Spin Distributions and Dynamics in Magnetic Nanostructured Materials

NSF NIRT Grant #DMR 0404252

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This research program seeks fundamental understanding of electron spin dynamics in nanometer-scale magnetic structures. The objectives are focused on understanding spin-damping mechanisms and high-speed manipulation of spins by applied magnetic fields or electric current. The basic scientific issues are: how fast can the magnetic state of a ferromagnetic structure be manipulated by an applied magnetic field or spin-polarized electric current, and what factors govern the spin configurations and their dynamics. The research objectives offer broad technological relevance to applications based on engineered magnetic nanostructured materials (metamaterials) used in telecommunications and radar applications, and in microstructured thin-film structures used in sensors, spintronic devices, and information storage media in which high-speed spin dynamics plays a central role.

The program combines expertise in thin-film growth, microstructure fabrication, magnetic characterization, numerical simulation of magnetic response, mesoscopic physics, and condensed matter theory. Highlights of some of the accomplishments and progress are outlined below.

(a) *Magnetic Energy Loss Scaling in Nanometer-Scale Structures*(1)*:*
Magnetic switching is accompanied by energy dissipation. Classical eddy-current losses and eddy-current damping govern energy dissipation and the frequency-dependent scaling of energy dissipation in bulk materials. Eddy current effects are non-local and scale with sample dimensionality – in a thin film (2D) sample, the loss scales inversely with thickness, and becomes negligible below about 1μm. Experiments performed in our NIRT have measured and explained the magnetic loss scaling in several magnetic microsturctures in which domain-wall motion dominates reversal dynamics. These results resolve significant confusion in the literature on this topic by demonstrating a simple relationship between the power-law scaling function and the mobility equation.

(b) *Magnetic Switching*(2) *and Barkhausen Effects*(3) *in 2D Structures:*
Anisotropy energies and pinning centers dominate spin distributions in small magnetic structures and particles leading to highly nonlinear magnetization reversal processes. Theoretical work in our NIRT has explored minimal field requirements in small particle switching(2), and experiments have studied magnetization reversal in the pinning-dominated (Barkhausen) regime. The experiments measure for the first time velocity distributions of Barkhausen jumps in a 2D system that establish the

damping mechanism limiting domain-wall mobility and test scaling models for Barkhausen jump distribution functions.

(c) Field$^{(4)}$*- and Electric-Current-Driven*$^{(5)}$ *Domain-Wall Dynamics in Model Nanometer-Scale 1D Structures:*

The competition between exchange energy and magnetostatic energy results in the creation of magnetic domains in magnetic structures larger than about 10nm. The dynamics of domain walls governs the manipulation of spin configurations in such structures. Experiments performed by our NIRT have explored field- and electric-current-driven domain dynamics in model nanometer-scale one dimensional structures$^{(4)}$. Figure 1 illustrates measurements of domain-wall velocity as a function of applied magnetic field in a permalloy thin-film nanowire fabricated using focused ion beam milling. The inserts represent numerical simulations of the domain-wall motion based on solving Landau-Lifshitz-Gilbert equations. These studies are beginning to reveal the nature of field-driven velocity breakdown.

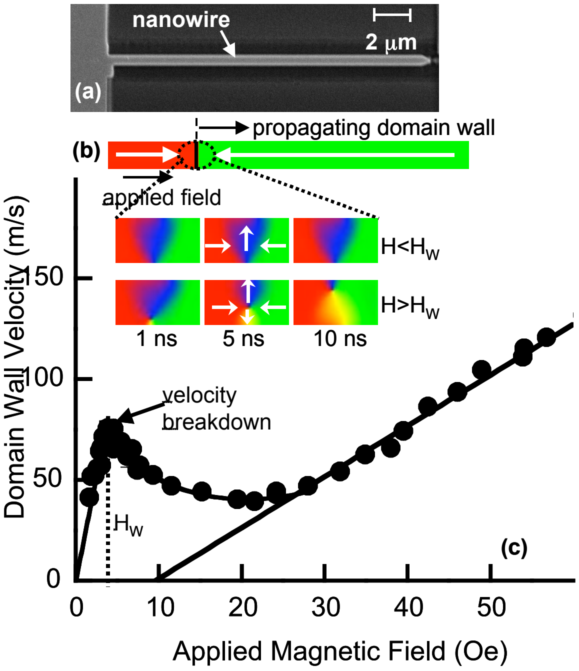
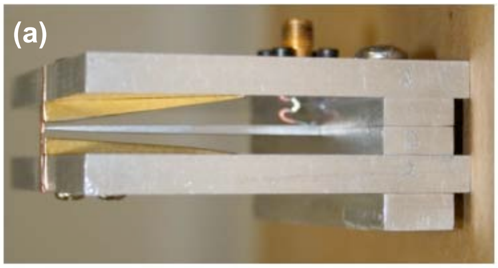


Figure 1. **(a)** Ferromagnetic nanowire measuring 600 nm wide by 20 nm thick. **(b)** Snapshots of the calculated spin configurations within a domain wall at three different times, as the wall moves under an applied field. At low fields (top row), the wall spin structure is unchanged as it moves. Above a critical field H_W, (bottom row) a "vortex" appears in the wall and moves across the wall with time, slowing the wall substantially. **(c)** Measured velocity versus field for a domain wall in the nanowire shown in (a), showing a "breakdown" in the capacity of the field to "push" the wall once the wall structure becomes unstable, in agreement with calculations.

The technological implications of our recently-published results have been noted in "News and Views," *Nature Mater* **4**, 721 (2005) and by "Materials Today" (*Research News*, Issue 11, Nov. 2005). Corresponding experiments carried out by our NIRT have explored electric-current-driven domain-wall motion in similar nanowires, and have revealed a new spin-torque force that drives domain-wall motion$^{(5)}$.

(d) Metamaterials Fabrication and Characterization:

Significant progress has been achieved in fabricating model magnetic nanoparticles for potential application in devices operating in the millimeter/sub-millimeter wavelength range. Ferromagnetic nanowire arrays have been fabricated using electrodeposition in anodic Al_2O_3 nanoporous templates. The prospects of using these nanowires in studies of mesoscopic magnetic effects are being explored. A new technique(6) for measuring magnetic susceptibilities of ferromagnetic micro-objects based on a tapered resonator has been developed and tested. Initial tests, described in Figure 2, suggest sensitivity gains of 10^6 allowing measurements of material volumes to $10^{-20}m^3$ (10 nm x 100nm x 10μm).



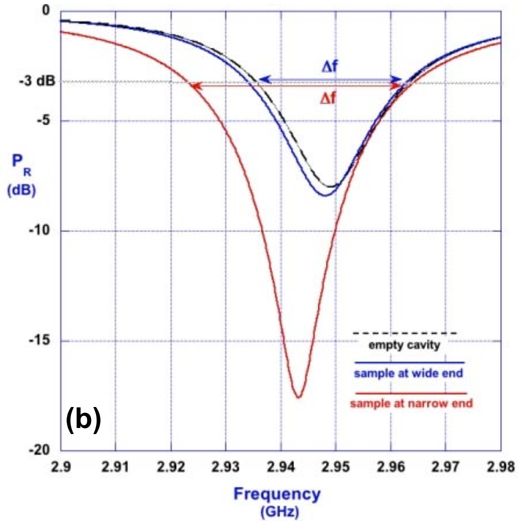


Figure 2. (a) Side view of a tapered inhomogeneous stripline resonator. **(b)** Measured resonance spectra of the empty resonator and of the resonator loaded with a thin magnetic film specimen at two different positions.

NIRT Publications

1) C. Nistor, E. Faraggi, and J. L. Erskine, "Magnetic Energy Loss Scaling in Permalloy Thin Film Microstructures," *Phys. Rev. B* **72**, 014404 (2005).
2) D. Xiao, M. Tsoi, and Q. Niu, "Minimal Field Requirement in Precessional Magnetization Switching," (Submitted to *J. Appl. Phys.*); D. Culcer, Y. Yao, A. H. MacDonald, and Q. Niu, "Electrical Generation of Spin in Crystals with Reduced Symmetry," *Phys. Rev. B* **77**, 045215 (2005).
3) S. Yang and J. L. Erskine, "Domain Wall Dynamics and Barkhausen Jumps in Thin-Film Permalloy Microstructures," *Phys. Rev. B* **72**, 064433 (2005).
4) G. S. D. Beach, C. Nistor, C. Knutson, M. Tsoi, and J. L. Erskine, "Dynamics of Field-Driven Domain-Wall Propagation in Ferromagnetic Nanowires," *Nature Mater.*, **4**, 741 (2005).
5) G. S. D. Beach, C. Knutson, C. Nistor, M. Tsoi, and J. L. Erskine, "Nonlinear Enhancement of Magnetic Domain Wall Velocity by a Spin-Polarized Electric Current," (submitted to *Science*).
6) R. M. Walser, A. P. Valanju, and P. M. Valanju, "Magnetic Material Measurements with Critically Coupled Resonators," (in preparation for *IEEE Trans. Magn.*; *Phys. Rev. B*).