Heat, charge, and spin flow in nanostructures for information and energy

Barry Zink

Department of Physics,
University of Denver, Denver, CO 80208

A long-standing goal of spintronics is to identify faster, more energy-efficient nanoelectronic technologies by harnessing the spin degree of freedom in materials. More recently harnessing spin has also been envisioned as a possible route to new energy harvesting materials, for example by improving the efficiency of thermoelectric energy generation with thermomagnetic or spin transport effects. For all these applications, understanding the fundamental interactions of heat, charge, and spin in nanoscale materials is critical to continued progress. Accurate measurements of heat flow in these tiny systems presents a particular challenge, as reliable measurements of thermal effects in thin films and nanostructures require accurate generation and control of the thermal gradient applied to systems with tiny thermal mass. In this talk I will first overview the challenges of nanoscale thermal measurements, continue to describe our experimental solutions for these measurements, and finally present recent results on two very different systems: doped carbon nanotube/polymer hybrid thermoelectrics and nanoscale metallic non local spin valves. If time allows I will briefly highlight ongoing work on spin transport in magnetic insulators and spin Hall effects in metallic alloys.

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Phase-sensitive inductive detection of AC charge currents due to spin-pumping and spin-charge transduction in unpatterned Permalloy/Pt bilayers

Andrew J. Berger[1], Eric R. J. Edwards[1], Hans T. Nembach[1], Justin M. Shaw[1],
Alexy D. Karenowska[2], Mathias Weiler[3], Tom J. Silva[1]
[1]NIST, Boulder, CO USA; [2]Physics, University of Oxford, UK; [3]Walther-Meissner-Institut, Germany

Using a phase-sensitive method for measurement of AC currents due to spin pumping and subsequent spin-charge transduction by spin-orbit coupling (SOC) in Permalloy/Pt bilayers, we separate the strength of field-like (e.g. Rashba-Edelstein) and damping-like (e.g. spin Hall) charge currents. Our technique uses conventional VNA-FMR measurements of thin film samples placed onto a coplanar waveguide (CPW). By comparison to previous efforts for detecting the AC charge currents produced by spin pumping, this is a relatively straightforward technique that requires no sample patterning[1] or complex microwave circuitry.[2] Here, we monitor the change in complex inductance as an out-of-plane DC magnetic field is swept through the ferromagnetic resonance (FMR) condition of the Permalloy (Py) layer. Time-varying magnetic fields produced by the Py/Pt sample will inductively couple into the CPW, altering the total inductance of the microwave circuit. Such fields are produced by: (1) the Py precessing magnetization, (2) Faraday effect induced AC currents in the NM layer, and (3) spin-orbit AC currents due to the spin Hall effect and (4) the Rashba-Edelstein effect. These four terms have distinct frequency dependencies and phase relationships with the driving microwave field such that a phase-sensitive measurement is able to separate them. By comparison, a Py/Cu sample (where Cu is assumed to have negligible SOC) only contributes inductances from terms (1) and (2). For the Py/Pt samples, the inductances due to terms (3) and (4) can be used to calculate the spin Hall angle and Rashba parameter.

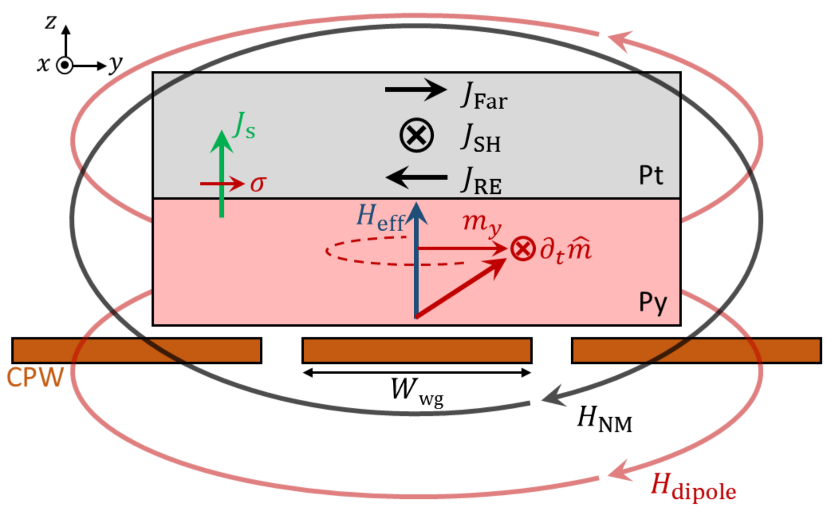

Figure 1. Cross-sectional view of Py/Pt sample on coplanar waveguide. Precessing magnetization in Py player produces H_{dipole} and J_{Far}, as well as spin pumped currents (J_s) with spin orientation σ into Pt layer. Spin-charge conversion currents due to the spin Hall (J_{SH}) and Rashba-Edelstein (J_{RE})effect are also shown. The total AC current in the Pt layer produces H_{NM}

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Hydrodynamic vortex-antivortex ordered nucleation from an obstacle in thin film ferromagnets

E. Iacocca[1,2], T. Silva[3], and M. Hoefer[1]

[1]Department of Applied Mathematics, University of Colorado at Boulder, Boulder, CO, USA.
[2]Department of Physics, Division for Theoretical Physics, Chalmers University of Technology, Gothenburg, Sweden
[3]National Institute of Standards and Technology, Boulder, CO, USA

Spin dynamics in ferromagnetic materials are mathematically described by the Landau-Lifshitz equation of motion. Recently, it has been shown that this equation can be exactly rewritten as a system of hydrodynamic equations [1] that are analogues of the isentropic Euler equations of compressible gas dynamics. These equations exhibit intriguing features such as a velocity-dependent pressure and broken Galilean invariance, implying that the ferromagnet's fluid-like physics are reference-frame dependent. A magnetic Mach number is defined from which subsonic and supersonic conditions are identified. By introducing finite-sized obstacles, we numerically observe laminar flow or the transient nucleation of ordered vortex-antivortex pairs in the subsonic regime; and the formation of a Mach cone, wavefronts, and irregular vortex-antivortex pairs in the supersonic regime. Our approach identifies a deep connection between ferromagnetism and fluid dynamics, enabling new predictions for thin film ferromagnets and opening up a new paradigm for magnetic research.

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References:
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Ferromagnetism in quantum dots

Yuri Dahnovsky

Department of Physics and Astronomy
University of Wyoming, Laramie, WY 82071

We consider d^0 ferromagnetism where Zn vacancies in ZnS semiconductor nanocrystals (NC) (quantum dots and nanowires). The absence of Zn atoms exhibits the ferromagnetic order at room temperatures. We find a magnetic moment in large quantum dots and nanowires by introducing a new model, the surface-bulk model, where a NC magnetic moment is presented as a sum of the surface and bulk contributions. We find how the magnetic moment depends on the concentration and size of a nanocrystal. In addition we discovered the large, three orders of magnitude discrepancy between the experimental and calculated magnetic moments. Such a large disagreement between the experiment and theory is explained due to the condensation of impurities inside a nanocrystal.

Magnetically Doped Quantum Dots

Jinke Tang

University of Wyoming, Laramie, WY 82071

Magnetically doping semiconductor quantum dots (QDs) may lead to interesting phenomena. Depending on the positions of the dopant (e.g., Mn or Eu) energy levels relative to the conduction and valence band of the QDs, different properties are anticipated. Mn or Eu doping may introduce intermediate states in the band gap of the QDs that enables absorption of visible light in wide band gap ZnS QDs. The lifetimes of the Mn/Eu excitonic states are quite long due to the spin forbidden transition, which results in improved charge transfer in quantum dot sensitized solar cells. When the dopant excited states are in close proximity with the conduction band of the QDs (realized for intermediate band gap semiconductor CdSe and CdS) strong exchange coupling can be observed. We have seen exchange coupling induced band gap reduction in Mn-doped CdSe and CdS QDs, consistent with the giant Zeeman effect often observed in such systems. For narrow band gap PbS, Mn doping tends to widen the band gap of PbS. We observed a magnetic hard gap in the transport properties of Mn-doped PbS.

Determination of Exciton Magnetic Polaron Formation Energies in Magnetically Doped Colloidal Quantum Dots

[1,2]W. D. Rice , [3]W. Liu, [2]V. Pinchetti, [3]T. A. Baker, [3]V. I. Klimov, [2]S. A. Crooker

[1]Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071, USA
[2]National High Magnetic Field Laboratory, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[3]Chemistry Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Strong quantum confinement in semiconductors can compress the wavefunctions of band electrons and holes to nanometer-scale volumes, significantly enhancing interactions between themselves and individual dopants. In magnetically doped semiconductors, where paramagnetic dopants (such as Mn^{2+}, Co^{2+}, and so on) couple to band carriers via strong *sp–d* spin exchange, significant magneto-optical effects, such as magnetic polaron formation and the giant Zeeman effect, can be realized in confined geometries using few or even single impurity spins. In this talk, we present the direct determination of the exciton magnetic polaron formation energy in magnetically doped CdSe nanocrystals (NCs) using selective excitation spectroscopy. We performed temperature- and magnetic field-dependent resonant photoluminescence (PL) measurements to examine polaron formation energies for magnetic NCs with Mn^{2+} doping concentrations ranging from 0.4 to 1.6%. From these temperature and field trends in the formation energy, we obtained the exchange field, B_{ex}, exerted by the exciton onto the magnetic dopants of ~7 T. We contrast our selective excitation measurements with temperature-dependent non-resonant PL and time-resolved PL measurements performed on the same magnetically doped NCs. Although these non-selective excitation experiments strongly support the presence of exciton magnetic polarons in the NCs, we show that they significantly over-estimate B_{ex}.

Understanding the magnetic damping in metallic ferromagnets

Michael Schneider
National Institute of Standard and Technology, Boulder, CO USA

The phenomenology of magnetic damping is critical to devices which seek to exploit the electronic spin degree of freedom since damping strongly affects the energy required to operate these devices. However, theory has struggled to quantitatively predict the damping, even in common ferromagnetic materials. This presents a challenge for a broad range of applications that depend on the ability to precisely control the damping of a material. I will discuss our recent work to precisely measure the intrinsic damping in several material systems and compare experiment with several theoretical models. In addition, this investigation uncovered a metallic material that exhibits ultra-low values of damping that begin to approach values found in thin film YIG. Such damping is unexpected for a conductor, but can enable a new class of experiments where ultra-low damping can be combined with a charge current. Finally, I will discuss a theoretical framework by which such ultra-low damping is achieved in metallic ferromagnets.

γ’-Fe_4N, a new soft magnetic material for inductors and motors

Todd C. Monson*, Baolong Zheng, Yizhang Zhou, Enrique Lavernia

[1]Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185, USA.
[2]Department of Chemical Engineering and Materials Science, University of California, Irvine, USA.
*tmonson@sandia.gov

New soft magnetic materials will be vital for the next generation of power conversion electronics and electrical machines. Therefore, new soft magnets will play a significant role in bringing new renewable energy sources online and improving energy efficiency. Magnetic nitrides, specifically γ’-Fe_4N, if manufactured in bulk form, offer a new class of affordable and better performing soft magnetic materials. In collaboration with UC Irvine, Sandia National Labs has developed new routes (patent pending) to synthesize iron nitride powders via a two-step ball milling process. The iron nitride powders are then consolidated using a low temperature field assisted sintering technique (FAST). FAST enables the direct consolidation and shaping of crystalline γ’-Fe_4N inductor cores and one piece motor stators from raw starting materials in a matter of minutes, without the decomposition of iron nitrides that would occur using conventional sintering techniques. Experimental results including the synthesis of iron nitrides, their consolidation, fabricated parts, and magnetic characterization will be presented.

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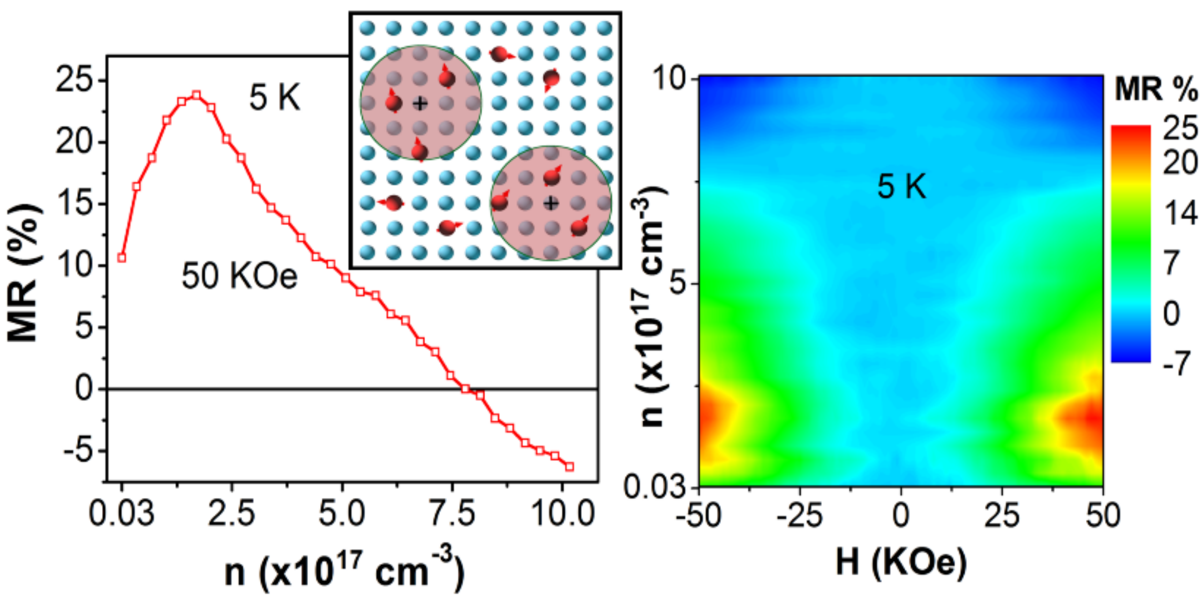
Magnetoresistance manipulation and sign reversal in Mn-doped ZnO nanowires

Keshab R. Sapkota

Department of Physics and Astronomy,
University of Wyoming, Laramie, WY, USA

In this study, we observed magnetoresistance (MR) manipulation and sign reversal induced by carrier concentration modulation in Mn-doped ZnO nanowires. At low temperatures positive magnetoresistance was initially observed. When the carrier concentration was increased through the application of gate voltage, the magnetoresistance also increased and reached a maximum value. However, further increasing the carrier concentration caused the MR to decrease, and eventually a MR sign reversal from positive to negative was observed. The MR change from the highest positive value to the lowest negative value was as high as 32 % at 5 K and 50 KOe. The observed MR behavior could be attributed to the combined effects of quantum correction to carrier conductivity and bound magnetic polarons. This work could provide important insights into the mechanisms that govern magnetotransport in dilute magnetic oxides, and it also demonstrated an effective approach to manipulating magnetoresistance in these materials that have important spintronic applications.



Magnetic Properties of Coupled Ferromagnet/Oxide Heterostructures

J. de la Venta

Department of Physics, Colorado State University, Fort Collins, CO 80523 USA

The coupling of electronic, magnetic, and structural properties between two dissimilar materials in contact can induce novel functionalities. Here we report on a drastic modification of the magnetization dynamics of thin Nickel films in V_2O_3/Ni bilayers. We performed temperature-dependent ferromagnetic resonance measurements across the first-order structural phase transition (SPT) of V_2O_3. The results show a strong coupling of the V_2O_3 lattice dynamics to the magnon spectra of the Ni film in proximity. Our results suggest that the phase coexistence across the first-order SPT of V_2O_3 is responsible for the effects observed in the V_2O_3/Ni hybrids. This suggests the existence of similar effects in other hybrid materials with first-order structural phase transitions.

Designing and Tuning Magnetic Resonance with Exchange Interaction

Xin Fan

Department of Physics
University of Denver, Denver, CO 80208

Exchange interaction at the interface between magnetic layers exhibits significant contribution to the magnetic resonance frequency. The *in situ* tuning of the resonance frequency, as large as 10 GHz, is demonstrated in a spintronics microwave device through manipulating the interface exchange interaction.

In-situ and ex-situ investigation on nanostructure evolution, magnetic and electrical property changes of nanomaterials under irradiation

You Qiang

Physics Department, University of Idaho, Moscow ID, USA,

CAES Center, Idaho Falls ID, USA

Nano-Nuclear Technology (NNT) deals with the use of engineered-nanomaterials for the improvement of performance and safety in the future generation nuclear reactors (GEN-IV Reactors). Based on a review of NNT, this talk is focused on the fundamental understanding of changes in-situ and ex-situ on nanostructures, magnetic and electrical properties of nanomaterials under irradiation. The contributors to the radiation sensitivity and stability were studied in detail using Fe-based nanomaterials using heavy ion and e-beam irradiations. Investigation shows that magnetic nanomaterials are good candidates for the radiation impact analysis and radiation environment applications. The results obtained from this investigation contribute to the scientific assessments done for predicting material performance in radiation environments and to recommend candidate nanomaterials for the development of high sensitive radiation detectors and monitors in nuclear energy applications.