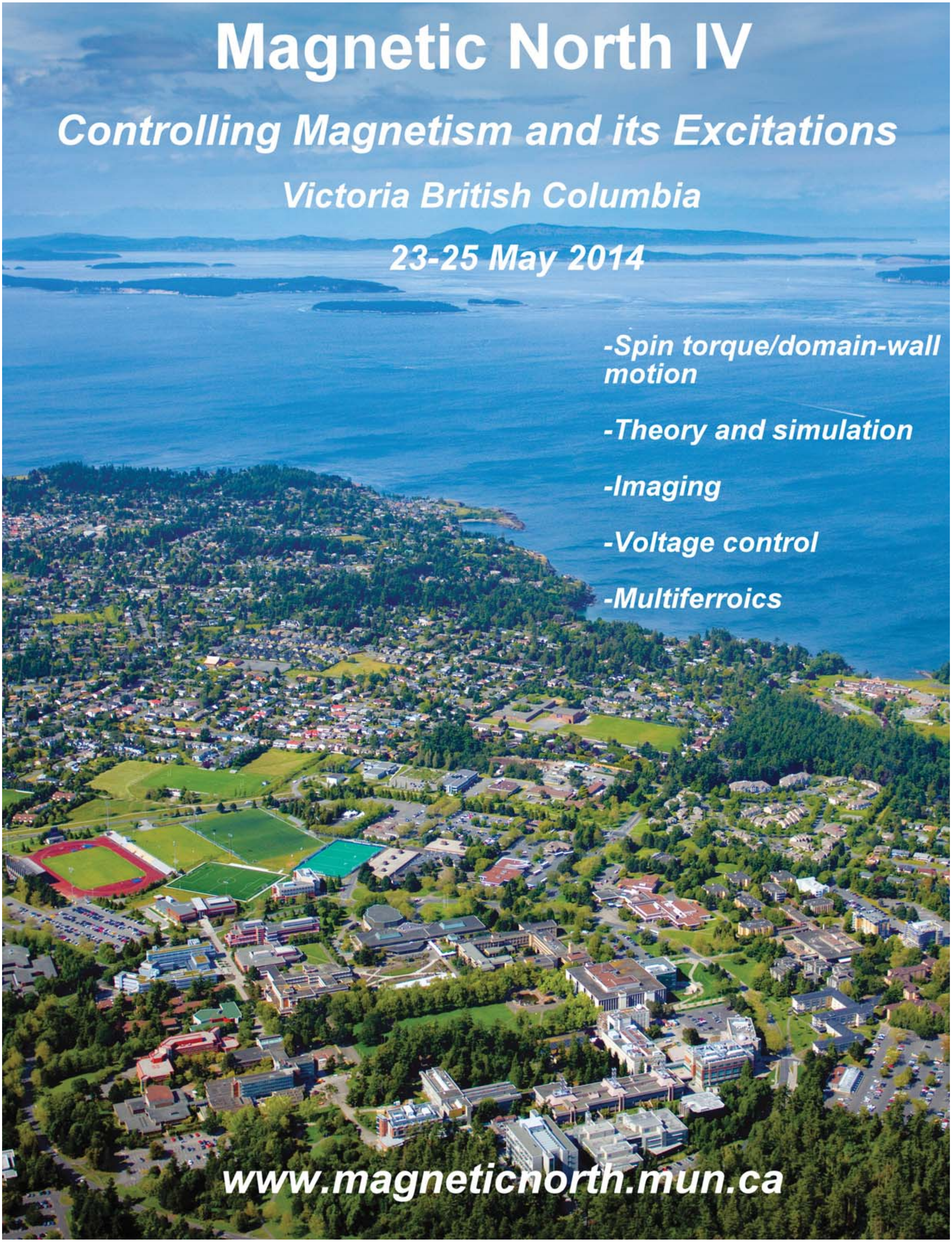

Magnetic North IV
Controlling Magnetism and its Excitations
Victoria British Columbia
23-25 May 2014
-Spin torque/domain-wall motion
-Theory and simulation
-Imaging
-Voltage control
-Multiferroics
www.magneticnorth.mun.ca

Magnetic North IV: Controlling Magnetism and its Excitations

May 23-25, 2014

University of Victoria
Victoria, British Columbia

Organizing Committee:
Rogério de Sousa, Byoung Choi, University of Victoria
Martin Plumer, Memorial University of Newfoundland

This fourth of a series of annual workshops is devoted to research related to the materials properties of magnetic systems with a focus on controlling magnetism and its excitations. Five themes are covered, Spin Torque/Domain Wall Motion, Theory and Simulation, Imaging Magnetism and its Excitations, Control of Magnetism in Ferromagnets, and Multiferroics, from areas of both classical and quantum magnetism involving aspects of experiment, simulation, and theory. A particular goal of the workshop is to bring together researchers who are active in fundamental and applied areas of magnetism in order to explore and benefit from mutual interests. Presentations will be from thirteen invited speakers, sixteen contributed talks and nine posters. It is hoped that the modest-sized venue and the organization of presentations and activities will foster informal interaction and future collaborations.

Magnetic North is an organization of magnetism researchers in Canada and their international collaborators: http://www.magneticnorth.mun.ca/. It is a forum for information exchange on individual and group research activities. There is a broad range of magnetic research activity in Canada, spanning various academic departments and government laboratories using a variety of experimental, theoretical and computational techniques. Research interests encompass geometrically constrained systems (thin films and wires), molecular magnets, dipolar systems, frustration, quantum effects, phase transitions, magneto-electric materials, and magnetic recording. A goal of Magnetic North is to facilitate the exchange of ideas between researchers involved in both fundamental and applied magnetism and to reveal overlapping areas of interest that can foster useful collaborations.

A list of the sponsors of the Magnetic North IV workshop is presented at the back of this booklet.

PROGRAM

Invited talks, listed in the Program as I.1 to I.13, are 40 minutes long which includes 5 minutes for questions. Contributed talks (listed as C.1 to C16) will be 20 minutes in length, including 3 minutes for questions. Abstracts for the posters P.1 to P.9 are included in this Program. The session chairs will ensure that these times are adhered to. Registration and all oral and poster presentations (along with the breakfasts, lunches, refreshment breaks that are included in the registration fee) will take place at the Bob Wright Centre on the University of Victoria campus (see map below).

There are three social events in the program: An informal gathering Thursday evening at Felicita's pub on campus, a Welcome Reception Friday starting at 5:30 pm at the University Club, and a Workshop Banquet on the Saturday evening at 7:00 pm, also at the University Club.

The Workshop will end after lunch on Sunday May 25 at about 1:30 pm.

Thursday, May 22

5:00 pm - 7:00 pm Registration at the Bob Wright Centre.
6:00 pm – not too late Informal gathering at Felicita's Pub on campus, see map below.

Friday, May 23 Bob Wright Centre room SCI A104

8:00 am - 9:00 am BREAKFAST
8:00 am - 9:15 am REGISTRATION

SESSION 1 **Controlling Magnetism in Ferromagnets** Session chair: Can-Ming Hu

9:15 am - 9:20 am Welcome and opening remarks

9:20 am - 10:00 am Paper I.1. Yoshishige Suzuki (Osaka University)
Electric field induced high speed dynamics in FeCo ultrathin films

10:00 am - 10:20 am Paper C.1. Steve Dodge (Simon Fraser University)
Magnetic and transport properties of a ferromagnetic topological insulator

10:20 am - 10:40 am Paper C.2. Nicholas Lee-Hone (Simon Fraser University)
Magnetization reversal in structures used for perpendicular STT-MRAM

10:40 am - 11:00 am BREAK

11:00 am - 11:40 am Paper I.2. Chia-Ling Chien (Johns Hopkins University)
Voltage-Controlled Magnetic Tunnel Junctions

11:40 am - 12:00 am Paper C.3. Igor Roshchin (Texas A&M University)
Fingerprinting Morphology of Magnetic Shape Memory Alloys Using First Order Reversal Curves Analysis of Magnetization

12:00 pm - 1:30 pm LUNCH

12:40 pm - 1:30 pm **POSTERS** (alphabetical)

Poster 1. Marc Allen (University of Victoria)
Theoretical determination of the electric field-magnetic field phase diagram of multiferroic $BiFeO_3$

Poster 2. Mona Alqarni (Memorial University of Newfoundland)
Analysis of the crystal electric field Hamiltonian of rare earth ions in geometrically frustrated magnets

Poster 3. David Cortie (University of British Columbia)
Antiferromagnets mimicking ferromagnets: Monte Carlo spin simulations compared with the analytical solution for the weak ferromagnetism in antiferromagnets with staggered Dzyalonshinskii-Moriya vectors

Poster 4. Tayyaba Firdous (University of Alberta)
Nanomechanical Torque Magnetometry of Magnetite Nanoparticles from Magnetostactic Bacteria on Silicon Nitride Membranes

Poster 5. Joseph Kolthammer (University of Victoria)
Inhomogeneous internal field dynamics in dual-vortex nanopillars: Dynamic dipole coupling during current pulse induced chirality switching

Poster 6. Martin Leblanc (Memorial University of Newfoundland)
Spin Waves in the FCC Kagome Lattice

Poster 7. Ryan McKenzie (University of British Columbia)
Hyperfine Interaction effects in a model Quantum Magnet

Poster 8. Conrad Rizal (University of Victoria)
Ferromagnetic Multilayer-based Surface Plasmon Resonance Sensors

Poster 9. Jonathan Rudge (University of Victoria)
Progress in Time-resolved Magneto-optic Scanning Near-field Microscopy

<u>SESSION 2</u> **<u>Multiferroics</u>.** Session chair: Guy Quirion

1:30 pm - 2:10 pm Paper I.3 Valery Kiryukhin (Rutgers University)
Manipulation of static and dynamic magnetism by an electric field at room temperature: the "hero" multiferroic $BiFeO_3$

2:10 pm - 2:30 pm Paper C.4 William Ratcliff (NIST-Gaithersburg)
Neutron Investigations of Multiferroic $LuFe_{1-x}Mn_xO_3$

Paper I.4 Cancelled

2:30 pm - 3:40 pm	BREAK / POSTERS	
3:40 pm - 4:20 pm	Paper I.5	Randy Fishman (Oak Ridge National Lab)
	Microscopic Model for Multiferroic $BiFeO_3$ in a Magnetic Field	
4:20 pm - 4:40 pm	Paper C.5	Guy Quirion (Memorial University of Newfoundland)
	A Model of the Magnetic Phase Diagrams of the Monoclinic Multiferroics CuO and $MnWO_4$	
4:40 pm - 5:00 pm	Paper C.6	Rogério de Sousa (University of Victoria)
	Electric-field control of magnetism: The case of multiferroic $BiFeO_3$	
5:30 pm - 7:30 pm	**RECEPTION**	University Club

Saturday, May 24

Bob Wright Centre room SCI A104

8:00 am – 9:00 am	BREAKFAST	
SESSION 3	**Theory and Simulation**.	Session chair: John Whitehead
9:00 am - 9:40 am	Paper I.6	Shufeng Zhang (University of Arizona)
	Spin Pumping from Linear Response Theory	
9:40 am - 10:20 am	Paper I.7	Hyun-Woo Lee (Pohang University)
	Interfacial spin-orbit coupling effects in magnetic bilayers	
10:20 am - 10:40 am	Paper C.7	So Takei (UCLA)
	Superfluid Spin Transport in Magnetic Insulators	
10:40 am - 11:00 am	BREAK	
11:00 am - 11:40 am	Paper I.8	Roy Chantrell (University of York)
	A model of thermally assisted magnetisation switching	
11:40 am - 12:00 am	Paper C.8	John Whitehead (Memorial University of Newfoundland)
	Modelling thermally activated switching at long time scales in Exchange Coupled Composite recording media	
12:00 am - 12:20 pm	Paper C.9	Eric Meloche (Seagate Technology)
	High Track Density Magnetic Recording	
12:20 pm - 1:40 pm	LUNCH	
1:00 pm - 1:40 pm	**POSTERS**	same as Friday
1:40 pm - 2:00 pm	Paper C.10	Bob Camley (University of Colorado at Colorado Springs)
	Magnetic Transients with Strongly Tunable Lifetimes	

SESSION 4 **Spin Torque/Domain Wall Motion.** Session chair: Bret Heinrich

2:00 pm - 2:40 pm Paper I.9 Stuart Parkin (IBM Research)
Chiral Spin Torque at Magnetic Domain Walls

2:40 pm - 3:20 pm Paper I.10 Mark Freeman (University of Alberta)
Quantitative Magneto-mechanical Detection and Control of the Barkhausen Effect

3:20 pm - 3:40 pm BREAK

3:40 pm - 4:20 pm Paper I.11 Paul Crowell (University of Minnesota)
Magnetization dynamics of pinned vortices and domain walls

4:20 pm - 4:40 pm Paper C.11 Lihui Bai (University of Manitoba)
Detection of ac spin current due to spin pumping

4:40 pm - 5:00 pm Paper C.12 Bret Heinrich (Simon Fraser University)
Quantum well state induced oscillation of pure spin currents in Fe/Au/Pd(001) systems

7:00 pm - **BANQUET** University Club.

Sunday, May 25

Bob Wright Centre room SCI A104

8:00 am - 9:00 am BREAKFAST

SESSION 5 **Imaging Magnetism and its Excitations.** Session chair: Bob Camley

9:00 am - 9:40 am Paper I.12 Joachim Stöhr (Stanford University)
Imaging Magnetic Excitations with X-Rays

9:40 am - 10:00 am Paper C.13 Akhtari-Zavareh (Simon Fraser University)
Measuring the Magnetic Induction of Isolated CoFeB Nanowires by Off-Axis Electron Holography

10:00 am - 10:20 am Paper C.14 Jacob Burgess (Max Planck Institute)
Induced Spin Dynamics in Atomically Assembled Nanomagnets

10:20 am - 10:40 am BREAK

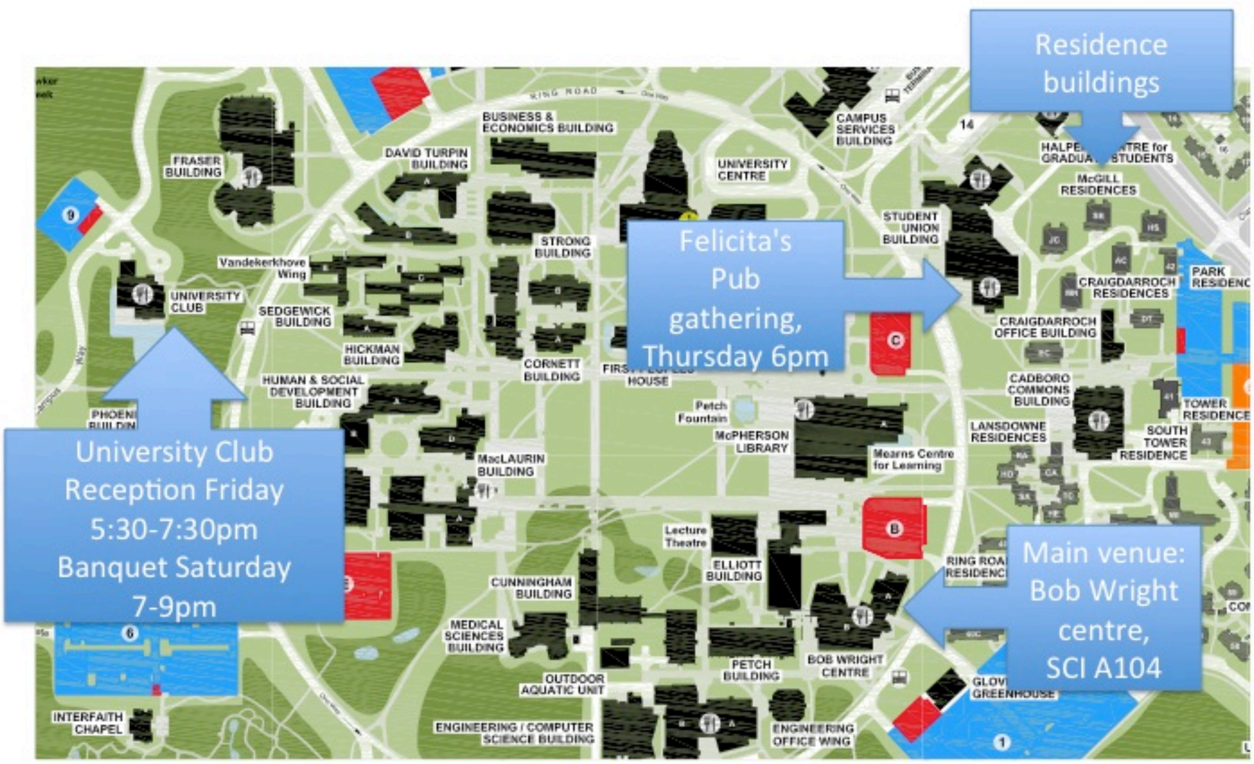
10:40 am - 11:20 am Paper I.13 Bob McMichael (NIST-Gaithersburg)
Imaging Magnetic Excitations with Ferromagnetic Resonance Force Microscopy

11:20 am - 11:40 am Paper C.15 Fatemeh Fani-Sani (University of Alberta)
Magnetometry and AC Susceptometry via Nanomechanical Torque Detection of an individual Monocrystalline YIG Disk

11:40 am - 12:00 pm Paper C.16 David Cortie (University of British Columbia)
Probing interfaces and surfaces in nanomagnetic thin films using Beta-detected NMR with spin polarized isotopes

12:00 pm to 1:30 pm LUNCH

Uvic campus map for Magnetic North IV



Invited 1. Electric field induced high speed dynamics in FeCo ultrathin films

Yoshishige Suzuki
Department of Materials Engineering Science, Graduate School of Engineering Science, Osaka University, Japan

Magnetization control using an electric field [1] will be useful because of its expected ultra-low power consumption and coherent behavior. Several experimental approaches to realize it have been done using ferromagnetic semiconductors [2], materials with magnetostriction together with piezo-driver [3], multiferroic materials [4], ferromagnetic metal films sintered in a liquid electrolyte [5], and ultra-thin ferromagnetic layer in solid-state junctions[6-8].

One of the critical issues in the electric field switching is a realization of bi-stable switching. Since the electric field does not break time reversal symmetry, it does not remove degeneracy of two magnetic states with opposite magnetization. Therefore, a selection of an arbitral magnetic state is not straightforward [9]. Here, we demonstrate a realization of the bi-stable switching using a coherent precessional magnetization toggle switching in nanoscale magnetic cells with a few atomic FeCo (001) epitaxial layers adjacent to MgO barrier [10].

Another interesting possibility in the electric field control of the magnetic anisotropy is an energetically efficient excitation of the FMR and spin-waves. In this talk, an electric field induced FMR in magnetic tunnel junctions and its homodyne detection [11] is also introduced.

If time allows, recent observations of electric states in our voltage samples using XAS and XMCD will also be presented.

References:

[1] Curie, P., J. Phys. 3, 393 (1894).
[2] Ohno, H. et al., Nature 408, 944-946 (2000), Chiba, D., et al, Science 301, 943-945 (2003).
[3] Novosad, V. et al., Journal of Applied Physics 87, 6400-6402 (2000), Lee, J.-W., et al., Applied Physics Letters 82, 2458-2460 (2003).
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[5] Weisheit, M. et al., Science 315, 349-351 (2007).
[6] Maruyama, T. et al., Nature Nanotechnology 4, 158-161 (2009).
[7] M. Endo, et al., Appl. Phys. Lett. 96, 212503 (2010).
[8] D. Chiba, et al., Nat. Mat. 10, 853 (2011) .
[9] Shiota, Y. et al. Applied Physics Express 2, 063001 (2009).
[10] Shiota, Y. et al., Nature Materials, 11, 39-43 (2012).
[11] Nozaki, T. et al., Nature Physics 8, 492–497 (2012) .

Invited 2. Voltage-Controlled Magnetic Tunnel Junctions

Chia-Ling Chien
Johns Hopkins University, USA
Weigang Wang
University of Arizona, USA

Magnetic tunneling junctions (MTJs) are superior spintronic devices with large tunneling magnetoresistance (TMR) effect suitable for magnetic field sensing and memory applications. With the advent of the spin transfer torque (STT) effect, a current through the MTJ can deterministically manipulate its resistance state; high resistance for one polarity and low resistance for the opposite polarity of the current. However, the critical current density (j_C) for switching of STT-MTJs of more than 10^6 A/cm^2 is too high for energy consideration, not to mention the looming threat of device damages. Electric voltage (or electric field) may offer a new way to manipulate MTJs. Although an electric field usually does not alter the bulk magnetic properties, it can significantly alter the surface-induced magnetic properties, such as the perpendicular magnetic anisotropy (PMA). Here we describe the pronounced electric field effects in MgO-MTJs with very thin CoFeB layers, where the PMA originates from the CoFeB/MgO interface.[1,2] The insulating MgO barrier within the MTJ facilitates the application of the electric voltage. By tuning the constituent layer thicknesses in $Co_{40}Fe_{40}B_{20}$/MgO/$Co_{40}Fe_{40}B_{20}$ MTJs, the PMA of the CoFeB electrodes can be significantly modified by the applied electric field. As a result, the coercivities of the two CoFeB layers, the magnetic configuration of the MTJ, and its TMR can be manipulated by voltage pulses, such that the high and low resistance states of the MTJ can be reversibly controlled by voltages less than 1.5 V in magnitude, and equally significant, under very low switching current densities.

This work has been supported by the NSF grant DMR 1262253.

[1]W. G. Wang, M. E. Li, S. Hageman and C. L. Chien, *Nature Mater.* **11**, 64 (2012).

[2]W. G. Wang and C. L. Chien, *J. Phys. D: Appl. Phys.* **46**, 074004 (2013).

Invited 3. Manipulation of static and dynamic magnetism by an electric field at room temperature: the "hero" multiferroic $BiFeO_3$

Valery Kiryukhin
Rutgers University, USA

$BiFeO_3$ (BFO) is a perovskite ferroelectric combining large electric polarization and a complex modulated antiferromagnetic structure exhibiting local weak ferromagnetism at room temperature. We describe the effects of an applied electric field on the magnetic structure of single-crystalline BFO, including field-induced rotation of the magnetic easy plane, field control of the magnetic domain populations, as well as related giant magnetic effects of uniaxial pressure. Most of the presented results are based on detailed neutron scattering studies of the magnetic structure and excitations in BFO crystals. Recent theoretical predictions of larger electric field effects, such as possible field-induced ferromagnetism, are reviewed. We also discuss effects of an electric field on the magnetic excitations in BFO. Finally, we briefly review other functional properties of BFO, such as photovoltaic and switchable diode effects. Combined with the demonstrated electric field control of magnetism, these effects make BFO the true "hero" of multiferroic materials.

Research supported by NSF and DOE.

Invited 4. Engineering the magnonic and spintronic response of $BiFeO_3$ films by epitaxial strain

Maximilien Cazayous
Université Paris Diderot-Paris 7, Laboratoire Matériaux et Phénomènes Quantiques (UMR 7162), France

Multiferroics display cross-coupling effects between ferroelectricity and magnetism. BiFeO3 has many properties such as a cycloidal magnetic order in the bulk and conductive domain walls, most related to its ferroelectric order. However its antiferromagnetic properties have not been investigated deeply in thin films. Here we show how the strain engineering can be applied to modify its static and dynamic magnetic properties. We have used Mössbauer and Raman spectroscopies combined with Landau-Ginzburg theory and effective Hamiltonian calculations. We show that the cycloidal spin modulation that exists at low compressive strain is driven towards collinear antiferromagnetism at both tensile and compressive high strain. Morover, we find that the spin excitations are entirely modified with the suppression of the magnon modes as strain increases and that the strain modifies the average spin angle from in-plane to out-of-plane. Our results illustrate the power of strain engineering for designing functional materials on demand.

Invited 5. Microscopic Model for Multiferroic $BiFeO_3$ in a Magnetic Field

Randy Fishman
Materials Science and Technology Division, Oak Ridge National Laboratory, USA

Because it is one of the very few room-temperature multiferroics, $BiFeO_3$ continues to attract a great deal of attention. The zone-center modes measured by THz spectroscopy provide the most detailed information available about the very small microscopic interactions responsible for the cycloidal spin state in multiferroic $BiFeO_3$. Because the electric polarization P pointing along one of the cubic diagonals breaks inversion symmetry, $BiFeO_3$ supports two different Dzaloshinskii-Moriya (DM) interactions. While the DM interaction perpendicular to P produces the long cycloidal period of 62 nm, the DM interaction along P produces a small tilt in the cycloid, which develops into the weak ferromagnetic moment ~0.03 mB of the canted phase above a critical field of about 18 T. Both DM interactions only couple neighboring spins on the pseudo-cubic lattice. A microscopic model that includes both DM interactions as well as easy-axis anisotropy along P quantitatively predicts the four spectroscopic frequencies that are observed in zero field. Without modifying the interaction parameters, this model also predicts the field dependence of the spectroscopic modes, including the activation of modes that were silent in zero field and their splitting in a magnetic field. At low fields, modes from both the stable and metastable domains are observed with frequencies that agree with this model. For magnetic field along m a cubic axis, only the stable cycloidal domain with wavevector perpendicular to m exists above about 6 T. Only one of the cycloidal modes is electromagnetically active in zero static magnetic field, meaning that it can be excited by both oscillating electric and magnetic fields. But due to mode mixing, all of the cycloidal modes are electromagnetically active in nonzero magnetic field.

Research sponsored by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering.

Invited 6. Spin Pumping from Linear Response Theory

Shufeng Zhang
University of Arizona, USA
Kai Chen
University of Arizona, USA

One of the most interesting spintronics phenomena is spin pumping which describes the generation of spin current of a non-magnetic metal in contact with a processing ferromagnetic layer [1]. The spin pumping has been applied to many experimental realizations such as the enhancement of the Gilbert damping of thin films, spin pumping induced spin torques, and spin pumping induced charge voltage. Up till now, the description of the spin pumping was carried out by the scattering formalism where the disorder in the layers, the interface roughness and the interface spin-orbit coupling are not explicitly taken into account.

In spite of the general acceptance of the spin pumping, the theory has been constructed in terms of the reflection and transmission coefficients which have been calculated only for an isolated interface and the effects of disorders in the layers or at interface are discarded. It has been known that the reflection and transmission coefficients are most useful for calculating transport of mesoscopic conductors, but rather inconvenient and complicated for a diffusive system due to the presence of transverse scattering paths [2]. Furthermore, it is rather arbitrary to divide the leads and scattering regime in the scattering theory, and thus it is desirable to establish a theory of spin pumping for diffusive systems where the spin pumping current is expressed in terms of the parameters such as mean free paths and spin-diffusion length so that the effect of disorders can be explicitly addressed.

By using time-dependent linear response theory, we reformulate the spin pumping with the disorders explicitly included. We expressed the spin pumping conductivity in terms of spectral density functions which are closely related to the disorders. In the case of disorder-free multilayers, our results reduce to those of the scattering theory. However, fundamental differences appear in the presence of the disorders. In particular, we find that 1) the spin pumping conductivity (or spin mixing conductance) depends not only on the interface reflection coefficients, but also or the disorders in the layers and at the interface; 2) the spin current in the non-magnetic layer decays with the mean free path, rather than the spin diffusion length; 3) the spin current also exists in the ferromagnetic layer and can be derived with an equal footing. We will discuss the consequences of our theory on various experiments involving the spin pumping.

Research supported by NSF and DOE.

[1] Y. Tserkovnyak, A. Brataas, and G. E. W. Bauer, Phys. Rev. Lett. **88**, 117601 (2002).
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Invited 7. Interfacial spin-orbit coupling effects in magnetic bilayers

Hyun-Woo Lee
Department of Physics, Pohang University of Science and Technology, Korea

Recent theoretical and experimental studies have revealed interesting properties of magnetic bilayers, where an atomically thin ferromagnetic layer (such as Co) is in contact with a nonmagnetic heavy metal (such as Pt and Ta). It is believed that those properties arise from the spin-orbit coupling in the system. In this talk, we present our recent theoretical studies on the interfacial spin-orbit coupling at the interface between the two constituent layers and its effects including spin-orbit torque, Dzyaloshinskii-Moriya interaction, and the perpendicular magnetic anisotropy.

Invited 8. A model of thermally assisted magnetisation switching

Joseph Barker
Department of Physics, The University of York, U.K.
Tom Ostler
Department of Physics, The University of York, U.K.
Oksana Chubykalo-Fesenko
ICMM, CSIC, Madrid, Spain
Roy Chantrell
Department of Physics, The University of York, U.K.

Ultrafast magnetization processes triggered by femtosecond laser pulses have been the subject of intense research since the original discovery [1] of sub-picosecond magnetization relaxation in nickel. Models treating the phenomenon as a thermodynamic process, such as atomistic spin dynamics, have been successful in describing the underlying physics of these processes. The physical basis of the models used will be described, and the importance of the linear reversal mechanism in terms of providing a route to magnetization reversal will be outlined. The spin Hamiltonian of Rare-Earth Transition metal alloys will be outlined together with calculations of the dynamical properties of the materials described. The response of ferromagnetic materials to ultrafast laser pulses, leading to the prediction of magnetization reversal driven by heat alone [2] will be described. A simple semi-analytical model of the heat-driven reversal process will be described. This model highlights the importance of angular momentum transfer between the sublattices in driving the reversal process. Recent results using the atomistic model quantify this effect in terms of magnon bound states which provide the mechanism of angular momentum transfer.

Research supported by the EU FP7 programme.

References

[1] E. Beaurepaire *et al., Phys. Rev. Lett.* **76**, 4250 (1996).
[2] T.A. Ostler *et al., Nat. Commun.* **3**, 666 (2012).

Invited 9. Chiral Spin Torque at Magnetic Domain Walls

Stuart Parkin
IBM Research, Almaden, CA, USA

Spin-polarized currents provide a powerful means of manipulating the magnetization of nanodevices, and give rise to spin transfer torques that can drive magnetic domain walls along nanowires. In ultrathin magnetic wires, domain walls are found to move in the opposite direction to that expected from bulk spin transfer torques, and also at much higher speeds. We show that this is due to two intertwined phenomena, both derived from spin–orbit interactions. By measuring the influence of magnetic fields on current-driven domain-wall motion in perpendicularly magnetized Co/Ni/Co trilayers, we find an internal effective magnetic field acting on each domain wall, the direction of which alternates between successive domain walls [1]. This chiral effective field arises from a Dzyaloshinskii–Moriya interaction at the Co/Pt interfaces and, in concert with spin Hall currents, drives the domain walls in lock-step along the nanowire. Elucidating the mechanism for the manipulation of domain walls in ultrathin magnetic films will enable the development of new families of spintronic devices such as Racetrack Memory [2].

[1] K.-S. Ryu, L. Thomas, S.-H. Yang, S.S.P. Parkin, *Nature Nanotechnology* **8**, 527 (2013).

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Invited 10. Quantitative Magneto-mechanical Detection and Control of the Barkhausen Effect

Mark Freeman
Department of Physics, University of Alberta, Canada

The irregular step-like changes in magnetization discovered by Barkhausen in 1919 are recognized as the first experimental evidence for ferromagnetic domains (postulated to exist by Weiss approximately twelve years earlier). The Barkhausen effect itself is challenging to fully quantify. There are seemingly too few experimental handles for determination of the disorder potentials, which collectively pin domain walls at large numbers of individual locations simultaneously.

The situation changes qualitatively for ferromagnetic disks in the micromagnetic vortex state. The vortex core localizes domain wall energy to a length scale characteristic of individual pinning sites. This opens the door to a "scanning vortex probe microscopy", in which minute magnetization changes are recorded while the core position is rastered within the disk through the application of in-plane magnetic fields. The requisite magnetization sensitivity is achieved using nanomechanical torque magnetometry. In this regime, the Barkhausen effect becomes a quantitative, 2D probe of local energetics, having spatial and energy resolutions on the scales of a few nanometres and ten millielectron-volts [1]. A two-parameter, piecewise analytical model of the vortex state capable of accurately describing both the net magnetization and vortex core position in the presence of pinning is key to the data analysis. The model accounts for both displacement and flexing of the overall dipole-exchange spring that is the magnetization distribution in the disk, under the influence of external applied magnetic field [2]. In addition to the mapping of intrinsic disorder in a polycrystalline permalloy film, this methodology enables quantification of deliberately created energetic landscapes drawn using very low-dose, focussed ion beam writing.

Such magnetostatic measurements are complementary to spin dynamics studies also sensitive to magnetic inhomogeneity. In general, knowledge of the quasi-static landscape is a prerequisite for fully quantitative understanding of magnetization dynamics. The evolution of this nanomechanical platform towards the simultaneous capture of statics and dynamic will be introduced [3].

Research supported by NSERC, NINT, CIFAR, and CRC.

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[2] Burgess, Losby, and Freeman (2014) Journal of Magnetism and Magnetic Materials 361, 140-149.

[3] J. E. Losby et al. (2013) Solid State Communications (in press, special issue on Spin Mechanics) http://dx.doi.org/10.1016/j.ssc.2013.08.006

Invited 11. Magnetization dynamics of pinned vortices and domain walls

Paul Crowell
University of Minnesota, USA

I will review a series of experiments on the dynamics of individual magnetic vortices and transverse domain walls. In the case of vortices, I will focus on the peculiar dynamics in the presence of pinning . For very low excitation amplitudes, the vortex gyrotropic frequency is determined by a combination of a long-range magnetostatic potential (due to the geometry of the confining particle) and a short-range pinning potential. The dynamics of depinning can be probed in both the time and frequency domains, and the resulting information is used to constructive a highly quantitative map of the pinning potential. I will show how this approach can be used to characterize the physical and magnetic microstructure of thin films as the thickness increases. In the limit of extremely thick (> 100 nm) films, a higher order gyrotropic mode with more exchange-like character appears. Unlike in the vortex case, the lowest frequency mode of a transverse wall exists only because of pinning. I will discuss the role of pinning in experiments on the dynamics of coupled transverse walls in adjacent nanowires. A semi-analytical approach allows us to model two pinned walls coupled magnetostatically.

This work was supported by NSF NEB Program under ECCS-1124831 and the NSF MRSEC program.

Invited 12. Imaging Magnetic Excitations with X-Rays

Joachim Stöhr
Stanford University and SLAC National Laboratory, USA

My talk will present recent results of how x-ray pulses can be used to image spin excitations that were triggered by femtosecond optical or picosecond voltage pulses. I will present the concepts of the employed pump-probe techniques and three examples: the direct observation of the temporal and spatial evolution of the magnetization in GdFeCo after femtosecond optical excitations, the visualization of spin waves excited near a nano-contact by voltage pulses, and the direct observation of transient spin-currents injected into copper.

Invited 13. Imaging Magnetic Excitations with Ferromagnetic Resonance Force Microscopy

Bob McMichael
Center for Nanoscale Science and Technology, National Institute of Standards and Technology, Gaithersburg, MD, USA
Feng Guo
Center for Nanoscale Science and Technology, National Institute of Standards and Technology, Gaithersburg, MD, USA
Maryland Nanocenter, University of Maryland, College Park, MD, USA
Lyubov Belova
Department of Materials Science and Engineering, Royal Institute of Technology, Stockholm, Sweden

We have been developing ferromagnetic resonance force microscopy (FMRFM) as a method for measuring magnetic properties of magnetic nanostructures. Similar to magnetic force microscopy, the detection mechanism involves magnetostatic forces between the sample and a cantilever's magnetic tip. The key difference for FMRFM is that we detect small changes in the sample magnetization that accompany magnetic excitation. In this talk I will highlight recent progress in FMRFM development. I will show examples of how the tip field can create field minima that can localize spin waves. Perhaps more usefully, I will demonstrate how ferromagnetic resonance can be used as a contrast mechanism that depends on the magnetic energy landscape rather than the static magnetization. We also use localized modes at film edges to probe film edge properties. To conclude, I will discuss prospects for improving the sensitivity and resolution of the technique.

Contributed 1. Magnetic and transport properties of a ferromagnetic topological insulator

Steve Dodge Simon Fraser University, Canada
Shreyas Patankar University of California, Berkeley, USA
Eric Thewalt University of California, Berkeley, USA
Derek Sahota Simon Fraser University, Canada
Daniel Golubchik Lawrence Berkeley National Lab, USA
Joe Orenstein University of California, Berkeley, USA, Lawrence Berkeley National Lab, USA
Eli Fox Stanford University, USA
Andrew Bestwick Stanford University, USA
David Goldhaber-Gordon Stanford University, USA
Xiao Feng Tsinghua University, China
Ke He Tsinghua University, China
Yayu Wang Tsinghua University, China
Qi-kun Xue Tsinghua University, China

Recently the quantum anomalous Hall effect has been observed in thin film samples of $Cr_{0.15}(Sb_{0.1}Bi_{0.9})_{1.85}Te_3$, a ferromagnetic topological insulator. Here we report on magneto-optical and transport measurements of this material, as a function of temperature, magnetic field, and applied bias voltage. The anomalous quantum Hall effect is observed, with properties that are qualitatively consistent with previous reports. The magneto-optical Kerr effect reveals a strong increase in the magnetic susceptibility below a characteristic temperature that we associate with the ferromagnetic transition temperature T_C. We also observe remanent magnetization at a lower temperature, T_{rem}, which increases with positive bias voltage but remains constant below zero bias voltage. Time-resolved pump-probe measurements reveal strong sensitivity of the magnetization dynamics to applied magnetic field and applied bias voltage. After excitation by a 100 fs laser pulse, the time-resolved magneto-optical Kerr effect (TR-MOKE) signal exhibits a rise time of several tens of picoseconds, then decays to zero on a nanosecond timescale. We associate the rise time with demagnetization and the fall time with remagnetization. Both the magnitude of the pump-probe signal and the fall time increase strongly with decreasing temperature. At low temperatures, the magnitude and the rise time both increase with increasing positive bias voltage; like the remanent magnetization, the dynamics are relatively insensitive to negative bias. We can explain many of these observations by assuming that the sample is composed of superparamagnetic islands which have magnetic properties that are tuned by the applied bias voltage.

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Contributed 2. Magnetization reversal in structures used for perpendicular STT-MRAM

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An extremely promising candidate for future memory devices is spin-transfer torque magnetic random access memory (STT-MRAM). These devices have the potential to have dynamic random access memory (DRAM)-like densities, to be non-volatile like flash memory, to allow read/write speeds comparable to those of static random access memory, and to have low power consumption. Of particular interest are perpendicular STT-MRAM devices, in which the magnetization is perpendicular to the material layers. This configuration requires lower polarised critical currents than is the case of in-plane STT-MRAM [1].
Storing information in an STT-MRAM device requires two layers: a free layer (FL) that stores the information and a reference layer (RL) that provides a stable reference magnetic orientation. The stability of the reference layer is of crucial importance to the operation of STT-MRAM devices since its reversal would effectively change the state of the information stored in the free layer, with a 1 becoming a 0 and vice versa. We therefore need the reference layer to have high switching resistance to external magnetic fields and polarised spin currents. The reference layer in in-plane STT-MRAM structures is commonly made of two ferromagnetic layers antiferromagnetically coupled across a ruthenium spacer, and such a structure is called a synthetic antiferromagnet (SAF). However, most research on perpendicular STT-MRAM devices has focused on reference layers consisting of a single magnetic layer instead of a SAF. To get the stability required for an STT-MRAM, they require high anisotropy layers containing Pt and Pd.

In this talk, I will describe how we created a SAF composed of Co/Ni multilayers for use in a perpendicular STT-MRAM, allowing us to increase the thermal stability of the reference layer while avoiding the use of precious materials such as Pt and Pd. I will also present a numerical simulation that helped us to understand the magnetization reversal in the SAF. The numerical simulation is based on the Landau-Lifshitz-Gilbert equation, which describes uniform precession of the magnetization in magnetic layers.

The model qualitatively explains the dependence of the intrinsic coercivity on the coupling strength between magnetic layers in the SAF. For antiferromagnetic coupling $J > 1$ mJ/m^3 the coercivity is ~50% of that predicted by the model, which assumes uniform magnetization reversal. However, for low coupling there is a large discrepancy between calculation and experiment indicating that the the films have nucleation centers allowing the reversal to happen at much lower fields.

Time permitting, I will also briefly discuss how to optimise the full Ta/Cu/SAF/Cu/FL/Ta structure, including GMR, damping and anisotropy.

Research supported by NSERC.

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Contributed 3. Fingerprinting Morphology of Magnetic Shape Memory Alloys Using First Order Reversal Curves Analysis of Magnetization

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Magnetic shape memory alloys (MSMA) are the materials that exhibit several interesting properties: ferromagnetism, antiferromagnetism, spin-glassiness, magneto-caloric and shape-memory effects, martensitic transformation. In Ni-Mn-In and Ni-Mn-Sn-based alloys, two different magnetic phases can coexist even in a single-crystalline material. According to the current models, this happens due to coexistence of the areas with the different degree of ordering of the Mn-In or Mn-Sn sublattice ($L2_1$ and B2 at room temperature, and corresponding martensitic phases) [1,2] that determines the distance between the two nearest Mn atoms. As a result the exchange coupling between the two atoms can be either ferromagnetic or antiferromagnetic in the martensitic phases of the material. The interaction between different magnetic phases in these materials leads to well-pronounced exchange bias: the magnetic hysteresis loop is shifted.

We report the results of magnetization measurements in comparison to the structural analysis obtained using wavelength-dispersive X-ray spectroscopy (WDS) and tunneling electron microscopy (TEM) [1,3]. We observe a correlation of exchange bias with the secondary heat treatment for Ni-Co-Mn-In alloys. Comparative first order reversal curve (FORC) analysis of magnetization for Ni-Co-Mn-Sn samples with different heat treatment demonstrates a strong correlation between the morphology and distribution of exchange bias values. For example, the sample after the secondary heat treatment for 3 hours at 700ºC shows H_E= -800 Oe compared to H_E= -600 Oe for the sample without the secondary treatment (Fig. 1). For a single-crystal NiCoMnIn, the FORC diagrams are drastically different, as can be seen in Fig. 2. The difference in FORC diagrams and the underlying properties will be discussed. Furthermore, we demonstrate that based on FORC analysis we can obtain information about cluster sizes of the structural phases in these alloys. This is especially important for polycrystalline alloy samples where dark-field images showing different phases are hard to obtain.

We also observe that the exchange bias can be induced by applying a constant field for 2 hours at 90 K, below the spin-glass transition temperature for some Ni-Mn-Sn samples. This unusual behavior is attributed to magnetic glassiness in these alloys at low temperature.

Work supported by Texas A&M University and US NSF-DMR Metals and Metallic Nanostructures Program/Materials World Network Initiative grant 1108396.

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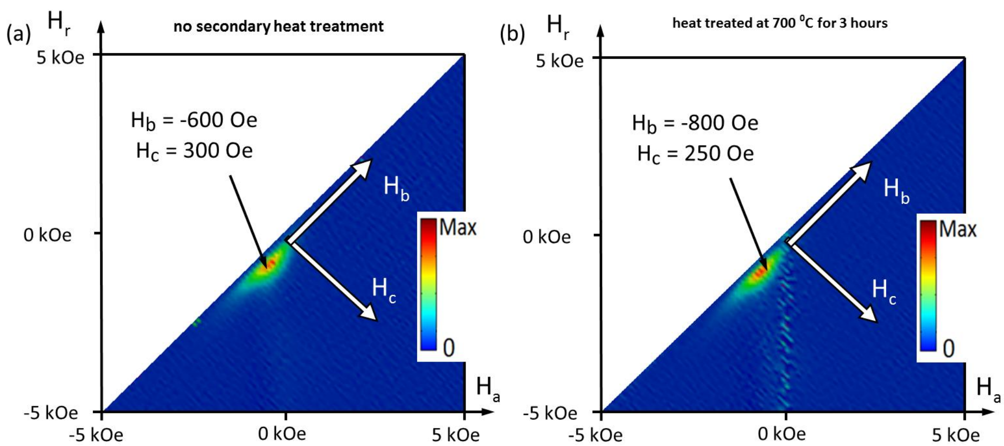

Fig. 1 FORC diagrams for two pre-alloyed powder Ni43Co7Mn39Sn11 samples (a) without secondary heat treatment, (b) with the secondary heat treatment at 700˚C for 3 hours.

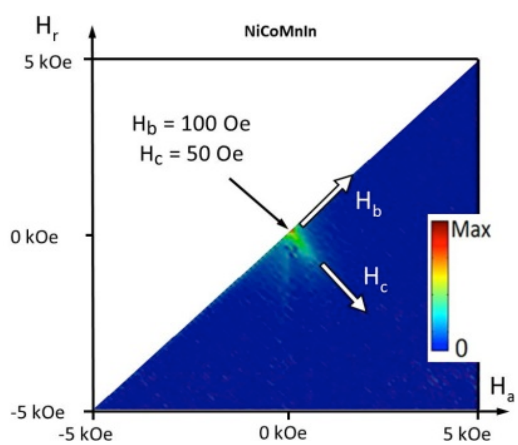

Fig. 2 FORC Diagram for a NiCoMnIn single crystal sample

Contributed 4. Neutron Investigations of Multiferroic $LuFe_{1-x}MnxO_3$

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Recently, multiferroic materials have been the subject of intense investigation. While many new materials have surfaced [6], thus far, only $BiFeO_3$ has been shown to evince coupling of both order parameters at room temperature. Also, thus far, it has been elusive to find materials in which the application of an electric field can directly switch the magnetization by 180 degrees. However, exciting new theoretical predictions suggest that this will be possible in hexagonal $LuFeO_3$ [5].

Recent measurements of $LuFeO_3$ are promising [3,4]. Bulk $LuFeO_3$ crystallizes in the Pbnm space group [2]. However, it can be stabilized in the $P6_3cm$ [3,4] space group in thin films. In films, it is found that the material is ferroelectric at room temperature with a remanent polarization of respectable magnitude, evincing long range magnetic order with spins in the plane forming the familiar 120 degree structure. At lower temperatures, it was found that the moments begin to cant. Theoretical predictions [5] suggest that this canted moment can be switched with an electric field. Unfortunately, this canting occurs at 130 K.

While the recent work in films is exciting, it is important to understand what is intrinsic to the material. Recently, we have been able to stabilize ceramic samples of $LuFeO_3$ in the hexagonal form. During this talk we will discuss the magnetic structure of this compound in the bulk. We will also discuss our inelastic neutron scattering results.

Research supported by the Department of Commerce, USA.

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Contributed 5. A Model of the Magnetic Phase Diagrams of the Monoclinic Multiferroics CuO and $MnWO_4$

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A mean-field Landau-type free energy model based on symmetry arguments is used to investigate the magnetic field - temperature phase diagrams of monoclinic multiferroics such as CuO and $MnWO_4$. Our analysis supports the existence of a collinear phase between the paramagnetic and magnetoelectric spin spiral phases, as determined by high resolution ultrasonic velocity measurements in CuO [1]. Further numerical predictions have been tested against the detailed magnetic and electrical polarization characteristics of $MnWO_4$ [2, 3]. The model reproduces the reported magnetic phase diagrams of this low-temperatures magnetoelectric compound for fields applied along different crystallographic axes and reveals the spin order in the high-field phases. The same model has also been modified to account for the high-field magnetic order in CuO. These new predictions are presently being tested using high pulsed field magnetization and polarization measurements.
Research supported by NSERC.

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Contributed 6. Electric-field control of magnetism: The case of multiferroic $BiFeO_3$

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The ability to control magnetism using electric fields is of great fundamental and practical interest. It may allow the development of ideal magnetic memories with electric write and magnetic read capabilities, as well as logic devices based on spin waves that dissipate much less energy. Multiferroic materials with coexisting magnetic and ferroelectric phases have emerged as the natural physical system to search for this kind of control. However, all demonstrations so far are based on changing the ferroelectric state in order to affect magnetism. I will show that in bismuth ferrite ($BiFeO_3$ or BFO) the combination of room temperature multiferroicity with strong spin-orbit interaction at the bismuth ion sites leads to a qualitatively different kind of E-field control of magnetism, based on the appearance of a strong magnetic anisotropy that is linear in the external E-field. I will argue that this interaction enables E-field control of magnetism without the need to pole the ferroelectric state, leading to spin-based devices that dissipate much less energy per switch.
Research supported by the NSERC Discovery program.

Contributed 7. Superfluid Spin Transport in Magnetic Insulators

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Theoretical proposals for realizing and detecting spin supercurrent in various magnetic insulators are reported. Superfluid spin transport is achieved by inserting a magnet between two metallic reservoirs and establishing a spin accumulation in one reservoir such that a spin bias is applied across the magnet. We first consider temperatures well below the magnetic ordering temperature where spin transport is mainly mediated by the condensate. There, Landau-Lifshitz and magneto-circuit theories are used to directly relate spin supercurrent in different parts of the heterostructure to the spin-mixing conductances characterizing the magnet-metal interfaces and the bulk magnetic damping parameters, quantities all obtainable from experiments. Thermal corrections to spin transport are also discussed. We show how spin superfluidity can be detected in a magnetically-mediated nonlocal conductance experiment.

Research supported by FAME (an SRC STARnet center sponsored by MARCO and DARPA), and the NSF.

Contributed 8. Modelling thermally activated switching at long time scales in Exchange Coupled Composite recording media

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Western Digital Corporation, USA

While the stochastic Landau-Lifshitz-Gilbert (LLG) equations provide a reliable method for modelling dynamic processes in magnetic recording media at finite temperature, such techniques are limited to time scales of the order of μs. The application of the stochastic LLG equations cannot therefore be used to study time dependent processes on a time scale of the order of minutes, as is the case for VSM measurements, or years, as is the case for the thermal degradation of a recorded bit pattern. Such processes are governed by the thermally activated reversal of individual grains, which, by design, are rare events separated by long times intervals. The Kinetic Monte Carlo (KMC) method provides a natural framework for modelling such processes. The KMC algorithm generates a stochastic time series based on the average attempt frequency for thermally activated grain reversal. From this it is possible to construct a sequence of quasi-equilibrium states separated by an essentially instantaneous (ps) thermally activated grain reversal that simulates non-equilibrium processes dominated by these relatively rare and sudden events over long times [1]. Results are presented which extend our earlier KMC simulation studies [2] on single layer media to the case of ECC media [3]. The average attempt frequencies are calculated using the Langer [4] formalism and are applied to calculate finite temperature MH-loops and the coercivity calculated as a function of sweep rate for several values of interlayer coupling of relevance to ECC media.

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Contributed 9. High Track Density Magnetic Recording

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The magnetic storage industry is searching for alternative technologies that can continue to increase areal density in Hard Disk Drives to meet the ever growing consumer demand. Although the increase has been remarkable, further improvements using conventional magnetic recording techniques is becoming more difficult due to issues regarding thermal stability and recording field strength. The latest technology used to push higher storage densities is known as Shingled Magnetic Recording (SMR). The increase in areal density in SMR drives is achieved by partially overlapping tracks, thereby squeezing more tracks per inch. In SMR there is an inherent writing asymmetry because successive tracks partially overwrite previous tracks leaving only the track edge. In this study, we perform SMR experiments on a precision spin-stand and micromagnetic recording simulations to study the effect of track writing asymmetry during the readback process. Experimental and modeling results show that further increases in SMR areal density can be obtained by optimizing the asymmetry of the reader response to match the track writing asymmetry of the shingled track layout.

Contributed 10. Magnetic Transients with Strongly Tunable Lifetimes

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We theoretically examine the behavior of magnetic transients in magnetic nanoparticles in the presence of strong microwave fields. We use a macrospin approximation, appropriate for small particles, and integrate the Landau-Lifshitz-Gilbert equations of motion forward in time. The nanoparticles have a structure which is close to cubic or spherical so there is no significant shape anisotropy, however there is a static magnetic field in the z direction. The transient, essentially the ferromagnetic resonance mode, is created by starting the system in a nonequilibrium configuration. If the amplitude of the microwave field is small, the transient decays quickly, typically in a few nanoseconds. An oscillating microwave field is applied at a frequency which can be far away from the frequency of the transient excitation. As the amplitude of the microwave field is increased, and as the system reaches the nonlinear limit where precession angles are large, the lifetime of the transient increases. Near a critical microwave amplitude the transient lifetime can be extended by factors of over 1000. As the amplitude of the microwave signal is increased beyond the critical amplitude, the lifetime again decreases. The critical amplitude is associated with a microwave induced change in the equilibrium orientation of the magnetization and is given approximately by $h = \omega / \gamma$, where h is the amplitude of the driving microwave field, γ is the gyromagnetic ratio and ω is the angular frequency of the oscillating microwave field. We discuss the dependence of this effect on applied static and microwave fields and on damping and make connections to real materials.

Research supported by an UCCS LAS Faculty/Student Research Award.

Contributed 11. Detection of ac spin current due to spin pumping

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Ac spin current is an exciting new concept in the spintronics field. Ac spin current pumped by Ferromagnetic resonance (FMR) was theoretically predicted by Jiao and Bauer in 2013[1], which was proposed to be detectable as an ac charge current through the inverse spin Hall effect. Such an experiment is very difficult because the ac signal is mixed with the ac charge current due to the cross-talking between excitation and detection of the microwave current in the device. Last year, two groups[2-3] posted their results on-line solving the cross-talking issue with their innovative ideas. However, Faraday inductive current in FMR mixes with the ac charge current too, which was noticed very recently[4-5], and makes the task of detecting ac spin current even more difficult. Here, we develop a completly new method of detecting ac spin current via the spin torque effect[6]. By separately detecting FMRs[7] in a novel structure (a ferromagnetic-metal/ferromagnetic-insulator junction), we demonstrated the simultaneous enhancement of the FMR amplitudes via the dynamical coupling of the FMRs in both layers, which is direct evidence of ac spin current driven by FMR.

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Contributed 12. Quantum well state induced oscillation of pure spin currents in Fe/Au/Pd(001) systems

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In normal metals, such Au, Ag, and Cu, the transport of pure spin currents is well described by spin diffusion theory where spin current relaxation is governed by spin flip relaxation due to the spin orbit interaction and the spin mean free path is appreciably longer than the momentum mean free path. In Au, the spin mean free path is 10 times longer than the momentum mean free path, leading to a spin diffusion length of 35 nm. In nonmagnetic materials having a large Stoner enhancement to the paramagnetic susceptibility, such as Pd and Pt, the transport of spin currents is not within the realm of spin diffusion theory. In these materials, strong spin-spin correlation effects lead to thermally excited, local fluctuating magnetic moments known as paramagnons. Interaction with these paramagnons lead to decoherence of spin currents on much shorter length scales than expected in normal metallic systems. In Pd, the spin decoherence length is 9.4 nm. In this respect, a Pd layer with a thicknesses over 9.4 nm acts as an effective spin sink.

The first two atomic layers of Pd at the Fe/Pd interface have an induced ferromagnetism, a phenomenon known as the (magnetic) proximity effect. To determine if the proximity effect leads to additional damping in the ferromagnetic layer in our structures, two samples were grown: GaAs/2.3 nm Fe/4.1 nm Au and GaAs/2.3 nm Fe/0.6 nm Pd/4.1 nm Au. Both samples were found to have the same Gilbert damping parameter, therefore the ferromagnetic Pd on its own does not contribute to damping.

Since spin transport through Au and Pd is governed by different mechanisms, it is interesting to investigate spin transport in Au/Pd heterostructures. GaAs/2.3 nm Fe/*d* nm Au/9.7 nm Pd/4.1 nm Au samples were studied, where *d*, the Au spacer thickness, has been varied. The ferromagnetic resonance (FMR) spin pumping mechanism was used to generate spin current at the Fe/Au interface. FMR was driven by a small rf field, therefore the magnetic precession was in the small angle regime and the resulting spin current's spin component was transverse to the Fe magnetization. The Fe layer acts not only as a spin pump but also as a spin sink, where any backflow spin current is absorbed by the Fe layer within a few atomic layers (< 0.7 nm).

Damping due to spin pumping rapidly decreased by adding the Au spacer, an effect recently reported in YIG/Pt and YIG/Cu/Pt heterostructures. The rapidity of this decrease is too great to be caused by the loss of spin current due to spin diffusion in Au, indicating reflection of the spin current at the Au/Pd interface. Furthermore, superimposed upon this rapid decrease in damping is an oscillatory dependence as a function of the Au spacer layer thickness. This represents, for the first time, the formation of quantum well states that affect the transport of spin currents that involve contributions of electrons across the whole Fermi surface.

Research supported by NSERC.

Contributed 13. Measuring the Magnetic Induction of Isolated CoFeB Nanowires by Off-Axis Electron Holography

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Arrays of ferromagnetic nano-wires (FMNWs) have been proposed for high frequency applications [1] and high-density storage media [2]. Understanding the crystallographic and magnetic properties of individual nano-wires (NWs) is crucial for optimizing the properties of these arrays. Here, soft and high saturation magnetization CoFeB FMNWs with diameters range between 20 to 170 nm, were studied by Selected Area Electron Diffraction (SAED) and Electron Holography (EH). Diffraction patterns obtained from the NWs suggest that they are nanocrystalline rather than amorphous. Electron holography was used to investigate the local magnetic behavior of a statistical number of these the FMNWs. This information was compared to the results obtained from magnetostatic and ferromagnetic resonance (FMR) of macroscopic NW arrays. Holograms show the magnetization inside the NWs is uniform over most of their length, except at their edge. Since the NWs consist of soft magnetic nanocrystals, the magnetic anisotropy is likely dominated by the shape anisotropy. Numerical simulations suggest that the stray fields at the top of the NWs are well reproduced by a truncated cone model, rather than a cylinder. The measured magnetic induction for NWs with diameters near 170 nm is 1.45 T, which is somewhat smaller than the saturation magnetization extracted from static magnetometry measurements of thin films of CoFeB (about 1.67 T). For the 40 nm diameter NWs the magnetic induction is ranging from an average of 0.5 T near the tip of the NWs to 1.5 T in the middle of the NWs. This significant decrease of magnetic induction near the end of the NWs could be related to the increased demagnetizing field and thinner sample thickness near the tip of NWs as well as an out-of-plane magnetic component due to NWs with tips pointing out of the plane of the sample holder.

This work was done in collaboration with: T. Kasama (Technical U of Denmark), L.P. Carignan (Apollo Microwaves), A. Yelon and D. Ménard (École Polytechnique de Montréal), R. Herring (University of Victoria), R.E. Dunin-Borkowski (Research Centre Jülich), and M.R. McCartney (Arizona State University).

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Contributed 14. Induced Spin Dynamics in Atomically Assembled Nanomagnets

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Recent developments in scanning tunneling microscopy (STM) have made possible atomic scale measurements of spin dynamics on the ns time scale through the application of all electronic pump-probe techniques [1]. Concurrently, the atomic manipulation capabilities of the STM have been developed and applied on an unprecedented scale [2]. This opens the door to the study of dynamics of custom designed atomic structures assembled, measured, and even controlled by the STM tip.

The system most extensively explored thus far with this technique is iron atoms deposited on a copper nitride monolayer grown on a copper (100) substrate. The Cu_2N monolayer serves to decouple the atoms from the metallic substrate, and provides strong anisotropy for iron atoms dependent on the atomic binding site [3]. Together these contribute to enhanced spin lifetimes [1]. Further stabilization of spin excitations can be accomplished by building artificial clusters atom-by-atom resulting in lifetimes of many microseconds.

In order to measure the dynamics of the chains, a spin polarized tip is required along with magnetic contrast between the excited state and the ground state. The magnetism of the tip additionally participates in the dynamics, providing a method of fine tuning the lifetimes of excited states by shifting the tip closer or further from the atomic chain. The interaction of the tip can be incredibly strong, controlling even the ability to excite and detect dynamics. Here we present the results of recent experiments on antiferromagnetic chains with net magnetic moment of zero. These chains feature no spin contrast in an applied field and exclude them from detection by conventional spin-sensitive techniques. We find, however, that by coupling the tip strongly to the chain, we are able to access a regime of excitations that feature exceptionally long lifetimes.

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Contributed 15. Magnetometry and AC Susceptometry via Nanomechanical Torque Detection of an individual Monocrystalline YIG Disk

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Nanomechanical torque magnetometry has proven to be a very sensitive probe of nanoscale magnets [1-4]. We have developed a new nanomechanical detection method for simultaneous measurement of both DC magnetization and AC susceptibility [5]. The power of the technique lies in its ability to probe the magnetic fingerprints of individual mesoscopic elements, which are defined by spatial non-uniformities (disorder), and are masked in measurements of arrays of similar structures. These inhomogeneities can significantly affect the net magnetization, and corresponding dynamic responses, in individual magnets. The simultaneous acquisition of DC and AC measurements provides a comprehensive knowledge of the unique magnetic landscapes in mesoscopic structures.

This nanomechanical detection scheme is demonstrated through the DC magnetization and AC susceptibility to the RF regime measurements of single crystalline YIG disks. The hysteresis curves of the individual YIG disk exhibit no apparent Barkhausen effect. A suite of hysteresis measurements as a function of in-plane field angle allows the magnetic anisotropy of the single object to be examined. The fully characterized YIG disk provides a pristine platform for the study of geometrically-confined magnetization dynamics via nanomechanical detection.

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Contributed 16. Probing interfaces and surfaces in nanomagnetic thin films using Beta-detected NMR with spin polarized isotopes

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Surfaces and interfaces in thin film materials provide a unique setting for the emergence of exotic magnetic and electronic phenomena associated with the high planar surface area and reduction in symmetry. The ability to accurately characterize the interface-localized magnetic structure is a key step towards unveiling the new physics which may be present in such environments. Here I will review recent experimental B-NMR studies including the investigations of fluctuating magnetic moments from 2D electron gases buried at the interfaces of $SrTiO_3/LaAlO_3$ multilayers [1], ferromagnetism in $Ga_{1-x}Mn_xAs$ semiconductors [2], and finite-size effects in nearly-ferromagnetic Pd thin films [3]. I will also discuss current work exploring the application of the technique to study antiferromagnetic and ferroelectric materials. The past three decades have seen the increasing development of existing techniques to study thin films such as polarized neutron reflectometry, circularly-polarized X-ray dichroism, and low energy muon spectroscopy. By comparison, the concept of using Beta-detected NMR of low energy spin-polarized isotopes is relatively new and is evolving in parallel with the availability of new sources of suitable particle beams at large scale accelerator facilities. In this presentation, the basic operational principles of B-NMR will be introduced to highlight mechanisms whereby the probe is sensitive to electronic and magnetic properties. This facilitates insights into the advantages and complementary nature of the various existing techniques available to investigate the local structure of magnetic thin films.

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Poster 1. Theoretical determination of the electric field-magnetic field phase diagram of multiferroic $BiFeO_3$

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The room temperature multiferroic bismuth ferrite ($BiFeO_3$ or BFO) has cycloidal spin order when the externally applied magnetic and electric fields are zero. In this configuration, both ferromagnetic and antiferromagnetic order parameters average out to zero over the period of the cycloid, precluding the design of memory devices. Previous theory has shown that the external B field necessary for converting the cycloid into a homogeneous state with non-zero ferromagnetism is of the order of B=20 Tesla. Using a novel numerical energy minimization scheme, we have found that a distorted conical cycloid state persists until a much higher magnetic field for B fields oriented along any direction perpendicular to the ferroelectric moment. In addition, we show that an external electric field $E \sim 10^5$ V/cm pointing along certain optimal directions can induce a similar transition even at B=0. We have determined the E-B phase diagram for BFO using our numerical method. When BFO is subject to moderate E and B fields at appropriate orientations, the competing interactions interfere in such a way that the system transitions into the homogeneous state at lower field intensities. These results clarify the conditions required to make BFO a useful material in device applications.
This work is supported by the NSERC Discovery program.

Poster 2. Analysis of the crystal electric field Hamiltonian of rare earth ions in geometrically frustrated magnets

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Geometric frustration occurs in the rare earth pyrochlores due to magnetic rare earth ions occupying the vertices of a network of corner-sharing tetrahedra. The rather large degeneracy of angular momentum J of the rare-earth ions tends to be lifted by the crystal electric field due to the neighbouring ions in the crystal. We analyse the crystal electric field Hamiltonian H_{CEF} of the pyrochlore $Tb_2Ti_2O_7$. By re-writing the Stevens operators in H_{CEF} in terms of charge quadrupolar operators, we can identify unstable order parameters in H_{CEF}.
Research supported by the Saudi Ministry of Higher Education and NSERC.

Poster 3. Antiferromagnets mimicking ferromagnets: Monte Carlo spin simulations compared with the analytical solution for the weak ferromagnetism in antiferromagnets with staggered Dzyalonshinskii-Moriya vectors

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Under normal conditions, the staggered magnetization in an ideal antiferromagnet leads to a negligible macroscopic magnetic moment in the absence of an applied magnetic field. In the presence of suitable staggered arrangement of local Dzyalonshinskii-Moriya vectors, however, the antiferromagnet sub-lattices may experience an effective uniform local field leading to a remnant magnetization and a weak ferromagnetic magnetization curve superimposed on the typical linear antiferromagnetic response. This situation is experimentally realized in certain pseudo-cubic antiferromagnetic perovskites and many orthoferrites where the spatial variation of the out-of-phase oxygen octahedral angle provides the required symmetry for the local anisotropic exchange vectors. Here we provide a simple derivation of the analytical solution for a two sub-lattice antiferromagnet with uniaxial anisotropy exposed to a net Dzyalonshinskii-Moriya field at zero temperature. We compare the analytical result for the infinite magnet with thermal Monte Carlo calculations of a classical Heisenberg model of finite size with periodic boundary conditions for various temperatures. Once validated, the numerical model is extended to simulate the magnetic response of small particles and planar thin film nanostructures with non-periodic boundary conditions where the net magnetization is increased via interfacial and finite size contributions.

Poster 4. Nanomechanical Torque Magnetometry of Magnetite Nanoparticles from Magnetotactic Bacteria on Silicon Nitride Membranes

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Magnetic properties for isolated and small-scale assemblies of nanoparticles are generally derived from measurements of bulk nanoparticle systems. To complement this, we aim to investigate these properties for small assemblies of single-domain magnetite nanoparticles.

The nanoparticles, ~ 50 nm in size and harvested from magnetostactic bacteria, were deposited by Nano eNnabler (BioForce Nanosciences TM) on a 100 nm thick, high stress Si_3N_4 membrane 40 × 200 µm in size. The nanoparticles form diverse patterns on the membrane, along with aggregates due to dipolar coupling. Nanomechanical torsional resonators were fabricated in the membrane using a focused ion beam, to get a countable number of nanoparticles on the device. The membrane was mounted on a silicon wafer to create Fabry-Perot cavity for optical interference detection. The magnetic measurements were obtained by nanomechanical torque magnetometry, a highly sensitive and non-invasive method to probe the quasi-static magnetization response in the nanoparticles.

We investigated the oscillatory modes of silicon nitride membrane with nanomechanical torsional resonators. Unexpectedly (but not surprisingly, in hindsight) the mechanical response was dominated by magnetic torque on larger aggregates driving flexure modes of the membrane. Of greatest interest are the membrane modes as modified by the introduction of rectangular windows for the torsional resonator and, to a lesser extent, by the resonator itself as shown in the figure below. The stress of the particle deposits on the membrane also led to serious deformation of the torsion rods and paddles of the resonators.

Multiple-mode flexural frequencies were measured in the megahertz frequency range by optical interferometric detection. The maximum signals were obtained at the edges of resonator window. Finite element simulations reveal how the openings break the symmetry of the membrane modes to yield the localized vibrations seen in the measurements. Engineered membrane flexural modes offer an interesting alternative for mechanical magnetometry in some circumstances.

The characterization and control of the magnetic properties of nanoparticles lead to applications of remarkable versatility. Using the beneficial properties accordingly, the wide variety of applications encompasses biomedicine/biotechnology, drug delivery and hyperthermia, MRI, catalysis, information storage, ferro-fluids. Beside these magnetic nanoparticles being used in bulk, there are other arenas in nanotechnology (high-end electronics, logic gates, magnetic storage, spintronics, magnetic sensors and devices) for low dimensional nanoparticle assemblies.[1]

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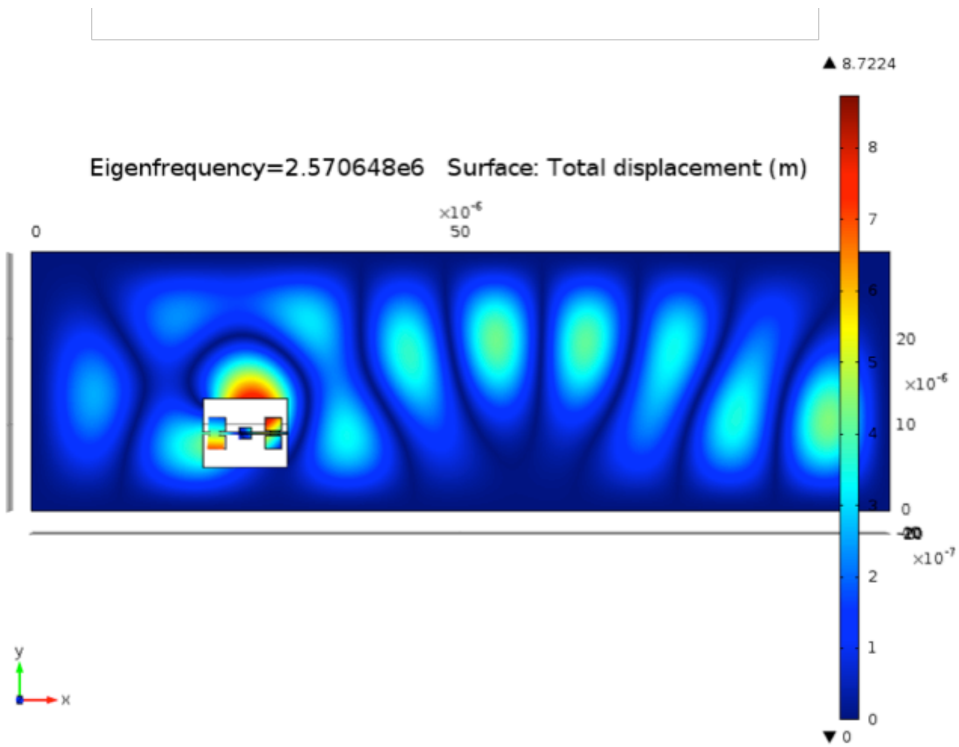

Poster 5. Inhomogeneous internal field dynamics in dual-vortex nanopillars: Dynamic dipole coupling during current pulse induced chirality switching

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In this study, current pulse induced dynamics of circular spinvalve nanopillars ($Ni_{80}Fe_{20}$/Cu/Co, φ = 100 nm) with a dual-vortex, parallel core ground state are investigated numerically. The spin-transfer excitation and dynamic response of the pillar exhibit aspects of the vortex configuration as well as the interlayer dipole coupling between the vortices. First, the strength of the spin-transfer excitation depends locally on the angle between the polarizer (Co) and free ($Ni_{80}Fe_{20}$) layer magnetizations. Initially determined by dipole coupling between the layers, this angle also parameterizes the volume demagnetization energy accrued by the pillar during the current pulse. The resulting nonlinear interplay of the spin torque and dynamic demagnetization field is evident in the excitation of order-GHz spinwave eigenmodes in the free layer. Second, with sufficient spin torque amplitude (subnanosecond current pulses with density on the order of 10^8 A/cm^2), the free layer chirality can be reversed. As the configuration of the harder Co layer is hardly perturbed by the switching process, the interlayer dipole field takes up the energy of the unwinding free layer magnetization. Relaxation is then dominated by a radial magnetostatic mode driven by the precession of the edge magnetization as it returns to its in-plane equilibrium. By examining the pulse parameter dependence of the spinwave eigenmodes, the switching excitation can be optimized. Then, successive current pulses, of sufficient amplitude and with duration chosen to minimize ringing after the pulse, can be used to toggle-switch the free layer chirality, and the resulting bistable states are readable via the giant magnetoresistance effect.

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Poster 6. Spin Waves in the FCC Kagome Lattice

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The impact of an effective local cubic anisotropy [1] on the spin wave excitations and inelastic neutron scattering intensity peaks of the Heisenberg model on the 3D fcc kagome lattice are examined through a linear spin wave theory. Previous Monte Carlo simulations revealed that the addition of anisotropy to the fcc kagome lattice changes the order of the phase transition from weakly first order to continuous and restricts the T=0 spin configuration to a number of discrete ground states, removing the continuous degeneracy [2]. It is shown that the addition of anisotropy removes the number of zero energy modes in the excitation spectrum associated with the removed degeneracies. These results are relevant to Ir-Mn alloys which have been widely used by the magnetic storage industry in thin-film form as the antiferromagnetic pinning layer in GMR and TMR spin valves [2].
Research supported by NSERC.

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Poster 7. Hyperfine Interaction effects in a model Quantum Magnet

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The model magnetic system $LiHoF_4$ is believed to be well described by the dipolar-coupled quantum Ising model at low temperatures. At T=0, application of a transverse magnetic field leads to a quantum phase transition, which is radically influenced by the hyperfine coupling to the nuclear spin bath. In this paper we derive low temperature correlations functions, taking full account of the hyperfine interaction. We discuss the effect of the nuclear spins on the phase diagram and susceptibility. We show that it is the anisotropy in the hyperfine interaction that leads to an enhanced susceptibility and the increase in the critical magnetic field.

Poster 8. Ferromagnetic Multilayer-based Surface Plasmon Resonance Sensors

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Ferromagnetic multilayers constitute interesting systems to investigate magneto-plasmonics (MP) - a combined effect of magnetization, M, or magnetic field, H, surface plasmons, and optical radiation, especially in biomagnetic applications [1, 2]. This importance stems from their high sensitivity, especially to the refraction indices and permeability of the biological samples and the metal layers involved, as they are based on the surface plasmon resonance (SPR) - a collective oscillation of the conduction electrons excited by the incident optical radiation. The SPR occurs at the metal-dielectric interface when the wavelength of the electron oscillation matches that of the incident radiation. The SPR sensors have been already found commercial applications, specially, in bio-molecular interaction in liquids. However, detecting low concentration of biomolecules is still a challenge using these sensors and the signal to noise ratio (SNR) of SPR sensors is limited.

Ferromagnetic multilayers composed of 3-d transition non-magnetic and ferromagnetic metals have attracted considerable attention in MP research, leading to the investigation and manipulation of the plasmonic properties via M or H to enhance their sensitivity and improve their SNR [3, 4]. We previously reported magnetic and plasmonic properties of Au, Co layers, and Co/Au multilayers [5, 6]. In this work, we investigate the effect of incident angle, layer thicknesses, and H on the refractive indices of the biological samples (i.e., the sensitivity characteristics of the transducer) and on the optical properties of the Ti/Au/Co/Au/X multilayer (where X is a dielectric material under test, e.g., protein), with the aim of improving the performance of the sensor, specifically, using magnetic modulation techniques. The sensitivity of the MOSPR sensor to the change in refractive index of the bio-sample, is found to be in the 10^{-06} order. The increased sensitivity of the MOSPR sensors with respect to the small changes in refractive indices, as opposed to the SPR sensors, can be linked to the amplified magneto-optical signal due to the excitation of the surface plasmon polaritons at the metal-dielectric interface.

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Poster 9. Progress in Time-resolved Magneto-optic Scanning Near-field Microscopy

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To obtain magnetic domain images with both high spatial resolution and high temporal resolution we are combining a time-resolved magneto-optic set-up with a near-field optical microscope. We have built a near field microscope based on commercially available fiber optic apertures (100nm diameter) fastened to tuning fork crystals. Working in an amplitude modulated, shear force mode we have obtained images which demonstrate sub-wavelength spatial resolution and magnetic contrast from patterned NiFe thin films with an applied Oersted field. These images are compared to images taken in the far field to show the improvement in spatial resolution. By using the near field we gain an order of magnitude in spatial resolution.

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