Emergent Phenomena and Functionality in Topological Magnets

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Since the discovery of quantum Hall effect in a two-dimensional electronic system, 1) the concept of topology has been appreciated in the classification of quantum states, leading to the identification of topological states and the emergent electromagnetism in condensed matters. With combinations of well-established physics of strongly-correlated systems, magnetism, superconductivity and so on, topology in the quantum system has been offering a platform of versatile electronic and spintronic phenomena. 2) For example, topological spin textures, such as skyrmions and hedgehogs, and topological electronic states of topological insulators and Weyl fermion systems can realize low-dissipative drive of magnetic domains or non-dissipative electron and spin currents. Also, Majorana fermions with non-Abelian statistics at an interface of superconductor and topological insulator are one of the promising candidates for robust bits in quantum computation technology. Nowadays, when a huge amount of electricity is consumed for information processing, it is expected to create power-saving electronic technology that utilizes these topological states, namely ‘topological electronics’. And control of topological states by external stimuli is an essential factor to realize such energy-saving technology.

In this talk, we introduce how topological states in electronic and spin structures are coupled with multiple degrees of freedom of electrons and provide unique electromagnetic responses. We illustrate that the effective electromagnetic fields, so-called emergent electromagnetic fields, have critical influence on quantum properties, and also overview the real-space topological spin textures of skyrmions and momentum-space topological electronic structures in magnetic topological insulators (Fig. 1).

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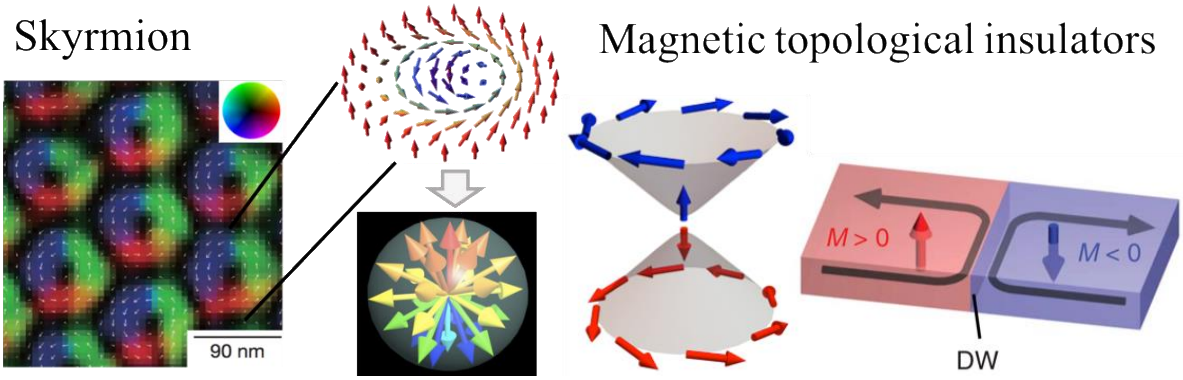

Fig.1 Skyrmions and magnetic topological insulators as representative examples of topological spin and electronic states in condensed matters.

Quantized surface transport in topological semimetal films

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Topological materials, which have nontrivial electronic structures in the momentum space, have recently attracted burgeoning research interest especially in terms of novel magnetotransport phenomena and emergent spintronic functions. In contrast to topological insulators, topological semimetals host three-dimensional Dirac or Weyl cones in the bulk state, besides the helical surface state due to the bulk band inversion. Exotic quantum magnetotransport proposed for such topological semimetals, such as chiral anomaly and Weyl orbit, are derived from characteristic Landau levels formed in the bulk Dirac dispersions, called a chiral zero mode.

Cd_3As_2 is an ideal material for exploring exotic magnetotransport and spintronic functions proposed for topological semimetals. In addition to its high electron mobility and long mean free path, its growth orientation is different from the rotational axis connecting the two Dirac points. This allows us to detect possible orbital motions in topological semimetal surfaces, which include the Weyl orbit, looping the two surface (top and bottom) arcs through a called bulk chiral mode. We have successfully developed a growth technique realizing high mobility Cd_3As_2 films with excellent surface flatness, and first observed quantum Hall states induced by quantum confinement 1). Related film techniques such as electric gating and chemical doping also enable systematic transport studies of the topological semimetal films, with controlling the bulk dimensionality 2), Fermi energy 3), and band topology 3).

More recently, by fabricating three-dimensional Cd_3As_2 films with controlled thickness above 85 nm, we have found surface quantum oscillations and their evolution into quantized states 4). This is confirmed by distinct differences in oscillation frequnecy, field angle dependence, and temperature change from the bulk ones. On the other hand, we have also revealed essential contribution of bulk carriers to the quantized surface transport and resultant changes in quantum Hall degeneracy depending on the bulk occupation. We discuss possible magnetic orbits realized in the quantized surface transport.

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Giant spin-orbit torque generated by BiSb topological insulator

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Topological insulators (TIs) are exotic materials with insulating (semiconducting) bulk states and metallic surface (edge) states. The electron spin on the surface of TIs is locked to its momentum, resulting in many novel physics. These include the quantum spin Hall effect in two-dimensional TIs, the quantum anomalous Hall effect in magnetic TIs, and Majorana Fermions at TI/superconductor interfaces. So far, those novel physics have been observed in TI-based heterostructures at extremely low temperatures, making them less attractive for device applications at room temperature. Here, we present our recent results on the giant spin Hall effect at room temperature in a conductive topological insulator, BiSb. We show that BiSb have both high electrical conductivity1) and giant spin Hall angle2) at room temperature, which are very promising for applications to ultralow power spin-orbit torque magnetoresistive random access memory (SOT-MRAM). Evaluation of spin-orbit torque in BiSb/MnGa bi-layers reveals a colossal spin Hall angle of 52 and a spin Hall conductivity of $1.3*10^7$ $\hbar/2e$ $\Omega^{-1}m^{-1}$ at room temperature. We demonstrate that BiSb thin films can generate a colossal antidamping-like effective field of 2.3 kOe·$MA^{-1}cm^2$ and a critical switching current density as low as 1.5 $MAcm^{-2}$ in BiSb/MnGa bi-layers. Furthermore, we identify the origin of the giant SHE in BiSb thin films by measuring the spin Hall angle under controllable contribution of surface and bulk conduction. Our quantitative analysis shows that the giant SHE in BiSb is almost governed by contribution from the topological surface states.3) We further show that the surface sheet spin Hall angle is proportional to the number of Dirac cones on the topological surface states, indicating the Berry phase nature of the observed giant SHE. BiSb is the best candidate for the first industrial application of topological insulators.

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Photocurrent in topological materials

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Materials with strong spin-orbit interaction show intriguing opto-electronic functionalities, including optical excitation of spin subsystem and generation of spin-current/spin-polarized charge-current. Dirac and Weyl materials are of recent interest, due to the possible wide-band operation coming from their zero-gap nature and the Berry phase contributions to excite large zero-bias photocurrents1,2).

Doping topological materials with magnetic elements brings about essential modifications in their originally mass-less Dirac dispersion, providing an additional path towards exotic physics and future dissipation-less electronics.3,4) With the progress in film fabrication techniques including modulation doping,5) we will be able to explore a variety of electron/spin dynamics at the modified Dirac states and cooperative phenomena between two surfaces (top/bottom of a film) in topological insulators.

Here we discuss several optical responses observed in (magnetic) topological insulators (TIs); (i) enhancement of photogalvanic current by chemically tuning the Fermi energy,6) and (ii) generation of large zero-bias photocurrent resulting from magnetic interactions.7) When a TI thin film is doped with magnetic elements, such as Cr, its easy-axis anisotropy induces an energy gap at the Dirac point. The surface-state dispersion recovers its mass-less state by the application of an in-plane magnetic field, due to the helical nature of the spin in the k-space, and further shifts/deforms through the Zeeman effect. In this situation, the photoexcitation at $+k_x$ and $–k_x$ becomes non-equivalent, even for the incidence of non-polarized photons, leading to a finite spin-polarized photocurrent j_x. We examine this magneto-photogalvanic effect and realized that the zero-bias photocurrent dramatically increases for the mid-infrared photoexcitation, pointing to the relevance of surface-state dispersions and the strong influence of bulk-surface scatterings. We also demonstrate that it is critical to precisely control the Fermi energy to observe intrinsic nature of TIs. For example, the photogalvanic current shows a pronounced peak when we tune the Fermi energy across the Dirac cone. If time allows, on-going works on the proximity effects and photocurrent in Rashba semiconductors/Weyl materials will also be presented.

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Topological Spintronics using Weyl Antiferromagnets

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Among magnets, only ferromagnets have been used for applications, for example, as the main active materials for memory devices. On the other hand, antiferromagnets have attracted recent interest for designing next generation high-density and ultrafast devices because they produce no stray fields and have much faster dynamics. Here we introduce a new type of functional antiferromagnets with vanishingly small magnetization, namely, topological Weyl magnets that can be easily controlled by magnetic field, produce large responses, and thus could be useful for future applications including spintronics. After brief discussion on emergent electronic phases based on a Luttinger semimetal found in pyrochlore iridates, we will introduce the frustrated antiferromagnets, Mn_3X (X =Sn and Ge) as the examples of a topological Weyl magnet [1,2,3]. We show that the cluster multipole order on the kagome lattice of Mn moments can be controlled and lead to a variety of new functions at room temperature that have never been seen in antiferromagnetic metals. These include the large anomalous Hall and Nernst effects in bulk and thin films[1,2,4,5], large magnetic optical Kerr effect [5] and a novel type of spin Hall effect (magnetic spin Hall effect) [7]. Finally, we show that they should be significantly useful for designing antiferromagnetic spintronics, and energy harvesting technology [8]. This presentation is based on the collaboration with Takahiro Tomita, Tomoya Higo, Muhammad Ikhlas, Ryotaro Arita, Michito Suzuki, Takashi Koretsune, YoshiChika Otani, Motoi Kimata, Kouta Kondou, Kenta Kuroda, Takeshi Kondo, Shik Shin, Pallab Goswami, Hua Chen, Allan MacDonald, L. Wu, J. Orenstein, R.D. Shull, O. van't Erve.

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Non-equilibrium skyrmion dynamics under the direct current

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Magnetic skyrmion is a topological spin texture originated from the competition between the exchange interaction and Dzyaloshinskii-Moriya interaction [1-4]. Skyrmions in bulks can be driven by the electric current through the spin transfer torque with the extremely low threshold current density of 10^6 A/m^2 [5] compared to that for the domain walls of 10^{10}-10^{12} A/m^2 . This outstanding property, in addition to their small domain size ranging from several nm to 1 μm, offers new spintronics applications including the non-volatile magnetic memories and current-driven shift resistors.

From an application point of view, ultrathin magnetic heterostructures are favorable systems rather than bulk magnets because of their compatibility with existing spintronic technologies. Intensive studies related to the skyrmion observation, driving, and manipulation have been reported in Co-based and CoFeB-based heterostructures[6-8].

Here we demonstrate the current-driven skyrmion motion in Ir/Co/Pt tri-layer thin films. Skyrmions segregate in the transverse direction to the current flow via the skyrmion Hall effect, which shows scalability for current density and wire width [9]. We also demonstrate several new findings: the significant material dependence of skyrmion dynamics, multiplication of skyrmions at the non-linear regime, and non-local accumulation of nonequilibrium skyrmions over several tens μm. These results suggest the importance of the collective nature of skyrmions, while only the behaviors of a single skyrmion have been discussed in previous studies.

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Energy saving AI using (artificial) topological materials

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Remarkable success in the deep learning triggered the 3rd boom in demand for the artificial intelligence (AI). Exploding demands requires R&D of energy saving AI system. One of the effective way is the usage of TPUs (tensor processing unit) that already reduced the energy consumption of the alpha-GO by a factor of 1/40. Another attempt is to make neuromorphic hard ware using certain physical phenomena. In this talk, two attempts to realize energy saving AI chips from topological magnetic system will be introduced.

The first attempt is to make neuromorphic system using MRAM technology. The neuromorphic system needs to have memory capability and non-linear calculation capability. Needless to say, MRAM is a memory. In addition, if magnetic cells in MRAM interact each other through dipole-dipole interaction, MRAM may get non-linear calculation capability. Such method was tested in our group using simulations. As a result, the device with 12 magnetic cells could be trained to calculated AND, OR and XOR of two bits among successive 3 bits inputs [1]. However, the training was possible only at low temperature, because of small energy of the dipole coupling. To overcome this difficulty, we started to use topological state to carry information. One of the example is an artificial spin-ice in a honeycomb lattice with 72 magnetic cells. The system is capable to learn XOR with 2-bit delay [2].

The second attempt is to make zero-power consumption calculator using magnetic skyrmions in a film. Magnetic skyrmion is known as a topological object appeared in ferro(antiferro)-magnetic materials without point symmetry. Interesting point of this object is its Brownian motion. Skyrmion shows Brownian motion in all solid state device without any motion of real mass. Therefore, it can be an ideal system to investigate a diffusion and information thermodynamics. By now, we have successfully controlled diffusion of skyrmions by an application of voltage [3] (Fig. 1), through a voltage induced change in the magnetic anisotropy [4], or DMI [5]. By using such techniques, we are now trying to design reconfigurable Boltzmann machine with zero energy consumption. It does not consume energy for the calculation in principle but small energy for the observation, just like the Maxwell's daemon does.

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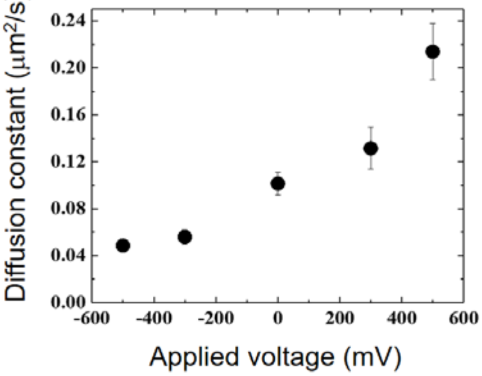

Fig. 1 Diffusion constant of skyrmions as a function of applied voltage [3].

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