Magnetic North V

Magnetism at Surfaces, Interfaces and in Nanostructures

Colorado Springs, June 26-30 2016

Workshop Details
and
Abstract Booklet

Welcome

Welcome to Magnetic North V, **Magnetism at Surfaces, Interfaces and in Nanostructures**, which is being held at the University of Colorado at Colorado Springs (UCCS). We have an exciting array of talks, with two tutorial talks scheduled for Sunday afternoon, and invited and contributed talks to be held Monday through Thursday morning.

In addition we have some special features for this conference. On Monday and Wednesday afternoons we will have a combined Bierstube and poster session. Tuesday will feature an excursion (bus transportation provided) to the Garden of the Gods, a National Natural Landmark with dramatic red rock formations, followed by the Conference Banquet (bus transportation provided) at the Margarita at Pine Creek.

On the following pages you will find

1) Travel tips, Campus Info and Maps
2) Program Overview for the conference and for each day of the conference
3) Abstracts

We hope you will have a good, informative, and interesting visit.

Organizing Committee
Karen Livesey, Robert Camley, Zbigniew Celinski, & Martin Plumer
http://www.magneticnorth.mun.ca/MagNorthV/

We would like to sincerely thank our generous sponsors:

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IEEE MAGNETICS

nsor of the Magnetic North V banquet

Travel tips

Local transport:

- Uber
- Springs Cab (719)-444-8989
- PHATUP (719) 966-7204
- A UCCS shuttle travels between Campus and the University Village restaurants until 10:30pm Monday-Friday. The bus stop is outside Centennial Hall (CENT on map). The bus schedule is at: http://www.uccs.edu/pts/transportation/shuttle-schedules/bus-schedule.html

Transport to Denver Airport DIA (approximately 1.5 hours):

- Front Range Shuttle (719) 237-2646
- Colorado Springs Shuttle (719) 687-3456
- Bustang to Denver Union Station, then train to DIA

Suggested tourist activities:

- Climb The Incline (gradient 66%) in Manitou Springs
- Taste the spring waters in Manitou Springs
- Drive to the top of Pikes Peak, America's Mountain
- Take the Cog Railway instead to the top of Pikes Peak, America's Mountain
- Watch the Pikes Peak Hill Climb (100th anniversary motorsport event, 26th June)
- Hike in one of the many city parks (Palmer, Ute Valley, Black Forest)
- Learn about the pioneers at Rock Ledge Ranch
- Visit Glen Eyrie castle (reservations needed)
- Visit America's only mountain-side zoo, Cheyenne Mountain Zoo
- Try one of many local microbreweries (Bristol, Red Leg, Trinity, etc)
- Other suggestions:
    - Woodland Park (mountain town)
    - Cripple Creek (gold mining, gambling)
    - Horseback riding

Dealing with altitude:

- Drink plenty of water
- Don’t over-exert yourself and take plenty of water hiking/biking
- The sun is stronger here! Wear hats and sunscreen.

Campus and registration details

All sessions will take place in **Columbine Hall, Room 128**.

Registration, coffee, bierstube and posters will all be in the corridors and the apse outside Room 128.

<u>Registration</u> will be open **2-6pm on Sunday**.
It will open again at **8am on Monday**.

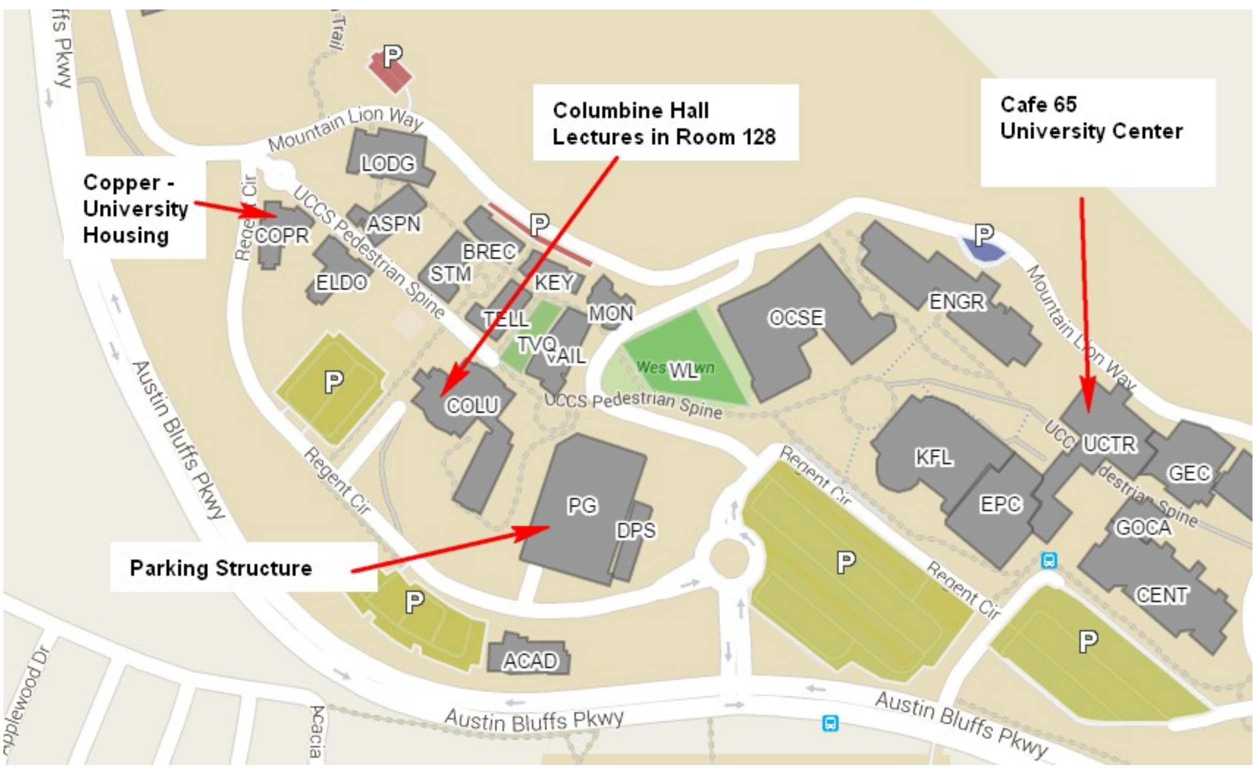
Lunches will be in **Café 65**, in University Center, a 5 minute walk across campus.

For those staying off campus, please note that parking is in the multi-level parking structure next to Columbine Hall and must be paid for.

For those staying on campus, rooms are in the **Copper Building**.

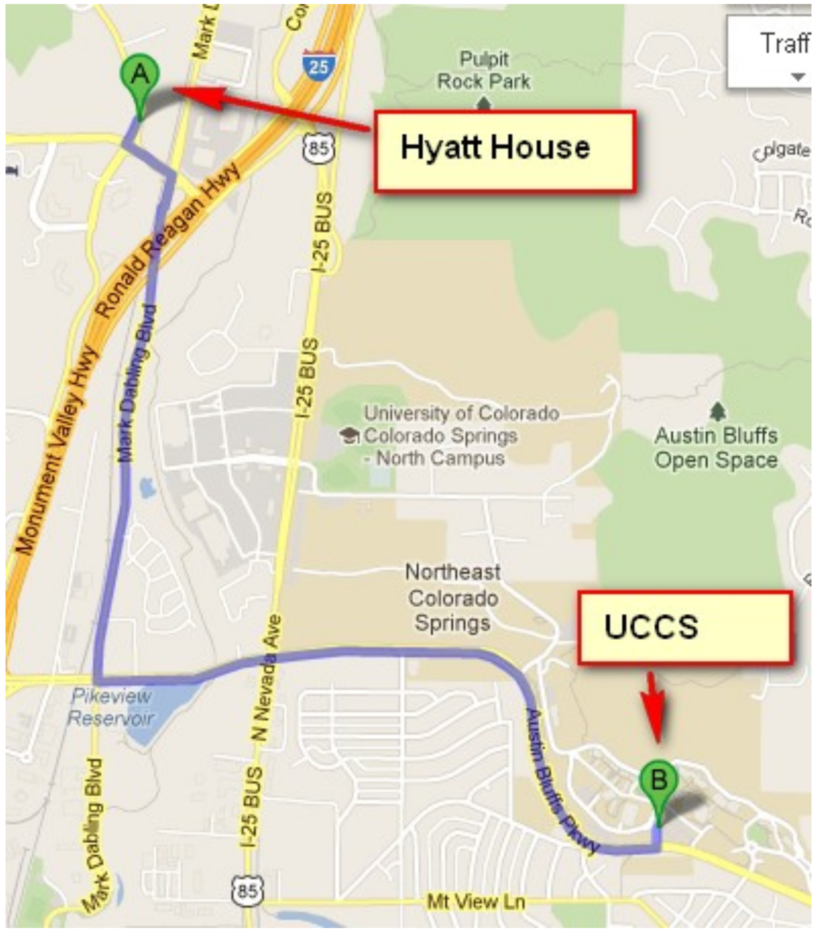
<u>Internet access for conference attendees:</u>
Select UCCS wireless network (not UCCS Info).
Username: g-c6791
Password: 8844

Local Map of UCCS



Directions to campus

Directions to UCCS from Hyatt House:



Take Delmonico Dr south.

At the lights, turn left onto Rockrimmon from the right-hand lane.

Immediately turn right at lights onto Mark Dabling Blvd (under the rail bridge).

After a while, at the first set of lights, turn left onto Garden of the Gods Rd that becomes Austin Bluffs Parkway. UCCS will be on your left, at the top of the hill.

Conference at a Glance

	Sunday June 26	Monday June 27	Tuesday June 28	Wednesday June 29	Thursday June 30
8:50		Intro remarks Karen/Martin			
9:00		Nanofabricated particles Chair: Camley **9:00 Novosad** (invited) **9:40 Zabow** (invited)	Miscellaneous Chair: Buchanan **9:00 Hojem** **9:20 Venus** **9:40 Przybylski**	Ultra-fast dynamics Chair: Silva **9:00 Nowak** (invited) **9:40 Plötzing** **10:00 Adam**	Novel exchange bias Chair: Cortie **9:00 Binek** (invited) **9:40 Plumer** **10:00 Budi**
10:00			10:00 Coffee		
10:20		10:20 Coffee	Assembled NPs Chair: Mefford **10:20 Crawford** (invited) **11:00 Whitehead** **11:20 VanLierop** (invited)	10:20 Coffee	10:20 Coffee
10:40		Nanoparticles Chair: Livesey **10:40 Moreland** (invited) **11:20 Mefford** **11:40 Skoropata** **12:00 Rice**		Dynamics 1 Chair: Iococca **10:40 Stamps** (invited) **11:20 Wysin** **11:40 Riley**	Dynamics 2 Chair: Plumer **10:40 Buchanan** (Invited) **11:20 Iococca** **11:40 Lougovski** **12:00 Cortie**
12:00			12:00 Lunch 1:00 Lab tour, or Hike on the bluffs	12:00 Lunch	
12:20		12:20 Lunch			12:20 Concluding remarks Lunch + Farewell
2:00	Registration opens	SO torque 1 Chair: Venus **2:00 Majetich** (invited) **2:40 Wu** (invited)	FMR to probe nanostructures Chair: Fan **2:00 Menard** (invited) **2:40 Cottam** (invited)	Novel expt techniques Chair: Celinski **2:00 Silva** **2:20 Losby** **2:40 Edwards** **3:00 Burgess**	Lab tour/hike for those who have time
3:00	**Tutorials** Chair: Livesey **3:00 Majetich** Magnetic Particles **4:00 Stamps** Thin Film Chiral Magnets				
3:20		3:20 Coffee + poster session A set-up	3:20 Coffee	3:20 Coffee + poster session B set-up	
3:50		SO torque damping Chair: Zink **3:50 Victora** (invited) **4:30 Janantha**	3:45 Excursion Then bus to banquet dinner	SO torque 2 Chair: Rice **3:50 Ross** (invited) **4:30 Evarts**	
5:00	Welcome reception 1 hour Form dinner groups	Poster session A & Bierstube Chair: Spendier 4:50-6:00		Poster session B & Bierstube Chair: Hankiewicz 4:50-6:00	

Program Overview

Sunday – Tutorial Sessions

3:00 Applications of magnetic particles, S. Majetich (invited)
4:00 An Introduction to Thin Film Chiral Magnets, R. L. Stamps (invited)

Monday Program

Monday Morning I – Nanofabricated particles, Chair: Camley
9:00 Multifunctional Ferromagnetic Particles, Valentine Novosad (invited)
9:40 Dynamic magnetic nanostructures as RF-addressable sensors, Gary Zabow (invited)

10:20 Coffee

Monday Morning II – Nanoparticles, Chair: Livesey
10:40 Prospects for ultra-low field magnetic imaging agents in medicine, John Moreland (invited)
11:20 Beyond Magnetite: Evaluation of Substituted Ferrites in MagMED, O. Thompson Mefford
11:40 Core-shell nanoparticle magnetism: The impact of interfacial intermixing, E. Skoropata
12:00 Revealing giant internal magnetic fields due to spin fluctuations in magnetically doped colloidal nanocrystals, William Rice

12:20 Lunch

Monday Afternoon I - Spin orbit torque 1, Chair: Venus
2:00 Conductive atomic force microscopy of magnetic tunnel junctions, Sara Majetich (invited)
2:40 Photo-Spin-Voltaic Effect, Mingzhong Wu (invited)

3:20 Coffee + poster session A set-up

Monday Afternoon II - Spin orbit torque, damping, Chair: Zink
3:50 Theoretical predictions of damping in high perpendicular magnetic anisotropy materials for nanostructured applications, R. Victora (invited)
4:30 The Roles of Damping in Spin Seebeck Effect in Yttrium Iron Garnet Thin Films, Praveen Janantha

Monday Program (continued)

4:50 - 6:00 Poster session A & Bierstube   Chair: Spendier

A1 Alghamdi, Magnetic Metallic Alloy Structures as a Temperature Contrast Agent in Magnetic Resonance Imaging

A2 Anderson, Why do magnetic nanoparticles agglomerate isotropically?

A3 Chang, Growth of high-quality $Y_3Fe_5O_{12}$ thin films on platinum via sputtering

A4 Fani Sani, Shape and smoothness of a core-shell monocrystalline YIG microdisk inferred from FMR spectroscopy

A5 Humphries, Detection of thermoelectric contributions in ferromagnetic/normal-metal bilayer devices for accurate spin-orbit torque analysis

A6 Janantha, Foldover of Nonlinear Eigenmodes in Magnetic Thin Film-Based Feedback Rings

A7 Li, Study of the rectification effect in the resonant cavity-based spin pumping technique

A8 Liu, Anomalous Anisotropic Magnetoresistance in Ultrathin Ta Films Grown on $BaFe_{12}O_{19}$

A9 Novosad, Spin vortex resonance in non-planar ferromagnetic dots

A10 Omelcheko, Study of spin transport in tantalum using magnetic single and double layers

A11 Smith, Using magnetic nanoparticles in a static and dynamic magnetic field to penetrate model mucus

A12 Stroud, Heating tissue by radio-frequency for hyperthermia therapy

Tuesday Program

Tuesday Morning - Various Topics, Chair: Buchanan

9:00 Anomalous Nernst effects in metallic nonlocal spin valves, Alex Hojem

9:20 Local vs. global manifestation of a surface phase transition, David Venus

9:40 Mössbauer spectroscopy of nanostructures – theory and experiment, Marek Przybylski

10:00 Coffee

Tuesday Morning II – Assembled Nanoparticles, Chair: Mefford

10:20 Triggered self-assembly of magnetic nanoparticles, Mas Crawford (invited)

11:00 Micromagnetic simulations of maghemite nanoparticles in FCC arrays, John Whitehead

11:20 Ill-condensed matter 2: Magnetic order from disorder with nanoparticles, Johan Van Lierop (invited)

12:00 Lunch

1:00 Lab tour, or Hike on the bluffs

Tuesday Afternoon I - FMR to probe nanostructures, Chair: Fan

2:00 Ferromagnetic resonance and strong coupling phenomena in arrays of ferromagnetic nanowires, David Menard (invited)

2:40 Interface coupling of spin waves in permalloy/Ru/permalloy multilayered nanowires: FMR and theory, Michael Cottam (invited)

3:20 Coffee

3:45 Tuesday Afternoon - Excursion to the Garden of the Gods (bus provided)

5:45 Buses leave Garden of the Gods

6:00 Conference Banquet (bus transportation provided)

Wednesday Program

Wednesday Morning I - Ultra-fast dynamics, Chair: Silva

9:00 Ultrafast laser control of magnetic materials, Ulrich Nowak (invited)
9:40 Electron and spin dynamics during ultrafast laser-induced demagnetization in Co/Cu(001), M. Plötzing
10:00 Element-selective investigation of the spin dynamics in NixPd1-x magnetic alloys in the extreme ultraviolet spectral range, Roman Adam

10:20 Coffee

Wednesday Morning II - Dynamics 1, Chair: Iococca

10:40 Dynamics of chiral spin systems: soliton lattices, defects and spin waves, R. L. Stamps (invited)
11:20 Vortex dynamics and statistics in thin elliptic ferromagnetic nanodisks, G. M. Wysin
11:40 Thermal control of spin wave propagation in Yttrium Irion Garnet (YIG) thin films, Grant A. Riley

12:00 – 2:00 Lunch

Wednesday Afternoon I - Novel experimental techniques, Chair: Celinski

2:00 Phase-sensitive inductive detection of ac currents due to spin-pumping /inverse spin orbit torques in unpatterned Permalloy/Pt bilayers, Tom Silva
2:20 Torque-mixing magnetic resonance spectroscopy, J. E. Losby
2:40 Michelson Microwave Interferometer for Broadband Ferromagnetic Resonance Experiments, Eric Edwards
3:00 Magnetic properties of Fe4 molecules compressed in the junction of a scanning tunneling microscope, Jacob Burgess

3:20 Coffee + poster session B set-up

Wednesday Afternoon II - Spin orbit torque 2, Chair: Rice

3:50 Electrical control of magnetization in ferrimagnetic insulator nanostructures, Caroline Ross (invited)
4:30 Three-terminal spin-torque oscillator devices using MgO-based magnetic tunnel junctions, Eric Evarts

4:50 - 6:00 Poster Session B & Bierstube, Chair: Hankiewicz

B0 Anderson, Temperature dependent magnetization in bimagnetic nanoparticles with antiferromagnetic interfacial exchange

B1 Bennet, Large spin hall angles in permalloy/gold heterostructures resulting from iron impurities

B2 DeJong, Bloch versus Néel domain walls in rectangular magnetic nanowires

B3 Ding, Growth of Nanometer-Thick Low-Damping Yttrium Iron Garnet Films by Sputtering

B4 Firdous, Torque Magnetometry and Susceptometry using Split-Beam Optomechanical Nanocavities

B5 Goldman, Permalloy thin film layers as coating materials for on-wafer inductors at radio and low GHz frequencies

B6 Haghshenasfard, Parallel pumping for ferromagnetic nanowires and nanotubes with circular cross sections

B7 Liu, Growth of $BaFe_{12}O_{19}$ Thin Films via Sputtering and Spin Transfer across $BaFe_{12}O_{19}$/Pt Interfaces

B8 Parsons, Magnonic Bragg mirror based on a stack of identical bi-layered ferromagnetic nanowire segments

B9 Przybylski, Effect of electron confinement on magnetism of nanostructures

B10 Richardson, Study of Grain-to-Grain Exchange Coupling in Perpendicular Magnetic Recording Media via FMR

B11 Wesenberg, Thermal gradients, Nernst effect, hall effect, and new limits on spin-current generation in metallic ferromagnets using suspended thermal platforms.

B12 Yarbrough, Ferromagnetic resonance power absorption by a magnetic nanowire

Thursday Program

Thursday Morning I - Novel exchange bias,   Chair: Cortie

9:00 Voltage-controlled exchange bias: A building block for ultra-low power memory and logic device applications, C. Binek (invited)

9:40 Monte Carlo simulations of ABC stacked kagome lattice thin films, M. Plumer

10:00 Exchange Bias in $CoFe_2O_4$-$BiFeO_3$ Nanofibers; Examining the Role of Phase Connectivity and Composition in Materials with High Shape Anisotropy, M. Budi

10:20 Coffee

Thursday Morning II - Dynamics 2,   Chair: Plumer

10:40 Spin waves interactions at an intersection: the role of an antivortex, K. Buchanan (Invited)

11:20 Dispersive hydrodynamics in ferromagnets, Iococca

11:40 Thermodynamic implications of spin impurities on scalability of silicon-based quantum computing, Lougovski

12:00 The magnetic surface states of antiferromagnets and correlated topological insulators probed with β-NMR, Cortie

12:20 Concluding remarks, Lunch + Farewell

2:00 Lab tour/hike for those who have time

Sunday Tutorial I, 3:00

Applications of Magnetic Particles

Sara A. Majetich
Department of Physics, Carnegie Mellon University, Pittsburgh, PA, USA

In 1930 Francis Bitter dusted fine magnetic particles on a ferromagnet to demonstrate the existence of magnetic domains; since that time the ability to disperse and control movement of magnetic nanoparticles has been important for many applications. Following a brief introduction to magnetic particles, we will survey a number of their applications. There will be a brief description of a range of applications of magnetic particles, explaining for each case the type of particles that are commonly used and how they work in the particular application. We will discuss the important magnetic characteristics, as well as the non-magnetic requirements that affect the design of magnetic particles. This survey will include ferrofluids, magnetorheological fluids and elastomers, magnetic anti-counterfeiting measures, and magnetic recording media. Magnetic particles have also found extensive application in biomedicine, since relatively high magnetic fields can be used without adverse effects on physiological processes. Examples include magnetic resonance imaging (MRI) contrast agents, magnetic beads for separation, nanoparticles for gene transfection, and magnetic hyperthermia cancer treatment.

Sunday Tutorial II, 4:00

An Introduction to Thin Film Chiral Magnets

R. L. Stamps
SUPA School of Physics and Astronomy, University of Glasgow, Glasgow, G128QQ, UK

Chiral magnetism has been studied for decades. Although chiral ordering of spins can occur in many systems, systems in which preferred chirality occurs are especially interesting. A variety of complex non-colinear spin structures can occur, and one of the most curious is the so-called skyrmion phase. Until recently nearly all examples of these types of systems were natural crystals lacking inversion symmetry. There are now many reports and studies of complex spin structures, including skyrmions, observed to occur in thin film geometries. Moreover, it may now be possible to create thin metallic films able to support magnetic skyrmions at room temperatures via interface engineering. This talk will provide a summary overview of magnetic states in helicoidal systems, and outline some of the key questions surrounding the appearance of skyrmions in thin films, high resolution measurements of skyrmion profiles, and allowed cone state and soliton lattice phases in monoaxial helicoids.

Multifunctional Ferromagnetic Particles

Valentine Novosad [a], and Elena A. Rozhkova [b]
[a] *Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[b] *Center for Nanoscale Materials, Argonne National Laboratory, Argonne, IL 60439, USA*

Nanoengineered magnetic materials are widely employed in fundamental studies and applied research. While the mainstream of reports deals with chemically synthesized superparamagnetic particles on the order of tens of nanometers or their conjugates [1, 2], an alternative approach based on the top-down physical methods commonly used in microelectronics is also of interest [3 - 5]. Microfabricated particles can be designed to possess higher values of the magnetization of saturation while maintaining almost no net magnetization in the absence of magnetic field due to formation of non-uniform magnetization [3] or antiferromagnetic [4] ground states. Compared to wet chemistry synthesis, lithographic methods allow for precise controlled fabrication of particles with virtually any size, shape and composition [5]. Physical vapour deposition, compatible with most types of photoresists, offers a wide choice of materials available. In this talk we will discuss the basic mechanisms governing their magnetic properties, as well as review some of the recent attempts to employ such particles for the MRI contrast enhancement, targeted drug delivery, cells separation, hyperthermia, and magneto-mechanical actuation.

The work at Argonne National Laboratory were supported by U Chicago Argonne, LLC, Operator of Argonne National Laboratory (``Argonne''). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357.

[1] D.-H. Kim, E.A Vitol, J Liu, *et al*., "Stimuli-responsive magnetic nanomicelles as multifunctional heat and cargo delivery vehicles", *Langmuir* **29** (24), 7425-7432.
[2] E. A. Vitol, *et al.,* "Efficient cisplatin pro-drug delivery visualized with sub-100 nm resolution: interfacing engineered thermosensitive magnetomicelles with a living system", *Advanced Materials Interfaces,* ***1,*** *1400182. doi: 10.1002/admi.201400182.*
[3] E. A. Rozhkova *et al*., "Ferromagnetic microdisks as carriers for biomedical applications", *Journal of Applied Physics,* **105**, 07B306.
[4] W. Hu, *et al*., "High-moment antiferromagnetic nanoparticles with tunable magnetic properties", *Advanced Materials*, **20**, 1479-1483.
[5] E. A. Vitol, V. Novosad, and E. A. Rozhkova, "Microfabricated magnetic structures for future medicine: from sensors to cell actuators", *Nanomedicine* **7** (10), 1611-1624.

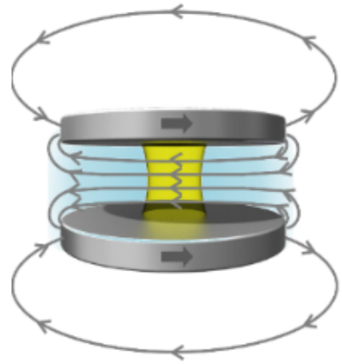
Dynamic magnetic nanostructures as RF-addressable sensors

Gary Zabow[a,b], Stephen Dodd[b], and Alan Koretsky[b]
[a] *Applied Physics Division, NIST, Boulder, Colorado, USA*
[b] *Laboratory of Functional and Molecular Imaging, NIH, Bethesda, Maryland, USA*

Magnetic nanoparticles already find much use in biomedical applications ranging from imaging, to drug delivery, to hyperthermia and even tissue engineering. But what if magnetic nanoparticles could also sense local physiological conditions in their immediate surroundings? What if magnetic particles could, for example, report back on local pH, or temperature, or *in vivo* analyte concentrations?

This talk introduces specially shaped, magnetic micro- and nanostructures incorporating 'smart' polymers that respond to chosen environmental conditions[1]. As the stimuli-responsive polymers change shape, so too does the magnetic microstructure, changing the resulting magnetic fields generated. These changing fields shift the resonant magnetic precession frequency of nuclei in the particle's surroundings (water hydrogen protons, for example), which can then be detected with regular nuclear magnetic resonance (NMR) equipment. In transducing the polymer response into an NMR frequency shift that can be detected remotely, the magnetic structures act as radio-frequency (RF) analogs to optical fluorescent or plasmonic colorimetric nanosensors. Because smart polymers can be specifically targeted, the same magnetic transduction platform should be adaptable to measure many different variables of interest. Such sensors may therefore offer similarly broad application to that of optical colorimetric sensors except, being probed in the RF, may also function in optically occluded locations, such as deep *in vivo.* As one example, we demonstrate RF-based pH sensing using an acid-sensitized hydrogel sandwiched between a pair of magnetic disks (Fig. 1), but this talk will also focus more generally on how such structures work and where else they may find application.

Figure 1: Schematic of shape-changing magnetic nanostructure. Expansion of a stimuli-responsive hydrogel (inner post) shifts a pair of attached magnetic disks changing the local fields, which shift the NMR frequencies of nuclei in the surrounding medium.



[1] G. Zabow, S. Dodd, A. Koretsky, *Nature* **520**, 73 (2015)

Prospects for ultra-low field magnetic imaging agents in medicine

John Moreland
National Institute of Standards and Technology, Boulder, CO 80303, USA

There are new opportunities for the application of magnetic thin-film structures and nanomaterials as smart tags for in-vivo medical imaging applications. Both microfabrication and chemical synthesis methods have advanced to the point that is possible to mass produce magnetic smart tags with specific geometries, materials, and unique gyromagnetic characteristics with nanometer scale reproducibility. There are some basic limitations that must be considered (see Fig. 1). First, the penetration depth for electromagnetic fields at frequencies above 1 GHz drops below 10 cm in the human body. Second, most magnetic materials become saturated at fields above 1 T which means the options for engineering their magnetodynamic properties are limited. The potential for applications of magnetic smart tags is expanding given the immergence of ultra-low field magnetic resonance imaging (ULF MRI) and magnetic particle imaging (MPI) as viable medical imaging modalities. I will discuss several prospects for fusing magnetodynamic phenomena with ULF MRI and MPI.

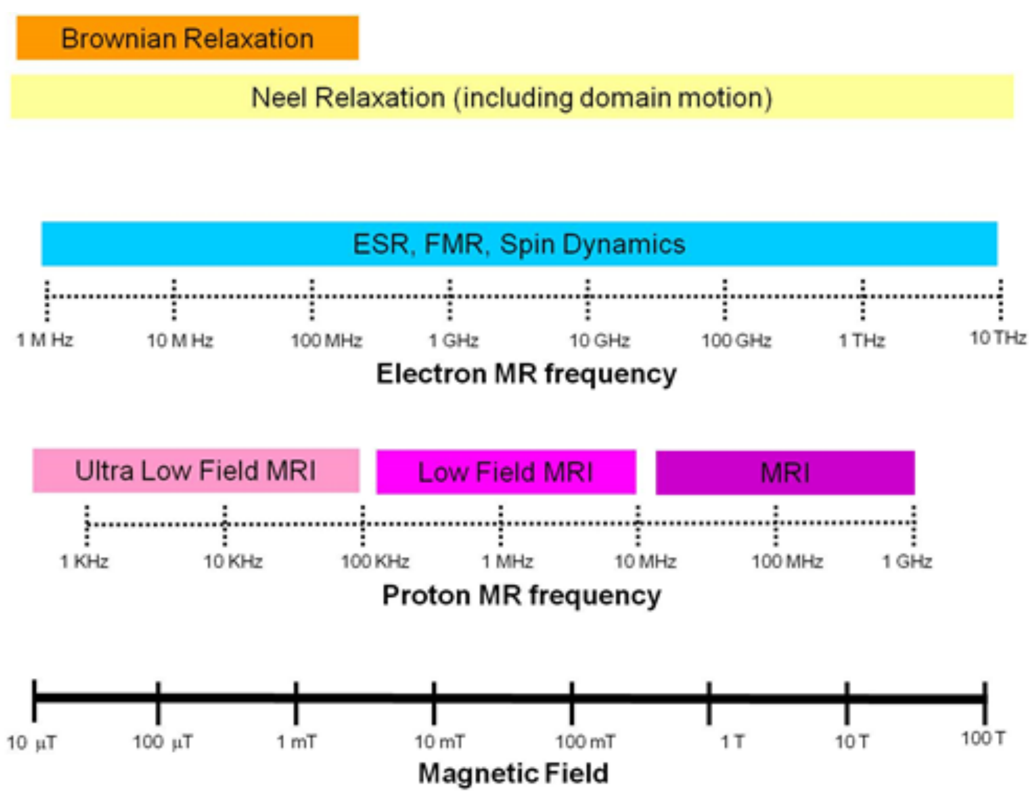


Figure 1 - Range of magnetodynamic phenomena that could be the basis for new smart tag imaging agents from 10 µT to 100 T. Note that for human imaging frequencies must be below 1 GHz due to the high specific absorption rate (SAR) at higher frequencies

Beyond Magnetite: Evaluation of Substituted Ferrites in MagMED

Benjamin D. Fellows [a], Jessica A. Bigner [a], Amy Goodling, Sarah Timmins [a], Ethan D. Kirkland [a], Martin Saunders[c], O. Thompson Mefford [a]*

[a] *Clemson Materials Science and Engineering Department, Clemson, SC 29634-0971, USA and Center for Optical Materials Science and Engineering (COMSET), Anderson, SC 29625, USA*

[b] *North Carolina State Materials Science and Engineering Department, 911 Partners Way, Raleigh, NC 27606, USA*

[c] *Centre for Microscopy, Characterization and Analysis, The University of Western Australia, Perth WA 6009, Australia*

In Magnetically mediated energy delivery (MagMED) an alternating magnetic field in applied to particles that have been delivered to targeted cells. The particles convert and deliver the energy of the field to the cells. Previously much of the work in this field has focused on iron oxide particles. Unfortunately, iron oxides lack sufficient magnetic saturation and effective magnetic anisotropy. Therefore, we have recently focused on improving the material properties of these particles by synthesizing substituted and doped ferrites. Specifically, we have focused on doping with various transition metals: copper, manganese, cobalt, nickel, and zinc. Monodisperse particles with predictable radii were synthesized using an extended LaMer model.[1] This required the production of metal oleate precursors, which were characterized with infrared spectroscopy (IR). In order to predict the size of the particles at a given time, the particles were synthesized and aliquots were taken at fifteen-minute time intervals. The particles in the aliquots were sized using dynamic light scattering (DLS) and these values were compared to sizes obtained by image analysis of selected images taken by transmission electron microscopy (TEM) (Figure 1). Specific absorption rate (SAR) values were calculated to determine the efficiency of energy conversion at a given field and frequency. Frequency response was determined using AC susceptibility. Findings indicate that doping of the ferrite particles result in increases in SAR efficiency. Notably, nickel and zinc ferrites were the most promising. Materials developed as part of this project have the potential for use in cancer therapy.

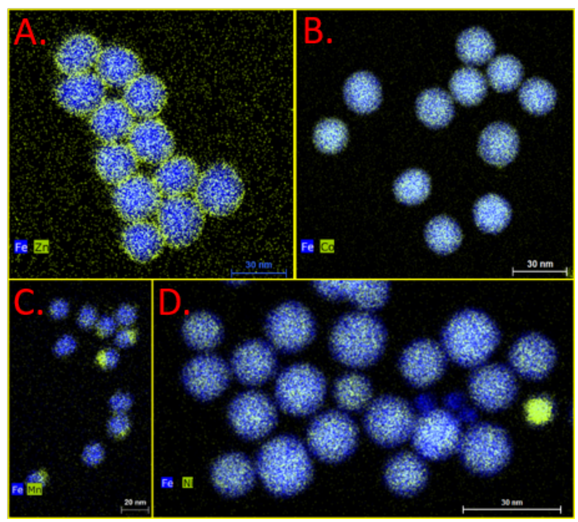


Figure 1. EDS maps of particles made using different metal acetyleacetonates. Fe is always in blue. A) Fe Zn, B) Fe Co, C) Fe Mn, D) Fe Ni.

1. Vreeland et al. Enhanced Nanoparticle Size Control by Extending LaMer's Mechanism. *Chemistry Of Materials* **2015**, *27* (17), 6059–6066

Core-shell nanoparticle magnetism: The impact of interfacial intermixing

E. Skoropata[a], R. D. Desautels[a], H. Ouyang[b], J. W. Freeland[c], and J. van Lierop[a]
[a] *Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba, Canada*
[b] *Department of Materials Science and Engineering, National Tsing Hua University, Hsinchu, Taiwan*
[c] *Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois, USA*

To understand the origin of the magnetic properties of core-shell nanoparticles necessitates a knowledge of core-shell intermixing effects; intermixed layers modify directly the disordered surface magnetism of the core particle, and determine the interfacial exchange interactions that mediate the magnetic coupling between core and shell. To investigate this issue, we report on the relationship between interfacial intermixing and magnetic properties of a series of γ-Fe_2O_3 based core-shell nanoparticles with Cu, CoO, MnO, and NiO shells. Using element specific techniques (Mössbauer spectroscopy, x-ray absorption spectroscopy (XAS) and x-ray magnetic circular dichroism (XMCD)), we identify an interfacial intermixed layer consisting of transition metal ions from the shell that substituted into the octahedral (O_h) and tetrahedral (T_d) sites of the γ-Fe_2O_3 core. For γ-Fe_2O_3/Cu and γ-Fe_2O_3/NiO, the intermixed layer consists of 2+ cations substituted into the O_h-sites exclusively. Interestingly, Cu and NiO shells had also similar effects on the nanoparticle magnetism, both resulting in an increased anisotropy (an enhanced H_C) while also reducing substantially the surface spin disorder intrinsic to γ-Fe_2O_3 cores (revealed by changes to H_{EX} and $M_S(T)$). By comparison, the interfacial layer in γ-Fe_2O_3/CoO contains predominantly Co^{2+} in O_h-sites and a slight T_d-site occupancy, resulting a large increase in intrinsic anisotropy and little effect on the γ-Fe_2O_3 surface spin disorder. For γ-Fe_2O_3/MnO, a mixture of Mn^{3+} O_h and Mn^{2+} T_d-sites revealed a more radical site substitution, which resulted in cooperative relaxation effects among the core and interfacial Fe-spins.

Revealing giant internal magnetic fields due to spin fluctuations in magnetically doped colloidal nanocrystals

William Rice[a,b], Wenyong Liu[c], Thomas Baker[c], Nikolai Sinitsyn[d],
Victor Klimov[c], and Scott Crooker[b]
[a] *Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071*
[b] *National High Magnetic Field Laboratory, Los Alamos National Laboratory, Los Alamos, NM 87545*
[c] *Chemistry Division, Los Alamos National Laboratory, Los Alamos, NM 87545*
[d] *Theory Division, Los Alamos National Laboratory, Los Alamos, NM 87545*

Strong quantum confinement in semiconductors can compress the wavefunctions of band electrons and holes to nanometer-scale volumes, significantly enhancing their interactions with individual dopants. In magnetically-doped semiconductors, where paramagnetic dopants (*e.g.*, Mn^{2+}) couple to band carriers via strong *sp-d* spin exchange, giant magneto-optical effects can therefore be realized in confined geometries using few or even single Mn^{2+} spins [1]. Importantly, thermodynamic spin fluctuations become increasingly relevant in this few-spin limit [2]. In nanoscale volumes, the statistical $N^{½}$ fluctuations of N spins are expected to generate giant effective magnetic fields $\mathbf{B}_{eff}$, which should dramatically impact carrier spin dynamics, even in the absence of any applied field. Here we directly observe the large fields $\mathbf{B}_{eff}$ that exist in Mn^{2+}-doped CdSe colloidal nanocrystals (NCs) using time-resolved Faraday rotation spectroscopy. At zero applied magnetic field, extremely rapid (>300GHz) spin precession of photo-injected electrons is observed, indicating $\mathbf{B}_{eff}$~15-30T for electrons. Precession frequencies exceed 2THz when magnetic fields are applied. These signals arise from electron precession about the random fields that arise from the statistically-incomplete cancellation of the embedded Mn^{2+} moments, thereby revealing the initial coherent dynamics of magnetic polaron formation and highlighting the importance of magnetization fluctuations on carrier spin dynamics in nanoparticles [3].

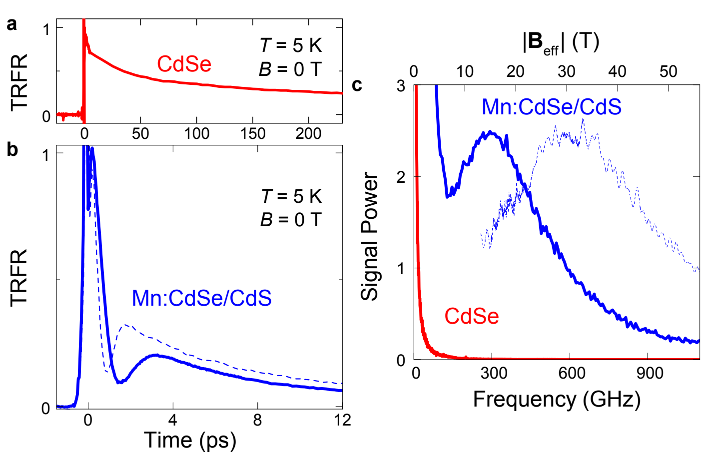


Figure 1: (a) Time-resolved Faraday rotation (TRFR) for undoped CdSe NCs. (b) In contrast to the simple exponential decay for CdSe NCs, a rapid, half-cycle precession at 0 T is observed for (bold line) lightly- and (dotted line) heavily-doped Mn:CdSe NCs. (c) Corresponding FFT powers of the signals show a zero-field, electron spin precession between 300 and 600 GHz that increases with increasing magnetic dopant concentration.

[1] L. Besombes et al., *Phys. Rev. Lett.* **93**, 207403 (2004).
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Conductive atomic force microscopy of magnetic tunnel junctions

Stephan K. Piotrowski[a], Mukund Bapna[a], Samuel D. Oberdick[a], and Sara A. Majetich[a]
[a] *Department of Physics, Carnegie Mellon University, Pittsburgh, PA, USA*

Magnetic tunnel junctions (MTJs) with thin CoFeB layers and perpendicular anisotropy can be switched at much lower current densities than those with thicker layers, in-plane anisotropy, and spin transfer torque reversal. The perpendicular anisotropy arises from the CoFeB/MgO interface and its magnitude depends on the applied voltage. Low power MTJs would be more compatible with existing CMOS transistors, provided the magnetic devices can be scaled to small sizes. Here we describe the fabrication of MTJs ranging from 20 to 500 nm and characterization of their switching as a function of magnetic field and voltage bias. Figure 1 shows an image of the tunnel current for an array of devices. Up to 100% tunnel magnetoresistance is observed at low bias. The size dependence of the free layer switching field shows the transition to single domain behavior. Voltage controlled magnetic anisotropy is seen even in 20 nm devices, though questions remain about the size dependence of this effect. In all magnetic properties there are greater device-to-device variations as the size decreases. Multiple hysteresis loop measurements on individual MTJs were used to determine switching field distributions, which were analysed in terms of an energy barrier model to extract the anisotropy. When the free layer was metastable, the tunnel current showed random telegraph noise. Surprisingly, the magnetization reversal mechanism differs, depending on whether the initial state of the MTJ is parallel or antiparallel. Stable switching in 20 nm MTJs is demonstrated, and prospects for low power MRAM are discussed.

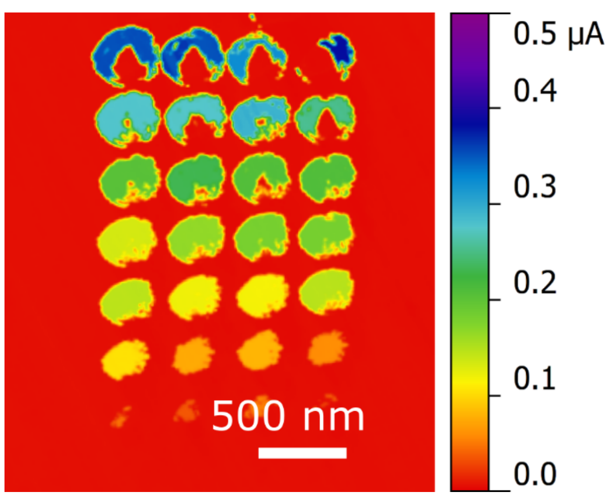


Fig. 1. Conductive atomic force microscopycurrent map of 50 – 100 nm patterned tunnel junctions at + 100 mV bias at zero magnetic field.

Photo-Spin-Voltaic Effect

Mingzhong Wu[a], David Ellsworth[a], Lei Lu[a], Jin Lan[b,c], Houchen Chang[a], Peng Li[a], Zhe Wang[c], Jun Hu[b], Bryan Johnson[a], Yuqi Bian[a], Jiang Xiao[c,d], and Ruqian Wu[b,c]

[a] *Department of Physics, Colorado State University, Fort Collins, CO 80523, USA*

[b] *Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA*

[c] *State Key Laboratory of Surface Physics and Key Laboratory for Computational Physical Sciences and Department of Physics, Fudan University, Shanghai 200433, China*

[d] *Collaborative Innovation Center of Advanced Microstructures, Fudan University, Shanghai 200433, China*

The photo-voltaic effect, discovered by Becquerel in 1839, has made a rather profound impact on the advancement of modern society. The effect typically occurs in semiconductors and involves photon-driven excitation of electrons from a valence band to a conduction band. In a region such as a p-n junction that has a built-in electric field, the excited electrons and holes diffuse in opposite directions, resulting in an electric voltage. This presentation reports that a spin voltage can be created by photons in a non-magnetic metal that is in close proximity to a magnetic insulator, a photo-spin-voltaic effect. A schematic of the effect is shown in Fig. 1. The experiments used normal metal/magnetic insulator (MI) heterostructures where the normal metal was a nm-thick Pt layer and the MI was an $Y_3Fe_5O_{12}$ (YIG), Ga-doped YIG, or $BaFe_{12}O_{19}$ film with a thickness in the 10-10^5 nm range. When light illuminates the Pt film, photons with appropriate energy excite electrons in the occupied bands to the unoccupied bands. For the Pt atomic layers in close proximity to the MI, the efficiency of the photon-driven electron excitation is different for electrons in different spin channels. This efficiency difference, together with the difference in the diffusion of the excited electrons and holes, gives rise to a spin voltage near the interface and a corresponding pure spin current across the Pt thickness. Such spin currents can produce a measurable electric voltage in the Pt film via the inverse spin Hall effect. This new phenomenon is an analogy to the photo-voltaic effect in semiconductors, but engages spin-dependent photon-driven electron excitation.

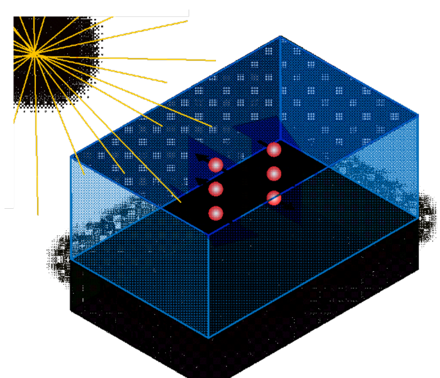


Figure 1. Photo-spin-voltaic effect in a platinum (Pt) /magnetic insulator (MI) bi-layered structure. The MI has in-plane magnetization (**M**). When the structure is exposed to light, a spin voltage ($\mu_\uparrow$-$\mu_\downarrow$) arises in Pt atomic layers in proximity to the MI. This spin voltage drives spin-up and spin-down electrons to move in opposite directions, resulting in a spin current.

Theoretical predictions of damping in high perpendicular magnetic anisotropy materials for nanostructured applications

Randall H. Victora[a,b], and Tao Qu[a]
[a]*School of Physics and Astronomy, University of Minnesota, Minneapolis, MN, USA*
[b]*Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN , USA*

The determination of damping mechanisms is one of the most fundamental problems of magnetism. The dynamic time scale in spintronic devices is controlled by the damping and the consumed power in spintronic applications can depend on the damping constant squared. Here, we apply Kambersky's torque correlation technique, within the tight binding method, to high perpendicular magnetic anisotropy (~10^7 erg/cm^3) materials, in both bulk and thin film structures. For the $L1_0$ ordered alloys: FePt, FePd, CoPt and CoPd, we predict that CoPt has the largest damping of 0.067 while FePd has the minimum value of 0.009 at room temperature. We introduce substitutional defects (inevitable in experiment) and identify the enhanced damping with reduced degree of chemical order, owing to the enhanced spin-flip channel allowed by the broken symmetry. We identify both the intrinsic interfacial and bulk damping of superlattices (Co/Pt and Co/Pd) growing along (001), (111), and (011) orientations. The interfacial damping shows dependence on the superlattice orientation in both Co/Pd and Co/Pt. The origin of the interfacial damping is due to both the distorted electronic states at the interface and the spin-orbit interaction in the weakly polarized Pt/Pd layers deposited on Co layers. The interfacial damping can make a dominant contribution in ultra-thin film Fe/MgO/Fe (magnetic tunnel junction). An optimized structure will be a trade-off between perpendicular anisotropy (~sub nm preferred) and damping.

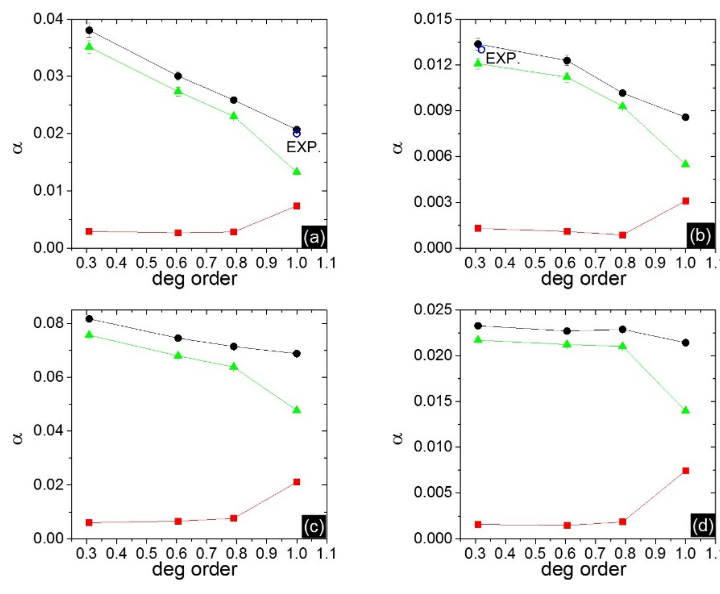


Figure: Total (solid circle), intraband (solid square), and interband (solid triangle) damping at room temperature vs chemical degree of order in disordered (a) FePt, (b) FePd, (c) CoPt, and (d) CoPd with varying number of substitutional defects (T. Qu and R.H. Victora, Appl. Phys. Lett. **106**, 072404 (2015)).

The Roles of Damping in Spin Seebeck Effect in Yttrium Iron Garnet Thin Films

Praveen Janantha[a], Houchen Chang[a], Jinjun Ding[a], Jiang Xiao[b,c], Kevin Cline[a], Joseph Gelfand[a], and Mingzhong Wu[a]*

[a] *Department of Physics, Colorado State University, Fort Collins, CO 80523, USA*

[b] *Department of Physics and State Key Laboratory of Surface Physics, Fudan University,Shanghai 200433, China*

[c] *Collaborative Innovation Center of Advanced Microstructures, Fudan University, Shanghai, 200433, China*

The spin Seebeck effect (SSE) refers to the generation of a spin voltage in a ferromagnet due to a temperature gradient. Although a complete understanding of the SSE has not been realized, three mechanisms have been proposed to interpret the SSE – "magnon-driven", "phonon-mediated", and "phonon-drag". In spite of their conceptual differences, these mechanisms all engage magnon-phonon coupling (MPC) in the materials. Specifically, the magnon-driven model suggests that for a given length scale the SSE is stronger in materials with weaker MPC, while the other two suggest that the strength of the SSE should increase with that of MPC. This presentation reports the role of damping in the SSE in yttrium iron garnet (YIG) thin films. The experiments used six YIG film samples made by sputtering under different conditions which exhibited different Gilbert damping constants (α), ranging from 8.5×10^{-5} to 59.0×10^{-5} (implying different strengths of MPC in the six samples). To probe the strength of the SSE, a 5-nm-thick Pt layer was grown on each sample by sputtering. The SSE in the YIG produced a pure spin current in the Pt, and via the inverse spin Hall effect (ISHE) the latter produced a voltage (V_{ISHE}) across one lateral dimension of the Pt layer. V_{ISHE} was measured as a function of the temperature difference (ΔT) across the sample thickness. The data show that the slope of the $V_{ISHE}(\Delta T)$ response increases with a decrease in α. This result is consistent with the magnon-driven mechanism.

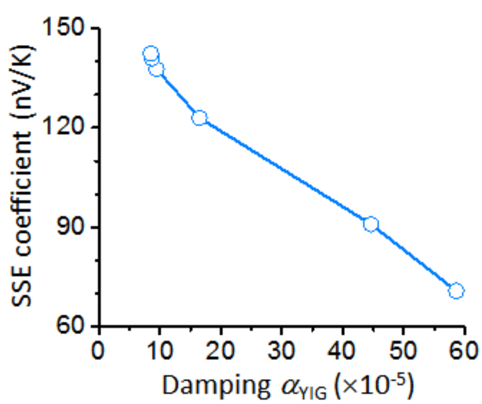


Fig. 1. SSE coefficient as a function of the Gilbert damping constant α_{YIG}.

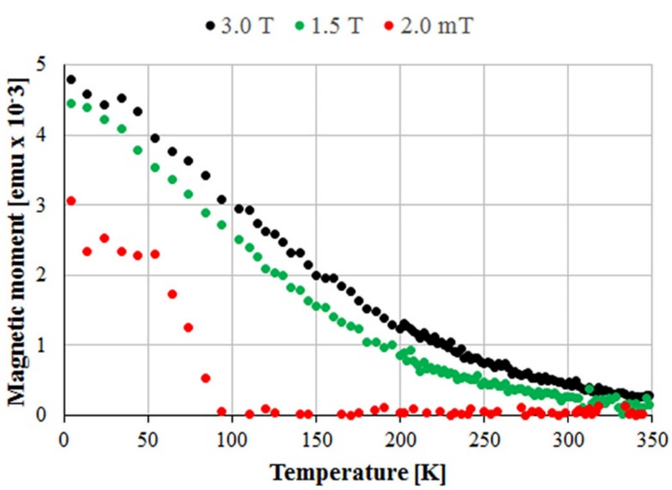
Magnetic Metallic Alloy Structures as a Temperature Contrast Agent in Magnetic Resonance Imaging

N. A. Alghamdi[a], J. E. Nobles[a], N. Sorensen[a], J. H. Hankiewicz[b] and Z. Celinski[a]

[a] *UCCS Department of Physics, University of Colorado Colorado Springs, Co, USA*

[b] *UCCS Center for BioFrontiers Institute, University of Colorado Colorado Springs, Co, USA*

We are researching the development of biocompatible magnetic structures suitable for use as a temperature contrast agent in magnetic resonance imaging (MRI) of the human body. Permalloy (Py), an alloy of 19 Wt% Fe and 81 Wt% Ni, exhibits a relatively high magnetic moment and good biocompatibility; however, fcc Py's Curie temperature (T_c) of 872 K makes it unsuitable for use as a temperature contrast agent at human body temperature (~37 ^{o}C). Py's T_c can be altered through alloying Py with a non-magnetic metal. We present experimental results for Py_xCu_{1-x} thin films (0.45<x<0.70). The 0.6-1.0 mm thick films were deposited on silicon substrates using a magnetron sputtering system. The films were characterized with a superconducting quantum interference device (SQUID). Tc was determined with an applied magnetic field of 2 mT. Measurements at 1.5 T and 3.0 T were taken to determine the expected change in magnetization as a function of temperature in typical clinical MRI scanners. The composition of the films was determined through energy-dispersive X-ray spectroscopy (EDX). As expected, the use of Cu as a Py alloying agent resulted in a significantly lower T_c. For example, the T_c of $Py_{0.45}Cu_{0.55}$ was determined to be approximately 100 K as shown in Figure 1. Our initial results indicate that Py_xCu_{1-x} is a promising candidate for use as an MRI temperature contrast agent. The next step is to study this alloy in micro-structures suitable for minimally invasive introduction into the human body as shown in Figure 2.



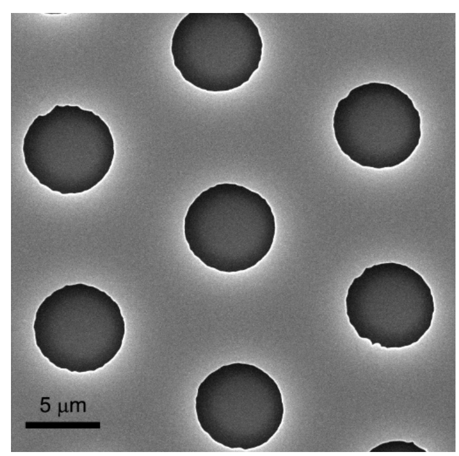


Figure 1. Magnetic moment as a function of temperature for $Py_{0.45}Cu_{0.55}$ measured in magnetic fields of 3.0 T, 1.5 T, and 2.0 mT.

Figure 2. Scanning electron microscope image of 6 micron diameter $Py_{0.45}Cu_{0.55}$ structures.

Why do magnetic nanoparticles agglomerate isotropically?

Nick Anderson[a], Dana Louie[a], David Serantes[a,b] and Karen Livesey[a]
[a] *BioFrontiers Center, University of Colorado Colorado Springs, USA*
[b] *Universidade de Santiago de Compostela, Galicia, Spain*

Magnetic nanoparticles in liquids may agglomerate in experiments to form isotropic clumps. This is in stark contrast to theoretical simulations which predict that chains or loops of particles will form to minimize the magnetic dipole-dipole interactions.[1] Therefore, other interactions must dominate the particle dynamics. It is important to understand agglomeration as it dramatically changes the magnetic response of particles for applications such as hyperthermia cancer treatment.[2] In this work, we use a Brownian dynamics simulation to explore under which conditions the isotropic clumps that are seen in experiments may form. Steric repulsion, van der Waal's (electrostatic), frictional, and dipolar interactions are considered. We characterize the shape of formed agglomerates using pair correlation functions, moment of inertia, and length. We find that 20 nm diameter magnetite particles coated with a 5 nm-thick ligand shell at 298 K form similar isotropic agglomerates to nanoparticles with no magnetic moment, if friction between particles is large. An example is shown in the figure below. At lower temperatures, chains and loops of nanoparticles form instead because the magnetic interactions are larger than random thermal forces.

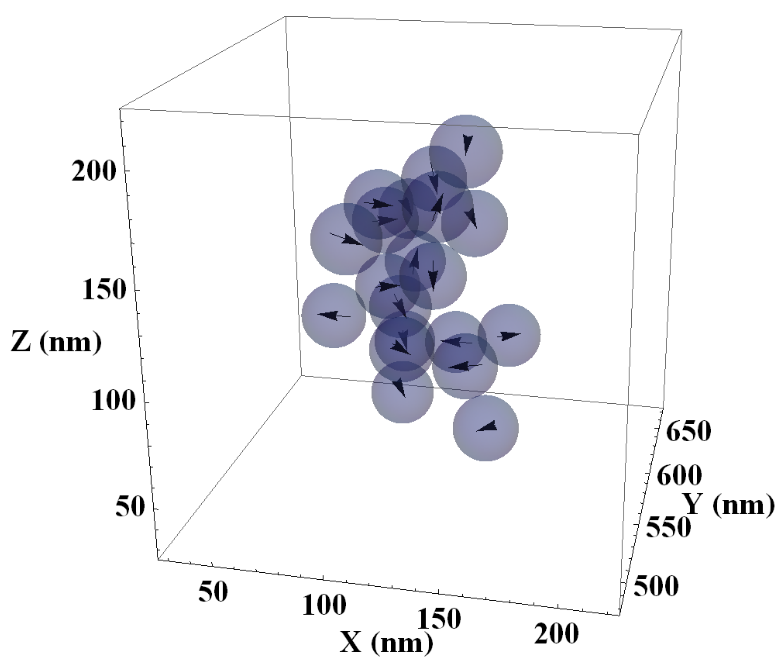


Figure 1: An agglomerate that is formed from 20 magnetite particles of 20 nm diameter, with T=298 K and ligand shells that are 5 nm thick. Arrows represent the magnetic moments.

[1] Chantrell *et al.*, J. Appl. Phys. **53**, 2742 (1982).
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Growth of high-quality $Y_3Fe_5O_{12}$ thin films on platinum via sputtering

Houchen Chang[a], Tao Liu[a], P. A. Praveen Janantha[a], and Mingzhong Wu[a]*
[a] *Department of Physics, Colorado State University, Fort Collins, Colorado, USA*

In recent years there is a strong interest in studying $Y_3Fe_5O_{12}$ (YIG)-based spintronics. The majority of those studies utilized YIG films that were grown on $Gd_3Ga_5O_{12}$ (GGG) substrates first and then capped with thin normal metal (NM) layers. The use of the GGG substrates is crucial as they have a crystalline structure almost perfectly matching that of YIG materials. This presentation reports on the feasibility of using sputtering to grow high-quality YIG thin films on Pt films. This feasibility is of great significance because it enables the fabrication of NM/YIG/NM layered structures, and such structures will facilitate various interesting fundamental studies as well as device developments. The fabrication process consisted of three main steps as follows: the growth of a Pt film on a GGG substrate by DC sputtering at about 400 °C, the growth of a YIG film by RF sputtering at room temperature, and the annealing of the sample in O_2 at about 700 °C. The Pt and YIG phases of the bi-layered structure were confirmed by X-ray diffraction measurements. Atomic force microscopy measurements indicated that the samples had uniform and smooth surfaces, with a surface roughness of about 0.2 nm. Ferromagnetic resonance measurements indicated that the YIG had a Gilbert damping constant in the 0.0004-0.0006 range. Measurements on spin pumping-produced damping enhancement in the YIG and inverse spin Hall voltage signals in the Pt indicated that the YIG/Pt interface had high quality in terms of transferring spins.

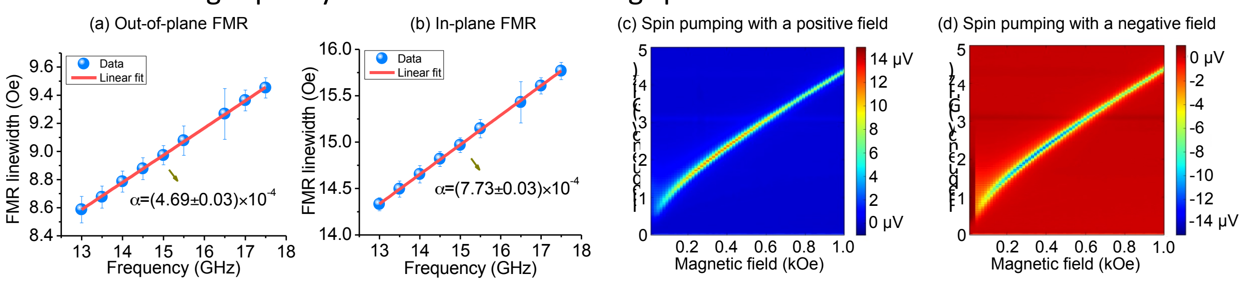

Figure 1: FMR linewidth and spin pumping-produced inverse spin Hall voltage data obtained with a YIG(36 nm)/Pt(10 nm)/GGG(0.5 mm) sample.

*corresponding author: mwu@colostate.edu

Shape and smoothness of a core-shell monocrystalline YIG microdisk inferred from FMR spectroscopy

Fatemeh Fani Sani[a,b], Joe E. Losby[a,b], Miro Belov [b], Doug Vick [b], and Mark R. Freeman[a,b]
[a] *Department of Physics, University of Alberta, Edmonton, AB, T6G 2E9, Canada*
[b] *National Institute for Nanotechnology, Edmonton, AB, T6G 2M9, Canada*

There is a rich resonance spectrum for a confined magnetic structure like a disk in the presence of radio frequency (rf) actuation. The magnetic vortex is ground state of disks with low anisotropy and small enough thickness-to-diameter aspect ratios. The lowest resonance in the vortex state is a gyrotropic mode, with sub-GHz frequency related to the aspect ratio of disk. The existence of higher order gyrotropic modes is owed to the thickness of the disk and has recently been presented in [1, 2].

Utilizing Ga^+ focused ion beam (FIB), an epitaxially-grown single-crystalline yttrium iron garnet (YIG) film is milled out to form an 1150 nm diameter, 450 nm thick disk. FIB offers unique possibilities for nanofabrication of monocrystalline objects but still suffers in comparison with lithographic methods in terms of dimensional accuracy. The disruption by Ga^+ ions reduces the magnetic properties of YIG crystal and creates a magnetically dead shell around the disk (magnetic core).

We present a study of gyrotopic resonances in the FIB-fabricated YIG disk as a function of in-plane magnetic field using torque-mixing magnetic resonance spectroscopy [3]. Through comparison with micromagnetic simulation, the study reveals the effect of slight (nm-amplitude) corrugations at the interface between the Ga beam-modified shell and the magnetic core of the disk. Additional spectroscopic results from the disk when perpendicularly magnetized will be presented and discussed in the context of implications for the shape of the magnetic core.

References

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[2] J. Ding, G. Kakazei, X. Liu, K. Guslienko, A. Adeyeye, Sci. Rep. 4, 4796 (2014).
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Detection of thermoelectric contributions in ferromagnetic/normal-metal bilayer devices for accurate spin-orbit torque analysis

Alisha Humphries[a], Jun Wu[b], John Q. Xiao[b], and Xin Fan[a]
[a] *Department of Physics and Astronomy, University of Denver, Denver, Co, USA*
[b] *Department of Physics and Astronomy, University of Delaware, Newark, De, USA*

Current-induced spin-orbit torque (SOT) has arisen as a highly desirable alternative to spin-transfer torque for current-driven magnetization switching in ferromagnetic/normal-metal bilayer devices. The mechanism of SOT is still under debate. Previous studies have aimed to separate the contributions to SOT from the spin Hall effect and the Rashba effect [1] using electrical detection, but thermoelectric contributions due to Joule heating and the anomalous Nernst effect have been largely ignored. The magnitudes of these contributions have been shown to be significant, leading to inaccurate estimations of the mechanisms contributing to SOTs [2]. Here, we present a method to extract the magnitudes of these thermoelectric effects through a Wheatstone bridge structure which eliminates all transverse voltage signals due to symmetry, except the signature thermal voltage (Figure 1a). This voltage is found from the voltage difference between positive and negative saturation values as seen in Figure 1b. We extract the magnitudes of the thermal contributions in Py(2nm)/Au(2nm), Py(2nm)/Pt(3nm), and Py(2nm)/Cu(5nm)/Au(1nm) devices, which are then used for a more accurate calibration of transverse voltage signals in the typical Hall bar geometry. These results allow for a more accurate understanding of the contributions to SOT by the spin Hall and Rashba effects which will be investigated in future studies.

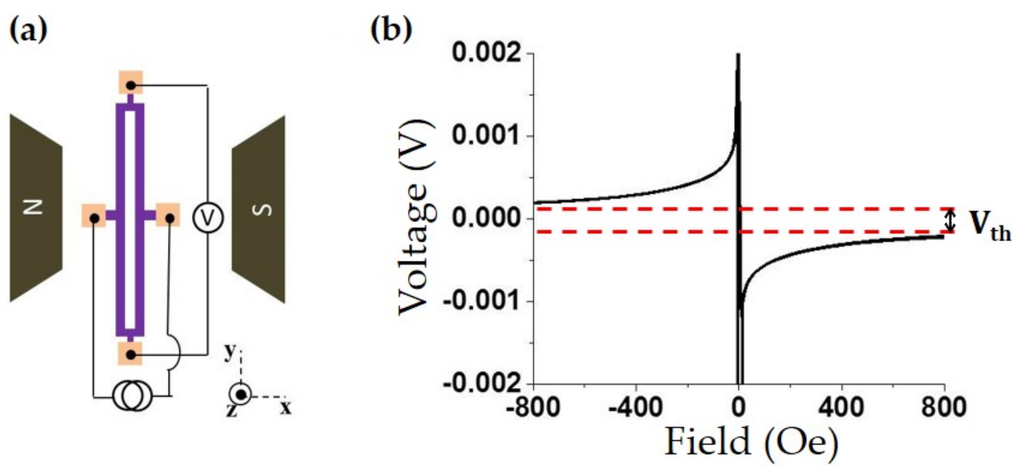

Fig. 1. (a) Schematic of the Wheatstone bridge used in the experiment. (b) The thermal voltage is found from the voltage difference between positive and negative saturation values.

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[2] Garello, K. et al. *Nature Nanotechnology* **8**, 587-593 (2013).

Foldover of Nonlinear Eigenmodes in Magnetic Thin Film-Based Feedback Rings

P. A. Praveen Janantha[a], Boris A. Kalinikos[a,b], and Mingzhong Wu[a]*

[a] *Department of Physics, Colorado State University, Fort Collins, Colorado 80523, USA*
[b] *St. Petersburg Electrotechnical University, 197376, St. Petersburg, Russia*

Active feedback ring systems that consist of a closed loop of a dissipative transmission line and an active element to compensate for the dissipation constitute an excellent testbed for exploring nonlinear dynamics in driven damped systems [1]. Example systems include electromagnetic transmission line ring oscillators, optical fiber rings, and magnetic thin film-based feedback rings. This presentation reports that active feedback rings also support another fascinating nonlinear effect - the foldover effect. This effect originates from the nonlinearity in which the oscillation frequency varies with the oscillation amplitude. It occurs in systems as diverse as driven pendula, spring-based oscillators, and precessional magnetic moments in both insulating and metallic magnets. The experiments made use of an active feedback ring that consists of an $Y_3Fe_5O_{12}$ (YIG) thin film strip serving as a spin-wave transmission line and a microwave amplifier which amplifies the output signal from the YIG strip and then feeds it back to the input of the YIG strip. With a decrease in the overall ring loss and an increase in the ring resonance amplitude, some resonant peaks evolved from symmetric peaks to asymmetric ones and then folded over to higher frequencies. This foldover effect is intrinsic and originates from the nonlinearity-caused frequency shift of the traveling spin wave. To better understand the physical origin of the observed foldover effect, theoretical calculations were carried out, where the results not only confirmed the experimental observations, but also showed the rolling over of the top part of the resonant peaks which cannot be measured experimentally.

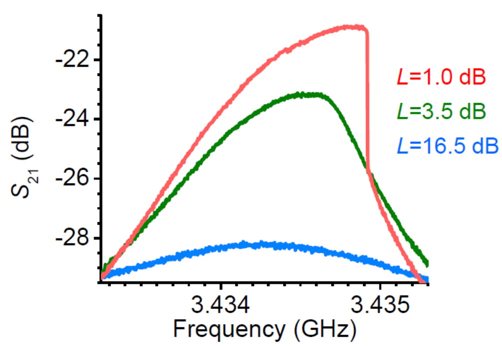

Fig. 1. Amplitude-frequency responses for one ring eigenmode measured at three ring loss levels.

[1] M. Wu, in Solid State Physics, edited by R. Camley and R. Stamps (Academic Press, Burlington, MA, 2011), vol. 62, pp. 163–224.

*corresponding author: mwu@colostate.edu

Study of the rectification effect in the resonant cavity-based spin pumping technique

Wanting Li[a], Brian Alpert[a], and Xin Fan[a]

[a] *Department of Physics and Astronomy, University of Denver, Denver, CO, USA*

Resonant cavity-based spin pumping technique has been widely used to study the inverse spin Hall effect[1]. However, it has been recognized that there is a persistent rectification effect[2,3] in the detection that complicates the extrapolation of spin pumping signal. Typically the spin pumping signal, which has a symmetric Lorentzian line shape, is extracted by assuming the voltage signal due to the rectification effect only has an antisymmetric Lorentzian profile. However, this assumption needs to be carefully examined. In this work, we study the rectification effect by using a single layer permalloy film grown on silicon wafer or glass, which should not induce a spin pumping signal. We find that the line shape of the rectification voltage signal strongly depends on the substrate and the relative position of the sample in the cavity. By using lossless glass substrate and position sample in the center of the cavity, we can achieve low symmetric component of rectification voltage, as shown in Figure 1. These results are important for understanding and improving the resonant cavity-based spin pumping technique.

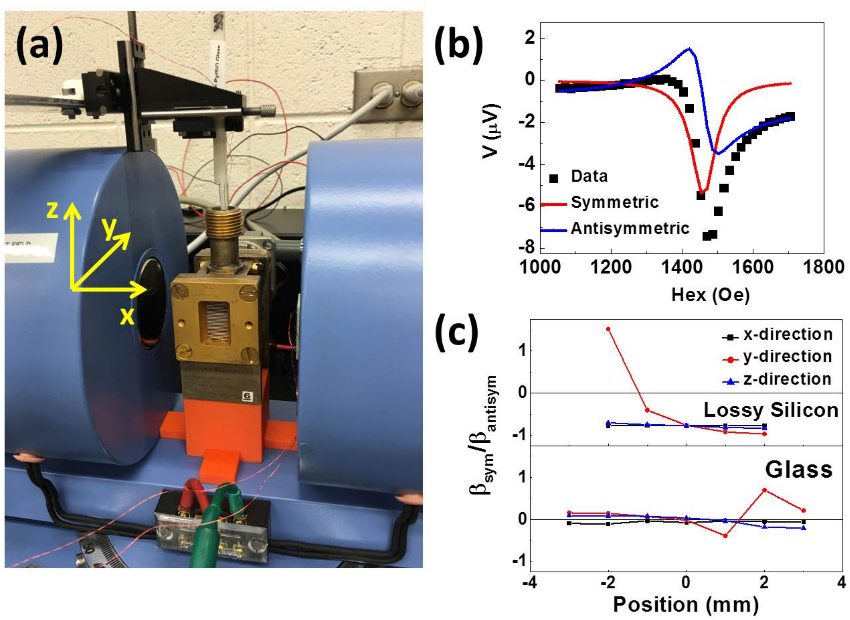

Figure 1: (a) Setup of the spin pumping measurement. (b) Exemplary voltage data and fitting to separate symmetric and antisymmetric component. (c) Symmetric/antisymmetric ratio dependence on the position of the sample.

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Anomalous Anisotropic Magnetoresistance in Ultrathin Ta Films Grown on $BaFe_{12}O_{19}$

Tao Liu[1], Peng Li[1], Houchen Chang[1], Christopher Safranski[2], Alejandro Jara[2], Wei Li[3], Jinjun Ding[1], Igor Barsukov[2], Mario C Marconi[3], Ilya N. Krivorotov[2], and Mingzhong Wu[1]*

[1]*Department of Physics, Colorado State University, Fort Collins, CO 80523, USA*
[2]*Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA*
[3]*Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80523, USA*

Conventional anisotropic magnetoresistance (AMR) occurs in ferromagnetic metallic films and typically shows $R_{||}>R_{\perp}\approx R_T$, where $R_{||}$, $R_{\perp}$, and R_T are the film resistance measured with an in-plane current **I** for the magnetization **M** parallel to **I**, normal to the film plane, and in the plane and transverse to **I**, respectively. There exists also AMR in non-magnetic metallic films grown on magnetic insulators, which, however, shows $R_{||}\approx R_{\perp}>R_T$. This AMR can be interpreted using the spin Hall effects and is thereby termed as spin Hall magnetoresistance (SMR). This presentation reports anomalous AMR in a Ta film grown on $BaFe_{12}O_{19}$, which differs from both conventional AMR and SMR. First, at room temperature *R* shows a $\cos(2\alpha)$ dependence when **M** is rotated in the plane containing both **I** and the film normal direction and the rotation is tracked by an angle α. This is contradictory to SMR, for which *R* should be constant when α varies. Second, at low temperatures $R(\alpha)$ also contains a $\cos(4\alpha)$ component. What's more, as the temperature decreases from 300 K to 8 K, the amplitude of the $\cos(4\alpha)$ term increases monotonically, while that of the $\cos(2\alpha)$ term flips its sign. These features cannot be explained by SMR. Third, when **M** is rotated in the plane perpendicular to **I** and the rotation is tracked by an angle β, *R* shows a $\cos(2\beta)$ dependence at room temperature and a $\cos(2\beta)$ plus $\cos(4\beta)$ response at low temperature. This result is inconsistent with AMR, for which *R* should not change with β.

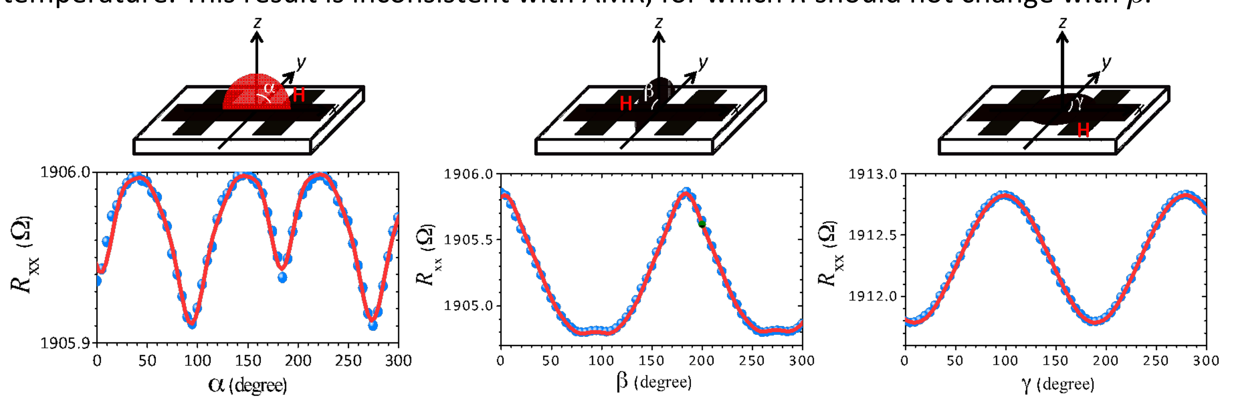

Figure 1: Longitudinal resistances of a Ta(5 nm)/$BaFe_{12}O_{19}$(30 nm) Hall bar measured with a 5 T magnetic field rotating in different planes at 13 K. The blue dots show the data, and the red curves are the fits to $R=R_0+R_2\cos(2\theta)+R_4\cos(4\theta)$.

* Corresponding author: mwu@colostate.edu

Spin vortex resonance in non-planar ferromagnetic dots

Junjia Ding, Pavel Lapa [1], Shikha Jain [2], Trupti Khaire, Sergi Lendinez, Wei Zhang, Matthias B. Jungfleisch, Christian M. Posada, Volodymyr G. Yefremenko [3], John E. Pearson, Axel Hoffmann, & Valentine Novosad

Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, USA

In planar structures, the vortex resonance frequency changes little as a function of an in-plane magnetic field as long as the vortex state persists. Altering the topography of the element leads to a vastly different dynamic response that arises due to the local vortex core confinement effect. In this work, we studied the magnetic excitations in non-planar ferromagnetic dots using a broadband microwave spectroscopy technique. Two distinct regimes of vortex gyration were detected depending on the vortex core position. By comparing the experimental data and micromagnetic simulations, it was found that the frequency of the gyrotropic mode increases as the thickness-diameter ratio of the barrier is increased. Further studies of such non-planar ferromagnetic elements will be focused on the details of the pinning mechanism, its possible impact on the energetics of the vortex core reversal process and the high frequency spin dynamics.

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[1] On leave from Texas A&M University, College Station, TX 77843, USA.
[2] Presently at HGST, A Western Digital Company.
[3] Presently at High Energy Physics Division, Argonne National Laboratory.

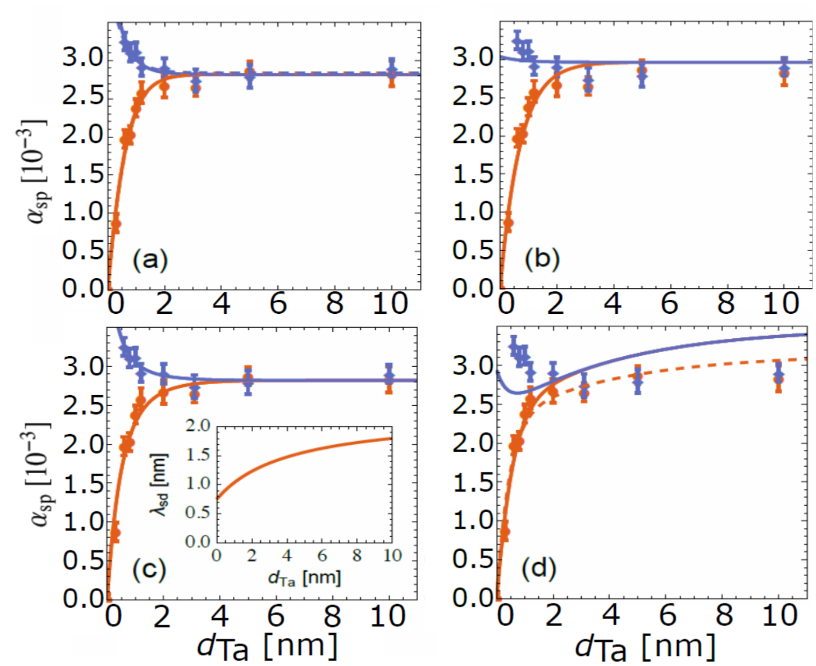
Study of spin transport in tantalum using magnetic single and double layers

Pavlo Omelcheko[a], Eric Montoya[a], Chris Coutts[a], Nicholas Lee-Hone[a], Rene Huebren[b], David Broun[a], Bret Heinrich[a] and Erol Girt[a]

[a] *Department of Physics, Simon Fraser University, Burnaby, BC, Canada*

[b] *Institute for Ion Beam Physics and Materials Research, Helmholtz Zentrum Dresden Rossendorf, Dresden, Saxony, Germany*

We report on magnetic damping measurements in magnetic single and double layer heterostructures, Py|Ta and Py|Ta|(Py|Fe) respectively, where Py = Ni80Fe20, see Figure below. Spin transport in Ta films is studied by varying the Ta films thickness and evaluating the changes in damping in the Py layer due to spin pumping and spin sink effects. The structure of the Ta films is determined using X-ray diffraction and transmission electron microscopy. Magnetic damping data is interpreted using established spin pumping/spin diffusion theory [1] with the following variations: **a)** r (resistivity) and l (spin diffusion length) are constants with respect to Ta thickness, **b)** r is fixed at bulk resistivity and l is a constant fitting parameter, **c)** r(x) is proportional to l(x), and both are thickness dependent and **d)** l is constant while r(x) is thickness dependent [2].



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Using magnetic nanoparticles in a static and dynamic magnetic field to penetrate model mucus

Meghan Smith[a,c], Austin Routt[a,b], Evangelos Economou[a,b], Guy Hagen[a], Zbigniew Celinski[a,b], and Kathrin Spendier[a,b]

[a] *Biofrontiers Center, University of Colorado at Colorado Springs, Colorado Springs, CO, USA*

[b] *Department of Physics, University of Colorado at Colorado Springs, Colorado Springs, CO, USA*

[c] *Department of Mechanical Engineering, University of Colorado at Colorado Springs, Colorado Springs, CO, USA*

Asthma affects millions of individuals worldwide and current treatment options are often hindered due to inefficient drug delivery methods. An asthmatic respiratory tract is usually covered in a layer of mucus which essentially stops inhaled medication from reaching the underlying inflamed tissue. This project tested magnetically guided iron oxide, Fe_3O_4, nanoparticles (FeNPs) and barium hexaferrite, $BaFe_{12}O_{19}$, nanoparticles (BaNPs) as a drug delivery system through model mucus. To do this, a high magnetic field gradient was generated using a permanent neodymium magnet with an iron core pole piece to pull the magnetic NPs through a 1 cm thick layer of hydroxyethyl cellulose (HEC) gel. In addition, two Helmholtz coils were used to produce an oscillating magnetic field to physically rotate the magnetic NPs. The penetration time of FeNPs and BaNPs through HEC gel was measured as a function of oscillation frequency. For a frequency range of 0 to 1900 Hz, the data illustrated that HEC gel penetration time of BaNPs is functionally dependent on oscillation frequency whereas penetration time of FeNPs showed no apparent correlation. This observation is consistent with theoretical predictions that will be discussed.

Heating tissue by radio-frequency for hyperthermia therapy

John Stroud[a], Jason Nobles[b], Zbigniew Celinski[b], and Janusz Hankiewicz[a]
[a]*UCCS Center for BioFrontiers Institute, University of Colorado Colorado Springs, CO, USA*
[b]*Department of Physics, University of Colorado Colorado Springs, Colorado Springs, CO, USA*

Hyperthermia is a medical procedure for warming tumour-affected tissue to 40 ^{O}C – 43 ^{O}C. The idea is based on the effect of initiation of cell killing (apoptosis) that are exposed to thermal stress at temperatures above 41 ^{o}C. Tumor tissue with more compact blood vessel systems has more difficulty dissipating heat than normal tissue, and its cells are prone to apoptosis in response to prolonged heat. Even if tumor cells are not dying immediately due to the heat, they are becoming more susceptible to radio- and chemo-therapy after hyperthermia. In this project, we study the efficiency of warming aqueous solutions and gels that are isotonic to fluids and tissue in humans using radio frequency (RF) pulses in the 15 MHz range. We present our first results from exposing samples made of deionized water (DI), Ringer's solution and agar gel to 100 seconds radiation of 50 ms, 40 Watt peak RF pulses with 250 ms repetition (17% duty cycle). For heating purposes, we utilize the resonant circuit of a pulsed nuclear magnetic resonance spectrometer; for temperature monitoring, we use the miniature thermally sensitive optical birefringent element. To increase the heat locally, different thin metallic films (1 μm thick and 6x12 mm surface) were added to solutions and gels to generate eddy currents. We report the increase of heating by about 12% when metallic films are present as seen in Figure 1. The remaining and dominating heating contribution at 15 MHz originates from dielectric losses. We currently extend the study of the heating efficiency by RF pulses to a frequency range of 10 MHz - 130 MHz. Additionally, to reduce the dielectric losses contribution, we explore the possibility of heating tissue by fast switching magnetic gradients.

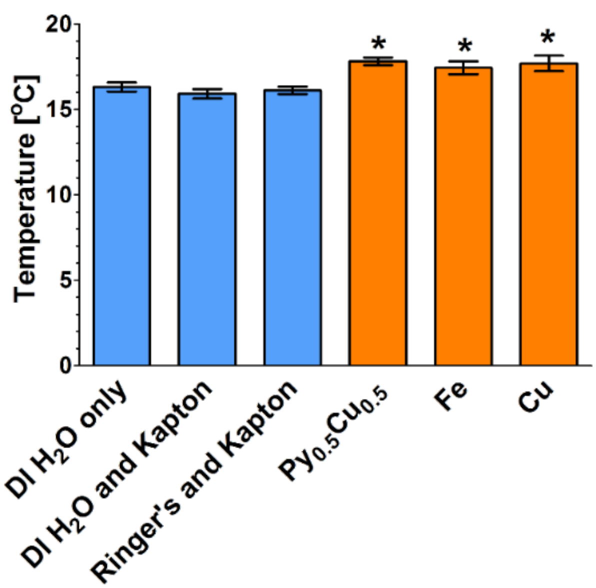

Figure 1. Temperature increase due to RF heating. Asterisks indicate a significant change of temperature in deionized water with different metallic thin films compared to different solutions without metallic films.

Anomalous Nernst effects in metallic nonlocal spin valves

Alex Hojem, Devin Wesenberg', and Barry L. Zink
Department of Physics and Astronomy, University of Denver, Denver, Colorado, USA

The study of non-local spin valves (NLSVs) has recently proven to be a fertile area for both applied and fundamental research in nanomagnetism due to the unique ability to separate charge currents and spin currents [1,2]. NLSVs may also prove essential for a new class of high-density hard disk read heads due to their favourable scalability [3]. Recent studies have shown thermal effects created by high current densities play a significant role in the response of NLSVs [4]. These thermal effects also provide the opportunity to create a pure spin current from thermal gradients [5,6]. Due to the challenges in control and measurement of thermal gradients in nanoscale structures, both the fundamental physics and materials dependencies of thermally-driven spin transport in nanoscale structures remains largely unexplored. One challenge is that thermal gradients applied to ferromagnetic contacts can cause signal components in NLSVs driven by the Anomalous Nernst Effect (ANE)[7], thermoelectric analogue of the anomalous Hall effect[8]. In this presentation we describe measurements that demonstrate and quantify both thermoelectric effects on electrical spin injection, purely thermal spin injection as well as the ANE in NLSVs.

We use electron beam lithography to pattern sub-micron FM injector and detector strips in contact with a NM channel on Si-N coated Si substrates and free-standing Si-N membranes. By combining these measurements with thermal parameters derived from thin film measurements [7] we observe an increase in the anomalous Nernst effect in NLSVs on membranes and possible thermally-assisted electrical spin injection.

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2. Ji, et al., APL 88, 052509 (2006)
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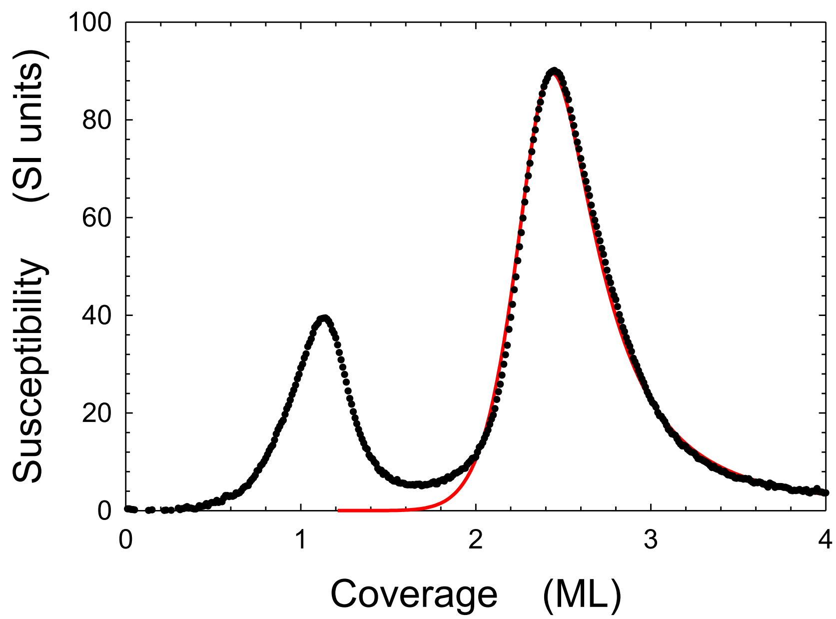
Local vs. global manifestation of a surface phase transition

David Venus, Gengming He, Harrison Winch and Randy Belanger
Department of Physics and Astronomy, McMaster University, Hamilton, ON, Canada

The reorientation transition of an ultrathin film from perpendicular to in-plane magnetization is driven by a competition between shape and surface anisotropy. It is accompanied by a "stripe" domain structure that evolves as the reorientation progresses. Often, an n layer film has stable perpendicular magnetization and an n+1 layer film has stable in-plane magnetization. If the domain walls are not pinned, the long-range stripe domain pattern averages over the layer structure so that the transition occurs at a non-integer layer thickness. We report *in situ* experimental measurements of the magnetic susceptibility (via MOKE) of the reorientation transition in Fe/2ML Ni/W(110) films as a function of Fe coverage as they are deposited at room temperature. In addition to a peak at the reorientation transition, we observe a strong precursor (see figure). This peak is described by a quantitative model of the response of small islands of thickness 3 ML with in-plane anisotropy in a sea of 2 ML Fe with perpendicular anisotropy. The fitted parameters give an estimate of the island size at which the response disappears. This size is consistent with a domain wall thickness, so that the islands become locally in-plane, demonstrating the self-consistency of the model.

Magnetic susceptibility of Fe/2 ML Ni/W(110) as a function of Fe coverage at room temperature. The peak at higher coverage is due to the reorientation transition. There is also an unexpected peak (?) at lower coverage.



Mössbauer spectroscopy of nanostructures – theory and experiment

Jan Żukrowski[1], Krzysztof Ruebenbauer[2], Artur Błachowski[2], Piotr Bujak[3], Adam Proń[3], and Marek Przybylski[1,4]

1 - Academic Centre for Materials and Nanotechnology,
AGH University of Science and Technology, Krakow, Poland,
2 – Faculty of Mathematics, Physics and Technical Science,
Pedagogical University, Krakow, Poland
3 – Faculty of Chemistry, Warsaw University of Technology, Warszawa, Poland
4 - Faculty of Physics and Applied Computer Science,
AGH University of Science and Technology, Krakow, Poland

Mössbauer spectroscopy provides an efficient means to understand ferromagnetism, particularly in nanostructures/nanoparticles. For example, by using ^{57}Fe atoms as probes, a local analysis of the hyperfine parameters is possible. Furthermore, by means of the hyperfine interaction between ^{57}Fe nuclei and their surroundings, information can be obtained about the local structure and composition of solids. The most effective technique to measure Mössbauer spectra of nanostructures/nanoparticles is to detect conversion electrons emitted when the constituent atomic nuclei absorb γ-rays.

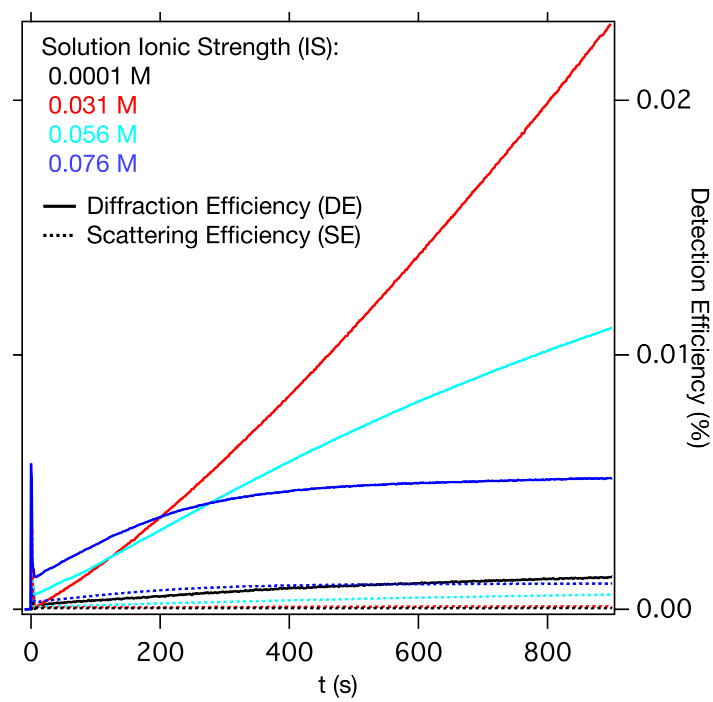
In the case of ferromagnetic nanoparticles, the collapse of the low-temperature, well-resolved hyperfine magnetic structure of the spectrum into a quadrupole doublet is accompanied by a line broadening at intermediate temperatures. Moreover, superparamagnetic spectra measured at the same temperature are strongly dependent on the size of the nanoparticles. It may also happen that the spectral lines remain narrow, and only the relative contribution of the well-resolved magnetic structure and the quadrupole doublet/doublets changes rapidly with increasing temperature. A quantum nature of the effect is then concluded from the well-defined energy states (resulting from the quantum confinement phenomena for electrons in nanoparticles) of populations which are temperature dependent. In the case of ferromagnetic particles, the ground state represents a quasi-continuous spectrum independent of the anisotropy constant, whereas is strongly anisotropy dependent in the case of the nanoparticles which are antiferromagnetic.

Another interesting feature measured for nanoparticles in a soft-matrix is their nonlinear dependence of the recoilless absorption fraction on temperature. This phenomenon can be explained by the unrestricted diffusion of nanoparticles under varying conditions.

Triggered self-assembly of magnetic nanoparticles

T. M. Crawford
Smart State Center for Experimental Nanoscale Phyiscs
Department of Physics and Astronomy
University of South Carolina, Columbia, SC 29208

Understanding how magnetic nanoparticles assemble and aggregate under external magnetic fields is critical for high-quality, safe, and reliable deployment of these particles in biology, medicine, and manufacturing**.** By tuning the balance between magnetic and colloidal stabilizing forces that suspend these particles in fluid, we can trigger self-assembly of magnetic nanoparticles [1]. We use real-time optical diffraction to monitor this triggering as the nanoparticles assemble into parallel lines on a magnetic recording medium. Triggered self-assembly depends strongly on the ionic properties of the colloidal fluid, but at a level too small to cause bulk colloidal aggregation. The figure below shows a rapid increase and decrease of grating efficiency with time as ionic strength is increased, while little change is observed in light scattered from the fluid. Simulations predict the triggering, but not the dynamics observed as a function of ionic strength. Beyond driving self-assembly via tuning nanoscale forces, this approach offers a metrology with sufficient sensitivity to identify subtle effects that could affect nanoparticle behaviour in a clinical setting.



Triggered nanoparticle assembly: light diffracted from a nanoparticle grating as it assembles shows a dramatic and peaked enhancement for small changes in solution ionic strength, while scattered light shows very little change.

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Micromagnetic simulations of maghemite nanoparticles in FCC arrays

Bassel Alkadour[1], J. I. Mercer[2], J. P. Whitehead[1], J. van Lierop[3] and B. W. Southern[3]
[1]*Department of Physics and Physical Oceanography, Memorial University, St. John's, NL, Canada*
[2]*Department of Computer Science, Memorial University, St. John's, NL, Canada*
[3]*Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB, Canada*

Encouraged by recent developments in synthesizing magnetic nanoparticle superlattices [1], results from a series of simulation studies on an FCC array of maghemite nanoparticles that includes the dipole interaction between the nanoparticles are presented. The simulation studies were performed using the stochastic LLG method in which the individual nanoparticles are represented by an atomistic core-shell model where the core has bulk-like exchange and the shell has weak exchange and radial anisotropy (to represent the different environments about atoms at and near the nanoparticle surface, e.g. broken coordination). Results from simulations of 7.5 nm diameter maghemite nanoparticles for different shell thicknesses show that a nanoparticle array orders ferromagnetically at low temperature in accordance with simulation studies on equivalent FCC dipole arrays [2]. However, a detailed comparison between the results for the nanoparticle arrays and the corresponding point dipole arrays reveals an additional orientational disorder in the FCC array below $T \sim 0.5\ T_C$ due to magnetic torques generated by the surface vacancies in the maghemite nanoparticles' shell [3].

[1] T. N. Shendruk, R. D. Desautels, B. W. Southern, and J. van Lierop. *The effect of surface spin disorder on the magnetism of -Fe_2O_3 nanoparticle dispersions*. Nanotechnology, **18**:455704, 2007.
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[3] B. Alkadour, J. I. Mercer, J. P. Whitehead, J. van Lierop, and B. W. Southern. *Surface vacancy mediated pinning of the magnetisation in γ-Fe_2O_3 nanoparticles: A micromagnetic simulation study*, Phys. Rev. B, Rapid Comm., accepted, 2016.

Ill-condensed matter 2: Magnetic order from disorder with nanoparticles

R. D. Desautels[a,b], E. Skoropata[a], O. Kasyutich[c], P. Ceci[d], M. A. Kostianinen[e], A. Fiorillo[d] and J. van Lierop[a]

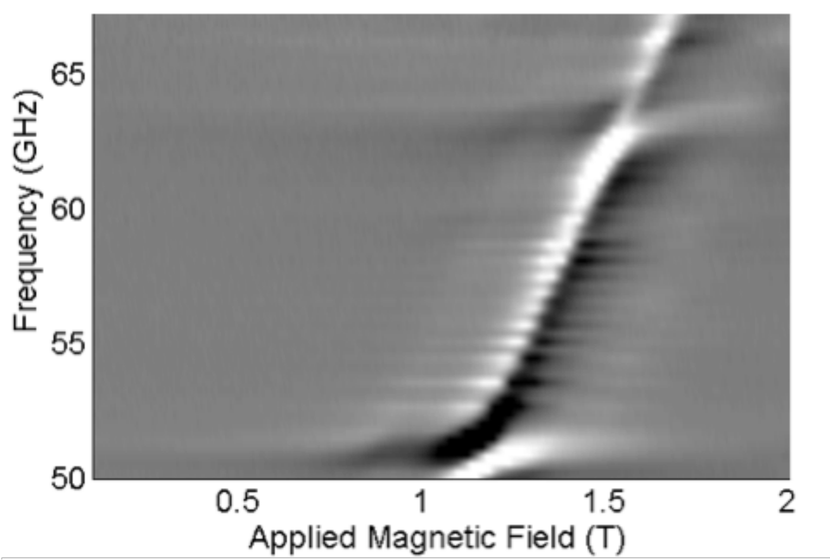
[a] *Department Physics and Astronomy, University of Manitoba, Winnipeg, MB, Canada*
[b] *Thin Films and Nanostructures in Quantum Condensed Matter Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[c] *School of Physics, University of Bristol, Bristol, UK*
[d] *CNR Institute of Molecular Biology, Department of Biological Sciences, University of Rome, Rome, Italy*
[e] *Institute for Molecules and Materials, Radboud University, University of Twente, Nijmegan, Netherlands*

Around 50 years ago, physicists began to turn their attention to systems that were rather unnatural to describe: If a material isn't an ordered solid, such as with glasses and polymers, what phenomena could be used to define them? Is there a phase transition when disorder and frustration rule? Magnetic systems are particularly well suited for answering such questions that are especially relevant at the nanoscale. Following a brief overview of the signatures of ill-condensed matter, I will introduce some of our recent research on very poorly condensed matter systems; nanoparticle-based magnets. With these systems, I will present our new chapter to the ongoing story of ill-condensed matter. Using disorder and dipolar interactions, we start with nanoparticle systems that are replica spin-glasses where we can tune the intrinsic anisotropy of the overall system. We then re-condense our matter (nanoparticles) and are able to create a novel form of magnetic order from disorder – macroscopic crystals made of nanoparticles. FCC- and BCO-packed nanoparticles present magnetism that is radically different from their disordered nanocrystalline counterparts. Using the rubric of static and dynamic scaling analysis, we show that long-range dipolar interactions amongst nanoparticles can be used to create novel ferromagnets with domains made of nanoparticles.

Ferromagnetic resonance and strong coupling phenomena in arrays of ferromagnetic nanowires

David Menard, Antoine Morin, Marc-Antoine Jalbert, and Christian Lacroix
Department of engineering physics, Polytechnique Montreal, Montreal, QC, Canada

Arrays of metallic ferromagnetic nanowires (FMNWs) electroplated in nanoporous alumina templates offer considerable design flexibility for the tailoring of their microwave behavior. Their magnetic anisotropy, often dominated by intra-wire and inter-wire dipolar interactions, can be modified at will by controlling their composition and geometrical characteristics. They can also exhibit features, which do not exist in microwave ferrites, such as configurable remanent states consisting of two subsystems of uniformly distributed magnetically bistable nanowires, with the relative fraction of wires in the up or down states being adjustable by partial demagnetizing curves. The collective ferromagnetic resonance (FMR) response of such systems is that expected from two uniform populations of nanowires, strongly coupled by dipolar interaction. However, this increased design flexibility is usually provided at the cost of higher microwave losses as compared to state-of-the-art ferrites and garnets currently used in devices. A common approach to investigate the losses is to measure the FMR linewidth as a function of frequency, but this procedure applied to FMNWs in the past, in the 25-40 GHz frequency range, has often lead to very irregular frequency dependencies of the linewidth, sometimes diminishing significantly as the frequency increases. We will present our recent investigation covering the 50-110 GHz frequency range, with an emphasis on the various coupling phenomena (see figure) which strongly distort the FMR spectra.



An example of two-dimensional map of the FMR (derivative of the absorption peak) measured in a 15 mm^2 array of CoFeB nanowires, with average diameter, spacing and length of 42 nm, 111 nm and 100 μm, respectively. The linear behavior is that expected from Kittel's condition. The system exhibit additional modes coupled to the main resonance of the sample.

Interface coupling of spin waves in permalloy/Ru/permalloy multilayered nanowires: ferromagnetic resonance and theory

P. Lupo[a], Z. Haghshenasfard[b], M. G. Cottam[b], and A. O. Adeyeye[a]
[a] *Department of Electrical and Computer Engineering, National University of Singapore, Singapore*
[b] *Department of Physics and Astronomy, University of Western Ontario, London, Ontario, Canada*

A study of the magnetization dynamics of multilayer nanowires with interface exchange coupling is presented. We consider stripes of ferromagnetic permalloy (Py or $Ni_{80}Fe_{20}$) coupled through a nonmagnetic Ru spacer. The stripes all have a common width *W*, and by varying the Ru thickness *t* in the layered structures Py(20 nm)/Ru(*t* nm)/Py(10 nm) in the range 0.5 to 1.5 nm the interwire coupling can be effectively controlled. Contributions to the coupling arise from the Rudermann-Kittel-Kasuya-Yosida (RKKY) exchange and the biquadratic exchange, as well as from dipole-dipole interactions. By contrast with earlier work on coupled films [1] and stripes with width *W* of order 300 nm or more [2], we consider here narrower stripes where the lateral spatial quantization of the coupled spin waves becomes important, giving additional branches. Ferromagnetic resonance (FMR) measurements are reported taking the applied magnetic field (along the length of the wires) to vary from 0 to 0.15 T, so that the overall magnetizations in the Py layers may be parallel, antiparallel, or in a spin-flop state relative to one another, depending on the interface coupling. Results for different stripe widths (*W* = 90, 110, 140, and 190 nm) are analyzed using two theories: a microscopic dipole-exchange theory and micromagnetic simulations.

[1] X. Liu, H. Nguyen, J. Ding, M. Cottam and A. Adeyeye, *Phys. Rev. B* **90**, 064428 (2014).
[2] X. Liu, P. Lupo, M. Cottam and A. Adeyeye, *J. Appl. Phys*. **118**, 113902 (2015).

Ultrafast laser control of magnetic materials

Ulrich Nowak[a], Unai Atxitia[a], Denise Hinzke[a], Marco Berritta[b], Peter Oppeneer[b]
[a] *Department of Physics, University of Konstanz, Konstanz, Germany*
[b] *Institute of Physicst, University of Uppsala, Uppsala, Sweden*

The term all-optical switching (AOS) refers to the fact that some magnetic materials can be switched solely by the effect of a femtosecond laser pulse, without any applied magnetic field involved. First, such effects were demonstrated for ferrimagnets [1-3] but later also for layered, synthetic ferrimagnets [4] and recently even for ferromagnets [5]. In this talk we investigate helicity dependent AOS in FePt granular films theoretically. We employ *ab initio* methods to calculate the laser-power and photon frequency dependence of the inverse Faraday field and the absorption [6] and calculate the magnetization dynamics triggered by the laser pulse via the thermal heating effect and the inverse Faraday field based on the Landau-Lifshitz-Bloch equation of motion for high-temperature magnetization dynamics. Closer analysis suggests the inverse Faraday effect to be strong enough to serve as mechanism for helicity dependent AOS in a multi-shot experiment.

[1] K. Vahaplar et al., Phys. Rev. Lett. 103, 117201 (2009)
[2] I. Radu et al., Nature 724, 205 (2011)
[3] T. Ostler et al., Nat. Commun. 3, 666 (2012)
[4] S. Mangin et al., Nat. Materials 13, 287 (2014)
[5] C.-H. Lambert et al., Science 345, 1337 (2014)
[6] M. Battiato, G. Barbalinardo, and P.M. Oppeneer, Phys. Rev. B 89, 014413 (2014)

Electron and spin dynamics during ultrafast laser-induced demagnetization in Co/Cu(001)

M. Plötzing[a], S. Eich[b], S. Emmerich[b], M. Rollinger[b], R. Adam[a], C. Chen[c], H. C. Kapteyn[c], M. M. Murnane[c], L. Plucinski[a], B. Stadtmüller[b], M. Cinchetti[b], M. Aeschlimann[b], C. M. Schneider[a], S. Mathias[d]

[a] *Forschungszentrum Jülich GmbH, Peter Grünberg Institut (PGI-6), 52425 Jülich, Germany*

[b] *Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, 67663 Kaiserslautern, Germany*

[c] *JILA, University of Colorado and NIST, Boulder, Colorado 80309-0440, USA*

[d] *Georg-August-Universität Göttingen, I. Physikalisches Institut, 37077 Göttingen, Germany*

Promising theories to explain the ultrafast changes of the magnetization in thin magnetic films after excitation with a laser pulse based on spin-flip scattering or spin-currents point towards an important role of the interplay between electron and spin dynamics. This interplay can be experimentally addressed by time-, energy-, momentum- and spin-resolved photoemission. For this purpose we developed and installed a photoemission setup capable of resolving fundamental magnetic properties of 3d ferromagnets including the exchange splitting and, simultaneously, providing a temporal resolution far below 100fs. The experiment is based on the combination of a bright high-order harmonic generation source [1] and a very efficient spin-detector [2]. Our results demonstrate that this approach can be successfully used to monitor sub-picosecond demagnetization processes directly in the electronic band structure. We observe an excitation of the electronic system over a wide momentum range, which is accompanied by a >50% quenching of the spin polarization for a broad range of energies (Fig. 1). Due to the combination of energy- and spin-resolution of our experimental approach, we are able to analyse the role of Stoner-like exchange quenching and spin-mixing during the demagnetization process.

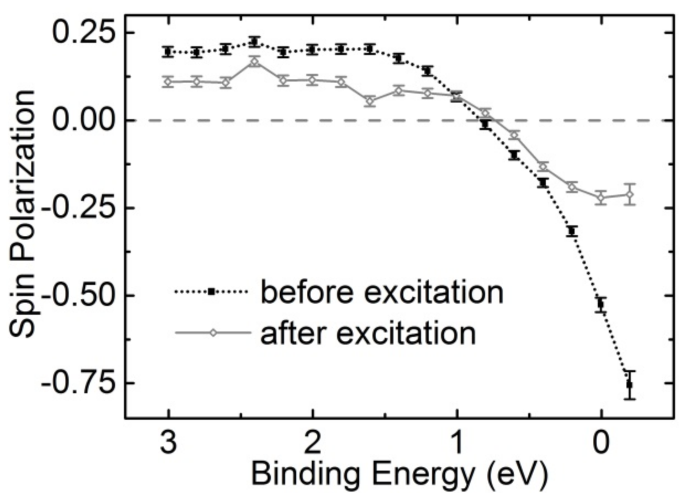


Fig. 1: Ultrafast quenching of the spin polarization in a thin Co film after laser excitation.

[1] S. Eich et al., J. Electron Spectrosc. Relat. Phenom. **195**, 231 (2014).
[2] M. Escher et al., e-J. Surf. Sci. Nanotech. **9**, 340 (2011).

Element-selective investigation of the spin dynamics in Ni_xPd_{1-x} magnetic alloys in the extreme ultraviolet spectral range

Seung-gi Gang[1], Roman Adam[1], Moritz Plötzing[1], Moritz von Witzleben[1], Christian Weier[1], Daniel Bürgler[1], Pablo Maldonado[3], Stefan Mathias[4], Henry C. Kapteyn[5], Margaret M. Murnane[5], Martin Aeschlimann[2], Peter M. Oppeneer[3] and Claus M. Schneider[1]

[1]*Peter Grünberg Institut PGI-6, Research Centre Jülich, 52425 Jülich, Germany*
[2]*Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, 67663 Kaiserslautern, Germany*
[3]*Department of Physics and Astronomy, Uppsala University, SE-75120 Uppsala, Sweden*
[4]*University of Göttingen, 37077 Göttingen, Germany*
[5]*Department of Physics and JILA, University of Colorado, Boulder, CO 80309-0440, USA*

Optical pump-probe experiments allow the investigation of spin dynamics in magnetic materials on femtosecond time scales [1]. Alloying *3d* magnetic transition metals with *4d* non-magnetic materials is expected to lead to better understanding of the exchange interaction in simple magnetic material systems [2]. In our project, we studied the ultrafast demagnetization of Ni_xPd_{1-x} alloys with varying composition which allows us to tune both the exchange interaction of the materials and the spin-orbit coupling in the system. Transversal MOKE (T-MOKE) employing laser-driven high harmonic source generating light in the extreme ultraviolet range (40-72eV) (Fig.1. left) was employed to measure the ultrafast demagnetization at both Ni $M_{2,3}$- and Pd N_3-edges, element-selectively (Fig.1. right). Our results provide a deeper insight into the exchange coupling between Pd and Ni in Ni_xPd_{1-x} alloys.

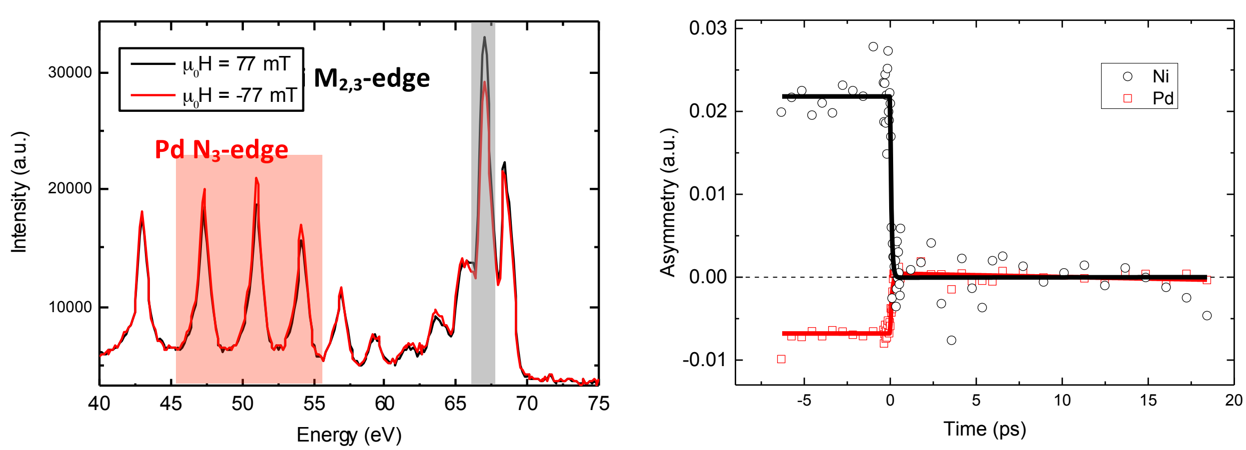


Fig.1 (Left) XUV spectra obtained in static T-MOKE of $Ni_{50}Pd_{50}$ showing magnetic asymmetries at Ni $M_{2,3}$-edge (grey-shaded area) and Pd N_3-edge (red-shaded area). (Right) Demagnetization dynamics obtained from integrated signal of the respective edges (black for Ni and red for Pd). Full lines are the double-exponential fits.

[1] E. Beaurepaire *et al.*, Phys. Rev. Lett. **76,** 4250 (1996)
[2] S. Mathias *et al.*, J. Electron Spectrosc. Relat. Phenom. **189,** 164 (2013)

Dynamics of chiral spin systems: soliton lattices, defects and spinwaves

R. L. Stamps[a], Y. Li[a], S. McVitie[a], and Y. Togawa[b]

[a]*SUPA School of Physics and Astronomy, University of Glasgow, Glasgow, G128QQ UK*
[b]*Osaka Prefecture Unviersity, Japan*

In this talk, I will discuss unusual features associated with chiral interactions and geometries that lead to chiral ordering. A central theme of the talk will be chirality in spin systems—its manifestation as skyrmionic and helicoidal textures, the possibility of its emergence in artificially designed structures, and potentials for its application.[1,2] Interface induced Dzyaloshinskii interactions can have significant effects on domain wall structure and mobility in thin ferromagnetic films. Moreover, spin wave propagation can be strongly affected, especially in regards to scattering from magnetic domain walls.[3]

[1] Silva, R. L., Secchin, L. D. , Moura-Melo, W. A. , Pereira, A. R., and Stamps, R. L. (2014) Emergence of skyrmion lattices and bimerons in chiral magnetic thin films with nonmagnetic impurities. *Physical Review B*, 89. p. 054434

[2] Togawa, Y., et al. (2015) Magnetic soliton confinement and discretization effects arising from macroscopic coherence in a chiral spin soliton lattice. *Physical Review B* 92 p. 220412(R)

[3] Garcia-Sanchez, F., Borys P., Soucaille R., Adam J.-P., Stamps, R. L. and Kim, J.-V., (2015) Narrow magnonic waveguides based on domain walls. *Physical Review Letters*, 114 p. 247206.

Vortex dynamics and statistics in thin elliptic ferromagnetic nanodisks

G. M. Wysin
Department of Physics, Kansas State University, Manhattan, KS, U.S.A.

Spontaneous vortex motion in thin ferromagnetic nanodisks of elliptical shape is described here for a vortex state, where thermal fluctuations initiate the motion [1]. The motion is dominated by a natural gyrotropic orbital part, whose frequency depends on the disk size and shape, together with superimposed thermal fluctuations. The system is analyzed via a Thiele equation [2] and also using numerical simulations of the Landau-Lifshitz-Gilbert equations, including the demagnetization field calculated with a Green's function approach for thin film problems. At finite temperature the thermalized dynamics is solved using a second order Heun algorithm [3] for the magnetic Langevin-LLG equation for the system. The vortex state is stable only within a limited range of ellipticity (as opposed to a quasi-single-domain state). A vortex is found to move in an elliptical potential with two principal axis force constants; the eccentricity of the vortex motion is directly related to the force constants. The vortex position and velocity distributions in thermal equilibrium are found to be Boltzmann distributions. The results show that vortex motion in elliptical disks can be described well by a Thiele equation [2].

[1] T.S. Machado, T.G. Rappoport and L.C. Sampaio, Appl. Phys. Lett. **100**, 112404 (2012).

[2] A.A. Thiele, Phys. Rev. Lett. **30**, 230 (1973); J. Appl. Phys. **45**, 377 (1974).

[3] J.L. García-Palacios and F.J. Lázaro, Phys. Rev. B **58**, 14937 (1998).

Thermal control of spin wave propagation in Yttrium Irion Garnet (YIG) thin films

Grant A. Riley[a], César L. Ordóñez-Romero[b], and Kristen S. Buchanan[a]
[a] *Department of Physics, Colorado State Unviersity, Fort Collins, CO, USA*
[b]*Instituto de Física, Universidad Nacional Autónoma de México, Ciudad de México, CU, México*

Magnonics, a field that utilizes spin waves to transmit information, is receiving a great deal of interest. Logic devices based on spin wave interactions have the potential to greatly reduce the footprint size of devices; however, new ideas for controlling spin waves are needed. Here we explore the interplay between travelling spin waves in a surface wave geometry and a linear thermal gradient that is applied along the length of a 6.3-μm thick YIG spin waveguide. We have used space- and time-resolved Brillouin light scattering (TR-BLS) to track spin wave pulses as they propagate into a region of increasing temperature. Microwave pulses with a duration of 100 ns and a repetition rate 500 kHz were used to generate spin waves using pulse power that was well below the nonlinear threshold. Figure 1 shows spatial scans of the time-integrated TR-BLS signal obtained at room temperature and with a thermal gradient. An intricate diamond-shaped propagation pattern is observed that includes strong bright spots at regions where constructive interference occurs. The BLS intensity increases measurably in certain regions when a thermal gradient is applied. Additionally, subtle differences are seen in the time domain. Previous work done in the backward volume geometry showed a modification of the wavelength corresponding directly to the changing saturation magnetization [1] but the response observed here for surface waves is considerably more complex. This type of effect may provide new means for controlling spin wave propagation by modifying the thermal landscape.

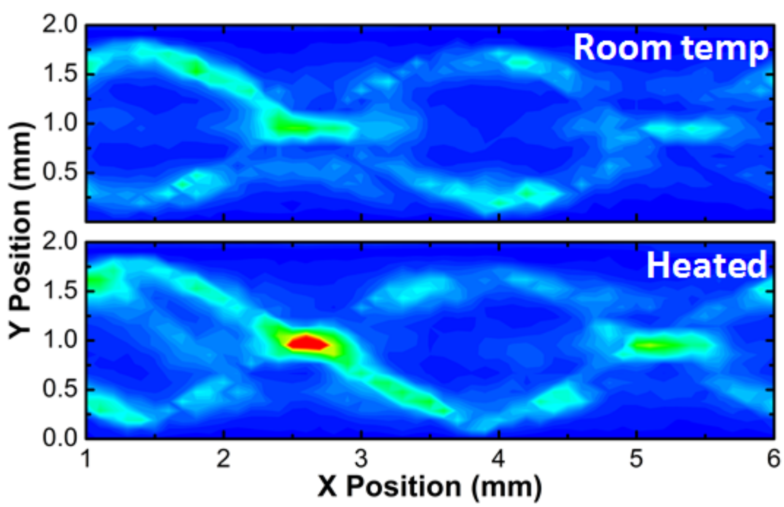


Figure 1: Two-dimensional spatially resolved BLS scans show a difference in intensity between the sample at room temperature and with a thermal gradient applied. A pumping frequency of f=3.925 GHz was used with a static field of H=779 Oe applied along Y. The spin waves were generated using an antenna located at X=0 mm.

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Phase-sensitive inductive detection of ac currents due to spin-pumping/inverse spin orbit torques in unpatterned Permalloy/Pt bilayers

Tom Silva[a], Hans Nembach[b], Justin Shaw[a], Alexy Karenowska[c], Mathias Weiler[d]
[a] *NIST, Boulder, CO USA*
[b] *JILA, University of Colorado, Boulder, CO USA*
[c] *Physics Dept., Oxford University, Oxford, UK*
[d] *Walther Meissner Institute, Garching, Germany*

We present a new method to measure the ac inverse spin Hall effect at GHz frequencies. Unlike previous methods [1-3], our does not rely on any patterning or electrical contacts. We utilize phase-sensitive, broad-band, perpendicular-field ferromagnetic resonance to detect the ac current by the inverse spin orbit torque (iSOT) in Py/Pt bilayers, where the SOT includes both damping-like bulk effects such as the spin Hall effect, and purely interfacial field-lke effects such as Rashba-Edelstein. The iSOT component of the signal is non-linear in the excitation frequency; while the inductive FMR response scales linearly with frequency, the iSOT signal scales quadratically because the iSOT current itself is proportional to dm/dt. This differential gain affords us detection of previously unreported higher order contributions to the iSOT signal. We compare FMR measurements with a control samples that do not include the high spin-orbit layer, e.g. Pt. Data sets with and without Pt are normalized by the complex Polder susceptibility, which nullifies any effects due to differences in line-width and anisotropy. The complex ratio of the normalized inductive amplitudes is analyzed with a simple model that considers how the ac currents generated by the iSOT couple inductively back into the excitations waveguide. Phase sensitivity affords us the ability to distinguish between inverse field-like and damping-like torques. The inverse damping-like torque agrees well with previous reported values for the inverse spin Hall effect, and is easily detected over the frequency range of 5-45 GHz. However, the inverse field-like torque is an order of magnitude smaller.

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[3] D. Wei, et al., Nat. Comm. 5, (2014).

Torque-mixing magnetic resonance spectroscopy

J.E. Losby[a,b], F. Fani Sani[a,b], D.T. Grandmont[a], Z. Diao[a,b], M. Belov[b], J.A.J. Burgess[a,b], S.R. Compton[a,b], W.K. Hiebert[a,b], D. Vick[b], K. Mohammad[c], E. Salimi[c], G.E. Bridges[c], D.J. Thomson[c], and M.R. Freeman[a,b]

[a]University of Alberta, Department of Physics, Edmonton, Canada
[b]National Institute for Nanotechnology, Edmonton, AB Canada
[c]University of Manitoba, Department of Electrical and Computer Engineering, Winnipeg, Canada

Magnetic resonance spectroscopy based on an optomechanical platform will be presented. The method relies on the choreographing of orthogonal RF fields to yield a torque amplitude (arising from the transverse component of a precessing dipole moment, in analogy to magnetic resonance detection by electromagnetic induction) on a nanoscale mechanical torsion sensor attached to a magnetic material. In contrast to induction, the method is fully broadband and allows for simultaneous observation of the spin dynamics with the associated equilibrium net magnetic moment. To illustrate the method, electron spin resonance spectra of a single-crystal YIG microdisk at room temperature will be presented.

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Reference: *Science* **350**, 798 (2015).

Michelson Microwave Interferometer for Broadband Ferromagnetic Resonance Experiments

Eric R. J. Edwards[a], Justin M. Shaw[a], Hans T. Nembach[a], Anthony B. Kos[a], and Tom J. Silva[a]

[a] *Quantum Electromagnetics Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA*

We present a Michelson-type microwave interferometer for use in ferromagnetic resonance experiments. The small filling factor in vector network analyzer ferromagnetic resonance (VNA-FMR) experiments performed with a broadband coplanar-waveguide (CPW) transmission line loaded with a ferromagnetic thin film results in a large background signal at the VNA receiver, which the interferometer suppresses at a discrete set of frequencies set by the electrical path length of its two arms. Measuring at this set of frequencies – in our prototype separated by 400 MHz – dramatically improves the setup's dynamic range and decreases the measurement noise. A prototype of the design exhibits a 20 dB increase in the signal-to-noise ratio in VNA-FMR experiments relative to non-interferometric measurements. These improvements in the measurement sensitivity can be used to measure samples of smaller magnetic volumes or increase the throughput of the setup. In our tests, we have realized a 100x speedup in VNA-FMR measurement times.

Magnetic properties of Fe_4 molecules compressed in the junction of a scanning tunneling microscope

Jacob Burgess[a,b], Luigi Malavolti[a,b,c], Valeria Lanzilotto[c], Matteo Mannini[c], Shichao Yan[a,b], Silviya Ninova[c], Federico Totti[c], Steffen Rolf-Pissarczyk[a,b], Andrea Cornia[d], Roberta Sessoli[c], Sebastian Loth[a,b]

a) Max Planck Institute for the Structure and Dynamics of Matter, 22761 Hamburg, Germany
b) Max Planck Institute for Solid State Research, 70569 Stuttgart, Germany
c) Department of Chemistry, University of Florence & INSTM, Italy
d) Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia & INSTM, Italy

Single molecule magnets (SMMs) offer a method of creating tailored magnetic clusters with a wide range of properties. This presents enticing possibilities in spintronics applications. However many promising SMMs are large and fragile. This constitutes a challenge in creating SMM based spintronic devices, as well as hindering scanning probe surfaces studies exploring how molecules would behave in device-like environments. Robust molecules, such as the Fe_4 molecule [1], therefore offer particularly important opportunities to make practical progress in SMM based spintronics.

Here we present low temperature scanning tunneling microscopy (STM) measurements where individual Fe_4 single molecule magnets are probed spectroscopically. Magnetic excitations at meV energies can be detected. Variations in excitation energies, due to environmental and configuration changes on the surface are resolvable. Strong tip interactions create a challenging experimental scenario and necessitate the use of a correlation between excitation energy and general topography to identify intact molecules. These intact molecules exhibit significantly boosted intramolecular exchange when compared to bulk molecular crystals. *Ab initio* calculations show that the boost can be explained by a minimal compression of the magnetic molecular core, likely induced by the STM tip [2]. This experiment emphasizes the possibility of tuning magnetic properties in spintronic devices by mechanical interactions as well as demonstrating that Fe_4 remains suitable for such applications when incorporated into prototype device.

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Electrical control of magnetization in ferrimagnetic insulator nanostructures

Caroline A. Ross, Andy Quindeau, Chi-Feng Pai, Maxwell Mann, Lucas Caretta, Can Onur Avci, Astera S. Tang, Mehmet C. Onbasli, G.F. Dionne, Geoffrey S. D. Beach, N. Aimon, Shuchi Ojha
Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge MA 02139

Electrical control of magnetic properties is appealing for low-energy memory or logic devices. We will describe here the electrical manipulation of magnetization in two nanostructured ferrimagnetic oxide systems. The first example is charge-current-induced switching of the magnetization in heterostructures consisting of 5 nm thick Pt or Ta/5 – 10 nm thick $Tm_3Fe_5O_{12}$ (thulium iron garnet, TmIG) films grown epitaxially on $Gd_3Ga_5O_{12}$ (111) substrates (Figure 1 left). Although numerous works have demonstrated the efficacy of SOT in manipulating the magnetization of ferromagnetic metals, SOT-controlled switching of FMIs has not yet been observed. Here we show that spin Hall currents in Pt and Ta can generate spin orbit torques in the adjacent TmIG film leading to full magnetization reversal (Figure 1 center). In the second example we describe a self-assembled two-phase epitaxial multiferroic nanocomposite consisting of a regular array of ferrimagnetic spinel $CoFe_2O_4$ pillars embedded in a ferroelectric perovskite $BiFeO_3$ matrix. The locations of the $CoFe_2O_4$ pillars are templated using substrate patterning to form a 100 nm period square array with vertical (110) interfaces within the $BiFeO_3$ (Figure 1 right). The arrays show magnetoelectric switching, in which an electric field leads to strain in the $BiFeO_3$ which is transferred to the $CoFe_2O_4$, lowering its total anisotropy and enabling switching to occur driven by the stray field of the neighboring pillars. Device applications of these materials will be discussed.

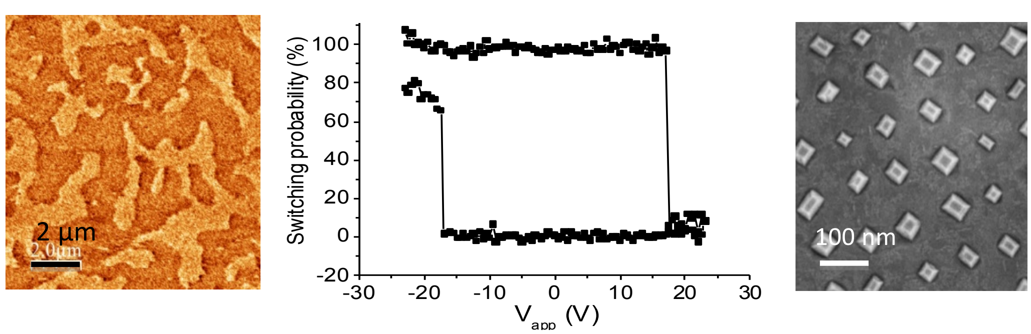

Figure 1: Left: MFM image of demagnetized film showing perpendicular domain structure. Center: Switching of a TmIG film by passing current through an adjacent Pt layer, represented by the applied voltage. Right: Templated nanocomposite of $CoFe_2O_4$ pillars in a $BiFeO_3$ matrix.

Three-terminal spin-torque oscillator devices using MgO-based magnetic tunnel junctions

Eric R. Evarts[a], Matthew Pufall[a], Emilie Jué[a], and William Rippard[a]
[a] *National Institute of Standards and Technology, Boulder, CO, USA*

Nanoscale oscillators are a potential component of future generations of specialized non-Boolean computational circuits. Traditionally, spin-torque oscillators (STOs) have been used as two-terminal devices with an inherent coupling between the input and output signals. When used in more complex circuits, the ability to decouple the input and output signals gives added flexibility and control. Here, we compare use of STOs in two-terminal and three-terminal geometry and probe the similarities and differences of the underlying physics of the interaction between the inputs and outputs in these geometries. In particular, the third terminal consists of either a microstrip field-generation line above the device or a spin-orbit-torque heavy metal (such as Pt) strip adjacent to the oscillation layer. As seen in the figure, injecting a microwave signal into the spin-orbit-torque metal can lead to similar injection-locking as traditionally seen by putting the microwave signal through the device in the two terminal geometry. Similar injection-locking results are observed in field-line driven microwave injection.

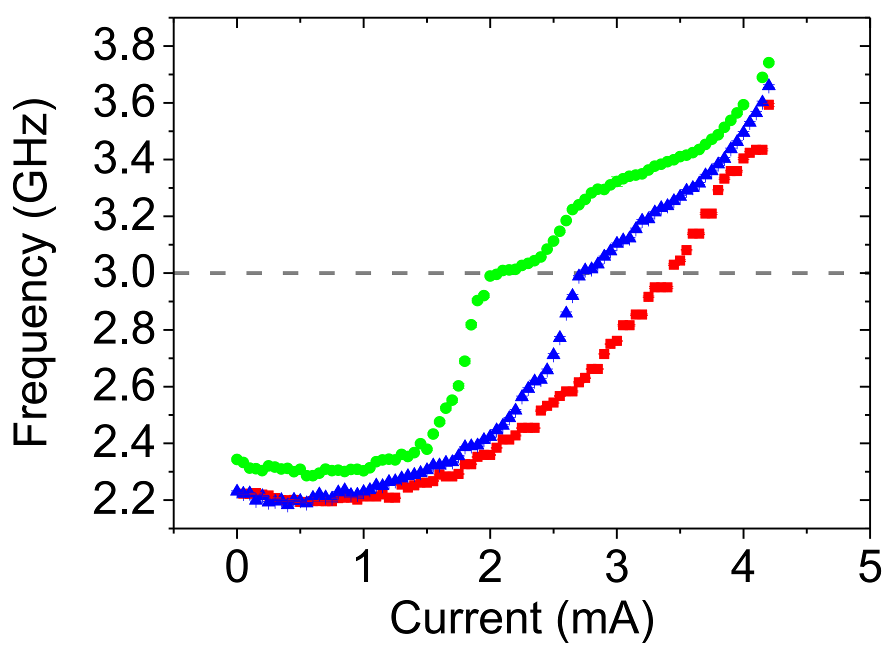

Figure caption: Oscillation frequency as a function of DC current through Pt for an oscillator with a microwave signal at 3 GHz injected into the Pt line with no microwaves (red square), moderate microwave amplitude/weak locking (blue triangle), and high microwave amplitude/ strong locking (green circle). The current through the device is fixed at 0.35 mA.

Temperature dependent magnetization in bimagnetic nanoparticles with antiferromagnetic interfacial exchange

Nick Anderson[a] and Robert Camley[a]
[a] *BioFrontiers Center, University of Colorado Colorado Springs, USA*

We present a self-consistent local mean field analysis of core-shell nanoparticles with ferromagnetic materials but with antiferromagnetic interface exchange coupling. The importance of this type of structure for a variety of applications, including biomedical applications and magnetic recording, has been emphasized in recent studies of core-shell nanoparticles of iron and manganese oxides. We develop theoretical results for a different combination of materials that also have antiferromagnetic coupling, namely nanoparticles comprised of Fe and Gd, and show how the magnetic properties depend on temperature and applied field. We examine results for the case where Gd is the core material and Fe is the shell and vice versa, as well as the results for an Fe/Gd alloy. We find that the size of the core (typically 4-5 nm in diameter), shell (typically < 2 nm wide) and the combined size of the nanoparticle all affect the magnetic behavior of the system. As the temperature is varied, the particles go through multiple phases, including one where the core magnetic moment is aligned with an external field, one where the shell magnetic moment is aligned with an external field and one where the core and shell magnetic moments are in a canted state (occurring for fields larger than 2 kOe) as shown in the figure below. In addition, we calculate the net magnetic moment versus temperature for the various structures and show that the compensation temperature (where the net magnetic moments of the Fe and Gd nearly cancel) depends on all the material parameters – the core radius, the shell radius, and the magnetic field. We also examine superparamagnetism in these structures and show that the nanoparticles can effectively be ferromagnetic at both low and high temperatures and superparamagnetic in the 100- 300 K range.

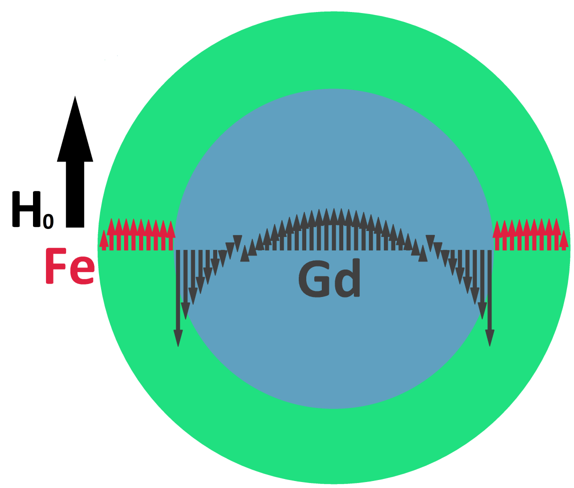

Figure 1: A schematic showing a representative line of atoms through the center of the nanoparticle. The canted state occurs at 230 K in a 2 kOe applied field.

Large spin hall angles in permalloy/gold heterostructures resulting from iron impurities

Rachel K. Bennet[a], Mathias Weiler[b], Sebastian T. B. Goennenwein[b], and Barry L. Zink[a]
[a] *Department of Physics and Astronomy, University of Denver, Denver, Colorado, U.S.A.*
[b] *Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany*

The spin Hall angle is related to the ability of a ferromagnetic/non-magnetic metal interface to transmit spin current from the ferromagnet to the non-magnet. For gold, this value is typically reported to be between 0.01 and 0.11 [1,2,3,4]. We present measurements of very high spin pumping efficiencies in samples of nickel-iron permalloy/gold heterostructures, which are evidence of very large spin Hall angles in gold (0.4 to 0.22) [5]. We interpret these large spin Hall angles as resulting from iron impurities in the gold, due to the orbital-dependent Kondo effect, as suggested by theoretical predictions [6]. We also present quantitative analysis of the metallic impurities in our gold samples through secondary iron mass spectroscopy (SIMS) or similar techniques.

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Bloch versus Néel domain walls in rectangular magnetic nanowires

M. D. DeJong and K. L. Livesey
Center for Magnetism and Magnetic Nanostructures, Department of Physics, University of Colorado at Colorado Springs, USA

Domain walls in rectangular magnetic nanowires have been proposed for a variety of important applications, including in logic schemes, for data storage and even for bio-sensing. For a constant wire thickness, reducing the wire width leads to a switch from the lowest energy domain wall being of Bloch-type to it being of Néel-type.[1-4] It is known that at the precise geometry where the switch between Bloch and Néel walls occurs, domain walls can be moved through a nanowire with the least amount of energy.[3] Here, we provide a one-dimensional (1D) ***analytic*** theory that accurately predicts the nanowire width at which the switch takes place. The domain wall's static magnetization profile depends on the dipolar energy, which in turn depends on the magnetization profile. Hence the problem is self-consistent, making an analytic calculation difficult. To circumvent this, we iterate the domain wall energy twice in order to accurately predict the energy of both Bloch and Néel structures. Our 1D analytic theory predicts the width and thickness of nanowires such that Bloch and Neel walls have equal energy (see plot below) with only a 3% difference compared to the 3D micromagnetic calculation of Martinez *et al.*[2] Results are also in excellent agreement with the experiments of Koyama *et al.*[3]

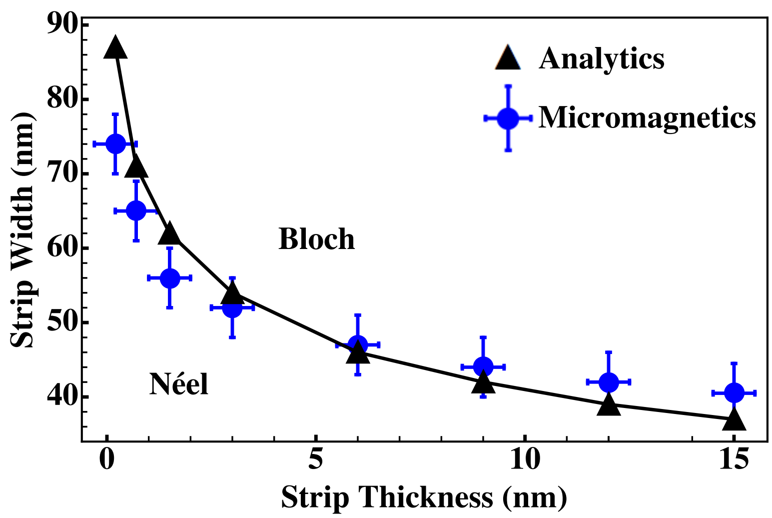

Figure caption: Comparison our analytic results to those of Martinez *et al.* [2] for the wire dimensions corresponding to transition from Bloch to Néel walls.

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Growth of Nanometer-Thick Low-Damping Yttrium Iron Garnet Films by Sputtering

Jinjun Ding[a], Tao Liu[a], Houchen Chang[a], Alejandro Jara[b], Ilya N. Krivorotov[b], and Mingzhong Wu[a]
[a] *Department of Physics, Colorado State University, Fort Collins, CO 80523, USA*
[b] *Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA*

Thanks to their low damping, $Y_3Fe_5O_{12}$ (YIG) materials have been widely used in microwave devices and have also shown high potential for magnonics and spintronics applications. The development of YIG-based spintronic devices demands YIG films that have a thickness (d) in the d < 100 nm range and at the same time exhibit low damping similar to YIG bulk materials. Recent work demonstrated the feasibility of growing such YIG films using sputtering, and YIG films with $d \approx 20$ nm showed a Gilbert damping constant (α) as low as 8.6×10^{-5} [1]. Thicker films, however, showed notably higher damping. This presentation reports the optimization of the sputtering and annealing processes that enabled the growth of YIG films thicker than 20 nm but with even lower damping. A 75-nm-thick YIG film grown on a (111) $Gd_3Ga_5O_{12}$ substrate, for example, showed $\alpha = (5.27\pm0.36)\times10^{-5}$ according to frequency-dependent ferromagnetic resonance (FMR) measurements in perpendicular magnetic fields. This value is significantly smaller than those reported previously for YIG films thinner than 200 nm. The inhomogeneity line broadening is as low as 1.9 Oe, indicating that the film is spatially homogeneous. In addition, the film showed (111) orientation as the GGG substrate, an rms surface roughness of 0.08 nm, a coercive field no higher than 1 Oe, a saturation induction of about 1780 G which agrees almost perfectly with the value for YIG bulk materials, and a gyromagnetic ratio of 2.82 MHz/Oe which is almost equal to the theoretical value.

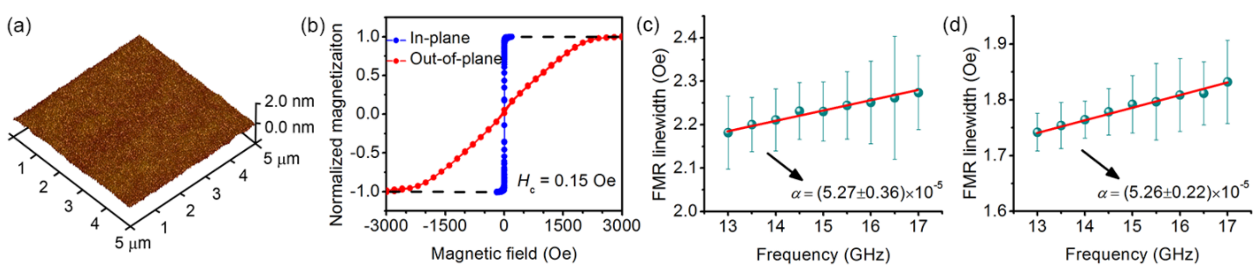

Figure 1: Properties of a 75-nm-thick YIG film grown on a (111) GGG substrate by magnetron sputtering. The data in (c) and (d) were obtained using out-of-plane and in-plane magnetic fields, respectively.

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Torque Magnetometry and Susceptometry using Split-Beam Optomechanical Nanocavities

Tayyaba Firdous[a,b], Marcelo Wu[b,c], Nathanael L.-Y. Wu[b,c], Fatemeh Fani Sani[a,b], Joseph E. Losby[a,b], Paul Barclay[b,c], Mark R. Freeman[a,b]
[a] *Department of Physics, University of Alberta, Edmonton, AB, T6G 2E9, Canada*
[b] *National Institute for Nanotechnology, Edmonton, AB, T6G 2M9, Canada*
[c] *Department of Physics and Astronomy & Institute for Quantum Science and Technology, University of Calgary, Calgary, AB, T2N 1N4, Canada*

Most ultra-sensitive magnetometry methods require or perform optimally under cryogenic conditions (SQUID, Hall sensors) and/or in vacuum (resonant micromechanical devices). We present a nanomechanical torque magnetometer incorporating a photonic crystal split-beam optical nanocavity. The nanocavity-enhanced optomechanical displacement sensitivity enables high-performance operation in air at room temperature. The chip-based magnetometer, as shown in the figure, is proficient for probing both the net magnetization and AC susceptibility of individual magnetic microstructures. This is demonstrated through the observation of nanoscale Barkhausen transitions in the magnetic hysteresis of a permalloy thin-film element. Control of the vector direction of the radio frequency drive allows detection of accompanying AC susceptibility terms.

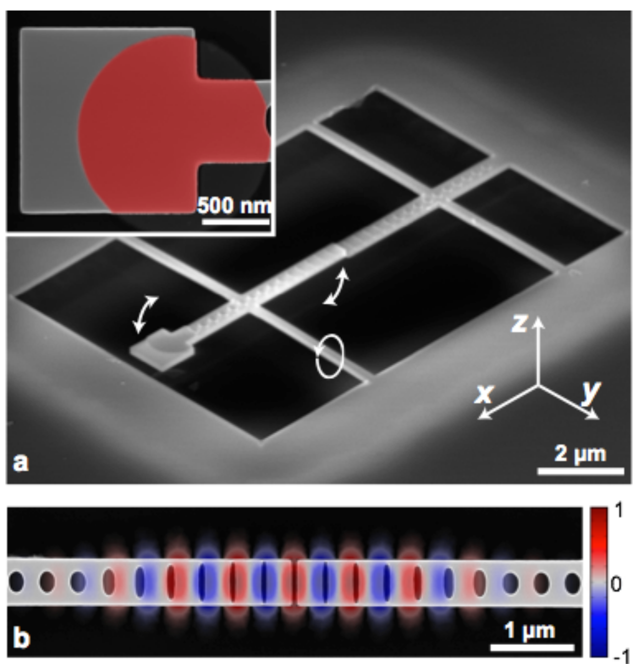

Figure caption: Chip-based magnetometer. (a) Scanning electron micrograph (SEM) of a split-beam nanocavity optomechanical torque sensor supporting a 40 nm thick permalloy island (inset). (b) Top-view SEM of the nanocavity overlaid with a finite element simulation (COMSOL) of the normalized field distribution Ey of its optical mode.

Permalloy and silicon dioxide multilayers for on-wafer inductors operating at radio and low GHz frequencies

Sara Goldman[a], Zbigniew Celinski,[a]
[a]*Center for Magnetism and Magnetic Nanostructures, University of Colorado at Colorado Springs, Colorado Springs, Colorado, USA*

We built copper core inductors sandwiched between magnetic multilayers for use in circuits operating at radio (specifically 25-100 MHz) and low GHz frequency ranges. Specifically, we designed and created a series of planar linear inductors (20-220 microns wide) which performed without the dramatic quality losses normally observed in miniaturized inductors at high frequency. Coating an inductor core with magnetic material can significantly increase its inductance. Permalloy layers (Py, selected for its high magnetic permeability), are sputter deposited, while the copper core is electroplated to ensure a well-determined value of resistivity and stress-free structure. In addition to inductors with individual Py layers, Py/SiO_2 multilayer samples were grown by depositing a (50nm Py / 5nm SiO_2)x50 structure. The multilayer approach resulted in the reduction of power loss, and simultaneously increased the inductance with its high magnetic permeability. Inductance measurements were performed using a network analyser by creating an on-wafer LC circuit. These inductors were constructed directly on silicon wafers, for ease of integration into current electronic systems. We will present characteristics of the prepared inductors such as inductance (L), quality (Q), and DC resistivity.

Parallel pumping for ferromagnetic nanowires and nanotubes with circular cross sections

Z. Haghshenasfard, and M. G. Cottam
Department of Physics and Astronomy, University of Western Ontario, London, Canada

Calculations are reported for the spin-wave instability thresholds of ferromagnetic nanowires with circular cross sections, as well as for nanotubes, under conditions of parallel microwave pumping. The quantized spin waves are characterized by a one-dimensional (1D) wave vector along the nanowire and the external applied magnetic field is taken be parallel to the longitudinal axis. Much of the previous work on nonlinear spin waves focused on effectively unbounded samples, or on macroscopic spheres or films, together with macroscopic theory. In nanowires with lateral dimensions less than about 200 nm the spatial quantization of the eigenmodes become predominant and our theory employs a microscopic (or Hamiltonian-based) dipole-exchange method analogous to that used recently for ultrathin films [1] and nanowire stripes with rectangular cross sections [2]. Numerical applications are made for wires with different diameters and compared to nanowires with square cross sections. When our nanowire results are compared with those for macroscopic samples or for ultrathin films [1], it is found that the "butterfly curves" (threshold field vs. applied field) are significantly modified and show more structural features. This is because the quantized spin waves are characterized by a 1D (instead of 2D or 3D) wave vector.

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Growth of $BaFe_{12}O_{19}$ Thin Films via Sputtering and Spin Transfer across $BaFe_{12}O_{19}$/Pt Interfaces

Tao Liu[1], Peng Li[1], Houchen Chang[1], Wei Zhang[2], J. Sam Jiang[2], Gaurab Rimal[3], Shengxiang Huang[1,4], Jinjun Ding[1], Wei Li[5], Mario Marconi[5], Jinke Tang[3], Axel Hoffmann[2], and Mingzhong Wu[1]*

[1]*Department of Physics, Colorado State University, Fort Collins, CO, USA*
[2]*Materials Science Division, Argonne National Laboratory, Lemont, IL, USA*
[3]*Department of Physics & Astronomy, University of Wyoming, Laramie, WY, USA*
[4]*School of Physics and Electronics, Central South University, Changsha, Hunan, China*
[5]*Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO, USA*

Due to its strong magneto-crystalline anisotropy, $BaFe_{12}O_{19}$ (BaM) has high potential for memory applications. This may be realized, for example, by taking a BaM/Pt bi-layered structure and using the spin Hall effect-produced spin currents in the Pt film to switch the magnetization in the BaM film. Such switching is expected to be more efficient than that in the ferromagnetic metal/Pt counterpart, thanks to the absence of the shunting current in the BaM film and the relatively low damping of the BaM film. This presentation reports on the growth of BaM thin films via sputtering and the demonstration of spin transfer across BaM/Pt interfaces. The films were deposited by RF sputtering at room temperature and subsequently annealed in O_2 at high temperatures. The films with thicknesses of 4-10 nm show an rms surface roughness of 0.2-0.4 nm, an effective perpendicular anisotropy field of about 17 kOe, and a remnant-to-saturation magnetization ratio of 85%-97%. Multiple BaM(9 nm)/Pt(5 nm) Hall bar structures were fabricated by photolithography and ion milling. Those structures show the anomalous Hall effect (AHE), the planar Hall effect, and magneto-resistance behaviour, which together clearly indicate the presence of strong interactions between the moments in the BaM and the spins in the Pt at the interfaces. When the coercivity of the BaM film was measured by sweeping an out-of-plane field, its value decreased or increased by as much as 200 Oe with applied charge currents.
These results provide strong evidence for spin transfer at the interfaces.

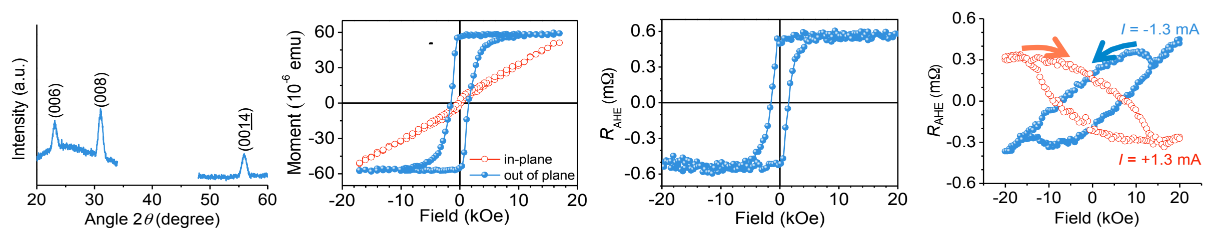

Figure 2: (a) X-ray diffraction spectrum and (b) hysteresis loops of a BaM (9 nm) film. Graph (c) presents the AHE resistance (R_{AHE}) measured on a Pt (5 nm)/BaM (9 nm) Hall bar with a perpendicular field, which shows a loop response very close to the out-of-plane loop in (b). Graph (d) presents the R_{AHE} loops measured for two charge currents of opposite signs, which evolved in an opposite manner.

*corresponding author: mwu@colostate.edu

Magnonic Bragg mirror based on a stack of identical bi-layered ferromagnetic nanowire segments

Lance C. Parsons[a]
[a] 25 Cole Thomas Drive, Conception Bay South, Newfoundland, Canada

A classical model for a magnonic Bragg mirror based on stacked identical bi-layered ferromagnetic nanowire segments is presented. In contrast to the work of Kruglyak et al. [1], the bi-component unit-cell of the system consists of an individual bi-layered nanowire segment and the interfaces between the segments are defined by the Barnaś-Mills boundary conditions [2]. While the related dispersion relation is generally dependent on the properties of the constituent layers as well as the inter-nanowire interface exchange coupling strength, focus is placed on a number of special cases that correspond to specific requirements on various system parameters. For example, if the constituent layers have the same phase thickness, the intensities of even-order Bragg peaks are strongly dependent on the inter-nanowire interface exchange coupling strength, with the peaks becoming more pronounced as the coupling strength decreases; this manifestation of the even-order magnonic band gaps is accompanied by a red-shift in the odd-order Bragg peaks (see Figure). It is also noted that spin wave attenuation can have a dramatic effect on the reflectance spectrum and, thus, the utility of such magnonic Bragg mirrors may be limited.

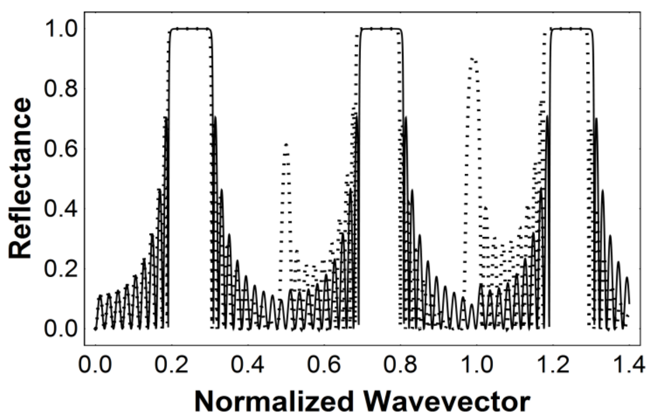

Figure caption: Spin wave reflectance versus constituent layer wavevector for a stack of bi-layered nanowire segments. Solid (dotted) curve: strong (weak) inter-nanowire exchange coupling. Note that spin wave attenuation is neglected in these calculations.

[1] V. V. Kruglyak, R. J. Hicken, A. N. Kuchko and V. Yu. Gorobets, J. Appl. Phys. **98**, 014304 (2005).
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Effect of electron confinement on magnetism of nanostructures

Maciej Dąbrowski[1], Marek Cinal[2], and Marek Przybylski[1,3]
1 - Max-Planck-Institut für Mikrostrukturphysik, Halle, Germany
2 – Institute of Physical Chemistry, Polish Academy of Sciences, Warszawa, Poland
3 - Academic Centre for Materials and Nanotechnology
and Faculty of Physics and Applied Computer Science,
AGH University of Science and Technology, Krakow, Poland

In thin films (and any other nano-objects), electron motion can be confined by the potential barriers at the surfaces/interfaces (or at the edges of nano-objects), leading to the formation of quantum well states (*QWS*). As a result, the electronic structure changes with film thickness.
The confinement of *d*-electrons in transition metal films such as Fe, Ni, and Co is particularly interesting, since the *d*-electrons themselves determine magnetism and magnetic anisotropy. Any manipulation of the *d*-electron bands that results in the change of occupied and/or unoccupied states close to the Fermi level (E_F) can significantly change the magnetic properties of transition metals. If a significant contribution to the magnetic anisotropy is due to spin-polarized *QWS* formed in the *d*-electron bands, an effect of enhanced anisotropy occurs at specific thicknesses. Since the oscillation period of enhanced anisotropy is determined by k_{z0}, i.e., k_z of the bulk *d*-band corresponding to *QWS* that cross E_F, it helps to identify the symmetry of the quantized states.
However, the mechanism of oscillatory anisotropy can be more complex. Only a combination of magneto-optical Kerr effect (or any other magnetometry technique), spin-resolved photoemission spectroscopy and x-ray magnetic circular dichroism helps to correlate the microscopic electronic structure and macroscopic magnetic phenomena. Only then, for example, were magnetic anisotropy oscillations in Fe films concluded to be a direct consequence of the quantization of *d* states with Δ_5 spatial symmetry (and majority-spin character) coupled with majority-spin states with $\Delta`_2$ symmetry.
The mechanisms discussed here can be extended to other magnetic materials, opening the possibility of tailoring magnetic anisotropy by appropriate electronic-structure engineering.

Study of Grain-to-Grain Exchange Coupling in Perpendicular Magnetic Recording Media via Ferromagnetic Resonance

Daniel Richardson[1], Kumar Srinivasan[2], and Mingzhong Wu[1]

1: Department of Physics, Colorado State University, Fort Collins, Colorado 80523

2: Western Digital Technologies, San Jose, California 95131

Understanding grain-to-grain (GG) exchange coupling in perpendicular magnetic recording (PMR) media is of both fundamental and practical significance. In particular, strong GG exchange interactions are believed to be a major limitation in small grain size PMR media, as they can lead to the degradation of the signal-to-noise ratio in the reading process. However, except some qualitative and indirect methods for its estimation, there is a paucity of techniques to directly measure the strength of GG exchange coupling in PMR media. This presentation reports the determination of the effective field (H_{ex}) for GG exchange coupling in PMR media via ferromagnetic resonance (FMR) measurements. Referring to Fig. 1(a), a large positive field is first applied (A) to saturate the sample and then a negative field is applied to reduce the magnetization (B). After that, FMR measurements are taken be sweeping the field between (B) and (C). M_s and M_r denote the magnetization values at points A and B, respectively. Figure 1(b) shows the plots for four samples with different levels of segregant. The H_{ex} value determined by extrapolating the plot to M_r/M_s=0 describes the GG exchange coupling strength in the media. One can see that as the segregant level increases from 0% to 10%, 20%, and 30%, H_{ex} decreases, increases slightly, and then drops to about zero. This study not only demonstrates the feasibility of using FMR to probe GG exchange coupling in granular films, but also provides direct evidence of tuning GG exchange coupling via controlling the segregant level.

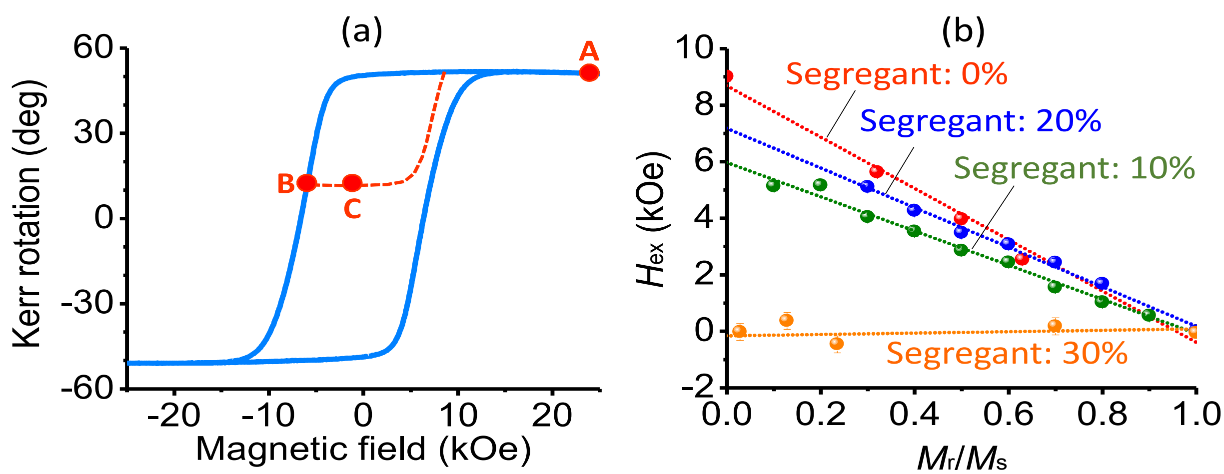
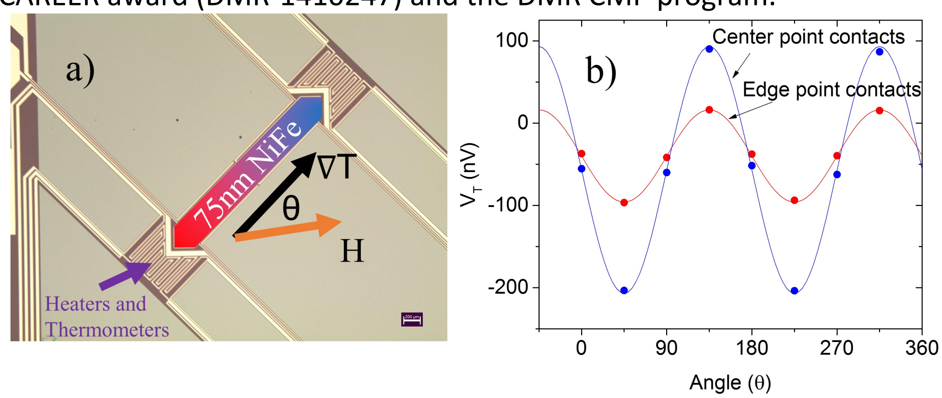


Figure 3: (a) Hysteresis loop of the sample with 20% segregant. (b) Exchange field data for four samples with different segregant levels.

Thermal gradients, nernst effect, hall effect, and new limits on spin-current generation in metallic ferromagnets using suspended thermal platforms.

D. Wesenberg[a], A. Hojem[a], and B. L. Zink[a]
[a] *Department Physics and Astronomy, University of Denver, Denver, CO, USA*

Interest in spincaloritronics, the interaction of heat, charge, and spin currents in ferromagnetic (FM) systems [1], continues to grow. However, potential optimization of these effects and eventual applications of spincaloritronic devices is possible only if the fundamental interactions are understood. Our work focuses on advancing this understanding with a particular emphasis on accurate control and measurement of thermal gradients on the micron scale in thin films and nanostructures [2-4]. We present experiments designed to probe Planar Nernst effect and Planar Hall effect in FM thin films, as well as to put a further limit on the generation of spin-currents across long length scales in FM metals using lateral thermal gradients. As shown in Fig. 1, our measurements are made using unique micromachined thermal isolation platforms. These allow “zero substrate” heating of thin films, eliminating unintended thermal gradients that can often complicate probes of the fundamental physics and materials properties. Platforms used here provide higher sensitivity and better control of thermal gradients at the location of both Pt strips and point contacts for measuring transverse voltages. As shown in Fig 1b, the location of transverse voltage leads affects the local thermal gradient and therefore the size of the Planar Nernst signal (proportional to sin2θ), while any contribution from the transverse spin Seebeck effect (proportional to cosθ) remains impossible to detect. 2D finite element modelling has been performed to better understand thermal gradients of our geometry. This work is supports by the NSF CAREER award (DMR-1410247) and the DMR CMP program.



a) A platform designed to further maximize the transvers voltage. b) Transverse voltage measurements in platforms >5x wider than our previous work [2] to provide higher sensitivity of evidence of PNE signals and field-independent background, but no sign of thermal spin-currents.

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Ferromagnetic resonance power absorption by a magnetic nanowire

P. Yarbrough, N. Sorensen, M. Rizzardi, I. Harward, Z. Celinski, and K. Livesey
Department of Physics, University of Colorado at Colorado Springs, Colorado Springs, CO, US

Magnetic nanowires have large shape anisotropy and small lateral size, which makes them useful for non- reciprocal microwave devices where low losses are required. [1] The power absorbed by such a nanowire is dependent on its shape, amount of material, and the orientation of the sample with respect to the rf driving field. We will present an analytic calculation of the power absorbed by a rectangular Permalloy nanowire on a coplanar waveguide. Specifically, nanowires with aspect ratio 2:1 (400 nm tall and 200 nm wide) or 1:2 (200 nm tall and 400 nm wide) are compared using a method similar to that used previously for thin films. [2] The applied static field is collinear with the waveguide's long axis, while the rf field is transverse to the static field, in the plane of the substrate. The figure below shows power absorption for the flatter (1:2) wire with the solid line, and the taller (2:1) wire with the dashed line, each with a 10 Oe rf field applied with frequency 14 GHz. The difference in power absorption between two nanowires with the same volume is as large as 40%, with the flatter (1:2) wire absorbing more power than the taller (2:1) wire. The analytic calculation is compared with experimental results. Permalloy nanowires are fabricated using electron beam lithography, and repeated along the coplanar waveguide with sufficient spacing to be considered non-interacting. Absorption is measured using a vector network analyser.

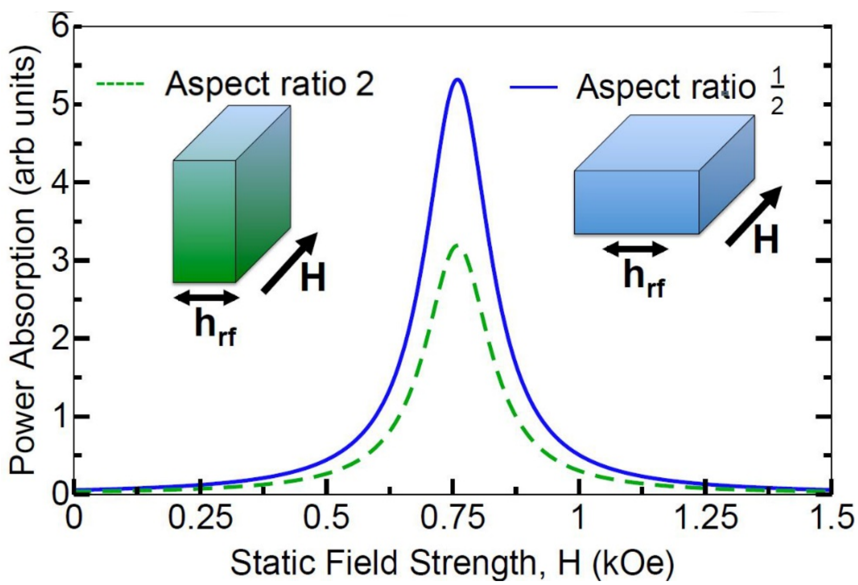

Figure: The power absorption of two Permalloy nanowires as a function of static field strength.

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Voltage-controlled exchange bias: A building block for ultra-low power memory and logic device applications

Christian Binek, W. Echtenkamp, M. Street, A. Mahmood, J. Wang, P. Dowben

Department of Physics & Astronomy and Nebraska Center for Materials and Nanoscience, University of Nebraska-Lincoln, USA

Voltage-controlled exchange bias (VCEB) enables dissipationless control of interface magnetic states thus paving the way towards ultra-low power, non-volatile spintronics. We exploit quantum mechanical exchange between a ferromagnetic (FM) CoPd thin film and the electrically switchable boundary magnetization (BM) of the magnetoelectric (ME) antiferromagnet chromia to enable VCEB, i.e., electrically shifting the FM hysteresis along the magnetic field axis [1,2]. The switchable remnant magnetization serves as non-volatile state variable in memory and logic devices. I report on the challenging realization of VCEB in all thin film geometry and the role of BM as a key element to overcome limitations by the weak linear ME susceptibility of bulk chromia. I introduce voltage-switchable BM and VCEB, provide experimental evidence, present our latest results on VCEB in patterned thin films with reference to applications, and introduce a tabletop method to measure switching of the antiferromagnetic order parameter in chromia [3]. The figure shows a cartoon of our magneto-optical method. It utilizes dispersion of the electric field-induced Faraday rotation in ME antiferromagnets to measure magnitude and sign of the order parameter and its coupling with BM.

We acknowledge supported by NERC, a wholly-owned subsidiary of the Semiconductor Research Corporation (SRC), through CNFD, an SRC-NRI Center under Task IDs 2398.001 and 2587.001, by C-SPIN, one of six centers of STARnet, a SRC program, sponsored by MARCO and DARPA, and by NSF through Nebraska MRSEC Grant No. DMR-1420645. Research was performed in part in the Nebraska Nanoscale Facility supported by the NSF under Award NNCI: 1542182.

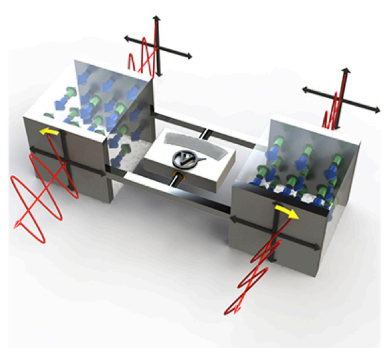

Figure caption: Schematics of the magneto-optical tabletop technique allowing to measure the antiferromagnetic order parameter via electric field induced Faraday rotation. Rotation of the plane of polarization of the probing linearly polarized light depends on the sign of the order parameter.

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Monte Carlo simulations of ABC stacked kagome lattice thin films

H.V. Yerzhakov,[a] M.L. Plumer, and J.P. Whitehead
Department of Physics and Physical Oceanography, Memorial University of Newfoundland, St. John's, Newfoundland, Canada, A1B 3X7
[a]*Current address: Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1*

Properties of thin films of geometrically frustrated ABC stacked antiferromagnetic kagome layers are examined using Metropolis Monte Carlo simulations [1]. The impact of having an easy-axis anisotropy on the surface layers and cubic anisotropy in the interior layers is explored. The spin structure at the surface is shown to be different from that of the bulk 3D fcc system [2], where surface axial anisotropy tends to align spins along the surface [111] normal axis. This alignment then propagates only weakly to the interior layers through exchange coupling. Results are shown for the specific heat, magnetization and sub-lattice order parameters for both surface and interior spins in three and six layer films as a function of increasing axial surface anisotropy. Potential relevance to the exchange bias phenomenon in $IrMn_3$ films is discussed [3].

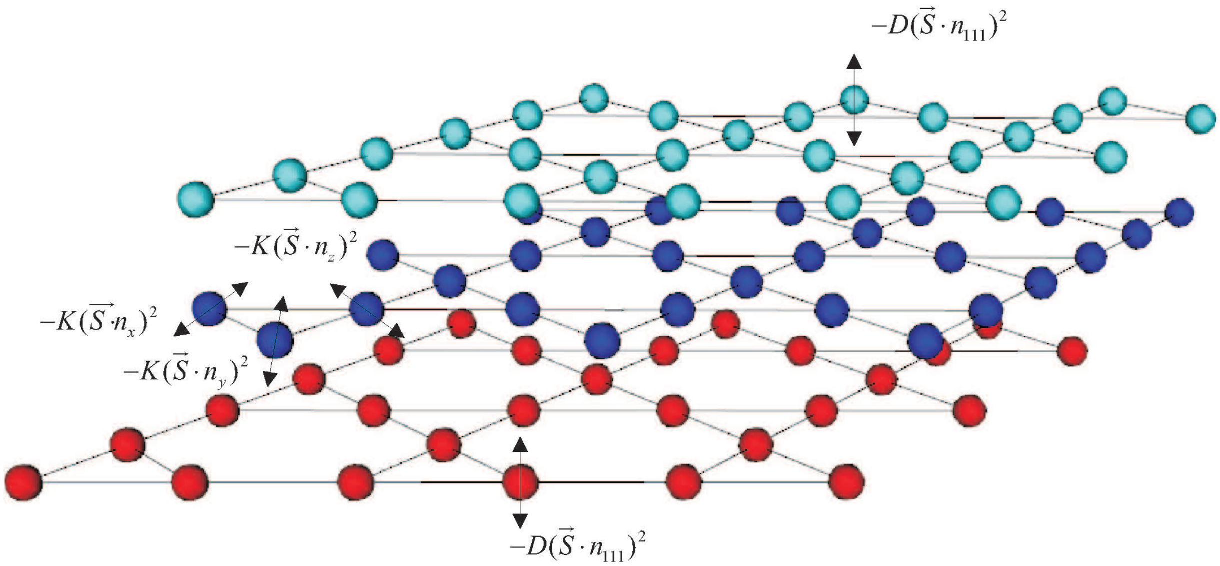

Figure caption: Schematic model of the film with three ABC stacked kagome layers.

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Exchange Bias in $CoFe_2O_4$-$BiFeO_3$ Nanofibers; Examining the Role of Phase Connectivity and Composition in Materials with High Shape Anisotropy

Maeve Budi[a], Evan Glass[a,], and Jennifer Andrew[a]
[a] *Department of Materials Science and Engineering, University of Florida, Gainesville, FL, USA*

Exchange bias is a unique interfacial phenomenon that involves the coupling between magnetic moments of disparate magnetically ordered materials and has garnered increasing interest due to its potential in spin valve applications. While a number of studies have focused on thin film and fine particle systems there have been limited studies on exchange bias in materials with high shape anisotropy, such as nanofibers. This work seeks to address this gap by examining exchange coupling in $CoFe_2O_4$-$BiFeO_3$ nanofiber systems with a range of phase connectivities and compositions. Two fiber morphology systems were chosen with different connectivities: (1) a Janus type system composed of bi-layer fibers where each phase is confined to one semi-cylinder of the nanofiber and the two phases are coupled longitudinally along the length of the nanofiber and (2) nanofibers where the grains of each phase are randomly distributed throughout the individual nanofiber. The relative ratios of $CoFe_2O_4$-$BiFeO_3$ were varied from 9:1 to 1:9 for both the Janus and randomly dispersed systems, and the effects on morphology, interfacial area, crystal structure, and magnetic properties were examined. The morphology and structural properties of the $CoFe_2O_4$-$BiFeO_3$ nanofibers were characterized with scanning electron microscopy (Figure 1), energy dispersive spectroscopy, and x-ray diffraction. Magnetic measurements were performed using a superconducting quantum interference device (SQUID) magnetometer, where both the Janus-type and randomly dispersed nanofibers showed evidence of exchange coupling, exhibited by shifts in field cooled magnetic hysteresis, the magnitude of which was dependent on both the nanofiber morphology and phase ratio.

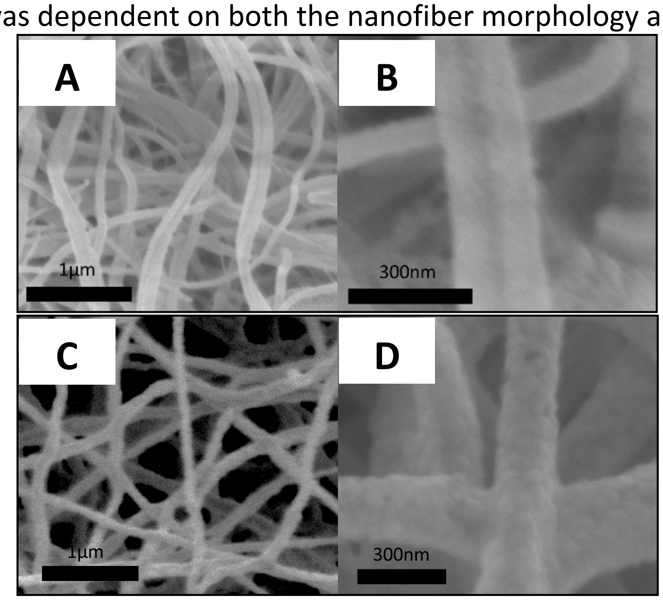

Figure 1: Scanning electron micrograph of $CoFe_2O_4$-$BiFeO_3$ fibers in (A) Janus morphology, scale bar 1µm; (B) Janus morphology, scale bar 300nm; (C) randomly dispersed morphology, scale bar 1µm; and (D) randomly dispersed morphology, scale bar 300nm.

Spin waves interactions at an intersection: the role of an antivortex

Kristen S. Buchanan[a], *Grant A. Riley*[a], *Martin Asmat-Uceda*[a], and *H.J. Jason Liu*[a]*, and Arabinda Haldar*[a]
[a] *Department of Physics, Colorado State University, Fort Collins, CO, USA*

Topological spin textures in patterned magnetic nanostructures including magnetic vortices and skyrmions are currently attracting a great deal of attention because they exhibit a variety of interesting properties, especially in the dynamic regime. The magnetic antivortex (AV), a topological spin texture that is the counterpart of a vortex that involves spins that sweep in from two opposite sides (e.g. the top and bottom) and out toward the other two (e.g., left and right), has received much less attention, in part because it is more difficult to stabilize. Here, we investigate the dynamic behavior of magnetic AV's stabilized at the intersection of orthogonal microstrips using a combination of micro-focus Brillouin light scattering (micro-BLS) and micromagnetic simulations. The simulations show a rich dynamic response that includes analogs of the gyrotropic, azimuthal, and radial modes of a magnetic vortex and we have recently detected some of these modes by micro-BLS [1]. Additional complexities are, however, observed due to coupling between the AV excitations and propagating spin waves in the attached microstrips. The modes in the microstrips are influenced by the symmetries and length scales of the intersection resonances and hence by the spin texture, as illustrated in Fig. 1, which suggests new possibilities for spin wave manipulation and generation.

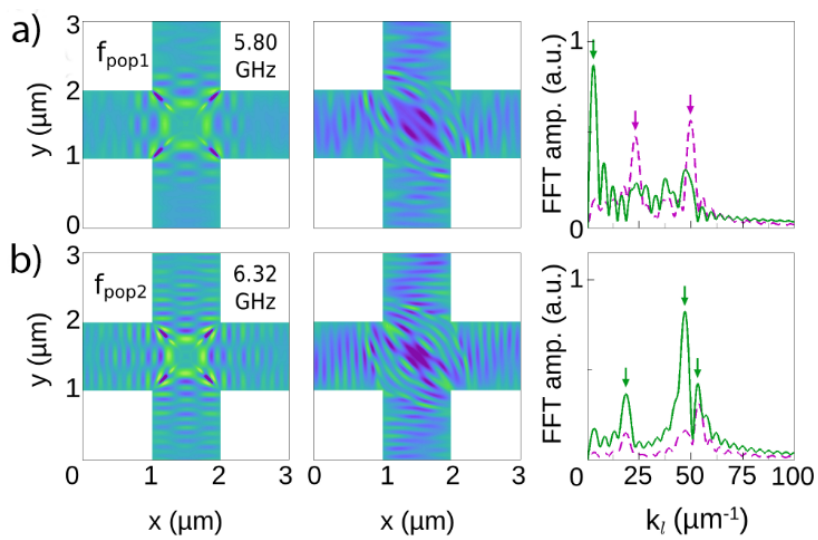

Figure 1: Simulated images of spin wave modes of an antivortex state (left) as compared to a saturated state (center) at an intersection of orthogonal Permalloy microstrips that are 1-mm wide and 37-nm thick for the strongest (a) and next-strongest (b) modes. The excitation field is applied out-of-plane. Spatial Fourier transforms of the excitations in the microstrips beginning 0.5 mm from the intersection (right) show a shift in the dominant leg-directed wavevectors k_l depending on the intersection state.

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Dispersive hydrodynamics in ferromagnets

Ezio Iacocca[a,b], Thomas Silva[c], and Mark A. Hoefer[a]
[a] *Department of Applied Mathematics, University of Colorado, Boulder, CO, USA*
[b] *Department of Physics, Chalmers University of Technology, Gothenburg, Sweden*
[c] *National Institute of Standards and Technology, Boulder, CO, USA*

Magnetodynamics in ferromagnets have typically been studied under the assumption of small-amplitude modes modulating a well-defined magnetization state. Using those assumptions, a hydrodynamic representation was first suggested in Ref. [1] and similar equations were obtained for spin superfluidity [2-4]. Here we show that dispersive hydrodynamic equations can be obtained from the full Landau-Lifshitz equation. A uniform hydrodynamic state (UHS) is defined by its spin fluid density *n* and velocity *u*. By making use of the Landau criterion for superfluidity, a phase diagram can be obtained (Figure). Our results demonstrate that nonlinear and dispersive terms are important to accurately describe magnetodynamics in thin film ferromagnets, enabling the determination of boundaries for the observation of superfluid-like states that may provide novel functionality at low applied fields.

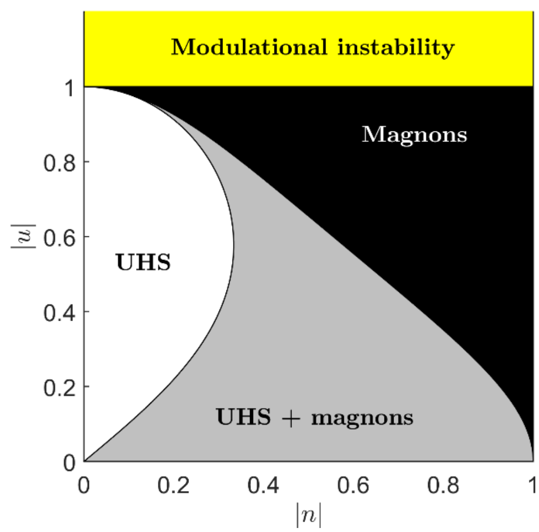

Figure caption: Phase diagram for the UHS. Regimes of stable superfluidity (white), coexistence with magnons (gray), magnons (black), and modulational instability (yellow) are observed.

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Thermodynamic implications of spin impurities on scalability of silicon-based quantum computing

Pavel Lougovski[a], and Nicholas A. Peters[a]
[a] *Quantum Information Science Group, Oak Ridge National Laboratory, Oak Ridge, TN, USA*

One of the most promising approaches to quantum computing utilizes a phosphorus donor in silicon [1]. The donor qubit's electron spin coherence time is well characterized both experimentally [2] and theoretically [3]. However, traditional modeling of spin decoherence assumes a static nuclear and electron spin environment in thermal equilibrium at a temperature T. This approximation is well justified for an environment that is put into contact with a heat sink of infinite cooling capacity. In reality, the cooling capacity of a cryostat is limited. This raises the following question: how might finite cooling capacity fundamentally limit the rate of gate operations in a silicon based quantum computer? Here we study this question by estimating heat dissipation due to unintended magnetization and relaxation of spin impurities from two sources: a) Si substrate impurities, e.g. 29Si and excess 31P donors, and b) undesired control signal losses due to interface coupling. We argue that the former can be readily mitigated with existing refrigeration technology while the latter may eventually limit the number of simultaneous qubits that can be reliably operated.

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The magnetic surface states of antiferromagnets and correlated topological insulators probed with β-NMR

D. L Cortie[a,b,c], R. L. M. Dehn[a], G.D Morris[c], I. McKenzie[c], R. Kiefl[a,c], and W. A MacFarlane[a]
[a] *Quantum Matter Institute, the University of British Columbia, BC*
[b] *Research School of Chemistry, Australian National University*
[c] *TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*

Interfaces can drastically affect local spin dynamics by introducing new states that manifest as additional degrees of freedom in the local electronic environment. For this reason, low energy spin dynamics can have an important influence on the ground state of quantum matter in thin films and in surface regions. Historically, the spin relaxation rate (SLR) measured in nuclear magnetic resonance (NMR) has been a useful technique for detecting sub-THz dynamics; however, nanointerfaces typically produce a very weak NMR signal that is conflated with the dominant signal of the bulk surroundings. This has motivated a variety of ingenious new NMR schemes specifically designed to study thin films and surfaces[1]. In this work, we present a radioactive ion-beam-based version of NMR[2] which performs sensitive read-out of implanted nuclear spins using the anisotropic beta-decay process, resulting in a billion-fold enhancement of the signal from interfacial regions. This is illustrated using some recent data which studied the spin lattice relaxation rate of low-energy radioactive ^{8}Li ion beams in order to detect spin dynamics in correlated metal oxides[3] and antiferromagnetic surfaces[4]. We discuss recent efforts to use this technique to detect spin-polarized electron currents near the surface of topological insulators, presenting first results for the near-surface region of the candidate topological insulator, SmB_6.

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