MAGNETIC NANOSTRUCTURES AND SPINTRONIC MATERIALS

TECHNICAL CLOSEOUT REPORT
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ABSTRACT

Nanoscale systems have been the basis for a wealth of novel phenomena in condensed matter magnetism. Of particular significance are effects arising from epitaxial and otherwise laterally constrained systems, which include spintronic systems, exchange biased structures and patterned nano-structures. In all such systems ferromagnetic resonance has played a significant role as a probe of anisotropy and magnetic relaxation. For example, both anisotropy and relaxation of the magnetization to equilibrium are key parameters in recording technology and knowledge of anisotropy, precession frequency and damping are crucial in the development of devices based upon spin torque phenomena. Over the 28 years of this grant, the PI explored magnetodynamics and magnetostatics in wide-ranging topics such as spin-glasses, exchange springs, exchange bias, perpendicular anisotropy, multiferroics, metal organic frameworks, magnetic vortices, core/shell nanoparticles and laterally confined spin waves. There was even a foray into superconductivity following the Woodstock of Physics in 1987. The work was performed in the context of an undergraduate and Masters program utilizing electron magnetic resonance as a primary research tool, although developments were also made in magneto-optical Kerr effect, torque and vibrating sample magnetometry. The work was largely done in collaboration with scientists from other universities and industrial laboratories both within the US and internationally.

TECHNICAL DESCRIPTION

Introduction

Five projects will be presented on the research supported in this award. These projects are among the most highly cited of the award's published work. Publications are referenced to the list at the end of this report.

Project 1: Dipolar induced, spatially localized resonance in magnetic antidot arrays

Dipole induced, spatially localized ferromagnetic resonances at 35 GHz are observed in micron-sized antidot arrays in permalloy films fabricated with photolithography. All square (3 μm × 3 μm) and rectangular (3 μm × 4, 5 and 7 μm) array samples exhibit double resonances, with each resonance possessing uniaxial in-plane anisotropy (Fig. 1). Interestingly, the easy axes of the two resonances are orthogonal in all cases. The magnitude of the induced dipolar anisotropy decreases with increasing rectangular aspect ratio for one of the resonances, but remains essentially constant for the other. Micromagnetic simulations reveal that the two resonance peaks are the consequence of a dipole field distribution producing two areas with distinctly different demagnetizing field patterns. (Fig. 2). [Publication #29]. Subsequent measurements confirm the existence of these modes using time-resolved Kerr microscopy TRKM as a local probe of the magnetodynamics—one at low frequency between the holes along the short axis and one at higher frequency between the holes along the long axis. TRKM also reveals additional mode structure, most notably a low-frequency mode localized along the edges of the antidots, similar to the edge modes observed in magnetic wires. [Publication #33].

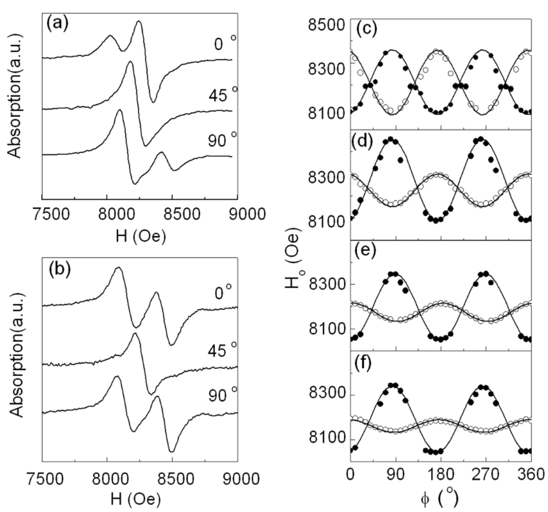

Fig. 1 FMR spectra of a a) rectangular (3μm x 4 μm) and b) square (3μm x 3 μm) antidot array with applied in-plane field at various angles, ϕ, from the long axis; b) through e) the in-plane angular dependence of resonance fields extracted from FMR spectra for different hole mesh. The solid and open circles are the data from the weak and main resonance peaks respectively, and the solid lines represent theoretical fits.

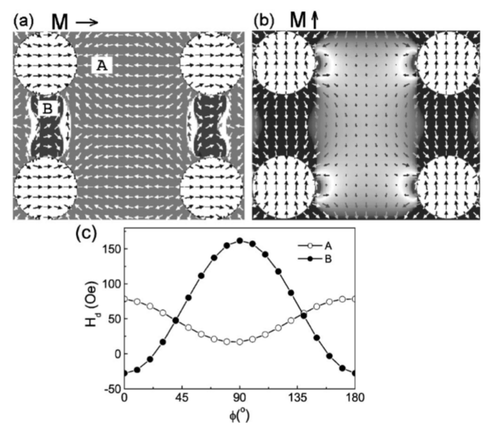

Fig. 2 Micromagnetic simulation of the 3 m 4 m sample with magnetization along a long axis (0 °) and b short axis 90° . Shading and arrow size indicate the induced dipole field strength. The antidot sample is approximately divided into two regions in terms of the demagnetization field orientation and amplitude.

Project 2: Induced anisotropy and positive exchange bias

Exchange-biased MnF_2/Fe bilayers, examined by variable angle and temperature ferromagnetic resonance FMR, exhibit a sudden onset of a unidirectional and fourfold anisotropy below the MnF_2 Neel temperature. (Fig. 3.) This unexpected fourfold symmetry arises from frustrated perpendicular coupling between the MnF_2 and the Fe overlayer in the presence of twinning in the antiferromagnet layer. These data are consistent with earlier polarized-neutron-reflectometry results. The FMR data show a clear reversal in the direction of the unidirectional anisotropy as a function of cooling field, switching sign at H_{FC} 13 kOe (Fig. 4), which is consistent with the onset of positive exchange bias observed in conventional magnetometry experiments. The low-temperature FMR linewidth reflects the in-plane symmetry of the resonance itself, exhibiting surprising divergence in the hard directions (Fig. 5). [Publication #26]

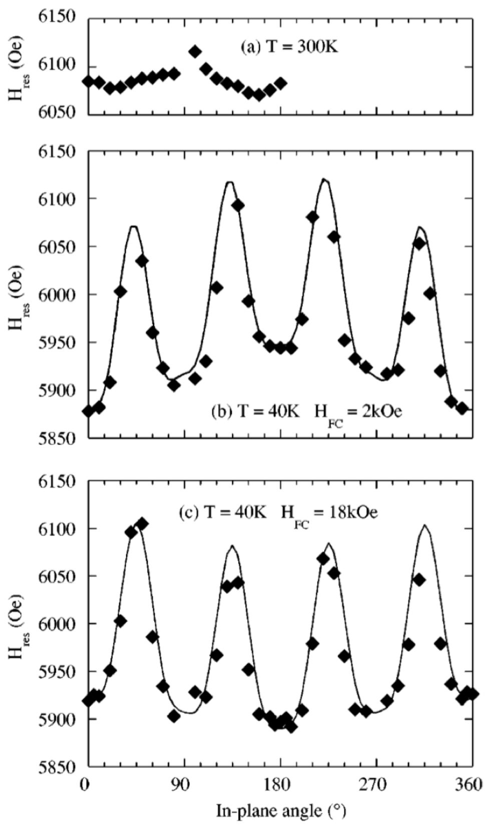

Fig. 3 Resonance field as a function of in-plane angle a) T=293K; b) T=40K and H_{FC} 2kOe; c) T=40K and H_{FC}=18 kOe. Symbols are data points and lines are model calculations. The cooling field is applied at 0°, which is along the MgO (100), a direction bisecting the perpendicular (110) flouride twins.

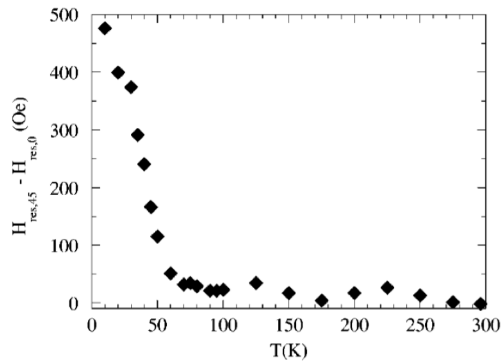

Fig. 4 Difference between resonance fields along the easy and hard directions as a function of temperature, which is proportional to the four-fold anisotropy energy.

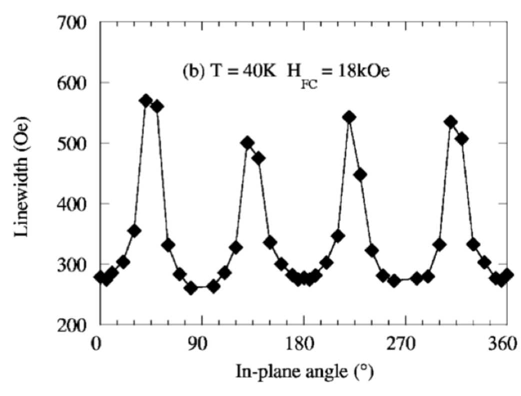

Fig. 5 FMR line-width as a function of in-plane angle.

Project 3: Antiferromagnetic (AFM) coupling in hard-soft bi-magnetic core/shell nanoparticles

The AFM coupling in iron oxide—manganese oxide based, soft/hard and hard/soft, core/shell nanoparticles is demonstrated by magnetometry, ferromagnetic resonance and X-ray magnetic circular dichroism. Two types of samples were synthesized using seeded-growth: (i) an inhomogeneous Mn-oxide layer was deposited on Fe-oxide seeds (with two different diameters—samples CS1 and CS2) and (ii) a homogeneous Fe-oxide layer was grown on Mn- oxide seeds (sample CS3) (Fig. 6). In particular, ferromagnetic resonance provided the foremost elucidation of positive exchange bias and AF coupling as exhibited in the dramatic changes of the resonance field and amplitude at the Mn_3O_4 ordering temperature (Fig. 7). [Publication #49]

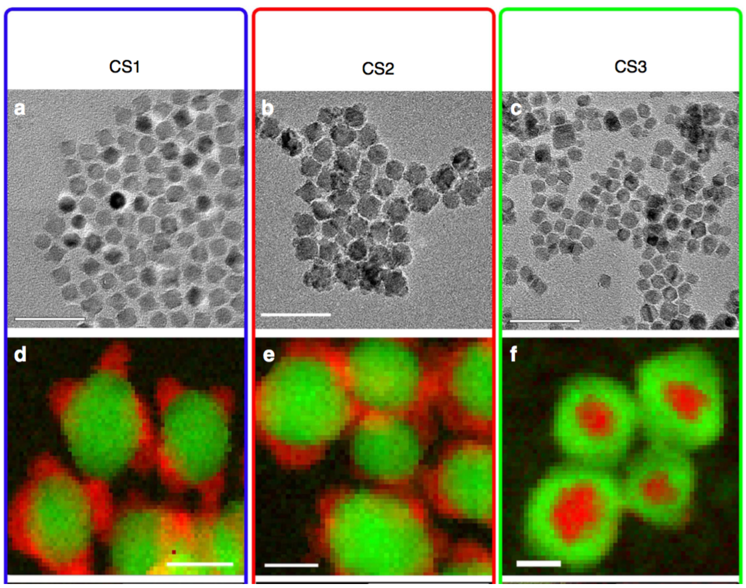

Fig. 6. Morphological and composition characterization. TEM images of the (a) CS1, (b) CS2 and (c) CS3 nanoparticles (scale bar = 50 nm). EELS-mapping of the (d) CS1, (e) CS2 (scale bar = 10 nm) and (f) CS3 (scale bar = 5 nm) nanoparticles (where green corresponds to the Fe L signal and red to the Mn L edge.

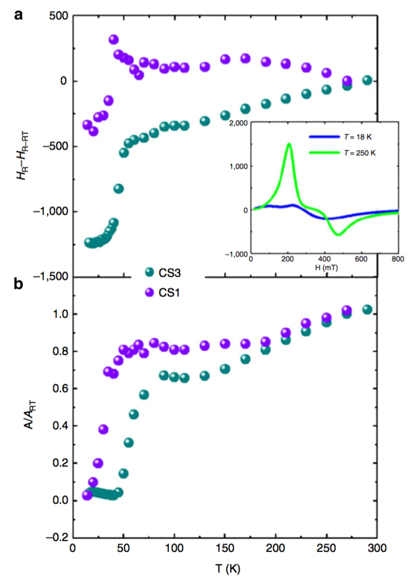

Fig. 7. Temperature dependence of the (a) relative FMR resonance position normalized to the room temperature resonance field and (b) normalized amplitude of the main resonance peak with respect to the room temperature amplitude for samples CS1 and CS3 at 9.5 GHz. Spectra at two temperature extremes for CS3 are shown in the inset.

Project 4: Remarkable strain-induced magnetic anisotropy in epitaxial Co_2MnGa (001) films

Remarkably large, strain-induced anisotropy is observed in the thin-film Heusler alloy Co_2MnGa (001) epitaxially grown on different interlayers/substrates with varied strain, and investigated with ferromagnetic resonance. The film grown on ErAs/InGaAs/InP experiences tension strain, resulting in an out-of-plane strain-induced anisotropy ($1.1x10^6$ erg/cm^3) adding to the effects of shape anisotropy. In contrast, the film grown on ScErAs/GaAs, experiences a compression strain, resulting in an out-of-plane strain-induced anisotropy ($3.3x10^6$ erg/ cm^3) which almost totally cancels the effects of shape anisotropy, thus rendering the film virtually isotropic (Fig. 8). This results in the formation of stripe domains in remanence. In addition, small, but well-defined 2-fold and 4-fold in-plane anisotropy coexist in each sample with weak, but interesting strain dependence (Fig. 9). [Publication #32].

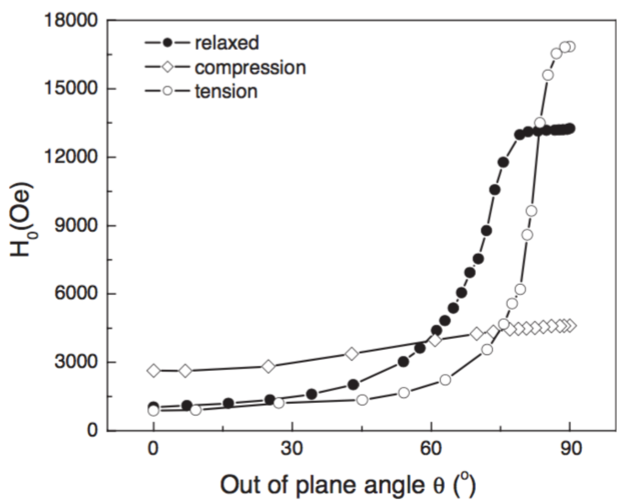

Fig. 8. FMR field (10 GHz) as a function of out-of-plane angle for the samples measured. The zero angle corresponds to the field applied in the film plane. Lines are guide to the eye. Note the sample under tension exhibits stronger angular dependence than the relaxed film, whereas the resonance of the sample under compression is nearly independent of angle.

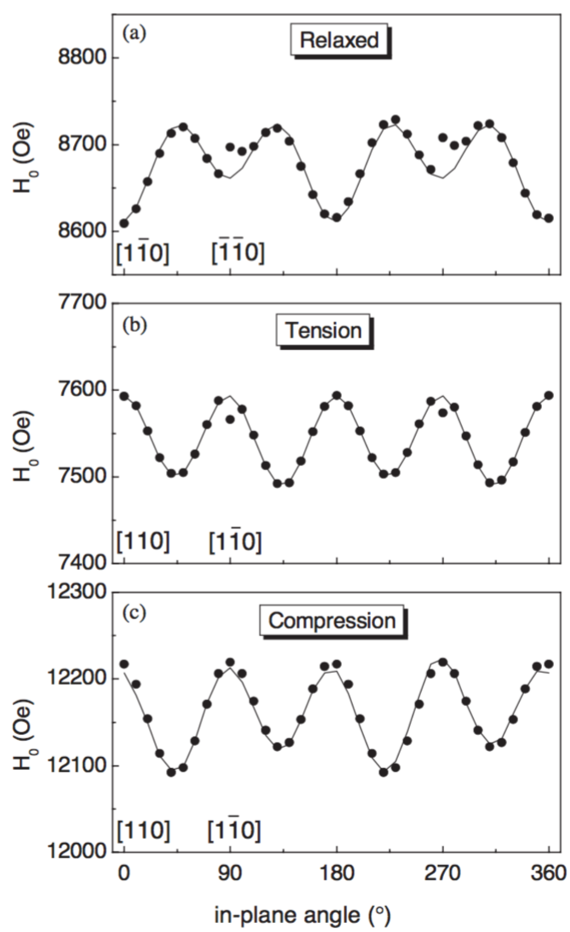

Fig. 9. FMR field (35 GHz) as a function of in-plane angle. The zero angle corresponds to [1 1 0] for the relaxed sample and [110] for other two samples. Solid lines represent fits to the model described in the text.

Project 5: Lateral standing spin waves in permalloy antidot arrays

Spin wave modes in permalloy antidot arrays have been investigated with ferromagnetic resonance at 9.7 GHz (Fig. 10). In contrast to a quadratic dispersion expected for exchange standing spin waves, nearly linear relationship exists between the resonance field and mode index, and it can be approximately described by the dipole-dipole and exchange theory (Fig. 11). Time-dependent micromagnetic simulations show that the spin wave modes are a result of lateral confinement from the vacant holes. Furthermore, the simulations visually reveal the existence of localized spin waves due to localized boundary conditions in antidots arrays (Fig. 12). [Publication #22]

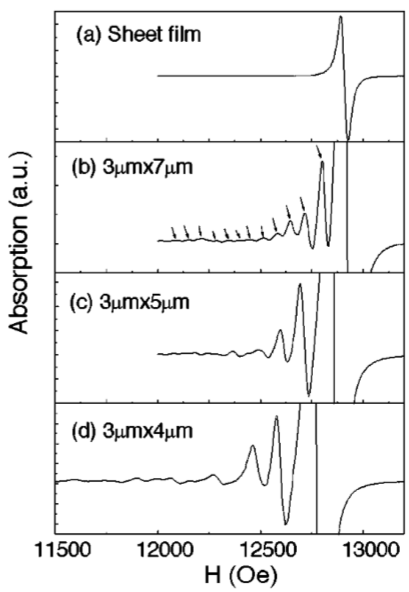

Fig. 10. FMR spectra in a perpendicular configuration (*H* normal to the film plane). Arrows in b indicate positions of spin wave resonances and are indexed sequentially from high to low field.

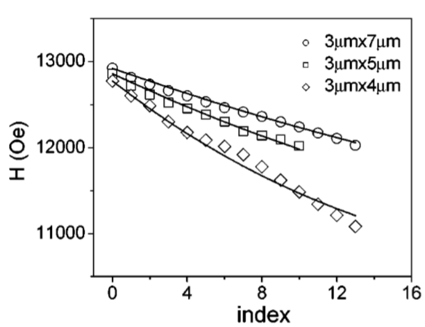

Fig. 11. Resonance fields of spin wave modes as a function of index number for the three antidot arrays. The solid lines are theoretical fittings from the Arias and Mills dipole-exchange theory.

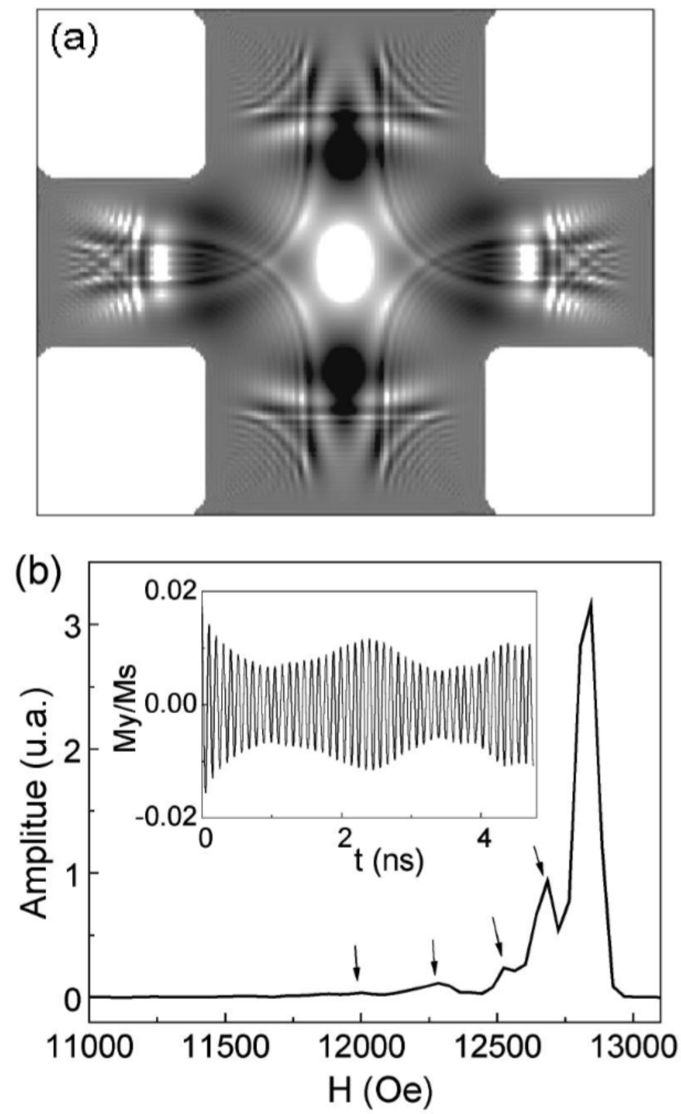

Fig. 12. Time-dependent micromagnetic simulations of the antidot arrays (3x4 μm2). (a) Snapshot of the spatial magnetization *M* distribution. (b) Simulated FMR spectra converted from the frequency (spectra not shown). The arrows indicate the spin wave modes. The inset shows *M*y as a function of simulation time. (Note *M*z ≃ *M*sat is normal to the page.)

DOE SUPPORTED PUBLICATIONS AND PRESENTATIONS

Papers Published

Fifty papers have been published with support from this award. See attached publication list.

Presentations Made

Approximately 120 DOE supported presentations were made by the PI and his students during the award period. These were presented at universities, national laboratories, industrial settings and national and international professional society meetings.

PERSONNEL INVOLVEMENT

Research Associates

Rob Compton, Chengtau Yu and Jian Dou

Masters Theses Graduated (28 total)

Michael Sinko, Daniel Stanley, Brian Kaster, Kyle Bechtel, Sarah Hernandez, Willis Agutu, Yongxue Yu, Wes Burgei, Jeremy Neal, Robert Compton, Nienchtze Teng, Fengling Zhang, Alexandra O'Brien, Charles Lynn, Laura Adams, Weixiao Liu, JiangHong Huang, Matthew Braught, Jiangsheng Xu, Alan Runge, Bradley Paul, Michael Bait, David Kingsbury, David Rader, Zhong Lu, Michael Ellison, Richard Little, Gregory Strouse

Undergraduate Student Participation

The award always contained support for one or two undergraduates for 10 weeks in the summer. The number of undergraduates participating in the supported research was considerably greater than the three dozen or so supported during the summer.

High School Student Participation

Seven high school students participated in summer projects over the period of the award.

UNEXPENDED FUNDS

There are no unexpended funds associated with the award.

Papers Published with Support of Award DE-FG-2-86ER45281

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