Electronics and Electrical Engineering Laboratory

National Institute of Standards and Technology
Technology Administration
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NISTIR 6628
January 2003

Magnetic Technology Division

Programs, Activities, and Accomplishments

The Electronics and Electrical Engineering Laboratory (EEEL)

One of NIST's seven measurement and standards laboratories, EEEL conducts research, provides measurement services, and helps set standards in support of the fundamental electronic technologies of semiconductors, magnetics, and superconductors; information and communications technologies, such as fiber optics, photonics, microwaves, electronic displays, electronics manufacturing supply chain collaboration; forensics and security measurement instrumentation; fundamental and practical physical standards and measurement services for electrical quantities; maintaining the quality and integrity of electrical power systems; and the development of nanoscale and micro-electromechanical devices. EEEL provides support to law enforcement, corrections, and criminal justice agencies, including homeland security.

EEEL consists of six programmatic divisions and two matrix-managed offices:

- Electricity Division
- Semiconductor Electronics Division
- Radio-Frequency Technology Division
- Electromagnetic Technology Division
- Optoelectronics Division
- Magnetic Technology Division
- Office of Microelectronic Programs
- Office of Law Enforcement Standards

This publication describes the technical programs of the Magnetic Technology Division. Similar documents describing the other Divisions and Offices are available. Contact NIST/EEEL, 100 Bureau Drive, MS 8100, Gaithersburg, MD 20899-8100, telephone 301-975-2220, http://www.eeel.nist.gov. These publications are updated biennially.

On the cover: Left, Michelle Chabot measuring the properties of nanometric magnetic dots on torsional oscillators. Right, Tony Kos placing a magnetic film in the recently developed temperature-variable pulsed inductive microwave magnetometer. Bottom, Jack Ekin adjusting a superconductor tape for mechanical property measurements at cryogenic temperatures. Photos © 2002 Geoffrey Wheeler.

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

MAGNETIC TECHNOLOGY DIVISION

PROGRAMS, ACTIVITIES, AND ACCOMPLISHMENTS

NISTIR 6628

January 2003

U.S. DEPARTMENT OF COMMERCE
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Technology Administration
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Contents

Welcome

The Magnetic Technology Division develops and disseminates measurement technology for industries broadly concerned with magnetic information storage and superconductor power. The division, part of the Electronics and Electrical Engineering Laboratory at NIST, is located in Boulder, Colorado.

The division's projects are led by senior scientists, often assisted by engineers, technicians, research associates, graduate students, or undergraduate students. The division has six projects divided into two groups:

Magnetics Group

Magnetic Recording Measurements
Magnetodynamics
Nanoprobe Imaging
Magnetic Thin Films and Devices

Superconductivity Group

Standards for Superconductor Characterization
Superconductor Electromagnetic Measurements

The work of the division spans the range from practical engineering to theoretical modeling. Some of the projects with unique expertise receive partial support from other government agencies.

The division disseminates the results of its research through publications in refereed journals, presentations at conferences and workshops, and participation in standards organizations. Please visit our Web site at http://www.boulder.nist.gov/div816, where you will find reprints of our publications and links to other magnetics and superconductivity work at NIST. Thanks for your interest in the Magnetic Technology Division.

— Al Clark, Division Chief
— Ron Goldfarb, Group Leader

Introduction to Technical Programs

Several of the Magnetic Technology Division's technical programs cut across projects. These programs include nanomagnetodynamics, spin electronics, scanned-probe microscopy, superconductor characterization, and standards.

Nanomagnetodynamics

The study of nanomagnetodynamics — high-frequency precession and damping of magnetization in films and devices below one micrometer in size — is undertaken in the Magnetodynamics Project, the Magnetic Thin Films and Devices Project, and the Nanoprobe Imaging Project, in collaboration with the Materials Science and Engineering Laboratory.

Advances in magnetic information storage are vital to economic growth and U.S. competitiveness in the world market for computer products and electronic devices. Key improvements needed are increases in data transfer rates during reading and writing, and increases in storage density in magnetic disk and tape media. Solid-state magnetic random-access memory will become a new factor in data storage. Future high-performance magnetic recording systems will have to write and read data in nanometric devices at rates exceeding 1 gigahertz, with corresponding magnetic switching times of less than 1 nanosecond.

Spin Electronics

Spin electronics is a new direction in electronics that promises to revolutionize telecommunications and information processing. Research in spintronics is conducted in the Magnetodynamics Project, the Magnetic Thin Films and Devices Project, and the Magnetic Recording Measurements Project.

Spin electronics is based on the manipulation and control of the quantum-mechanical spin of a semiconductor's charge carrier. Spintronics holds the promise of extending telecommunications frequencies into the terahertz regime. The frequency performance of devices based on charge transfer is limited by electron velocities, charge-transfer times, and carrier mobilities, whereas the electron spin has no fundamental frequency limitation, as long as coherence can be preserved.

Recent advances in spin-based semiconductor devices have demonstrated that coherent spin precession can be maintained for hundreds of microseconds. The precession frequency can be controlled by applied magnetic fields, gate voltages, and modulation doping techniques. We aim to develop new techniques to measure and control spin precession in small spin-based devices. The goal is to create and characterize precessing spin packets, consisting of one million spins, using high-speed electrical and optical techniques.

In addition to exploring spin dynamics in semiconductors, we are studying metallic devices that use spin-momentum transfer to induce coherent precession. Recent theoretical work predicts that a spin-polarized direct current injected into nanometric magnetic structures can generate coherent precession of the magnetization. The precession frequency can be tuned from 1 gigahertz to 50 gigahertz by changing the current amplitude or the polarization angle. Spin-polarized currents can switch small magnetic elements. We are working on using this effect as a source of precessing spins for semiconductor devices and as the basis for a novel spin amplifier.

Scanned-Probe Microscopy

We are developing scanned-probe microscopy in support of the magnetic data-storage industry, the microelectronics industry, and national security agencies of the government. Work is undertaken in the Magnetic Recording Measurements Project and the Nanoprobe Imaging Project.

We emphasize instrumentation for high-resolution imaging, and work with our collaborators to relate scanned-probe images to magnetic and electronic properties of recording media and electronic devices. Probes include giant-magnetoresistive devices and particles that undergo ferromagnetic resonance. Among the applications are the recovery of data from damaged recording media and certification of the authenticity of recorded media. Our goals include not only the qualitative imaging of materials but quantitative imaging of magnetic fields that have their sources in magnetic domains or current distributions.

Superconductor Characterization

We have a quarter-century history of making accurate measurements of — and developing the theory of measurement for — the electric, magnetic and mechanical properties of superconductor wires and tapes for power applications. This effort is centered in the Standards for Superconductor Characterization Project and the Superconductor Electromagnetic Measurements Project.

The properties we measure include critical-current density as a function of temperature and mechanical strain, residual resistivity ratio, and magnetic hysteresis loss. We investigate both high-temperature and conventional low-temperature superconductor compounds. The overarching theme of our work is to help establish best practices for superconductor characterization.

Standards

Activities undertaken by the division include the development of both artifact standards for device calibration and consensus standards for measurement procedures. Standards work is undertaken by the Standards for Superconductor Characterization Project, the Magnetic Recording Measurements Project, the Magnetic Thin Films and Devices Project, the Nanoprobe Imaging Project, and by Division management staff.

Artifact standards — established or under development — include those for superconductor critical current, weak magnetic moments, and magnetic imaging. Several of our staff members are active in consensus-standards organizations — including the International Electrotechnical Commission, the Versailles Project on Advanced Materials and Standards, the American Society for Testing and Materials, the Institute of Electrical and Electronics Engineers, and the National Electronics Manufacturing Initiative — in the areas of superconductor measurements, magnetic measurements, and metric practice.

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Magnetic Recording Measurements

Goals

This project addresses national measurement needs in magnetic data storage for industry, advanced applications, and national security. The project is developing magnetic calibration standards for magnetometers in the form of low-moment thin films that use integrated superconducting loops to determine the absolute flux. It is also developing magnetoresistive arrays and readout electronics that can image magnetic fields from data storage media and current distributions in integrated circuits. These are targeted to homeland security (forensics and passive field-disturbance monitors) and failure analysis. Using ultra-high-vacuum technology and spin-resolved electron spectroscopy, the project studies the transmission and emission of spin-polarized electrons through and from ultrathin (1 to 10 atomic layers) magnetic films. These techniques are used for measurements on potential spin-electronic materials and device architectures for spin-polarized electron injection.

Customer Needs

Magnetic data storage has been a growing industry for almost one hundred years. With the advent of wide-spread use of computers and mass-storage media, it can be expected to continue to grow for the foreseeable future. Magnetic data storage products include analog audio and video products in various formats (standard and micro-cassettes, audio tapes, VHS), digital-media removable data storage (digital audio tapes, floppy disks, read/write compact disks), and non-removable data storage (such as hard-disk drives and airline flight-data recorders). Because of this wide range of products, there are many customers for magnetic-recording metrology. The hard-disk-drive industry represents the cutting edge of technology in this area, highly competitive in terms of both scientific development and profit margins.

Justin Mitchell, Jeff Bridges, Fabio da Silva, and Alexander Popov (front), Dustin Hite and David Pappas (back).

The requirements of the high-density-storage industry for reproducible fabrication of thin magnetic films have pushed quality assurance to its limit. This extends to a wide range of magnetic properties and requires magnetometers that are calibrated over many orders of magnitude in sensitivity. We are currently working on a novel standard for calibrated measurements of magnetic moments of thin films.

Forensic analysts are constantly battling to keep up with the combined effects of increased usage of magnetic recording and the improved technology that allows higher densities. We address these needs by utilizing state-of-the-art magnetoresistive sensors to study relatively low-density storage media (analog audio, VHS) most encountered by the forensics investigator. In addition, the possibility of recovering digital data from recording media that were either intentionally erased or accidentally damaged is an important problem in criminal and airline-crash investigations.

Spin-electronic devices will require spin injection into semiconductors. We are working on the injection of spin-polarized electrons into semiconductors using epitaxially grown Ag/Fe/Ag multilayers on GaAs to try to increase the injection efficiency through control of interface morphology.

Finally, recent experiments suggest that a quantum computer may be made using a superconducting integrated circuit. An initial goal of the Integrated-Circuit Quantum Computer project in EEEL is to build a computer with 4 to 20 quantum bits (qubits). In support of this effort, we are investigating Al oxide growth on Ta single crystals that will be required for these circuits.

Technical Strategy

Magnetic Calibration Standards

In order to respond to immediate needs of the data-storage industry and the magnetic-instrumentation companies that serve it, the efficacy of low-moment, dipole or flux-magnetometer reference samples is being investigated. Results of our first interlaboratory comparison indicate that dipole

Project Leader:
David Pappas

Staff-Years (FY 2002):
1 professional
1 technician
2 research associates

specimens may serve as reasonable reference materials. We are currently conducting a second interlaboratory comparison that will identify the specific sizes needed for these samples and the impact they would have on industry. The second interlaboratory comparison will be conducted in parallel, and the participating laboratories will be allowed to keep the samples they measure. All participants will be anonymous, but they will have access to the others' data and to NIST measurements on their samples.

DELIVERABLES:

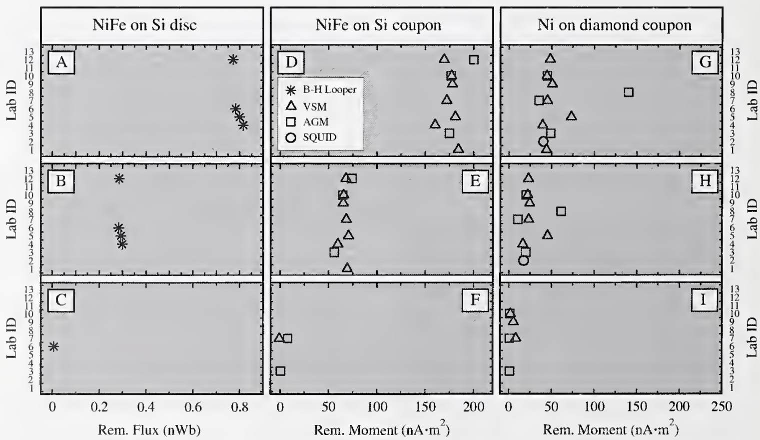
Fabricate samples for an interlaboratory comparison. Measure the samples with different magnetometers. Distribute the samples to participating laboratories. (FY 2003)

Compile and analyze results of the interlaboratory comparison. (FY 2004)

Scanned Magnetoresistive Imaging

The Magnetic Technology Division has been developing metrology for magnetic data storage since 1996. This program has resulted in advanced measurement techniques for imaging information stored on magnetic media with high resolution and relative ease. The nanoscale recording system **(NRS)** developed under this program is a general-purpose instrument that uses read/write heads similar to those in computer hard-disk or tape drives to read and write data on magnetic media. The NRS can image by rastering either the head, using computer-controlled micrometers with 50 nanometer resolution, or the storage medium, using a piezoelectric *x-y* stage with 1 nanometer resolution. The NRS is being used as a prototype for forensic analysis of audio tapes. We have been able to perform high-speed imaging of tape samples, identify the signatures of erase and write heads, and reconstruct analog and digital data.

The NRS is also capable of magnetic field imaging for non-destructive analysis of integrated circuits and materials. Failure analysis of very-large-scale-integration **(VLSI)** chips at the die level and after packaging is critical to identifying short circuits due to defects and design flaws. Inversion of the magnetic fields above these devices can provide high-resolution images of the current distributions noninvasively. In addition, hidden corrosion and cracks in materials can be imaged using induced eddy-current magnetic-field mapping. We have developed both single-element and multiple-element magnetoresistive probes on a scanning system to measure these fields. The inversion can isolate currents and defects with very high accuracy. We have developed 64- and 256-element



Remanent moments of samples in the first interlaboratory comparison. Samples A, B and C were thin Ni-Fe films on Si wafers, 7.6 centimeters diameter. Samples D, E and F were Ni-Fe films of the same thickness on 1 centimeter square dies. Samples G, H and I were ultra-thin, single-crystal Ni films on diamond substrates, 3 millimeters square. Measurement techniques: induction-field (B-H) looper, vibrating-sample magnetometer (VSM), alternating-gradient magnetometer (AGM), and superconducting-quantum-interference-device (SQUID) magnetometer.

linear arrays of multiplexed sensors. The system has been applied to failures in flip-chip high-density processors, random-access memory chips, and failure analysis of fastener materials.

DELIVERABLES:

Design, fabricate and test a linear, eight-element anisotropic-magnetoresistance **(AMR)** "comb" array and controller. Extend the comb array to 64 elements and compare it to on-chip arrays. (FY 2003)

Develop 50 ohm single magnetoresistive probes and characterize their frequency response. Test linear arrays with both in-plane and perpendicular transforms. (FY 2003)

Demonstrate the ability to scan audio tape and credit cards with the comb array. (FY 2004)

Spin Electronics

Basic research is being conducted in the area of surface and interfacial magnetism. This area is important for development of metrology relevant to advanced devices, such as giant magnetoresistive heads, tunnel junctions, and perpendicular recording media. In our surface-science laboratory we use spin-resolved electron spectroscopy as a magnetometer to map magnetic phase transitions as functions of temperature and film thickness. All three components of spin polarization are analyzed, allowing us to study any type of recording medium. The electrons are sensitive to the first few atomic layers of the surface.

Our approach for spin electronics is to achieve direct spin injection from Fe across a Ag/GaAs Schottky barrier at room temperature. The challenge consists of the injection of spins, experimental verification of spin polarization, and measurement of spin coherence times. The possibility of spin injection from Fe into GaAs was first demonstrated by researchers at the Paul Drude Institute in Berlin in 2001. However, the spin-injection efficiency was only 2 percent. We are investigating whether an ultra-thin Ag buffer layer can prevent undesired intermixing associated with the Fe/GaAs system.

Other approaches to spin injection use dilute magnetic semiconductors or hyperfine-enhanced paramagnetic semiconductors instead of Fe as the injector. Although not yet practical for electronic devices, spin-polarized electrons may also be created in semiconductors with circularly polarized laser light.

DELIVERABLES:

Obtain electron injection from metals into semiconductors. Prepare and measure multilayers of Fe and Ag on GaAs spin injectors. Measure magnetic properties of multilayers on GaAs. (FY 2003)

Fabricate devices using samples grown in ultra-high vacuum and measure transport properties in magnetic field. (FY 2004)

Quantum Computing

One of the most promising candidates for quantum computing devices is quantum bits based on Josephson junctions. These junctions form a fundamental piece of many areas of current research — magnetic detectors, bolometers, high-resolution X-ray spectrometers — and as such, their basic fabrication has been investigated in some detail. However, the quantum bit has far more stringent noise requirements that are now only barely met by current fabrication technologies. The significant limitation to devices is the generation of defects in the oxide interlayers. The structural origin of these defects is not well established, but is likely a consequence of both the amorphous oxides and preparation methods. Work in crystalline oxides has shown that these systems contain three to four orders of magnitude fewer defects in the frequency range of interest for microelectronic quantum circuits based on Josephson junctions.

Epitaxial devices based on $Ta/Al_2O_3/Ta$ should show significantly decreased noise (potentially by orders of magnitude), while also offering significantly decreased dispersion of defects per wafer, allowing the fabrication of high-coherence, multi-element quantum computers. In addition, epitaxially grown junctions will allow us to apply precise surface-science characterizations to the device, improving our understanding of the fabrication and optimization of all such structures. A better understanding of growth physics in these systems will allow us to leverage related tunnel-junction, dielectric, and microwave research from the past decade.

The noise reductions in these devices may assist other efforts that employ Josephson junctions and tunnel barriers, such as voltage standards and magnetic tunnel junctions.

DELIVERABLES:

Grow $Al/Al_2O_3/Al$ samples with H doping on Si. Characterize electrically, with Auger electron spectroscopy, and with low-energy electron diffraction. (FY 2003)

Grow Al oxide on Ta single crystals. Deposit AlO and characterize using angle-resolved Auger electron spectroscopy and low-energy electron diffraction. (FY 2004)

Grow amorphous and polycrystalline $Al/AlO_x/Al$ samples on Si wafers and compare to crystalline AlO_x on Ta. (FY 2005)

Characterize dielectric loss for amorphous versus crystalline oxide tunnel barriers. (FY 2005)

Accomplishments

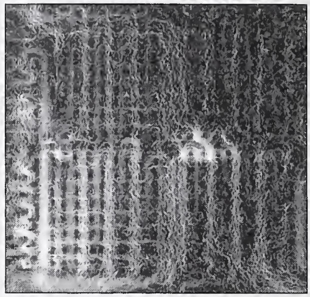
Magnetic Calibration Standards

■ **Magnetic/Superconducting Thin-Film Reference Sample** — We measured the magnetic properties of two sets of magnetic/superconducting thin-film reference samples at low temperature using a superconducting quantum interference device **(SQUID)** directly coupled to the superconducting leads surrounding the magnetic film. The first set of films had magnetic moments of about 25 nanojoules per tesla (25 micro-emu). The second set had magnetic moments of about 250 nanojoules per tesla (250 micro-emu). The uncertainty for the magnetic flux depends on the coil geometry, the shielding effect of the superconducting coil on the sample, and the SQUID sensor internal coupling. Comparison hysteresis loops were measured using a SQUID magnetometer, a vibrating-sample magnetometer, an induction-field looper, and an alternating-gradient magnetometer.

As demonstrated in our previous interlaboratory comparison, these two types of films may be suitable reference samples. For fluxmetric systems — such as inductive loop tracers — round samples of $Ni_{81}Fe_{19}$ **(Permalloy)** were good candidates, with an interlaboratory variation of 3 percent. For magnetometric systems — such as vibrating-sample magnetometers, SQUID magnetometers, or alternating-gradient magnetometers — candidates must have highly square hysteresis loops with low coercive fields. Permalloy films on square Si coupons are good candidates, with an interlaboratory variation of 6 percent. Based on this information, we designed a new interlaboratory comparison.

Scanned Magnetoresistive Imaging

■ **Applications in Magnetic Forensics** — We worked with the Federal Bureau of Investigation to upgrade its scanning magnetic field microscope with magnetoresistive sensors. The microscope is used for forensic authenticity analysis of magnetic storage-tape evidence, for example, audio cassette and videotapes. The system originally used a VHS

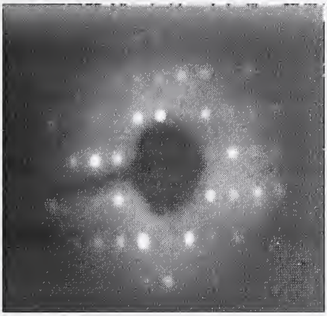


Failure-analysis image of currents in a flip-chip random-access memory. The image is 2.5 centimeters by 2.5 centimeters and shows the currents in the chip as calculated by inverting the z-component of the magnetic field using Maxwell's equations.

inductive tape head sensor coupled to a SQUID magnetometer. The new sensors have higher resolution and incorporate a second-harmonic modulation and sense scheme that rejects thermal anomalies. This allows the sensor to slide in contact with the sample, giving the maximum possible resolution. At present, the resolution allows for 2 micrometer wide tracks with 0.02 micrometer downtrack resolution. Other enhancements to the system were vibration isolation and an electronic triggering method to more closely map the actual position of the head over the media. We have extended this technique to analyze magnetic fields from defective integrated circuits. This application will be focused on helping companies screen production devices for anomalous current drain, thereby enhancing their failure analysis methods.

Spin Electronics

■ **Electrical Injection of Electrons from Fe into Ga Achieved Using a Ag Buffer Layer** — Electrical transport characteristics for epitaxially grown Ag/Fe/Ag multilayers on GaAs(100) and GaAs(110) were studied under various growth conditions. The surfaces and structure of the multilayer were characterized by low-energy electron diffraction and angle-resolved Auger electron diffraction at all steps of the fabrication. We were able to prepare clean, well ordered, epitaxial multilayers. The ultrathin Ag buffer layer was able to control the growth morphology of the Fe layer, prevent undesired intermixing associated with the Fe/GaAs system, and create a tunneling barrier in reverse bias. *In-situ* conductance spectroscopy measurements were performed to characterize the rate of electron injection into the semiconductor as a function of bias



Low-energy electron diffraction image from a single-crystal film of Fe, 10 atomic layers thick, grown on an ultra-smooth Ag film, 10 atomic layers, on GaAs.

voltage. These multilayer diodes exhibit a reverse-bias tunneling effect at energies consistent with transport through sub-bands in the Ag buffer layer. This is significant because it shows that we have been able to overcome the problem of conductivity mismatch by tunneling between the Fe and GaAs using quantum-confined states in an ultra-smooth, ultra-thin Ag buffer layer. A possibility exists of using these structures for direct spin injection from the Fe across the Ag/GaAs Schottky barrier.

Recent Publications

F.C.S. da Silva, C.M. Wang, and D.P. Pappas, "Magnetic Thin Film Interlaboratory Comparison," submitted for publication.

D.P. Pappas and C.S. Arnold, "*In-Situ* Ultra-High Vacuum Use of W-Re Thermocouples over a Wide Temperature Range," submitted for publication.

Z.Y. Lui, P.A. Dowben, A. Popov, D. P. Pappas, "Consideration of Possible Mass and Velocity Corrections to Magnetic Experiments," submitted for publication.

A.P. Popov, A.V. Anisimov, and D.P. Pappas, "Two Mechanisms for the Multi-Step Spin Reorientation Transition in Fe films on Gd," submitted for publication.

W.F. Egelhoff, Jr., M.D. Stiles, D.P. Pappas, D.T. Pierce, J.M. Byers, M.B. Johnson, B.T. Jonker, S.F. Alvarado, J.F. Gregg, J.A.C. Bland, and R.A. Buhrman, "Spin Polarization of Injected Electrons," Science, **296**, 1195a (May 2002).

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T. Komesu, C. Waldfried, J. Hae-Kyung, D. Pappas, T. Rammer, M.E. Johnston, T.J. Gay, and P.A. Dowben, "Apparatus for Spin-Polarized Inverse Photoemission and Spin Scattering," Proc. SPIE 3945, 6-16 (2000).

Magnetodynamics

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Staff-Years (FY 2002):
2 professionals
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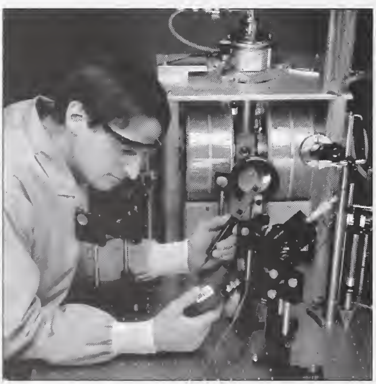
Goals

This project develops instruments, techniques, and theory for the understanding of the high-speed response of commercially important magnetic materials. Techniques used include linear and nonlinear magneto-optics, and pulsed inductive microwave magnetometry. Emphasis is on broadband (above 1 gigahertz), time-resolved measurements for the study of magnetization dynamics under large-field excitation. Research concentrates on the nature of coherence and damping in ferromagnetic systems and on the fundamental limits of magnetic data storage. Exploratory research on spin-electronic systems and physics is underway. The project provides results of interest to the magnetic-disk-drive industry, developers of magnetic random-access memory, and the growing spintronics community. Project members have measured deleterious magnetic turbulence during the magnetic switching process, evanescent flux-pulse propagation in metallic films, and anisotropic coupling (damping) between uniform excitations and the crystal lattice. Coherent-control methods have been used to switch magnetization without unwanted precessional ringing. An inductive current probe was developed to assess trace-suspension interconnects for disk-drive recording heads.

Customer Needs

Our primary customers are the magneto-electronics industries. These include the magnetic-disk-drive industry, the magnetic-sensor industry, and those companies currently developing magnetic random-access memory **(MRAM)**. As commercial disk drives approach data-transfer rates of 1 gigabit per second, there is increased need for an understanding of magnetization dynamics. In addition, measurement techniques are needed that can quantify the switching speeds of commercial materials. Once the response of a material has been benchmarked, the engineer can develop electronic components (e.g., heads, disks, or MRAM) that can fully exploit the bandwidth potential of the material.



Electronics engineer Tony Kos aligning optics for pump/probe measurements of spin populations in GaAs. Photo © 2002 Geoffrey Wheeler.

We are providing novel metrology for the burgeoning spintronics industry. The spin precession of charge carriers in semiconductor hosts has significant potential for telecommunications applications. Unlike the case of conventional semiconductor switching, the frequency of spin precession is not fundamentally limited by the physical thickness of dielectric spacers. We plan to investigate novel magnetic/semiconductor heterostructures of interest to the telecommunications industry.

Technical Strategy

Nanomagnetodynamics

The focus of this project is the measurement of switching time of magnetic materials for applications in data storage. This has led to the development of instrumentation and experiments using magneto-optics and microwave circuits. Microwave coplanar waveguides are used to deliver magnetic-field pulses to materials under test. In response, the specimen's magnetization switches, but not smoothly. Rather, the magnetization vector undergoes precession. Sometimes, the magnetization can precess nonuniformly, resulting in the generation of spin-waves or, in the case of small devices, incoherent rotation.

Our technical strategy is to identify future needs in the data-storage and other important industries, develop new metrology tools, and do the experiments and modeling to provide data and theoretical underpinnings.

We concentrate on two major problems in the magnetic-data-storage industry: (1) data-transfer rate, the problem of gyromagnetic effects, and the need for large damping without resorting to high fields; and (2) storage density and the problem of thermally activated reversal of magnetization.

Data-transfer rates are increasing at 40 percent per year (30 percent from improved linear bit density, and 10 percent from greater disk rotational speed). The maximum data-transfer rate is currently 100 megabytes per second, with data channel performance approaching 1 gigahertz. In two years, frequencies for writing and reading will be well into the microwave region, which raises the question, "How fast can magnetic materials switch?"

The current laboratory demonstration record for storage density is over 16 gigabits per square centimeter (100 gigabits per square inch). How much farther can longitudinal media (with in-plane magnetization) be pushed? Can perpendicular recording, patterned media with discrete data bits, or heat-assisted magnetic recording extend magnetic recording beyond the superparamagnetic limit at which magnetization becomes thermally unstable? As the data-storage industry seeks its own answers to these pressing questions, we must strive to provide the necessary metrology to benchmark the temporal performance of new methods of magnetic data storage.

We have sought to extend magneto-optics for the quantitative measurement of magnetization dynamics in practical ferromagnetic films. Methods include time-resolved generalized magneto-optic ellipsometry **(TRe-GME)**, time-resolved second-harmonic magneto-optic Kerr effect **(TRe-SHMOKE)**, and quantitative wide-field Kerr microscopy. All these systems rely upon RF waveguide technology for the delivery of fast magnetic field pulses to excite magnetization switching in specimens. We use several methods to detect the state of magnetization as a function of time. These include the following:

- The magneto-optic Kerr effect **(MOKE)** makes use of the rotation of polarization of light upon reflection from a magnetized film. We have used MOKE with an optical microscope to measure equilibrium and nonequilibrium decay of magnetization in recording media.

- The second-harmonic magneto-optic Kerr effect **(SHMOKE)** is especially sensitive to surface and interface magnetization. We have used SHMOKE for time-resolved vectorial measurements of magnetization dynamics and to demonstrate the coherent control of magnetization precession.

- In our pulsed inductive microwave magnetometer **(PIMM)**, the changing magnetic state of a specimen is deduced from the change in inductance of a waveguide. This technique is fast, inexpensive, and easily transferable to industry. It may also be used as a time-domain permeameter to characterize magnetic materials. Since the development of the PIMM at NIST, similar systems have been built at two industrial research laboratories and one university by former NRC post-doctoral associates. Another system is currently under development at a university in Australia.

While the aforementioned instruments have immediate use for the characterization of magnetic data-storage materials, they are also powerful tools for the elucidation of magnetodynamic theory. The primary mathematical tools for the analysis of magnetic switching data are essentially phenomenological. As such, they have limited utility in aiding industry in its goal to control the high-speed switching properties of heads and media. We have sought to provide firm theoretical foundations for the analysis of time-resolved data, with special emphasis on those theories that provide clear and unambiguous predictions that can be tested with our instruments.

DELIVERABLES:
Magnetodynamic Characterization

Measure static and dynamic magnetic properties of $Ni_{81}Fe_{19}$ **(Permalloy)** as a function of thickness for recording head applications. Determine effective anisotropy due to magnetostatic mode distribution for varying waveguide widths. Study temperature dependence of damping and compare with theory for magnon-electron scattering. Correlate temperature dependence of damping with conductivity. (FY 2003)

Measure nonlinear contributions to damping in soft metallic films using waveguides with varying-width center conductors. Determine surface contributions to damping. (FY 2003)

Measure damping in soft-underlayer **(SUL)** materials for perpendicular magnetic recording. (FY 2003)

Measure rotational symmetry of enhanced anisotropy below 100 kelvins. (FY 2003)

Study periodically etched samples (magnon diffraction grating) to control nonlinear dynamics in thin-film samples. (FY 2004)

DELIVERABLES:
Magnetodynamic Instrumentation

Set up and automate waveguide milling facility. Fabricate coplanar waveguides with varying center conductor widths for PIMM and SHMOKE measurements. (FY 2003)

Complete development of the cryogenic PIMM. Determine uncertainty due to systematic effects. (FY 2003)

Develop dual-waveguide structure for on-chip differential PIMM measurements. (FY 2003)

Modify SHMOKE system to study dynamics of precessional switching in patterned structures. (FY 2004)

Spin Electronics

To enable future applications in spin electronics, such as ultra-high-frequency oscillators, our goal is to obtain and measure coherent spin dynamics in metal/semiconductor heterostructures. We are investigating both spin-momentum transfer **(SMT)** and optically generated spin populations in semiconductors.

We are using mechanical point contact spectroscopy to investigate current-induced excitations in multilayer films. It is known that, for sufficiently high current densities and applied magnetic fields, there is an abrupt increase in the resistance of a point-contact junction. The resistance step is attributed to the generation of magnons (spin waves) by the SMT effect. We find that SMT is a generic effect, occurring for a wide range of experimental conditions: for both in-plane and out-of-plane fields, for multilayers grown at the both the first and second maxima in giant magnetoresistance **(GMR)**, and for ferromagnetically coupled multilayers. We found that SMT occurs in a number of different and previously unexplored alloys of Co, Fe and Ni.

In addition to SMT, we are working on a pulsed-laser technique to pump and probe spin populations in semiconductors at cryogenic temperatures. The spin population is measured using the rotation of linear polarized light that is transmitted through a bulk sample. The project's work in spin electronics is funded by the Defense Advanced Research Projects Agency **(DARPA)**.

DELIVERABLES: Spin-Momentum Transfer

Measure the rectification of RF radiation in Ni-Cu films by point-contact geometry and the dependence on applied magnetic field and exchange stiffness. Develop direct RF probe of SMT-induced excitations based on time-varying resistance modulation using high-bandwidth waveguides and interconnects. Develop local RF probe of SMT-induced excitations using Josephson junction technology. (FY 2003)

Determine the frequency of SMT-induced excitations as a function of applied field for varying multilayer structure and different materials. Demonstrate SMT resonance for a current-perpendicular-to-the-plane **(CPP)** spin-valve structure with only two magnetic layers: the "free" layer and the "pinned" layer. (FY 2003)

Lithographically fabricate point-contact structures for study of SMT dynamics in single magnetic films. Study size effects associated with patterned islands of ferromagnetic film much larger than the point-contact area (spin-wave Fabry-Perot interferometer). (FY 2004)

DELIVERABLES: Spins in Semiconductors

Measure relaxation times, relative spin polarizations, and spatial variation of spin polarized populations for CW-pumped GaAs as functions of pump wavelength and doping density. Measure time-resolved spin dynamics in GaAs using a dual pulsed laser diode system. (FY 2003)

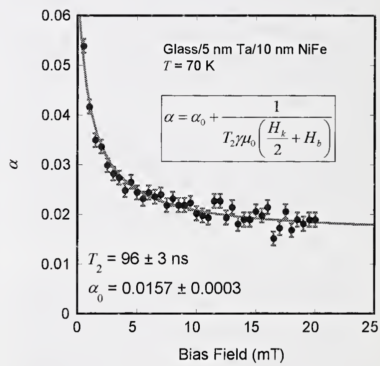
Develop an RF system for coherent control of optically injected spin populations in GaAs. Demonstrate coherent manipulation of optically injected spin populations by RF excitation with lithographically patterned waveguides. (FY 2003)

Study the feasibility of peristaltic spin pumping from ferromagnetic metal into GaAs using ferromagnetic resonance. (FY 2004)

Accomplishments

Magnetodynamic Theory

■ **New Equation for Magnetization Dynamics Based Upon Transverse Relaxation Processes —** We developed a new equation to describe magnetodynamic response derived from the Bloch-Bloembergen formulation for spin relaxation phenomena. The equation makes use of different longitudinal and transverse relaxation rates. It may be used for all possible field geometries and is amenable to finite-element micromagnetic simulations. The model accounts for the highly elliptical pre-



Damping as a function of applied magnetic bias field along the easy axis of a Ni-Fe sample. The data were obtained using the CryoPIMM. The data are fitted using a new magnetodynamic equation based upon the Bloch-Bloembergen formulation, but with the magnitude of the magnetization equal to the saturation magnetization. The new equation permits quantitative extraction of fundamental damping parameters such as the spin decoherence time T_2.

cessional modes incurred in thin metallic films. Under conditions where the transverse relaxation rate is constant, the resulting equation is of the usual Landau-Lifshitz form but with an additional dependence of the damping term on longitudinal field. This can result in both nanosecond damping times in thin films and significant contribution from weak spin-orbit effects to the overall damping of precessional excitations in thin films. An inverse field dependence for the damping parameter in thin films is predicted by the new equation, in agreement with our data obtained by inductive and optical methods. In addition, highly viscous response is predicted when the magnetization is subject to large magnetic field pulses along the hard axis of uniaxial anisotropy films, also in agreement with recent observations of metastable states in homogeneous Permalloy films.

■ **Magnetodynamics Lecture Series** — In January 2002, the division hosted a series of lectures by Robert Stamps, University of Western Australia, on the underpinnings of magnetodynamic theory. The lectures focused on the fundamental principles that lead to the ferromagnetic ground state and methods for analyzing excitations above the ground state. The lectures concluded with a timely discussion on the validity of conventional spin-relaxation theory in a regime of large-angle precessional motion, such as might occur when switching the magnetization orientation with a large field pulse.

Magnetodynamic Instrumentation

■ **Cryogenic Capability Added to Pulsed Inductive Microwave Magnetometer** — As part of our program in high-speed magnetics, we developed an automated pulsed inductive microwave magnetometer (PIMM) to characterize magnetic thin films. The PIMM is designed to measure the magnetodynamical properties of materials used in recording heads for magnetic data storage. The data-storage industry is developing new magnetic alloys with high saturation magnetization to use in write heads. The magnetic damping behavior of these new alloys will determine their usefulness for high-speed recording.

The PIMM has now been enhanced with variable temperature capability. The new instrument can measure the magnetodynamic response of magnetically soft thin-film materials at temperatures from 25 kelvins to 325 kelvins. In addition, the CryoPIMM has been augmented with high-field magnets that can apply DC bias fields as high as 45 milliteslas, permitting the study of materials with high anisotropy, such as single-crystal films of iron and nickel.

The CryoPIMM will be a powerful new tool to investigate the fundamental origins of precessional damping in thin metallic films. Most magnetic materials with a high permeability also exhibit underdamped response when driven with RF fields.

The origin of the oscillatory response stems from the gyromagnetic properties inherent in all ferromagnets. The magnetic moment of the electron is fundamentally coupled to the quantum-mechanical spin angular momentum: When a torque is applied to the magnetization, the intrinsic response of the electron moment is precession, much as a gyroscope precesses under the influence of the Earth's gravitational field. However, in sharp contrast to a mechanical gyroscope, the angular momentum of the electron spin precesses at megahertz to gigahertz frequencies.

In the absence of any coupling between the electron spins and the rest of the crystal environment,

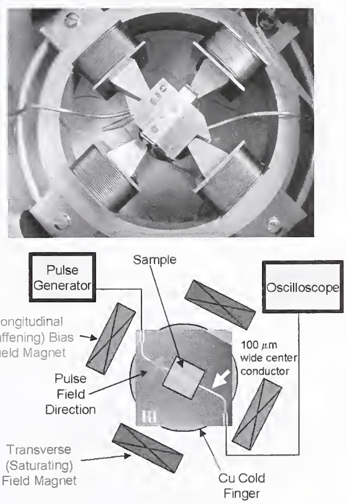
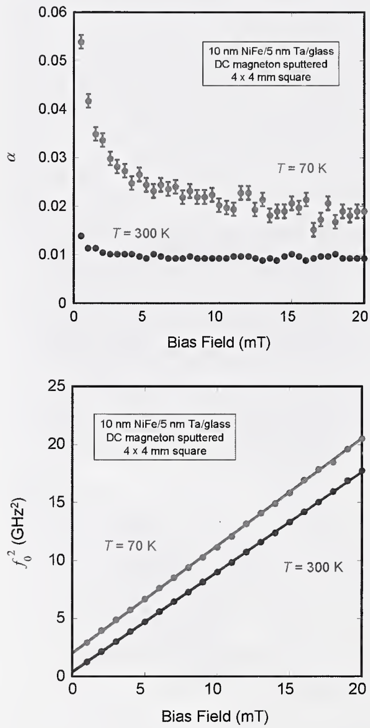


Photo and schematic of the CryoPIMM. The photo shows the longitudinal and transverse magnets surrounding the coplanar waveguide structure, which is underneath the brass fixture in the center. Measurement samples are placed between the waveguide and a cold finger beneath it. Data obtained with the CryoPIMM will shed light on the physical mechanism of damping in materials used for data-storage applications.

the precession would continue indefinitely. In reality, the spins are coupled to the atomic lattice such that the precession is eventually damped. Nevertheless, the resulting oscillations of the magnetic moment can be deleterious in practical applications such as magnetic data storage. For example, the data transfer rate in commercial disk drives is now approaching 1 gigabit per second. Disk-drive engineers must be careful to avoid effects stemming from gyromagnetic precession at these frequencies. Most importantly, there is a need to determine sources of damping, with the goal of controlling the damping as a material design parameter.



Ni-Fe exhibits dramatically enhanced damping coefficient α and precession frequencies f_0 when cooled below 100 kelvins. The measured enhancement in damping and anisotropy scales inversely with film thickness, which suggests interfacial origins of the effects. Further study will result in greater understanding of how magnetic film interfaces affect the dynamics of magnetization within the film.

There are multiple conflicting theories for damping in metallic thin films. One is "magnon-electron scattering" or "sd-exchange." This theory predicts a strong temperature dependence in the range of 4 kelvins to 100 kelvins. The coupling between conduction electrons and fundamental magnetic excitations ("magnons") is enhanced when the time interval between inelastic scattering events for the conduction electrons is longer than the inverse of the magnon-electron coupling energy. At this point, energy and angular momentum are efficiently transferred from the magnetization to the electrons at the Fermi surface. Observation of a temperature dependence in the damping would be confirming evidence for the sd-exchange theory.

■ **Signal-to-Noise Ratio Improved for Pulsed Inductive Microwave Magnetometer** — We discovered a method for enhancing the signal-to-noise ratio for the PIMM by a factor of 4. The method makes use of eddy currents generated in a thick conductive sheet placed over the sample to be measured. The eddy currents boost by a factor of 2 the magnetic field pulse that drives the magnetization dynamics. At the same time, the sensitivity of the waveguide detector is also enhanced by a factor of 2 due to the principle of reciprocity, which states that the inductive coupling between two Amperian currents is reciprocal. The enhanced signal-to-noise ratio makes possible the study of much thinner samples than was previously possible. Work has now commenced on the study of dynamics in ultra-thin Permalloy films of only 2 nanometers thickness. Such extremely thin films are routinely used in state-of-the-art spin-valve sensors used in commercial disk drives. Little is known about how the extreme thinness of these sputtered films affects the dynamical properties.

Magnetodynamic Characterization

■ **Differing Dynamic and Static Magnetic Anisotropy in Thin Permalloy Films** — We found that the values of dynamic and static uniaxial anisotropy in thin polycrystalline Permalloy films differ by as much as a factor of 1.5. The dynamic anisotropy has an additional isotropic component not observed in static measurements. The time-resolved precessional response was measured as a function of an in-plane applied bias field. The frequency dependence on bias field was fitted with high precision to the Kittel formula for ferromagnetic resonance, thereby extracting anisotropy field. We interpret the constant offset field as a transient component of the magnetic anisotropy that affects dynamical response at time scales only below 10 nanoseconds.

■ **Damping as a Function of Pulse Amplitude and Bias Field in Thin-Film Permalloy** —We found that the damping parameter in thin-film Permalloy is independent of *transverse* pulse field amplitudes but decreases monotonically with increasing *longitudinal* bias fields. Even though the magnetization is rotated in response to the transverse field by angles well in excess of the ferromagnetic resonance **(FMR)** spinwave instability threshold, there is no evidence for any nonlinear dependence of damping on pulse amplitude. We surmise that the intrinsic damping in Permalloy is sufficiently large to damp any precessional motion before any spinwave instabilities have a chance to grow to measurable levels.

Magnetic Relaxation

■ **Stability of Nanoparticles for Magnetic Data Storage** — We have found a simple formula that describes the effects of exchange interactions on the thermal stability of nanoparticles in magnetic recording media. Since the production of the first hard-disk drive in the early 1950s — the IBM RAMAC, with an areal density around 150 bits per square centimeter — data storage density has improved immensely. The capacity of computer hard disks has increased by more than seven orders of magnitude in 45 years. At the same time, the price per megabyte has dropped from hundreds of dollars in the 1980s to a few cents in 2002.

The current growth rate in areal density of 100 percent per year raises questions regarding the stability of small magnetic bits. As the bit size approaches the nanometer scale, thermal fluctuations compromise the stability of bits over time: the so-called "superparamagnetic limit." One of the new approaches that have been proposed to improve stability in this regime is the use of exchange-coupled media with bits oriented perpendicular to the substrate.

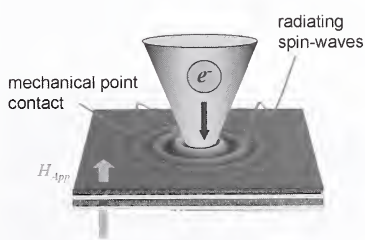
The magnetic exchange interaction causes individual particles to become correlated. That is, thermal fluctuations sensed by each particle are shared with the others, making the collection of particles more thermally stable. Our formula relates stability parameters, such as the "blocking" temperature, to the magnitude of the exchange interactions, which is measured as a mean magnetic field. This formalism will facilitate the engineering of media for data storage by quantifying the effect of interparticle exchange interactions on thermal stability.

Spin-Momentum Transfer

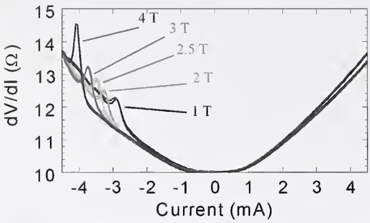
■ **Spin-Momentum Transfer Effects Seen in Multilayer Structures** — Initial work on SMT consisted of obtaining Andreev reflection spectra using a superconducting point contact and a magnetic film. The spectroscopic structure of the Andreev reflection measurement is determined by the formation of Cooper pairs when electrons leave a normal metal and enter a superconductor. The net spin of the Cooper pairs must be zero, forcing every electron that enters the superconductor to accompany another electron of opposite spin. However, in a ferromagnet, there is an asymmetric spin distribution that reduces the statistical odds that every "up" spin entering the superconductor will be correlated with an available "down" spin. The successful observation of the Andreev reflection signature was proof-of-concept for the ability to establish ballistic point contacts.

The next step was to observe magnon scattering peaks in point contact spectra of magnetic multilayers. The peaks indicate dynamic excitations generated by an electron current flowing from a silver tip into a magnetic exchange-coupled multilayer. Such peaks have been observed before in antiferromagnetic exchange-coupled multilayers. The peaks are apparent even in zero applied magnetic fields, which had never before been seen.

■ **Spin-Momentum Transfer Efficiency Estimated at 30 Percent** — An estimate of the SMT efficiency from a polarized conduction current was



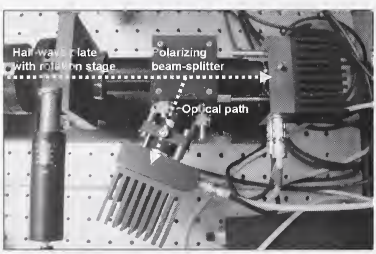
Sketch of spin-momentum transfer with mechanical point contacts. The Ag tip is in electrical contact with a magnetic film made of alternating layers of a ferromagnetic metal (Co, Ni-Fe, Cu-Ni-Fe, Co-Fe or Fe) and Cu. When electrons are injected from the Ag wire, theory predicts that spin waves are generated due to the transfer of spin angular momentum between the ferromagnetic layers in the multilayer stack. The onset of spin-wave generation results in a discontinuous step in the resistance of the point contact.



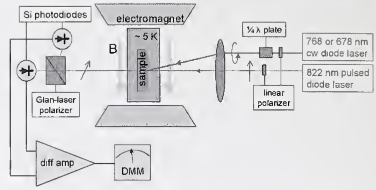
Differential resistance of a Co/Cu multilayer obtained with a mechanical point-contact measurement. The peaks correspond to steps in DC resistance of the contact. The asymmetric dependence of the peaks on the sign of the applied current and the linear dependence of the peaks on applied field are hallmarks of the spin-momentum transfer effect. An understanding of the SMT effect may result in nanoscale microwave sources and improved switching of bits in MRAM.

obtained from point-contact data for Cu/Co multilayers. The analysis uses the theory of IBM researcher John Slonczewski, who first predicted the SMT effect in 1996. From this theory, the critical current at which the point-contact resistance experiences a sudden jump can be used to determine the SMT efficiency in an experimental geometry with an applied field oriented perpendicular to the magnetic multilayer. These first estimates of SMT efficiency for point-contact data give values from 25 to 35 percent, close to the maximum expected values calculated by Slonczewski for Co-based multilayers.

■ **Spin-Momentum Transfer Ubiquitous in Multilayer Magnetic Films** — We were able to measure SMT effects in numerous multilayer structures, including Cu/Co-Fe, Cu/Fe and Cu/Ni-Fe. These



Optical bridge assembly for the detection of minute rotations of optical polarization induced by coherent spin populations in GaAs. The cooling fins are attached to thermoelectrically cooled, large-area photodiode detectors with integrated low-noise amplifiers.



Optical probe facility for the study of optically injected spins in GaAs. The instrument uses commercial photodiodes to both pump and probe spin populations in the semiconductor. The study of spin populations pumped at energies greatly exceeding the band gap will allow a quantitative assessment of spin dephasing processes that can affect "hot" spins injected through tunnel barriers into spin-electronic devices.

results indicate that SMT, which gives rise to resistance steps in point contact measurements, is a general property of magnetic multilayers and is not specific to Cu/Co multilayers. The multilayer films that exhibit SMT features need not even exhibit a measurable GMR signal: no GMR was measured for the Cu/Fe multilayers.

Spins in Semiconductors

■ **Pulsed Laser Technique Pumps and Probes Spin Populations in Semiconductors** — We obtained the first spin-detection data for optically oriented GaAs using a pulsed-laser Faraday detection mechanism. All measurements were conducted at 5 kelvins. Using pump lasers at 780 nanometers and 670 nanometers, we found that a nondegenerate system can be used to pump and probe the spin population injected into moderately doped GaAs. The spin population is measured using the rotation of linear polarized light that is transmitted through a bulk sample. The degree of rotation is directly proportional to the spin polarization. The spin coherence times were measured by sweeping an applied magnetic field and measuring the dependence of the spin polarization. In what is effectively a zero-frequency measurement of electron spin resonance, the full-width-at-half-maximum is proportional to the spin-dephasing rate. Initial measurements of the spin-dephasing times yielded only a weak dependence on the pump power used to inject the polarized spins.

Recent Publications

T. J. Silva, P. Kabos, and M. R. Pufall, "Vector-Resolved Precessional Dynamics Using Nonlinear Magneto-Optics," submitted for publication.

W. Rippard, M. Pufall, and T.J. Silva, "Quantitative Studies of Spin-Momentum-Transfer-Induced Excitations in Co/Cu Multilayer Films Using Point-Contact Spectroscopy," submitted for publication.

R. Lopusnik, J. Nibarger, T.J. Silva, and Z. Celinski, "Different Dynamic and Static Magnetic Anisotropy in Thin Permalloy Films," submitted for publication.

A.B. Kos, T.J. Silva, and P. Kabos, "Pulsed Inductive Microwave Magnetometer," Rev. Sci. Instrum. **73**, 3563-3569 (October 2002).

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Nanoprobe Imaging

Project Leader:
John Moreland

Staff-Years (FY 2002):
1 professional
3 research associates
1 graduate student

Goals

This project develops scanned-probe microscopy **(SPM)** and micro-electromechanical systems **(MEMS)** for nanometer-scale magnetic measurements in support of the magnetic data storage industry. Project members perform research to understand and relate SPM images and MEMS magnetometer measurements to the performance of magnetic materials and devices for future recording technologies. The project is currently focusing on ultra-small magnetic-force-microscopy tips for imaging recording heads and media at a resolution of 10 nanometers. Quantitative field mapping of heads and media is based on electromechanical detection of magnetic resonance. MEMS magnetometers with integrated specimens and high sensitivity are being developed. Over the next few years, the project will work on a "magnetic resonance spectrometer on a chip" to achieve magnetic-resonance imaging resolution of 1 nanometer on ferromagnetic thin films. Recent research includes the development of new ferromagnetic resonance spectrometers based on calorimetry, torque, and transfer of spin angular momentum. Such sensors can be integrated with atomic-force microscopes for imaging of local DC and RF magnetic fields. The project also develops manipulation and measurement techniques for isolating and probing the behavior and structure of single molecules. Finally, the project is developing microfabricated Cs vapor cells and cantilever-based magnetic detectors for a chip-scale atomic clock.

Customer Needs

The Information Storage Industry Consortium recently drafted a recording-head metrology roadmap that calls for high-resolution, quantitative magnetic microscopes and magnetometers that go beyond the limitations of current technology. Magnetic measurement systems have become increasingly complex. Our expertise in magnetism, probe microscopy, and clean-room microfabrication techniques helps move instruments from the development stage to routine operation in the industrial laboratory and on the factory floor.

John Moreland, Dong-Hoon Min, Li-Anne Liew, Elizabeth Mirowski, and Michelle Chabot.

Industry also looks to NIST for fundamental constants and representations of magnetic units as it pushes to smaller time and length scales. The physics of nanometer-scale magnetism must be explored so that industry can make the right choices for recording at densities of over 100 gigabits per square centimeter.

In order to improve upon magnetic microscopes, our project is focusing on specialized magnetic-force-microscope **(MFM)** tips for imaging heads and media. Ultra-small tips are being developed for magnetic image resolution of 10 nanometers. We are looking at new technologies for making very sharp probe tips and for controlling nanoscale magnetic structure near the tip. In addition, more sensitive MFM instruments are being developed. Quantitative field mapping of heads and media can be done with tiny field probes based on electromechanical detection of magnetic resonance. We are developing ways to attach submicrometer magnetic resonance particles to ultra-sensitive cantilevers and to position particles a few nanometers from the sample surface. Instrumentation will also be adapted to a new class of microwave probe stations that use micromachined probe chips to extend voltage and current probe measurements on microwave circuits with submicrometer spatial resolution in the 100 gigahertz range.

The project also develops single-molecule manipulation and measurement **(SM^3)** techniques. This program will advance single-molecule metrology by developing a novel platform, based on bio-nano-electromechanical systems, that integrates electrical, optical and spectroscopic technologies. Specifically, we are developing SM^3 technologies to address significant inaccuracies in the base-pair ordering inferred from current gene-sequencing tools, affecting such efforts as the Human Genome Project. Our program is an effort to ensure the integrity of such bio-informatic databases through the development and utilization of a high-throughput SM^3 platform to directly manipulate and measure the structure and dynamics of single RNA or DNA molecules. By directly working with an individual molecule of DNA, many of these sources of error are eliminated. Currently, the lack of measurement tools and methods for isolating, manipulating and probing the behavior and structure of single molecules prevents such an effort. This is a collaboration among divisions in EEEL, the Physics Laboratory, the Chemical Science and Technology Laboratory, and the Information Technology Laboratory.

We are also working with the Physics Laboratory to develop a chip-scale atomic clock **(CSAC)**. The most common type of passive frequency standard is the vapor-cell frequency reference. In these clocks the atoms are part of a thermal vapor contained inside a cell. The atomic vapor cell is placed inside a microwave cavity resonant at the atomic transition frequency. Light from a laser or discharge lamp, resonant with an optical transition in the atoms, optically pumps the atoms into one of the hyperfine ground states. Microwaves, usually synthesized from a crystal oscillator, are then injected into the cavity. When their frequency exactly equals the atomic transition frequency, a change of atomic state occurs, which is measured by the change in absorption of the laser. This change in absorption is used to correct the local oscillator frequency and lock it to the atomic transition.

What is the smallest size for an atomic clock? The difficulty associated with the large size of the microwave cavity can be overcome by using an all-optical excitation method based on coherent-population-trapping **(CPT)** resonances. In the CPT clock, no microwaves are applied directly to the atoms. Instead, an optical field is modulated at the atomic hyperfine frequency, resulting in two optical fields separated by the atomic oscillation frequency. Due to the CPT effect, the absorption of these two optical fields is altered when the separation frequency exactly equals the atomic hyperfine splitting. This change in absorption can be used to lock the local oscillator frequency to the atomic transition. Thus, the fundamental limit to the clock size is the wavelength of the optical radiation, which is of the order of 1 micrometer.

The CSAC research will help protect satellite transmissions, including global positioning systems, from being jammed. We expect that one of the first spin-offs of the research program will be the development of compact, accurate magnetometers based on the Zeeman shift of Cs atoms.

Technical Strategy

We are developing new tools for measurements of nanoscale magnetic phenomena and representations of magnetic units for the next generation of data-storage devices. We are developing MEMS magnetometers with integrated magnetic samples that can offer tremendous gains in magnetic-moment sensitivity. Our micromachining facility is at the state of the art, providing the tools necessary for bulk and surface micromachining on Si wafers. Our plans over the next four years are to demonstrate new metrology instrumentation based on MEMS devices that will enable us to create instruments that have superior performance compared to current magnetic-measurement methods.

Micro-Electromechanical Systems Magnetometer Development

Micrometer- and submicrometer-scale magnetic measurements have proven to be a challenge for conventional magnetometers, and new methods are being employed to probe magnetism on this scale. Conventional measurements are made on arrays of micromagnetic dots. However, due to fabrication limitations, the results are clouded by statistical variations in dot shape, size and spacing. Thus, more sensitive detectors are needed that can measure magnetic properties of individual dots.

In particular, there is a need to understand atomic-scale spin damping in ferromagnetic systems in order to improve the switching speed of magnetic devices. For example, data-transfer rates for commercial disk drives will soon require operational bandwidths in excess of 1 gigahertz. For switching times less than 1 nanosecond, gyromagnetic effects dominate. One way to understand damping is to investigate size effects as magnetic devices are reduced to sub-micrometer dimensions. Studies of magnetic nanodots will give a better understanding of spin damping and therefore aid in the development of faster disk drives.

We will provide new magnetometers based on highly specialized MEMS chips fabricated at NIST. The instruments will be inexpensive, since MEMS can be batch-fabricated in large quantities. In addition, large-scale magnetic wafer properties can be transferred to smaller MEMS magnetometers so that nanometer-scale measurements can be calibrated with reference to fundamental units. In particular, our focus will be the development of torque and force magnetometers, magnetic-resonance spectrometers, and magnetic-resonance imaging **(MRI)** microscopes on MEMS chips. Over the long term, we expect that this technology will lead to atomic-scale magnetic instrumentation for the measurement and visualization of fundamental magnetic phenomena.

DELIVERABLES:

Perform ferromagnetic resonance **(FMR)** spectroscopy using MEMS detectors on isolated submicrometer dots to measure spin decay. Correlate decay with size effects, spin-wave spectra, and phonon spectra. (FY 2003)

Develop high-gradient micro-electromagnets and micro-RF coils for MRI based on a MEMS sensor. Integrate microcoils and torsion oscillator sensor for pulsed-field-gradient MRI. Demonstrate conventional MRI by replacing the inductive pickup coil with a torsion oscillator for measuring spin decay. (FY 2004)

Demonstrate a fully integrated MRI microscope on a chip. (FY 2005)

Scanning Probe Development

In order to improve upon scanning probe microscopes, such as MFM, and keep pace with industry needs, we are focusing on specialized MFM tips for imaging heads and media. Ultra-small tips are currently being developed for magnetic-image resolution of 20 nanometers. We are looking at new technologies for fabricating, controlling and measuring nanometer-scale magnetic structures near the probe tip. In particular, MFM resolution can improve only with the development of more sensitive cantilevers for measuring the small magnetic forces associated with nanometer-scale magnetic probe tips. Conventional MFM is not an intrinsically quantitative technique. However, quantitative field mapping can be done with tiny field probes based on mechanical detection of magnetic resonance in the probe. We are developing ways to fabricate small magnetic-resonance particles on ultra-sensitive cantilevers and position the particles a few nanometers from the sample surface for field mapping with 1 nanometer resolution.

DELIVERABLES:

Characterize MEMS high-frequency sensors with integrated magnetic and microwave structures for microwave probing. Develop nanoscale magnetic recording scanning stand based on SPM. (FY 2003)

Develop probes based on direct mechanical coupling between microwave fields and the magnetic moment of a 100 nanometer magnetic particle fabricated near the tip of an atomic force microscope **(AFM)** cantilever. Compare MFM, scanning electron microscopy with polarization analysis **(SEMPA)**, and Lorentz microscopy on prototype magnetic imaging standards for magnetic-recording applications. (FY 2004)

Single-Molecule Manipulation and Measurement

The semiconductor electronics industry has driven the development of fabrication tools that are capable of patterning structures on the order of 100 nanometers, smaller than cellular dimensions. Using MEMS, it is possible to create three-dimensional structures that are commensurate with the size of biomolecules.

Interactions of single molecules with nanoscale mechanical structures, restriction elements, and other single molecules will be probed by electronic, electromechanical and optical techniques. The effort will result in a well characterized SM^3 platform integrated with AFM, fluorescence resonance energy transfer **(FRET)**, optical microscopy, and electronics, thereby enabling a wide variety of single-molecule studies. Determination of DNA structure will be performed by directly interrogating ordered bases as they are threaded through a well characterized nanopore.

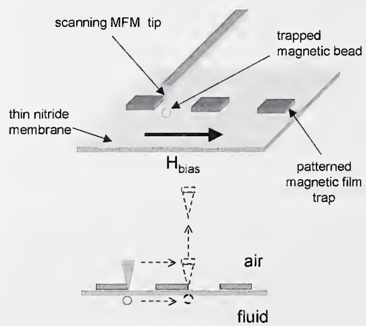
DELIVERABLES:

Fabricate magnetic nanofluidic capture cell and demonstrate capture-and-release of magnetic nanobeads. Develop methods to attach DNA to beads. Demonstrate magnetic bead position control with fluid-cell MFM. (FY 2003)

Fabricate prototype nanofluidic SM^3 platform. (FY 2004)

Fabricate and test magnetic random access array sorter. (FY 2005)

Integrate SM^3 measurement chips with nanofluidic SM^3 platform. (FY 2006)



Concept of magnetic trap for single-magnetic-bead manipulation in a microfluidic cell. Biomolecules will be attached to the beads for single-molecule manipulation and measurements.

Chip-Scale Atomic Clock

The main thrust of the **CSAC** project is to develop a Cs vapor cell with submillimeter dimensions and to study the effect of the vapor cell wall coatings and buffer gases on the intrinsic line width of the Cs atomic transitions. The challenges for developing a microfabricated atomic-clock vapor cell are threefold. First, the process must be performed at the wafer level in order to take advantage of batch fabrication of the cells. Second, the process must provide a means for evacuating and subsequently back-filling the cell with Cs or Rb without the need for microvalve technology or glass tubing connections to the cell. Third, the process must allow for the introduction of cell coatings or buffer gases to minimize size-effect spectral broadening. We are currently investigating several approaches to cell microfabrication based on wafer bonding and bulk and surface micromachining techniques of Si. In addition, we will be investigating schemes that rely on direct magnetic coupling between a mechanical micro-oscillator and the Cs vapor, thus eliminating the need for external feedback control.

DELIVERABLES:

Design and fabricate submillimeter Cs/Rb gas cells using MEMS. Develop methods for cell filling and sealing. (FY 2003)

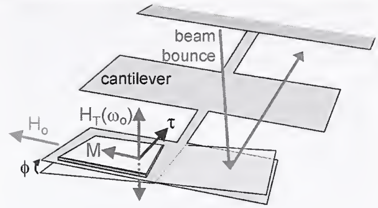
Develop wall coating for Cs/Rb cells. Optimize Cs/Rb gas cell process for batch fabrication. (FY 2004)

Integrate cells with clock components. Design prototype chip-scale clock. Transfer the technology. (FY 2005)

Accomplishments

Micro-Electromechanical Systems Magnetometer Development

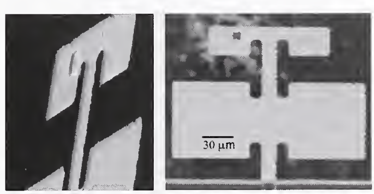
■ **Ultra-sensitive Microcantilevers for Micrometer-Scale Magnetometry** — We have quantitatively measured micrometer-scale magnetic dots based on the detection of mechanical torques on thin films deposited onto microcantilevers. A main challenge of these techniques is getting well defined micromagnetic samples onto the cantilevers. To this end, we developed a wafer-level microfabrication process in which the film deposition and patterning are combined with the cantilever micromachining process. This allows magnetic measurements of samples with a total magnetic moment smaller than that detectable with conventional magnetometers.



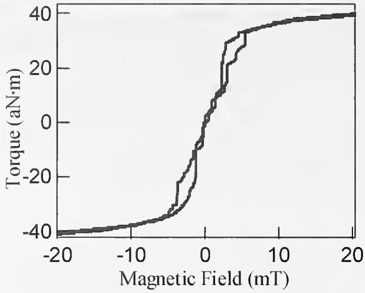
Experimental configuration for measuring the magnetic properties of magnetic dots patterned on a double-torsional oscillator, microtorque magnetometer.

Cantilevers with low spring constants and high mechanical quality factors are essential for these measurements. The cantilevers are double torsional oscillators made from single-crystal Si with resonant frequencies of 120 kilohertz and mechanical quality factors of 12 000 or more. In the dynamic deflection method, the cantilever and magnetic film are placed in an external magnetic field. A small orthogonal AC torque field is applied at the cantilever resonant frequency, and the resulting torque is measured as a function of external field.

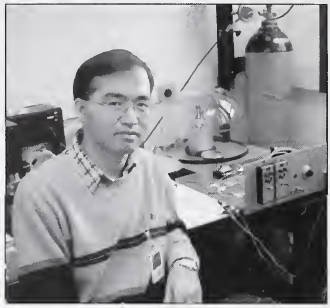
We have been able to measure quantitative hysteresis loops of Ni-Fe films. A 5 micrometer by 5 micrometer by 30 nanometer Ni-Fe square had a measured saturated magnetic moment of $5.1 \times 10^{-13} \pm 2 \times 10^{-14}$ joules per tesla (5.1×10^{-10} emu). The curves for the smaller films showed hysteretic switching consistent with a series of stable multidomain states. The saturation magnetization was within 3 percent of the value measured on similar samples by FMR. The signal-to-noise ratio was about 50, indicating a torque resolution of 8.4×10^{-19} newton-meters, corresponding to a magnetic moment noise level of 6.7×10^{-15} joules per tesla (6.7×10^{-12} emu). With improvements in microfabrication, the target sensitivity is 10^5 Bohr magnetons at room temperature, with the potential for single-spin detection below 1 kelvin, where thermomechanical noise is suppressed.



Scanning electron micrographs of double-torsional oscillators with a square Ni-Fe thin-film dot.



Magnetization versus applied magnetic field for a Ni-Fe dot showing hysteresis and multiple switching due to the magnetic domain structure of the dot.



Dong-Hoon Min developed a portable fiber-optic interferometer for in-situ magnetometry of magnetic multilayers during deposition.

■ **Resonating Torque Microbalance Developed for *In-Situ* Measurements of Ferromagnetic Films with Submonolayer Sensitivity** — Our work to develop ultra-sensitive magnetometers based on micromechanical sensors has led to a new instrument for *in-situ* measurements of ferromagnetic films. The project is in response to the need to develop metrologies for thin-films critical to the development of read-head sensors and magnetic recording media.

The production and development of many contemporary magnetic devices require that consistent growth conditions be maintained during thin-film deposition processing steps. Typically, film properties are determined *ex situ* with induction-field loopers that measure the product of the saturation magnetization and the thickness of the film. The goal of this project is to develop an instrument that depends on inexpensive, batch-fabricated, micromechanical substrates for quantitative measurements with submonolayer magnetic moment sensitivity.

We have developed an instrument that measures the magnetic torque on a film as it is being deposited onto a single-crystal Si microcantilever. An optical-fiber interferometer is used to measure the deflection of the cantilever. Optic-fiber detectors work well in the high-noise environment typical of deposition systems. To take advantage of the quality-factor enhancement of the mechanical torque signal, the magnetic torque is applied near the mechanical resonance of the cantilever. Dynamic feedback is used to balance the magnetic torque by applying a mechanical force at the base of the cantilever that is just equal and opposite to the magnetic torque. The dynamic feedback approach minimizes the mass loading and the effects of a temperature-dependent elastic modulus that change the resonant frequency of the cantilever during deposition. The cantilevers were custom designed for this application and fabricated in the MEMS facility in Boulder.

The technique provides a way to make quantitative measurements of the saturation magnetization of thin-film samples with very small total magnetic moments. The Brownian motion of the cantilever sensor fundamentally limits its ultimate sensitivity; at room temperature this corresponds to a ferromagnetic film, 0.02 nanometer thick, with the current cantilever geometry.

Scanning Probe Development

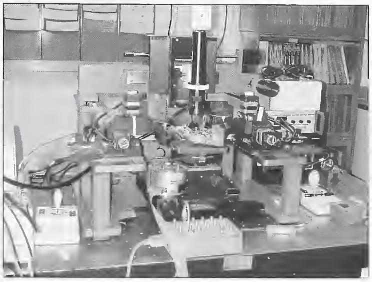
■ **All-Dielectric Micromachined Probe for High-Resolution Microwave Power Measurement** — We developed a new instrument for measuring microwave fields near active devices in response to the need for probe metrologies for the semiconductor industries. High-resolution, noninvasive measurements of high-frequency signals exceeding 20 gigahertz are critical to the development of microwave circuits and high-frequency, Si-based technologies. The semiconductor industry needs accurate metrology for the at-speed test of digital integrated circuits **(ICs)**, but traditional IC contact probing technology requires large contact pads incompatible with the operation and economic constraints of modern IC designs.

We developed a micromachined bi-material cantilever with a thin-film FMR sensor to probe microwave fields near active devices. A patterned Ni-Fe alloy film deposited at the tip of the cantilever serves as the localized FMR probe. Power absorption at the tip, under FMR conditions, results in a proportional bending of the bi-material cantilever due to heating; the deflection of the cantilever is measured with an optical lever. The small dimensions of the probe, 20 micrometers by 20 micrometers by 0.05 micrometer, allows for measurements of microwave magnetic fields near devices with 20 micrometer spatial resolution. The cantilever itself consists of dielectric thin films of silicon nitride and glass to minimize the background signal produced by eddy-current heating.

Absorption of microwave energy in the Ni-Fe tip is maximized when the microwave frequency matches the FMR condition determined by an externally applied DC magnetic bias field. The resonant frequency can be adjusted by changing the bias field, whereas different orientations of the bias field can be used to sense different components of the microwave field. The probe has been used to measure vector microwave field distributions near a strip-line resonator, 500 micrometers wide, driven at 9.15 gigahertz.

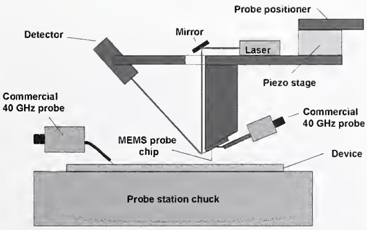
Since the absorbed power is proportional to the local microwave intensity, the sensor can be used as a quantitative, microscopic, scanning microwave power meter. The Brownian motion of the cantilever sensor fundamentally limits its ultimate sensitivity, which in turn limits the lateral resolution.

■ **Microwave Probe Station** — In a collaboration with the Radio-Frequency Technology Division, the Optoelectronics Division, and the Materials Science and Engineering Laboratory, we are developing a microwave probe station tailored to testing micromachined probe tips. Several other probes are being considered, including an all-dielectric calorimetric probe, optical probes, magnetoresistive probes, and carbon nanotubes. The instrument is a combination of high-bandwidth



Prototype AFM microwave probe station.

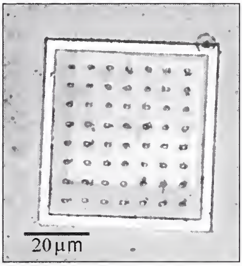
microwave probe station and high-resolution AFM that will allow "drop-in" testing of micromachined probes with the appropriate form factor.



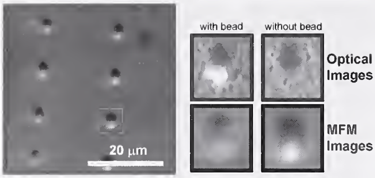
Concept for a "drop-in" probe station for testing micromachined microwave probes used for testing integrated circuits at 40 gigahertz.

Single-Molecule Manipulation and Measurement

We are adapting an ultra-sensitive atomic-force molecular puller for single-molecule measurements. The puller is mounted onto the stage of a fluorescence microscope for simultaneous force and optical measurements. The instrument will be used to characterize the motion of magnetic beads that are attached to biomolecules. Forces introduced by the local fields from a scanning MFM tip will be used to manipulate and move the beads between microfabricated magnetic traps patterned on thin membranes. The beads consist of polystyrene and magnetite and are chemically compatible with antigens for attaching DNA, RNA or proteins. We are developing magnetic beads and magnetic nanotraps for different applications, including single-molecule sequencing, sorting, and structure/function measurements. We have obtained fluo-



Microfabricated Ni-Fe magnetic dots for trapping biomagnetic beads. The dots are suspended on a silicon nitride membrane, 1 micrometer thick, stretched over a micromachined Si frame.



Magnetic force microscopy images of the top (air) surface of an array of bead traps. The presence of a biomagnetic bead in the trap removes the bright spot in the MFM image. Corresponding fluorescence microscope images indicate the location of trapped magnetic beads that have been coated with fluorescent dye molecules.

rescence and magnetic images for beads trapped in fluid cells microfabricated at NIST. The movement of beads between traps has been accomplished by applying external fields, and the Brownian motion of the beads near the trap is being used to estimate the force constants of the trap.

Recent Publications

J. Moreland, "Micromechanical Instruments for Ferromagnetic Measurements," invited, J. Phys. D, in press.

M.D. Chabot and J.M. Moreland, "Micron-Scale Magnetometry of Thin Magnetic Films Using Ultra-Sensitive Microcantilevers," J. Appl. Phys., in press.

J. Moreland, J.A. Beall, and S.E. Russek, "Resonating Torque Microbalance for *In Situ* Measurements of Ferromagnetic Films," J. Magn. Magn. Mater. **242-248**, 1157-1159 (April 2002).

J. Moreland and T.J. Hubbard, " High Q Resonating Cantilevers for *In Situ* Measurements of Ferromagnetic Films," Proc. 2001 IEEE Microelectromechanical Systems Conference (Berkeley), pp. 36-39, 2002.

J. Moreland, A. Jander, J.A. Beall, P. Kabos, and S.E. Russek, "Micromechanical Torque Magnetometer for *In Situ* Thin-Film Measurements," IEEE Trans. Magn. **37**, 2770-2772 (July 2001).

A. Jander, J. Moreland, and P. Kabos, "Micromechanical Detectors for Local Field Measurements Based on Ferromagnetic Resonance," J. Appl. Phys. **89**, 7086-7090 (June 2001).

A. Jander, J. Moreland, and P. Kabos, "Angular Momentum and Energy Transferred Through Spin Resonance," Appl. Phys. Lett. **78**, 2348-2350 (April 2001).

J. Moreland, P. Kabos, A. Jander, M. Löhndorf, R. McMichael, and C.-G. Lee, "Micromechanical Detectors for Ferromagnetic Resonance Spectroscopy," Proc. SPIE 4176: Micromachined Devices and Components VI, Eric Peters and Oliver Paul, eds., 84-95 (September 2000).

J. Moreland, M. Löhndorf, P. Kabos, and R.D. McMichael, "Ferromagnetic Resonance Spectroscopy with a Micromechanical Calorimeter Sensor," Rev. Sci. Instrum. **71**, 3099-3103 (August 2000).

M. Löhndorf, J. Moreland, P. Kabos, and N.D. Rizzo, "Microcantilever Torque Magnetometry of Thin Magnetic Films," J. Appl. Phys. **87**, 5995-5997 (May 2000).

M. Löhndorf, J. Moreland, and P. Kabos, "Ferromagnetic Resonance Detection with a Torsion-Mode Atomic-Force Microscope," Appl. Phys. Lett. **76**, 1176-1178 (February 2000).

Magnetic Thin Films and Devices

Goals

This project develops measurements and standards for the magnetic data storage and magneto-electronics industries. These measurements and standards assist industry in the development of magnetic thin-film materials and devices required for advanced magnetic recording systems, magnetic solid-state memories, magnetic sensors, and magnetic microwave devices. The emphasis is on the performance of nanoscale devices, consisting of multilayer and multicomponent thin-film systems, operating at microwave frequencies. Project members have successfully devised better methods to measure and control the dynamical properties of magnetic devices operating in the gigahertz regime. They have fabricated magnetic nanostructures to measure new spin-dependent transport phenomena and to determine the resolution of magnetic imaging systems. In addition, the project is developing new combinatorial materials techniques for magnetic thin films and new types of on-wafer magnetic metrology. Long-term goals include the development of metrology for advanced magnetic data storage on the nanometer size scale, metrology for emerging spin-electronics technologies, and novel electron spin resonance techniques (down to the single-spin limit).

Customer Needs

The data storage and magneto-electronics industries are pushing toward smaller and faster technologies that require sub-micrometer magnetic structures to operate in the gigahertz regime. New techniques are required to characterize the magnetic structure on nanometer size scales and over a wide range of time scales varying from picoseconds to years. For example, the response of a 100 nanometer magnetic device may be determined by a 5 nanometer region that is undergoing thermal fluctuations at frequencies of 1 hertz to 10 gigahertz. These fluctuations give rise to noise, nonideal sensor response, and long-term memory loss. Further, new calibration artifacts, such as magnetic imaging reference standards, are required to help characterize metrology tools that will be needed to develop nanoscale magnetic data storage technologies.

Stephen Russek, Bill Rippard, Brant Cage, and Shehzaad Kaka in the magnetic-film deposition laboratory.

Magnetic thin-film systems have become increasingly complicated, often containing quaternary alloys or multilayer systems with up to 12 layers and 20 elements. Fabrication of these multilayer systems requires atomic-level control of the layers. New techniques are required to characterize these multilayer structures *in situ,* while the structures are being grown. New *ex-situ* measurement techniques are required to efficiently and systematically characterize the magnetic, electronic, and mechanical properties of these advanced thin-film systems. In particular, new metrological systems are required that will be capable of making on-wafer measurements on a large number of sites over large regions of parameter space.

Finally, advances in technology are dependent on the discovery and characterization of new effects, such as giant magnetoresistance **(GMR)** and spin-dependent tunneling. A detailed understanding of spin-dependent transport is required to optimize these effects and to discover new phenomena that will lead to new device concepts. New effects, such as spin-momentum transfer and coherent spin transport in semiconductor devices, may lead to new classes of devices that will be useful in data storage, computation, and communications applications. The study of molecular nanomagnets may lead to data storage on the nanometer scale and to a better understanding of the fundamental limits of magnetic data storage.

Technical Strategy

We are developing several new techniques to address the needs of U.S. industries that require characterization of magnetic thin films and device structures on nanometer-size scales and gigahertz frequencies.

Device Magnetodynamics and Noise

We have fabricated test structures that allow the characterization of small magnetic devices at fre-

Project Leader:
Stephen Russek

Staff-Years (FY 2002):
1 professional
2 research associates
2 graduate students

quencies up to 10 gigahertz. The response of submicrometer magnetic devices, such as spin-valves, magnetic tunnel junctions, and GMR devices with current perpendicular to the plane **(CPP)**, have been characterized both in the linear-response and the nonlinear switching regimes. The linear-response regime is used for magnetic recording read sensors and high-speed isolators, whereas the switching regime is used for writing or storing data in magnetic random-access memory **(MRAM)** devices. We measured the sensors using microwave excitation fields and field pulses with durations down to 100 picoseconds. MRAM devices have been switched with field pulses down to 200 picoseconds. We compared measured data to numerical simulations of the device dynamics to determine the ability of current theory and modeling to predict the behavior of magnetic devices. We developed new techniques to control and optimize the dynamic response of magnetic devices. These include the engineering of magnetic damping using rare-earth doping and precessional switching, which controls switching using the timing of the pulses rather than pulse amplitude.

We are developing new techniques to measure the high-frequency noise and the effects of thermal fluctuations in small magnetic structures. Understanding the detailed effects of thermal magnetization fluctuations will be critical in determining the fundamental limit to the size of magnetic sensors, magnetic data bits, and MRAM elements. High-frequency noise has been measured in our fabricated structures and in commercial read heads. High-frequency noise spectroscopy directly measures the dynamical mode structure in small magnetic devices. Devices with dimensions of 200 nanometers have been measured and the technique can be extended to measure the dynamical modes in structures with dimensions down to 20 nanometers. Further, the stochastic motion of the magnetization during a thermally activated switching process can be directly measured and can lead to a better understanding of the long-time stability of high-density magnetic memory elements.

DELIVERABLES:

Measure the high-frequency response of magnetic layers in GMR devices separately and in combination to assess interaction effects on device dynamics. Measure response of GMR devices to high-speed current pulses. Measure thermal relaxation and switching of exchange bias direction. (FY 2003)

Develop a low-noise measurement environment for high-precision noise measurements of GMR sensors over the frequency range 0.1 hertz to 20 gigahertz. Measure noise in electron-beam-lithographed GMR devices. Develop methods to characterize high-frequency noise and high-frequency response of commercial recording heads. (FY 2003)

Characterize commercial recording heads as microwave field sensors. Fabricate high-frequency GMR sensors on cantilevers for use on a universal test bed. (FY 2003)

Fabricate a magnetic device with dimensions less than 50 nanometers and characterize the fluctuations as they approach the superparamagnetic transition. (FY 2004)

Spin Electronics

We are exploring new physical effects to create the foundation to develop entirely new technologies relying on spin-dependent transport at the quantum level. We are investigating the use of spin-momentum transfer **(SMT)** to induce a dynamical response for microwave and high-speed signal processing systems. We are investigating methods of measuring small numbers of spins in semiconductor devices and spin traps. Developing this metrology will be essential to the development of methods to control and manipulate small numbers of spins in a spin circuit.

DELIVERABLES:

Optimize the design and fabrication of sub-100 nanometer CPP SMT devices. Determine the presence of and investigate SMT-induced dynamics in small nanostructures. (FY 2003)

Measure spin transport in GaAs two-dimensional electron gas **(2-DEG)** samples. Measure electron-spin resonance **(ESR)** in 2-DEG sheet films using electrical detection. Fabricate spin field-effect transistor **(Spin FET)** device and measure ESR. (FY 2003)

Complete the design and fabrication of a Spin FET with ferromagnetic injectors. Demonstrate a voltage-tunable spin-based oscillator. (FY 2004)

Combinatorial Materials, Meta-Materials, and On-Wafer Metrology

We are developing combinatorial materials techniques to assist industry in the development and characterization of complicated magnetic thin-film systems. Combinatorial materials techniques involve the fabrication of libraries of materials with a systematic variation of materials properties, such as composition and growth temperature. In addition to fabrication of libraries of materials, the combinatorial process involves the development of high-throughput on-wafer metrologies that can systematically characterize the libraries and scan for desirable materials properties.

DELIVERABLES:

Assist a contractor in the development of on-wafer magnetic characterization system. (FY 2003)

Characterize magnetic susceptibility and microstructure in nanostructured magnetic materials. (FY 2003)

Install an on-wafer magnetic metrology system capable of measuring local magnetic, magneto-transport and magnetostriction properties. (FY 2004)

In-Situ Magnetoconductance and Magnetometry

We are developing new techniques to measure the electronic and magnetic properties of magnetic thin-film systems *in situ* (as they are deposited). One such technique, *in-situ* magnetoconductance measurements, can determine the effects of surfaces and interfaces on spin-dependent transport in a clear and unambiguous manner. The effects of submonolayer additions of oxygen, noble metals, and rare earths on GMR have been studied.

DELIVERABLES:

Use *in-situ* conductance measurements to determine current distribution in spin valves. Measure the effects of interface mixing on loss of moment and increased conductance in magnetic multilayers. (FY 2003)

With the Nanoprobe Imaging Project, optimize the *in-situ* magnetometer in a magnetic deposition system. (FY 2004)

Molecular Magnetism

We are developing methods to characterize the magnetic properties of molecular nanomagnets. These systems contain from 3 to 12 transition-metal atoms that form small magnets with Curie temperatures of 1 to 30 kelvins. The magnetic properties will be characterized with a magnetometer based on a superconducting quantum interference device **(SQUID)** and high-frequency ESR. The modulation of the magnetic properties by electric and magnetic fields, and adsorption onto substrates will be studied. We will investigate ways to use these molecular nanomagnets as molecular transistors.

DELIVERABLES:

Develop a compact, high-frequency ESR system to characterize molecular nanomagnets. Design and construct the cryostat and microwave components. Synthesize Mn-based nanomagnets. (FY 2003)

Demonstrate high-resolution ESR spectra at 100 gigahertz. Characterize the magnetic-field-split energy levels in molecular nanomagnets. (FY 2004)

Magnetic Imaging Reference Samples

We have fabricated magnetic nanostructures that can be used to determine the resolution and relative merits of various magnetic-imaging systems. These structures include bits recorded on commercial media, small Co-Pt nanostructures fabricated by electron-beam lithography, and small structures fabricated by focused-ion-beam techniques. The magnetic structures must have stable, well characterized features on length scales down to 10 nanometers to allow the testing of commercial imaging systems. We are currently designing the second generation of magnetic imaging reference samples that should have repeatable magnetic structures on length scales down to 1 nanometer.

DELIVERABLES:

Design and fabricate prototypes of the second generation of magnetic imaging reference samples based on exchange-coupled multilayers. (FY 2003)

Collaborate with a company to fabricate reference samples in large quantities and distribute them to users in industry, university, and government laboratories. (FY2004)

Accomplishments

Device Magnetodynamics and Noise

■ **Precessional Switching in Magnetic Memory Devices** — A primary technical hurdle for precise control of the switching of individual magnetic memory devices has been overcome. We have been studying the dynamics of magnetization reversal in a particular type of thin-film magnetic device called a "spin valve." Spin valves can be engineered to have two stable states of electrical resistance based on the relative magnetization orientation of its ferromagnetic layers. This property has motivated a strong interest in using spin valves as recording bits in non-volatile MRAM.

Devices have submicrometer dimensions and are fabricated within a test structure that includes high-bandwidth transmission lines. One line delivers ultra-fast magnetic field pulses to the device. The other line is electrically connected to the device and carries the voltage pulse generated as the device changes state. This voltage pulse serves as a probe of the magnetization dynamics of the device.

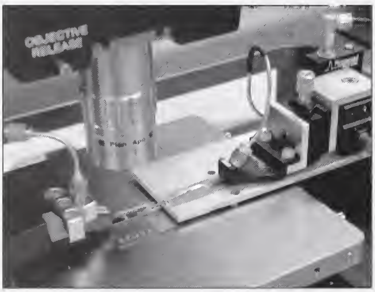
In a spin valve, only one ferromagnetic layer, the "free layer," responds to external fields. Internal magnetic fields within the device allow only two stable magnetization directions, 180 degrees apart, along an easy axis. Current implementation of

MRAM requires field pulses applied for 10 to 20 nanoseconds along either the positive or negative easy axis, depending on the desired state.

We discovered a way to switch the devices using field pulses of less than 300 picoseconds duration directed *perpendicular* to the easy axis. The magnetization is reversed due to large-angle precessional motion. For longer-duration pulses, the device does not switch because the magnetization rotates back to its initial direction while the pulse is on. Precessional switching requires only a single-polarity pulse applied perpendicular to the device easy axis, which results in a toggle operation of the magnetic state of the device. This is a simpler and more efficient bit-setting operation than using pulsed fields along the easy axis, which requires longer pulses in both directions.

Precessional switching relies on precise timing of the pulse width. The system is driven far above its quasistatic switching threshold and, therefore, the reversal is much faster than conventional switching. If the pulse is turned off precisely at the right time, when the system is in one of its low energy states, the system will switch cleanly. If, however, the pulsed field is turned off when the magnetization is far from a low-energy state, the magnetization, influenced by nonuniform internal fields, relaxes slowly and chaotically through inhomogeneous spin-wave type modes.

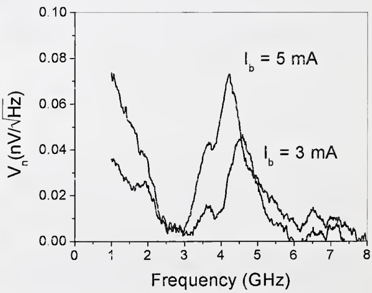
■ **Characterization of Commercial Spin Valve Heads** — We have characterized several commercial heads for use in high-frequency imaging systems. A system was built to allow high-bandwidth contact to the heads and allow mounting of the heads on the microwave probe stations in collaboration with the Radio-Frequency Technology Division. Noise measurements show that the heads have a 6 gigahertz resonant frequency and have the potential for imaging microwave circuits at frequencies up to 5 gigahertz with 200 nanometer spatial resolution. In addition to demonstrating the potential for high-bandwidth imaging, a new method of measuring the high-frequency characteristics of commercial heads was developed. The S-parameters of the heads/integrated trace assembly were measured over a range of frequencies from 100 megahertz to 10 gigahertz. This novel three-port measurement may allow precise characterization of the microwave performance of commercial head assemblies, which, at present, is not possible to do by other means.



High-frequency characterization of a commercial recording head. A high-frequency probe connecting to the spin-valve reader is on the right. A high-frequency probe driving a microwave waveguide (used to excite the read head) is on the left.

■ **Noise Peaks in Giant Magnetoresistive Spin-Valve Devices** — Characterization of noise spectra will be important in the design of the next generation of magnetic recording heads. These read heads will use submicrometer GMR spin-valve sensors, which will need to operate at rates above 1 gigahertz. We have measured the high-frequency noise in GMR spin-valve devices.

The devices, with dimensions of 0.8 micrometer by 2.0 micrometers, show high-frequency noise peaks near 2 gigahertz, corresponding to the uniform magnetic precession resonance of the devices. Several devices show multiple noise peaks, which indicates that other modes, in addition to uniform precession, are excited. The noise peaks shift with the application of a longitudinal magnetic field, similar to the shift in transverse magnetic susceptibility of the device. The noise amplitude, about 0.5 nanovolts per root hertz, indicates that the intrinsic thermal magnetic fluctuations of these devices will dominate the high-frequency noise as device

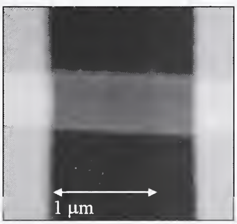


Measured high-frequency noise spectra of a 200 nanometer spin-valve read element.

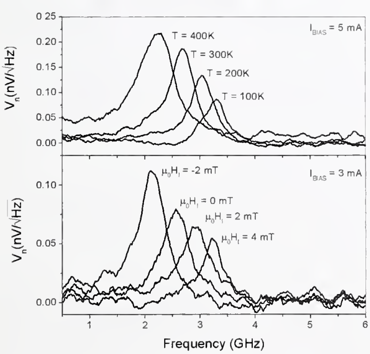
dimensions shrink. Thus, thermal noise will likely dictate the fundamental size and performance limitation of GMR read heads. The data further suggest that thermal magnetic noise spectroscopy will be a powerful technique to characterize magnetodynamics in small magnetic structures.

- **Temperature Dependence of High-Frequency Magnetic Noise in Spin-Valve Devices** — We measured the high-frequency thermal noise in micrometer-size spin-valve devices as a function of temperature from 100 to 400 kelvins. The noise spectrum yields the imaginary part of the transverse susceptibility of the spin-valve free layer, from which the ferromagnetic resonance **(FMR)** frequency and the magnetic damping parameter can be obtained.

The increase in the FMR frequency with decreasing temperature is much larger than expected from the measured increase in saturation magnetization or the large change in the coupling field between the free and fixed layers, indicating the presence of other temperature-dependent anisotropies. Structure in the high-frequency noise, beyond what is predicted by a simple single-domain model, can be resolved at various temperatures and bias fields.



AFM image of a small spin-valve element.



Voltage noise generated by the spin-valve element for several temperatures and bias fields.

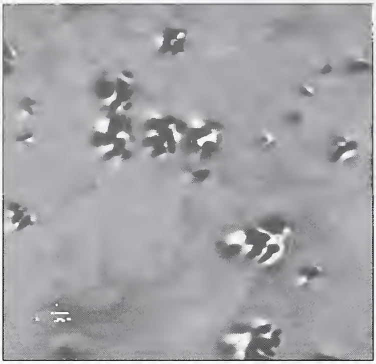
Spin Electronics

- **Methods for Spin-Induced Switching Transferred to Industry** — We developed techniques to fabricate and characterize spin-current-induced switching in CPP multilayer, nanometric devices. The measurement system to characterize these nanostructures was improved to allow measurements up to 1.4 teslas and 40 gigahertz. Devices consistently showed current-induced switching, but no microwave radiation had been detected. The techniques were transferred to a U.S. company along with a former NRC post-doctoral associate. There, the work has been extended to allow large-scale production of magnetic nanodevices with a much higher yield.

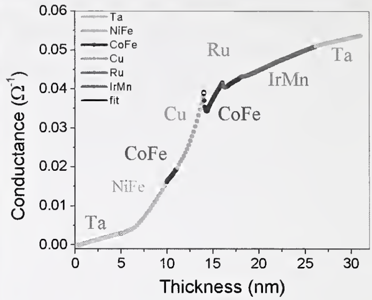
Combinatorial Materials, Metamaterials, and On-Wafer Metrology

- **Preparation of Left-Handed Metamaterials** — Masks have been designed for "left-handed" materials made from wires and split ring resonators. The system was designed to have a negative index of refraction near 10 gigahertz. (Left-handed materials can have negative electric permittivity or negative magnetic permeability.) This frequency was chosen to match the waveguide measurement systems that are available in the Radio-Frequency Technology Division. An initial wafer was fabricated with a single layer of wires and split-ring resonators. The goal is to stack 20 layers on a single wafer.

- **Tuned Magnetotransport in Nanocomposites** — In collaboration with the Mechanical Engineering Department at the University of Colorado, Boulder, we completed a study of colossal magnetoresistance **(CMR)** nanocomposites. LaCaMnO was combined with SiCN and ZrO_2 ceramics to make multiphase nanocomposites. We found that the magnetic and magnetotransport properties could be tuned by adjusting composition and processing parameters. The LaCaMnO-ZrO composites showed high magnetoresistance (greater than 90 percent), high transition temperature (280 kelvins), and much improved mechanical and high-temperature properties. Further studies were made on Fe and Co particles in a SiCN matrix. This material, which is electrically insulating and magnetically and structurally stable to above 1000 degrees Celsius, may be useful in applications that require operation at high frequency and high temperature.



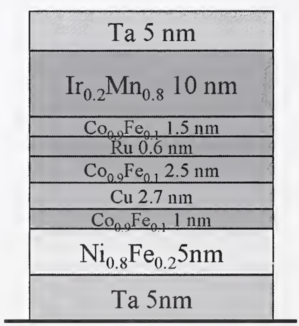
MFM image of Co particles in a SiCN matrix. The alternating white and black regions show the magnetic domain structure of the Co particles. This nano-structured magnetic material has very high thermal and mechanical stability.



In-situ conductance measurements of a spin-valve taken as it is deposited. The conductance due to each atomic layer can be resolved. The contribution of each atomic layer and interface to the conductance can be measured, which can then be used to precisely determine the current distribution.

Magnetoconductance

■ **Accurate Measurement of Current Distribution in Multilayer Spin-Valve Device** — Using *in-situ* conductance measurements, which precisely measure the conductance of each atomic layer and the effects of each interface of electron transport, we measured the current density in a spin-valve structure with greater accuracy than had been done previously. Knowledge of the current distribution in a GMR device is important for controlling the effects of the self-fields that are produced by the device currents. An understanding of the current distribution will further allow the device structures to be optimized by allowing non-magnetization-dependent current paths to be minimized.



Typical layer structure for a spin-valve device.

Recent Publications

S.E. Russek, S. Kaka, J. Nibarger, N.A. Stutzke, and S.L. Burkett, "High-Frequency Measurements of Spinvalve Films and Devices," submitted for publication.

N.A. Stutzke, S.L Burkett, and S.E. Russek, "High-Frequency Noise Measurements in Spinvalve Devices," submitted for publication.

J.M. Moreland, J.A. Beall, and S.E. Russek, "Micromechanical Instruments for Ferromagnetic Measurements," submitted for publication.

S.E. Russek, R.D. McMichael, M.J. Donahue, and S. Kaka, "High-Speed Switching and Rotational Dynamics in Small Magnetic Thin-Film Devices," invited, in *Spin Dynamics in Confined Magnetic Structures II,* B. Hillebrands and K. Ounadjela, eds., Springer-Verlag, Berlin, in press.

N.A. Stutzke, S.L. Burkett, and S.E. Russek, "Temperature and Field Dependence of High-Frequency Magnetic Noise in Spinvalve Devices," Appl. Phys. Lett., in press.

F.B. Mancoff and S.E. Russek, "Spin-Current-Induced Magnetotransport in Co-Cu-Co Nanostructures," IEEE Trans. Magn. **38**, 2853-2855 (September 2002).

S. Kaka and S.E. Russek, "Precessional Switching of Submicrometer Spin Valves," Appl. Phys. Lett. **80**, 2958-2960 (April 2002).

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R.D. McMichael, D.J. Twisselman, J.E. Bonevitch, P.J. Chen, W.F. Egelhoff, and S.E. Russek, "Ferromagnetic Resonance Mode Interactions in Periodically Perturbed Films," J. Appl. Phys. **91**, 8647-8649 (May 2002).

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J. Moreland, A. Jander, J.A. Beall, P. Kabos, and S.E. Russek, "Micromechanical Torque Magnetometer for *In Situ* Thin-film Measurements," IEEE Trans. Magn. **37**, 2770-2772 (July 2001).

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S.E. Russek and W.E. Bailey, "Magnetic Domain Structure and Imaging of Co-Pt Multilayer Thin-Film Nanostructures," IEEE Trans. Magn. **36**, 2990-2992 (September 2000).

P. Kabos, S. Kaka, S.E. Russek, and T.J. Silva, "Metastable States in Large Angle Magnetization Rotations," IEEE Trans. Magn. **36**, 3050-3052 (September 2000).

S.E. Russek, S. Kaka, and M.J. Donahue, "High-Speed Dynamics, Damping, and Relaxation Times in Submicrometer Spin-Valve Devices," J. Appl. Phys. **87**, 7070-7072 (May 2000).

S. Kaka and S. Russek, "Switching in Spin-Valve Devices in Response to Subnanosecond Longitudinal Field Pulses," J. Appl. Phys. **87**, 6391-6393 (May 2000).

Standards for Superconductor Characterization

Project Leader:
Loren Goodrich

Staff-Years (FY 2002):
1 professional
1 technician

Goals

This project develops standard measurement techniques for critical current, residual resistivity ratio, and hysteresis loss, and provides quality assurance and reference data for commercial high-temperature and low-temperature superconductors. Applications supported include magnetic-resonance imaging, research magnets, fault-current limiters, magnetic energy storage, magnets for fusion confinement, motors, generators, transformers, transmission lines, magnets for crystal growth, high-quality-factor resonant cavities for particle accelerators, and superconducting bearings. Project members assist in the creation and management of international standards through the International Electrotechnical Commission for superconductor characterization covering all commercial applications, including electronics. The project is currently focusing on measurements of variable-temperature critical current, residual resistivity ratio, magnetic hysteresis loss, critical current of marginally stable superconductors, and the irreversible effects of changes in magnetic field and temperature on critical current.

Customer Needs

We serve the U.S. superconductor industry, which consists of many small companies, in the development of new metrology and standards. We participate in projects sponsored by other government agencies that involve industry, universities, and national laboratories.

The potential impact of superconductivity on electric-power systems makes this technology especially important. We focus on (1) developing new metrology needed for evolving, large-scale superconductors, (2) participating in interlaboratory comparisons needed to verify techniques and systems used by U.S. industry, and (3) developing international standards for superconductivity needed for fair and open competition and improved communication.

Loren Goodrich (center) with Jolene Splett and Dom Vecchia (Statistical Engineering Division) discussing the statistical analysis of residual resistivity ratio of high-purity Nb specimens.

Technical Strategy

International Standards

With each significant advance in superconductor technology, new procedures, interlaboratory comparisons, and standards are needed. International standards for superconductivity are created through the International Electrotechnical Commission **(IEC)**, Technical Committee 90 **(TC 90)**.

DELIVERABLES:

Serve as Chairman of IEC TC 90 and as U.S. Technical Advisor to TC 90. (Ongoing)

Develop Committee Drafts and maintain International Standards from Working Groups 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11. (Ongoing)

Critical Current Measurements

One of the most important performance parameters for large-scale superconductor applications is the critical current. Critical current is difficult to measure correctly and accurately; thus, these measurements are often subject to scrutiny and debate.

The next generation of Nb_3Sn and Nb_3Al wires is pushing towards higher current density, less stabilizer, larger wire diameter, and higher magnetic fields. The latest Nb-Ti conductors are also pushing these limits. The resulting higher current required for critical-current measurements turns many minor problems into significant engineering challenges. For example, heating of the specimen, from many sources during the measurement, can cause a wire to appear to be thermally unstable.

The figure below is an illustration of the voltage-current characteristic and two criteria for critical current. Typical criteria are electric-field strength of 10 microvolts per meter and resistivity of 10^{-14} ohm-meters. An actual voltage-current characteristic for a Nb-Ti wire is also shown.

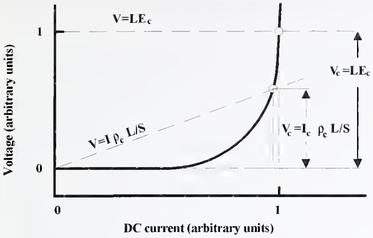
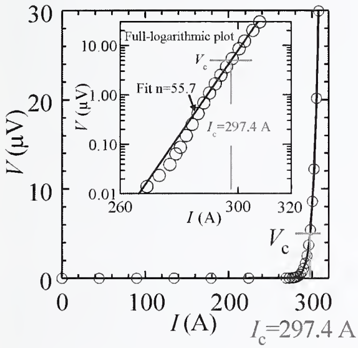


Illustration of a superconductor's voltage-current characteristic with two common criteria applied.



The voltage-current characteristic of a Nb-Ti wire in a magnetic field of 2 teslas. The critical current I_c is determined using one of the criteria. The corresponding voltage $V_c = E_c \cdot L = 5$ microvolts when $E_c = 10$ microvolts per meter and the voltage-tap separation $L = 0.5$ meters. The inset is a plot of these same data on a logarithmic scale.

This actual curve is much steeper than in the illustration. Typically, the curve can be approximated by the equation $V = V_0 (I/I_0)^n$, where V_0, I_0 and the n-value are constants. The n-value is the slope of the voltage-current curve when plotted on a logarithmic scale (see inset in the plot).

DELIVERABLES:

Determine the current limits of a variable-temperature cryostat made for coil samples. Make variable-temperature critical-current measurements on Nb_3Sn wire provided by Lawrence Livermore National Laboratory for the U.S. Department of Energy's **(DOE's)** Fusion program. (FY 2003)

Design and construct a sample-mounting fixture for marginally stable Nb_3Sn conductors with currents up to 1000 amperes. Participate in an interlaboratory comparison of critical current measurements on Nb_3Sn wires for the DOE Fusion and High Energy Physics programs. (FY 2003)

Provide variable-temperature critical-current measurements for the DOE Fusion program. (FY 2004)

Measure marginally stable Nb_3Sn samples for U.S. companies and national laboratories. (FY 2005)

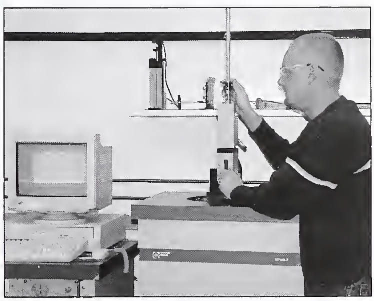
Metrology for Superconductors

We are comparing two methods of measuring the residual resistivity ratio **(RRR)** of high-purity Nb specimens. This comparison will set limits on the expected difference between the two methods and may lead to best procedures for acquiring and analyzing these data. The value of RRR is an indication of the purity and the low-temperature thermal conductivity of the Nb, and is often used as a material specification in commerce. Pure Nb in its superconducting state is used for high-quality-factor resonant cavities for particle accelerators, synchrotron light sources, and neutron sources.

Another activity of the project is the measurement of the magnetic hysteresis loss in superconductors. A few years ago we demonstrated that flux jumps could be suppressed during the measurement of hysteresis loss by immersing marginally stable Nb_3Sn conductors in liquid He. The increased thermal conduction affords dynamic stability against flux jumps, which allows AC losses to be estimated from the area of the magnetization-versus-field loop. Many measurements we do for superconductor wire manufacturers require special techniques to obtain accurate results.

DELIVERABLES:

Complete a statistical analysis on the comparison of two methods of measuring the RRR of high-purity Nb specimens. (FY 2003)



Ted Stauffer removing an AC loss sample from the SQUID magnetometer.

Provide RRR measurements for U.S. companies and national laboratories. (Ongoing)

Measure AC losses for U.S. companies and national laboratories. (Ongoing)

Accomplishments

International Standards

■ **New IEC Superconductivity Standards**—New international standards on superconductivity were recently published by IEC TC 90. The documents are:

- IEC 61788-4 Superconductivity – Part 4: Residual resistance ratio measurement – Residual resistance ratio of Nb-Ti composite superconductors
- IEC 61788-7 Superconductivity – Part 7: Electronic characteristic measurements – Surface resistance of superconductors at microwave frequencies
- IEC 61788-10 Superconductivity – Part 10: Critical temperature measurement – Critical temperature of Nb-Ti, Nb_3Sn, and Bi-system oxide composite superconductors by a resistance method
- IEC 61788-12 Superconductivity – Part 12: Matrix to superconductor volume ratio measurement – Copper to non-copper volume ratio of Nb_3Sn composite superconducting wires

We worked extensively on these documents and helped resolve many difficulties encountered during the development process. The standard on surface resistance of superconductors at microwave frequencies is the first IEC standard for electronic applications of superconductivity. This brings to 10 the number of IEC TC 90 published standards. Currently, 4 more documents are at various stages of development within TC 90.

TC 90 Working Groups and Status		
1	Terms and definitions (301 terms)	IS
2	Critical current measurement of Cu/Nb-Ti	IS
3	Critical current measurement of Bi-based superconductors	IS
4	Residual resistivity ratio measurement	IS & CDV
5	Room temperature tensile test	IS
6	Matrix composite ratio measurement	two ISs
7	Critical current measurement of Nb_3Sn	IS
8	Electronic characteristic measurements	IS
9	AC loss measurement	two CDVs
10	Trapped flux density measurements of oxides	CD
11	Critical temperature measurement	IS

Document stages: Working Draft (WD), Committee Draft (CD), Committee Draft for Voting (CDV), Final Draft International Standard (FDIS), International Standard (IS).

IEC Technical Committee 90	
Secretariat	Japan
Chairman	L. F. Goodrich
Secretary	K. Sato
Participating Countries	13
Observing Countries	15

Critical Current Measurements

■ **Critical-Current of Nb-Ti** — We continue to provide measurements of critical current of Cu/Nb-Ti samples for U.S. wire manufacturers. The current or magnetic field requirements are occasionally beyond their measurement capabilities. One recent sample was an Al-clad Cu/Nb-Ti wire where we had to make a difficult low-resistance solder connection to the Al. Another difficult sample had a wire diameter of only 1.9 millimeters and carried more than 900 amperes in a magnetic field of 9 teslas.

■ **Magnetoresistance Correction for Resistance Thermometers** — We constructed and used a new cryostat to determine the magnetoresistance correction for eight resistance thermometers as a function of magnetic field (0 to 12 teslas) and at several temperatures (4, 5, 6, 7, 8, 10, 12, 14, 16, 18, 20, 25, 30, and 35 kelvins). These corrections will be used in our future variable-temperature critical-current measurements where we use three or four thermometers simultaneously. The literature on magnetoresistance corrections indicated a wide range of possible corrections (as large as 0.15 kelvins at 12 teslas) for individual thermometers, especially in the temperature range from 4 to 10 kelvins. Thus, we needed to determine the correction for our individual thermometers and reduced the temperature uncertainty due to magnetoresistance to about 0.01 kelvins. As expected, we found differences among the thermometers, although thermometers from the same batch seemed to have very similar magnetoresistance. The main differences were the maximum value of magnetoresistance and the temperature at which the maximum occurred. The magnitude varied by a factor of 2 for different thermometers. In some cases the maximum effect was at 5 kelvins and in other cases the maximum effect was at 8 kelvins.

■ **Critical-Current of Bi-Sr-Ca-Cu-O films** — We made critical current measurements on two $Bi_2Sr_2CaCu_2O$ **(Bi-2212)** thin-film samples for researchers at a national laboratory. Our transport results were lower by a factor of 10 than they expected based on their magnetization measurements. This prompted them to make a microstructural analysis, which showed the presence of voids that explained the difference between the magnetization and current-transport measurements. Since most applications require a transport current, this result confirmed that periodic verification of current transport is worth the extra difficulty.

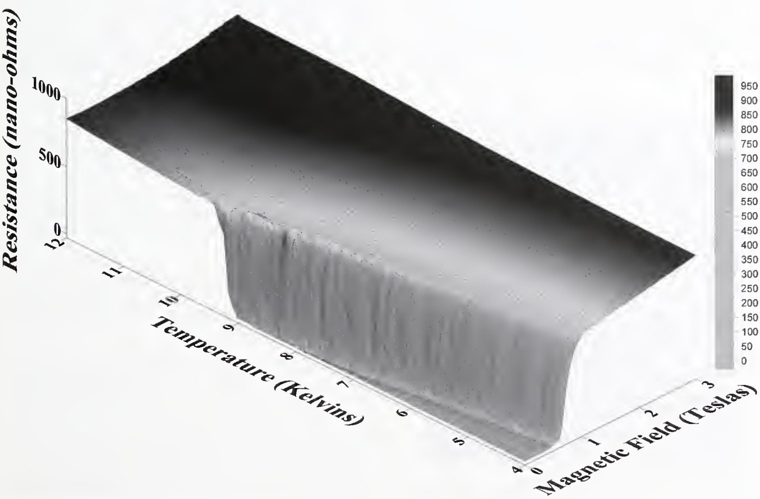
Metrology for Superconductors

■ **Critical-Current of Marginally Stable Nb_3Sn** — We recommended that simple measurements be made that would show that critical-current density measured at another laboratory was too high by a factor of about 6. We based this recommendation on our 1995 paper ("Anomalous Switching Phenomenon in Critical-Current Measurements when Using Conductive Mandrels," *IEEE Trans. Appl. Supercond.* **5**, 3442-3444) in which we showed that a subtle effect creates misleading results. The researchers made the additional measurements, verified our explanation, and presented the results at the 2002 Applied Superconductivity Conference.

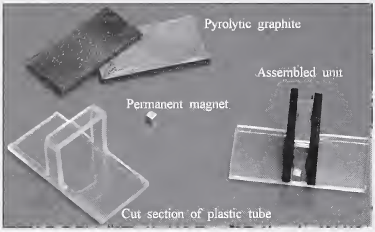
Two common myths about critical-current measurements are that the highest measured value is correct and that the repeatable value is correct. The study supports our suggestion that the end-to-end sample voltage is an important diagnostic, especially when measuring marginally-stable conductors.

■ **Residual Resistivity Ratio Measurements of High-Purity Nb** — We compared two methods of measuring the RRR of high-purity Nb and achieved agreement within 6 percent. The RRR is typically defined as the ratio of the electrical resistivities or resistances measured at 273 kelvins and 4.2 kelvins (the boiling point of helium at standard atmospheric pressure). However, pure Nb is superconducting at 4.2 kelvins, so the low-temperature resistance is defined as the resistance in the normal (nonsuperconducting) state extrapolated to 4.2 kelvins and zero magnetic field.

The two methods to obtain this extrapolated normal-state resistance are (1) measure the normal-state resistance as a function of field at 4.2 kelvins and extrapolate to zero field (field extrapolation), or (2) measure the normal-state resistance as a function of temperature in zero field and extrapolate to 4.2 kelvins (temperature extrapolation). Both methods require the precise measurement of resistance as small as 0.5 micro-ohms on a specimen that resists wetting by solder. Both methods have their difficulties and typically would be performed with different experimental apparatus. In our experiment we can make both types of measurements during a single sequence with one apparatus to directly compare methods on a given specimen.



Three-dimensional resistance surface of a pure-Nb specimen.



Components and assembled unit for the magnetic levitation demonstration.

The resistance surface as a function of temperature and magnetic field is shown above. When the combination of field and temperature are low enough, the sample is in the superconducting state and the resistance is zero. The transition from superconducting to normal state occurs at lower magnetic fields as the temperature is increased. For temperatures above 9.4 or 9.5 kelvins, the sample is normal at zero magnetic field. The surface was generated with measurements of resistance R versus temperature T at zero magnetic field H and measurements of R versus H at various T.

Outreach

■ **Demonstration Experiments** — We hosted a high school physics teacher under the Practical Hands-On Application to Science Education **(PHASE)** program during the summer of 2002 to develop and construct demonstrations in superconductivity and magnetism for outreach programs. He constructed multiple kits of five different demonstrations. A set of instructions was written for the two superconductivity demonstrations (magnetic bearing and levitated train) that will be used by NIST staff and local science teachers through the Career Awareness and Resource Education **(CARE)** program. Two of the magnetism demonstrations were detailed in a paper to be published in *The Physics Teacher*. One illustrated the diamagnetic properties of water and the other demonstrated diamagnetically stabilized magnetic levitation.

Teacher Chris Conery demonstrating diamagnetically stabilized levitation for his high school class.

Standards Committees

■ Loren Goodrich is the Chairman of IEC TC 90, the U.S. Technical Advisor to TC 90, the Convener of Working Group 2 (WG2) in TC 90, the primary U.S. Expert to WG4, WG5, WG6 and WG11, and the secondary U.S. Expert to WG1, WG3, and WG7.

■ Ted Stauffer is Administrator of the U.S. Technical Advisory Group to TC 90.

Recent Publications

C. Conery, L.F. Goodrich, and T.C. Stauffer, "More Diamagnetism Demonstrations," Physics Teacher **41**, 74-75 (February 2003).

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L.F. Goodrich, IEC/TC 90, "Superconductivity – Part 3: Critical Current Measurement – DC Critical Current of Ag-sheathed Bi-2212 and Bi-2223 Oxide Superconductors," International Electrotechnical Commission International Standard IEC 61788-3 (December 2000).

L.F. Goodrich, IEC/TC 90, "Superconductivity – Part 5: Matrix to Superconductor Volume Ratio Measurement – Copper to Superconductor Volume Ratio of Cu/Nb-Ti Composite Superconductors," International Electrotechnical Commission International Standard IEC 61788-5 (December 2000).

L.F. Goodrich, IEC/TC 90, "Superconductivity – Part 6: Mechanical Properties Measurement – Room Temperature Tensile Test of Cu/Nb-Ti Composite Superconductors," International Electrotechnical Commission International Standard IEC 61788-6 (December 2000).

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Superconductor Electromagnetic Measurements

Project Leader:
Jack Ekin

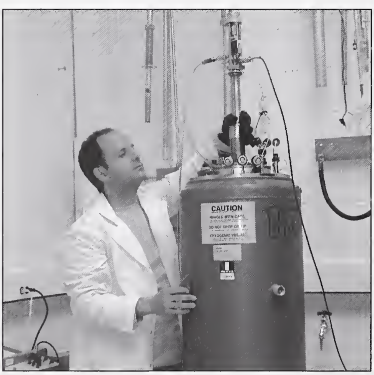
Staff-Years (FY 2002):
1 professional
1 technician
1 research associate

Goals

This project specializes in measurements of the effect of mechanical strain on superconductor properties, such as critical-current density, for applications in magnetics, power transmission, and electronics. Recent research has produced the first electromechanical data for the new class of high-temperature coated conductors, one of the few new technologies expected to have an impact on the large electric power industry and the next generation of accelerators for high-energy physics. The Strain Scaling Law, previously developed by the project for predicting the axial-strain response of superconductors in high magnetic fields, is now being generalized to three-dimensional stresses for use in finite-element design of magnet structures. Recent research also includes extending the high-magnetic-field limits of electromechanical measurements for development of 23.5 tesla nuclear-magnetic-resonance spectrometers operating at 1 gigahertz. The project's research, which previously led to the first four patents on contacts for high-temperature superconductors, is being broadened to develop electrical contacts with ultra-low interface resistivity for coated high-temperature superconductors.

Customer Needs

The project serves industry primarily in two areas. First is the need to develop a reliable measurement capability in the severe environment of superconductor applications: low temperature, high magnetic field, and high stress. The data are being used, for example, in the design of superconducting magnets for the magnetic-resonance imaging industry, which provides invaluable medical data for health care, and contributes 2 billion dollars per year to the U.S. economy.



Najib Cheggour preparing to measure electromechanical properties of superconductor tape.

The second area is to provide data and feedback to industry for the development of high-performance superconductors. This is especially exciting because of the recent deregulation of the electric power utilities and the attendant large effort being devoted to developing reliable superconductors for power-conditioning and enhanced power-transmission capability. We have received numerous requests, from both industry and government agencies, for reliable electromechanical data to help guide their efforts in research and development in this critical growth period.

The recent success of the second generation of high-temperature superconductors has brought with it new measurement problems in handling these brittle conductors. We have the expertise and equipment to address these problems.

Technical Strategy

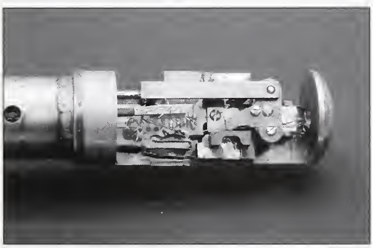
Our project has a long history of unique measurement service in the specialized area of electromechanical metrology. Significant emphasis is placed on an integrated approach. We provide industry with first measurements of new materials, specializing in cost-effective testing at currents less than 1000 amperes. Consultation is also provided to industry on developing their own measurements for routine testing. We also provide consultations on metrology to the magnet industry to predict and test the performance of very large cables with capacities on the order of 10 000 amperes, based on our tests at smaller scale. In short, our strategy has consistently been to sustain a small, well connected team approach with industry.

Electromechanical Measurements of High-Temperature Superconductors

We have developed an array of specialized measurement systems to test the effects of mechanical stresses on the electrical performance of superconducting materials. The objective is to simulate the operating conditions to which a superconductor will be subjected in magnet applications. In particular, since most technologically important superconductors are brittle, it is crucial to know the value of strain at which fractures occur in the superconductor. This value is referred to as the *irreversible strain*, since the damage caused by the formation of cracks is permanent. The effect of cracks is extrinsic. In contrast, below the irreversible strain, there exist an *elastic strain* regime where the effect of strain is *intrinsic* to the superconductor. In this elastic regime, the variation in the critical-current density **(J_c)** with strain, if any, is reversible and is primarily associated with changes in the superconductor's fundamental properties, such as the critical temperature **(T_c)** and the upper critical field **(H_{c2})**, as well as changes in the superconductor's microstructure due to the application of strain.

Among the measurement systems we have are apparatus for measuring the effects of axial tensile stress, the effects of transverse compressive stress, and the stress-strain characteristics. We have a unique system for determining the electromechanical properties of reinforced superconducting composite coils. Our electromechanical test capability for superconductors is one of the few of its kind in the world, and the only one providing specialized measurements for U.S. superconductor manufacturers.

These measurements are an important element of our ongoing work with the U.S. Department of Energy **(DOE)**. The DOE Office of High Energy Physics sponsors our research on electromechanical properties of candidate superconductors for particle-accelerator magnets. These materials include low-temperature superconductors (Nb_3Sn and Nb_3Al), and high-temperature superconductors — Bi-Sr-Ca-Cu-O **(BSCCO)** and Y-Ba-Cu-O **(YBCO)** — including conductors made on rolling-assisted, biaxially textured substrates **(RABiTS)** and conductors made by ion-beam-assisted deposition **(IBAD)**. The purpose of the database produced from these measurements is to allow the magnet industry to design reliable superconducting magnet systems.



Measurement probe for J_c as a function of axial tensile strain.

Some of our research is sponsored in part by the DOE Office of Energy Efficiency and Renewable Energy. Here, we focus on high-temperature superconductors for power applications, including transformers, power-conditioning systems, motors and generators, magnetic energy storage, and transmission lines. In all these applications, the electromechanical properties of these inherently brittle materials play an important role in determining their successful utilization.

DELIVERABLES:

Measure the stress-strain characteristics of nominal-size high-quality substrates for RABiTS and IBAD conductors at room temperature, 76 kelvins, and 4 kelvins. (FY 2003)

Measure the dependence of J_c on *transverse stress* in Ni-alloy YBCO coated RABiTS and IBAD conductors having different substrate compositions. Study the microstructure after transverse stress testing to evaluate failure modes. (FY 2003)

Measure the dependence of J_c on *axial tensile strain* in YBCO coated pure-Ni and Ni-alloy RABiTS samples and IBAD conductors, having various YBCO film thickness and different substrate materials. Determine the microstructural crack patterns of the samples after axial tensile strain testing to evaluate failure modes. (FY 2003)

Measure the dependence of J_c on *axial tensile strain* in new high-current Bi-2212 wires, multifilamentary Bi-2212 wires, and three-ply Bi-2223 conductors. (FY 2003)

Measure the dependence of J_c on *transverse stress* and fatigue cycles in new three-ply Bi-2223 conductors. (FY 2003)

Measure the dependence of J_c on *axial tensile strain* and on *transverse stress* in recently developed MgB_2 tapes and wires. (FY 2004)

Electromechanical Measurements of Low-Temperature Superconductors

In the area of low-temperature superconductors, we have embarked on a fundamental program to generalize the Strain Scaling Law **(SSL)**, a magnet design relationship we discovered two decades ago. Since then, the SSL has been used in the structural design of most large magnets based on superconductors with the A-15 crystal structure. However, this relationship is a one-dimensional law, whereas magnet design is three-dimensional. Current practice is to generalize the SSL by assuming that distortional strain, rather than hydrostatic strain, dominates the effect. Recent measurements in our laboratory suggest, however, that this assumption is invalid. We are now developing a measurement system to carefully determine the three-dimensional strain effects in A-15 superconductors. The importance of these measurements for very large accelerator magnets is considerable.

DELIVERABLES:

Complete the data set of *transverse stress* effects in two series of Nb_3Sn tape conductors. Measure the effect of *axial strain* on J_c. Test for a correlation between the magnitude of the intrinsic (reversible) strain effect and phonon anharmonicity in superconductor crystal structures. (FY 2003)

Measure the effect of axial strain on J_c of Nb_3Sn wires developed for a new generation of accelerator magnets. (FY 2003)

Measure the Young's modulus in Nb_3Sn tape conductors and relate stress and strain for developing the multidimensional SSL. Complete the data set of *axial strain* measurements in two series of Nb_3Sn tape conductors. Combine the two orthogonal sets of data into a unified model. (FY 2004)

Conclude the study of the correlation of uniaxial strain effects with phonon anharmonicity in the A-15 superconductors. Determine the hydrostatic (volume-change) and deviatoric (shape-change) coefficients to generalize the SSL from one to three dimensions. Apply the model to finite-element strain designs of large superconducting magnet systems. (FY 2004)

Textbook on Cryogenic Measurement Apparatus and Methods

We are in the process of finishing a textbook on experimental techniques for cryogenic measurements. This book covers the design of cryogenic measurement probes, and provides cryogenic materials data in the appendices for their construction. Topics include thermal techniques for designing a cryogenic apparatus, selecting materials appropriate for such apparatus, how to make high-quality electrical contacts to a superconductor, and how to make reliable critical-current measurements. The textbook is written for beginning graduate students, industry measurement engineers, and materials scientists interested in learning how to design successful low-temperature measurement systems. The appendices are written for experts in the field of cryogenic measurements and include electrical, thermal, magnetic, and mechanical properties of technical materials for cryostat construction; properties of cryogenic liquids; and temperature measurement tables and thermometer properties. These appendices aim to collect in one place many of the data essential for designing a new measurement apparatus.

DELIVERABLES:

Edit chapters on superconductor critical-current measurement techniques and analysis. Complete appendix material. Send drafts to international reviewers. (FY 2003)

Check and return publisher's proofs of the book. (FY 2004)

Accomplishments

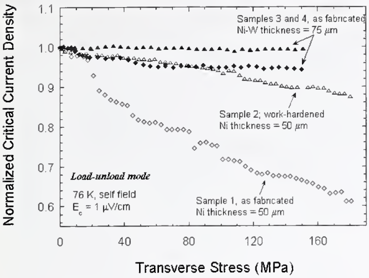
Electromechanical Measurements of High-Temperature Superconductors

■ **YBCO on Alloy Substrate Exhibits Tolerance to Compressive Stress** — One of the major challenges facing the development of an economical, practical high-temperature superconductor has been the extremely weak mechanical behavior of YBCO coated onto RABiTS. Of all the manufacturing processes, the RABiTS process is the one that is most easily scalable to fabricate industrial quantities of this promising superconductor.

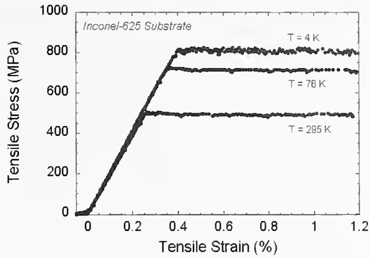
Recently, a U.S. company has produced a new RABiTS coated conductor with substrates made of Ni plus 5 atomic percent W. We completed a series of experiments using our speeialized equipment for both transverse stress and transport current to measure the electromechanical performance of this new coated superconductor.

The results are striking. The data show that, in repeated testing, J_c is degraded by only 1 to 5 percent at the benchmark stress level of 100 megapascals. This result opens the path for commercialization of RABiTS coated conduetors. Projections are that this conductor could be manufactured at about $10 per kiloampere-meter, a cost that would be competitive with copper in transformers and in other electric-utility applications, and far less expensive than Cu for increasing the capacity of underground transmission lines in urban areas.

Until now, the RABiTS process had worked only with soft, pure Ni substrates. Our earlier measurements showed that its J_c degraded by as much as 28 percent at the benchmark 100 megapascal stress level, which made it unacceptable for use as a practical conductor. Our results provide evidence that the mechanical properties of the substrate material play a dominant role in determining the response of these samples to transverse compressive stress. Another possible source for the degradation of J_c could be delamination of the ceramic layers due to



Effect of transverse stress on J_c in YBCO films on pure Ni and Ni-W alloy RABiTS. The results illustrate the benefits of work-hardening pure Ni and provide a comparison between YBCO coatings on pure Ni and Ni-W alloy substrate materials.

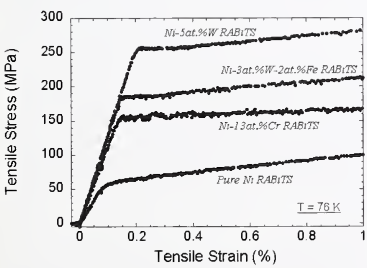


Comparison of stress-strain curves at room temperature, liquid-nitrogen temperature, and liquid-helium temperature of annealed Inconel-625 substrate material for IBAD technology.

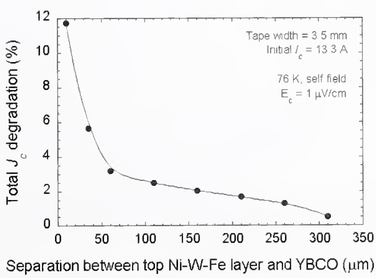
application of stress. More comprehensive data are still required to draw definitive conclusions.

■ **Mechanical Properties of Candidate Substrate Materials** — Our electromechanical testing showed a correlation between the mechanical properties of the RABiTS substrate material and the tolerance of a YBCO-coated conductor to transverse stress. In order to guide manufacturers in their selection of a suitable substrate material and in designing processing equipment for the manufacturing of the coated conductors, we characterized the mechanical properties of several substrate materials that are potential candidates both for the RABiTS and IBAD processing technologies. The tensile yield strength, Young's modulus, and proportional limit of elasticity of these materials at 295 kelvins, 76 kelvins, and 4 kelvins were tabulated and compared. This database has been generated to guide the development of the YBCO coated conductors. We will expend it as new substrate materials being developed become available.

■ **Limiting the Magnetic Substrate Effect in YBCO Coated Conductors** — We have shown that the degradation in J_c of YBCO due to the magnetic substrate effect can be significantly mitigated if a thick spacing layer is inserted between the YBCO film and the magnetic cap layer. High-temperature superconducting tapes based upon coatings of YBCO on biaxially textured, buffered, magnetic Ni-W-Fe substrates showed a degradation of 12 percent in J_c when the YBCO layer is sandwiched between two Ni-W-Fe substrates. We found that this degradation of J_c can be reduced dramatically to less than 1 percent if a 300 micrometer-thick Kapton tape is placed between the YBCO film and magnetic cap layer. Such a spacing layer could naturally be incorporated into the manufacture of YBCO coated conductors as an insulating coating on the



Comparison of stress-strain curves at 76 kelvins of pure Ni, Ni-Cr, Ni-W-Fe, and Ni-W alloy substrate materials for RABiTS technology.

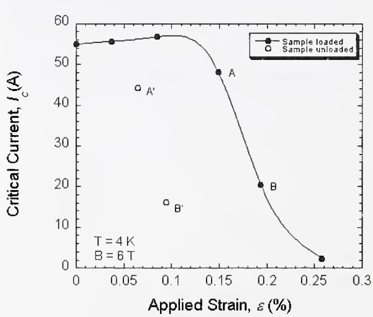


Inserting a thick, nonmagnetic spacing layer between the YBCO film and the magnetic cap layer can significantly mitigate the magnetic substrate effect.

conductors. A systematic study as a function of the thickness of the Kapton layer showed that the degradation of J_c is reduced substantially to 3 percent by a separation of just 50 micrometers.

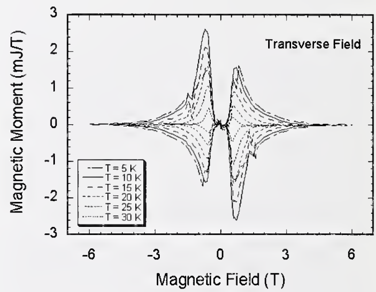
The magnetic substrate effect resulting from sandwiching YBCO between two magnetic layers may occur in some applications where the coated conductor needs to be wound or cabled. The spacing tape, which limits the magnetic interaction of the top and bottom Ni-W-Fe layers, represents an engineering solution for limiting the magnetic substrate effect in low magnetic field applications such as underground power-transmission cables. The separation layer could be made of a high conductivity material, such as Cu, to enhance the electrical and thermal stability of the cable.

- **Mechanical Tests on Magnesium Diboride** — We made a preliminary investigation of the electromechanical properties of the newly discovered MgB_2 superconductor as a function of magnetic field. A Ni-sheathed MgB_2 tape was tested as a function of axial strain in high magnetic fields. MgB_2 was found to exhibit a small reversible increase of J_c as a function of strain, driven by an intrinsic strain effect on the effective upper critical field of this material. The data indicate that the strain sensitivity of MgB_2 is significantly smaller than that of Nb_3Sn superconductor. As the applied strain is increased beyond the irreversible strain limit of the conductor, J_c shows a dramatic drop as cracks form in the superconductor due to the application of strain.



MgB_2 with a pure Ni sheath exhibits a small reversible increase in J_c as a function of strain before reaching the irreversible strain limit.

- **Loss in Magnesium Diboride Multifilamentary Wires Suppressed at Low Fields by Magnetic Shielding** — We measured the magnetization-field curves of multifilamentary MgB_2 superconductors in an Fe matrix. The magnetic measurements demonstrated that the filaments were shielded from external fields by the Fe material. The hysteresis loops, measured at different temperatures, suppressed magnetization at low fields up to about 0.3 tesla. These results suggest that the use of a magnetic material in the architecture of MgB_2 wires could be beneficial for low-field applications such as transformers.



Magnetization curves of a Fe-sheathed multifilamentary MgB_2 square wire. The filaments are shielded from external fields up to 0.3 tesla by the Fe matrix.

Electromechanical Measurements of Low-Temperature Superconductors

- **Electromechanical properties of Nb_3Sn Tapes** — We carried out measurements of the effect of strain in Nb_3Sn tapes made by chemical vapor deposition and found results that seem to contradict the deviatoric-strain model. At a field of 11 teslas and a strain of 0.26 percent, the effect of axial strain on J_c amounts to about +15 percent, whereas that of transverse compressive stress is only about –0.5 percent at 170 megapascals. This result does not support the deviatoric-strain model, which would predict an increase of J_c with transverse stress, just the opposite of the sign of the observed effect and far different from the measured magnitude. One possibility to explain the results obtained is to consider a large hydrostatic strain effect, which was previously neglected by the deviatoric-strain model.

Recent Publications

Y. Xu and J.W. Ekin, "Tunneling Characteristic and Low Frequency Noise of High-T_c Superconductor/Nobel-Metal Junctions," submitted for publication.

N. Cheggour, J.W. Ekin, C.C. Clickner, R. Feenstra, A. Goyal, M. Paranthaman, and N. Rutter, "Effect of Transverse Compressive Stress on Transport Critical Current Density of Y-Ba-Cu-O Coatings on Biaxially Textured Ni and Ni-W-Fe Substrates," Ceramic Trans., in press.

J.W. Ekin, "Superconductor Contacts," in "Handbook of Superconducting Materials," Institute of Physics, U.K., in press.

N. Cheggour, J.W. Ekin C.C. Clickner, D.T. Verebelyi, C.L.H. Thieme, R. Feenstra, A. Goyal, and M. Paranthaman, "Transverse Compressive Stress Effect in Y-Ba-Cu-O Coatings on Biaxially Textured Ni and Ni-W Substrates," IEEE Trans. Appl. Supercond., in press.

N. Cheggour, J.W. Ekin, C.C. Clickner, R. Feenstra, A. Goyal, M. Paranthaman, D.F. Lee, D.M. Kroeger, and D.K. Christen, "Transverse Compressive Stress, Fatigue, and Magnetic Substrate Effects on the Critical Current Density of Y-Ba-Cu-O Coated RABiTS Tapes," Adv. Cryo. Eng. (Materials) **48**, 461-468 (2002).

J.W. Ekin, S.L. Bray, N. Cheggour, C.C. Clickner, S.R. Foltyn, P.N. Arendt, A.A. Polyanskii, D.C. Larbalestier, and C.N. McCowan, "Transverse Stress and Fatigue Effects in Y-Ba-Cu-O Coated IBAD Tapes," IEEE Trans. Appl. Supercond. **11**, 3389-3392 (March 2001).

J.W. Ekin, "Superconductor Measurement Techniques and Cryostat Design," in Applications of Superconductivity, H. Weinstock, ed., Kluwer Academic Publishers, Dordrecht, pp. 641-658 (June 2000).

S.E. Bray, J.W. Ekin, C. Clickner, and L. Masur, "Transverse Compressive Stress Effects on the Critical Current of Bi-2223/Ag Tapes Reinforced with Pure Ag and Oxide-Dispersion-Strengthened Ag," J. Appl. Phys. **88**, 1178-1180 (July 2000).

Appendix A: Laboratory Facilities

Materials Preparation and Film Deposition

Computer-controlled, ultra-high-vacuum deposition system
Computer-controlled, ultra-high-vacuum, multi-target sputtering system with *in-situ* measurement of magnetoresistance*
Ultra-high-vacuum surface-analysis system
Laser-ablation system
Anaerobic chamber
Electron-beam deposition system
Electron-beam lithography
Optical lithography
Furnaces for preparation of micro-electromechanical systems, including boron diffusion doping, wet and dry oxidation, and low-pressure chemical-vapor deposition of polysilicon, silicon nitride, and low-temperature oxide
Deep reactive ion etcher
Critical-point dryer
Furnaces for reacting superconductors

Structural Characterization

High-resolution X-ray diffractometer
Scanning electron microscope with X-ray fluorescence
Atomic-force microscope
Scanning-tunneling microscope
Low-energy electron diffraction
Reflection high-energy electron diffraction
Angle-resolved Auger electron spectroscopy

Characterization of Magnetic Materials

Vibrating-sample magnetometer
AC susceptometer
SQUID magnetometer
Alternating-gradient force magnetometer
Induction-field looper
Time-resolved second-harmonic magneto-optic Kerr effect*
Wide-field magneto-optic microscope
Microwave pulsed-magnetic-field sources
Pulsed inductive microwave magnetometer*
Magnetic-force microscope
Magnetic-resonance force microscope*
Ferromagnetic-resonance probe microscope*
Microresonating torque magnetometer*
Spin-resolved secondary-electron emission spectroscopy*
Optical cryostat with split-pair superconducting magnet
Time-resolved magneto-optic Kerr effect with vector sensitivity*
Molecular foree puller for single-molecule measurements
Fluorescence stereo microscope

Characterization of Magnetic Devices

Local magnetoresistance scanning-probe station
Time-resolved magnetoresistance of magnetic random-access memory devices*
Variable-temperature microwave probe station
Industry-standard spin stand
Scanning magnetoresistance probe for forensic analysis of recording media*
Microwave probe station for developing micromachined high-frequency probes*

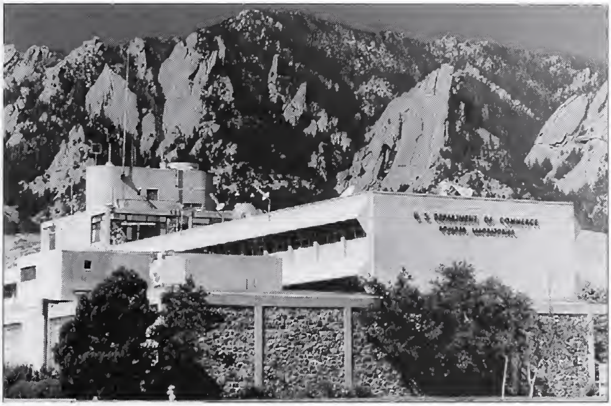
Characterization of Superconductors

Large-bore superconducting magnets up to 18.5 teslas
Measurement of critical current up to 2500 amperes*
Low-resistance (1 nano-ohm) measurements of stabilizer materials
Simulation of superconductor transport properties at room temperature*
Low-noise, 1000 ampere DC power supply with current ramp rates up to 10 000 amperes per second
High-field electromechanical measurement apparatus (axial, transverse, and hoop stress)*
Stress-strain apparatus for measurements at room temperature and cryogenic temperatures
Measurement of electrical transport and noise in superconductor interfaces
Magnetic measurement of AC losses in superconductors
Variable-temperature critical-current measurements up to 500 amperes

* Asterisks indicate that apparatus is unique or one of only a few in the world

Appendix B: Post-Doctoral Research Associateships

NIST offers post-doctoral research associateships in collaboration with the National Research Council (NRC). Research topics and associated advisors for the Magnetic Technology Division are listed below. Complete information and applications forms for all NIST NRC post-doctoral offerings are available at http://www.nas.edu/rap/ (click on "RAP SEARCH"). Contact a prospective advisor to discuss details of proposed work and the application process. If you do not find a topic that exactly matches your interest, please contact an advisor in a similar discipline. U.S. citizenship is required for NRC post-doctoral appointments.



NIST's Boulder laboratories are located adjacent to the eastern foothills of the Rocky Mountains.

High-Critical-Temperature Superconducting Measurements and Materials

Contact: Jack Ekin, 303-497-5448

We study the electrical and mechanical properties of high-T_c superconducting materials including the effects of stress on transport properties, weak-link effects, and anisotropy limitations on superconduction properties. Short-sample conductors are tested and their mechanical, magnetic-field, and electrical limits are modeled and correlated with tests on composite magnet coils. In this program, we work closely with superconductor industries to develop the new generation of coated Y-Ba-Cu-O superconductors for use in high-energy-physics accelerator magnets and electric-power utility applications.

Measurements for Low-Critical-Temperature Superconductors

Contact: Jack Ekin, 303-497-5448

An interdisciplinary study of the physical, mechanical, and electrical properties of superconducting and composites is being conducted. Experimental programs include the effect of stress and fatigue on superconducting critical parameters, electrical and/or metallurgical studies of the problems of superconductor stabilization, and characterization studies of new superconducting materials. Theoretical studies concentrate on flux pinning and the intrinsic effect of strain on the superconducting state.

Superconductor Measurements

Contact: Loren Goodrich, 303-497-3143

We develop and evaluate measurement techniques to determine the critical parameters and matrix properties of superconductors. Capabilities include variable-temperature critical-current measurement, low-noise current supplies up to 3000 amperes, high-field magnets up to 18 teslas, and voltage sensitivity to 1 nanovolt. We study conventional superconductors (NbTi and Nb_3Sn) and the newer high-transition-temperature materials. We conduct fundamental studies of the superconducting-normal transitions and the parameters that affect their accurate determination, such as current transfer, strain, or inhomogeneities in materials and fields. We develop theoretical models to interpret current redistribution and component interactions in composite superconductors.

Magnetic Measurement of Hydrogen in Batteries and Fuel Cells

Contact: Ron Goldfarb, 303-497-3650

Low-mass Zr and Mg "AB_2" alloys are candidates to replace lanthanide rare-earth alloys used in Ni/metal-hydride, solid-state-electrolyte battery cathodes in order to achieve higher gravimetric energy densities, greater number of recharge cycles, better durability and corrosion resistance, and lower cost. The utility of these alloys will depend on their hydrogen-storage capacity and rates of absorption and desorption at ambient temperature. Such materials would also have application to hydrogen storage in fuel cells. Hydrogen in Ni/metal-hydrides may be either bound or diffusible (i.e., useful in absorption/desorption). Nondestructive magnetic measurement techniques could provide a convenient tool to screen candidate alloys for their capacity to store and release diffusible hydrogen. In addition to "AB_2" alloys, measurements will be made on "AB_5" alloys such as La-Ni-Co and La-Ni-Al.

New Magnetoresistive Sensors for Medical and Other Applications

Contact: Ron Goldfarb, 303-497-3650

We invite proposals for the development and electronic implementation of low-noise, high-sensitivity, ambient-temperature, magnetoresistive field sensors for applications in security, medicine, and magnetic disk-drive read heads. Medical applications include magnetocardiography, magnetoencephalography, and *in-vivo* measurement of iron stores in the body. We have facilities for microelectronic device fabrication and testing.

Perpendicular Recording Media

Contact: Ron Goldfarb, 303-497-3650

We invite proposals to study the thermomagnetic and magnetodynamic properties of patterned and unpatterned perpendicular media for future high-density magnetic data storage. Film deposition and lithography facilities are available. University and industrial collaborators are able to provide other unconventional materials for measurement. We have a spin stand and instruments for characterization of magnetic properties and switching speeds.

Atomic-Scale Information Storage

Contact: John Moreland, 303-497-3641

We are investigating novel techniques capable of ultra-high-density information storage at atomic scales. Devices that rely on magnetic, electrostatic, morphological, or other variations in storage media approaching atomic scales are considered in response to a recognized need to shift information storage paradigms in the 21st century. Scanned probe microscopy is being used to write atomic-scale "bits" and to study the properties and fundamental recording processes in different kinds of storage media.

Magnetic Resonance Force Microscopy

Contact: John Moreland, 303-497-3641

Magnetic resonance force microscopy (MRFM) is a promising imaging technique based on the magnetic coupling between magnetic spins and an ultra-sensitive microcantilever. In principle, MRFM should have elemental identification capabilities with tenth-nanometer spatial resolution in three dimensions, representing a tremendous advancement in the field of magnetic resonance imaging (MRI). Several technical problems must be addressed before an atomic-scale apparatus of this kind can work: (1) fabrication of high-sensitivity cantilevers, (2) development of computer-based MRI imaging schemes for a scanning probe, and (3) construction of an ultra-sensitive atomic force microscope readily adaptable to cryogenic high-field operation.

Micro-Electromechanical Systems for Metrology

Contact: John Moreland, 303-497-3641

We are developing micro-electromechanical systems (MEMS) with integrated components for precision measurement purposes. Work focuses on the following goals: (1) improving the performance of fundamental standards instrumentation by developing novel detectors and more fully integrated measurement systems, (2) exploring the impact of MEMS and MEMS-based metrology on the future development of the microelectronics and data storage industries, and (3) improving the manufacturing yield with MEMS probe assemblies designed for production-line testing. Our cleanroom facility is equipped for bulk micromachining of Si and low-pressure chemical-vapor deposition of polysilicon and silicon-nitride films on sacrificial glass layers. We are interested in all aspects of research, including the design and fabrication of novel MEMS structures, as well as the testing and integration of MEMS structures into precision measurement instruments.

Nanoscale Imaging for Magnetic Technology

Contact: John Moreland, 303-497-3641

The magnetic storage industry has advanced to the stage where nanometer-scale morphological and physical properties play an important role in current and future disk-drive performance. In its many forms, scanned probe microscopy (SPM) can be used to measure roughness, device dimensions, electromagnetic field patterns, and various physical processes at nanometer scales, which provides important information about the fundamental operation and limitations of drive components. Our goal is to help tailor SPM techniques for these applications. We are investigating scanning tunneling microscopy, atomic force microscopy, magnetic force microscopy, scanning potentiometry, and scanning thermometry for their usefulness.

Single-Molecule Manipulation and Measurement

Contact: John Moreland, 303-497-3641

We are developing a nano-electromechanical system platform to contribute to new methods for single-biomolecule manipulation and measurement. Measurements to determine the structure and function of protein and DNA are currently made using large populations of molecules rather than single molecules. Researchers in biotechnology have shown that the behavior of single molecules in living systems can be different from results obtained by measuring the statistical average of large populations of molecules. The limitation in making single-molecule measurements is primarily due to the lack of measurement tools and methods that are capable of isolating, manipulating, and probing the behavior and structure of the molecules. As a result, there is a rapidly growing interest in the development and application of nanotechnology to support single-molecule measurements.

High-Frequency Characterization of Novel Thin-Film Materials

Contact: Stephen Russek, 303-497-5097

The goal of this project is to fabricate novel nano-engineered thin-film materials and measure their electromagnetic properties in the 1-100 gigahertz regime. The materials include nanostructured materials, composite ferromagnetic-ferroelectric materials, "left-handed" materials, and frequency-tunable materials. The materials can be fabricated using an ultra-high vacuum, eight-source sputtering system; a laser ablation system; and optical and e-beam lithography systems. The dielectric and magnetic properties can be engineered by patterning arrays of elements on two different length scales. Patterning on a scale comparable to the excitation wavelength — about 1 millimeter — will allow the development of artificial crystals (photonic band-gap materials) in the microwave regime. Patterning on a scale much shorter than the wavelength, 10-100 nanometers, will allow the permittivity, permeability, and conductivity to be engineered and controlled to have new functionalities. Examples of such materials engineering include light- and field-tunable exchange coupling, low-loss amorphous/nanoparticle composites, negative-permittivity negative-permeability ("left handed") systems, and ferroelectric-ferromagnetic multilayers. Measurements will be conducted on state-of-the-art, 100 gigahertz microwave test systems and cryogenic microwave probe stations.

Nanoscale Magnetic Structures

Contact: Stephen Russek, 303-497-5097

Ultra-small magnetic structures will be fabricated using e-beam and scanned probe lithographies in a variety of magnetic thin-film systems. The systems studied will include advanced longitudinal and perpendicular media, multilayer systems, and single-crystal films. The goal of this research will be to understand the physics of ultra-small magnetic structures and their implications for the limits of magnetic data storage. The switching process will be studied as a function of size, shape, and temperature to characterize thermally activated and quantum-mechanical switching mechanisms. The interaction of magnetic particles in large arrays will be studied. The magnetic structure will be characterized using magnetic force microscopy, magnetometry, and transport measurements.

Study of Spin-Dependent Electron Transport in Metals, Conducting Oxides, and Semiconductors

Contact: Stephen Russek, 303-497-5097

Spin-dependent transport is a widely used, yet poorly understood phenomenon. Giant magnetoresistive (GMR) devices and magnetic tunnel junctions (MTJ) are being developed for use in magnetic recording heads, magnetic random-access memory, and industrial magnetic sensors. The goal of this research is to develop a better fundamental understanding of spin-dependent transport in magnetic metals, normal metals, conducting oxides, and semiconductors, and through interfaces between these materials. Research involves the fabrication of novel GMR, MTJ, and magnetic semiconductor devices using a state-of-the-art, eight-source, ultra-high-vacuum (UHV) deposition system and a combination of optical, e-beam, and scanned probe lithography. Spin dependent scattering and spin-injection effects will be studied in nanoscale devices over a temperature and frequency range of 4 kelvins to 500 kelvins and DC to 40 gigahertz. Device-level measurements will be compared with spin-polarized transport measurements using an *in-situ* UHV scanning tunneling microscope.

Magnetism in Thin Films and Surfaces

Contact: David Pappas, 303-497-3374

Opportunities are available to work in a wide range of topics. Areas of interest include spin-polarized electron attenuation in solids, surface magnetic studies, magnetoresistive microscopy, high-sensitivity magnetoresistive sensors, and perpendicular magnetic recording materials.

High-Speed Magnetic Phenomena

Contact: Tom Silva, 303-497-7826

Experimental methods to determine fundamental limits to the data-transfer rate of magnetic devices are being developed. Both low-coercivity ("soft") and high-coercivity ("hard") materials are studied. Experimental techniques include electrically sampled inductive detection and time-resolved magneto-optics for the study of soft magnetic materials. Quantitative Kerr microscopy is used for the measurement of switching speed in hard magnetic materials. Extensive facilities exist, including a 20 gigahertz sampling oscilloscope, a 50 femtosecond mode-locked Ti:sapphire laser, and a digital Kerr microscope with a high-performance chilled charged-coupled-device (CCD) camera. Commercial and experimental solid-state instrumentation is used for the generation of microwave pulses. Waveguide technology is employed to deliver subnanosecond magnetic field pulses to samples. Waveguide structures are lithographically fabricated on site in a state-of-the-art cleanroom that includes mask-generation facilities. Applications are encouraged from those who have a strong experimental background in magnetism, especially high-frequency magnetic phenomena such as ferromagnetic resonance.

Nonlinear Magneto-Optics

Contact: Tom Silva, 303-497-7826

The second-harmonic magneto-optic Kerr effect (SHMOKE) is under investigation as a tool for the study of interfacial magnetism. SHMOKE shows strong sensitivity to the magnetization at optically accessible interfaces between ferromagnetic and non-ferromagnetic films, yet SHMOKE does not require exotic facilities, such as ultra-high vacuum (UHV) or synchrotron radiation. Therefore, SHMOKE shows great promise as an industrial diagnostic instrument for the optimization of giant magnetoresistive sensors and magnetic tunnel junctions, where interfacial magnetism strongly influences device performance. SHMOKE also exhibits a strong magneto-optic signal, with the magnetic contrast approaching 60 percent in some sample systems. Extensive resources for the study of SHMOKE exist, including a mode-locked 50 femtosecond Ti:sapphire laser, coincident photon detection electronics, photo-elastic modulators, lock-in amplifiers, and sample translation stages. Samples may be produced on site with a state-of-the-art, eight-source UHV sputtering system. Applicants are preferred with a strong experimental background in magnetic thin films, magnetic multilayers, magneto-optics, and/or nonlinear optics.

Spintronics

Contact: Tom Silva, 303-497-7826

This project focuses on the investigation of spin dynamics in semiconductors. Time-resolved magneto-optics is used to generate and study coherent spin dynamics in direct-bandgap semiconductors. Equipment includes a femtosecond Ti:sapphire laser system, an optical cryostat to vary temperature from 4 kelvins to 300 kelvins with a superconducting magnet capable of 8 tesla magnetic fields, and comprehensive optical polarization analysis facilities. Investigations will determine the feasibility of coherent spin diffusion from ferromagnetic contacts. Mechanisms to be studied include near-field coupling of the electromagnetic fields from the precessing spins in a nanomagnet and direct diffusion across a forward-biased Schottky junction.

Thermal Instability of Magnetic Thin Films

Contact: Tom Silva, 303-497-7826

As the grain size of thin-film magnetic recording media steadily decreases with increasing areal capacities, we are concerned that recorded information may be erased as a result of thermally activated switching of the individual grains — the so-called "superparamagnetic limit." Our goal is to understand the fundamental mechanisms that result in thermal erasure through the measurement of various phenomena, including magnetic viscosity and the time dependence of coercivity. Emphasis is placed on determining the thermal stability of media over a wide range of time scales, from those accessible with large-scale magnetometers to those that use pulsed microwave fields. The final goal is a measurement technique for the determination of data stability in media without resorting to mean-time-before-failure analysis. Extensive facilities exist, including numerous magnetometers (vibrating-sample magnetometer, alternating-gradient magnetometer, SQUID magnetometer), a transmission electron microscope for the determination of grain size, and a state-of-the-art, eight-source ultra-high-vacuum sputtering system for the preparation of samples. Applicants with a strong experimental background in magnetism — especially preparation and characterization of magnetic thin films — are encouraged to apply.

Appendix C:
Prefixes for the International System of Units (SI)

Multiplication Factor	Prefix	Symbol	Multiplication Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

Appendix D: Units for Magnetic Properties

Symbol	Quantity	Conversion from Gaussian and cgs emu to SI
Φ	magnetic flux	1 Mx $\rightarrow 10^{-8}$ Wb $= 10^{-8}$ V·s
B	magnetic flux density, magnetic induction	1 G $\rightarrow 10^{-4}$ T $= 10^{-4}$ Wb/m^2
H	magnetic field strength	1 Oe $\rightarrow 10^3/(4\pi)$ A/m
m	magnetic moment	1 erg/G = 1 emu $\rightarrow 10^{-3}$ A·m$^2 = 10^{-3}$ J/T
M	magnetization	1 erg/(G·cm^3) = 1 emu/cm$^3 \rightarrow 10^3$ A/m
$4\pi M$	magnetization	1 G $\rightarrow 10^3/(4\pi)$ A/m
σ	mass magnetization, specific magnetization	1 erg/(G·g) = 1 emu/g $\rightarrow$ 1 A·m^2/kg
j	magnetic dipole moment	1 erg/G = 1 emu $\rightarrow 4\pi \times 10^{-10}$ Wb·m
J	magnetic polarization	1 erg/(G·cm^3) = 1 emu/cm$^3 \rightarrow 4\pi \times 10^{-4}$ T
χ, κ	susceptibility	$1 \rightarrow 4\pi$
χ_ρ	mass susceptibility	1 cm^3/g $\rightarrow 4\pi \times 10^{-3}$ m^3/kg
μ	permeability	$1 \rightarrow 4\pi \times 10^{-7}$ H/m $= 4\pi \times 10^{-7}$ Wb/(A·m)
μ_r	relative permeability	$\mu \rightarrow \mu_r$
w, W	energy density	1 erg/cm$^3 \rightarrow 10^{-1}$ J/m^3
N, D	demagnetizing factor	$1 \rightarrow 1/(4\pi)$

Gaussian units are the same as cgs emu for magnetostatics; Mx = maxwell, G = gauss, Oe = oersted, Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.

Appendix E:
Symbols for the Chemical Elements

Symbol	Element	Symbol	Element	Symbol	Element
Ac	Actinium	Gd	Gadolinium	Po	Polonium
Ag	Silver	Ge	Germanium	Pr	Praseodymium
Al	Aluminum	H	Hydrogen	Pt	Platinum
Am	Americium	He	Helium	Pu	Plutonium
Ar	Argon	Hf	Hafnium	Ra	Radium
As	Arsenic	Hg	Mercury	Rb	Rubidium
At	Astatine	Ho	Holmium	Re	Rhenium
Au	Gold	I	Iodine	Rh	Rhodium
B	Boron	In	Indium	Rn	Radon
Ba	Barium	Ir	Iridium	Ru	Ruthenium
Be	Beryllium	K	Potassium	S	Sulfur
Bi	Bismuth	Kr	Krypton	Sb	Antimony
Bk	Berkelium	La	Lanthanum	Sc	Scandium
Br	Bromine	Li	Lithium	Se	Selenium
C	Carbon	Lr	Lawrencium	Si	Silicon
Ca	Calcium	Lu	Lutetium	Sm	Samarium
Cd	Cadmium	Md	Mendelevium	Sn	Tin
Ce	Cerium	Mg	Magnesium	Sr	Strontium
Cf	Californium	Mn	Manganese	Ta	Tantalum
Cl	Chlorine	Mo	Molybdenum	Tb	Terbium
Cm	Curium	N	Nitrogen	Tc	Technetium
Co	Cobalt	Na	Sodium	Te	Tellurium
Cr	Chromium	Nb	Niobium	Th	Thorium
Cs	Cesium	Nd	Neodymium	Ti	Titanium
Cu	Copper	Ne	Neon	Tl	Thallium
Dy	Dysprosium	Ni	Nickel	Tm	Thulium
Er	Erbium	No	Nobelium	U	Uranium
Es	Einsteinium	Np	Neptunium	V	Vanadium
Eu	Europium	O	Oxygen	W	Tungsten
F	Fluorine	Os	Osmium	Xe	Xenon
Fe	Iron	P	Phosphorus	Y	Yttrium
Fm	Fermium	Pa	Protactinium	Yb	Ytterbium
Fr	Francium	Pb	Lead	Zn	Zinc
Ga	Gallium	Pd	Palladium	Zr	Zirconium
		Pm	Promethium		

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