H2020 FET-Open Research and Innovation Actions Project Number 766566
Antiferromagnetic spintronics (ASPIN)

Work package 1, Deliverable D1.1: Report on modeling of antiferromagnetic spin torque, magnetoresistance, domain structure, and dynamics

This report summarizes the work of the ASPIN project consortium aiming at predicting new and explaining existing experimental observations on writing, reading, processing, and storing information in antiferromagnetic spintronic devices. It spans a broad range of works from those directly relevant to our proof-of-concept digital and analogue antiferromagnetic memory cells to fundamental studies of spin-dependent transport, domain structure and dynamics in antiferromagnets. Apart from the reference to several of our comprehensive reviews, covering our as well as world-wide research in the field, the report outlines our original results in selected specific topics. We give references to the corresponding publications featuring details of these results and for each topic we also explicitly list the contributing teams from the consortium comprising: Institute of Physics in Prague (IOP), University of Nottingham (NOT), Max-Planck Institutes (MPG), IGS Ltd. (IGS), Charles University in Prague (CHU), Johannes Gutenberg University in Mainz (JGU).

Contents

1 Reviews

1.1 The multiple directions of antiferromagnetic spintronics

Contributing teams: IOP, JGU, IGS, MPG

New developments in spintronics based on antiferromagnetic materials show promise for improved fundamental understanding and applications in technology. We have reviewed [?] these latest developments, which range from demonstrations of experimental microelectronic memory devices and optical control of antiferromagnetic spins to the interplay of antiferromagnetic spintronics with topological phenomena, noncollinear antiferromagnets, antiferromagnet/ ferromagnet interfaces and synthetic antiferromagnets. We illustrate that the envisaged applications of antiferromagnetic spintronics may expand to areas as diverse as terahertz information technologies or artificial neural networks.

1.2 Spin transport and spin torque in antiferromagnetic devices

Contributing teams: MPG, IOP, NOT

Ferromagnets are key materials for sensing and memory applications. In contrast, antiferromagnets, which represent the more common form of magnetically ordered materials, have found less practical application beyond their use for establishing reference magnetic orientations via exchange bias. This might change in the future due to the recent progress in materials research and discoveries of antiferromagnetic spintronic phenomena suitable for device applications. Experimental demonstration of new concepts of electrical switching and detection of the Néel order (see Fig. 1) open a route towards memory devices based on antiferromagnets. Apart from the radiation and magnetic-field hardness, memory cells fabricated from antiferromagnets can be inherently multilevel, which could be used for neuromorphic computing. Switching speeds attainable in antiferromagnets far exceed those of ferromagnetic and semiconductor memory technologies. We have reviewed [1] recent progress in electronic spin-transport and spin-torque phenomena in antiferromagnets that are dominantly of the relativistic quantum-mechanical origin. We discuss their utility in pure antiferromagnetic or hybrid ferromagnetic/antiferromagnetic memory devices.

1.3 Antiferromagnetic spin textures and dynamics

Contributing team: JGU

Antiferromagnets provide greater stability than their ferromagnetic counterparts, but antiferromagnetic spin textures and nanostructures also exhibit more complex, and often faster, dynamics, offering new functionalities for spintronics devices. We have reviewed [2]these key distinctions in dynamics and magnetic textures between ferromagnets and antiferromagnets.

Synthetic antiferromagnetic spintronics

Contributing team: MPG

Spintronic and nanomagnetic devices often derive their functionality from layers of different materials and the interfaces between them. We have reviewed [3] the opportunities that arise from synthetic antiferromagnets consisting of two or more ferromagnetic layers that are separated by metallic spacers or tunnel barriers and have antiparallel magnetizations.

1.4 Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems

Contributing teams: IOP, JGU

Spin-orbit coupling in inversion-asymmetric magnetic crystals and structures has emerged as a powerful tool to generate complex magnetic textures, interconvert charge and spin under applied current, and control magnetization dynamics. Current-induced spin-orbit torques mediate the transfer of angular momentum from the lattice to the spin system, leading to sustained magnetic oscillations

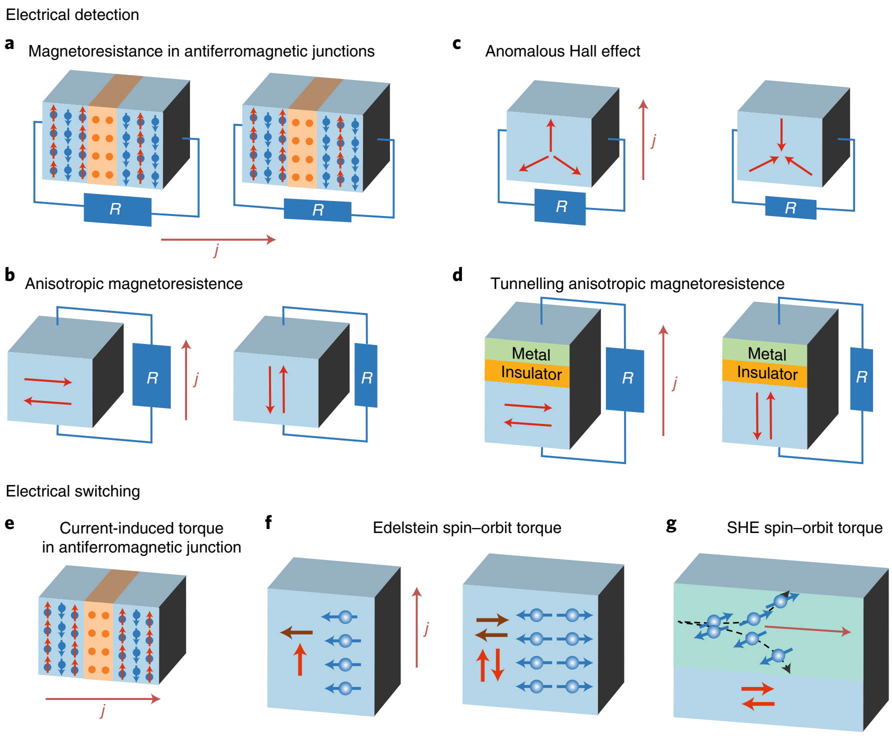

Figure 1: Illustration of the various concepts proposed for the electrical detection and manipulation of antiferromagnetic order [1].

or switching of ferromagnetic as well as antiferromagnetic structures. The manipulation of magnetic order, domain walls and skyrmions by spin-orbit torques provides evidence of the microscopic interactions between charge and spin in a variety of materials and opens novel strategies to design spintronic devices with potentially high impact in data storage, nonvolatile logic, and magnonic applications. We have reviewed [4] recent progress in the field of spin-orbitronics, focusing on theoretical models, material properties, and experimental results obtained on bulk noncentrosymmetric conductors and multilayer heterostructures, including metals, semiconductors, and topological insulator systems. Relevant aspects for improving the understanding and optimizing the efficiency of nonequilibrium spin-orbit phenomena in future nanoscale devices are also discussed.

2 Antiferromagnetic memory devices

2.1 Antiferromagnetic CuMnAs multi-level memory cell with microelectronic compatibility

Contributing teams: IOP, IGS, NOT

Following our models of electrical 90° switching and detection of antiferromagnetic moments, we have shown in this work [5] that elementary-shape memory cells fabricated from a single-layer antiferromagnet CuMnAs deposited on a III?V or Si substrate by molecular beam epitaxy have deterministic multi-level switching characteristics (see Fig. 2 and 3). They allow for counting and recording thousands of input pulses and for responding to pulses of lengths downscaled to hundreds picosecond. To demonstrate the compatibility with common microelectronic circuitry, we have implemented the antiferromagnetic bit cell in a standard printed circuit board managed and powered at ambient conditions by a computer via a USB interface. These results open a path towards specialized embedded memory-logic or neuromorphic-computing applications based on antiferromagnets.

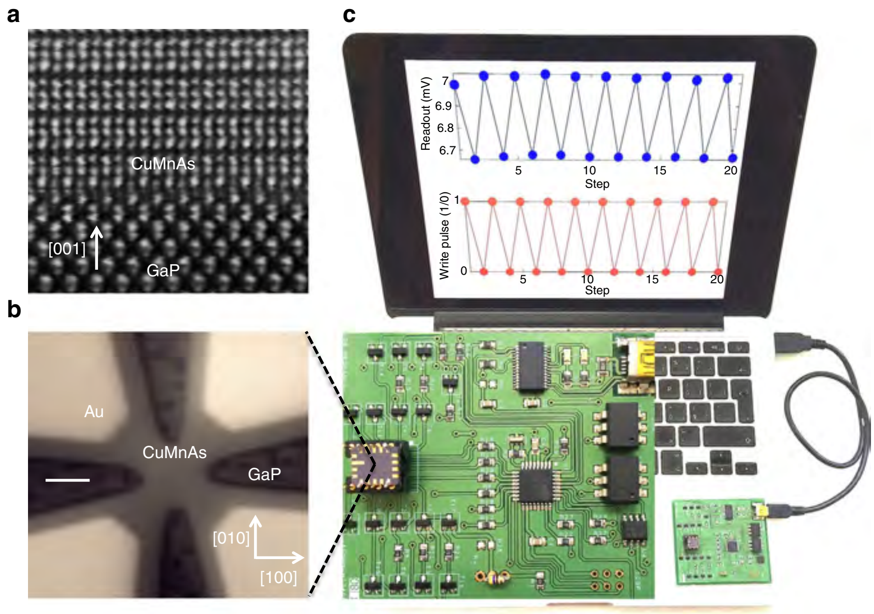

Figure 2: Antiferromagnetic microelectronic memory device operated from a PC via a USB port. [5].

2.2 Electric Control of Dirac Quasiparticles by Spin-Orbit Torque in an Antiferromagnet

Contributing teams: IOP, JGU, NOT

Spin-orbitronics and Dirac quasiparticles are two fields of condensed matter physics initiated independently about a decade ago. In this work [6] we have predicted that Dirac quasiparticles can be controlled by the spin-orbit torque reorientation of the Néel vector in an antiferromagnet. Using CuMnAs as an example, we show that the protection of Dirac band crossings can be switched on and off by the Néel vector reorientation. We predict that this concept, verified by our modeling and ab initio calculations, can lead to a large topological anisotropic magnetoresistance.

2.3 Writing and reading antiferromagnetic Mn_2Au by Néel spin-orbit torques and large anisotropic magnetoresistance

Contributing teams: JGU, IOP, NOT, CHU

Following our earlier theory predictions we have demonstrated in this work [7] in Mn_2Au reproducible 90° switching using current-induced spin-orbit torques and read-out by anisotropic magnetoresistance measurements. Mn_2Au has high ordering temperature particularly suitable for memory applications with high retention. Reversible and consistent switching signals in sputtered Mn_2Au films were generated by pulse current densities of $\sim 10^7$ A/cm^2. The symmetry of the observed torques agrees with our theoretical predictions and a large read-out anisotropic magnetoresistance of more than 6% and strong crystalline component is reproduced by our ab initio calculations and reflects the Dirac band crossing effects predicted in Ref. [6].

2.4 Electrically induced and detected Néel vector reversal in a collinear antiferromagnet

Contributing teams: IOP, NOT, CHU, MPG

Electrical detection of the 180 deg spin reversal, which is the basis of the operation of ferromagnetic memories, is among the outstanding challenges in the research of antiferromagnetic spintronics. In this work [8] we have demonstrated electrical detection of the 180 deg Néel vector reversal in CuMnAs which comprises two collinear spin sublattices with no net magnetic moment. We detect the spin reversal

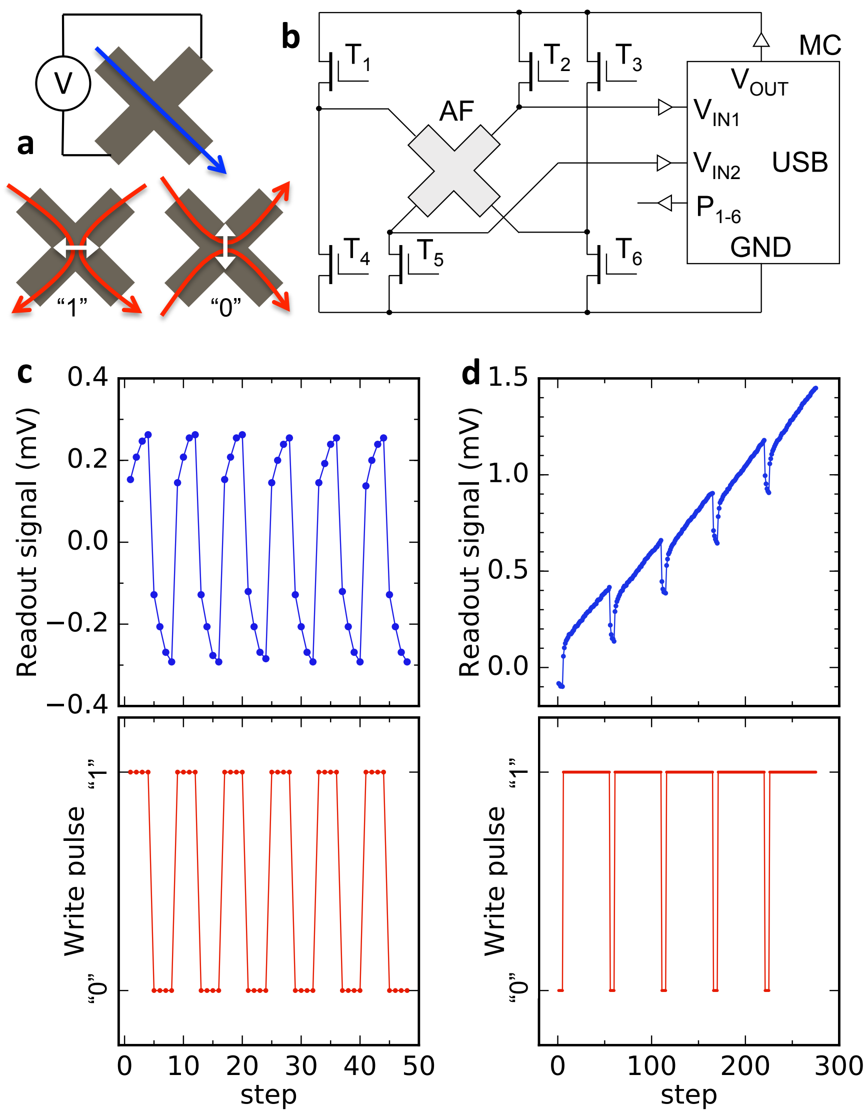

Figure 3: Antiferromagnetic multi-level memory bit-cell [5].

by measuring a second-order magnetotransport coefficient whose presence is allowed in systems with broken space inversion symmetry. Following our earlier models of spin-orbit torque and anisotropic magnetoresistance, we ascribe the observed phenomenology of the non-linear transport effect to a microscopic scenario combining anisotropic magneto-resistance with a transient tilt of the Néel vector due to a current-induced, staggered spin-orbit field (see Fig. 4). We used the same staggered spin-orbit field, but of a higher amplitude, for the electrical switching between reversed antiferromagnetic states which are stable and show no sign of decay over 25 hour probing times.

3 Spin transport in complex antiferromagnetic systems

3.1 Spin transfer torques and spin-dependent transport in antiferromagnetic tunneling junction

Contributing teams: JGU, IOP

In this work [9] we have studied spin-dependent electron transport through a ferromagnetic-antiferromagnetic-normal metal tunneling junction (see Fig. 5) subject to a voltage or temperature bias, in the absence of spin-orbit coupling. We derive microscopic formulas for various types of spin

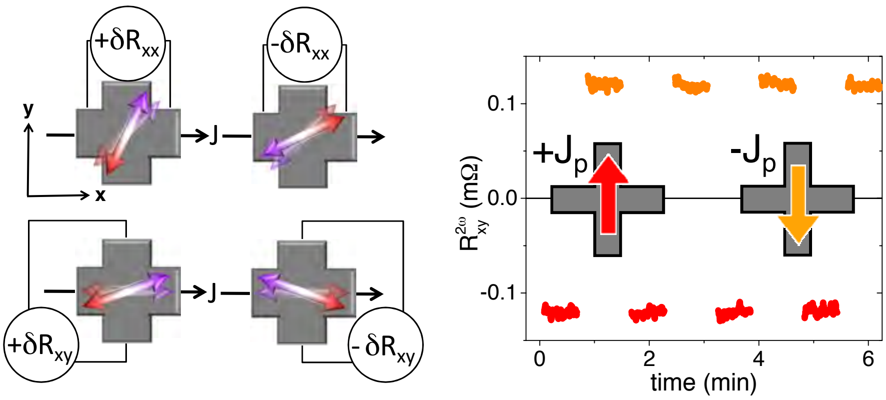

Figure 4: Schematics of the mechanism of the second-order magneto-resistance in antiferromagnetic CuMnAs and experimental electrical detection of the180 deg reversal of the Néel order in a CuMnAs memory device [8].

torque acting on the antiferromagnet as well as for charge and spin currents flowing through the junction. The obtained results are applicable in the limit of slow magnetization dynamics. We identify a parameter regime in which an unconventional damping-like torque can become comparable in magnitude to the equivalent of the conventional Slonczewski's torque generalized to antiferromagnets. Moreover, we show that the antiferromagnetic sublattice structure opens up a channel of electron transport which does not have a ferromagnetic analog and that this mechanism leads to a pronounced field-like torque. Both charge conductance and spin current transmission through the junction depend on the relative orientation of the ferromagnetic and the antiferromagnetic vectors (order parameters). The obtained formulas for charge and spin currents allow us to identify the microscopic mechanisms responsible for this angular dependence and to assess the efficiency of an antiferromagnetic metal acting as a spin current polarizer.

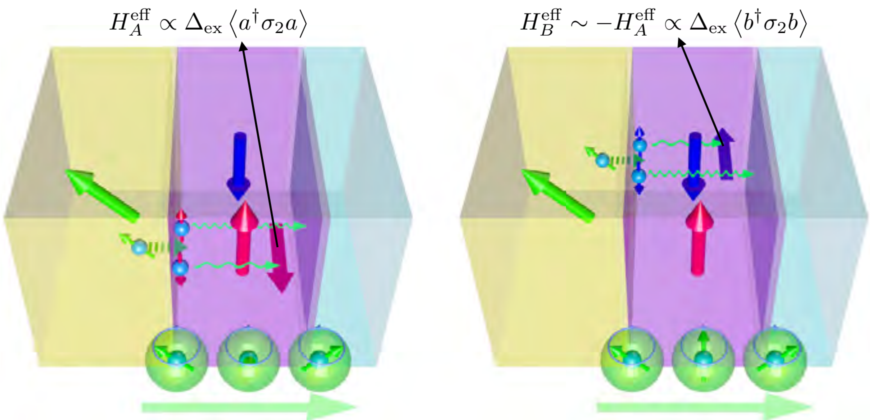

Figure 5: Illustration of dephasing processes through antiferromagnetic spin-sublattices; the dephasing leads to precession of the electron spin, whose chirality is opposite for the two sublattices. [9].

3.2 Spin-Polarized Current in Noncollinear Antiferromagnets

Contributing teams: MPG, IOP

Noncollinear antiferromagnets, such as Mn3Sn and Mn3Ir, were recently shown to be analogous to ferromagnets in that they have a large anomalous Hall effect. In this theoretical work [10] we have shown that these materials are similar to ferromagnets in another aspect: the charge current in these materials is spin-polarized. In addition, we show that the same mechanism that leads to the spin-polarized current also leads to a transversal spin current, which has a distinct symmetry and origin from the conventional spin Hall effect. We illustrate the existence of the spin-polarized current and the transversal spin current by performing ab initio microscopic calculations and by analyzing the symmetry. Based on the spin-polarized current we propose an antiferromagnetic tunneling junction, analogous in functionality to the magnetic tunneling junction (see Fig. 6).

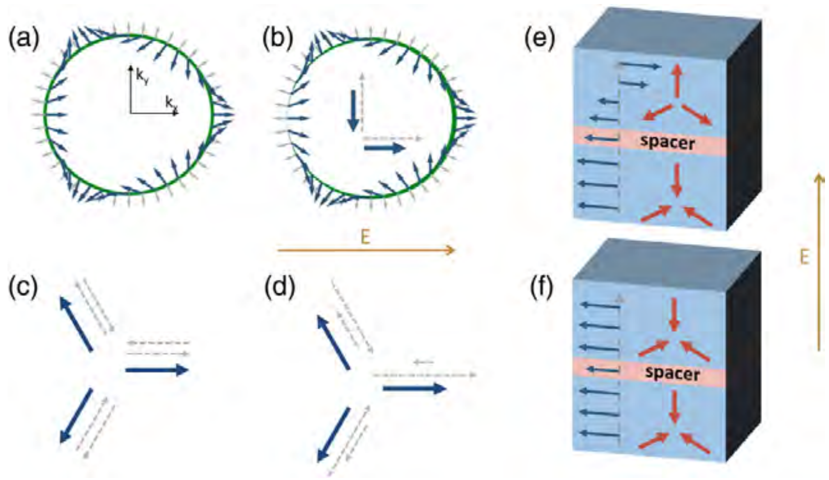

Figure 6: Models of Fermi level spin textures, spin-polarized current and tunnel junction in non-collinear antiferromagnets [10].

4 Spintronics in insulating antiferromagnets

4.1 Spin Hall magnetoresistance in antiferromagnet/heavy-metal heterostructures

Contributing team: JGU

In this work [11] we investigate the spin Hall magnetoresistance in thin film bilayer heterostructures of the heavy metal Pt and the antiferromagnetic insulator NiO. While rotating an external magnetic field in the easy plane of NiO, we record the longitudinal and the transverse resistivity of the Pt layer and observe an amplitude modulation consistent with the spin Hall magnetoresistance. In comparison to Pt on collinear ferrimagnets, the modulation is phase shifted by 90 deg and its amplitude strongly increases with the magnitude of the magnetic field. We explain the observed magnetic field-dependence of the spin Hall magnetoresistance in a comprehensive model taking into account magnetic field induced modifications of the domain structure in antiferromagnets. With this generic model we are further able to estimate the strength of the magnetoelastic coupling in antiferromagnets. Our detailed study shows that the spin Hall magnetoresistance is a versatile tool to investigate the magnetic spin structure as well as magnetoelastic effects, even in antiferromagnetic multidomain materials.

4.2 Full angular dependence of the spin Hall and ordinary magnetoresistance in epitaxial antiferromagnetic NiO(001)/Pt thin films

Contributing team: JGU

In this work [12] we report the observation of the full angular dependence of the spin Hall magnetoresistance (SMR) in a thin film of epitaxial antiferromagnetic NiO, without any ferromagnetic element. The angular dependence of the magnetoresistance was measured in magnetic fields up to 11 T, using three orthogonal angular scans. We find that the total magnetoresistance has contributions arising both from SMR and ordinary magnetoresistance. Due to the particular NiO(001) orientation, and due to the fact that NiO(111) planes are easy-planes for the antiferromagnetic moment rotation, SMR is observable in all orthogonal planes. The onset of the SMR signal occurs between 1 and 3 T and no saturation is visible up to 11 T. The sign of the SMR is consistent with recent theoretical predictions and our results can be explained more quantitatively by a model considering the field-induced redistribution of S-domains, competing with the destressing energy arising from the interaction of the magnetostrictive NiO layer with the nonmagnetic MgO substrate. From the observed SMR ratio, we estimate the spin mixing conductance at the NiO/Pt interface to be greater than $1 \times 10^{14}\ \Omega^{-1}\ m^{-2}$, comparable to early works on YIG/Pt systems. Our results highlight the presence of negative SMR in antiferromagnetic thin films, confirming the existence of efficient spin transport and suggesting the possibility of an electrical detection of the Néel vector in this class of materials, even for thin films relevant for applications. Moreover, we show that a careful subtraction of the ordinary magnetoresistance contribution is crucial to correctly estimate the size of the SMR.

4.3 Spin caloric effects in antiferromagnets assisted by an external spin current

Contributing teams: JGU, IOP

Searching for novel spin caloric effects in antiferromagnets we study in this work [13] the properties of thermally activated magnons in the presence of an external spin current and temperature gradient. We predict the spin Peltier effect – generation of a heat flux by spin accumulation – in an antiferromagnetic insulator with cubic or uniaxial magnetic symmetry. This effect is related with spin-current induced splitting of the relaxation times of the magnons with opposite spin direction. We show that the Peltier effect can trigger antiferromagnetic domain wall motion with a force whose value grows with the temperature of a sample. At a temperature, larger than the energy of the low-frequency magnons, this force is much larger than the force caused by direct spin transfer between the spin current and the domain wall. We also demonstrate that the external spin current can induce the magnon spin Seebeck effect. The corresponding Seebeck coefficient is controlled by the current density. These spin-current assisted caloric effects open new ways for the manipulation of the magnetic states in antiferromagnets.

4.4 Spin colossal magnetoresistance in an antiferromagnetic insulator

Contributing team: JGU

Colossal magnetoresistance (CMR) refers to a large change in electrical conductivity induced by a magnetic field in the vicinity of a metal-insulator transition and has inspired extensive studies for decades. In this work [14] we demonstrate an analogous spin effect (see Fig. 7) near the Néel temperature T_{N}=296 K of the antiferromagnetic insulator CrO. Using a yttrium iron garnet YIG/CrO/Pt trilayer, we injected a spin current from the YIG into the CrO layer, and collected via the inverse spin Hall effect the signal transmitted in the heavy metal Pt. We observed a change by two orders of magnitude in the transmitted spin current within 14 K of the Néel temperature. This transition between spin conducting and nonconducting states could be also modulated by a magnetic field in isothermal conditions. This effect, that we term spin colossal magnetoresistance (SCMR), has the potential to simplify the design of fundamental spintronics components, for instance enabling the realization of spin current switches or spin-current based memories.

5 Antiferromagnetic THz detector and emitter based on spin torques

Contributing teams: JGU, IOP

In this work [15] we have theoretically studied dynamics of antiferromagnets induced by simultaneous application of dc spin current and ac charge current, motivated by the requirement of all-electrically controlled devices in the terahertz (THz) gap (0.1-30 THz). We show that ac electric current, via Néel spin-orbit torques, can lock the phase of a steady rotating Néel vector whose precession is controlled by a dc spin current. In the phase-locking regime the frequency of the incoming ac signal coincides with the frequency of auto-oscillations, which for typical antiferromagnets falls into the THz range. The frequency of auto-oscillations is proportional to the precession-induced tilting of the magnetic

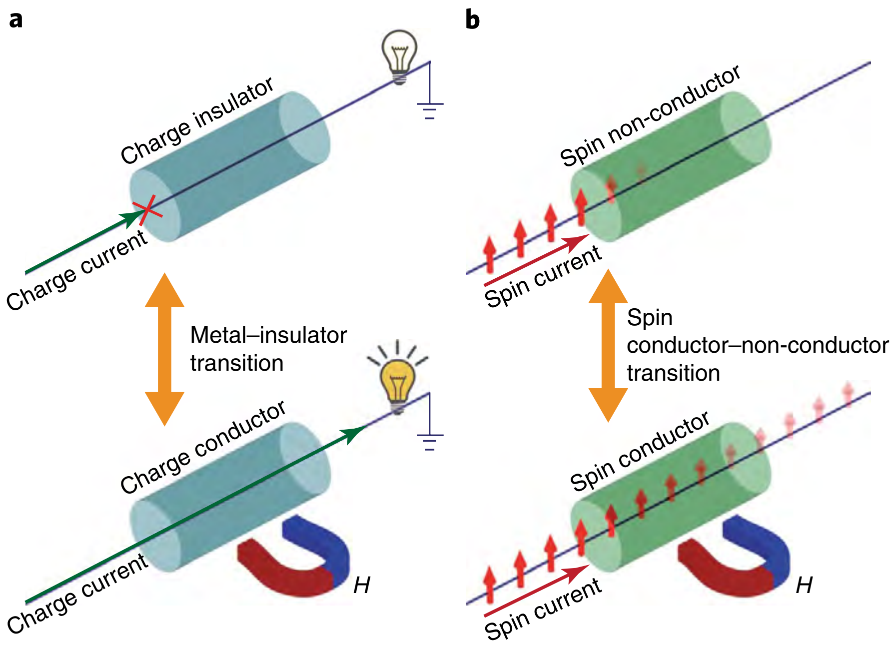

Figure 7: Concept of spin colossal magnetoresistance (b) compared with the charge colossal magnetoresistance (a) [14].

sublattices related to the so-called dynamical magnetization. We show how the incoming ac signal can be detected and formulate the conditions of phase locking. We also show that the rotating Néel vector can generate ac electrical current via inverse Néel spin-orbit torque. Hence, antiferromagnets driven by dc spin current can be used as tunable detectors (see Fig. 8) and emitters of narrow-band signals operating in the THz range.

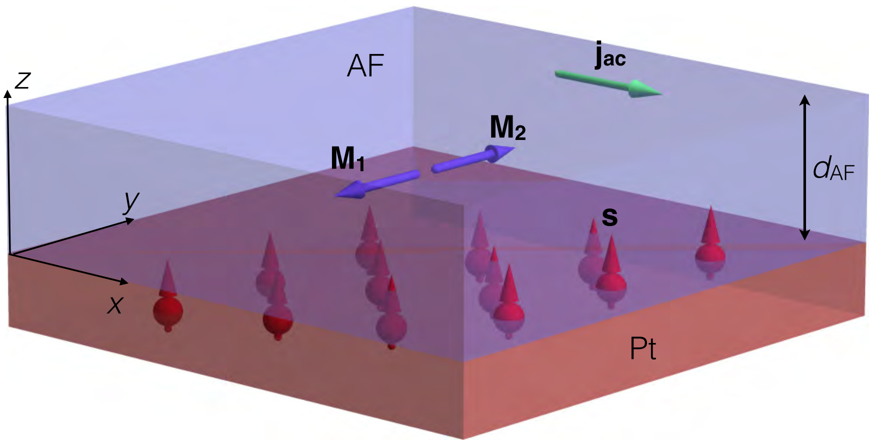

Figure 8: Schematics of a bilayer system of an antiferromagnet and a heavy metal for detection of THz signal [15] .

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