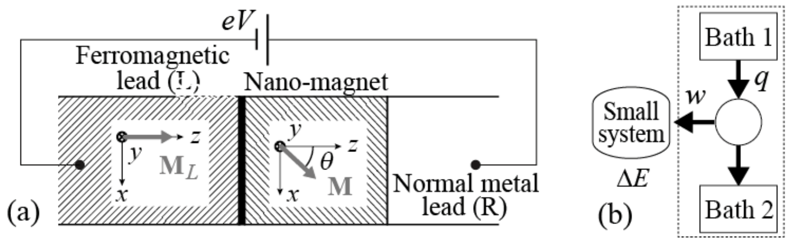

Figure 1: (a) A nano-magnet coupled to the left ferromagnetic lead and the right normal metal lead. The directions of magnetic moments of the ferromagnetic lead and the nano-magnet are $\mathbf{e}_z = (0,0,1)$ and $\mathbf{m} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$. (b) Schematic picture of a small engine. The input heat q and the output work w fluctuate.

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S12-7

Spin-dependent thermoelectric effects and spin-triplet-supercurrent in mesoscopic superconductors

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The usually negligibly small thermoelectric effects in superconducting heterostructures can be boosted dramatically due to the simultaneous effect of spin splitting and spin filtering. Building on an idea we published in [1], we propose realistic mesoscopic setups to observe thermoelectric effects in superconductor heterostructures with ferromagnetic interfaces or terminals. We focus on the Seebeck effect being a direct measure of the local thermoelectric response and find that a thermopower of the order of ~250 μV/K can be achieved in a transistor-like structure. A measurement of the thermopower can furthermore be used to determine quantitatively the spin-dependent interface parameters that induce the spin splitting. For applications in nanoscale cooling we discuss the figure of merit for which we find values exceeding 1.5 for temperatures ≲1K. In the talk I will explain the quasiclassical circuit theory behind the prediction, which takes into account the usually present diffusive scattering at interfaces and surfaces. A crucial ingredient are spin-dependent boundary conditions for the diffusive Greens functions, which need to take into account the microscopic details of the spin-dependent interface scattering and are a long-standing problem for the quasiclassical theory. The relevance for possible spin-triplet supercurrents are discussed.

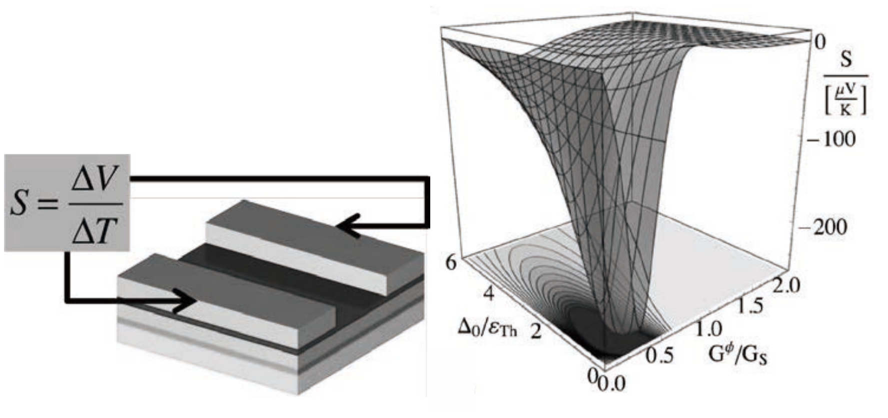

Figure 1: The left panel shows a setup to observe the predicted thermoelectric effect. The structure consists of a superconducting substrate (green), coupled to normal metal film (yellow) covered by ferromagnetic insulating film (blue). Current is injected and extracted by two normal contacts on top. By applying a temperature difference ΔT a thermovoltage ΔV can be measured (at zero current). The resulting Seebeck coefficient $S = \Delta V/\Delta T$ is plotted on the right. [2]

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S12-8

Waiting for rare entropic fluctuations in mesoscopic physics

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Non-equilibrium fluctuations of various stochastic variables, such as work and entropy production, have bee widely discussed recently in the context of large deviations, cumulants and fluctuation relations. Typically, one looks at the distribution of these observables, at large fixed time. To characterize the precise stochastic nature of the process, we here address the distribution in the time domain. In particular, we focus on the first passage time distribution (FPTD) of entropy production, in several realistic models. We find that the fluctuation relation symmetry plays a crucial role in getting the typical asymptotic behavior. Similarities and differences to the simple random walk picture are discussed. For a driven particle in the ring geometry, the mean residence time is connected to the particle current and the steady state distribution, and it leads to a fluctuation relation-like symmetry in terms of the FPTD

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S12-9

Coupled Charge and Magnetization in a Weyl Semimetal

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We theoretically investigate ferromagnetic ordering in magnetically doped solid-solution narrow-gap semiconductors with the strong spin-orbit interaction such as Cr-doped $Bi_2(Se_xTe_{1-x})_3$. We compute the spontaneous magnetization of impurities and itinerant electrons, and estimate the critical temperature as a function of the concentration of magnetic dopants and the strength of the spin-orbit interaction. It is found that the critical temperature is proportional to the concentration of dopants and enhanced with the strong spin-orbit interaction. When the original band gap is suppressed, the ferromagnetic transition could make the system turn to the Weyl semimetal which possesses a pair of Weyl points separating in momentum space. We discuss coupled spin and charge dynamical effect realized in this type of material. We propose a magnetically induced current with temporal varying chiral vector potential. Applying field theoretical methods we derive the expression of the current induced by the dynamics of magnetic collective excitations. Furthermore, we also conduct the numerical calculation for the lattice model, and obtain the results which agree with the analytical result. This work was done in collaboration with Daich Kurebayashi.

S12-10

Imaging the wave functions of Dirac–Landau levels in the topological surface state

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Topological insulators are characterized by a metallic surface state where electrons behave as massless Dirac particles described by the two-component wave function. In topological insulators, these two components are associated with the spin degrees of freedom, thereby governing the magnetic properties. Thus, it is highly desirable for spintronics applications to elucidate where and how the two-component nature emerges.

We found that the two-component nature manifests itself in the internal structures of Landau orbits formed in a magnetic field [1]. Using spectroscopic-imaging scanning tunneling microscopy, we directly image the local density-of-states (LDOS) distributions associated with the Landau orbits in the topological surface state of Bi_2Se_3. In the presence of the potential variation, Landau orbits drift along the equipotential lines. The energy-dependent ring-like structures shown in Fig. 1 represent such drift states surrounding the potential minimum. The LDOS variation across the ring includes the information of the internal structure of the wave function. With increasing Landau-level index *n*, width of the ring increases and two concentric rings become evident. We found that the observed internal structures are qualitatively different from those of conventional massive electrons [2] but are well reproduced by the calculation based on a two-component model Dirac Hamiltonian. Our model further predicts non-trivial energy-dependent spin-magnetization textures around the potential minimum. This is originated from the interplay between the two components and may provide a clue to manipulate spins in the topological surface state.

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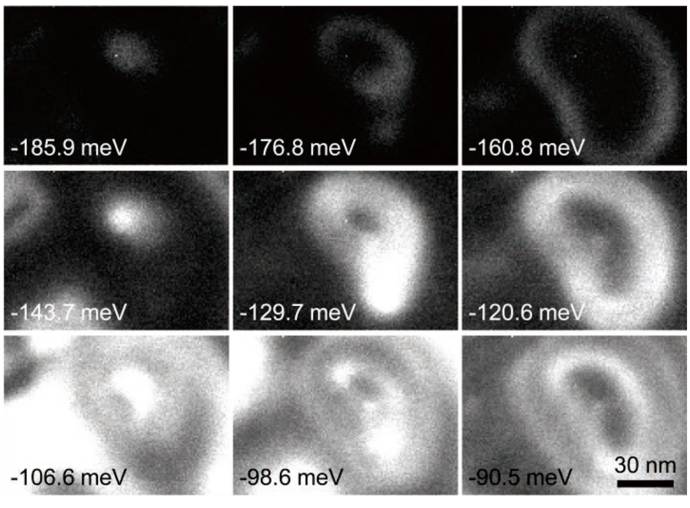

Figure 1: LDOS distributions in the topological surface state of Bi_2Se_3 at 11 T, showing the Landau orbits drifting around the potential minimum. Top, middle and bottom rows correspond to n = 0, 1 and 2 states, respectively [1].

S12-11

Helical transport in helical crystals

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Tellurium (Te) and selenium (Se) crystals consist of helices, and they are classified by their handedness. This unique crystal structure and its low crystalline symmetry gives rise to a radial spin texture, as is found by first-principle calculation [1].

Such a helical structure is reminiscent of a solenoid, and it may lead to new possibilities for electromagnetic transport. As is known, a current flowing along a solenoid induces a magnetic field along its axis, depending on its handedness. In this presentation, we pursue an analog of a "solenoid" in three-dimensional helical crystals. In a 3D metallic crystal with helical crystal structure, we expect that a current will induce a magnetization. We theoretically demonstrate it with a simple 3D tight-binding model with a helical crystal structure (Fig. 1). It turns out that an orbital magnetization is induced when a current flows along the helical axis (Fig.2(a)). Moreover, when the spin-orbit coupling is included, the spin polarization is also induced by a current (Fig. 2(c)). When the current is along the helical axis, the induced magnetization is also along the helical axis, with its sign dependent on the handedness of the crystal. This current-induced spin polarization comes from the radial spin texture (Fig. 2(b)), which is different from the tangential spin texture in typical Rashba spin-orbit coupling.

This chiral transport is nontrivial, because the lattice structure itself is a three-dimensional network, and the current flows in the whole crystal, unlike a solenoid. These results can be generalized to any helical crystals.

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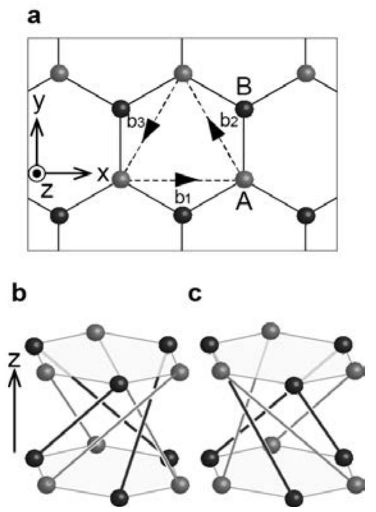

Figure 1: Helical lattice structure for the model. **a:** Structure within *xy* plane. Right-handed (**b**) and left-handed (**c**) helical structure.

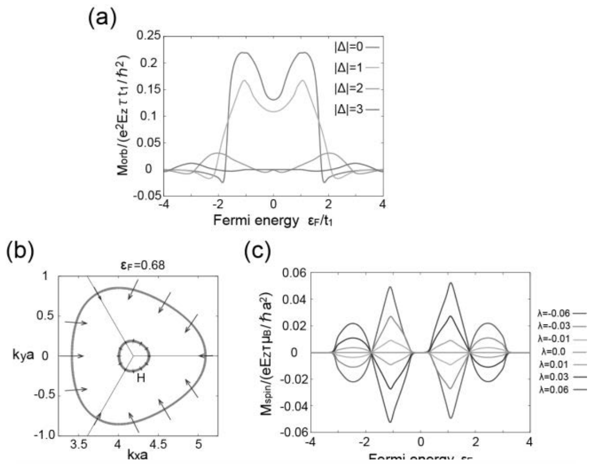

Figure 2: Numerical results for the helical model. (a) Current-induced orbital magnetization, (b) spin texture, and (c) current-induced spin magnetization.

S12-12

Conversion from a charge current into a spin polarized current in the surface state of three-dimensional topological insulator

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Conversion from a charge current into a spin current and vice versa i.e., charge-spin conversion attracts tremendous amount of attention. A charge current through a ferromagnetic material/nonmagnetic material interfaces is one of the fundamental ways to realize the charge-spin conversion [1,2]. Surface state of the three-dimensional (3D) topological insulators (TIs), which is classified in terms of Z_2 topological invariant, has been expected to represent a novel charge-spin conversion.[3] The topological surface state presents a single Dirac cone with a helical spin polarization. Therefore it is expected that spin quantization axis of the conduction electron in the TI surface state is perpendicularly locked to the carrier momentum i.e., spin-momentum locking [3-5]. Due to the spin-momentum locking, it is expected that charge current naturally induces spin polarized current, whose axis and the sign can be controlled by the direction of the charge flow and the Fermi level. Therefore, magnetoresistance at an interface between ferromagnetic metal and TI, caused by a spin polarized current in TI surface state has been expected.[7]

In this presentation, we report conversion from a charge current into spin polarized current due to the spin-momentum locking of a bulk-insulating TI, $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ (BSTS) surface, BSTS. The surface-dominated transport has been demonstrated in this compound,[8] and the angle-resolved photoemisison spectroscopy study has confirmed its Fermi level to be located in a bulk band gap,[9] realizing the intrinsic insulating state. In the magnetoresistance measurement of a ferromagnetic $Ni_{80}Fe_{20}$(Py) film/BSTS structures, we observed a rectangular hysteresis behavior which is governed by the resistance at the interface between BSTS and the Py electrode. The interface resistance changed both with the magnetization direction of the Py electrode and with the current direction as shown in Fig. 1. [9]

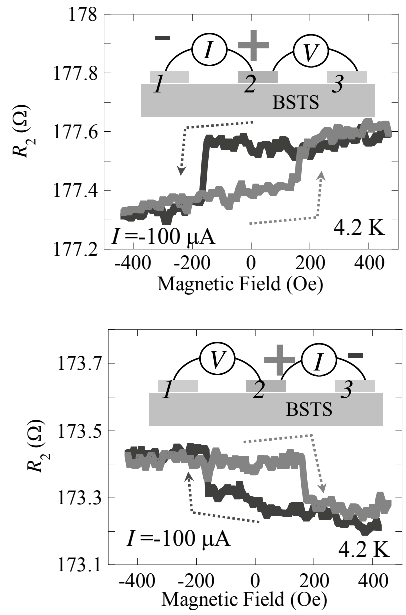

Fig. 1 Results of magnetoresistance measurement in Py/BSTS devices measured at 4.2 K .

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Abstracts of Poster

PS01

Magnetization dynamics with inertia in metallic ferromagnets

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Usually, the magnetization dynamics are described by the Landau-Lifshitz-Gilbert (LLG) equation, which includes only the first-order time derivative of magnetization. However, when the magnetization dynamics are very fast (typically sub-picosecond order for metallic ferromagnets), it is expected that the LLG equation should be generalized to include a term with the second-order time derivative. This term plays the role of the inertia of magnetization [1,2,3].

The appearance of the inertial term is due to the effect of the environmental degrees of freedom surrounding the magnetization. In the case of metallic ferromagnets, they are conducting electrons. Usually, the effects of conducting electrons can be treated at the adiabatic limit, where the spin of the conducting electrons is assumed to align with magnetization vector. This means that the angular momentum vector points in the direction of the magnetization vector, which is the usual gyromagnetic relation. When the inertia is included, this is not the case: the angular momentum vector and the magnetization vector generally point in different directions. Such a generalized gyromagnetic relation will provide rich variety of magnetization dynamics.

We study mainly three points about the inertia of magnetization [4]:
1. A concrete expression of the inertia in terms of the spin polarization of the conducting electrons and the coupling constant between the magnetization and the conducting electrons.
2. The basics of the magnetization dynamics with inertia. In particular, their equivalence to the dynamics of a spinning top, and of a charged particle on a sphere under a monopole background.
3. Typical behavior of magnetization with inertia: effects of the inertia on spin waves, domain wall dynamics and so on. In particular, how magnetization with inertia responds to a large and rapidly changing magnetic field.

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PS02

Coherent control of magnetizations and spin currents in quantum magnets with laser

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Recently periodically-driven quantum states have attracted much attention [1-6]. In particular, thanks to the recent development of laser science, it is gradually possible to realize various periodically-driven nonequilibrium states by applying laser to solid. The control of electron and spin motions by laser is becoming a hot topic. Many theoretical studies for driven systems have concentrated on electric charge dynamics. Remarkably, for example, it is shown [1,2] that when a circularly polarized laser is applied to two-dimensional Dirac electron systems on lattices, a topologically-insulating state with a gapless chiral edge mode emerges. Furthermore, experimental signatures of laser-driven electron states in band-insulating materials have been reported very recently [3].

On the other hand, we have recently explored novel nonquilibrium phenomena in insulating magnetic systems. In particular, we are focusing on magnetic phenomena in quantum antiferromagnets [4,6] and multiferroic models [5]. In this conference, we would like to discuss two of our recent results, i.e., two new methods of (1) controlling magnetizations in a wide class of quantum magnets "without static magnetic field" [4] and (2) generating additional Dzyaloshinskii-Moriya (DM) interactions in a class of multiferroic systems [5] by applying circularly polarized lasers. The control of DM interaction could also be regarded as that of spin current. I will discuss in detail these new theoretical proposals for laser control of physical quantities.

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PS03

Thermodynamics of Mesoscopic Steady-State Heat Engine beyond Linear-Response Regime

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Recently, a new type of heat engine, which we call here the steady-state heat engine, has appeared in the context of research of the efficiency at maximum power [1]. In particular, the mesoscopic thermoelectric steady-state heat engine (Fig.1) is attractive in the following two points. Practically, this engine is realizable experimentally with high efficiency because of the potential of nanoscale thermoelectricity. Theoretically, this engine can be a powerful tool to investigate how quantum mechanics affects thermodynamics.

However, researches on this engine are mostly limited to the linear-response regime [1,2]; its thermodynamic structure beyond the regime is yet to be clarified. Although some researchers have already used the definition of the heat current which we will derive in this Poster beyond the linear-response regime, few discussions have been publicized regarding even its origin and validity.

In this Poster, we will give a thermodynamically consistent definition of the heat current of the steady-state heat engine beyond the linear-response regime, which is the main result of this Letter. We then apply it to the mesoscopic thermoelectric steady-state heat engine, which produces the following two interesting results: the efficiency of the mesoscopic thermoelectric engine reaches the Carnot efficiency if and only if the transmission function is a delta function at a certain energy; the unitarity of the scattering matrix guarantees the second law of thermodynamics, invalidating Benenti *et al.*'s argument in the linear-response regime that one could obtain a finite power with the Carnot efficiency under broken time-reversal symmetry.

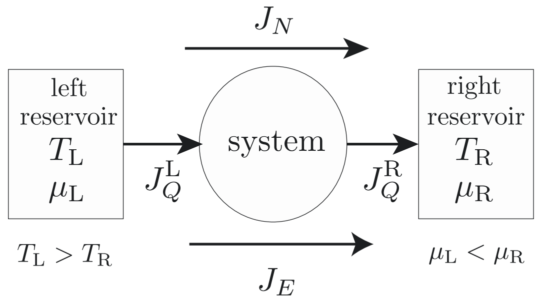

Figure. 1. A mesoscopic thermoelectric engine.

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PS04

Mode engineering with a one-dimensional superconducting metamaterial

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We propose a way to control the Josephson energy of a single Josephson junction embedded in one-dimensional superconducting metamaterial (Fig. 1): an inhomogeneous superconducting loop, made out of a superconducting nanowire or a chain of Josephson junctions. The Josephson energy is renormalized by the electromagnetic modes propagating along the loop [1]. We study the behavior of the modes as well as of their frequency spectrum when the capacitance and the inductance along the loop are spatially modulated. We show that, depending on the amplitude of the modulation, the renormalized Josephson energy is either larger or smaller than the one found for a homogeneous loop. Using typical experimental parameters for Josephson junction chains [2,3] and superconducting nanowires [4,5], we conclude that this mode-engineering can be achieved available metamaterials.

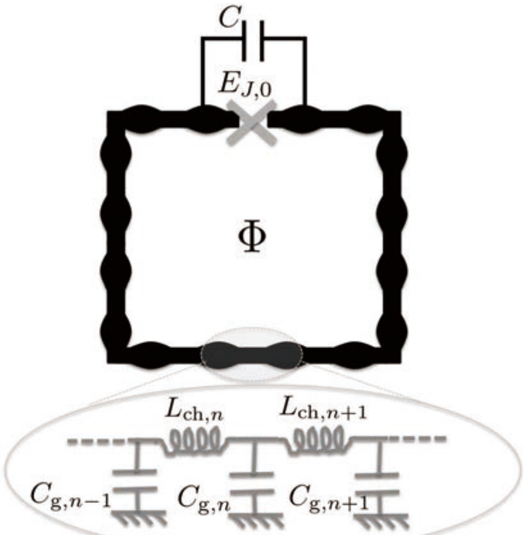

Figure 1: Single Josephson junction with Josephson energy $E_{J,0}$ and capacitance C, embedded in a loop made out of one-dimensional superconducting metamaterial threaded by a magnetic flux Φ. The metamaterial can be either a thin superconducting wire whose parameters (such as cross-sectional area or distance to a nearby screening gate) are spatially modulated, or a chain of Josephson junctions (see inset) with spatially distributed capacitances $C_{\mathrm{g},n}$ and inductances $L_{\mathrm{ch},n}$.

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PS05

Persistant metastability in periodically driven systems

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We investigate the periodic dynamics of isolated quantum many-body systems. Generically, such systems are known to heat up to infinite temperature in the thermodynamic limit, while the behaviors for finite time scales is still a challenging issue. Even if a state goes to the chaotic state under infintite-time periodic dynamics, the state may remain a metastable state with rich structures. Indeed, the existence of such metastable states has been reported in periodically driven Friedrichs models [1]; that is, we still have the possibility to construct the universal Floquet theory at a finite time scale.

Here, we give several universal properties of finite-time Floquet theory. We mathematically prove the existence of the metastable states, whose lifetimes exponentially increases with the driving frequency $\boldsymbol{\omega}$. In the proof, they are given by the eigenstates of a Hamiltonian which comes from the finite-order truncation of Floquet-Magnus expansion; there, we prove that the Floquet-Magnus expansion exponentially converges by a certain order of $\mathbf{O}(\boldsymbol{\omega})$ and then breakdown beyond it. This way, the Floquet Hamiltonian can be well-approximated by the Floquet-magnus expansion for finite-time scale, although it might look completely random for the infinite-time limit. To relate our result to the physically interesting phenomenon, we prove exponentially slow heat absorption for the driving frequency, which is relevant to so called many-body energy localization (or ergodicity breaking).

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PS06

Giant spin Hall magnetoresistance in metallic bilayers

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Recently spin-orbit interaction draws great interests due to its potential to alternative mechanism for magnetization manipulation. As a result, several interesting concepts and phenomena were introduced. Spin Hall magnetoresistance (SMR), which shows distinctive to conventional magnetoresistance, is one of them. The SMR is combined effect with ordinary and inverse spin Hall effect (SHE). So far, the reported SMR was only measured from magnetic insulator/heavymetal system, i.e. $Y_3Fe_5O_{12}$ (YIG)/Pt and YIG/Ta [1,2].

Here we show there is a ten-fold larger SMR in metallic bilayer using with W/CoFeB/MgO heterostructures. The films were prepared using with magnetron sputtering and patterned by photo-lithography and Ar ion-etching. To evaluate the SMR, measurements were given by three kinds of methods: large-field induced method and two methods with small field. We verified that there is few difference of the SMR among the mentioned methods [3]. The measurements were given for several devices with various thicknesses of W layer. As shown in Fig. 1, the SMR is quite sensitive to W layer thickness in accord with theoretical expectation [4]. From the fitting of the SMR, we obtained ~0.2 magnitude of spin Hall angle and 1.4~1.6 nm spin diffusion length for W layer. Similar study was also given for Ta/CoFeB/MgO heterostructures. Further discussion will be given.

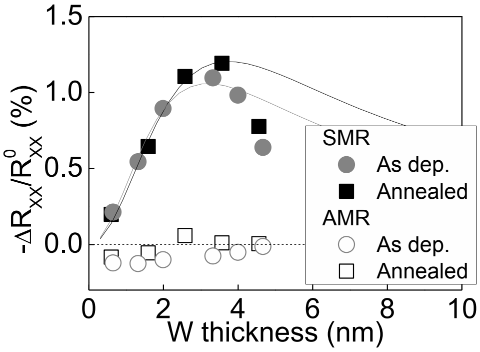

Figure 1: W layer thickness dependence on SMR (solid symbol) and anisotropic magnetoresistance (opened symbol) from annealed (square) and as deposited (circle) W/CoFeB/MgO heterostructures.

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PS07

Topological superconductivity in Dirac semimetals

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Dirac semimetals are a three dimensional (3D) material that possesses a gapless (Dirac) point in a bulk Brillouin zone, whose low energy excitation is effectively described by Dirac fermions. With time-reversal and inversion symmetries preserved, a pair of Dirac points can be formed at the crossing of two doubly degenerate bands in a high symmetric direction and protected by discrete rotation (C_n) symmetry [1,2], which prohibits a band mixing to open a gap. As a consequence of bulk boundary correspondence, a Fermi loop (FL) lives in a surface [2,3]. This is in sharply contrast with a Fermi arc in Weyl semimetals because of the different topological origin.

Most recently, the superconducting transition has been reported on Cd_3As_2 [4] and Au_2Pb [5], both of which support the C_4 symmetry protected Dirac points. A bulk Cd_3As_2 is superconducting around a point contact region on the surface or under the high pressure, and the pressurized Cd_3As_2 involves a structure transition from a Dirac semimetal to a semiconductor [6]. Thus, it is expected that the superconductivity can be accompanied with a breakdown of Dirac point. In addition, the observed tunneling conductance showed a zero-bias conductance peak. Interestingly, Au_2Pb also invokes a structure transition of the crystal before the superconducting transition [5]. Thus, although detailed analysis of the superconductivity is still missing in the Dirac semimetals, it is highly desirable to establish a general criterion for the TSC and a relation to a structure transition of the crystal.

In this poster, we address how the non-trivial topology, involving the Dirac point and the FL, affects the superconducting properties. It is known that topological materials are a promising candidate of the TSC, which stems from the fact that the non-trivial topology of wave function affects its superconducting state. For instance, the Fermi surface topology, which is the simplest topological structure in the normal state, directly influences a TSC for odd-parity superconductors [7].

Key quantities of our theory are a C_4 invariant and a mirror Chern number, which ensure the Dirac point and the FL, respectively. We show that these two topological numbers are intrinsically related and are inherited as a node and a double Majorana fermion in the superconducting state for a type of pairing symmetries. This feature opens a path for realizing a fully gapped TSC and reveals a relationship between the TSC and a structure transition of the crystal. Also, the Majorana fermions are induced by the FL, which is clearly distinguished from one in other TSCs, including superfluid ^{3}He-A [8] and Weyl superconductor [9].

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PS08

Spin Hall effect of Dirac fermions with vanishing spin current operator

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We study Dirac electron systems with spin-mixing alpha-matrices. The spin transport of the system would be quite different from usual spintronics materials due to its spin-mixing linear dispersion. In a spin-non-conserved system, however, the conventional definition of a spin current $\{S_z, \mathbf{j}\}/2$ does not satisfy the continuity equation and sometimes leads crucial problems [1]. Hence it is difficult to judge whether or not we can apply the definition to our system.

Instead of using the conventional definition, we derive a quantum kinetic equation microscopically [2] in a three-dimensional Dirac electron system with $\alpha_i = \sigma_i \times \tau_1$($\sigma$'s: spin Pauli matrices, τ's: orbit Pauli matrices). Then we define the spin current from diffusion equations [2, 3], which can be derived by the quantum kinetic equation. According to the new definition, we find that the spin Hall coefficient has a finite value, though the conventional spin current operator is identical to zero in this system.

We also discuss a relation between anomalous electric current, which originates from the vertex correction of impurities, and the spin Hall coefficient.

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PS09

Electrical transport in three-dimensional cubic Skyrmion crystal

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Two-dimensional magnetic Skyrmions have been well characterized experimentally in the bulk or on epitaxial thin films. Besides, a topologically nontrivial three-dimensional cubic Skyrmion crystal in the bulk, which is essentially a hedgehog-antihedgehog pair structure predicted theoretically, has also been observed. Equipped with a sophisticated spectral analysis method, we adopt finite temperature Green's function technique to calculate the longitudinal electrical transport in such system. We consider conduction electrons interacting with spin-waves of the topologically nontrivial spin texture, whereupon fluctuations of monopolar emergent electromagnetic field enter. We study in detail the behavior of electrical resistivity under the influence of temperature, Skyrmion number and a characteristic monopole motion, especially a novel magnetoresistivity effect tentatively describing some up-to-date experimental observations.

PS10

Topological Phase Transitions and Sweep Dynamics of a Generalized Cluster Model in One Dimension

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Quest for topological phases is a hot topic in quantum information science and quantum statistical physics. It has been recognized that topological ordered states can be used for resource states in quantum information processing. In addition, a couple of beautiful relations between some physical properties and entanglement properties have been reported in topological systems and exactly solvable lattice-gas models [1-4].

The cluster model would be one of the simplest models, in which the ground state is a topological state called cluster state [5-7]. The cluster model in one dimension characterizes a string order parameter that is a nonlocal order parameter. By adding the Ising coupling term into the one-dimensional cluster model, a topological phase transition emerges [7]. This suggests that additional terms would involve novel phases and phase transitions.

We consider a generalized cluster model in one dimension [8]. The Hamiltonian of the model is represented by

$$H = \sum_{i=1}^{N}\left(-J^{XZX}\sigma_i^x\sigma_{i+1}^z\sigma_{i+2}^x + J^{YY}\sigma_i^y\sigma_{i+1}^y + J^{YZY}\sigma_i^y\sigma_{i+1}^z\sigma_{i+2}^y\right),$$

where the first, second, and third terms respectively represent cluster, Ising, dual cluster interactions. Since the excitation gap of the model can be obtained exactly, the phase boundaries of the model can be determined. To characterize each phase, order parameters including string order parameters and the entanglement spectra are calculated. We find that nontrivial phases appear in the parameter regions where all coupling constants are comparable. Next, we study dynamic behavior of the model under a sweep of interaction parameter across a critical point. When the interaction parameter changes slowly, the string correlation function and the entanglement entropy have a characteristic spatial structure. The fact would be related with the topological blocking found in topological systems [9,10].

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PS11

Magnetization damping in antiferromagnetically coupled spin valves

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Recently, a new direction in spintronics has been emerging in which antiferromagnets (AFMs) complement or replace ferromagnet (FMs) as active elements of memory or logic devices [1], e.g. because AFMs do not generate unwanted stray fields. On the other hand, it is difficult to control AFMs by an external magnetic field. Moreover, natural AFM materials resonate at a much higher frequencies (THz rather than GHz), which is difficult to match to conventional electronic circuits.

Motivated by experimental results that hitherto have been unexplained [2], we focus on the theory of the simplest of synthetic antiferromagnets, i.e. the antiferromagnetically exchange-coupled spin valve. These devices have the features of natural AFMs but with easily accessible resonance frequencies that are tunable by weak magnetic fields. By rigorous model calculations, we investigate the magnetic damping of synthetic AFMs as affected by mutual pumping of spin currents and spin transfer torques or "dynamic exchange interaction" [3]. We derive the Landau-Lifshitz-Gilbert equations for the coupled magnetizations including the spin transfer torques by spin pumping based on the spin diffusion model with quantum mechanical boundary conditions at the interfaces. We obtain analytic expressions for the linewidths of magnetic resonant modes (acoustic and optical) for magnetizations canted by applied magnetic fields. We find that noncollinear magnetizations induce an additional damping and that FMR linewidths strongly depend on the type of the resonant modes as well as the strength of magnetic fields. Our calculated results compare favorably with experiments [4] as shown in Fig. 1, thereby proving the importance of dynamics spin currents in these devices. Our model calculation paves the way for the theoretical design of synthetic AFM material with an application potential for data-storage technologies in antiferromagnetic spintronics.

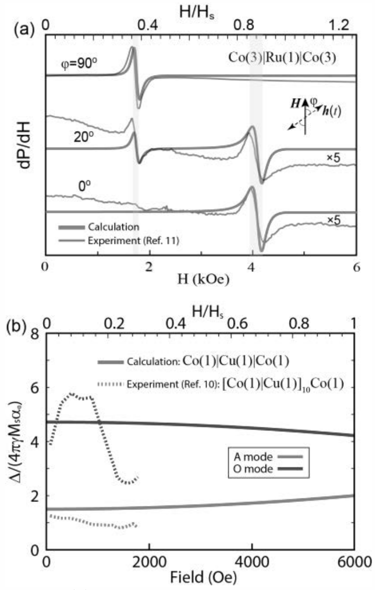

Fig.1: (a) Derivative of the microwave absorption spectrum [5] (b) Computed linewidths of the acoustic (A) and optical (O) modes [2].

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PS12

Majorana fermions with spatially periodic modulation

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Recently, motivated by mesoscopic physics and quantum information science, novel topological phases have been discovered. These phases are characterized by emergent edge excitations and entanglement spectrum (ES). The Kitaev model of one-dimensional spinless p-wave superconductor is one of the simplest fermion models exhibiting such a topological phase. In the topological phase, the system possesses Majorana zero modes at the ends of the system, which is responsible for the degeneracy of the lowest levels in the ES of the ground state. The robustness of the Majorana zero modes has attracted both theoretical and experimental attention. The fate of the modes under spatially periodic modulation and disorder has been considered in Ref. 1, where the authors found out the transitions from topological phase to trivial phase.

We numerically analyzed the one-dimensional Majorana fermions with the third-nearest interactions to show the robustness of the Majorana zero modes. We calculated the ES and the string correlation functions using the exact diagonalization method. The model without the periodic modulation has two Majorana zero modes and the ES shows four-fold degeneracy in lowest levels [2]. We impose the chemical potential periodically modulating in space. Varying the amplitude and the phase of the modulation, the number of the Majorana zero modes change. Remarkably, for certain values of the amplitude and the phase, the ground state shows topological phase with *one* Majorana zero mode. Correspondingly, the lowest levels of the ES are two-fold degenerate (Fig.1) and the string correlation functions show characteristic behaviors in the ground state. The above results indicate that the robustness of Majorana zero modes strongly depends on the spatial modulation of the chemical potential.

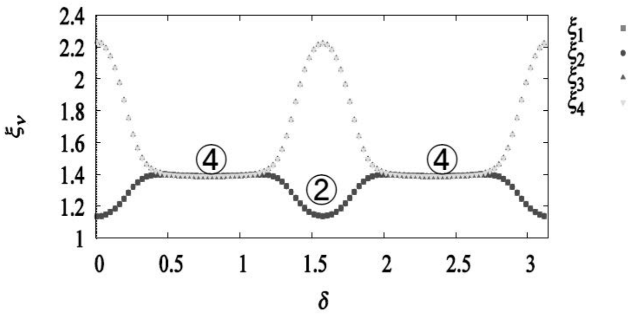

Figure 1: The lowest four ES ξ_ν for each phase δ of the modulation of the chemical potential. The amplitude is $0.5t$ and the wave length is $4a$, where t is the hopping integral and a is the lattice constant. The number enclosed by a circle represents the degeneracy of the lowest levels of the ES.

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PS13

Effect of Rashba spin-orbit coupling in diamagnetic current induced by nonuniform magnetic field

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A dissipative electric current in systems with Rashba spin-orbit coupling is accompanied by a spin polarization. This phenomenon is known as the Edelstein effect. [1] On the other hand, there are permanent currents which do not suffer from dissipation, such as a diamagnetic current induced by a magnetic field. It flows at the edge of the sample for a uniform magnetic field, whereas it flows in the bulk if the magnetic field is nonuniform.

In this work, we examine whether a spin polarization accompanies a diamagnetic current. We calculate the diamagnetic susceptibility and spin susceptibility subject to Rashba spin-orbit coupling. We specifically consider a 2D Dirac electron system, which is known for a large diamagnetism due to the interband magnetic effect [2]. Such a system is realized in graphene on Au substrate, in which a large Rashba constant of order 100 meV was reported [3]. Figure 1 shows the momentum dependence of spin susceptibility. This graph reveals existence of spin polarization. The relation between the spin polarization and the interband magnetic effect is also discussed.

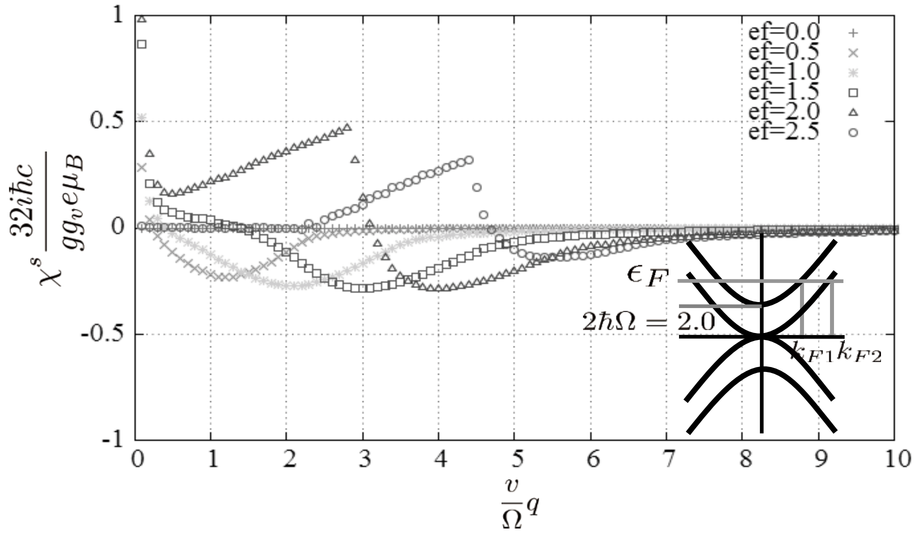

Figure 1

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PS14

Cyanide-Bridged Fe_{42} High-Spin Nanocage with S = 90/2

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One of the major topics in the molecular magnetism field is the development of high-spin molecules. We synthesized a cyanide-bridged magnetic Fe_{42} nanocage comprising 18 high-spin Fe^{III} ions and 24 low-spin Fe^{II} ions. The magnetic metal centers are ferromagnetically coupled, yielding the highest ground-state spin number (S = 45) of any reported molecule [1].

The reaction of $Fe(CF_3SO_3)_2$, 1,3-di(4-pyridyl)propane (dpp), L-ascorbic acid, and $Li[Fe(Tp)(CN)_3]$ in H_2O led to the isolation of a new $[Fe^{III}_{18}Fe^{II}_{24}]$ spin nanocage (Fig.1), $[\{Fe^{II\text{-}LS}(Tp)(CN)_3\}_{24}\{Fe^{III\text{-}HS}(H_2O)_2\}_6\{Fe^{III\text{-}HS}(dpp)(H_2O)\}_{12}(CF_3SO_3)_6]\cdot 18H_2O$ (**1**$\cdot 18H_2O$) (LS = low-spin, HS = high-spin), where **1** contains 42 iron ions, the largest number of metal centers in any cyano-bridged cluster reported to date. Crystallographic analysis reveals that 24 $\{Fe(Tp)(CN)_3\}$, 12 $\{Fe(NC)_4(dpp)(H_2O)\}$, and 6 $\{Fe(NC)_4(H_2O)_2\}$ building units are symmetrically disposed in an O space around a central point, providing the cube cage with a separation of 1.96 nm between the most distant Fe ions.

The magnetic properties indicate the existence of predominantly ferromagnetic interactions. The magnetization data in the range of 300–30 K can be fitted to the Curie–Weiss law, yielding $C = 83.2$ cm^{3}mol^{-1}K and $\theta = 6.7$ K. The magnetization (M) at 2 K rapidly increases at low fields and then steadily increases with $H > 15$ kOe to reach a near saturation value of 88.4 μ_B at 50 kOe, which is in good agreement with the expected value of 90 μ_B (with $g = 2.0$) for a ground state of $S_T = 90/2$ (Fig. 2). This magnetization behavior is significantly higher than that shown in the Brillouin curve corresponding to 18 non-interacting S_{Fe} spins ($S = 5/2$), fitting more closely the Brillouin curve for one $S = 45$ center (with $g = 2.0$). These data support the maximum possible spin state $S = 45$, which is the largest spin ground state number of any molecule ever prepared.

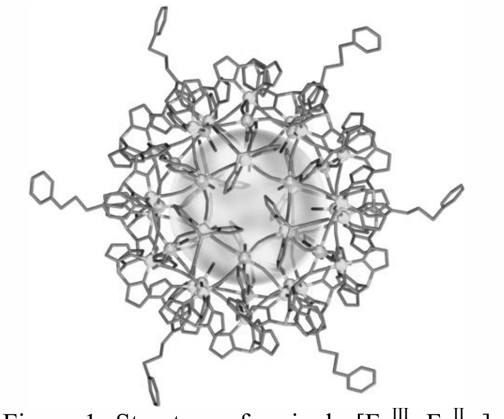

Figure 1: Structure of a single $[Fe^{III}_{18}Fe^{II}_{24}]$ high-spin (S = 45) nanocage: **1**$\cdot 18H_2O$.

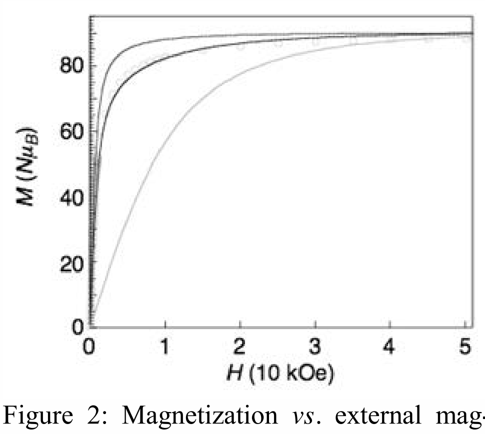

Figure 2: Magnetization *vs*. external magnetic field curve for **1**$\cdot 18H_2O$ at 2 K.

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PS15

Valley coupling, spin-orbit interaction and vernier-scale-like spectrum in finite-length metallic single-wall carbon nanotubes

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Metallic single-wall carbon nanotubes (m-SWNTs) are ideal one-dimensional conductors of nanometer to micrometer length. Due to the confinement in finite-length, energy levels of electrons are quantized. Fourfold degeneracy of the energy levels has been considered as an intrinsic property of SWNTs reflecting the two non-equivalent, degenerate valleys of K and K' in the two-dimensional Brillouin zone together with two spin degrees of freedom. Recent measurements with ultraclean SWNTs have found fine structures of the order of sub-milli-electron-volt in tunneling conductance spectra caused by the spin-orbit interaction. On the other hand, the gate-dependent two- and fourfold oscillations in measurements may imply strong coupling of the two valleys.

We will show that the degeneracy of energy levels of m-SWNTs strongly depends on the chirality, boundary condition, length and the spin-orbit interaction by numerical and analytical calculations [1]. The two valleys are strongly coupled for the so-called metal-2 chiral nanotubes with both ends orthogonal-shaped edges as well as the armchair nanotubes. The effect of strong valley coupling combined with the asymmetric velocities [2] appears as a vernier-scale-like spectrum, showing two- and fourfold oscillations as observed in experiments. For a so-called minimal boundary, which has a geometry removing the Klein-type terminations from the orthogonal-shaped edges, nearly fourfold degeneracy and its lift by the spin-orbit interaction [3] are shown as the result of decoupling of two valleys. For shorter nanotubes, a geometrically induced splitting of the valley degeneracy overcomes the effect of spin-orbit interaction.

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PS16

Novel Coupling between Spin and Electromagnetic Field in a Ferromagnetic Metal with Rashba Spin-orbit Interaction

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In ferromagnetic metals, an effective electromagnetic field emerges due to the presence of the strong *sd* interaction and an inhomogeneous magnetization texture. This emergent field is called the spin electromagnetic field [1]. The spin electromagnetic field couples to conduction electron spins and plays important roles in spintronics. How the ordinary electromagnetic field interacts with the spin electromagnetic field was investigated by the authors [2]. Recently, the emergent spin electromagnetic field arising from the Rashba spin-orbit interaction has been investigated in detail.

The purpose of our study is to clarify how the ordinary electromagnetic field couples to the emergent field induced by the Rashba interaction. In order to achieve our aim, we derive the effective Hamiltonian by integrating out the conduction electrons in the path-integral representation. We show that the product between the momentum of the electromagnetic field and the emergent field (called the Rashba-induced effective vector potential) appears in the effective interaction Hamiltonian. We also discuss how the behavior of the ordinary electromagnetic field and the Maxwell's equations are affected with the Rashba-induced effective vector potential.

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PS17

Detection of ferromagnetic resonance in CoFeB by tunnel anisotropic magnetoresistance

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Spin-torque diode effect [1] is an effective tool for a highly sensitive detection of the magnetization dynamics [2]. The diode effect usually results from a ferromagnetic resonance (FMR) induced by spin-transfer and/or voltage-induced torques and is detected by tunnel magnetoresistance (TMR). Observation of the diode effects therefore needs two ferromagnetic layers, that is, free and reference magnetic layers

In the present study, we tried to detect FMRs in tunnel junctions using just one ferromagnetic layer. We fabricated a $Co_{16}Fe_{64}B_{20}$(1.4 nm)/MgO(t_{MgO} = 1.9, 2.2, 2.5 nm)/Ta(10 nm) multilayer by magnetron sputtering systems since the appearance of tunnel anisotropic magnetoresistance (TAMR) is expected due to an interfacial spin-orbit interaction at CoFeB/MgO interface. The multilayer was post-annealed at 320℃ and patterned into the junction with 5 μm in a diameter (Fig. 1a). The resistance-are product was 2.9 kΩμm^2. The TAMR was measured under perpendicular magnetic field, and one's ratio was 0.3%. Firstly, a microwave current was applied into the junction to excite a FMR in the CoFeB. Then the FMR signal was detected as a DC homodyne voltage measured using a lock-in amplifier. The FMR spectra were clearly obtained as shown in Fig. 1b. The FMR signals (~0.5 μV) are hundreds times smaller than those of the FMRs detected by TMR with similar structure [3], and the decrease in the FMR signals is almost same as that in the MR ratio. The FMRs of the CoFeB can be excited by voltage-induced torque and detected by TAMR. This research was supported by Grant-in-Aid for Scientific Research (No. 23226001, 26103002), Japan.

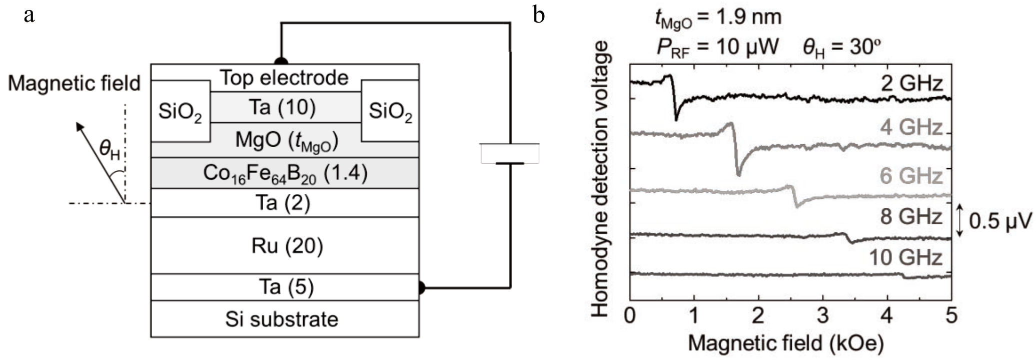

Figure 1 (a) Device structure. (b) Typical FMR spectra of CoFeB detected by TAMR.

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PS18

Shot-noise of a superconductor/nanotube junction in the Kondo regime

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We measured the conductance and the shot noise of a carbon nanotube contacted by Pd/Al superconducting electrodes, in both SU(2) and SU(4) Kondo regime. Varying the gate voltage, two different electronic transport regimes can be observed: if the contacts are symmetric, we observe a multiple Andreev reflections (MAR) regime, governed by the transmission coefficients provided by the Kondo effect [1]. On the other side, if the contacts are asymmetric, the less coupled contact will play the role of a tunnel probe [2]. The conductance the reflects the energy of the Andreev bound states formed in the quantum dot and thus depends strongly on the ratio Δ/T_{K} , which determines if the ground state of the system is a Kondo singlet or a doublet. We measured the shot noise in both situations.

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PS19

Single-shot readout of electron spins in a quantum dot using spin filtering by quantum Hall edge states

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To prepare and probe an electron spin in a quantum dot (QD) is indispensable for spintronics and quantum information processing. Spin-resolved quantum Hall edge states can be applied for these purposes, since their spatial separation provides spin-dependent tunnel couplings to the QD [1]. Recently, we have improved the spin-filtering efficiency high enough for spin injection and detection by the electrical tuning of the local filling factor near the QD [2].

In this work, we demonstrate the single-shot readout of electron spins in a gate-defined GaAs QD (Fig. 1). We first detect two-electron spin states with a spin angular momentum of $S_z = 0$ and $S_z = 1$. For the transition from these $S_z = 0$ and $S_z = 1$ states to three-electron ground spin state $S_z = +1/2$, a spin-up and spin-down electrons tunnel into the QD, respectively. Because of the highly-efficient spin filtering, the tunnel rate of the spin-up electron is much higher than that of the spin-down electron. We discriminate the two-electron spin states by monitoring such a tunnel-rate difference. The maximum readout visibility reaches 94% (Fig. 2), the highest ever reported for GaAs-based QDs.

Moreover, we apply this spin readout scheme to measure the spin relaxation rates of multi-electron high-spin states, three-electron $S_z = +3/2$ and four-electron $S_z = +2$. These high-spin states are prepared by loading spin-up electrons into the two-electron $S_z = +1$ ground state. For the readout of these states, first they are converted into two-electron spin states by removing one or two electrons. Because spin-up electrons are predominantly removed from the QD due to the spin filtering, the two-electron spin states after the removal have one-to-one correspondence to the multi-electron spin states. Then, the high-spin states are detected from the two-electron spin readout described above. As a result, we find that the spin relaxation rates of the high-spin states are approximately 10 times higher than that of $S_z = 0$ state (Fig. 3).

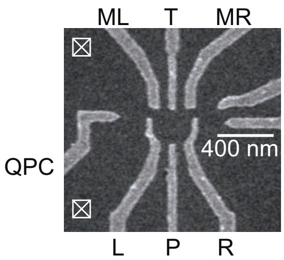

Figure 1: Scanning electron micrograph of the device

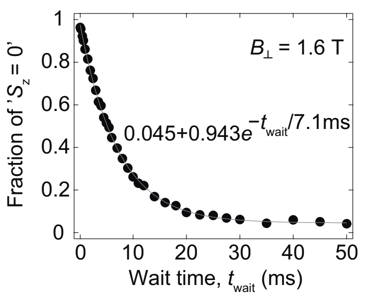

Figure 2: Fraction of the ' S_z = 0' count as a function of wait time

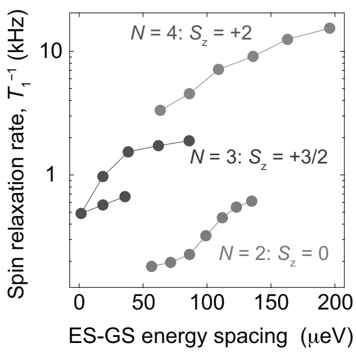

Figure 3: Spin relaxation rates of N = 2, 3 and 4 spin states

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PS20

Enhanced Spin Hall Effect in CuBi Alloys

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Recently, a surprising large spin Hall angle (SHA) of -0.24 with negative sign was experimentally obtained in CuBi alloys [1], and the problem of sign in SHA becomes significant to the physics, where the calculations of the SHA obtained by phase-shift analysis, which has been well tested in many contexts, and by the first-principles simulation are, then, both found to be opposite in sign to the experiment [2]. This confusing situation seems to be a serious challenge to our understanding of the spin and anomalous Hall effects.

Here, we show that the confusing sign problem of SHA in CuBi alloys between the experiment and the established theories was due to the inconsistent definitions of SHA. Once the confusion of definitions is removed there is no contradiction to a skew scattering mechanism, and thus we restore the possibility of properly microscopic understanding of the effects. We find that the SHA can be dramatically enhanced by Bi impurities close to the Cu surface. The mechanisms are two-fold. One is that the localized impurity state on surface has a decreased hybridization and combined with Coulomb correlation effect, this leads to an enhanced SHA. The other comes from the low-dimensional state of conduction electrons on surface, which results in a further enhancement of skew scattering by impurities. Our results [3] may explain the giant SHA experimentally observed in CuBi alloys.

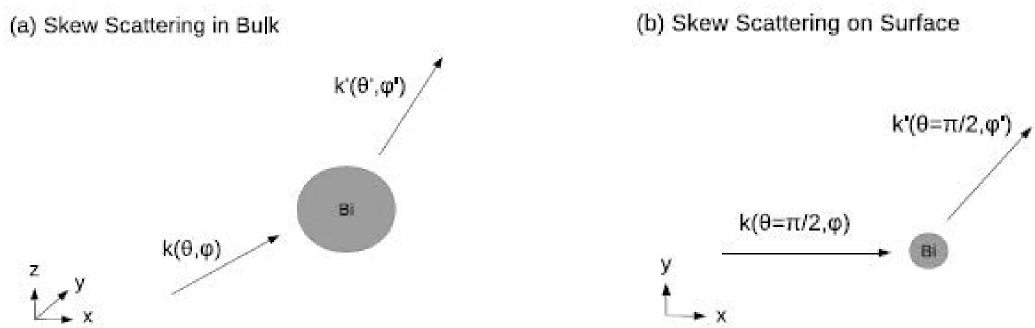

Figure 1: Schematic picture of skew scattering of conduction electrons by the Bi impurity in Cu bulk (a) and on a Cu surface (b). The Bi impurity has very extended state (large circle) in the bulk and a much more localized state (small circle) on the surface. The conduction electron in Cu is described by a three-dimensional wave vector in the bulk, and a two-dimensional wave vector on the surface

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PS21

Artificial Control of Magnetic Phase Transition of B2 Ordered FeRh-based Thin Films

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Controlling magnetic properties without magnetic field is a key issue for improving energy efficiency in spintronic devices. Recently, manipulating the magnetic phases of a material has been demonstrated by using spin polarized current injection and magnetoelectric coupling effect in ferromagnetic (FM)/ferroelectric (FE) heterostructures. It is well known that B2 ordered FeRh alloys show the first-order magnetic phase transition from the antiferromagnetic (AFM) state to the FM state at around 370 K, accompanied by isotropic volume expansion[1]. This clearly indicates that there is a strong lattice-spin coupling in FeRh, and the AFM-FM phase transition could be controlled by external lattice manipulating, accordingly. In this presentation, we will show recent results on strain transfer effect on the magnetic nature of FeRh/FE $BaTiO_3$ (BTO) heterostructures, arising from elastic lattice distortion of BTO[2].

30 nm-thick Ga-doped FeRh thin films (Ga-FeRh)/BTO(001) heterostructures were used for investigating the strain effect. Details of sample preparation are given elsewhere[2]. Figure 1 shows the temperature dependence of magnetization of Ga-FeRh/BTO and Ga-FeRh/MgO. A reference sample on MgO substrate shows a clear AF-FM magnetic phase transition at around 270 K. The magnetic phase transition of Ga-FeRh/BTO, on the other hand, is slightly broader than that of Ga-FeRh/MgO, while sudden changes in the magnetization are seen at 290 and 190 K in the cooling process. The features are clearly associated with the successive structural phase transitions of BTO from the tetragonal (T) to orthorhombic (O), O to rhombohedral (R) phases. Also, magnetization and magnetoresistance data indicate that the feature at the O-R phase transition is likely due to a FM to AFM phase transition induced by the compressive lattice strain transfer from BTO whereas that at the T-O transition arises from a change in the magnetic anisotropy of FM FeRh in the film plane. These results clearly demonstrate that lattice manipulation could provide a promising approach to controlling the magnetic phases of FeRh without magnetic field. Effect of piezoelectric strain on the magnetic phases in FeRh will also be shown at the symposium.

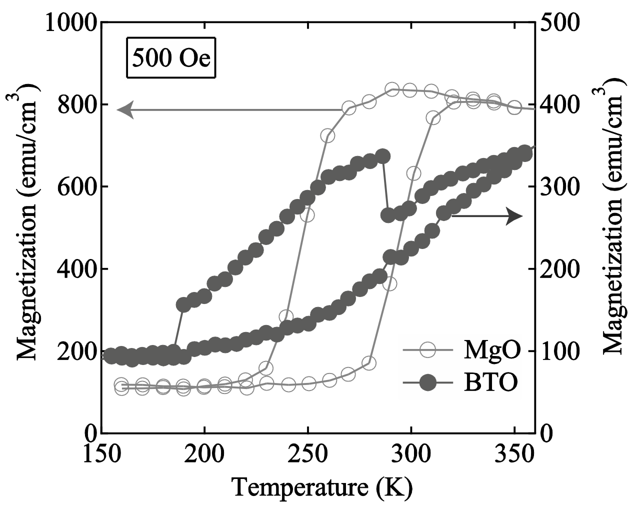

Fig. 1 Temperature dependence of magnetization of Ga-FeRh/MgO and Ga-FeRh/BTO structures.

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PS22

Domain wall of a ferromagnet on a three-dimensional topological insulator

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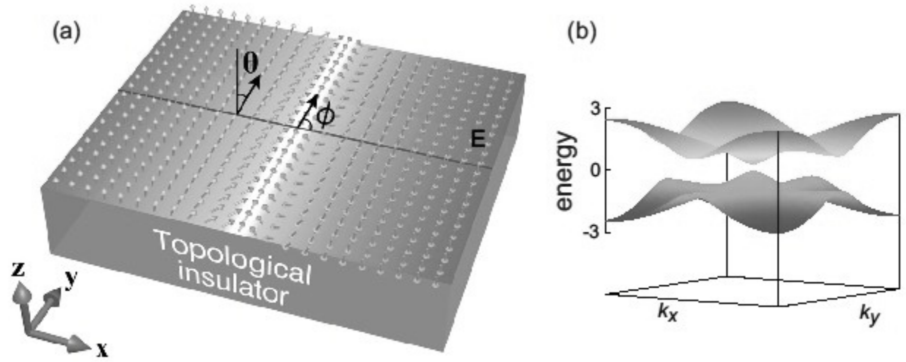
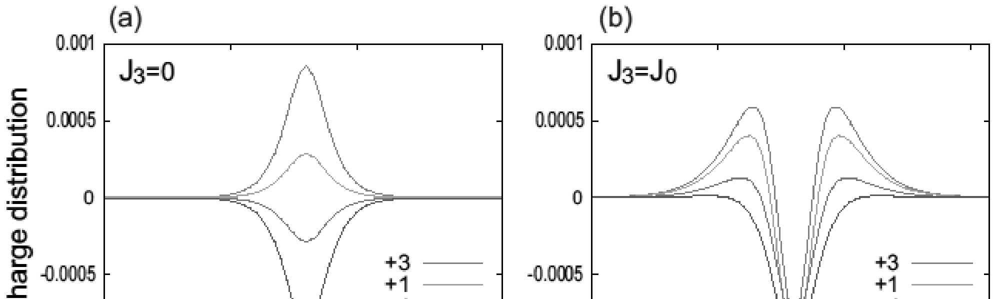
Topological insulators (TIs) show rich phenomena and functions which can never be realized in ordinary insulators. Most of them come from the peculiar surface or edge states. Especially, the quantized anomalous Hall effect (QAHE) without an external magnetic field is realized in the two-dimensional ferromagnet on a three-dimensional TI which supports the dissipationless edge current. Here we demonstrate theoretically that the domain wall of this ferromagnet, which carries edge current, is charged and can be controlled by the external electric field. The chirality and relative stability of the Neel wall and Bloch wall depend on the position of the Fermi energy as well as the form of the coupling between the magnetic moments and orbital of the host TI. These findings will pave a path to utilize the magnets on TI for the spintronics applications.





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PS23

Photon-assisted current noise through a quantum dot system with an oscillating gate voltage

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Photon-assisted transport through mesoscopic conductors has attracted much attention because the quantum nature of transport processes is significantly modified by time-dependent fields. While the photon-assisted transport of the noninteracting electrons has been studied in detail, the interacting case has not been clearly understood. Studying the effect of the Coulomb interaction is an important next step to discuss interesting physics, such as the Coulomb blockade and the Kondo effect.

In this presentation, we discuss photon-assisted transport in a single-level quantum dot system under a periodically oscillating field [1]. Photon-assisted current noise in the presence of the Coulomb interaction is calculated based on a gauge-invariant formulation of time-dependent transport. We derive the vertex corrections within the self-consistent Hartree-Fock approximation in terms the Floquet-Green's functions (Floquet-GFs) and examine the effects of the Coulomb interaction on the photon-assisted current noise. Moreover, we utilize an effective temperature to characterize nonequilibrium properties under the influence of the ac field. The present result provides a useful viewpoint for understanding photon-assisted transport in interacting electron systems.

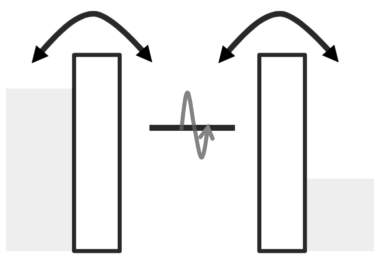

Figure 1: The quantum dot with an oscillating gate voltage.

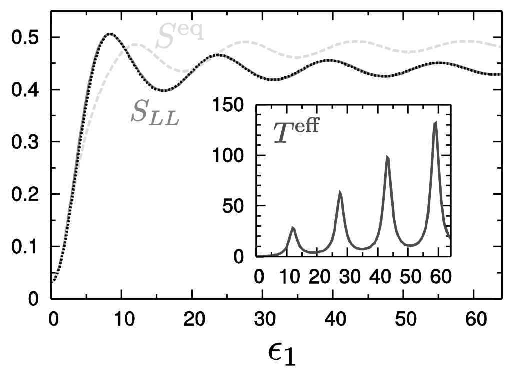

Figure 2: The dependence of the current noise and the effective temperature on the AC amplitude.

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PS24

Quantized Anomalous Hall Effects in Skyrmion Crystal

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Magnetic Skyrmion, a topological spin texture, attracts much attention since it was discovered experimentally in many chiral magnets. The periodic formation of skyrmion is reported and known as skyrmon crystal (SkX) phase. The twisted spin structure of skyrmion can generate an emergent magnetic field felt by conducting electrons which couple to the skyrmions. The Hall effect due to this emergent magnetic field is called topological Hall effect (THE). In SkX, the emergent magnetic field reaches 4000T when we spatially average out the effective flux. Then, it is natural question that can Hall conductance quantize? In periodic system such as complete SkX, Hall conductance is given by the integral of the Berry curvature in momentum space. On the other hand, in strongly disordered system, momentum space description is irrelevant therefore the crossover between real-space and momentum-space Berry curvature must occur. SkX is an ideal laboratory to study quantized anomalous Hall effect (QAHE) since one can change skymion size, mean free path and carrier concentration, to clarify the crossover and stability of quantization as these parameters are changed.

In this poster presentation, we will introduce our theoretical study on QAHE in SkX based on the tight-binding model in 2D square lattice. The obtained band structure (Fig. 1) has finite gaps like Landau Levels and same topology (Chern numbers) therefore the Hall conductance calculated by Kubo formula (Fig. 2) shows the quantized plateaus.
The band gap Δ (red points in Fig. 3) is estimated to be $\Delta = \Delta_0/5$ with Δ_0 being the gap in corresponding uniform magnetic field system (blue line in Fig. 3). However, due to the gigantic emergent magnetic field of SkX, the gap Δ is still large enough to guarantee the robust QAHE.
We also study the conditions to realize QAHE. The disorder V destroys the quantization when $V \gtrsim \Delta_0$ while the thermal effect destroys when . $T \gtrsim \Delta = \Delta_0/5$ This means our system is extremely robust especially against disorder beyond the expectation from the gap size. We also suggest that the QAHE in SkX can be observed even at room temperature when the electron density is of the order of skyrmion density.

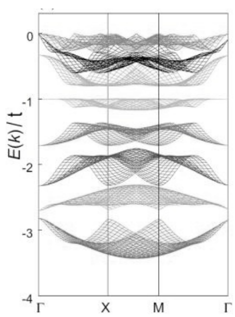

Fig. 1

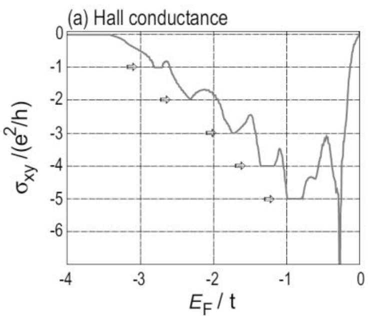

Fig. 2

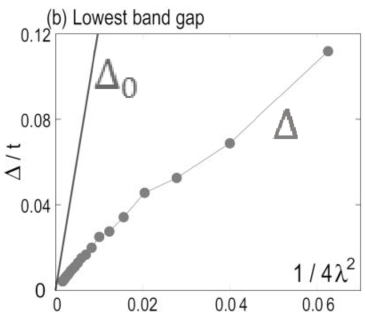

Fig. 3

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PS25

The Cu alloys doped with 5d elements as materials for the control of the sign of spin Hall effect

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The spin Hall effect (SHE), which converts the injected longitudinal charge current into the transverse spin current via the spin-orbit interaction (SOI), is crucial for the development of spintronic devices. The sign of the spin Hall angle (SHA) describes the direction of the induced transverse current.

We perform a systematical analysis of the SHE in the dilute Cu alloys doped with a series of 5d elements, by the combined approach of density functional theory and Hartree-Fock approximation. We find out that not only the SOI in the 5d orbitals, but also the SOI in the 6p orbitals and the local correlations effects in the 5d orbitals of the impurities, are decisive to the sign of the SHA. Including all of these factors properly, we predict the sign of SHA for each alloy in the series, different from the previous theoretical calculations [1,2]. A positive SHA is obtained for CuIr alloys [3,4], which is consistent with experiment [5], while negative SHA are obtained for several alloys including CuOs and CuRe.

Furthermore, to activate the sign of SHA as a new degree of freedom by the external control will give birth to innovative designs of spintronic devices. We analyze the alloys whose sign of SHA are sensitive to the perturbation of the local correlations, which will be considered as materials for the control of the sign of SHE.

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PS26

Cavity optomagnonics in a ferromagnetic sphere

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Vast amount of research on the opto-/electro-mechanical cooling and control of mechanical oscillators have been made in the scope of realizing quantum transducers, ultra-high-sensitivity measurements and macroscopic quantum systems. Cavity cooling, which is realized by enhancing the anti-Stokes scattering and suppressing the Stokes one via optical resonators, paves the way for the ground state cooling of mechanical oscillators and controlling them in the quantum regime[1,2]. Optical whispering gallery mode (WGM) in a dielectric sphere is not only used for these purposes[3] but also expected to become an efficient optical nonlinear element.

We propose that, by extending the idea of optomechanical systems, uniformly precessing ferromagnetic magnon in a sphere of a ferrimagnet, yttrium iron garnet (YIG), can be optically manipulated using whispering gallery mode, i.e., using itself as an spherical optical resonator. Here we show experimental results on the observation of magneto-optical interactions including the non-reciprocal optical effect in a WGM-magnon coupled system.

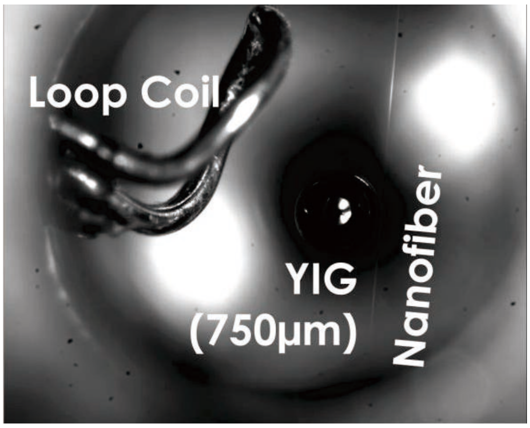

Fig. 1 Spherical optical resonator made of a ferrimagnetic YIG. YIG sphere is optically coupled via the nanofiber and magnon is excited by microwave.

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PS27

Anomalous Hall effect and persistent current due to spin chirality in a diffusive regime

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Anomalous Hall effect (AHE) in ferromagnetic metals has been known to arise as a combined effect of magnetization (exchange splitting) and spin-orbit coupling (SOC) after the works by Karplus, Luttinger and Smit in 1950s [1,2]. Later in 1990s, another mechanism was found by Ye *et al*. for systems with a non-coplanar spin configuration having spin chirality; in such systems, the spin chirality gives a Berry phase to electrons through the exchange interaction and leads to AHE [3].

Subsequently, Tatara and Kawamura showed that AHE can result without the concept of Berry phase by treating the exchange coupling perturbatively [4]. They considered a model with discretely-distributed quenched spins, and calculated the Hall conductivity for the case that the distance r between the localized spins is shorter than the electron's mean free path l (ballistic regime). As a physical picture of this chirality-induced AHE, Tatara suggested a (equilibrium) persistent current around the spin chirality in the ballistic regime [5].

In this work, we extend the previous works [4,5] to the diffusive regime ($r > l$) by considering vertex corrections due to normal impurities [6]. This amounts to electron's diffusive motion as well as spin conservation at each scattering from the normal impurity, and leads to an expression of the AH conductivity which respects spin conservation. We also investigate the persistent current in the diffusive regime, and show that the "typical" value of the persistent current reproduces the AH conductivity in the diffusive regime [6].

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PS28

Spin current transport in a Nb/Cu/NiFe tri-layer structure

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The ferromagnet/superconductor hybrid structures have attracted much attention owing to the Cooper pairs in the ferromagnet, which induce unique transports such as a crossed Andreev reflection and spin-polarized supercurrent[1]. These spin-dependent transport related to a superconductor can be induced also in the nonmagnetic metal under the spin injection because the spin accumulation in the nonmagnetic metal can be treated theoretically as a conduction electron state in a ferromagnet with a certain aspect. However, the experimental studies in these structures have not been performed sufficiently due to the influence of the charge current such as a Joule heating and Oersted field. Here, we investigated spin current transport in a nanopillar-based lateral spin valve structure, in which the aforementioned charge-current-inducing effects are strongly suppressed.

The spin transport properties have been evaluated in the sample consisting of Permalloy(Py)/Cu/Nb trilayer by measuring the nonlocal spin valve signal (Fig.1), which is called as a spin signal. As a results of the measurements, the spin signals below 30 K are almost constant when the Nb is in the normal state. On the other hand, when the Nb becomes superconductor below the superconducting transition temperature 6.8 K, the spin signal increases with decreasing the temperature (Fig.2). This indicates that the spin current is insulated at the Cu/Nb interface because the spin polarized current cannot enter into the superconducting energy gap without forming the Cooper pair, while the spin current in the Cu is absorbed into the Nb in the normal state. From this result, we can estimate the temperature dependence of the superconducting gap magnitude at the Nb/Cu interface. Moreover, around 2.3 K, we observe the superconducting proximity effect in the Cu layer. These results indicate that the spin-polarized electrons and Cooper pairs coexist in the Cu layer around 2.3 K. This may open the new way to the observation of the spin dependent superconducting phenomena.

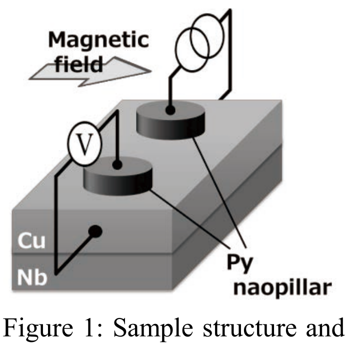

Figure 1: Sample structure and the probe configuration for measuring the spin signals.

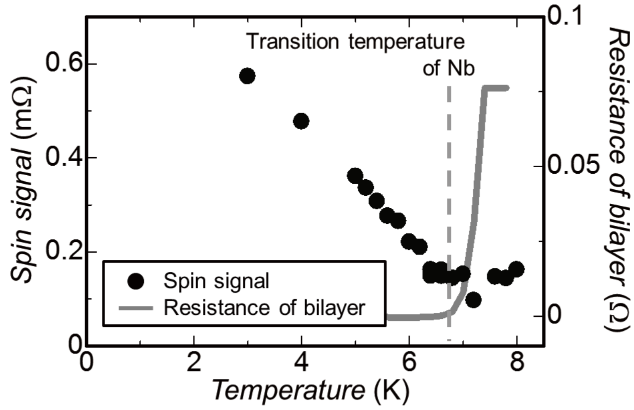

Figure 2: Temperature dependence of the measured spin signals.

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PS29

Barnett effect of gadolinium in a paramagnetic state

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The Barnett effect is a phenomenon that a rotating object is magnetized. The effect was discovered in 1915 [1, 2]. We report the first observation of the Barnett effect in a paramagnetic state by mechanically rotating a gadolinium. We developed a magnetic measurement setup comprised of a high-speed rotation system and a fluxgate magnetometer for the measurement (Fig.1). Fig. 2 shows the rotational frequency dependence of the magnetization of the gadolinium sample at 300±0.5 K and that of a blank capsule. We estimate the magnetization of the rotating sample, M_Ω, from the stray field measured by the fluxgate magnetic sensor using a dipole model. We find that the magnetization is proportional to the rotational frequency and its polarity changes with the rotation direction. For the blank capsule, no rotation frequency and direction dependence are observed. Thus, the magnetization arises from the rotating Gd sample.

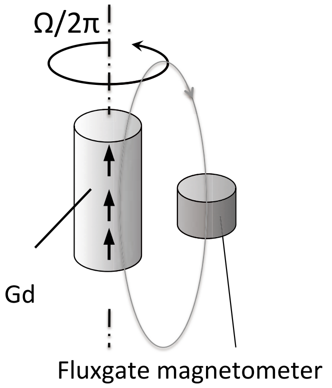

Figure 1: The experimental setup for observation of the Barnett effect.

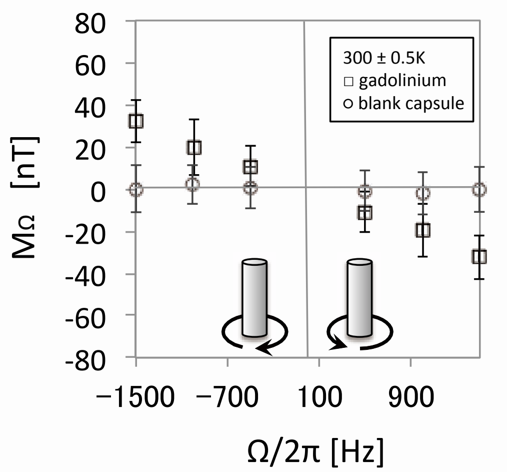

Figure 2: Rotational frequency dependence of the magnetization observed at 300±0.5K for the Gd sample and the blank capsule. Each data point is averaged over three measurements with the error bar in the standard deviation 1σ including the rotational frequency fractionation.

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PS30

Universal Conductance Distributions in Disordered Topological Insulator Nanofilms

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The three-dimensional (3D) topological insulators show the specific *surface transport* due to the surface helical Dirac cones. When the 3D topological insulator is cut out in a film geometry, and the thickness (number of layers) is small enough with respect to the film area, it can be regarded as an effective two-dimensional (2D) system and is expected to show the *edge transport* that is a characteristic of 2D topological insulators. Because the finite size effect (aspect ratio) is crucial for this kind of dimensional crossover, the property of the *clean bulk*, such as topological numbers, alone is insufficient for describing the dimensional crossover. However, we have shown that the transport property visualizes both the 2D and 3D topological nature of finite size (and furthermore, disordered) systems [1].

In this work, we employ the Wilson-Dirac Hamiltonian on the cubic lattice with on-site random potential as a typical model for disordered 3D topological insulator nanofilms. We have calculated the conductance by using the transfer matrix method and obtained a kind of phase diagram, the conductance map [2]. It shows the topological insulator to metal transition as well as the shift of the phase boundary due to the disorder effect. At the disorder-induced metal-insulator transition (Anderson transition) point, it is known that the probability distribution function of the conductance shows the universal (scale and model independent, but dimensionality and symmetry dependent) shape. We show that the conductance distributions in the nanofilms converge to the universal shapes for 2D [3] (see Fig. 1).

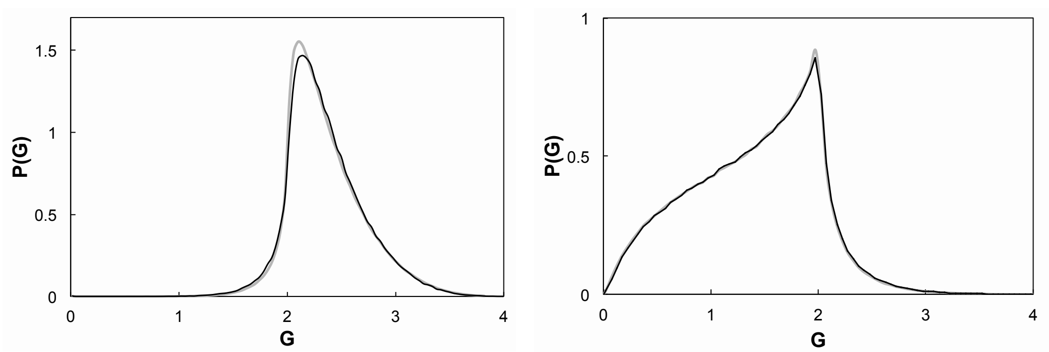

Figure 1: Conductance distribution functions $P(G)$ in disordered topological insulator nanofilms (thin solid lines) and in 2D quantum network model (thick gray lines) [3]. (a) For the number of layers $N_z = 3$, the conductance distribution at the topological insulator-metal transition point converges to the universal critical distribution for 2D quantum spin Hall transition point. (b) For $N_z = 1$, the Hamiltonian is block diagonalized and belongs to the Unitary symmetry class (class A), and the conductance distribution coincides with the universal distribution for 2D integer quantum Hall transition.

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PS31

Electromotive force in a $L1_0$-FePt / $Ni_{81}Fe_{19}$ bilayer element

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Recently, the electromotive force with spin origin, which is called "spinmotive force", has attracted much attention as a new aspect for the generalization of Faraday's law because of the developments of theory [1] followed by experimental observations [2]. However, the systems showing the spinmotive force are limited, and the obtained signals in most cases are transient and small, which is not suitable for practical applications. Thus, a systematic investigation is required to enhance the voltage originating from the spinmotive force. In this study, we investigated the electromotive force generated in a $L1_0$-FePt / $Ni_{81}Fe_{19}$ (Permalloy; Py) bilayer element. The exchange-coupled $L1_0$-FePt / Py bilayer element shows a twisted magnetic structure due to the difference in the magnetic anisotropy energy between $L1_0$-FePt and Py [3]. This difference leads to the spatial modulation in magnetization dynamics, which is suitable to observe the spinmotive force.

The device was microfabricated from a continuous thin film with the stacking structure of MgO (110) sub. // Fe (2 nm) / Au (60 nm) / FePt (10 nm) / Py (100 nm) / Au (5 nm). The FePt layer was deposited at 350 ˚C, leading to the formation of the $L1_0$ ordered structure with the in-plane easy axis along the [001] direction of the MgO substrate. The FePt / Py bilayer was etched into an element with the size smaller than several micrometers. The voltage (*V*) between the top and bottom of the element was measured using a lock-in amplifier while the radiofrequency (RF) power was constantly applied to the device using a signal generator in order to induce the magnetization dynamics. From the magnetic field dependence of *V*, several peaks of *V* were observed. The amplitudes of the peaks were of the order of tens nV. The magnetic field of the peak was shifted as the frequency of the RF power was varied, indicating the signals originated from the magnetization dynamics in the FePt / Py element. We consider that one of the possible origins for the observed *V* is the spinmotive force.

The authors are grateful to Dr. J. Ieda for valuable discussions.

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PS32

Emergent quantum spin Hall effect in topological insulator nanofilms

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Recently, much effort has been made to grow thin films of a topological insulator (TI) [1-2]. Naturally, its primary purpose was to reduce the contribution of the bulk to transport quantities. In this work, we have performed a theoretical study of such a TI thin film [3].

We consider a standard example of AII symmetry class. We use three-dimensional Wilson-Dirac Hamiltonian as a model of TI and adapt it to the thin film geometry of a finite number of stacked layers. The thin film geometry allows for physically interpolating the two and three dimensions (2D and 3D) limits by changing the number of stacked layers [4-5].

One way to characterize topological properties of the thin film system is to consider 2D type Z_2 index (ν) by regarding the film as an effective 2D system. In this work, we establish Z_2 index maps by calculating the ν as a function of the number of stacked layers (N) and gap parameter (m_0) (see Fig. 1). We also perform numerical study of the conductance of TI thin films. As a result,

1. We have shown that by reducing the number of stacked layers (N), quantum spin Hall phase, which is characterized by non-trivial 2D type Z_2 index (ν=1), can be "emergent" in TI nanofilms.
2. Through numerical study of the conductance of TI thin films, we have revealed how the 2D topological character evolves to its 3D counterpart as the number of stacked layers is increased (see the "conductance maps" in Ref. [3]).

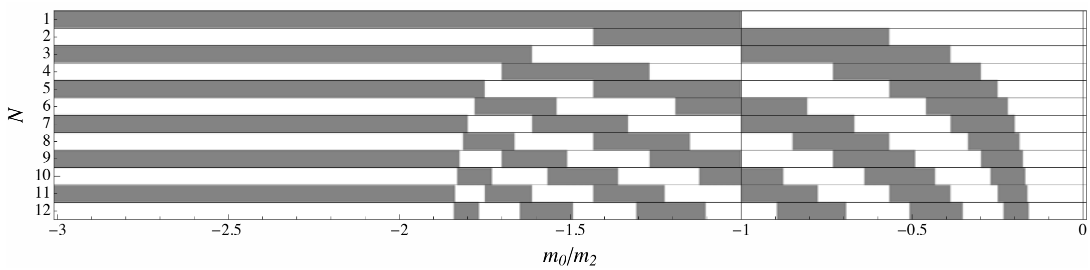

Fig. 1 The Z_2 index map. Painted (unpainted) region corresponds to ν=1 (ν=0)

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PS33

Quantum Entanglement Conservation in Coherent Quantum State Transfer from a Single Photon Polarization to an Electron Spin in a Lateral Double Quantum Dot

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Quantum entanglement is one of the most representative phenomena of quantum physics. Entanglement generation and detection in some kinds of quantum system are well established[1,2,3]. However, whether quantum entanglement can be conserved in coherent quantum state transfer between different quantum systems has not been researched so far. To give an experimental proof for this question, we try to prove that quantum entanglement is conserved through the transfer between polarization entangled photon pairs and spin entangled electron pairs using GaAs/AlGaAs semiconductor[4].

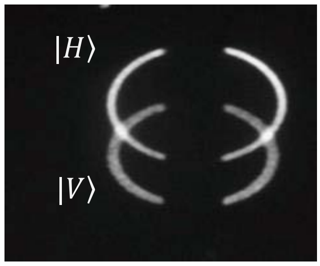

Fig. 1 Optical image of the SPDC

First, we will talk about generation of entangled photon pairs which is based on a non-linear optical phenomenon called spontaneous parametric down conversion (SPDC) in a Type-II BBO crystal. We have succeeded in observing the SPDC using a high sensitive CCD camera (Fig. 1) and also single photon counting modules (SPCM). As a result we evaluated the generation efficiency. We have observed the spatially separated paired photons using an optical aperture.

Second, we will report a way to improve the probability of photo-electron trapping in a quantum dot. We have fabricated a double quantum dot device introducing a GaAs heterostructure with a distributed Bragg reflector cavity structure (Fig. 2 left). We have also attached a solid immersion lens on the surface of the device. Our device has metal gates (Fig. 2 right) which define lateral double quantum dots in a two-dimensional electron gas. We irradiated pulsed photons onto one of the two dots to generate single photo-electrons in the dot. The single photo-electron is detected from observation of real-time charge sensing traces of electron tunneling between the two dots upon the photon irradiation.

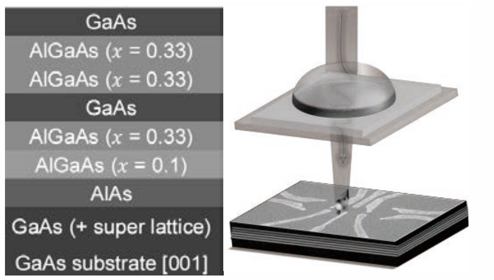

Fig. 2 Layer structure of the wafer (left) and fine pattern fabrication (right)

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PS34

Quantum dot thermometry at millikelvin temperature

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We study a way how to determine the electron temperature using the quantum dot thermometry in millikelvin regime. The temperature can be obtained from a measurement of the current through the sensor dot as a function of gate voltage by fitting the electron Fermi-Dirac distribution function. In this setup, we focus on the role of the mutual Coulomb energy between the dot and the sensor dot with an aim of understanding the feedback effects (or back-action; the measurement itself affects the experimental results) in quantum dot thermometry device.

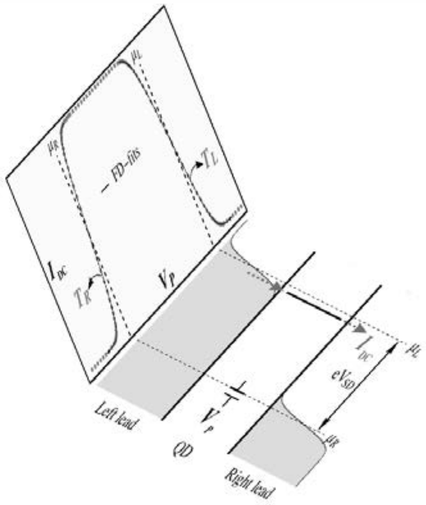

Figure 1: Illustration for the quantum dot thermometry

PS35

How to detect helical order of a one-dimensional magnet

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I consider methods of detection of a helical spin order which arises in the thermodynamical equilibrium in a one-dimensional (semi-)conductor with spin impurities (e.g., nuclear spins, or spins of localized magnetic impurities).[1] The helical order in localized spins is a consequence of the dimensionality, and thus very general, arising in metals, semiconductors, and even gapped phases, like superconductors. Formally, it follows from the resonant peak of the response (spin susceptibility) of a one-dimensional system. Recent low temperature transport experiments with semiconducting wires suggest that such helical order was established in nuclear spins of atoms of the wire.[2] Because of the auto-tuning property, such an order can be useful in the semi-super hybrid platform to stabilize Majorana fermions[3] and to produce even more exotic many body excitations like fractionally charged fermions.[4]

The question therefore arises how to detect unambiguously the presence of helically ordered spins. I will overview the methods suggested theoretically for such detection based on:

- reduction of conductance by a factor of two,[5]
- anisotropic spin susceptibility,[6]
- NMR response at the frequency set by the singular RKKY peak,[7]
- unusual temperature dependence of the nuclear spin relaxation rate,[8]
- dynamical nuclear polarization at zero external magnetic field.[9]

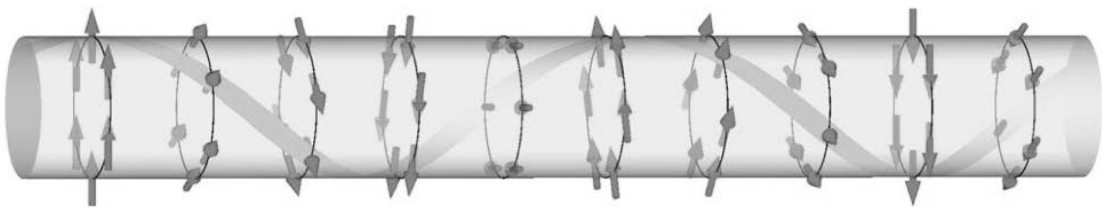

Figure 1: One dimensional conductor (yellow) with helically oriented spins (red).

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PS36

Electrical spin injection and detection across epitaxial Ge/Fe_3Si heterointerfaces

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To date, we have demonstrated the low-temperature epitaxial growth of Ge layers on a ferromagnetic Heusler compound, Fe_3Si, by molecular beam epitaxy (MBE).[1] Although the vertically stacked Ge/Fe_3Si heterostructure will open new perspectives for next-generation Ge-based spintronic devices, spin transport properties across the Ge/Fe_3Si heterointerface have not been clarified yet. Here, we present electrical spin injection and detection in a Cu-based lateral spin valve (LSV) consisting of the Ge/Fe_3Si heterostructure.

Epitaxial Ge(~50 nm)/Fe_3Si(~25 nm) films were grown on a Si(111) substrate (ρ = ~1000 Ωcm) by low-temperature MBE[1] and were processed into two Ge/Fe_3Si electrodes by conventional electron-beam lithography and Ar^+ milling techniques.[2] In order to cover the sidewalls of the electrodes, RF-sputtered SiO_2 films were deposited. After that, Cu strips were fabricated by conventional lift-off techniques. The center-to-center distance between the electrodes is ~300 nm, and the junction size between Ge and Cu is ~150 x 150 nm^2. Nonlocal spin valve measurements were carried out by standard AC lock-in techniques (f_{AC} = 173 Hz).

Figure 1 shows a representative nonlocal spin valve signal measured at 50 K when I_{AC} = 0.75 mA. We can see a clear hysteretic behavior reflecting parallel and antiparallel magnetization states of the electrodes. Although the spin signal is smaller than that for LSV without Ge epilayers,[2, 3] it is noteworthy that pure spin currents flow through the 50 ~ 100-nm-thick Ge epilayers and the ~150-nm-length Cu strip. More detailed information will be discussed in the poster presentation.

This work was partially supported by Grant-in-Aid for Scientific Research on Innovative Areas 'Nano Spin Conversion Science' (No. 26103003) and Grant-in-Aid for Scientific Research(A) (No. 25246020) from JSPS. M.K. and S.O. acknowledge JSPS Research Fellowships for Young Scientists.

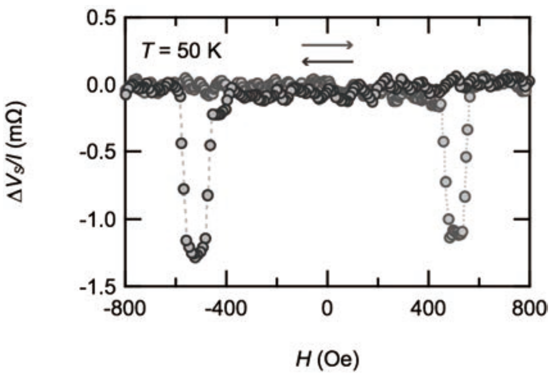

Fig. 1 A nonlocal spin valve signal measured at 50 K.

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PS37

Spin Injection from Epitaxially Grown Fe to Two-dimensional Electrons in InAs Quantum Well

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One of the main interests in electrical spin injection from ferromagnets into semiconductors[1] is the behavior of spins in quantum confined structures like two-dimensional electron systems (2DESs), which usually lie deep beneath the surfaces and the injection efficiencies remain as low as 1-2%.[2] A way to enhance the efficiency is the usage of MgO as a tunneling barrier and 8% efficiency to InAs 2DES was reported.[3] In this poster we report a further improvement of spin-injection efficiency from a ferromagnet (Fe) to a 2DES in an InAs quantum well.

Figure 1(a) shows the layered structure, which is lattice matched to an InP substrate, besides an InAs pseudo-morphic quantum well, which contains an inverted 2DES, the wave-function in which tails up close to the surface. The layers were deposited in an ordinary molecular beam epitaxy and on top of them, an iron (Fe) layer was epitaxially grown in the same chamber at the substrate temperature around 0ºC. Figure 1(b) shows time-evolution of RHEED pattern during the growth of the Fe layer. In the beginning of the growth, the RHEED pattern once almost disappeared and then the pattern for body-centered cubic α-Fe appeared. The streaky pattern changed into bulky after 20nm growth. The surface was covered with a 2nm Al polycrystal film.

The Fe film was fabricated into strips of widths 1 and 2 μm and the final form is shown in the inset of Fig.1(c). The main panel of Fig.1(c) displays magnetic field dependence of the non-local voltage between the 1 μm Fe strip and InAs 2DES when the current was applied between 2 μm strip and another InAs electrode. From the spin-valve magnetoresistance, we estimate the spin-injection efficiency as high as 34 % based on the theory in Ref.4.

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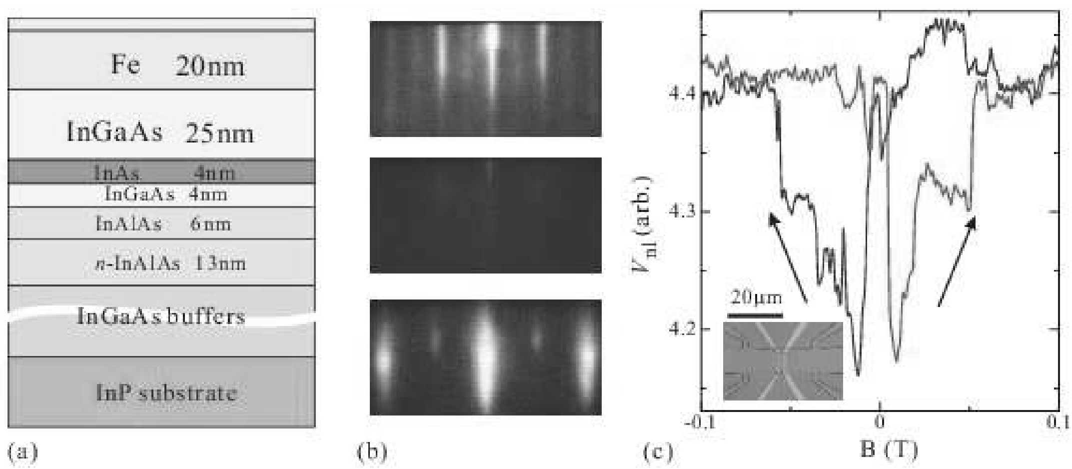

Figure 1: (a) Layered structure of MBE grown sample. (b) RHEED patterns. Top: (In,Ga)As surface. Middle: First monolayer of Fe. Bottom: 8nm thick Fe layer. (c) Non-local spin-valve voltage for spin-injection from Fe into InAs well. The inset shows a micrograph of the specimen.

PS38

Spin-dependent Peltier effect in Co_2FeSi/Cu lateral spin-valve devices

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In a new field of spin caloritronics, the spin-dependent Peltier effect, the conversion of spin current to heat current, was experimentally detected in nanopilar spin-valve structures [1]. If giant pure spin currents are injected from a ferromagnetic material into a nonmagnetic one, one can detect the spin-dependent Peltier effect even in a lateral spin-valve (LSV) structure [2]. Recently, we have developed a technique for generating giant pure spin currents at room temperature by using epitaxial Co-based Heusler-compound Co_2FeSi (CFS) films [3]. Here, we demonstrate the spin-dependent Peltier effect in a LSV with the epitaxial CFS electrodes.

We first confirmed the generation of giant pure spin currents in LSVs [3]. For detecting the Spin-dependent Peltier effect, we used the terminal configuration in Fig. 1(a). When the pure spin current are injected from the Cu side into CFS2, a temperature difference between Cu and CFS2 is created by the spin-dependent Peltier effect. To detect this temperature difference indirectly, we have used a method proposed by Slachter et al. [2] for placing the thermocouple on the CFS2 electrode. As shown in Fig. 1(b), we detected clear spin Peltier signals (V_{1f}^{P}) and obtained the spin-dependent Peltier coefficient of ~ -3.84 mV.

This work was partly supported by CREST from JST and by Grant-in-Aid for Scientific Research on Innovative Areas “Nano Spin Conversion Science” (Grant No. 26103003).

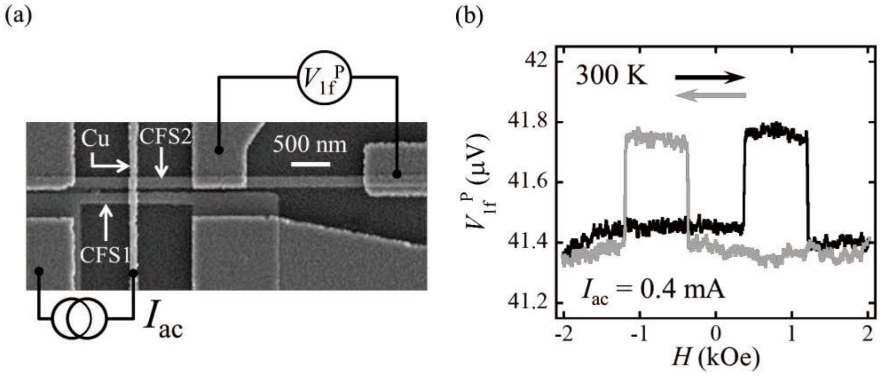

Fig 1: (a) SEM image of a fabricated LSV for the spin-Peltier measurements. (b) Field-dependent nonlocal voltage detected by the Cu thermocouple on the CFS2 wire at 300K under electrical spin injection at I_{ac} = 0.4 mA.

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PS39

First-Principles Study of Spin-Orbit Coupling Parameters and Bult-in Electric Field in $LaAlO_3/SrTiO_3$

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Recently, the oxide interface has attracted much attention since it can be used to realize novel physical properties not found in the bulk system [1]. Heterostructure $LaAlO_3/SrTiO_3$ is one of such systems extensively studied. A high mobility two-dimensional electron gas in the heterostructure of $LaAlO_3/SrTiO_3$ has been reported [2] in contrast to insulating properties of bulk $LaAlO_3$ and $SrTiO_3$.

In this study, we have performed fully-relativistic first-principles density functional calculations for articfical superlattice $(LaAlO_3)_n/(SrTiO_3)_n$. Calculated band structures show interface-induced metallic states for $n \geq 6$. We found electron doping in the TiO_2 layer at LaO interface and hole doping in the AlO_2 layer at SrO interface. Due to the built-in electric field at the interface, the interface states show spin splitting and vortex-like spin textures in momentum space, i.e. Rashba effect. Calculated Rashba coefficient is of the same order as that of the experimental value[3] and theoretical value for n=2[4]. We will discuss tunability of interface metallic states by using magnetic-atom doping and epitaxial strain. The spin-orbit coupling parameters and built-in electric field in related oxide heterostructures are also discussed.

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PS40

Surface Electronic State of Topological Crystalline Insulator in Superconducting State

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There has been a growing interest in topological materials which can be superconducting state since they can host wide variation of surface Andreev bound states (SABSs). Topological crystalline insulator (TCI) whose surface state is protected by crystal symmetry has also received broad attention as a new type of topological material. SnTe is one of the TCI, whose surface states are protected by mirror symmetry [1]. It has been known that Indium doped SnTe become superconducting state. And also, the existence of SABS has been suggested by point contact experiments [2].

Motivated by the experiments, we theoretically study the TCI in the superconducting state. We introduce possible fully-gapped pair potentials to the TCI and calculate the surface spectral function by using the recursive Green's function method.

We find that the superconducting TCI (STCI) can host mirror protected SABSs which has never been seen before. We also reveal that the SABSs twist since they merge with the Dirac cone originating from the normal state. In the superconducting topological insulator (STI), topologically protected zero-energy SABS must across the time reversal invariant momentum. For this reason, the dispersion of the SABS becomes flat like at zero energy when it twists[3]. On the other hand, in the STCI, zero-energy SABS can move along the mirror symmetric line. Therefore, the dispersion of the SABSs in the STCI is not necessary to become flat like at zero energy when it twists.

In order to understand the topological nature of the STCI, we also calculate the mirror Chern number and make a phase diagram as a function of pair potential and the spin-orbit interaction. Consequentry, we find that there are three phases: the mirror Chern number = 0, -2 and -4 in the STCI, instead of three phases: mirror Chern number = 0, -1 and -2 phases in the STI.

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PS41

Theory of Tunnel Conductance in Helical Metal / Superconductor Junction

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Manipulations of spin transports are central issues in spintronics. Recently, spin related transports have been studied in helical metals in which the direction of spin and momentum are linked each other, that is called spin-momentum locking [1,2]. In the helical metal, the spin-momentum locking is realized by a manipulation of the magnitude of Rashba spin-orbit interactions (RSOI) and Zeeman fields (U), when a chemical potential (μ) satisfies $|\mu| < |U|$. There has been works of Josephson currents in the presence of the spin-momentum locking in superconductor/helical metal/superconductor junction [3,4]. However, studies of tunneling conductance have not been, so far.

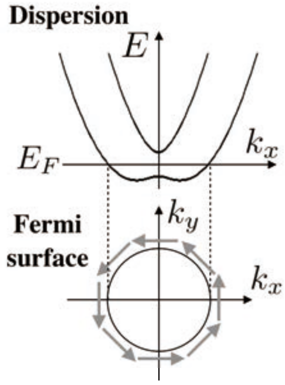

Fig.1:The energy dispersion and the spin sturucture on the Fermi surface in the helical metal.

We study the tunneling conductance for several symmetries of Cooper pairs in helical metal/superconductor junction by using the extended BTK formula and quasi-classical approximation. As results, we find that the zero bias conductance becomes finite, and its origin is caused by RSOI in the case of the two dimensional junction with the spin-singlet superconductor. In the junction with the p_x-wave superconductor, the zero bias conductance depends on not only RSOI, but also the in-plane direction of the d-vector, although the zero bias conductance doesn't depend on the in-plane direction of the d-vector in the ferromagnet/p_x-wave superconductor.

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PS42

Conductance Fluctuation versus In-Plane Magnetic Field in an InAs Quantum Corral

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An electron-wavefunction confined in a two-dimensional (2D) plane is directly affected by perpendicular magnetic field through the Aharonov-Bohm (AB) phase while spin-orbit interaction (SOI) works as an effective in-plane magnetic field on spin. Hence an external in-plane magnetic field can be a useful tool to investigate the effect of SOI [1]. Here we report conductance fluctuation (CF) versus in-plane magnetic field B caused by SOI.

The sample was corralled 2D electrons in an InAs quantum well with several quantum point contact (QPC) gateways (Fig.(a)). Mobility 66000 cm^2/Vs, concentration 1.21×10^{12} cm^{-2} and Rashba strength 3.6×10^{-11} eVm were estimated from Shubnikov-de Haas oscillation [2]. When in-plane magnetic field B was applied, conductance between contacts 5 and 2 exhibited clear dip at B=0 and fluctuating but reproducible pattern at high B. The fluctuation diminished with increasing temperature, manifesting that it originated from quantum interference. We observed the CF amplitude increased (Fig.(b) upper panel) when the direction of B was rotated from $\theta = 0$ (*x*-oriented) to $\pi/2$ (*y*-oriented), which clearly appeared in the figures of the conductance variances (Fig.(c)). This can be attributed to the fact that the effective magnetic field B_{SOI} is oriented to y-axis. We also found that the CF amplitude changed with the path of electrons (Fig.(b) lower panel), with the highest CF at the straight path (between contacts 5 and 2) and the lowest at the wound path (between contacts 5 and 4). This presumably resulted from the distribution of B_{SOI} and reflected semi-ballistic nature of the electron propagation.

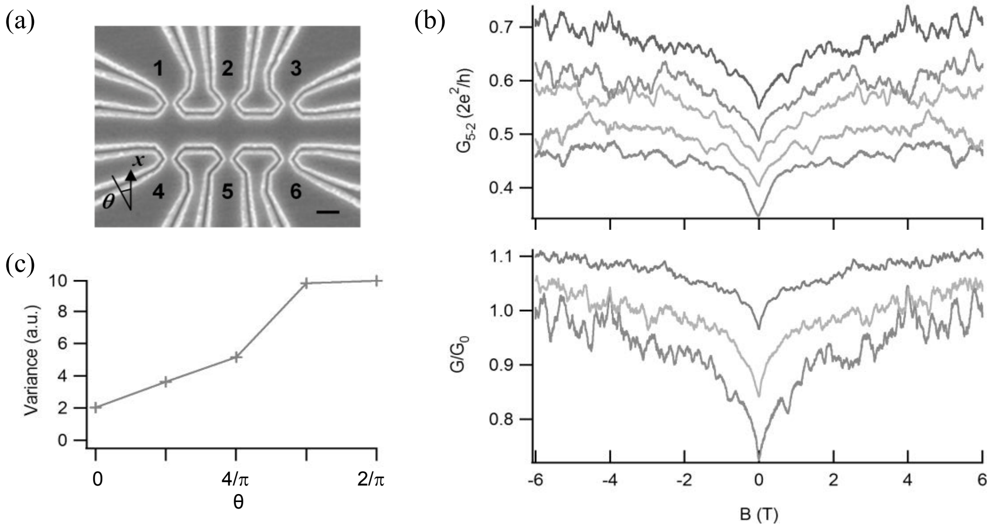

Figure: (a) The SEM image of sample with scale bar of 1μm.T = 135 mK. (b) The upper panel is magnetoconductance *G* between contacts 5 and 2 in the unit of $2e^2/h$. The offset corresponds θ (rotation angle of B) changing from 0 (bottom) to π/2 (top). The lower panel is *G* between contacts 5 and 2 (bottom), 5 and 1 (middle), 5 and 4 (top) with θ = π/2, normalized by values at B=-6.0 T (G_0). (c) Conductance variance versus θ calculated from (b). Data from B=-6.0 T to -1.5T were used after subtracting the background.

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PS43

Detection of topological states in two-dimensional Dirac systems by dynamic spin susceptibility

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We discuss dynamic spin susceptibility (DSS) in Landau quantized two-dimensional (2D) Dirac systems with spin-orbit interactions to characterize the topological phases. We show that the imaginary part of DSS appears as absorption rate of a transverse AC magnetic field, just like electron spin resonance experiment for localized spin systems. We found that when a system is in a static magnetic field, the topological state can be identified by an anomalous absorption peak related to transition between the two Landau levels close to the Fermi level, which does not appear in the trivial state.

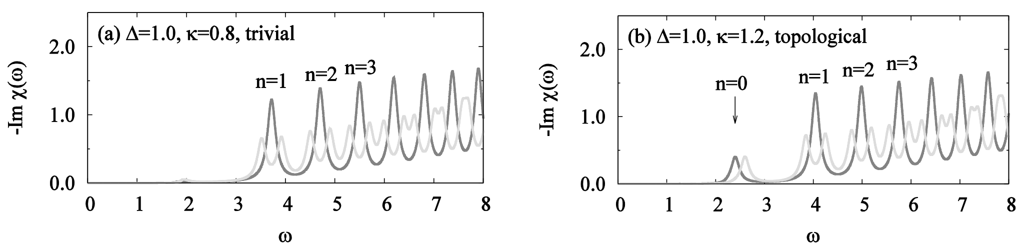

Figure 1: Imaginary part of the dynamic spin susceptibility of a 2D Dirac system with spin-orbit interactions [red (green): without (with) Zeeman effect]. An anomalous peak appears only in the topological phase.

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PS44

Linear response theory of spin torques due to spin waves

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Manipulation of magnetic structures by unconventional means is one of the important topics in spintronics. Among various means, driving a magnetic structure by temperature gradient has received a particular attention. Such phenomena were observed experimentally [1,2], but the relevant mechanism is under discussion. One of the expected mechanisms is the spin torque due to thermally induced spin waves.

There are some studies on the effects of propagating spin waves on magnetic structures [3,4,5]. A temperature gradient can also induce a flow of spin waves, whose spin current will exert spin torques. Ordinary spin torques (in the absence of Dzyaloshinsky-Moriya interaction) have two components, one comes from the conservation of angular momentum (spin-transfer torque), and the other is its dissipative correction (called β-term) which is related to the damping constant α of magnetization. A calculation of spin torques due to spin waves was performed based on a phenomenological equation (stochastic Landau-Lifshitz-Gilbert equation) [6].

In this work, we formulate a theory of spin torques due to spin waves induced by a temperature gradient based on the linear response theory, and calculate the spin-transfer torque and the β-term. To treat temperature gradient, we follow Luttinger and introduce a 'gravitational potential' [7]. We discuss, in particular, the relation of the β parameter to α. Also, we apply the results to some specific magnetization structures, such as a domain wall, and discuss their dynamics.

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PS45

Enhancement of spin-orbit interaction in graphene due to hydrogenation

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Graphene is one of the monolayer materials beyond silicon with weak spin-orbit interaction (SOI) of a few tens of microelectronvolts. It is difficult to modulate the SOI in graphene by applying gate voltage unlike the two-dimensional systems in semiconductor heterostructures[1]. However, functionalization is considerable method to tune the SOI for graphene. Recently, Balakrishnan *et al*. reported that weak hydrogenation greatly enhances SOI in graphene [2]. They discovered anomalous increase of non-local resistance by hydrogenation and estimated the SOI strength of 2.5 meV for 0.05% hydrogenated graphene. This value is three orders of magnitude larger than that of pristine graphene. A plausible mechanism of the enhancement is based on breaking the reflection symmetry across the graphene plane induced by the lattice distortion due to the C-H covalent bonding. But there is also a skeptical view about the enhancement itself because of the lightness of the composition elements.

In order to clarify the enhancement of SOI, we have investigated spin-valve devices using hydrogenated graphene and confirmed spin-charge conversion phenomena caused by the enhanced SOI. The devices were fabricated from exfoliated graphene and $Ni_{0.78}Fe_{0.22}$ ferromagnetic electrodes and gold electrodes were deposited using conventional lift-off process. The graphene was hydrogenated just before measurements using hydrogen silsesquioxane resist and electron beam irradiation [3]. Figure 1(a) exhibits a conventional lateral spin-valve signal, which guarantees successful spin injection. Another type of non-local voltage between non-magnetic electrodes displayed in Fig.1(b) is obtained, and it oscillates by the magnetic fields perpendicular to the ferromagnetic electrodes. This signal is likely to exhibit inverse spin Hall effects induced by the SOI.

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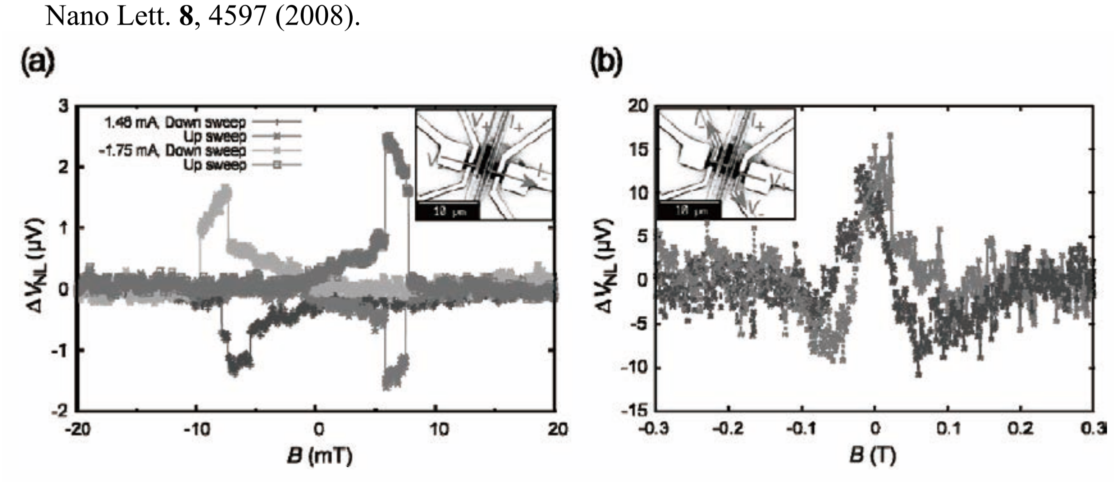

Fig. 1. Non-local voltage with the terminal configurations displayed in inset SEM images. The white, gray and black figures indicate gold, permalloy, and graphene. The magnetic fields are parallel and perpendicular to the permalloy electrodes in (a) and (b), respectively.

PS46

Rotating angle dependence of NMR line structures in various nuclides

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Barnett effect [1], magnetization by body rotation, is one of the fundamental phenomena of the angular momentum conversion between spin angular momentum and mechanical rotation motion. The Barnett effect shows that a rotating body feels an effective magnetic field. Recently, the effective magnetic field called Barnett field has been observed directly in terms of solid state nuclear magnetic resonance (NMR) [2] using a new coil-spinning technique [3] in which a sample and a detector are synchronously rotated.

We report experimental results and theoretical analysis for the angle dependence of the NMR measurement with mechanical rotation in kHz range. By changing the angle θ between rotation axis and an external field, NMR line splitting is found even in nuclear spin I = 1/2 system [4]. We obtain that the θ dependences of NMR line structure and peak intensity are independent of nuclear spin by calculation of dynamic magnetic susceptibility. Figure 1 shows the θ dependences of peak intensities for deuteron (D) nucleus with I = 1. The results are well reproduced by the calculation (solid lines).

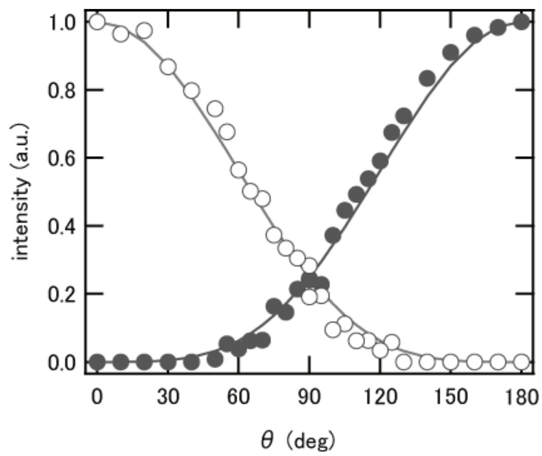

Figure 1: Rotating angle dependences of peak intensities in D_2O NMR measurement.

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PS47

Effects of Dirac Points on Rashba Spin-Orbit Torques

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PS48

Persistent spin helix on the ZnO (10-10) surface: Fully relativistic study

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Recently, spin-orbit coupled systems attracted much scientific interests because they allow manipulation of the electron spin[1]. One of the most interesting physical properties induced by the SOC is the persistent spin helix (PSH) since it enables the long spin life time[2]. However, the PSH is widely studied only for the zinc-blende semiconductors [3,4]. Wurtzite structure semiconductors are promising candidates since the high quality of the two dimensional system has been experimentally observed[5]. In this presentation, we show that the PSH is realized by using wurtzite ZnO (10-10) surface.

We performed fully relativistic first-principles calculation on ZnO (10-10) surface by using the openMX code[6]. We calculate the spin textures of the spin-split surface state and found the quasi-one dimensional spin orientations, which is similar to PSH spin textures. We clarify the origin of the spin textures based on the simplified spin-orbit Hamiltonian. The calculated values of the spin-orbit strength and the wavelength of the PSH are comparable with those observed for various zinc-blende quantum well structures. This findings open the new possibility in the study of wurtzite-based PSH systems.

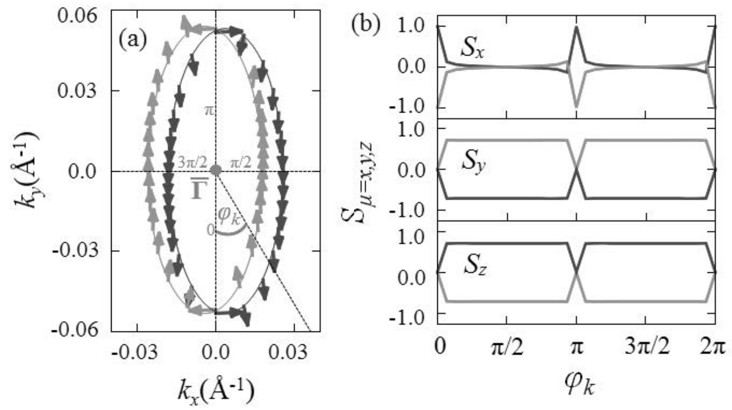

Figure 1. The spin textures on the spin-split surface states of ZnO (10-10) surface

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PS49

Topological Transitions in Spin Interferometers

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We calculate nonadiabatic electronic transport in mesoscopic loop-shaped spin interferometers and show topological transition in the interference effects (see Figure 1). Due to complex spin-state structure the dynamic and bare geometric phases [1] show intricate mixing and they lose relevance as separate quantities near the line of transition. Instead, the transition is determined by an effective Berry phase that is observable and related to the topology of the field texture via parity of the windings around the Bloch sphere. The transition manifests as a distinct dislocation of the interference pattern in the quantum conductance [2]. The phenomenon is robust against disorder and can be demonstrated by a controlled manipulation of spin-guiding fields within experimental reach [3]. We find an analogous transition for SO(3) rotations in simulations of magnetic moment dynamics.

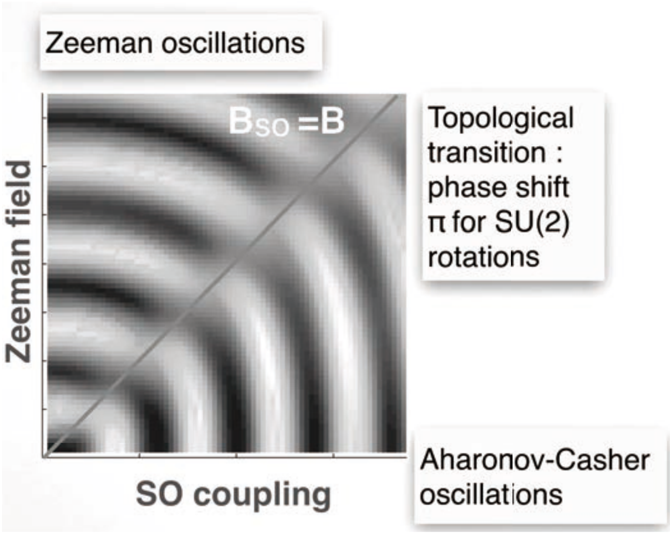

Figure 1. Topological transition in the calculated interference pattern in conductance of a ballistic single-mode loop.

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Quantum transport through 3D Dirac materials

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We study the quantum transport properties of three dimensional Dirac materials (3DDM) within the framework of Landauer-Buttiker formalism. Bismuth and its alloys provide a paradigm to realize three dimensional materials whose low-energy effective theory is given by Dirac equation in 3+1 dimensions[1, 2]. Charge carriers in normal metal satisfying the Schrodinger equation, can be split into four-component with appropriate matching conditions at the boundary with the 3DDM. We calculate the conductance and the Fano factor [3] of an interface separating 3DDM from a normal metal, as well as the conductance through a slab of 3DDM. As shown in Fig.1, under certain circumstances the 3DDM appears transparent to electrons hitting the 3DDM. We find that electrons hitting the metal-3DDM interface from metallic side can enter 3DDM in a reversed spin state as soon as their angle of incidence deviates from the direction perpendicular to interface. However the presence of a second interface completely cancels this effect.

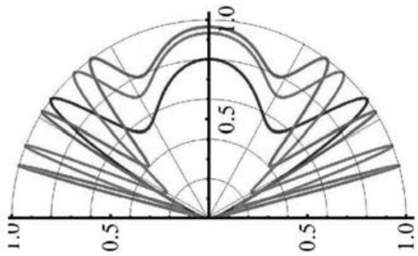

Figure 1: (Color online) angular dependence of quantum transport of an excitation with energy $\varepsilon/\Delta = 2, 3, 4$ corresponding to red, brown and blue curves, respectively. We set Δ=10 meV and $v_D = 10^5$ m/s. The length of junction is L=1μm.

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PS51

Half-metallic ferromagnetism in Mn-doped zigzag AlN nanoribon from first-principles

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Based on first-principles calculations, we investigate the effect of Mn impurity on the electronic and magnetic properties of H-terminated zigzag AlN nanoribbon (ZAlNNR), using the band structure results obtained through the full potential linearized augmented plane wave (FP-LAPW) method within the density functional theory (DFT). The exchange-correlation potential is treated by the generalized gradient approximation (GGA) within the Perdew et al. scheme [1]. The calculated results show that the H-terminated ZAlNNR is semiconducting and non magnetic material with a direct band gap of about 2.78 eV which in good agreement with previous experimental and theoretical reports [2,3]. Density of state (DOS) analyses shows that the top of the valence band for the H-terminated ZAlNNR (bare) is mainly contributed by N atoms, while just beside the conduction band the whole DOS is mainly contributed by Al atoms.

The main result is a transition from non-magnetic semiconducting character to ferromagnetic half-metallic one upon doping. The ZAlNNRs doped with Mn impurity, display strong spin polarization very close to the Fermi level which will result in spin-anisotropic transport. The Mn-doped ZAlNNR shows complete (100%) spin polarization at the Fermi level and the charge transport is totally originated from Manganese spin up electrons in the nanoribbon. These results propose potential application for the development of AlN nanoribbon-based in magneto-electronic devices.

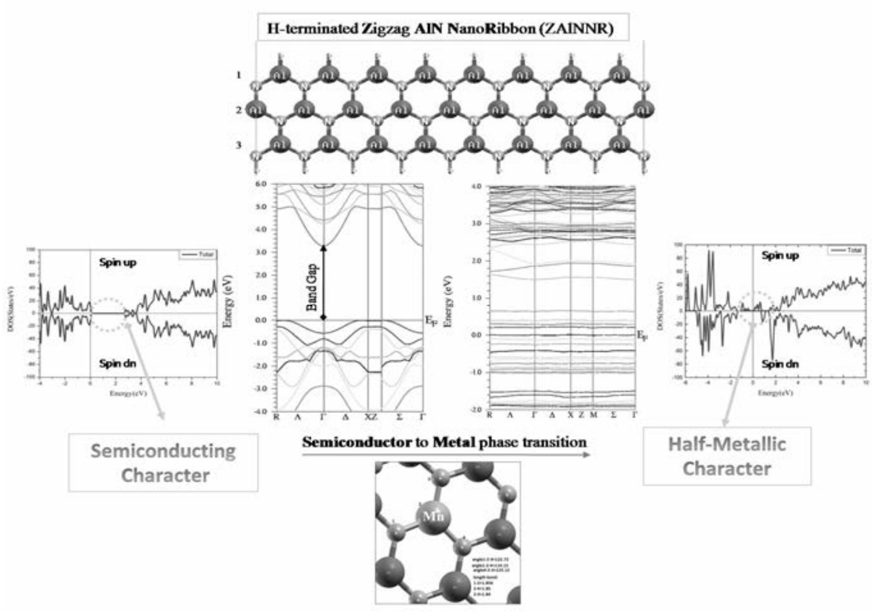

Figure 1: Graphical abstract.

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PS52

Kondo effect in a carbon nanotube quantum dot with a finite orbital splitting and a magnetic field

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We study ground-state properties of a carbon nanotube quantum dot, for which high-sensitive current and current-noise measurements have recently been carried out [1,2]. This system shows SU(4) and SU(2) Kondo effects depending on the gate voltages and external fields, and some corresponding situations were examined by Izumida, Sakai and Shimizu in their seminal numerical-renormalization-group (NRG) study of quantum dots [3]. Our purpose is to explore the wide parameter space of this system, especially the realistic regions relevant to the experiments. We calculate the conductance, linear noise, and renormalized local-Fermi-liquid parameters, using the NRG, to clarify effects of a level splitting $\varepsilon_{\rm sp}$ and a magnetic field b which break the SU(4) symmetry.

We consider an impurity Anderson model with two orbitals $\mu = +, -$, and spin $\sigma = \uparrow, \downarrow$

$$\mathcal{H} = \sum_{\mu\sigma} \varepsilon_{d,\mu\sigma}\, d^{\dagger}_{\mu\sigma} d_{\mu\sigma} + \frac{U}{2}\, N_d\,(N_d - 1) + \sum_{\mu\sigma} V \left(d^{\dagger}_{\mu\sigma}\psi_{\mu\sigma} + \text{H.c.}\right) + \sum_{\mu\sigma} \int_{-D}^{D} d\epsilon\, \epsilon\, c^{\dagger}_{\epsilon,\mu\sigma} c_{\epsilon,\mu\sigma},$$

$$\varepsilon_{d,\pm,\sigma} \equiv \varepsilon_d \pm \varepsilon_{\rm sp} - b\ \text{sign}\,\sigma, \quad N_d = \sum_{\mu\sigma} d^{\dagger}_{\mu\sigma} d_{\mu\sigma}\ , \quad \psi_{\mu\sigma} = \int_{-D}^{D} d\epsilon\, \sqrt{\rho}\, c_{\epsilon,\mu\sigma}.$$

Here, $\Delta \equiv \pi\rho V^2$, and $\rho = 1/(2D)$ with D the half-width of the conduction band. Figure 1 shows some results of (left) conductance and (right) occupation number for zero field $b = 0$ at $T = 0$. Typical value of the Kondo temperature in this situation is given by $T_K/(\pi\Delta) \simeq 0.13$ for the SU(4) particle-hole symmetric point $\varepsilon_{\rm sp} = 0$ and $\varepsilon_d = -1.5U$. We see that the unitary limit conductance at this symmetric point decreases as level splitting $\epsilon_{\rm sp}$ increases whereas the average of the total occupation $\langle N_d \rangle$ does not changes so much. We will also dicuss effects of additional magnetic field b and other details.

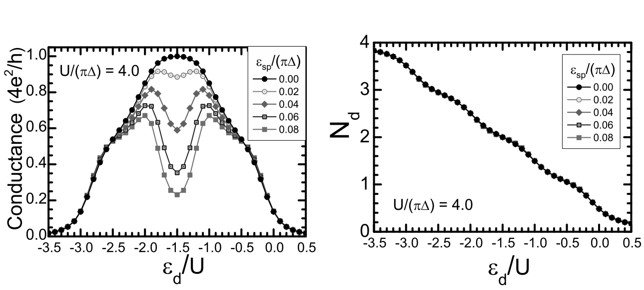

Figure 1: NRG results of (left) conductance and (right) average of N_d for Coulomb repulsion $U/(\pi\Delta) = 4.0$ and zero field $b = 0$, are plotted vs ϵ_d, for several different orbital splittings $\epsilon_{sp}/(\pi\Delta) = 0.00, 0.02, \ldots, 0.08$. Typical energy scale is $T_K/(\pi\Delta) \simeq 0.13$.

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PS53

Phasons and Excitations in Skyrmion Lattice

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Excitations of two-dimensional skyrmion lattice are theoretically studied based on a collective coordinate description[1]. Starting from the representation of skyrmion lattice in terms of three helices, we identify the canonical coordinates describing low energy excitations as phasons. The phason excitation spectra turn out to have one gapless mode with a quadratic dispersion and one massive mode, in agreement with previous studies. We will show that there is another collective mode governing the topological nature and the stability of skyrmion lattice and that the fluctuation of this mode leads to a screening of the topological charge of the lattice. Experimental implications of the screening effect in microwave absorption, topological Hall effect and depinning threshold current in metals are discussed.

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PS54

Application of NV-Center Spin Probe to Spintronics

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Recently, nitrogen vacancy center (NV center) in diamond crystal, single spin state in a pair of carbon defect and substituted nitrogen, is attracting much attention for utilizing it as a magnetometer. NV center can detect stray magnetic field from spins and magnets existing around at single spin sensitivity and nanometer-scale resolution [1, 2].

We focus on applying NV center to sensing and mapping magnets and spins unravelling underlying physics. For instance, magnetic domains and accumulated spins at the interface of ferromagnet and paramagnet of the spintronic device can be imaged by NV center spin probe.

In this study, we detected stray field by NV center from magnetic domains of yttrium iron garnet film (YIG), which is interested in using for magnon-based spintronic devices. Figure 1(a) shows polarization-microscope image of magnetic domains in the YIG film, where vertically magnetized up and down domains are formed. Nanodiamonds, which contains single NV center were spread on the YIG film surface and the stray magnetic fields from magnetic domains were optically detected by the NV center in naodiamonds. Figure 1(b) shows optically detected magnetic resonance (ODMR) signal from one of NV nanodiamonds on the YIG film. The observed data shows broadened ODMR signal which can be explained that the magnetic domains are dynamically oscillated by the microwave field for exciting NV center and the averaged stray fields were detected by NV center. From the broadening of ODMR signal information of domain wall motion can be extracted.

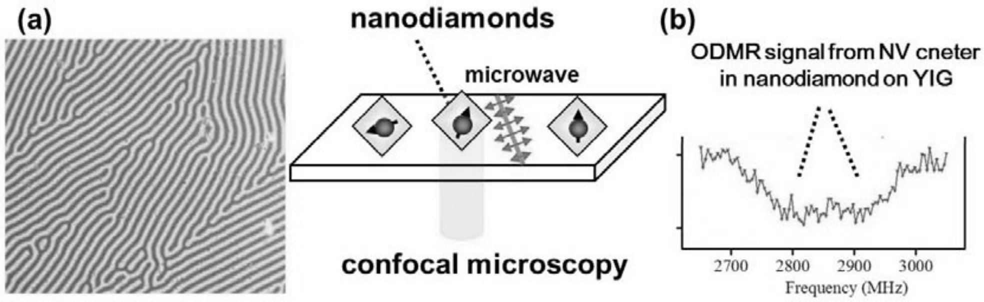

Figure 1: (a) polarization-microscope image of magnetic domains in the YIG film. (b) ODMR signal from NV center in nanodiamond on YIG.

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Timetables of Bus

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15	02 20 32 41 42 57		02 12 20 42 57		02 12 20 42 57
16	12 18 43 45		02 12 42		02 12 42
17	02 06 12 30 37 46 55		02 02 14 42 55		02 02 14 42 55
18	11 15 24 25 47 50 56		02 12 25 32 42 47		02 12 25 32 42 47
19	18 19 26 44 56		12 19 36 42 59		12 19 36 42 59
20	12 13 34 36 47 55		13 19 24 34 47 48 55		13 19 24 34 47 48 55
21	04 32 38 43 56		01 29 33 38 58		01 29 33 38 58
22	28 29 34 58		29 34		29 34

To “Todai-mae (ISSP, University of Tokyo)” from “Kashiwa-no-ha Campus” Station

	For Weekdays		For Saturdays		For Sundays and Holidays
5	45		52		52
6	00 24 40 51		00 38 40		00 38 40
7	00 02 07 25 34 37 49 54		00 02 20 25 37 43 50 54		00 02 20 25 37 43 50 54
8	02 12 21 31 35 45 55		12 30 35 55		12 30 35 55
9	00 11 21 42 50		04 13 35 43 50		04 13 35 43 50
10	03 21 33 35 43		05 21 33 52		05 21 33 52
11	03 11 27 33 42 55		05 21 42 51		05 21 42 51
12	05 21 35 42 52		05 21 35 42 51		05 21 35 42 51
13	05 18 33 48		05 18 21 42 51		05 18 21 42 51
14	03 13 33 43 52		05 13 21 35 43 51		05 13 21 35 43 51
15	03 18 22 48 55		18 21 35 51		18 21 35 51
16	18 25 33 40 55		21 25 35 51		21 25 35 51
17	11 18 35 44 48 53		03 18 21 35 48 51		03 18 21 35 48 51
18	08 10 33 42 52		03 10 21 32 42 51		03 10 21 32 42 51
19	06 18 34 36 45 50		10 33 36 52		10 33 36 52
20	04 08 17 28 46		08 10 35 48		08 10 35 48
21	02 07 16 49 53		00 02 12 49 53		00 02 12 49 53
22	01 13 51		51		51

Timetables of Tsukuba Express from “Kashiwa-no-ha Campus” Station

For Weekdays to Akihabara Station

*C: Commuter Rapid, S: Semi-Rapid

5	15	27	S 29	39	49	S 55	59								
6	S 05	12	S 14	21	S 24	31	S 36	40	46	S 52	56				
7	01	S 04	09	C 11	14	17	S 19	22	25	S 27	30	33	S 35	39	42
	C 44	48	S 50	55	S 57										
8	01	04	S 06	10	C 12	17	S 20	25	30	S 32	37	C 39	47	S 51	55
9	02	S 09	12	20	S 23	31	39	51	S 55						
10	02	11	20	S 24	31	40	50	S 54							
11	01	10	21	S 25	32	40	50	S 54							
12	02	10	20	S 24	32	40	50	S 54							
13	02	10	20	S 24	32	40	50	S 54							
14	02	10	20	S 24	32	40	50	S 54							
15	02	10	20	S 24	32	40	50	S 54							
16	02	10	20	S 24	30	S 35	40	51	S 54						
17	02	S 06	12	S 15	22	S 25	33	S 37	41	50	S 54				
18	02	S 07	13	22	S 24	34	42	S 45	52	S 54					
19	04	13	S 17	23	S 26	32	38	46	52						
20	00	06	14	S 22	26	35	46	S 49	59						
21	S 01	11	S 14	23	S 34	38	S 49	54							
22	S 04	09	S 19	24	S 34	39	S 48	53							
23	05	15	S 21	27	38										

For Saturdays and Holidays to Akihabara Station

*C: Commuter Rapid, S: Semi-Rapid

5	15	27	S 29	42	S 55	59				
6	09	S 16	20	S 28	34	S 38	47	S 56		
7	01	10	20	S 22	29	S 31	39	48	S 51	57
8	04	14	S 17	24	S 28	34	41	51	S 54	
9	00	06	S 09	17	23	34	S 40	44	51	S 54
10	01	08	19	S 23	31	39	49	S 52		
11	01	10	20	S 24	32	40	50	S 54		
12	01	10	20	S 24	32	40	50	S 54		
13	02	10	20	S 24	32	40	50	S 54		
14	02	10	20	S 24	32	40	50	S 54		
15	02	10	20	S 24	32	40	50	S 54		
16	02	10	20	S 24	32	40	50	S 54		
17	02	10	20	S 24	32	40	50	S 54		
18	02	10	20	S 24	32	40	50	S 54		
19	02	10	20	S 24	32	40	50	S 54		
20	02	10	20	S 24	32	40	50	S 54		
21	02	10	20	S 24	34	43	57			
22	S 09	13	25	36	S 38	51				
23	S 03	06	S 18	24	38					

For Weekdays to Tsukuba Station

*C: Commuter Rapid, S: Semi-Rapid, M: to Moriya Station

5	42														
6	02	19	33	M 44	S 48	58									
7	04	M 10	S 15	M 20	27	M 32	M 38	46	M 53	S 59					
8	M 05	S M 08	M 14	S 17	M 25	32	M 36	S M 39	M 41	M 45	M 48	S 52	M 54	M 57	
9	02	M 05	S M 08	M 11	S 15	M 18	S M 23	M 25	30	M 35	S M 39	M 42	S 46	M 49	M 53
10	00	M 05	M 10	S 15	M 19	M 24	32	M 39	S 45	M 49					
11	00	M 08	S 15	M 19	30	M 38	S 45	M 49							
12	00	M 08	S 15	M 19	30	M 38	S 45	M 50							
13	00	M 08	S 15	M 20	30	M 38	S 45	M 50							
14	00	M 08	S 15	M 20	30	M 38	S 45	M 50							
15	00	M 08	S 15	M 20	30	M 38	S 45	M 50							
16	00	M 08	S 15	M 20	30	M 38	S 45	M 50							
17	00	M 08	S 15	M 20	30	M 38	S 41	M 48	S 51						
18	01	M 08	S 11	M 18	S 21	C 30	32	M 38	S 42	M 48	S 52				
19	C 00	02	M 08	S 13	M 19	S 22	M 28	C 32	S 38	M 41	M 48	S 51	M 58		
20	C 01	S 08	M 11	M 19	S 22	32	M 38	S 42	M 48	S 57	M 59				
21	M 04	S 11	M 13	M 18	S 22	31	M 38	M 46	S 50	M 56					
22	S 05	M 07	M 16	S 20	31	M 41	S 45	M 54							
23	S 01	M 07	17	30	M 39	S 46	M 52								
0	04	M 13	19	M 30	M 42	M 52									

For Saturdays and Holidays to Tsukuba Station

*C: Commuter Rapid, S: Semi-Rapid, M: to Moriya Station

5	42									
6	02	19	35	M 45	S 49					
7	02	M 12	S 17	30	M 38	S 45	M 50			
8	01	M 05	M 10	S 16	M 20	30	S M 38	M 40	S 46	M 50
9	01	M 05	M 10	S 16	M 21	31	M 35	M 40	S 46	M 51
10	01	M 07	S 15	M 19	30	M 34	M 40	S 46	M 50	
11	00	M 08	S 15	M 19	30	M 38	S 45	M 49		
12	00	M 08	S 15	M 19	30	M 38	S 45	M 49		
13	00	M 08	S 15	M 19	30	M 38	S 45	M 49		
14	00	M 08	S 15	M 19	30	M 38	S 45	M 49		
15	00	M 08	S 15	M 19	30	M 38	S 45	M 49		
16	00	M 08	S 15	M 19	30	M 38	S 45	M 49		
17	00	M 07	S 16	M 18	30	M 37	S 46	M 48		
18	00	M 07	S 16	M 18	30	M 37	S 46	M 48		
19	00	M 07	S 16	M 18	30	M 37	S 46	M 48		
20	00	M 07	S 16	M 18	30	M 37	S 46	M 48		
21	00	M 07	S 16	M 18	30	M 37	S 46	M 48		
22	00	M 07	S 16	M 18	31	M 41	S 45	M 57		
23	S 01	M 12	S 16	31	M 42	S 47	M 54			
0	05	19	M 30	M 42	M 52					