Spin based information processing

686. WE-Heraeus-Seminar

January 6 - 9, 2019
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 686. WE-Heraeus-Seminar:

Modern information technology relies on the computing power provided by information processors which are dominated by silicon technology. Since the 1970ies Moore's law guaranteed every second year a doubling of the number of transistors or fundamental processing units per unit area, resulting in an exponential growth of computing power. Presently, we are entering an age, where physical dimensions of the transistors approach the few nano-meter scale and therefore finite size effects like tunnelling or quantum effects will obstruct their key operation feature: being a programmable on / off switch.

The development and innovation of information technology therefore is expected to explore new directions beyond the pure drive for scaling. Questions in this respect are related to (i) energy consumption and (ii) enhanced, or highly efficient computing concepts. In particular, the fact that the information and communication technologies (without television) consumed 920 TWh or about 5% of the annual electricity produced in 2012 underlines the importance for innovation in this sector.

Complementary approaches are therefore intensely discussed. Spinelectronics or in a broader sense logic circuits based on magnetic systems can contribute to these global challenges. In particular, we plan to bring together the areas of information processing with magnetic textures, neuromorphic computing, logic based on magnetic order, ultrafast magnetization control as well as spin based quantum information processing, to discuss the opportunities and challenges of the individual subfields as well as potential overlap between these fields in this workshop.

Scientific Organizers:

Dr. Ulrike Ritzmann	Uppsala University, Sweden E-mail: Ulrike.ritzmann@physics.uu.se
PD Dr. Hans Hübl	Bayerische Akademie der Wissenschaften, Germany E-mail: Hans.huebl@wmi.badw.de
Prof. Dr. Evangelos Papaioannou	Technische Universität Kaiserslautern, Germany E-mail: Papaio@rhrk.uni-kl.de

Program

Program

Sunday, January 6, 2019

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and get-together*	

Monday, January 7, 2019

08:00	*BREAKFAST*	
09:00 – 09:15	Scientific organizers	**Opening**

Information processing with magnetic textures

09:15 – 10:00	Julie Grollier	**Neuromorphic computing with spintronic nano-oscillators**
10:00 – 10:45	Alice Mizrahi	**Unconventional computing with stochastic magnetic tunnel junctions**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 12:00	Karin Everschor-Sitte	**Reservoir computing with Skyrmion fabrics**
12:00 – 12:30	Christina Psaroudaki	**Quantum dynamics of Skyrmions in chiral magnetic insulators**
12:30 – 12:40	**Conference Photo** (in the front of the lecture hall)	
12:40	*LUNCH*	

Program

Monday, January 7, 2019

Information processing with magnetic textures/ Magnon based logic

14:15 – 15:00	Stephan Heinze	**Exploring magnetic skyrmions for spintronics from first-principles**
15:00 – 15:30	Silvia Viola Kusminskiy	**Cavity optomagnonics with magnetic textures: coupling a magnetic vortex to light**
15:30 – 16:15	Felix Casanova	**Spin-to-charge current conversion for logic devices**
16:15 – 16:45	Andrew Ross	**Efficient magnonic spin transport in insulating antiferromagnetic thin films**
16:45 – 17:15	*COFFEE BREAK*	
17:15 – 18:45	**Shotgun-Presentation**	
19:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	
20:00	**Poster-Session**	

Program

Tuesday, January 8, 2019

08:00	*BREAKFAST*	
09:00 – 09:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**

Magnon based logic

09:15 – 10 :00	Andrii Chumak	**Integrated magnonic half-adder**
10 :00 – 10 :45	Sebastian Gönnenwein	**Spin transport experiments**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 12:00	Bart van Wees	**Magnon transport and dynamics in magnetic insulators**
12:00 – 12:45	Matthias Althammer	**All-electrical control of spin conductance in magnetically ordered insulators**
12:45	*LUNCH*	

Program

Tuesday, January 8, 2019

Spin based information processing

14:15 – 15:00	Anton Akhmerov	**Fermionic quantum computation with Majorana states**
15:00 – 15:45	Wolfgang Wernsdorfer	**Operating quantum states in single magnetic molecules**
15:45 – 16:30	Juan Pablo Dehollain	**Analogue and digital simulations with spins in quantum dots**
16:30 – 17:00	Hans Werner Schumacher	**Gate controlled loading of singlet and triplet electron pairs in a single electron pump**
17:00 – 17:30	*COFFEE BREAK*	
17:30 – 19:00	**Poster-Session**	
19:00	*DINNER*	
20:00 – 20:45	Jian-Ping Wang	**Computing with magnetic tunnel junctions for AI**

Program

Wednesday, January 9, 2019

08:00	*BREAKFAST*	

Ultrafast magnetization control

09:00 – 09:45	Ulrich Nowak	**Spin dynamics beyond GHz: ferro- versus antiferromagnets**
09:45 – 10:30	Yuriy Mokrousov	**Electrical and optical manifestations of emergent monopoles in complex magnets**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Dmitry Turchinovich	**Ultrafast terahertz magnetometry**
11:45 – 12:15	Dennis Meyer	**Approaching THz spin-wave generation in optically-driven acoustic resonators**
12:15 – 12:30	Scientific organizers	**Closing words**
12:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Thursday morning

Posters

Posters

Unai Atxitia	**Thermally induced magnetisation dynamics; ferromagnets vs antiferromagnets**
Nassima Benchtaber	**Electronic bands structure of type II superlattice InAs/Gasb for medium infrared detection**
Victor Bittencourt	**Magnon heralding in cavity optomagnonics**
Joel Cramer	**Modulation of non-local spin signals by heat and Oersted fields**
Boris Divinskiy	**Bridging magnonics and spin-orbitronics**
Hans-Joachim Elmers	**Origin of spin polarization of photoemitted electrons from paramagnetic bulk states**
Luis Flacke	**Spin pumping and low Gilbert damping in $Co_{25}Fe_{75}$ heterostructures**
Felix Fuhrmann	**Controlling spin transmission in collinear ferroic magnetic multilayer systems**
Olena Gomonay	**Ultrafast switching in antiferromagnets induced by spin-orbit torques**
Markus Hoffmann	**Simultaneous stabilization of skyrmions and antiskyrmions in rank-1 DMI materials allowing the concept of a skyrmion-antiskyrmion racetrack memory**
Philipp Jäger	**Employing exactly solvable 1D quantum lattice models for information processing**
Timo Joas	**Sensing weak microwave signals by quantum control**
Alex Kolmus	**Atom-by-atom engineering of associative memories in finite size spin systems**

Posters

Viola Krizakova	**Spin wave observation in metastable thin films prepared by focused ion beam direct writing**
Georg Lefkidis	**ERASE, SHIFT, Boolean OR, XOR, and AND, as well as quantum √NOT gates on Ni_4 from first principles**
Lukas Liensberger	**Phase-sensitive and spatially resolved detection of magnetization dynamics**
Nina Meyer	**Laser induced DC photocurrents in 3D topological insulators structured to hallbar and nanowire devices**
Markus Münzenberg	**Ways towards optical spin manipulation in topological systems**
Maximilian Paleschke	**Development of time-resolved photoemission electron microscopy of magnetization dynamics triggered by back-side illumination**
Philipp Pirro	**Spin-wave logic: towards neuromorphic computing**
Klaus Raab	**Utilization of room temperature skyrmion diffusion in information processing by probabilistic computing**
Philipp Rüßmann	**Type-II Weyl semimetals – spin-polarization, impurity scattering, and a polar instability**
Jonas Schäfer	**Skyrmion meets magnetic tunnel junction: an efficient way for electrical skyrmion detection investigated by ab initio theory**
Helmut Schultheiss	**Domain wall based spin-Hall nano-oscillators**
Katrin Schultheiss	**How to generate whispering gallery magnons**
Henning Ulrichs	**A micromagnetic model for ultrafast spin current-driven magnon dynamics**

Posters

Patrick Vorndamme	**Investigation of relaxation and decoherence in closed quantum spin systems**
Jakob Walowski	**All-optical magnetization switching of FePt magnetic recording media**
Werner van Weerdenburg	**An orbitally-derived single atom memory**
Mathias Weiler	**Spin torque excitation of spin waves at the yttrium iron garnet / cobalt interface**
Tobias Wimmer	**All-electrical control of spin transport in a three-terminal yttrium iron garnet/platinum nanostructure**
Tim Wolz	**Dynamic control of magnon cavity coupling**
Wentao Zhang	**Reconstruction of ultrafast magnetization dynamics in optically excited Fe films from emitted THz signals**

Abstracts of Talks

(in chronological order)

Neuromorphic computing with spintronic nano-oscillators

Julie Grollier

[1]Unité Mixte de Physique CNRS/Thales, Palaiseau France

The purpose of neuromorphic computing is to take inspiration from the brain to build hardware neural networks that can learn to perform useful tasks with low energy consumption [1]. In this talk, I will show that spintronic nano-oscillators based on magnetic tunnel junctions can act as artificial neurons [2]. I will present our first results of pattern recognition with small networks of coupled oscillators [3]. I will then show that these microwave nano-neurons open the path to wireless deep learning.

References

[1] J. Grollier, D. Querlioz, et M. D. Stiles, « Spintronic Nanodevices for Bioinspired Computing », Proc. IEEE, vol. 104, no 10, p. 2024-2039, oct. 2016.

[2] J. Torrejon et al., « Neuromorphic computing with nanoscale spintronic oscillators », Nature, vol. 547, p. 428-431, juill. 2017.

[3] M. Romera et al., « Vowel recognition with four coupled spin-torque nano-oscillators », Nature, vol. 563, p. 230-234, oct. 2018.

Unconventional computing with stochastic magnetic tunnel junctions

A. Mizrahi[1,2,3], **T. Hirtzlin**[4], **M. Daniels**[2,3], **N. Locatelli**[4], **A. Fukushima**[5], **H. Kubota**[5], **S. Yuasa**[5], **M.D. Stiles**[3], **J. Grollier**[1], **D. Querlioz**[4]

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[4]Centre de Nanosciences et de Nanotechnologies, Univ. Paris-Sud, CNRS, Université Paris-Saclay, 91405, Orsay, France
[5]Spintronics Research Center, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, 305-8568, Japan

Magnetic tunnel junctions are bi-stable nanodevices which magnetic state can be both read and written electrically. Their high endurance, reliability and CMOS-compatibility have made them flagship devices for novel forms of computing. While they are mostly used as non-volatile binary memories, they can be made unstable and thus behave as stochastic oscillators. Here, we show how stochastic magnetic tunnel junctions are promising elements for low energy implementations of unconventional computing. In this goal, we present several uses of these devices.

First, an analogy can be drawn between stochastic magnetic tunnel junctions and stochastic spiking neurons. We apply neuroscience computing paradigm to these devices and demonstrate that they can be the building blocks of low energy artificial neural networks capable of on-chip learning.

Then, we demonstrate that these stochastic oscillators are capable of harnessing noise to synchronize on a source at much lower energy consumption than deterministic oscillators. This opens the way to low energy implementations of synchronization based computing.

Finally, we show that these devices are low energy true random number generators, which can be used for various applications such as cryptography and stochastic computing.

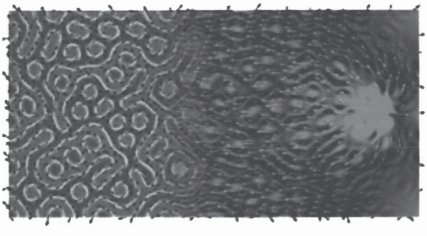
Reservoir Computing with Skyrmion Fabrics

D. Pinna[1], G. Bourianoff[2] and K. Everschor-Sitte[1]

[1]Johannes Gutenberg University, Mainz, Germany
[2] Intel Corporation (Retired), USA

Many real-world phenomena depend not only on the environment but also on their history like weather or the evolution of complex dynamical systems. Such spatially-temporally correlated effects can be studied within recurrent neural networks which typically require i) high computational training costs and ii) provide slow convergence. A different approach to solve temporally correlated problems is reservoir computing[1,2]. A reservoir computing system consists of three building blocks, the reservoir, an input and an output layer. The main idea is that the reservoir is left untrained, and only the output is trained via simple linear regression techniques. The task of the reservoir is to project different spatial-temporal events into a sparsely populated high dimensional space where they become easier to recognize and categorize. Besides bypassing the training constraints by making the reservoir random and static, the main advantage of RC is the opportunity to search for different features simultaneously via multiple output arrays.

In this talk we present how a random skyrmion "fabric" composed of skyrmion clusters embedded in a magnetic substrate can be effectively employed to implement a functional reservoir.[3,4] Complex time-varying current signals injected via contacts into the magnetic substrate are shown to be modulated nonlinearly by the fabric's anisotropic magneto resistance effect. By tracking resistances across contacts, we show how the instantaneous current distribution effectively carries temporally correlated information about the injected signal. This in turn allows us to numerically demonstrate simple pattern recognition.



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[4] G. Bourianoff et al, AIP Advances **8**, 055602 (2018)

Quantum dynamics of Skyrmions in chiral magnetic insulators

Christina Psaroudaki[1] and Daniel Loss[1]

[1] *Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

We study the quantum propagation of a skyrmion in chiral magnetic insulators by generalizing the micromagnetic equations of motion. The fluctuations around the skyrmionic configuration give rise to a damping derived microscopically, which in some limit reduces to a skyrmion mass [1]. We demonstrate that a skyrmion in a confined geometry behaves as a massive particle, a discovery with great impact on the technologically important case of linear tracks relevant for magnetic memory devices. An additional quantum mass term is predicted with an explicit temperature dependence which remains finite even at zero temperature. In the presence of time-dependent oscillating magnetic field gradients, the unavoidable coupling of the external field to the magnons gives rise to time-dependent dissipation for the skyrmion, with measurable consequences on the skyrmion's path [2]. These ac fields act as a net driving force on the skyrmion via its own intrinsic magnetic excitations."

[1] C. Psaroudaki, S. Hoffman, J. Klinovaja, and D. Loss, *Quantum Dynamics of Skyrmions in Chiral Magnets*, Phys. Rev. X **7**, 041045 (2017).
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Exploring magnetic skyrmions for spintronics from first-principles

S. Heinze

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Magnetic skyrmions – stable localized magnetic whirls – hold high promises for future spintronic devices due to their unique topological and dynamical properties [1,2]. The discovery of skyrmions at transition-metal interfaces [3,4] opened a new class of materials. Such systems allow engineering skyrmion properties by film composition and structure. Room temperature skyrmions in transition-metal multilayers have already been demonstrated, however, their diameter is still above 30 nm. To become technologically competitive a diameter below 10 nm is envisioned [5].

Here I will show how a combination of first-principles calculations based on density functional theory (DFT) and atomistic spin dynamics simulations can help to guide experimental efforts towards realizing sub-10 nm skyrmions at room temperature. From DFT an atomistic spin model is parametrized including the exchange interaction, the Dzyaloshinskii-Moriya interaction and the magnetocrystalline anisotropy [6]. Skyrmion properties are studied using spin dynamics simulations. The energy barriers for skyrmion collapse are calculated using the geodesic nudged elastic band method [7]. To obtain skyrmion lifetimes the attempt frequency within the Arrhenius law is calculated using harmonic transition-state theory [8]. Surprisingly, the pre-factor can drastically influence skyrmion lifetimes. Based on our approach the properties of skyrmions in experimentally well studied ultrathin film systems can be explained and the occurrence of sub-10 nm skyrmions at novel interfaces is predicted [9-11].

References

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Cavity optomagnonics with magnetic textures: coupling a magnetic vortex to light

Jasmin Graf,[1] Hannes Pfeifer,[1] Florian Marquardt,[1,2] and Silvia Viola Kusminskiy[1]

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[2]Institute for Theoretical Physics, University Erlangen-Nürnberg, Staudtstraße 2, 91058 Erlangen, Germany

Optomagnonic systems, where light couples coherently to collective excitations in magnetically ordered solids, are currently of high interest due to their potential for quantum information processing platforms at the nanoscale. Efforts so far, both at the experimental and theoretical level, have focused on systems with a homogeneous magnetic background. A unique feature in optomagnonics is however the possibility of coupling light to spin excitations on top of magnetic textures. We propose a cavity-optomagnonic system with a non homogeneous magnetic ground state, namely a vortex in a magnetic microdisk. In particular we study the coupling between optical whispering gallery modes to magnon modes localized at the vortex. We show that the optomagnonic coupling has a rich spatial structure and that it can be tuned by an externally applied magnetic field. Our results predict cooperativities at maximum photon density of the order of $C \approx 10^{-2}$ by proper engineering of these structures.

Reference: arXiv:1807.10626

Spin-to-charge current conversion for logic devices

F. Casanova[1,2]
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The integration of the spin degree of freedom in charge-based electronic devices has already revolutionized both sensing and memory capability in microelectronics. A second generation of devices is now envisioned in which pure spin currents (a diffusive flow of spins with no net charge flow) could be used instead, with several proposals that advance towards the integration of spin logics and memory and could represent a post-CMOS paradigm [1].

A key player in this quest is the spin Hall effect (SHE), a phenomenon that occurs in non-magnetic materials with strong spin-orbit coupling and allows to electrically create or detect pure spin currents without using ferromagnets (FM). Understanding the different mechanisms giving rise to the SHE allows to find and optimize promising materials for an efficient spin-to-charge current conversion. We have unveiled these mechanisms in prototypical materials such as Pt [2], Ta [3], and Au.

Finally, I will present a novel and simple FM/Pt nanostructure to detect locally the in-plane magnetization of the FM electrode using the SHE, which is promising for the reading process in a spin-orbit-based non-volatile logic [1]. The obtained SHE signals are 20 times higher than those measured locally in a related FM/Pt nanostructure [4], and three orders of magnitude higher than those measured nonlocally in lateral spin valves [2].

References

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Efficient Magnonic Spin Transport in Insulating Antiferromagnetic Thin Films

A. Ross[1,2], R. Lebrun[1], S. Bender[3], J. Cramer[1,2], A. Kay[4], D. Ellis[4], D. Grave[4], L. Baldrati[1], A. Qaiumzedah[5], A. Brataas[5], A. Rothschild[4], R. Duine[3,5,6] and M. Kläui[1,2]

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In contrast to ferromagnets (FM), antiferromagnets (AF) benefit from unparalleled stability with respect to applied external fields, magnetisation dynamics at THz frequencies and a lack of stray fields. Numerous theoretical studies have been undertaken, describing the mechanisms through which AFs could be integrated into current magnonic and spintronic devices, even replacing FM components[1,2,3]. AF insulators have been shown to have low Gilbert damping, which should allow for efficient switching mechanisms and long-range propagation of magnonic spin waves[4] as we recently demonstrated in a single crystal of the common insulating AF, hematite (α-Fe2O3)[5]. In this compound, AF spin-waves propagate as far as in YIG, the FM material which has the lowest damping, but the magnons are at far higher frequencies.

Here we investigate the underlying mechanisms behind electrical switching and long distance magnonic transport in AF thin films. We focus on two prototypical insulating AFs, easy-axis α-Fe2O3 and easy-plane nickel oxide (NiO). By exciting high frequency magnons through a spin bias with a neighbouring platinum layer[4], we study the transport mechanisms in these model systems. We find that efficient spin transport is possible across µm in nm thick thin films when reducing the magnon gap with an external field, contrary to previous studies reporting nm spin-diffusion lengths in AF thin films[7,8]. In parallel to our electrical measurements, we perform XMLD imaging of the AF domains to evidence the role of disorder and magnetic correlation in the propagation of magnons. We achieve efficient control over the AF system and establish the possibility to propagate long-distance spin-waves in AF thin films. These first promising results open a new area for the field of magnonics, paving the way towards the development of AF spintronic devices.

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Integrated magnonic half-adder

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Spin waves and their quanta, magnons, open up a promising branch of high-speed and low-power information processing [1]. Several important milestones were achieved recently in the realization of separate magnonic data processing devices including logic gates [2], magnon transistor [3], and units for non-Boolean computing [4]. In particular, the realization of the prototype of the transistor opened up a way towards all-magnon data processing in which information will be carried and processed purely by magnons rather than by electrons.

Nevertheless, the realization of an integrated magnonic circuit consisting of at least two logic gates suitable for further integration is still a challenge. Such an integrated circuit at the example of a magnonic half-adder will be presented in the talk. Its key element is a nonlinear magnonic data processing element serving as an AND logic gate. It is combined with a simplest interference-based XOR logic gate using a nano-scale directional coupler [5]. The functionality of this nano-sized magnonic circuit is investigated and tested by means of numerical simulations.

The progress towards the experimental realization of such a device will be presented in the second part of the talk. Spin-wave conduits made of Yttrium Iron Garnet (YIG) of widths down to 50 nm were fabricated and characterized by means of Brillouin Light Scattering (BLS) Spectroscopy [6]. The conduits were fabricated from a plain film grown by liquid phase epitaxy with consequent ion etching. The BLS measurements show that a good lifetime comparable to the value from the unpatterned film can be preserved during the nano-structuring.

This research was supported by the European Research Council Starting Grant 678309 MagnonCircuits and by the DFG (DU 1427/2-1).

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Spin Transport Experiments

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The spin Hall effect couples charge and spin transport channels, enabling a variety of spin transport experiments. In this context, magnetic insulators are a very attractive class of materials, since they allow for pure spin current transport, while charge currents are prohibited.

In the presentation, I will discuss different spin transport experiments in heterostructures consisting of spin Hall active metal films and magnetic insulators. More specifically, I will introduce the spin Hall magnetoresistance (SMR) [1] arising in magnetic insulator/metal bilayers, and then address the so-called magnon mediated magnetoresistance (MMR) [2,3] detected in non-local experiments in such structures. I will show how the MMR concept enables the realization of a proof-of-principle majority gate based on the incoherent superposition of magnons generated by several different spin Hall active metal strips [4]. Last but not least, I will critically discuss the importance of magnons for the MMR.

References

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Magnon transport and dynamics in magnetic insulators

B.J. van Wees

Zernike Institute of Advanced Materials, Groningen, The Netherlands

I will give an overview of our recent results of the transport of thermal magnons in the magnetic insulator materials YIG and NFO. We have shown that these can be generated electrically and by Joule heating, and can propagate with a typical relaxation length of 10 micrometers[1].

We have developed a theoretical description, where the magnon transport is driven by (a combination of) a gradient of the temperature (magnon spin Seebeck effect) or by the gradient of the magnon chemical potential[2].

Recently we demonstrated that the magnon transport can be modulated by the injection of magnons by an intermediate electrode, which acts analogous to a gate electrode in electrical field effect transistors[3]. I will discuss the relevance of these results for electrical control of Bose Einstein condensation of magnons.

Despite the success of modelling magnon transport with our diffusion/relaxation model, we have observed several discrepancies between our experiments and the theoretical modelling[4]. I will discuss various possible explanations.

Recently we investigated the interaction between (non-local) magnon transport of thermal magnons and GHz magnetization precession and GHz magnons generated by FMR excitation. We observe both enhancement and suppression of the magnon transport, and I will discuss the possible origins[5].

Finally we have compared the high quality magnon transport in YIG with that in NFO. We have compared their properties (SMR, and non local magnon transport). Similarities and differences will be discussed[6].

References

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All-electrical control of spin conductance in magnetically ordered insulators

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Pure spin currents, i.e. the flow of angular momentum without an accompanying charge current represents a new paradigm in the field of spintronics. Most importantly, pure spin currents can be transported by fermions, i.e. by electrons, in electrical conductors as well as by bosons, i.e. by quantized magnetic excitations, in magnetically ordered insulators. Interestingly, heterostructures consisting of spin-orbit coupled metals interfaced with magnetically ordered insulators allow to investigate pure spin current transport in both regimes and their interconversion at the interface [1]. Utilizing the spin Hall effect and the inverse spin Hall effect in the spin-orbit coupled metal allows to transform a charge current into a pure spin current and vice versa. Thus enabling all-electrical generation and detection of pure spin currents in such heterostructures.

We will present our recent progress in this field with a special focus on the manipulation of pure spin current transport in magnetically ordered insulators. In our experiments, we use yttrium iron garnet (YIG) layers with a thickness of several nm. On top of these YIG films we deposit three electrically isolated Pt strips separated by several 100 nm to study the spin transport via quantized magnetic excitations (magnons) in YIG. For this purpose, we drive a charge current through one Pt strip and inject a pure spin current into the YIG layer. A second Pt strip then allows detecting the pure spin current flowing in the YIG layer via the inverse spin Hall effect. The third Pt modulator strip acts as an additional injector for pure spin currents. We will discuss the influence of this additional pure spin current injection via a DC charge current flowing in the modulator on the magnon transport in YIG. Our results show that depending on the charge current density driven through the modulator linear and non-linear effects influencing the magnon transport in YIG are observed. Last, but not least, we discuss the physical origin of these effects and provide an insight in how these effects can be utilized for novel applications.

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Fermionic quantum computation with Majorana states

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Because Majorana zero modes store quantum information nonlocally, they are protected from noise, and have been proposed as a building block for a quantum computer. We show how to use the same protection from noise to implement universal fermionic quantum computation. Our architecture requires only two Majorana modes to encode a fermionic quantum degree of freedom, compared to alternative implementations which require a minimum of four Majorana modes for a spin quantum degree of freedom. The fermionic degrees of freedom support both unitary coupled cluster variational quantum eigensolver and quantum phase estimation algorithms, proposed for quantum chemistry simulations and have a lower complexity cost compared to the conventional qubits.

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Operating quantum states in single magnetic molecules

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The endeavour of quantum electronics is driven by one of the most ambitious technological goals of today's scientists: the realization of an operational quantum computer. We start to address this goal by the new research field of molecular quantum spintronics, which combines the concepts of spintronics, molecular electronics and quantum computing. The building blocks are magnetic molecules, i.e. well-defined spin qubits. Various research groups are currently developing low-temperature scanning tunnelling microscopes to manipulate spins in single molecules, while others are working on molecular devices (such as molecular spin-transistors, Fig. 1) to read and manipulate the spin state and perform basic quantum operations. We will present our recent measurements of geometric phases, the iSWAP quantum gate, the coherence time of a multi-state superposition, and the application to Grover's algorithm [1-5].

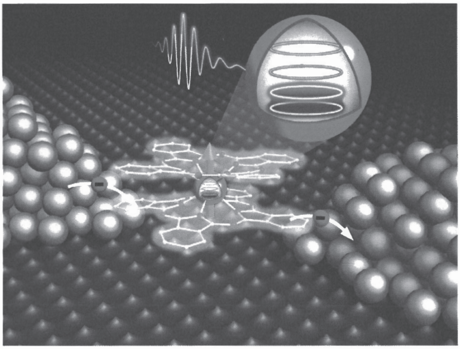

Fig.: A molecular spin transistor based on a single TbPc2 molecular magnet

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Analogue and digital simulations with spins in quantum dots

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Electrostatically defined quantum dots in semiconductors are one of the leading platforms for the development of quantum technologies, owing to their fast and efficient control and measurement, as well as their compatibility of fabrication with commercial semiconductor industry processes. At the Vandersypen Lab, we focus on using the spin and charge degrees of freedom of electrons confined in quantum dots, to explore physics through analogue and digital quantum simulations.

In this talk I will delve into some of our latest and most exciting experiments. I will begin with a description of the types of quantum dot arrays that we operate, highlighting the techniques that we have developed recently to overcome the problem of disorder and efficient control [1], which is crucial to the operation and scale-up of these systems as quantum simulators and processors. I will then describe our latest quantum simulator device—a 2x2 plaquette of quantum dots in a GaAs heterostructure [2] (Fig. 1)—which we use to demonstrate Nagaoka ferromagnetism, one of the well-known theories of ferromagnetism based on the Hubbard model, which had yet to be demonstrated experimentally. Finally, I will present the capabilities of our silicon-based 2-qubit quantum information processor [3] (Fig. 2), with an outlook on how this technology can be further developed towards a large-scale universal quantum computer.

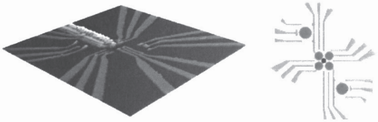

Fig. 1: AFM image and top-view schematic of the 2x2 quantum dot analogue simulator

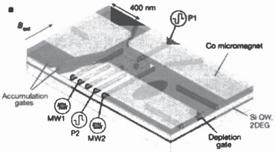

Fig. 2: Schematic of the 2-qubit programmable quantum processor

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Gate controlled loading of singlet and triplet electron pairs in a single electron pump

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We study the loading of electrons near the Fermi edge into a dynamic gate defined GaAs/AlGaAs quantum dot as used for metrological single electron pumps [1]. In this regime, our experimental data reveals that electrons can tunnel either directly into the single electron ground state or can enter the dot via excited orbital states. Using a rate equation model, we show that loading into excited states and subsequent fast orbital relaxation into the ground state is vital for single-electron capture. In contrast to fast orbital relaxation, singlet-triplet spin relaxation of electron pairs occurs on a much slower timescale than the inverse pumping rates of our experiments. In this regime, our data clearly indicates loading into specific singlet or triplet ground states as function of gate voltages. This opens the door to voltage controlled fast state and spin initialization of quantum dots.

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Computing with Magnetic Tunnel Junctions for AI

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Artificial intelligence (AI) has been enabled by the invention of transistor and its ever-decreasing size and ever-increasing integration at a large scale. However, to enable local or edge AI like family-based robots and self-driving cars without using cloud computing, the power consumption for any available computing system is still four to six orders of magnitude higher than needed. We have been envisioning and exploring a new pathway, nanomagnet-based spintronic devices, to address this grand challenge. Among all proposed spintronic devices for computing, magnetic tunnel junctions (MTJs) [1] hold the brightest future with large practical impacts considering the maturity of manufacturing MTJs array in a various of semiconductor Foundries worldwide. Magnetic tunnel junctions (MTJs) were proved to provide high endurance and low-cost solutions for non-volatile, stochastic and nonlinear activation functions and the combinations [2]. Those enable both the stochastic computing and probabilistic computing. MTJs based random access memory array has been demonstrated to be capable for different neuromorphic computing architectures. This talk will review several successful outcomes through STARnet/C-SPIN era [2] to use MTJs for the computational random-access memory (CRAM), computing near memory, cognitive computing, stochastic and probabilistic computing and reconfigurable information processing, which are all the key build blocks for different AI accelerators.

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Bio:

Jian-Ping Wang is the Robert F. Hartmann Chair and a Distinguished McKnight University Professor of Electrical and Computer Engineering and a member of the graduate faculty in Physics and Chemical Engineering and Materials Science at the University of Minnesota. He established and managed the Magnetic Media and Materials program at Data Storage Institute, Singapore, from 1998 to 2002. He joined the faculty of the Electrical and Computer Engineering department at the University of Minnesota in 2002. He was the director of the Center for Spintronic Materials, Interfaces and Novel Architectures (C-SPIN), one of six STARnet program centers, and the largest vertically integrated spintronic center in the world. He is the director of the Center for Spintronic Materials for Advanced Information Technologies (SMART), one of two SRC nCORE centers. He received the information storage industry consortium (INSIC) technical award in 2006 for his pioneering experimental work in exchange coupled composite magnetic media and the outstanding professor award for his contribution to undergraduate teaching in 2010. His group is also known for several pioneering experimental demonstrations and visionary conceptual proposals including the perpendicular spin transfer torque device, the magnetic tunnel junction-based logic device and random number generator, ultra-fast switching of thermally stable MTJs, sputtered topological insulator materials, and a computation architecture in random access memory. He is an IEEE fellow.

Spin dynamics beyond GHz: ferro- versus antiferromagnets

Ulrich Nowak

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Antiferromagnetic materials are in the focus of current research in magnetism because of their potential for applications in spintronics. Possible advantages of spintronic devices based on antiferromagnetic materials include their lack of stray fields, the low susceptibility to external fields, and the rich choice of new materials, including a variety of antiferromagnetic insulators.

This talk focuses on a comparison between spin dynamics in ferromagnets and antiferromagnets, respectively, based on spin model simulations. We present a new concept for a magnonic spin valve based on a trilayer of insulating ferromagnetic and antiferromagnetic materials and we compare the difference of the spin dynamics of ferro- and antiferromagnets regarding the mobility of their domain walls, their superparamagnetic limit in nanoparticles, and their efficiency for spin torque switching.

Electrical and Optical Manifestations of Emergent Monopoles in Complex Magnets

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In the field of topological condensed matter the so-called topological semimetals have recently attracted great attention due to their exceptional properties stemming from monopoles in momentum space. On the other hand, there is a strong belief that combining monopole physics with complex collinear and non-collinear magnetism can give rise to novel effects and strong magneto-electric coupling [1, 2]. For example, we will show that the monopole physics in skyrmions and strongly frustrated antiferromagnets is responsible for prominent topological Hall effect and topological orbital magnetism relying on the non-trivial distribution of spins on a lattice rather than spin-orbit interaction (SOI) [3, 4]. Additionally, we will demonstrate that such magnets can exhibit strong topological magneto-optical effects without SOI, which in two dimensions can result in the quantization of Kerr and Fraday rotation angles, implying the appearance of quantum topological magneto-optical effects, accessible e.g. by time-domain THz spectroscopy [5]. Finally, we will argue that realizing isolated spin monopoles in real-space, as observed for example in chiral bobbers, can prove to be utterly fruitful for spintronics. We will present evidence that the unique transport and orbital characteristics of such monopoles can be used to drastically alter their emergent response properties, which bears great potential for various applications ranging from chiral dynamics to cognitive computing [6].

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Ultrafast Terahertz Magnetometry

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In this presentation we will show that using terahertz (THz) emission spectroscopy it is possible to measure the dynamics of magnetization in a material in a fully calibrated manner, and with (sub-)picosecond time resolution. As an example, we will demonstrate the transient demagnetization dynamics in a laser-excited Fe nanofilm, where two distinct contributions are clearly distinguishable: direct laser-induced transient demagnetization signal, and the few-picosecond-timescale magnetization dynamics driven by the coherent acoustic phonon pulse created by the laser excitation of the nano-film. The relative strength of the acoustic contribution to the total demagnetization is rather significant, and amounts to ca. 10% of the direct laser-induced transient demagnetization signal.

Approaching THz spin-wave generation in optically-driven acoustic resonators

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Coherent spin-wave generation between 100 GHz and a few THz is hard to achieve with current methods which either produce incoherent or non-monochromatic spin-waves [1].
While normally an unwanted dissipation channel in spintronics, it was already shown that magneto-elastic coupling can be exploited to generate spin currents [2] and coherent magnetic oscillations in the low GHz regime [3]. Here, we propose a novel design to generate THz spin waves by laser excitation of an acoustic nano oscillator magneto-elastically coupled to a ferromagnetic layer.

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Abstracts of Posters

(in alphabetical order)

Thermally induced magnetisation dynamics; ferromagnets vs antiferromagnets

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Antiferromagnetic materials are in the focus of current research in magnetism because of their potential for applications in spintronics [1]. Antiferromagnetic spin dynamics are proposed to beat ferromagnetic dynamics both in speed and efficiency. However, little is known about their dynamics in a wide range of relevant timescales, such as i) thermally activated magnetic reversal, and ii) femtosecond laser induced sub-picosecond magnetic order relaxation.

First, as for ferromagnets, their magnetic stability in nanostructures will be limited by thermal excitations [2]. Here, we investigate the superparamagnetic limit of antiferromagnetic nanoparticles theoretically, focusing on a comparison to the known properties of ferromagnetic particles. We find a drastically reduced stability because of the exchange enhancement of the attempt frequencies and the effective damping during the antiferromagnetic switching process.

Second, we investigate the relaxation time of the antiferromagnetic order parameter under the application of an ultrafast heat pulse, and find that indeed antiferromagnets can respond up to one order of magnitude faster than ferromagnets. We find theoretical expressions for the relaxation times, and that the reason behind this strong difference relies in the effective damping of the system caused by the exchange coupling between sublattices, absent in ferromagnets. These findings have strong implications for ultrafast control of magnetic states in antiferromagnets.

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Electronic bands structure of type II superlattice InAs/Gasb for medium infrared detection

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We report in this abstract the electronic bands structure of type II superlattice InAs(d_1=21 Å)/GaSb(d_2=24Å).The study is performed in the envelope function formalism we calculated E (d1), E (k_z), E(k_p) and the effective mass in the direction of growth and in plane., with a valence band offset of 510 meV, predicts that, the system is semiconductor. We do the calculation for four temperature T= 5, 10, 77, 300K and the band gap in this temperature is Eg= 316, 315.53, 306.21, 243.91meV respectively and the corresponding wavelengths is $3.92\ \mu m<\lambda_c<5.98\ \mu m$. The effect of temperature on the band gap show that E_g decreases with temperature and the corresponding cutoff wavelength increases. Shows, that this sample can be used as medium Infrared (MWIR) detector.

On the other hand transport and magneto-transport measurements have been performed. In intrinsic regime, $R_H\ T^{3/2}$ [3] indicates a gap E_g=377 meV. So this sample is two-dimensional and medium infrared detector ($3.92\ \mu m<\lambda_c<5.98\ \mu m$). The SL is a stable alternative for application in infrared optoelectronic devices.

Keywords: InAs/GaSb type II SL; Electronic bands structure; Cut-off frequency; Long Wavelength Infrared and Terahertz Photodetection; Shubnikov de Hass Effect, Quantum Hall effect.

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Magnon heralding in cavity optomagnonics

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Cavity optomagnonics is an emergent field where photons couple to elementary magnetic excitations in solid state systems. For optical photons, the coupling is parametric and the magnetic material is both the optical cavity and the host of the magnetic excitations (magnons). These systems are promising for integration in hybrid quantum platforms. In this context, we propose a magnon heralding protocol to generate a magnon Fock state by detecting a cavity photon. We analyze the constraints imposed by the magnonic decay rate and by the strength of the optomagnonic coupling. We show that the detrimental thermal effects can be overcome by initially actively cooling the magnon mode. We discuss the feasibility of the proposed protocol for state of the art YIG cavity optomagnonic systems.

Modulation of non-local spin signals by heat and Oersted fields

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An ultimate goal of magnonics[1] is the effective control and manipulation of spin wave propagation in magnetic systems. Among others, this includes the realization of magnon circuitry that allows one to perform logic operations. Potential advantages of this approach over charge-based concepts are, without limitation, the possibility to implement wave-based computing (e.g. encode information in the wave phase) and reduced power losses.

So far, magnon logic concepts mainly focused on schemes using coherent spin waves[2,3], which basically allow one to exploit interference effects. For example, the all-magnon transistor[4] and a logic majority gate[5] have been presented. Recently, logic operations based on thermal, incoherent magnons as information carrier have gained increased interest, triggered by the discovery of long-range magnon transport in insulators induced by electrically excited spin currents in heavy metals[6]. For example, Cornelissen *et al.* recently reported on the spin current-controlled modulation of magnon transport signals in the ferrimagnetic insulator yttrium iron garnet[7] (YIG).

Here, we present a different approach as compared to that of Cornelissen *et al.* to investigate the impact of heat and Oersted fields on spin transport signals in magnetic insulators. A non-local device structure was realized, which in addition to two Pt wires on a YIG film includes a third Cu wire, which is positioned in the center of the Pt wires. Due to a negligible spin Hall effect, applying a charge current to this wire only heats the YIG sample locally and results in a localized Oersted field. By means of angular-dependent spin transport measurements in rotating magnetic fields of low and high amplitude we show that, indeed, this approach allows for a modulation of the spin signal, suggesting a further approach towards spin signal processing.

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Bridging magnonics and spin-orbitronics

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The emerging field of nanomagnonics utilizes high-frequency waves of magnetization—spin waves—for the transmission and processing of information on the nanoscale. The advent of spin-transfer torque has spurred significant advances in nanomagnonics, by enabling highly efficient local spin wave generation in magnonic nanodevices. Furthermore, the recent emergence of spin-orbitronics, which utilizes spin–orbit interaction as the source of spin torque, has provided a unique ability to exert spin torque over spatially extended areas of magnonic structures, enabling enhanced spin wave transmission. Here, we experimentally demonstrate that these advances can be efficiently combined. The same spin–orbit torque mechanism is utilized for the generation of propagating spin waves, and for the long-range enhancement of their propagation, in a single integrated nanomagnonic device. The demonstrated system exhibits a controllable directional asymmetry of spin wave emission, which is highly beneficial for applications in nonreciprocal magnonic logic and neuromorphic computing.

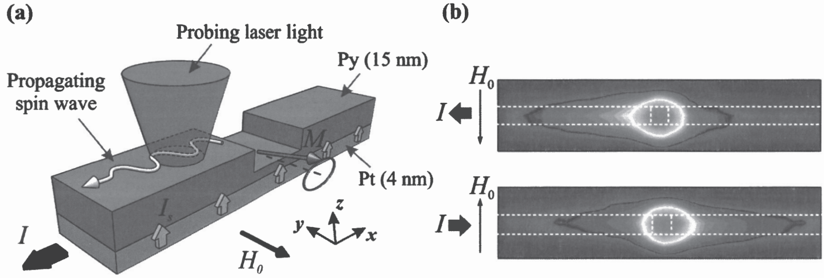

Figure. (a) Schematic of the experiment. **(b)** Unidirectional spin wave emission by the nanonotch oscillator. Dashed lines on the maps show the outlines of the waveguide and of the nanonotch.

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Origin of Spin Polarization of Photoemitted Electrons from Paramagnetic Bulk States

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Angular- or momentum-resolved photoelectron spectroscopy in the soft X-ray range gives access to the bulk electronic structure of materials. Time-of-flight momentum microscopy with parallel spin detection extends this information to the spin degree of freedom. We choose a non-magnetic model system (tungsten) in order to exclude any initial-state spin polarization from exchange-split bands. By measurement of four independent photoemission intensities for two opposite spin directions and opposite light helicity, one can distinguish between spin polarization contributions of optical spin-orientation by circularly polarized X-rays (Fano component) and a second contribution with polarization direction perpendicular to the scattering plane. The latter phenomenon has been observed for surface states and is usually attributed to surface-related inversion symmetry breaking. In the case of soft X-ray radiation, true bulk states are probed and the perpendicular spin polarization represents a novel phenomenon originating from spin-dependent interference of final state partial waves.

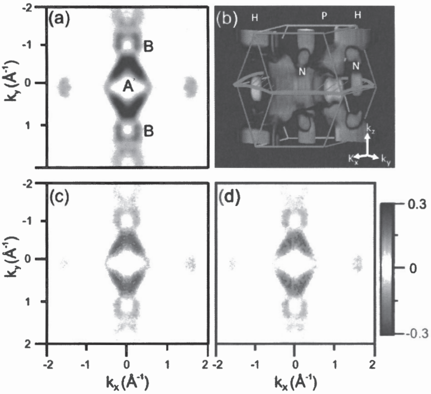

Fig. 1.
(a) Measured photoemission intensity.
(b) 3-dimensional Fermi surface.
(c) Spin-polarization for sigma minus.
(d) Spin-polarization for sigma plus. Color bar quantifies the spin-polarization.

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Spin Pumping and Low Gilbert Damping in $Co_{25}Fe_{75}$ Heterostructures

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Spin wave propagation plays an important role in magnonics, where quantized magnetic excitations are used as information carriers. A crucial parameter for the spin wave propagation length is the magnetic Gilbert-damping constant. Itinerant ferromagnets offer advantages for magnonics and spintronics, but typically suffer from drastically higher damping than insulating ferrimagnets. Motivated by the work of Schoen *et al.* [1], we investigated $Co_{25}Fe_{75}$-heterostructures and analyzed their Gilbert damping using broadband ferromagnetic resonance spectroscopy.
Using different sputtering parameters and thicknesses for the ferromagnet and the seed and cap layers (e.g. Pt and Ta), we systematically investigated the spin pumping contribution to the Gilbert damping. From these measurements, we extrapolated the intrinsic damping of the magnetic alloy. From our results we find an optimal approach to obtain low 10^{-3} Gilbert damping in $Co_{25}Fe_{75}$. Our results are further confirmed by inelastic light scattering experiments (microfocused Brillouin-Light-Scattering), which spatially resolve the spin wave. In our nanopatterned devices, we found spin wave propagation lengths in agreement with the Gilbert-damping of corresponding plain films. Our results confirm that $Co_{25}Fe_{75}$ thin films are ideal candidates for future magnonic devices and pave the way for novel functionalities.

Financial support by Deutsche Forschungsgemeinschaft via projects WE5386/4 and WE5386/5 is gratefully acknowledged.

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Controlling spin transmission in collinear ferroic magnetic multilayer systems

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Almost three decades ago the research field of spintronics was boosted by the discovery of the giant magnetoresistance (GMR) [1, 2]. Instead of only relying on the electronic charge, the utilization of the spin degree of freedom allows for the implementation of devices with increased speed, decreased power consumption and further advantages [3]. In recent years, the basic idea of spintronics has been pursued further by the investigation of pure spin currents in (non-)magnetic materials, which eventually find application in, for instance, spin orbit torque driven memory devices [4].

We report on spin pumping [5] measurements in collinear magnetic yttrium iron garnet (YIG)/CoO/Co multilayers. By means of microwaves and external magnetic fields, YIG is brought into ferromagnetic resonance, resulting in a pure spin current that propagates through the sample stack and is finally detected in the Co layer via the inverse spin Hall effect [6]. In addition to facilitating spin current transmission and de-coupling of the ferromagnets, the CoO layer increases the Co coercive field by exchange biasing. This effect enables switching between a parallel or antiparallel alignment of the YIG and Co magnetization at the resonance field of the YIG. For the different alignment states different spin pumping amplitudes are observed, signifying a Co orientation dependent spin pumping efficiency and thus magnon spin-valve-like behavior [7]. Besides the spin pumping signal peak, a second peak is observed at ferromagnetic resonance that depends on the Co orientation, which is ascribed to an anomalous Hall effect induced spin rectification in the Co layer [8].

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Ultrafast switching in antiferromagnets induced by spin-orbit torques

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Antiferromagnets are considered as prospective materials for information storage due to their robustness and potentially fast switching dynamics. Possible way to write information is based on utilization of spin-orbit torques produced by spin Hall effect, as it was recently demonstrated for NiO-based films [1,2]. Here we analyse a mechanism responsible for such current-induced switching between noncollinear states of an antiferromagnet. We propose a universal model of the switching resulting from the domain wall motion under the action of two types of spin current-induced forces. One of the forces, so called ponderomotive force, favours domains with the parallel orientation of the Néel vector and current and enables deterministic switching. This force is related with the ability of anti-damping spin-orbit torque to modify the magnetic anisotropy. Anot her force predicted in [3] is chiral-dependent and can locally induce switching in both direction (parallel or perpendicular to the current). Taken alone this force cannot produce detectable response in a multidomain sample, however, in combination with the ponderomotive force it enables fast domain wall motion and facilitates reliable switching. We compare the threshold currents and effective forces for each of the possible mechanisms and analyse experimental situations in which these mechanisms can be implemented. In conclusion, our model for current-induced switching is applicable to any antiferromagnetic system for which the depinning fields of domain walls is lower than the anisotropy field, which is the case in most reported insulating antiferromagnetic thin films like NiO.

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Simultaneous stabilization of skyrmions and antiskyrmions in rank-1 DMI materials allowing the concept of a skyrmion-antiskyrmion racetrack memory

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Recently, we extended the scope of skyrmions and antiskyrmions and introduced a classification scheme of chiral magnets [1]. Typically investigated Bloch-type skyrmions in B20 alloys and Néel-type skyrmions at (111) oriented interfaces belong to isotropic rank-three Dzyaloshinskii-Moriya (DM) bulk and rank-two DM film magnets with a DM interaction described by a single spiralization constant. Within this class, antiskyrmions are stable only for bulk crystals with certain point group symmetries. New are the anisotropic rank-two DMI film magnets where skyrmions and antiskyrmions can coexist while the determinant of the spiralization tensor determines which of them have lower energy. Finally, zero determinant indicates a rank-one DMI material in which skyrmions and antiskyrmions have the same energy.

Here, we discuss the behavior of skyrmions and antiskyrmions in the same magnetic system of rank-one solids. Our focus lies on the analysis of their (common) motion and the orientation dependent interaction between the two skyrmionic objects of opposite topological charge.

Based on this, we propose a design of a racetrack memory based on the coexistence of skyrmions and antiskyrmions [2].

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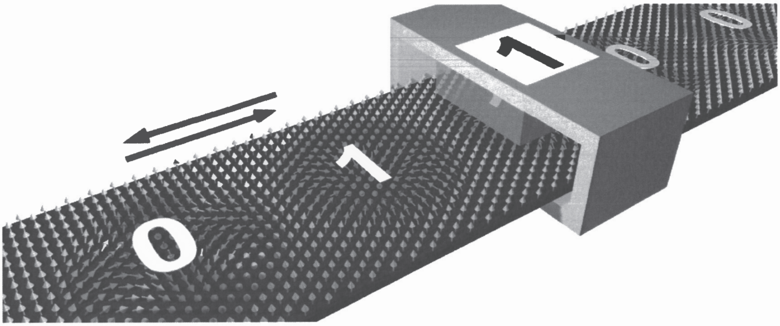

Employing exactly solvable 1D quantum lattice models for information processing

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Researchers around the globe are engineering information processing devices based on spin interactions. Typical experiments in the field range from ultra-cold atoms to solid-state physics. Either way, the underlying theoretical models are often quantum spin chains. Some of them, for example non-interacting quantum chains are exactly solvable. However, many real systems include interactions and are hence not well described by free models.

Certain interactions can be described within the framework of integrable models. One of the most important representatives of this class of models are the Heisenberg model and its relatives. Exact solutions are available for these models via Bethe ansatz, which makes them very convenient starting points for theoretical research. From the exact solution, one can add integrability-breaking terms perturbatively in order to obtain results for a wide range of systems.

The key step in this machinery is the breaking of integrability, as it can lead to singularities both in the large-time and the large-volume limit. It is unclear how this affects the physics on intermediate time and volume scales, as these are typically not accessible with standard techniques. Here, several numerical approaches to the problem are presented.

Sensing Weak Microwave Signals by Quantum Control

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Solid state qubits, such as the Nitrogen-Vacancy (NV) center in diamond, are attractive sensors for nanoscale magnetic and electric fields, owing to their atomically small size. A major key to their success have been dynamical decoupling protocols (DD), which enhance sensitivity to weak AC signals such as the field of nuclear spins from a single protein. However, those methods are currently limited to signal frequencies up to several MHz.

Here we harness a quantum-optical effect, the Mollow triplet splitting of a strongly driven two-level system, to overcome this limitation. We microscopically understand this effect as a pulsed DD protocol and find that it enables sensitive detection of fields close to the driven transition. To this end, we create a pair of photon-dressed qubit states which support a new transition with narrow linewidth. Generally, our scheme is applicable to any qubit but we consider sensitive detection of signals close to the NV's transition frequency (≈ 2 GHz). As a result, we demonstrate slow Rabi oscillations with a period up to $\Omega_{Rabi}^{-1} \sim T_2$ driven by a weak signal field. The corresponding sensitivity could enable various applications. Specifically, we consider single microwave photon detection, as well as fundamental research on spin-phonon coupling.

Atom-by-atom engineering of associative memories in finite size spin systems

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We demonstrate that a two-dimensional finite and periodic array of spins coupled via RKKY-like exchange can exhibit tunable magnetic phases ranging from robust double well potentials, multi-well attractor potentials, towards spin glass-like landscapes. These magnetic phases can be tuned by one gate-like parameter, namely the ratio between the lattice constant and the long-range interaction wavelength. We characterize theoretically the various magnetic phases, quantifying the distribution of low energy states, aging relaxation dynamics, and scaling behavior. The glassy behavior results from self-induced glassiness, which is driven by the incommensurability of the RKKY period and the periodic array. Finally, we detail how memory states can be created, based on associative memories in a Hopfield model, and pattern recognition can be performed utilizing a modifying bi-associative memory scheme.

Spin wave observation in metastable thin films prepared by focused ion beam direct writing

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Innovative approach to the fabrication of structures suitable for application in magnonics is presented: Direct writing into a Ni stabilized paramagnetic fcc Fe thin films epitaxially grown on a Cu(100) substrate [1]. These films are known for their capability to undergo ion-beam-induced phase transformation into a ferromagnetic bcc phase. To bring these metastable films closer to the application, the Cu(100) substrate can be further substituted by Cu(100) buffer layer grown on standard Si(100) substrate [2]. With the use of a focused ion beam, magnetic properties of the films – such as saturation magnetization or strength and direction of magnetic anisotropy – can locally tailored [3]. This allows fabrication of a magnonic structures unattainable by conventional lithography techniques.

Structures prepared in this way are studied by all-electrical spin-wave spectroscopy (Fig.1). Microscale coplanar waveguides are used for inductive excitation and detection of spin waves with defined wavevectors. A broadband ferromagnetic resonance and propagating spin wave spectroscopy experiments are performed on transformed continuous layers and microstructures, exploring damping properties of this material and its possibilities to be used for spin-wave guidance.

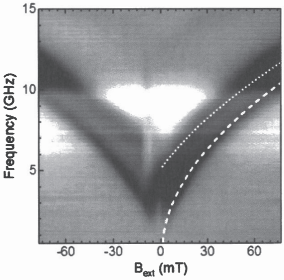

Fig. 1: Spin wave spectra obtained in Damon-Eshbach geometry. White lines indicate calculated ferromagnetic resonance (dashed) and propagating modes corresponding to the first excitation maximum of the used antenna (dotted).

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ERASE, SHIFT, Boolean OR, XOR, and AND, as well as quantum $\sqrt{\text{NOT}}$ gates on Ni_4 from first principles

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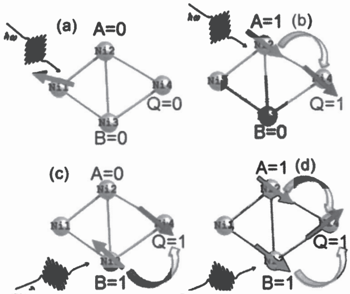

Fig. 1: Pure-spin OR gate on Ni_4 [5]

Based on state-of-the-art quantum chemistry calculations we implement different logic operations on molecular magnets, mainly on the example of the highly correlated Ni_4. The spin degree of freedom acts as the information carrier (input and output bits), while specially designed laser pulses trigger the processes [1].

We start with the ERASE functionality, for which we need to break the time-reversal symmetry of the process. We achieve this in two ways: (i) with chirped laser pulses [2], and (ii) by exploiting decoherence effects [3].

Already with three-magnetic-center molecules we first derived Boolean-logic operations (OR, AND, XOR) and a cyclic SHIFT register by combining two elementary processes, i.e., spin flip and spin transfer [4]. Adding a fourth center leads to additional elementary processes, i.e., spin merging, spin bifurcation [5], and spin bouncing [6], allowing us to derive *pure-spin* logic gates. We also go beyond classical logic, by exploiting the *which-path* interference effect (where the phase of the spin after a transfer process reveals the path taken) [5], and the coherent superposition of many-body states, which allows to build quantum logic gates. More specifically, we present our newest results on the universal $\sqrt{\text{NOT}}$ logic gate (analogue to the Hadamard gate).

Finally we show, how the proper use of the Goodenough-Kanamori rules in conjugate systems can enable optical spin transfer over almost mesoscopic distances (more than 26 Å), thus slowly reaching typical CMOS scales. Our results help pave the way towards future realistic nanospintronics devices.

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Phase-sensitive and Spatially Resolved Detection of Magnetization Dynamics

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Spintronic devices based on ferromagnet/normal metal bilayers exploit charge currents in the normal metal to manipulate the magnetization in the ferromagnetic layer. The coupling between the charge current and the magnetization is thereby mediated by spin-orbit torques (SOTs) or in the reciprocal process according to Onsager reciprocity via the inverse spin-orbit torques (iSOTs). As recently demonstrated, the quantitative detection of SOTs is possible by using a phase-sensitive broadband ferromagnetic resonance technique based on vector network analysis [1]. Although this technique is versatile for measuring SOTs in the thin films, it cannot be used to investigate SOTs in thin film nanostructures.
Here, we use the micro-focused frequency-resolved magneto-optic Kerr effect (μFR-MOKE), which is based on the FR-MOKE-technique demonstrated by Schneider *et al.* [2]. In contrast to the broadband ferromagnetic resonance technique, our method is spatially resolved with sub-micrometer resolution, while retaining the phase-sensitive detection that is crucial for determination of SOTs. Furthermore, μFR-MOKE can be used to detect spinwaves with $\boldsymbol{k}\neq 0$. In order to demonstrate the capability of this technique, we investigated the magnetization dynamics of spinwaves in microstructured ferromagnet/normal metal samples with $Co_{0.25}Fe_{0.75}$ as the ferromagnet. Furthermore, we will compare the μFR-MOKE data to corresponding data obtained using the established micro-focused Brillouin light scattering (μBLS) technique.

Financial support by Deutsche Forschungsgemeinschaft via project WE5386/4 is gratefully acknowledged.

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Laser induced DC photocurrents in 3D Topological insulators structured to hallbar and nanowire devices

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Topological Insulators (TI) open up a new route to influence the transport of charge and spin in a surface film via spin-momentum locking [1,2]. It has been demonstrated experimentally [2] that illuminating a TI by circularly polarized light can result in excitation of a helicity-dependent photocurrents.

In this poster, we will sum up our results on (Bi, Sb)$_2$Te$_3$ thin films hallbar structures and Bi$_2$Se$_3$ core-shell nanowires. We illuminate for both kinds of samples the TI with visible laser light and analyze the photocurrent measured between two gold contacts, and determine the periodicity in the polarization dependence of the laser light. The position of the laser light can be changed in two directions parallel to the surfaces of the sample. As a result, we measure a 2D map of polarization dependent photocurrents.

We detect in both cases a polarization dependent photoinduced current depending on the position of the laser light, consistent with results at room temperature reported by McIver et. al [1]. The signal can be switched by the lights polarization properties but is very weak. Moreover, we see lateral accumulation of spin polarization at the TI's edges which is related to the spin Nernst effect that allow a new degree of manipulation of the spin currents in TI's [3].

We acknowledge funding through DFG priority program SPP "Topological Insulators" and DAAD PPP Czech Republic "FemtomagTopo".

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Ways towards optical spin manipulation in topological systems

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The developing field of ultrafast magnetism and THz spintronics of the last 20 years has been rapidly gaining knowledge in spin manipulation that finally allows to look for applications [1].

Most interest has catched in the past the idea of manipulating the spins by light: I will compare the possibilities to manipulate spins system with topological textures – in real space and in reciprocal space. In real space fast heating can generate spin textures from vortices (Merons with +-1/2) to Skyrmions (+-1) by fast and ultrafast quenching. Spin textures in k-space vice versa allow us to use spin-textures in k-space. Spin-momentum locking allows to generate spin currents via topological textures. Moreover, we see an influence of topology on the possibilities to manipulates spins by light, the size and robustness of these effects, and the effectiveness of topological protection in experiments.

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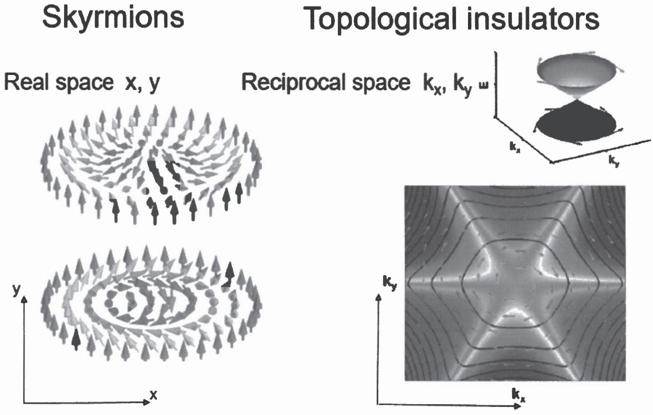

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Fig. 1. The spin Nernst effect in topological insulators.

Development of time-resolved photoemission electron microscopy of magnetization dynamics triggered by back-side illumination

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Over the last decades, both ultrafast microscopy and spintronics have progressed in a remarkable manner. Experimental and theoretical methods have been developed in order to understand and eventually control the spin transport and magnetization dynamics approaching the spatial-temporal limit of available techniques [1]. Supported by the newly founded "Collaborative Research Center / Transregio 227 Ultrafast Spin Dynamic" we plan to study spin and magnetization dynamics of magnetic thin films on nanometer-femtosecond scales [2]. Our approach is to combine state-of-the-art time-resolved photoemission electron microscopy (PEEM) with a back-side pumping geometry [3] as shown in Fig.1. With this setup, we would like to image magnetic domains using magnetic dichroism in photoemission [4] and record nm-fs movies of domain switching and domain wall motion triggered by fs spin and optical excitations.

In this poster, we will present the plan of our experimental setup including the quantitative estimations of the excitation density required to trigger ultrafast magnetization dynamics [5], the accessible temporal resolution including the implementation of pulse front tilting [6], as well as the size of the expected magnetic linear and circular dichroic effects in PEEM [7]. The design of a new vacuum chamber will be shown, which is specified for an optimal optical access in PEEM. Additionally, the corresponding optical beam paths for a flexible combination of back-side pumping with front and back side probing will be discussed.

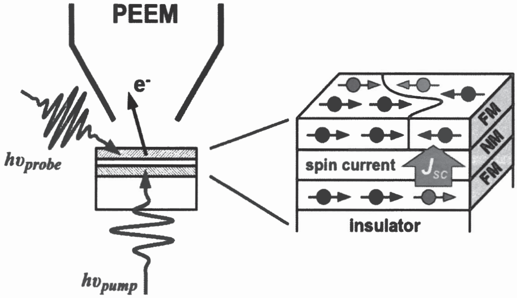

Figure 1: Left: Back-side-pump, front-side probe geometry in PEEM. Right: Back-side fs optical excitation on a ferromagnetic (FM) underlying layer triggers a spin current (J_{SC}) that propagates through the non-magnetic (NM) spacer. Because of J_{SC} impinging on the top FM layer, fs domain dynamics occur and can be imaged by time-resolved PEEM at the front side.

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Spin-wave logic: towards neuromorphic computing

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Today's computational technology based on CMOS has experienced enormous scaling of data processing capability as well as of price and energy consumption per logic element. However, to continue this development successfully into the future, and with the rapid development of artificial intelligence and neural networks in mind, complementary approaches to conventional logic schemes are needed. One of these alternative routes is wave-based computing, which, however, suffered longtime from the lack of a down-scalable system which could be interconnected with conventional CMOS technology. In this context, spin waves, the elementary excitations of the spin system and their quanta, the magnons, have been intensively investigated and successfully brought to the micro- and nanoscale. Also, the connections to conventional electronic and spintronics circuits have been established within a new field known as magnon spintronics. Due to their large variety of intrinsic linear and nonlinear wave phenomena, spin waves constitute a promising candidate for nanoscaled wave-based computing and data processing in general.

We will discuss different computing approaches based on (spin-) waves and the advantages and challenges of a linear interference-based logic. Inspired by the hybrid analog and digital data processing structure of biological brains, we use the unique nonlinear properties of spin-waves to develop an approach to realize neuromorphic computing based on spin waves.

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Utilization of room temperature skyrmion diffusion in information processing by probabilistic computing

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A key problem for probabilistic computing is that cascading gates propagate undesired correlations and thus vitiate the functionality of the logic device. Therefore, in order to implement probabilistic computing, one needs to reshuffle the signals to keep them uncorrelated for further calculations. While for many non-conventional computing approaches non-magnetic implementations have been identified as promising, for building a reshuffler device, skyrmions [1-2] might be ideally suited due to the low footprint and low power compared to e.g. CMOS implementations [3].

We present a Ta-based material, where we can stabilize skyrmions and controllably nucleate and displace them by current injection due to spin-orbit torques [4]. We find topologically non-trivial N=1 skyrmions that move synchronously due to the application of current pulses. We find strong motion also at zero applied current, which we ascribe to thermally activated skyrmion dynamics. After tracking the trajectories of skyrmions and based on the dependence of their mean-square-displacement (MSD) on time, we can identify motion by diffusion and obtain the diffusion constant [4].

As a reshuffler, we develop a device with leads for skyrmion transport and a chamber where the reshuffling occurs. We evaluate its performance for the decorrelation of the input signal and find an uncorrelated output signal while keeping the stream's mean value with high fidelity showing the applicability of skyrmions for information processing in stochastic computing approaches.

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Type-II Weyl semimetals – spin-polarization, impurity scattering, and a polar instability

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Weyl semimetals are a new class of materials which host topologically protected crossings in their bulk electronic structure. Recently, a Lorentz-invariance broken version of these topological semimetals, so called type-II Weyl semimetals, have been discovered in the $MoTe_2$ class of inversion-symmetry-broken materials. These crystals show very high mobility, a strong magnetoresistance and more exotic phenomena like the chiral anomaly, which forms a promising platform for radically new technology based on topological materials.

To fully exploit their potential in the future, a microscopic understanding of the Weyl phase in terms of their nature of the phase transition and the functional response to impurities is needed. Here, we focus on the theoretical side of our joint theoretical and experimental investigations of the type-II Weyl semimetal candidates $MoTe_2$ and WTe_2 [1,2]. We discuss evidences for a polar instability near the structural transition from the topologically trivial phase to the non-centrosymmetric Weyl phase in $MoTe_2$ [1]. This is deduced from the spin-texture observed by spin- and angle-resolved photoemission spectroscopy experiments in the bulk Fermi surface in combination with our first principles calculations.

Furthermore, we explore the two extreme cases of the Weyl semimetal phase diagram by studying the response of both surface and bulk states to perturbations in both topologically trivial WTe_2 and the stable Weyl phase in $MoTe_2$ [2]. Our density functional theory calculations together with scanning tunneling microscopy experiments allow us to uncover the existence of a universal response of surface- and bulk-derived topologically protected quasiparticles, i.e., Fermi arcs and Weyl points of the Weyl semimetal.

Overall, our observations provide a unifying picture of the type-II Weyl phase diagram.

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Skyrmion meets magnetic tunnel junction: an efficient way for electrical skyrmion detection investigated by ab initio theory

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Building devices based on skyrmions requires a sufficiently sensitive detection method. The most straightforward way would be a device based on tunnel magnetoresistance, where a second magnetic electrode has to be used. However this approach is not practical since the magnetic counter electrode is most likely going to interfere with the skyrmion. This issue can be overcome by nonmagnetic counterelectrodes, which detect skyrmions from their non-collinear magnetization. Up to now, skyrmion induced non-collinear effects on transport were only investigated for STM tips based on the Tersoff and Hamann model, reaching about 20% [1] for specific energies.

In our work we examine the effects of skyrmions on electronic transport in Cu/Fe/MgO/Cu, Cu/Fe/MgO/V and V/Fe/MgO/Cu tunnel junctions, incorporating the influence of the barrier and the non-magnetic reference electrode material. Using our KKR based NEGF code [2], we show that non-collinear effects on transport strongly depend on the material of the leads, beyond energy dependent variations in the density of states. While for the copper electrodes only a variation in conductivity of a few percent can be reached, for vanadium the effect reaches up to 125% and is large over a wide energy range. The calculated large effect for vanadium is quite surprising and motivates further investigation.

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Domain wall based spin-Hall nano-oscillators

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In the last decade, two revolutionary concepts emerged in nano-magnetism from research for advanced information processing and storage technologies. The first suggests the use of magnetic domain walls (DWs) in ferromagnetic nanowires to permanently store information in DW racetrack memories. The second proposes a hardware realisation of neuromorphic computing in nanomagnets using nonlinear magnetic oscillations in the GHz range. Both ideas originate from the transfer of angular momentum from conduction electrons to localised spins in ferromagnets, either to push data encoded in DWs along nanowires or to sustain magnetic oscillations in artificial neurones. Even though both concepts share a common ground, they live on very different time scales which rendered them incompatible so far. Here, we bridge both ideas by demonstrating the excitation of magnetic auto-oscillations inside nano-scale DWs using pure spin currents.

How to generate whispering gallery magnons

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One of the most fascinating topics in current quantum physics are hybridized systems, in which resonators of different quantum systems are strongly coupled. Prominent examples are circular resonators with high quality factors that allow the coupling of optical whispering gallery modes to microwave cavities or magnon resonances. However, the coupling to magnons with finite wave vectors has not yet been achieved due to the lack of efficient excitation schemes.

Here, we present the generation of whispering gallery magnons with unprecedented high azimuthal wave vectors via nonlinear 3-magnon scattering in a µm-sized magnetic disk exhibiting a vortex state. These modes show a strong localization at the perimeter of the disk and practically zero amplitude in an extended area around the vortex core. They originate from the splitting of the fundamental radial magnon modes, which can be resonantly excited in a vortex state by an out-of-plane microwave field. We will shed light on the basics of this non-linear scattering mechanism from experimental and theoretical point of view. Using Brillouin light scattering (BLS) microscopy, we investigated the frequency and power dependence of this nonlinear mechanism. The spatially resolved mode profiles give evidence for the localization at the boundaries of the disk and allow for a direct determination of the modes' wavenumbers. Furthermore, time resolved BLS in combination with pulsed microwave excitation revealed the temporal evolution of the 3-magnon splitting and its dependence on the applied microwave power.

Financial support from the Deutsche Forschungsgemeinschaft within programme SCHU 2922/1-1 is gratefully acknowledged. Samples were prepared at the Nanofabrication Facilities (NanoFaRo) at the Institute of Ion Beam Physics and Materials Research at the Helmholtz-Center Dresden-Rossendorf (HZDR). K.S. acknowledges funding within the Helmholtz PostDoc Programme.

A micromagnetic model for ultrafast spin current-driven magnon dynamics

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Recent experimental reports have demonstrated that optically induced femtosecond spin currents can excite coherent magnon dynamics in the THz frequency range.[1,2] Here I will present a simple micromagnetic (numerical and analytical) model for this process. [3] The basic ingredient of this practically 1d model is a Slonczewski-like spin-transfer torque term. With this, we can reproduce the salient features of the experiments presented in reference [1]. Furthermore, the model provides insight into the factors which govern the spin wave mode-specific excitation efficiency. Lastly, I will show results for a collinear spin injection geometry. Our modelling shows that then, a thermally occupied magnon ensemble can be heated or cooled on fs time-scales. HU acknowledges financial support by the DFG within project A06 of the SFB 1073.

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Investigation of relaxation and decoherence in closed quantum spin systems

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Magnetic molecules are considered as promising constituents of quantum simulators or quantum computers. At low temperatures the magnetic levels of molecular nanomagnets enable the use as qubits. For such an application the investigation and understanding of decoherence caused by external and internal effects is very important. We perform time evolutions of the overall system, including qubits and bath spins. For now, we think of one qubit in a central spin model and consider the other N spins as bath. As the initial state we choose a product state of qubit and bath and visualize decoherence as decay of non-diagonal elements of the reduced density matrix and perform Loschmidt echos. We examine the behavior of the qubit as a function of the considered interactions (SU(2) symmetric or dipolar) and the properties of the (nuclear) spin bath.

All-optical magnetization switching of FePt magnetic recording media

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On the way to spin based information processing, magnetization manipulation is an indispensable tool. The fastest established techniques to trigger magnetization dynamics processes are based on femtosecond laser pulses. There, the speed of ultrafast magnetization is determined by the energy transfer from the laser excited electrons to the spins.

A special material of interest for magnetic storage development is FePt. In a seminal experiment, all optical writing was demonstrated for FePt nanoparticles of a magnetic hard disc media, by Lambert et al. in Science 2014. This opened many questions in the search about the extension of possibilities for all optical writing as a general mechanism.

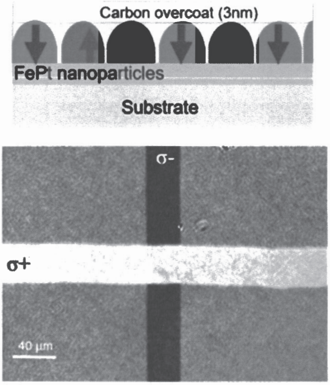

Figure 1 *Schematics of the FePt grains with up/ down magnetization entering our rate model. Below: Writing and overwriting of a magnetization in the FePt-medium, starting from the demagnetized medium.*

Meanwhile writing experiments by single laser spots point to an asymmetric writing per shot. This is consistently observed by different groups. In the current understanding, supported by ab-initio calculations of the optical effects (inverse Faraday Effect and magnetic dichroism induced heating) together with thermal modeling, the switching rates of individual FePt nanoparticles is calculated. The latter provides a switching rate of an FePt particle ensemble. The different processes are traced from the beginning of the laser pulse impact. Additionally, this theoretical description allows optimizing the number of shots necessary to turn the FePt nanoparticle magnetization and to pinpoint how all-optical writing can be optimized. All-optical writing of magnetic memory is a potential application in the future.

An Orbitally-Derived Single Atom Memory

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Single atoms at the surfaces of solids have demonstrated rich electronic [1], chemical [2] and magnetic [3-5] properties. In this direction, we show that we can manipulate the valency of a single cobalt atom on a crystalline black phosphorus surface. Using the local electric field generated from an STM tip, individual cobalt atoms residing at the same hollow site can be reversibly switched between two stable states (Fig. 1), which correspond to the different valencies. Consistency between experimentally observed charge densities and density functional theory calculations reveal distinct high and low total magnetic moments for each state. We investigate the stability of each configuration, as well as compare the experimentally measured impurity states with DFT calculations. Finally, we probe the switching dynamics to determine the underlying mechanism and energy scale of the switching. This system opens up the horizon to explore complex memory based on both the orbital and spin degrees of freedom.

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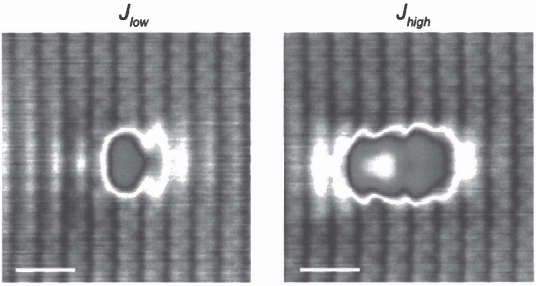

Figure 1: Cobalt on Black Phosphorus in J_{low} and J_{high} configurations.

Spin torque excitation of spin waves at the yttrium iron garnet / cobalt interface

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The field of magnonics is concerned with the use of spin waves (magnons) for information processing applications. Magnonics based on exchange spin waves is particularly appealing, as exchange spin waves have isotropic dispersion with small wavelengths and large group velocities. However, the excitation of exchange spin waves by conventional nanolithographically defined microwave antennas is inefficient due to high ohmic losses and impedance mismatch.

Here, we show that exchange spin waves with wavelengths as small as 50 nm can be efficiently excited by interfacial spin torques in YIG/Co heterostructures [1]. To this end, we excite YIG/Co thin film bilayers by a quasi-uniform, magnetic driving field in the GHz frequency range using a broadband magnetic resonance technique at room temperature. We study YIG/Co(50 nm), YIG/Cu(5 nm)/Co(50 nm) and YIG/AlOx(1.5 nm)/Co(50nm) bilayers, all based on 1 μm thick YIG films grown by liquid phase epitaxy. We observe an efficient excitation of perpendicular standing spin waves (PSSWs) in the YIG layer, when the resonance frequencies of the YIG PSSW and Co ferromagnetic resonance (FMR) coincide. PSSW excitation is also observed in YIG/Cu/Co trilayers, but not in YIG/AlOx/Co. Our data are very well described in the context of a modified Landau-Lifshitz-Gilbert model that takes interfacial spin torques and direct exchange coupling into account.

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All-electrical control of spin transport in a three-terminal yttrium iron garnet/platinum nanostructure

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In modern day information technology, the manipulation of charge currents is of key importance. This manifests itself in the worldwide usage of transistor components in almost any technological device. However, we gradually approach the technological limits of devices based on electron transport. Thus, novel routes for information processing are currently explored. Among them, the field of spintronics, and in particular the transport of information via spin waves (magnons) in ferromagnetic materials, provide novel, intriguing pathways towards information processing and manipulation beyond charge-based semiconductor technology.

In this study, we report on a high performance device enabling the transport and control of magnon spin currents over a large signal range. To this end, we utilize three electrically isolated platinum (Pt) electrodes deposited on an ultrathin (13 nm thickness) yttrium iron garnet (YIG) film. Magnon excitation is achieved via spin torque upon applying a low frequency AC current to an injector electrode. The excited magnons diffuse and are detected as the first harmonic Lock-In signal at a second Pt electrode (detector). The third electrode, the modulator, is deposited in between the injector and detector contacts and is sourced with a DC current. In this way, we are able to increase the magnon spin conductance in the YIG by up to 60% per mA. Moreover, and most interestingly, we find a highly non-linear regime indicating a threshold behavior of the spin conductance modulation.

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Dynamic control of magnon cavity coupling

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Cavity-magnon-polaritons are hybrid modes consisting of magnon and photon excitations, and are expected to pave ways for microwave applications ranging from magnon gradient memory [1] via microwave photon transducers to magnonics. The underlying physics for these applications are magnon Rabi oscillations [2], the coherent energy exchange between magnonic and photonic subsystems. Static and dynamic control of the coupling strength between these two quasi-particles is imperative for future devices. This control is realized with an additional second drive tone directly applied to the magnon. Depending on the relative phase and amplitude ratio between the two tones, the coupling can be even turned off completely in a steady state experiment [3,4].

In our work, as the next step, we are implementing a dynamic control of the coupling on time scales similar to the exchange time. Using a heterodyne detection setup with single-sideband mixing, we are able to apply independent control pulses to magnon and cavity while recording time traces of the cavity response. For phase and amplitude matched excitations to magnon and cavity, both oscillators will “swing” in-phase and no energy exchange will take place, similarly to coupled mechanical pendulums. Stopping one oscillator with another pulse starts the magnon Rabi oscillations again. With this technique, a magnon excitation could be stored in a long living cavity mode and stabilized with a few short pulses over time.

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Reconstruction of ultrafast magnetization dynamics in optically excited Fe films from emitted THz signals

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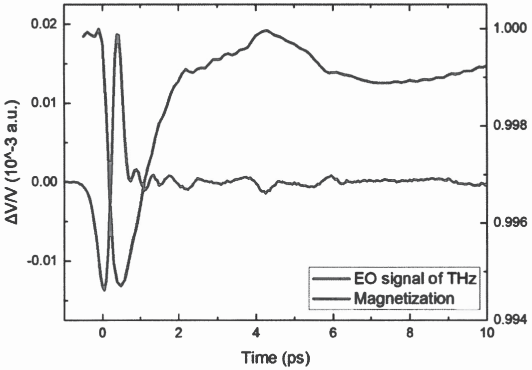
THz emission spectroscopy is a powerful tool to access the ultrafast magnetization dynamics in laser-excited magnetic systems. In this presentation we demonstrate that it is possible to rigorously reconstruct the (sub)picosecond-timescale magnetization dynamics in a Fe nanofilm, excited by an 800 nm, 100 fs laser pulse, from the electrooptic signal measured in the far field, and corresponding to the magnetically-driven THz emission from the laser-excited nanofilm. We numerically model the complex propagation of the THz field from the surface of the sample to the THz electrooptic sampling unit, as well as the process of electrooptic sampling itself. As a result, a complex transfer function is established, that allows us to establish the ultrafast magnetization dynamics in the laser-excited sample in a calibrated manner.



Fart-field electrooptic signal of the THz transient, emitted from a laser-excited Fe nanofilm (red line), and the reconstructed transient magnetization dynamics in the nanofilm (green line).