Abstract

Workshop Third Week

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W15-1

Spintronics Beyond Magnetoresistance: Putting Spin in Lasers

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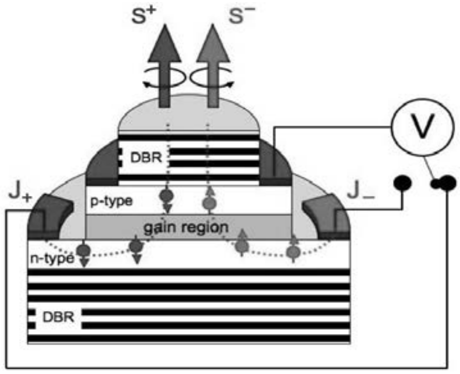
Practical paths to room-temperature spin-controlled devices are typically limited to magnetoresistive effects, successfully employed for magnetically storing and sensing information. However, spin-polarized carriers injected optically or electrically in semiconductors can also enhance the performance 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.

W15-3

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]

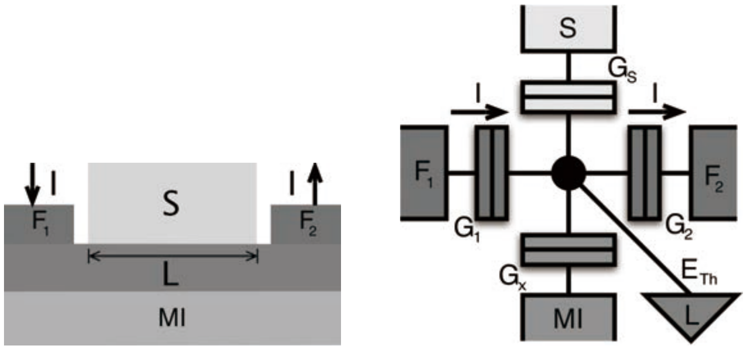

Figure 1: The left panel shows a sketch of typical experimental structuresetup to observe the predicted thermoelectric effect. The structure consists of a ferromagnetic insulating substrate (green), coupled to normal metal film (grey) covered by superconductor (yellow). Current is injected and extracted 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.

W16-2

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:

$$H=\frac{\hbar^2}{2m}\left(k_x^2+k_y^2\right)-J_0S\hat{\mathbf{m}}\cdot\boldsymbol{\sigma}+\alpha_{\mathrm{R}}\left(k_y\sigma_x-k_x\sigma_y\right),$$

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:

$$E_{\mathrm{MA}}=E_{\mathrm{R}}\left(1-\frac{2T}{J_0S}\right)\cos^2\theta$$

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].

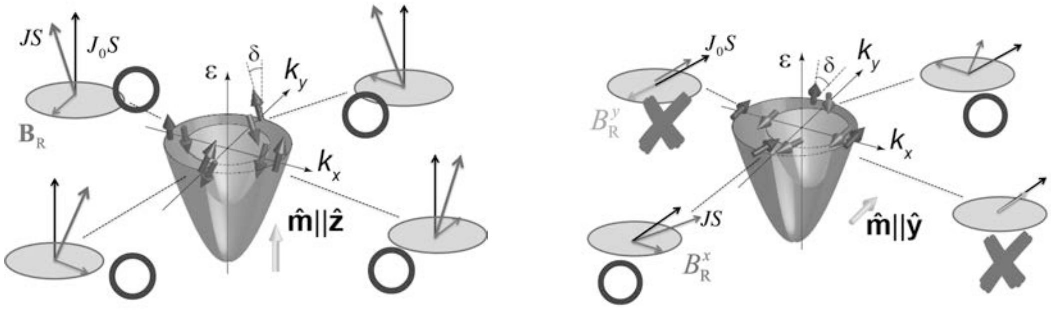

Figure 1: The spin splitting bands and contribution of the Rashba field $\mathbf{B}_{\mathrm{R}}$ to the exchange field enhancement. Left: The perpendicular configuration (θ=0). Right: The in-plane configuration (θ=π/2).

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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 separates up-spin and down-spin electrons simply by passing the electric current through the boundary.

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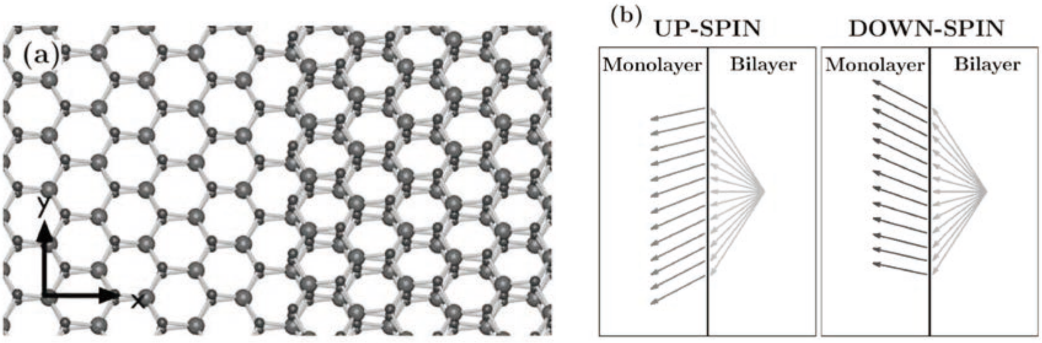

Figure 1: (a) Atomic structure of TMD monolayer and bilayer junction.
(b) Electron refraction at the atomic step between monolayer and bilayer of MoTe2 for an incident electron from the bilayer side.

W17-3

The effect of spin waves in the spin Seebeck Effect

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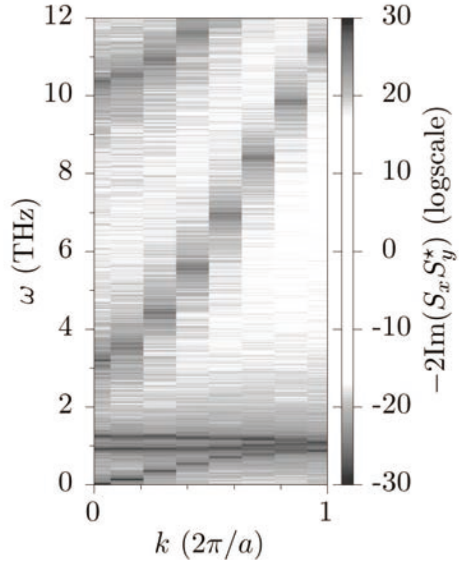

Figure 1: Low frequency part of the spin wave spectrum in GdIG.

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.

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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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W19-1

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.

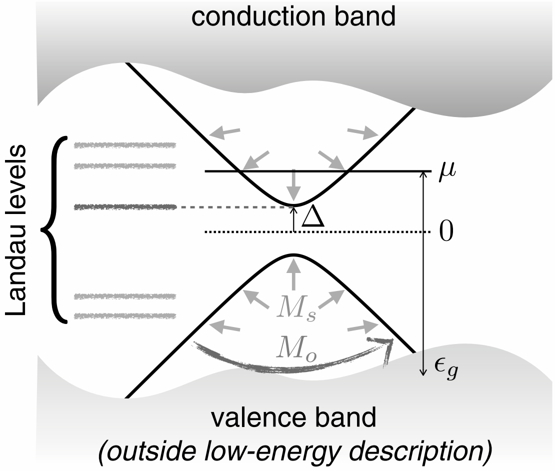

Figure 1: Schematic of the low-energy description, which captures contributions to the spin, M_S, and orbital, M_O, components of the magnetization that stem from the Dirac electrons.

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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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