Abstracts of INVITED SPEAKERS
of Spintronics with Antiferromagnets workshop

Spin Currents in Antiferromagnets

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Harnessing spin currents is one of the promising pathways towards low-power electronics [1]. Towards this end it has recently been recognized that antiferromagnetic materials can play a more active beyond their traditionally established role for providing reference magnetization direction via exchange bias. Namely, it has been shown both theoretically and experimentally that antiferromagnets may be a conduit for spin currents, as well as, actively enable spin current generation and detection. With respect to the later aspect, we recently demonstrated spin current generation both via spin Hall effects in conducting antiferromagnets and spin Seebeck effects in insulating antiferromagnets. Using CuAu-I-type metallic antiferromagnets (PtMn, IrMn, PdMn, and FeMn) we showed by using spin pumping that these alloys have significant spin Hall effects, which in the case of PtMn become comparable to the ubiquitously used Pt [2]. The spin Hall angles increase for the alloys with heavier element; a behavior that is well reproduced by first-principle calculations of the spin Hall conductivities based on intrinsic spin Hall effects. Furthermore, the calculations suggest pronounced anisotropies of the spin Hall conductivities, which we tested using spin transfer torque ferromagnetic resonance measurements using epitaxially grown antiferromagnetic films [3]. We observe that indeed the spin Hall conductivity is maximized for different growth orientations (a-axis for PtMn and PdMn, and c-axis for IrMn) in accordance with the first principle calculations. Lastly, using epitaxial MnF_2/Pt bilayers, we observe spin Seebeck voltages with distinct features due to the well-known spin-flop transition in MnF_2.

Work at Argonne was supported by the U.S. DOE, Office of Science, Materials Sciences and Engineering Division. Work at Jülich was supported by SPP 1538 Programme of the DFG. Work at WVU was supported by a Research Challenge Grant from the West Virginia Higher Education Policy Commission (HEPC.DSR.12.29), a grant from the U.S. NSF (grant No. DMR-1434897), and the WVU Shared Research Facilities.

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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.

Antiferromagnetic spintronics

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Louis Néel pointed out in his Nobel lecture that while abundant and interesting from theoretical viewpoint, antiferromagnets did not seem to have any applications. Indeed, the alternating directions of magnetic moments on individual atoms and the resulting zero net magnetization make antiferromagnets hard to control by tools common in ferromagnets. Strong coupling would be achieved if the externally generated field had a sign alternating on the scale of a lattice constant at which moments alternate in AFMs. However, generating such a field has been regarded unfeasible, hindering the research and applications of these abundant magnetic materials.

We have recently predicted [1] that relativistic quantum mechanics may offer staggered current induced fields with the sign alternating within the magnetic unit cell which can facilitate a reversible switching of an antiferromagnet by applying electrical currents with comparable efficiency to ferromagnets. Among suitable materials is a high Néel temperature antiferromagnet, tetragonal-phase CuMnAs, which we have recently synthesized in the form of single-crystal epilayers structurally compatible with common semiconductors [2]. We demonstrate electrical writing and read-out, combined with the insensitivity to magnetic field perturbations, in a proof-of-concept antiferromagnetic memory device [3].

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TITLE: **Spinning of spins: ferro- vs antiferromagnetic spintronics**

SPEAKER: **Olena Gomonay**

ABSTRACT: Spintronics of antiferromagnets is a new emerging field which opens new perspectives for the element base of information technologies. Practical application of AFM materials however encounters the problems of deterministic switching (writing), measuring (reading) and stabilization (storage) of AFM state in the presence of spin current. This talk gives some fundamental principles of AFM magnetic dynamics and overviews our recent results on manipulation the state of AFM nanoparticle by spin current. Starting from general principles we demonstrate that spin current pumped into AFM particle induces nontrivial magnetic dynamics and present simple analytical tool for its description. We also compare the peculiar features of ferro-and antiferromagnetic dynamics for the typical spintronic materials and highlight the problems of the predictable switching between different AFM states.

Spin Hall Effects due to Critical Spin Fluctuations in Spin Glass and Other Magnetic States

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Based on the skew scattering via collective spin fluctuations, it is proposed theoretically that the direct and inverse spin Hall effects (DSHE and ISHE) are unique tools to study spin fluctuations in metals [1].

The theoretical results are applied to the recent experiments in a weak ferromagnetic NiPd by Wei et al. [2] and a CuMnBi spin glass state by Niimi et al. [3].

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Interconnections between magnetic state and transport currents in antiferromagnetic Sr_2IrO_4

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Interconnections between magnetic state and transport currents in ferromagnetic (F) heterostructures are the basis for spintronic applications, e.g. tunneling magnetoresistance and spin-transfer torque phenomena provide a means to read and write information in magnetic memory devices like STTRAM. Similar interconnections were proposed [1] to occur in systems where F-components are replaced with antiferromagnets (AFM). We demonstrated experimentally the existence of such interconnections in antiferromagnetic Mott insulator Sr_2IrO_4: first, we found [2] a very large anisotropic magnetoresistance (AMR) which can be used to monitor (read) the magnetic state of AFM; second, we demonstrated [3] the feasibility of reversible resistive switching driven by high-density currents/high electric fields which can be used for writing in AFM memory applications. These results support the feasibility of AFM spintronics where antiferromagnets are used in place of ferromagnets. This work was supported in part by C-SPIN, one of six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA, and by NSF grants DMR-1207577, DMR-1265162 and DMR-1122603.

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Spin-Transfer and Antiferromagnets

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I will make some general remarks about antiferromagnets in spintronics and then talk about current-induced torques including spin-orbit torques and the possible use of non-collinear antiferromagnetic states as spin-torque generators.

Propulsion of a domain wall by magnons in an antiferromagnet

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Domain walls in magnetic nanowires can be used to store information and perform logical operations. Whereas the mechanism of domain wall propulsion in ferromagnet (by an applied field, spin-polarized current, or a flux of magnons) are well understood, much less is known about the antiferromagnetic domain walls.

We analyze the dynamics of a domain wall in an easy-axis antiferromagnet driven by a current of circularly polarized magnons. Magnons pass through a stationary domain wall without reflection and thus exert no force on it. However, they reverse their spin upon transmission, thereby transferring two quanta of angular momentum to the domain wall and causing it to precess. A precessing domain wall partially reflects magnons back to the source. The reflection of spin waves creates a previously identified reactive force. We point out a second mechanism of propulsion, which we term redshift: magnons passing through a precessing domain wall lower their frequency by twice the angular velocity of the domain wall; the concomitant reduction of magnons' linear momentum indicates momentum transfer to the domain wall. We solve the equations of motion for spin waves in the background of a uniformly precessing domain wall with the aid of supersymmetric quantum mechanics and compute the net force and torque applied by magnons to the domain wall. Redshift is the dominant mechanism of propulsion at low spin-wave intensities; reflection dominates at higher intensities. We derive a set of coupled algebraic equations to determine the linear velocity and angular frequency of the domain wall in a steady state.

Spin pumping and spin-transfer torques in antiferromagnet

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Spin pumping and spin-transfer torques are key elements of coupled dynamics of magnetization and conduction electron spin, which have been widely studied in various ferromagnetic materials. Recent progress in spintronics suggests that a spin current can significantly affects the behavior of an antiferromagnetic material [1], and the electron motion become adiabatic when the staggered field varies sufficiently slowly [2]. However, pumping from antiferromagnets and its relation to current-induced torques is yet unclear. In a recent study [3], we have solved this puzzle analytically by calculating how electrons scatter off a normal metal-antiferromagnetic interface. The pumped spin and staggered spin currents are derived in terms of the staggered field, the magnetization, and their rates of change. We find that for both compensated and uncompensated interfaces, spin pumping is of a similar magnitude as in ferromagnets; the direction of spin pumping is controlled by the polarization of the driving microwave. Via the Onsager reciprocity relations, the current-induced torques are also derived, the salient feature of which is illustrated by a terahertz nano-oscillator.

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Optical control of antiferromagnetism

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All-optical magnetization switching has been studied extensively in recent years. A typical form of non-thermal magnetization control is the inverse Faraday effect. It involves rotation of the linear polarization of a probe pulse induced by a circularly polarized pump pulse in a transparent medium. Spin precession is also triggered with a linearly polarized pump pulse, in particular, a pulse polarized in a direction non-parallel to the crystal axes. This phenomenon is called the inverse Cotton-Mouton effect (ICME).
The interaction between light and magnetism is considered a promising route to the development of energy-efficient data storage technologies. To date, however, ultrafast optical magnetization control has been limited to a binary process. Here, we report an arbitrary optical polarization state to be written magnetically. The effect is demonstrated using a three-sublattice antiferromagnet hexagonal $YMnO_3$. Its three magnetic oscillation eigenmodes are selectively excited by the three polarization eigenstates of the light via the inverse magneto-optical effects. The magnetic oscillation state is then transferred back into the polarization state of an optical probe pulse, thus completing an arbitrary optomagnonic write-read cycle [1].

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Relativistic spin-orbit torques in anti-ferromagnets and related effects

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Understanding the origin and properties of the different phases of materials and how to control them is at the heart of condensed matter physics and physics in general. One of the grand challenges of the field is to control spin-dependent properties without using magnetic fields. To do so, one must resort to the relativistic nature of electrons, the spin-orbit coupling (SOC), which connects the spin and charge of the electron. We have learned how to exploit the relativistic SOC to create new paradigms of spin control in complex materials. At the heart of these effects is the spin Hall effect and the inverse spin-galvanic effect. Each of them have lead to new types of torques that generate magnetization dynamics by different origins. The spin Hall effect generates a spin current that transfers its angular momentum via the spin transfer torque, whereas the other effect transfers orbital angular momenta from the lattice to the magnetization via the SOC – a bit like a cat flipping itself. Transferring these questions to AFM we have predicted a new Neel type spin-orbit torques (SOTs) which are able to electrically manipulate the domain orientation of the Neel order parameter. This prediction has been recently realized in CuMnAs experiments. We explore these new Need-SOTs in other systems and study their relative strength. We also are extending some of their notions to manipulation of spin-textures which may prove also useful in antiferromagnetic spintronics.

Magnetism and transport in topological insulators

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Topological insulators (Tis) with magnetism offer many interesting opportunity from the viewpoint of spintronics. Especially, their surface states show the spin-momentum locking, i.e., the strong coupling limit of the spin-orbit interaction. In this talk, I will discuss the quantum Hall effect (QHE) and the quantized anomalous Hall effect (QAHE) of TIs. The novel \nu=0 state is the issue in the former system, while the focus is on the spin textures such as domain wall and skyrmions in the latter system.

Collaborators of these works are R. Wakatsuki, M. Ezawa, T.Morimoto, and A. Furusaki.

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Thermal vector potential theory of transport induced by temperature gradient

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A microscopic formalism to calculate thermal transport coefficients was presented by Luttinger [1] in 1964. He introduced a fictitious scalar field called a 'gravitational' potential, Ψ, which couples to the local energy density, $\mathcal{E}$, by an interaction Hamiltonian

$$H_{\rm L} = \int d^3r \Psi \mathcal{E}. \tag{1}$$

It was argued that Ψ satisfies $\nabla\Psi = \frac{\nabla T}{T}$ and that thermal transport coefficients are calculated based on linear response theory (Kubo formula) taking account of the interaction $H_{\rm L}$. Many works have been carried out based on the Luttinger's formalism. It turned out that naive application of Kubo formula may result in wrong thermal coefficients diverging at zero temperature, and the divergence was argued to be due to a wrong treatment of equilibrium contribution [2].

In this talk, we present a description of thermal effects by using a thermal vector potential $\boldsymbol{A}_T$, which couples to the energy current density $\boldsymbol{j}_\mathcal{E}$ via

$$H_{A_T} \equiv - \int d^3r \boldsymbol{j}_\mathcal{E} \cdot \boldsymbol{A}_T \tag{2}$$

and satisfies

$$\partial_t \boldsymbol{A}_T = \frac{\nabla T}{T}. \tag{3}$$

The vector potential formalism [3] is free from unphysical divergences in Luttinger's formalism, because the equilibrium ('diamagnetic') 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: In the case of free electron with mass m and energy ϵ_k (k is the wave vector) the interaction reads (including electromagnetic vector potential $\boldsymbol{A}$)

$$H = \frac{\hbar^2}{2m} \sum_{\boldsymbol{k}} \left(\boldsymbol{k} - e\boldsymbol{A} - \epsilon_{k-eA} \boldsymbol{A}_T \right)^2 . \tag{4}$$

Thermal vector potential thus acts as a gauge field coupling to the energy instead of the charge e. The formalism is applied to thermally-induced dynamics of magnetization structures [4].

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Anti-damping spin transfer torque through antiferromagnet

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Spin transfer torque (STT) has been an efficient and promising technique to control magnetizations of ferromagnetic materials in modern spintronic devices. This novel technique is based on an interaction between electron spin and local magnetic moments. The same interaction should be conserved in antiferromagnets (AFMs), in which there are microscopic local magnetic moments that compensate each other to exhibit no net magnetization.

In this work, we prepared MgO(001) substrate/Pt 5nm/NiO 10nm/FeNi 3nm/SiO_2 5nm multilayers, in which the films are epitaxially grown until the NiO layer, and performed a spin torque ferromagnetic resonance (ST-FMR) measurement to quantify the anti-damping spin torque transported between the Pt and the FeNi through the antiferromagnetic NiO layer. A pure spin current is created by the spin Hall effect of the Pt and injected into the NiO. The schematic layer structure of the injection scheme is shown in Fig. 1(a). As shown in Fig. 1(b), it is found that the FMR linewidth monotonously varies with the d.c. current flowing in the structure. As the ST-FMR measurement is only sensitive to the linewidth (i.e. damping) of the FeNi layer, this change in the linewidth in Pt/NiO/FeNi can be interpreted in a way that the spin current is transferred through the NiO and interacts with the FeNi. This intriguing spin current transport can be explained by the angular momentum transfer mediated by the antiferromagnetic magnons [1,2]. Our results assure that the spin current exerts a torque on the NiO magnetic moments and excites their dynamics. In the talk, recent results will be also discussed.

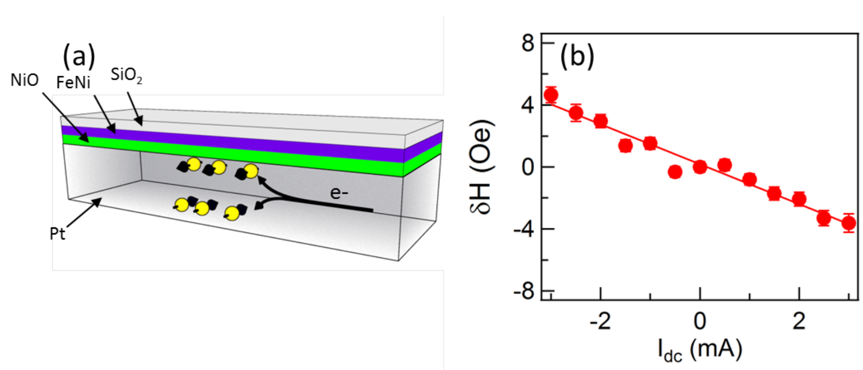

Figure 1 (a) Schematic illustration of the sample structure. (b) FMR linewidth change as a function of the d.c. current flowing in the sample.

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Ultrafast pulses, spin torque and artificial antiferromagnets

Dr Xavier Waintal
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Artificial antiferromagnets (Ferromagnetic-Normal-Ferromagnetic spin valves Antiferromagnetically coupled by the interlayer exchange interaction) can be viewed as the spintronics version of the Fabry-Perot interferometer. In this talk, I will introduce the concept of dynamical control of interference pattern with ultra fast voltage pulses.
I will show that this idea can be used on artificial antiferromagnets to control the magnetic exchange interaction leading to a new sort of (dynamical) spin torque. In a second part,
I will discuss the magnetic response of theseartificial antiferromagnets to spin torque, that naturally leads to spin torque oscillator (STO) behavior even in the absence of external fields.

Collective spin transport through antiferromagnets

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Antiferromagnetic insulators are 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 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 (electric) transconductance 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. Finally, I will discuss how thermally-activated topological transport of chiral domain walls recovers superfluid spin hydrodynamics in the presence of parasitic anisotropies.

Facet-dependent giant spin orbit torque in single crystalline antiferromagnetic Ir-Mn / ferromagnetic permalloy bilayers

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There has been considerable interest in spin-orbit torques for the purpose of manipulating the magnetization of ferromagnetic (FM) films or nano-elements for spintronic technologies. Spin orbit torques are derived from spin currents created from charge currents in materials with significant spin orbit coupling that diffuse into an adjacent FM material. There have been intensive efforts to search for candidate materials that exhibit large spin Hall angles, i.e. efficient charge to spin current conversion. Here we report, using spin torque ferromagnetic resonance, the observation of a giant spin Hall angle θ_{SH}^{eff} of up to ~0.35 in (100) oriented single crystalline antiferromagnetic $IrMn_3$ thin films, coupled to ferromagnetic permalloy layers, and a θ_{SH}^{eff} that is about three times smaller in (111) oriented films. Two distinct mechanisms are identified that contribute to θ_{SH}^{eff} : a first mechanism, which is facet independent, that arises from conventional bulk spin-dependent scattering within the $IrMn_3$ layer; and a second novel mechanism that derives from the $IrMn_3$ antiferromagnetic structure itself. By manipulating the populations of the various AF domains we show that θ_{SH}^{eff} can be dramatically enhanced for (100) oriented $IrMn_3$ films.

Spin Currents in Antiferromagnets and Ferrimagnets

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Antiferromagnetic materials were discovered a long time ago, but due to their zero net magnetization they have been considered for a long time not to be useful. Furthermore the manipulation using conventional magnetic fields is challenging. However recently, these materials have received renewed attention due to possible manipulation based on new approaches such as photons [1], spin-orbit torques [2] and thermal spin currents [3].
We firstly study the spin Seebeck effect (SSE) that has opened a new avenue to generating spin currents in insulators by exploiting a temperature gradient [4]. While in ferromagnets the origin has been identified as bulk magnonic spin currents [5], the situation is more complex in ferrimagnets and antiferromagnets with a complex interplay of different sub-lattices comprising different atom species. We study Gadolinium Iron Garnet (GIG), where at high temperatures, the *d* site Fe ions dominate the net magnetization of GIG and as the temperature is reduced, the magnetization of the Gd sub-lattice strongly increases, and together with the Fe magnetization at the *a* site eventually overwhelms the Fe magnetization at the *d* site, resulting in so-called magnetic compensation temperature [6]. When measuring the SSE measurements of GIG films, two sign changes of SSE signal are observed with decreasing temperature: The first sign change at a temperature close to the compensation temperature where the signal changes sign abruptly with unaltered amplitude, indicating that the majority of the spin current is mainly caused by the Fe sub-lattices, which reorient their direction at this temperature. A second sign change appears more gradually at low temperatures and it can be attributed to an interplay of i) the temperature dependent ordering of the Gd and Fe sub-lattices leading to a change in the magnon dispersion and occupation and ii) the temperature dependence of the spin-mixing conductances of the different sub-lattices [6]. We furthermore study the SSE also in antiferromagnets, such as $LaMnO_3$ and Sr_2IrO_4 and find signatures of the SSE.
Finally we study spin orbit torques in the antiferromagnet Mn_2Au where large effects have been predicted [2]. We establish the growth of the material and characterize its magnetic properties [7] as well as the effects of current injection.

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Electric probe for spin transition and fluctuation

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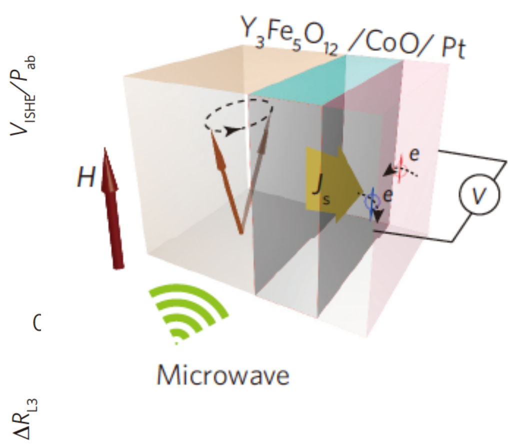
Spin fluctuation and transition have always been one of central topics of magnetism and condense matter science. In this talk I would like to introduce our recent progress that spin pumping, frequently used in nanoscale spintronic devices, provides a desktop micro probe for spin fluctuation and transition; not only a neutron beam, spin current is also a flux of spin without an electric charge and its transport reflects spin fluctuation in a sample. We demonstrate detection of anti-ferromagnetic transition in ultra-thin CoO films via frequency dependent spin-current transmission measurements. This method allows us to access spin realm in an electric manner in minute devices which are necessary in today's electronics and spintronics.



Poster Abstracts

of Spintronics with Antiferromagnets workshop

Macrospin Dynamics in Antiferromagnets Triggered by Sub-20 femtosecond Injection of Nanomagnons

D. Bossini, S. Dal Conte, Y. Hashimoto, A. Secchi, R. Pisarev, Th. Rasing, G. Cerullo and A.V. Kimel

The understanding of how the sub-nanoscale exchange interaction evolves in macroscale correlations and ordered phases of matter, such as magnetism and superconductivity, requires to bridge the quantum and classical worlds. This monumental challenge has so far only been achieved for systems close to their thermodynamical equilibrium. Here we follow in real time the ultrafast dynamics of the macroscale magnetic order parameter triggered by the impulsive optical generation of spin excitations with the shortest possible nanometer-wavelength and femtosecond-period. Our experiments demonstrate even the coherent manipulation of the phase and amplitude of these femtosecond nanomagnons, whose frequencies are defined by the exchange energy. These findings open up novel opportunities for fundamental research on the role of short-wavelength spin excitations in magnetism and strongly correlated material; they also suggest that nanospintronics and nanomagnonics can employ coherently-controllable spin waves with frequencies in the 20 THz domain.

Magnetization dynamics in trilayer synthetic antiferromagnets

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Recently, a new direction in spintronics has been emerging in which antiferromagnets (AFMs) take the role of ferromagnet (FMs) as active elements of memory or logic devices [1], e.g. because AFMs do not generate stray fields themselves. On the other hand, drawbacks are the difficulty to control AFMs by magnetic fields and much higher resonant frequencies (THz), which make difficult to match with 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 resonant frequencies that are tunable by weak magnetic fields. By rigorous model calculations, we study the magnetic damping of synthetic AFMs as affected by mutual pumping of spin currents and spin transfer torques or "dynamic exchange interaction" [3]. We formulate the dynamic exchange of spin currents in a noncollinear texture based on the spin diffusion model with quantum mechanical boundary conditions at the interfaces and derive the Landau-Lifshitz-Gilbert equations coupled via the static interlayer non-local and the dynamic exchange interactions. We also 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. We also investigate a resonant frequency modulation in both modes via spin Hall effect. 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.

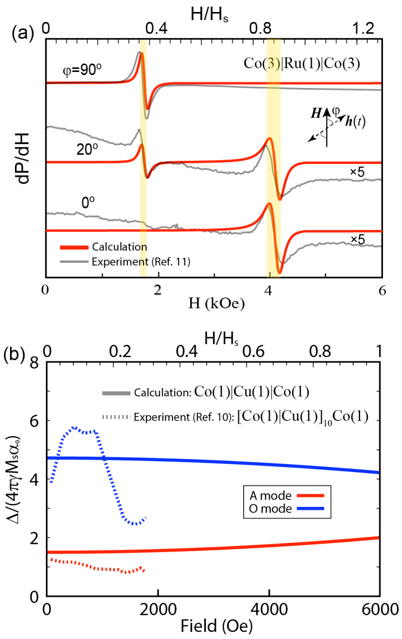

Fig.1: (a) Derivative of the microwave absorption spectrum [5] (b) Computed linewidths of the acoustic (A) and optical (O) modes [2].

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Anisotropic magnetoresistance of antiferromagnetic MnTe

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Recent studies have demonstrated the potential of metallic antiferromagnets as the active component in spintronic devices. In addition to their static role as pinning layers in hard disk read heads and magnetic memories they were shown to exhibit memory behavior when cooled in different field directions [1] and are even electrically switchable [2] due to current induced torques [3]. In order to move the research on antiferromagnetic spintronics one step further, new antiferromagnetic materials need to be explored with respect to their electronic and magnetotransport properties. Especially appealing are antiferromagnetic semiconductors which allow the combination of spintronic and semiconductor-microelectronic functionalities in one and the same material.

In this work we present magnetotransport investigations of hexagonal MnTe epitaxial thin films. MnTe is an antiferromagnet with the Neel temperature of 310 K and exhibits semiconducting properties with an optical gap of ~1.3 eV [4] and the possibility of tuning the carrier concentration by doping [5]. We use MnTe thin films grown epitaxially on InP (111)A substrates by molecular beam epitaxy from which we produce Hall bar structures by e-beam lithography and wet etching. We observe the development of two distinct resistance states when we cool our structures from above the transition temperature in an applied magnetic field. Once these states are set, they cannot be switched at low temperature by magnetic fields up to our largest experimentally available field of 2 T. During heating the states remain distinct until the transition temperature. By performing field cooling with magnetic field in different directions we study the symmetry of this effect. We find a sine-square behavior as regularly observed in ferromagnets and expected for an effect quadratic in the magnetic field. The amplitude of the effect is >1% at low temperature, but remains detectable up to the transition temperature close to 300K.

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Two-Fluid Theory for Spin Superfluidity in Magnetic Insulators

(B. Flebus, S. A. Bender, Y. Tserkovnyak and R. A. Duine)

We investigate coupled spin and heat transport in easy-plane magnetic insulators. These materials display a continuous phase transition between normal and condensate states that is controlled by an external magnetic field.

Using hydrodynamic equations supplemented by Gross-Pitaevski phenomenology and magnetoelectric circuit theory, we derive a two-fluid model to describe the dynamics of thermal and condensed magnons, and the appropriate boundary conditions in a hybrid normal-metal|magnetic-insulator|normal-metal heterostructure.

We discuss how the emergent spin superfluidity can be experimentally probed via a spin Seebeck effect measurement.

Phenomenology of antiferromagnetic dynamics

Hristo Velkov and Jairo Sinova

Abstract

Ferromagnets are the established components of current electronic and spintronic devices. Recently, however, a lot of effort has been put into investigating an alternative platform for spintronics - antiferromagnetic materials. Much faster magnetization dynamics and abundance in nature are a few characteristics that makes them stand out compared to the ferromagnets.

In this work we study collinear antiferromagnets which consist of two magnetic sublattices and develop the phenomenological theory in the presence of an external magnetic field and the Dzyaloshinskii-Moriya interaction. We derive the LLG equations for the Nèel order parameter and apply the theory to investigate the magnetization dynamics of rigid magnetic textures.

Spin-Orbit effects in Exotic 2-D Anti-Ferromagnetic Materials with Non-Collinear Spin

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We calculate first spin-orbit effects in exotic two-dimensional materials governed by berry-phase physics using first principle calculations. We see anti-ferromagnetic state in half passivated graphene and stanene with Fluorine and Chlorine respectively. These systems show sizable DMI that is less than the exchange interaction and would cause long wavelength spin-spirals to be the ground state. We show the type of magnetism and the strength of the spin-orbit effects is controlled by the passivated ion. Additionally, these systems display Heisenberg exchange and in some case superexchange where we show how spin-orbit physics plays a role in simple band structures. Furthermore graphene like systems have attracted much attention for magnetic devices. Furthermore we perform ”coarse grain” calculations to understand the dynamics of these systems in the presence of external fields.

Spin caloric transport in compensated ferrimagnets

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In recent years, it has been shown that the application of temperature gradients allows for the generation of spin currents in various ferromagnetic materials. Referring to its thermo electrical equivalent, this phenomenon is called spin Seebeck effect (SSE) [1]. In case of insulators, spin currents are carried by spin waves (magnons) with finite propagation length moving from the hot to the cold end of the solid [2]. In adjacent heavy metal layers these spin currents are converted into detectable charge currents due to the inverse spin Hall effect (ISHE) [3].
The occurrence of the SSE has been investigated in Gadolinium Iron Garnet (GIG)/Platinum (Pt) hybrids [4]. GIG is a ferrimagnetic insulator which comprises antiferromagnetically coupled Fe and Gd/Fe sublattices with different temperature dependences, exhibiting a magnetic compensation point T_{comp}. By probing the spin Seebeck voltage as a function of temperature two sign changes of the signal appear (Fig. 1). This observation and the fact that the signal does not follow the trend of the sample's net magnetization point towards a complex interplay of the involved sublattice. In addition to that, as the observation of the SSE in antiferromagnetic insulators has recently been shown by [5, 6] preliminary results on similar systems will be presented.

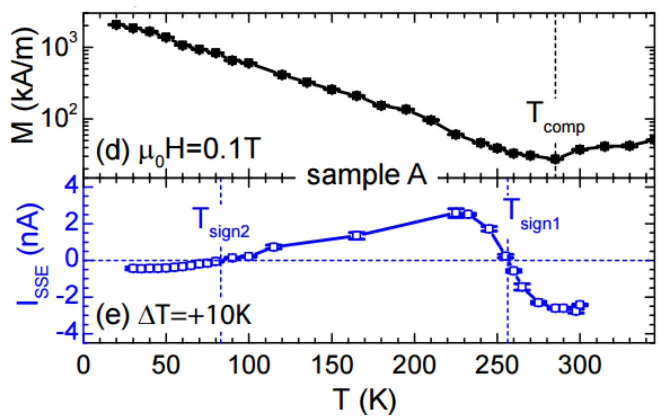

Fig. 1 Temperature dependence of net magnetization M and the spin Seebeck signal I_{SSE}. M shows a minimum near the compensation point T_{comp} while I_{SSE} reveals two sign changes. Taken and modified from [4].

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Enhanced spin pumping by antiferromagnetic IrMn thin films around the magnetic phase transition

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We report experimental measurements of a spin pumping effect owing to fluctuating IrMn thin films [1]. Spin injection by a precessing NiFe ferromagnet into IrMn spin sinks is used. Enhanced damping is observed around the IrMn magnetic phase transition [2], [3]. Our data are corroborated by a recent theory [4] and converted into interfacial spin mixing conductance enhancements. This latter quantity depends on the imaginary part of the transverse spin susceptibility of the spin sink which is known to vary around critical temperatures. By spotting the spin pumping peak we also determined the thickness dependence of the IrMn critical temperature and deduced the characteristic length for the spin-spin interactions [5], which has been inaccessible to experiments. By highlighting the feasibility of detecting magnetic phase transitions by spin pumping this work opens a new pathway for the deeper investigation of non-trivial magnetic orders such as antiferromagnetism, with no net magnetic moment and potentially large magneto-transport effects [6].

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Change of Critical Exponent Near Transition Temperature from Bulk to Surface Behaviour in Thin-Film Antiferromagnetic Cr_2O_3

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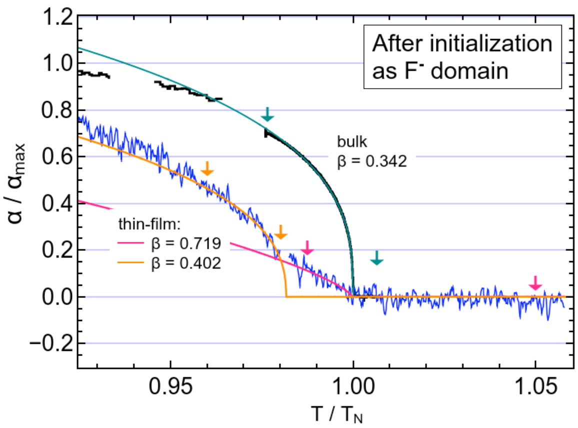
Antiferromagnets (AFM) have zero magnetization. This means they are stable against applied magnetic field, which is advantageous for data retention, but problematic for reading and writing. One way is to utilize the exchange coupling with a ferromagnetic layer as a readout, and control AFM domain by another external stimulus, *e.g.* electric field. This succeeded in the typical antiferrmagnetic magnetoelectric material chromia (Cr_2O_3) [1].



Chromia is an AFM with spins aligned parallel to *c*-axis, with spins at the same *c*-plane pointing along the same direction. It was reported that Cr_2O_3 changes behaviour from 3D bulk-like to 2D surface-like near Neel temperature (T_N) inferred from measurements on exchange-bias of a Co layer [2]. Such assertion is difficult only from exchange-bias measurement. So we measured the magnetoelectric susceptibility (α) versus temperature near T_N of a bulk Cr_2O_3 crystal and a 500-nm thin-film single-layer sample (see figure). We extracted the criticality exponent (β) from fitting to a power law (solid lines with fitting range indicated by arrows). For bulk crystal, bulk behaviour was obtained. For a thin-film, β changes from a value (0.402) close to bulk value at lower temperature, to a value closer to 2D (0.719) near T_N. A possible explanation is the distribution of T_N in the film plane, that would give a similar change of β when some domains become paramagnetic near the average T_N. The same effect can be argued against the observation made on Co/Cr_2O_3 exchange coupling system, with distribution in exchange interaction at the interface. We will present more discussion and details on which is the origin. This work was partly funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Japan Government).

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Current induced effects in structures with ultra-thin IrMn antiferromagnet

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Relativistic current induced torques and devices utilizing antiferromagnets have been independently considered as two promising new directions in spintronics research. Here we report electrical measurements of the torques in structures comprising a ~ 1 nm thick layer of an antiferromagnet IrMn. The reduced Néel temperature and the thickness comparable to the spin-diffusion length allow us to investigate the role of the antiferromagnetic order in the ultra-thin IrMn films in the observed torques. In a Ta/IrMn/CoFeB structure, IrMn in the high-temperature phase diminishes the torque in the CoFeB ferromagnet. At low temperatures, the antidamping torque in CoFeB flips sign as compared to the reference Ta/CoFeB structure (shown in Fig. 1 (a) and (b)), suggesting that IrMn in the antiferromagnetic phase governs the net torque acting on the ferromagnet. At low temperatures, current induced torque signatures are observed also in a Ta/IrMn structure comprising no ferromagnetic layer (shown in Fig. 1 (c)).

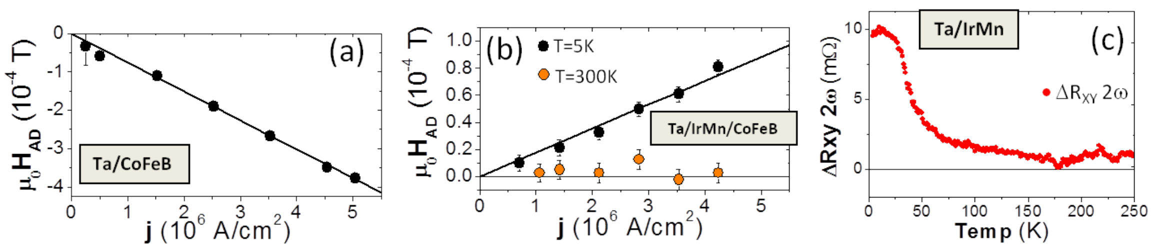

FIG. 1. (a) Current density j-dependence of the out-of-plane field H_{AD} (black dots) in the reference Ta/CoFeB sample. (b) Same as for the Ta/IrMn/CoFeB sample at 5 K (black dots) and 300 K (orange dots). (c) Temperature-dependent difference in the $R_{xy}^{2\omega}$ signal measured while cooling the sample in applied in-plane and and out-of-plane magnetic fields of 2 T.

Thermally-Activated Phase Slips in Superfluid Spin Transport in Magnetic Wires

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We theoretically study thermally-activated phase slips in superfluid spin transport in easy-plane magnetic wires within the stochastic Landau-Lifshitz-Gilbert phenomenology, which runs parallel to the Langer-Ambegaokar-McCumber-Halperin theory for thermal resistances in superconducting wires. To that end, we start by obtaining the exact solutions for free-energy minima and saddle points. We provide an analytical expression for the phase-slip rate in the zero spin-current limit, which involves detailed analysis of spin fluctuations at extrema of the free energy. An experimental setup for a magnetoeletric circuit is proposed, in which thermal phase slips can be inferred by measuring nonlocal magnetoresistance.

[1] S. K. Kim, S. Takei, and Y. Tserkovnyak, arXiv:1509.00904

Phenomenology of dynamics in noncollinear antiferromagnets $IrMn_3$

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The magnetic structure of the thin films of IrMn has been probed experimentally quite recently.[1] These materials are particularly interesting due to the high Néel temperature (up to 1000 K), strong

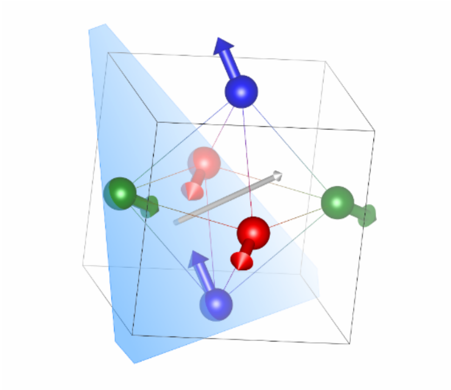

*Figure **Error! No sequence specified.** Three magnetic sublattices of $IrMn_3$ in ground state lie within the (111) plane.*

exchange bias and pronounced spin-orbit coupling effects,[2] therefore they are used for instance as a pinning layers in spin valves. Recently the relativistic current induces torques have been measured in the ultrathin layers of IrMn in the Ta/IrMn/CoFeB structure.[3]

The main part of the poster is focused on the phenomenology of noncollinear antiferromagnetic (AFM) order dynamics. We show that noncollinear AFM order (see Fig. 1) can be triggered via antidamping like torque $T m\times m\times p$,where m is sublattice magnetization and p is nonequilibrium spin polarization. We proposed a mechanism of the ultrafast large angle reorientation between two metastable states distinguishable by anisotropic magnetoresistance.[4] It is theoretically demonstrated that the dynamics might be restricted to the quazi-one-dimensional case. The estimation of the critical current densities, magnetic anisotropy energy landscape and other material parameters necessary for the succesful observation of the proposed effect are calculated from the fully relativistic first principles.

Presented findings together with predictions of large galvanomagnetic effects[4,5] makes noncollinear AFM particularly appealing to experimental studies of current induced dynamics.

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Electrical manipulation of a ferromagnet by an antiferromagnet

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Abstract

Several recent studies of antiferromagnetic (AFM) spintronics have focused on transmission and detection of spin-currents in AFMs. Efficient spin transmission through antiferromagnets was inferred from experiments in ferromagnet/antiferromagnet/normal metal (FM/AFM/NM) structures [1-3]. Measurements in FM/AFM bilayers have demonstrated that a metallic AFM can also act as an efficient ISHE detector of the spin-current injected from the FM, with comparable spin-Hall angles to heavy NMs [4,5]. Here we demonstrate that an antiferromagnet can be employed for a highly efficient electrical manipulation of a ferromagnet [6]. We use an all-electrical excitation and detection technique of ferromagnetic resonance in a NiFe/IrMn bilayer. At room temperature, we observe antidamping-like spin torque acting on the NiFe ferromagnet, generated by the in-plane current driven through the IrMn antiferromagnet. A large enhancement of the torque, characterized by an effective spin-Hall angle exceeding most heavy transition metals, correlates with the presence of the exchange-bias field at the NiFe/IrMn interface. It highlights that, in addition to strong spin-orbit coupling, the antiferromagnetic order in IrMn governs the observed phenomenon.

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Effect of field-like spin orbit torque on spin sublattices of ultra-thin polycrystalline FeMn films

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Spin orbit torque (SOT) in ferromagnet (FM)/heavy metal (HM) bilayers has been reported to be a promising alternative to spin transfer torque for switching magnetization directly by an in-plane current. A natural question to ask is whether similar SOT effect can affect the spin sublattices or magnetic order of antiferromagnet (AFM). To this end, we have fabricated a series of Pt/FeMn bilayers with different thicknesses and investigated how the spin sublattices of FeMn can be altered by a current using the planar Hall effect (PHE). A large SOT effective field of 2.05×10^{-5} - 2.44×10^{-5} Oe/(A/cm^2) is obtained for FeMn in the thickness range of 2 nm - 5 nm. The experimental observations can be reasonably accounted for by using a macrospin model under the assumption that the FeMn layer is composed of two spin sublattices with unequal magnetization. The uncompensated net magnetization, originating from both the thin FeMn layer and proximity induced moment in Pt, is much smaller than the magnetization of a typical FM; this leads to a much larger SOT effective field in FeMn. The uncompensated spins provide a convenient mechanism to probe the SOT effect in AFM using PHE. To further confirm the interaction of spin current with FeMn, we fabricated Pt/FeMn/NiFe trilayers and investigate how far the spin current generated in Pt can travel across the FeMn layer. It was found that the spin current can only travel through the FeMn layer with a thickness smaller than 4 nm. By quantifying the field-like effective field induced in NiFe in the trilayers, a spin diffusion length of 2 nm is obtained for FeMn. This value is in good agreement with those reported in literature obtained by other techniques. Although it remains a challenge to achieve a well-defined AFM order for ultrathin FeMn films, our results do demonstrate that SOT can potentially be a useful technique for manipulating the spin states of AFM.

Antiferromagnetism: creative applications for the invisible magnets

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In 1970, at the time when compact cassettes made it to the market after a century of experimenting with ferromagnetic storage, the Nobel Prize was awarded for the "*fundamental work and discoveries concerning antiferromagnetism*". Louis Neel pointed out in his Nobel lecture that while abundant and interesting from a theoretical viewpoint, antiferromagnets did not seem to have any applications. Indeed, the alternating directions of magnetic moments on individual atoms and the resulting zero net magnetization make antiferromagnets hard to control by tools common in ferromagnets. While preoccupied with the inherent difficulties to read and write magnetic information in antiferromagnets, scientists and engineers have largely overlooked the positive sides of antiferromagnets as being magnetically invisible [1] and uniquely robust against magnetic perturbations [2, 3]. In this talk, we will review recent developments in the emerging field of antiferromagnetic spintronics [4], retracing the footsteps of the ferromagnetic based technologies. We will examine the path starting from seminal basic science down to a survey of the potential markets for the coming up *invisible magnetism*.

[1] https://www.youtube.com/watch?v=X1Ft_OnRaq4

[2] https://www.youtube.com/watch?v=HWZLJ02sb0U

[3] *Room-temperature antiferromagnetic memory resistor*. X. Marti et al., Nature Materials 13, 367–374 (2014)

[4] *Prospect for Antiferromagnetic Spintronics*. X. Marti et al., IEEE Transactions on Magnetics 51(4), 2900104 (2015)