National Institute of Standards and Technology

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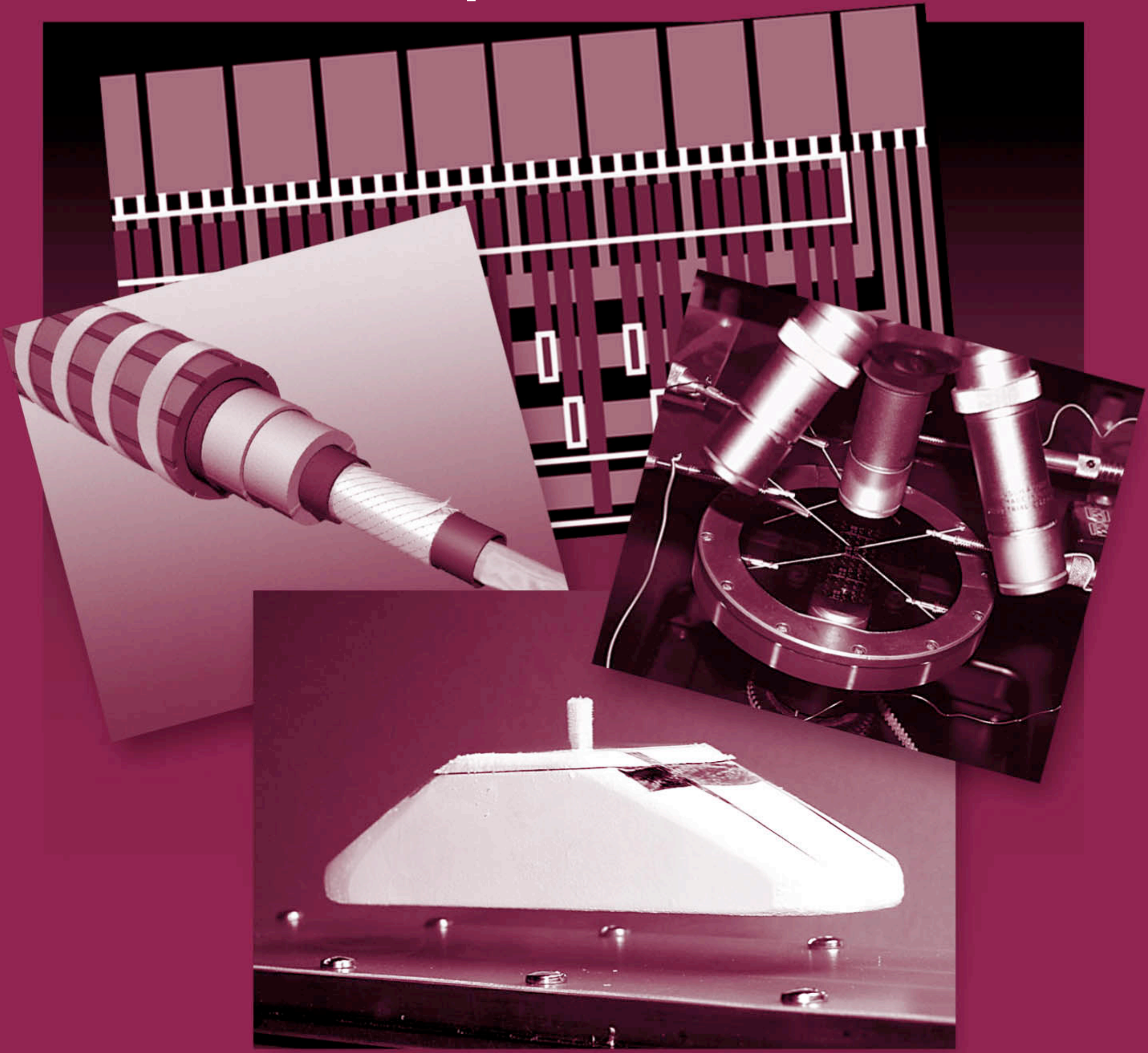
Electronics and Electrical Engineering Laboratory

Magnetic Technology Division

Programs, Activities, and Accomplishments



The Electronics and Electrical Engineering Laboratory

Through its technical laboratory research programs, the Electronics and Electrical Engineering Laboratory (EEEL) supports the U.S. electronics industry, its suppliers, and its customers by providing measurement technology needed to maintain and improve their competitive position. EEEL also provides support to the Federal government as needed to improve efficiency in technical operations, and cooperates with academia in the development and use of measurement methods and scientific data.

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 document 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, on the Web at www.eeel.nist.gov.

The cover illustrates some of the research areas of the Magnetic Technology Division. Clockwise from the right, these are: (1) probing sub-micrometer magnetoresistive spin-valve sensors for recording heads and magnetic random-access memory (optical microscope for aligning current and voltage contacts), (2) superconductors for magnet applications (model levitated train for educational demonstrations), (3) superconductors for the electric power industry (cutaway view of high-current superconducting transmission line to replace conventional underground copper lines; photo courtesy of American Superconductor Corporation), and (4) recovery of data from damaged or erased magnetic recording tape (photolithographed array of magnetoresistive sensors for the acquisition of images of recorded bits).

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U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
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Contents

Welcome

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

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 and industrial consortia.

Research is conducted in areas that include:

Magnetic calibration standards
Superconductor standards and best practices
High-density and high-speed magnetic recording
Magnetoresistive sensors and memory elements
Magneto-optic and inductive magnetometry
Recovery of data from damaged or erased recording media
Scanned-probe microscopy and micro-electromechanical systems
Electromechanical properties of superconductors

The division disseminates the results of its research through publications in refereed journals, presentations at conferences and workshops, and participation in standards organizations.

For additional information, please visit our Web site at www.boulder.nist.gov/div816/. Thanks for your interest in the Magnetic Technology Division.

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

Magnetic Recording Measurements

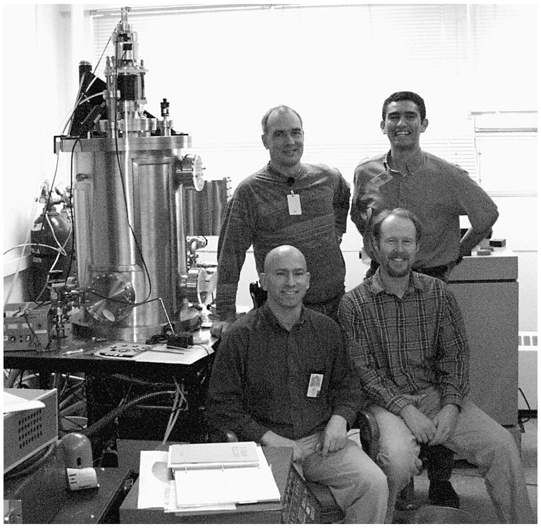
Project Leader:
David Pappas

Staff-Years (FY 2001):
1 professional
2 research associates
1 student

Funding Sources:
NIST (50 %)
Other (50 %)

Goals

This project addresses national measurement needs in magnetic data storage for industry, advanced applications, and national security. It is developing novel calibration standards, ranging from standards for the determination of the absolute magnetic moment of thin magnetic films to active inductive standards for magnetometers. Using state-of-the-art vacuum technology and spin-resolved electron spectroscopy, project members are doing research on the magnetic anisotropy of thin films used in data storage. Magnetic imaging techniques and measurements are developed for the authentication of recorded information and the recovery of data from samples of damaged magnetic recording media. The project has recently developed new techniques for imaging forensic evidence for the Federal Bureau of Investigation **(FBI)** and for data recovery for the National Transportation Safety Board **(NTSB)**. It has published definitive work on the magnetic-reorientation transition of ultra-thin (two atomic layers) films of Fe on Gd as well the magnetic phase transition of the atomically clean Gd surface.



David Pappas and John Nibarger (front) and Jeff Bridges and Fabio da Silva (back) in the Magnetic Recording Measurements lab. An electron-beam deposition system is at the left.

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.

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 two types of novel standards 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.

Technical Strategy

A three-pronged approach is used. This includes standards development, imaging with advanced magnetoresistive heads for forensic analysis, and *in-situ* surface magnetometry for metrology and scientific research. In order to respond to immediate needs of the data-storage industry and the magnetic instrumentation companies that service it, two types of magnetometer reference samples are being developed in collaboration with instrument manufacturers. These will be magnetic thin-film coupons that have an integral superconducting flux-measurement loop and an inductive magnetic-flux standard.

In 1996, NIST initiated a five-year program to develop competence in the area of metrology for magnetic data storage. 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 image and write data on magnetic media. The NRS can image by rastering either the head with computer controlled micrometers with 50 nanometer resolution or the storage medium with a piezoelectric x-y stage with 1 nanometer resolution. The NRS is being used as a prototype for forensic analysis of audio tapes.

It has been shown that high-speed imaging of tape samples can be accomplished, and the signatures of erase heads and write heads have been identified on test samples. In addition, reconstruction of both analog and digital data from test samples has been accomplished.

The NRS is also capable of detecting magnetic fields due to currents. This is useful for failure analysis of very-large-scale-integration **(VLSI)** semiconductor chips, where it is necessary to locate the location of a current drain due to a short circuit somewhere in a buried circuit. By imaging the magnetic fields and inverting Maxwell's equations within the appropriate limits, an important metrological tool is being developed for the semiconductor industry.

Finally, 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-out 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 media. The electrons are sensitive to the first few atomic layers of the surface.

Deliverables

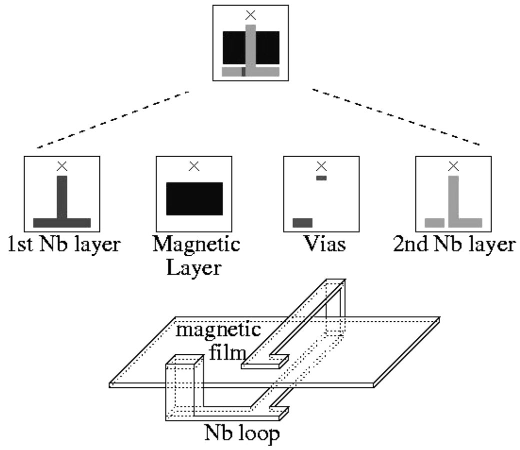
High-Sensitivity Magnetoresistive Sensors

- In FY 2002, we will develop two types of magnetoresistor arrays. Linear arrays will be used for imaging magnetic field distributions, and staggered, high-density, planar arrays will be used for imaging analog magnetic storage media.

- In FY 2002, we will develop a single-element magnetoresistive probe that has a low profile and wide bandwidth (up to 3 gigahertz).

Standards for Thin Film Magnetometers

- In FY 2002, we will test our fluxmetric superconducting/magnetic thin-film standard at low temperature. We will measure the magnetic flux in the sample using the magnetic flux quantum as a reference.



Layout of the low-magnetic-moment reference standard, consisting of a superconducting Nb coil wound around a thin Ni-Fe magnetic film. The middle row shows the four different layers: bottom Nb loop (100 micrometers wide), magnetic layer (4 millimeters × 4 millimeters × 2 nanometers), vias, and top Nb loop. The top figure shows the superposition of the four layers. The bottom figure is a perspective view (not to scale).

- In FY 2002, we will produce a prototype planar solenoid for cross-calibrating induction-field **(B-H)** loopers using a known current through the solenoid.

Magnetic Surface Science

- In FY 2002, we will test a compact spin-polarized electron gun and conduct scattering experiments to determine the magnetic moment and spin-dependent reflectivity of the topmost atomic layers of magnetic films.

- In FY 2002, we will grow Fe films on GaAs using an ultra-thin Ag buffer layer. We will characterize the growth of both the Ag and Fe films using low-energy electron diffraction and Auger electron spectroscopy. In addition, the emission and reflection of spin-dependent electrons from these surfaces will be measured.

Accomplishments

Magnetic Calibration Standards

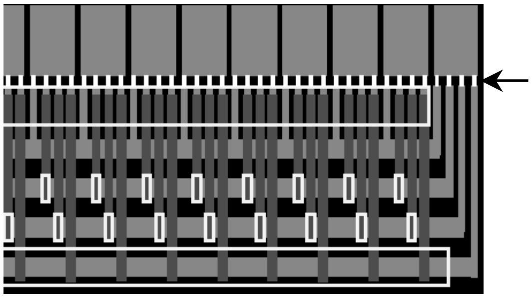
- Prototype Fluxmetric Standards Fabricated — A prototype wafer of fluxmetric superconducting/magnetic thin-film standards has been fabricated. The wafer includes large dies that are useful for the calibration of B-H loopers as well as small dies that are well suited for vibrating-sample magnetometers **(VSMs)**, magnetometers based on superconducting quantum interference devices **(SQUIDs)**, and alternating-gradient force magnetometers. The magnetic properties of the samples have been measured in a B-H looper and a SQUID magnetometer to verify that the superconducting loop is continuous and functional.

- Mask Set for Planar Solenoids — A complete mask set has been developed for patterning planar solenoids on 7.6 centimeter silicon wafers. The solenoid will be used to calibrate B-H loopers.

Scanned Magnetoresistive Imaging

- Scanned Magnetoresistive Recording Head Used to Map Currents in Integrated Circuits — We measured the magnetic fields at the backs of VLSI “flip-chip” circuits. The currents in the chips were then calculated from the fields by inverting Maxwell’s equations. Two devices mapped were a random-access memory **(RAM)** chip and a central processing unit **(CPU)**. The locations of the calculated currents compared well with those expected.

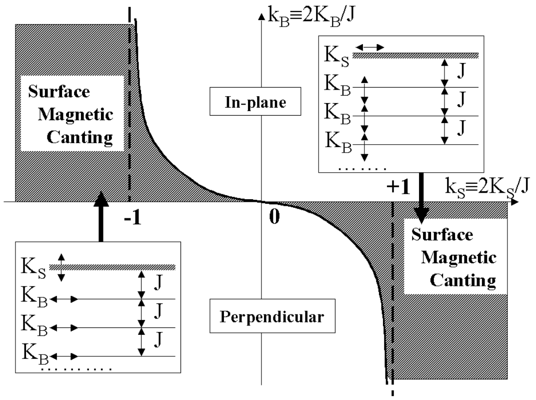
- Multiplexed Magnetoresistive Elements — We developed a new method for multiplexing arrays of magnetoresistive elements. This scheme is based on using the virtual ground of an operational amplifier to eliminate the effects of multiple ground paths in the separate rows of the array. Additionally, a multiple-frequency method of reading columns was devised. This technology will be applied to magnetoresistive imaging arrays for the forensics imaging tool.



Array of magnetoresistive sensors. Arrow points to the linear array of GMR sensors.

Surface Magnetometry

- Theory for Ferromagnetic Surface Phases — We developed a complete theory that describes the phase diagram of the surface magnetization of a semi-infinite ferromagnet The phase diagram for the orientation of the surface region was calculated in the parameter space defined by the surface and bulk anisotropy. Surface magnetic canting always occurs when the magnitude of the surface anisotropy is comparable with the inter-layer exchange interaction. Increasing the thickness of a thin film supported on a hard magnetic substrate induces a spin-reorientation transition from the uniform, in-plane magnetic structure to a canted state. The inverse spin-reorientation transition from the canted state to the uniform, in-plane magnetic structure with thickness was demonstrated for a thin film supported on a nonmagnetic substrate. We considered the 1.5 atomic-layer system of Fe on Gd and found that it is a good physical realization of the model.



Phase diagram for surface magnetic canting in a semi-infinite ferromagnet in coordinates of the surface and bulk magnetic energies, k_S and k_B.

Workshops

- The Magnetic Technology Division hosted a Tape Roadmap Workshop sponsored by the National Storage Industry Consortium **(NSIC)**. Technical leaders in the recording tape industry met at NIST laboratories in Boulder, Colorado, to outline directions for tape technology during the next decade in the areas of read and write channels, heads, media, and tape transport. Projected trends included increases in data-transfer rate, bit density, track density, tape speed, and cartridge capacity; improvements in tape strength, dimensional stability, and smoothness; the use of adaptive transport systems; and continued decrease in cost. Part of the discussion centered on needed metrics and measurement standards.

Recent Publications

C. S. Arnold and D. P. Pappas, “Reduced Exchange Coupling at the Surface of the Heisenberg Ferromagnet Gd(0001),” submitted.

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

L. Malkinski, N. Cramer, A. Hutchison, R. Camley, Z. Celinski, D. Skrzypek, and R. B. Goldfarb, “Exchange Bias and Anisotropy in the Fe/KCoF$_3$ Structure,” J. Magn. Magn. Mater., in press.

A. P. Popov and D. P. Pappas, “Surface Magnetic Phase Diagram for a Semi-Infinite Ferromagnet,” Phys. Rev. B **64**, 184401/1-11 (November 2001).

D. P. Pappas, C. S. Arnold, G. Shalev, C. Eunice, D. Stevenson, S. Voran, M. E. Read, E. M. Gornley, J. Cash, K. Marr, and J. J. Ryan, “Second Harmonic Magneto-Resistive Imaging to Authenticate and Recover Data from Magnetic Storage Media,” in Enabling Technologies for Law Enforcement and Security, Proc. SPIE (January 2001).

C. S. Arnold and D. P. Pappas, “Gd(0001): A Semi-Infinite Three-Dimensional Heisenberg Ferromagnet with Ordinary Surface Transition,” Phys. Rev. Lett. **85**, 5202-5205 (December 2000).

C. S. Arnold, D. P. Pappas, and A. P. Popov, “Magneto-Optic Kerr Effect Study of a Two-Step Reorientation Transition of an Ultrathin Magnetic Film,” J. Appl. Phys. **87**, 5478-5480 (May 2000).

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).

C .S. Arnold, D. P. Pappas, and A. P. Popov, “Second and First Order Phase Transitions in the Magnetic Reorientation of Fe/Gd,” Phys. Rev. Lett. **83**, 3305-3308 (October 1999).

D. P. Pappas, C. S. Arnold, and A. P. Popov, “Spin Reorientation Phase Transition of Ultrathin Fe Films Grown on Gd(0001),” in Magnetism and Electronic Correlations in Local-Moment Systems: Rare Earth Elements and Compounds, M. Donath, P. A. Dowben, and W. Nolting, eds., World Scientific, 141-152 (1999).

Z. Celinski, D. Lucic, N. Cramer, R. E. Camley, R. B. Goldfarb, and R. B. Skrzypek, “Exchange Biasing in Ferromagnet/Antiferromagnet Fe/KMnF$_3$,” J. Magn. Magn. Mater. **202**, 480-484 (August 1999).

C. S. Arnold, M. Dunlavy, D. Venus, and D. P. Pappas, “Magnetic Susceptibility Analysis of the Relaxation-Time for Domain-Wall Motion in Perpendicularly Magnetized, Ultrathin 1.5 ML Fe/2 ML Ni/W(110) Films,” J. Magn. Magn. Mater. **198-199**, 465-467 (June 1999).

C. S. Arnold, D. P. Pappas, and D. Venus, “Domain Formation Near the Reorientation Transition in Perpendicularly Magnetized Ultrathin Fe/Ni Bilayer Films,” J. Appl. Phys. **85**, 5054-5059 (April 1999).

Magnetodynamics

Project Leader:
Tom Silva

Staff-Years (FY 2001):
2 professionals
1 research associate

Funding Sources:
NIST (75 %)
Other (25 %)

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 inductive response. 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 spintronic systems and physics is underway. The project provides results of interest to the magnetic-disk-drive industry, developers of magnetic random-access memory **(MRAM)**, and the growing spintronics community. Recent achievements include the observation of 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. Recently, 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 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 operating the pulsed inductive microwave magnetometer (PIMM).

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

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 “cutting-edge” 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, much as a spinning top precesses in the Earth’s gravitational field. 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 80 megabytes per second. In five years, frequencies for writing and reading will be in the microwave region, which raises the question, "How fast can magnetic materials switch?"

The current laboratory demonstration record for storage density is 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 or discrete data bits 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 radio-frequency **(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.

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.

We are committed to supporting new magnetic technologies as they emerge in the 21st century. Spintronics is a novel direction in electronics that promises to revolutionize telecommunications and information processing. The essential idea behind spintronics is the manipulation and control of the quantum-mechanical spin of a semiconductor's charge carrier. The extension of electronic manipulation toward the spin degree-of-freedom has intrinsic advantages that warrant further exploration. For example, the fundamental problem with high-frequency semiconducting devices is nonzero resistance R coupled with gate capacitance C. In essence, the RC time constant limits the maximum frequency attainable. A key feature of spin-based RF circuitry is the fundamentally quantum-mechanical nature of spin precession. Spin-precession frequencies are not intrinsically limited by loss mechanisms such as carrier mobility, as long as coherence can be preserved. Spintronics technology holds the promise of extending telecommunications frequencies into the terahertz regime.

The Magnetic Technology Division has started a new program sponsored by the Defense Advanced Research Projects Agency **(DARPA)** to explore the use of electron-spin-based devices for applications in high-frequency communications. The four-year, $7.1 million program is a collaboration among NIST, Motorola, and Cornell University.

The motivation to use electron-spin-based devices for high-frequency communication applications comes from the fact that the electron spin degree-of-freedom forms the most fundamental quantum oscillator. Unlike devices that are based on charge transfer, whose frequency performance is limited by electron velocities and charge-transfer times, the electron spin has no fundamental frequency limitations.

Recent advances in spin-based semiconductor devices have demonstrated that coherent spin

Based upon the pioneering work at NIST in developing the inductive time-domain permeability measurement, I have implemented the same measurement capability at Seagate Technology. We use this measurement technology daily for measuring the high frequency properties of magnetic materials. The ongoing efforts by the NIST-Boulder group to develop new magnetic measurements often have the added benefit of creating new technologies which may be incorporated into actual products.

Dr. Thomas Crawford
Seagate Research
Seagate Technology LLC

precession can be maintained for hundreds of nanoseconds in III-V semiconductors and hundreds of microseconds in Si. The precession frequency can be controlled by applied magnetic fields, gate voltages, and modulation doping techniques. Terahertz precession has been observed in Mn-doped InAs heterostructures with no applied magnetic fields. Modulation of the electron g-factor has been observed in the presence of electric fields that move the spin packets between regions of different g-factors, e.g., GaAs and AlGaAs.

Motorola, a leading producer of high-frequency semiconductor components, will be fabricating high-mobility GaAs/GaAlAs and InGaAs/InAlAs heterostructures specifically designed for spin-based devices. NIST will lead the effort to develop new techniques to measure and control spin precession in small spin-based devices. The goal will be to characterize precessing spin packets with one million spins, using high-speed electrical and optical techniques. The NIST team hopes to extend the metrology down to systems consisting of a single spin.

In addition to exploring spin dynamics in semiconductors, the we will look at metallic devices that use spin-momentum transfer to induce coherent precession. Recent theoretical work has predicted that a spin-polarized direct current injected into a small magnetic structure (50 nanometers × 100 nanometers × 2.5 nanometers) 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.

The Cornell group has recently shown that spin-polarized currents can switch a small magnetic element, an effect predicted by the theory. We have further developed these ideas and proposed using this effect as a source of precessing spins for semiconductor devices and as the basis for a novel spin amplifier. Motorola, starting from a process developed at Cornell and NIST, will fabricate 50 nanometer to 100 nanometer magnetic multilayer structures on 20 centimeter Si wafers using magnetic processing techniques developed for their MRAM program. Motorola will use precision chemical-mechanical polishing to contact the devices and expects to obtain large numbers of devices with highly controlled magnetic properties. NIST will characterize the dynamics induced by spin-momentum transfer in these devices using high-speed electrical and optical techniques.

Deliverables

Magnetic Recording Diagnostics

- In 2002, we will further develop the inductive current probe for the characterization of write-current pulses used in magnetic disk drives. The current probe uses a magnetic thin film as a noninvasive inductive transformer to sense the current pulses sent from a write driver to the recording head. In the next iteration, the current probe will be implemented as part of a trace suspension assembly. The work will be done in collaboration with two recording-head companies.

Nanotechnology

- In FY 2002, we will collaborate with researchers at the University of Idaho, University of Alabama, and Washington University in Saint Louis on nanotechnology studies using magnetic materials. We will use inductive and optical methods to investigate the high-speed switching properties of patterned arrays of magnetic dots. We will investigate iron-nitride films, which have promise as a high-performance head material. These films will have engineered nanostructures for optimal recording properties. We will use the PIMM to search for correlation between nanostructural properties and the damping of precessional ringing.

Ferromagnetic Damping

- In FY 2002, we will measure the dependence of damping on substrate sound velocity. If magnon-phonon coupling is the primary means of damping, there should be some dependence on sound velocity according to one theory. Our intent is to find whether the acoustic properties of

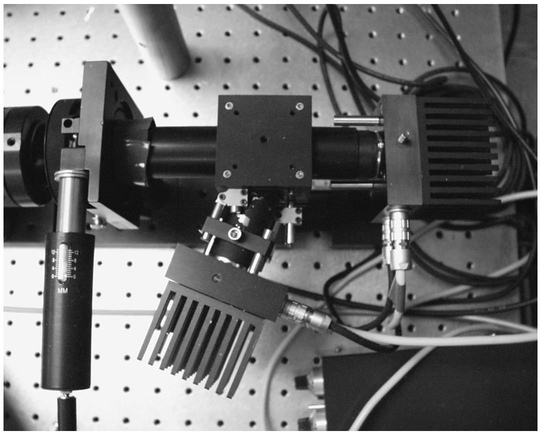
View through the bore of an optical cryostat and magnet assembly with 4 kelvin, 8 tesla capability. It will be used to study spin dynamics in various spintronic devices, including magnetic precession induced by spin-polarized currents and spin coherence in semiconducting media.

a substrate can be used to improve the performance of recording heads in high-performance disk drives.

- In FY 2002, we will study the dependence of damping on magnetic anisotropy in Permalloy ($Ni_{80}Fe_{20}$) thin films. It is possible to vary the anisotropy in Permalloy from 80 to 400 amperes per meter by annealing thin films in a magnetic field. It can be argued that damping torque and anisotropy torque should be related by conservation of angular momentum; this study should clarify the validity of that argument. A correlation between damping and permeability will establish a fundamental limit to the operational bandwidth of magnetic recording.

- In FY 2002, we will complete a study of dynamic anisotropy in Permalloy films of thickness ranging from 10 to 500 nanometers. We have found that the anisotropy measured by dynamic measurements are significantly higher than the anisotropy found with a quasi-static measurement. Mechanisms for the discrepancy are under review. The goal is to find a means to increase the dynamic permeability of recording-head materials, thereby improving data-writing efficiency.

- In FY 2003, we will investigate the generation of standing spin-waves through the thickness of 200-300 nanometer Permalloy films. Preliminary PIMM data indicate that such standing waves occur during the switching process. Of particular interest is how these waves couple to the uniform mode to act as a source of damping. Understanding how such modes arise, whether it is due to eddy-current generation or surface-pinning of spins, will influence current models of magnetic recording-head performance.



Optical bridge assembly for sensitive measurement of polarized light. It can be used for both time-resolved measurements of magnetization dynamics in thin-film recording head materials and for the study of spin precession in semiconductors with spintronic applications.

- During FY 2002-2003, we will continue to investigate the mechanisms that lead to nonuniform magnetization dynamics during the switching process when the magnetic spins reorient into a new equilibrium direction. We will use both linear and nonlinear optical methods to measure both the surface and subsurface spin dynamics during the switching process. Results should help us understand whether such nonuniform dynamics will have a deleterious effect on the high-speed performance of recording heads.

Spintronics

- In FY 2002, we will search for a direct signature of spin-wave generation from the injection of a spin-polarized current in magnetic multilayers. Experiments will rely upon a point-contact geometry to produce the requisite high current densities of 10^8 amperes per square centimeter. Measurements will rely on both static and time-resolved magneto-optic contrast using a laser beam focused in proximity to the point contact. These results should help select among the many theoretical explanations that have been forwarded to explain the exchange of angular momentum between a spin-polarized current and a ferromagnet.

- In FY 2002, we will develop a simple and inexpensive method to measure spin precession in GaAs substrates using time-resolved magneto-optic techniques. The methods will rely on a low-cost laser diode system that is tuned to the electron band gap of GaAs. Development of such a system should greatly expand the research opportunities in this important segment of spintronics research and development.

- In FY 2004, we will investigate the possibilities to use the spin-momentum-transfer effect for telecommunications applications. Device possibilities include high-frequency oscillators and amplifiers based on spin-wave amplification by stimulated emission of radiation **(SWASER)**. We will seek to establish whether the SWASER effect is real and what parameters exist to manipulate the effect.

- In FY 2003, we will seek to manipulate coherent spin populations in a semiconductor medium using pulsed RF signals. The spins will be induced by optical orientation methods. We will use waveguide structures to apply the RF signals to the spin packets. Optical methods will then be used to monitor the spin polarization during the RF manipulations. With such a technique, it should be possible to determine the degree to which inhomogeneities determine the measured coherence times. Long coherence times are desirable for the development of high-quality-factor **(high-Q)** oscillators and amplifiers.

Accomplishments

- Pulsed Inductive Microwave Magnetometer — As part of our program in high-speed magnetics, we have developed an automated, pulsed inductive microwave magnetometer **(PIMM)** to characterize magnetic thin films. The PIMM is designed to measure the magnetodynamic 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 uses a coplanar waveguide as both a source of fast, pulsed magnetic fields and as an inductive flux sensor. Magnetic field pulses are provided by a 10 volt, 55 picosecond rise-time pulse generator. Orthogonal Helmholtz coils provide the magnetic bias and saturating fields required for the measurement. A 20 gigahertz digital sampling oscilloscope is used to acquire the data. The system can measure dynamical behavior as a function of several variables, including applied bias field, pulsed field amplitude and width, and sample orientation. Using fast Fourier transforms, the PIMM can determine the frequency dependence of the complex magnetic permeability, as well as the step and impulse responses of magnetic systems.

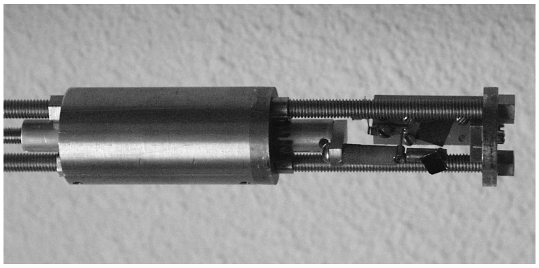
The PIMM includes components necessary for completely automated magnetodynamic measurements. No user intervention is required to insert or remove attenuators on the front end of the high-bandwidth sampling oscilloscope. This reduces the chance of an electrostatic discharge that could damage the sensitive front-end circuitry of the oscilloscope. It also increases the system sensitivity, since the attenuators can be set in finer increments to give the largest signal as the pulse amplitude is adjusted.

In order to generate a precise impulse with repeatable characteristics, the system can automatically insert a passive impulse-forming network into the output pulse path. This allows the impulse response of the magnetic system to be measured, which is useful for characterizing the system's transfer function. The automatic operation allows measurements of pulsed magnetic switching dynamics at different pulse amplitudes interspersed with measurements of system impulse response.

This unique magnetometer has been used by visiting scientists from university data-storage research centers and disk-drive manufacturers.

- Vector Magnetodynamic Measurements at the Surface and Interior of Films for Recording Heads — We have made quantitative, vectorial measurements of magnetization dynamics of Ni-Fe magnetic thin films, simultaneously at the surface and approximately 50 nanometers in the interior. The measurements were performed using the linear and nonlinear magneto-optic Kerr effects. The linear effect **(MOKE)** is sensitive to the magnetization in the interior of the film, whereas the nonlinear effect **(SHMOKE)** is sensitive to the magnetization of only the first few atomic layers.

These measurements address the problem of inhomogeneous magnetization response of magnetic materials when subjected to rapidly changing magnetic fields. When the rate of change of the applied field approaches the characteristic response time of the material (the precessional frequency, typically several gigahertz), the magnetization's response can become complicated. At these frequencies, the magnetization does not simply align with the field, but instead swings toward the field and oscillates (precesses) around it before finally settling into the field direction. However, it was not known whether the surface and the interior of the magnetic material reacted to the applied field in the same way.

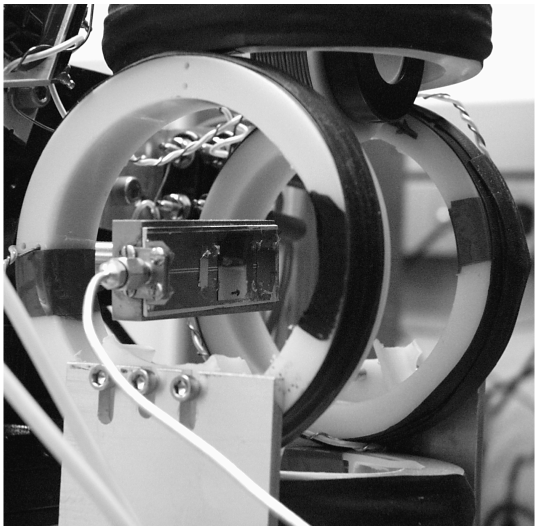


Point-contact assembly for the study of the spin-momentum-transfer (SMT) effect, whereby spin-polarized carriers can manipulate the magnetic state of a nanometer-scale element. It will be used with a cryostat and magnet assembly capable of operation at 4 kelvins and 8 teslas. Experiments performed with this instrument will elucidate the role of spin-wave generation in the SMT effect.

We induced rapid, near-90 degree rotations of the magnetization of Ni-Fe films in a geometry similar to that of the ferromagnetic cores of magnetic recording write heads. The rotation of the magnetization vector was probed with a 50 femtosecond laser pulse. The system had an overall temporal sensitivity of 50 picoseconds and a sensitivity to magnetization angle of about 3 degrees. We found that, contrary to the expectations of some models for magnetic response, the surface and the interior region responded identically. Detailed measurements showed that the magnetization exhibited a fast rotational response over about one nanosecond followed by a smaller, slow response over tens of nanoseconds.

These effects will soon be important in magnetic data storage devices as data rate increases. Disk drives store information by switching small regions of magnetic material to represent binary data. It is necessary to have a detailed understanding of the induced precessional magnetodynamics in order to optimize the recording process. Modeling of these large, rapid magnetization motions in real materials is difficult, so direct dynamic measurements are important for continued device development.

Work is ongoing to study the dependence of the response on the thickness of the film to find when the response of the surface might deviate markedly from the interior due to eddy currents.



Coplanar waveguide used to deliver high-speed magnetic field pulses to thin-film samples. Field pulses with rise times as short as 50 picoseconds can be produced with such a waveguide. Magnetic response is obtained using time-resolved magneto-optic methods with vector measurement capability.

- Relative Rates of Spin-Spin and Spin-Lattice Relaxation Measured for Thin-Film Permalloy — We completed an investigation of damping in a Ni-Fe thickness series ranging from 10 to 100 nanometers. Films in this thickness range do not exhibit significant damping as a result of eddy-current generation. The damping parameter was extracted by fitting of the data to the Landau-Lifshitz-Gilbert **(LLG)** phenomenological model for damped precessional dynamics. The resultant damping parameter was found to decrease monotonically with increasing longitudinal bias field from 0 to 2000 amperes per meter. A theory was developed that considers the competing role of spin-lattice and linear magnon-magnon coupling. It was presumed that the spin-lattice interaction was independent of applied field to first order, whereas the magnon-magnon coupling was proportional to the density of states **(DOS)** for spin-wave modes that have the same frequency as the uniform precessional mode. Conventional spin-wave dispersion theory predicts that the DOS of degenerate modes is a strong function of applied field in the range measured. Fitting of the data to the theory finds that the spin-lattice relaxation path is 10 times faster than the formation of degenerate magnons in the absence of any applied bias field along the anisotropy axis. This result was substantiated by vector-resolved dynamics measured with the time-resolved second-harmonic magneto-optic Kerr effect **(TRe-SHMOKE)**, where coherent dynamics were observed in Ni-Fe films, 50 nanometers thick, similar to those used for the present study.

- Relative Role of Nonlinear Effects Elucidated for Large-Angle Magnetic Motion — We measured the dependence of damping in Ni-Fe films, 50 nanometers thick, on the amplitude of an applied field step. The measurements were conducted with the pulsed inductive microwave magnetometer **(PIMM)** using a pulse generator that produces field steps with 50 picosecond rise-time and 10 nanosecond duration. The pulse bandwidth is sufficient to induce underdamped precessional dynamics in the Permalloy film. The pulse amplitude ranged from 20 to 200 amperes per meter. The film anisotropy was 320 amperes per meter. For this range of pulses, the magnetization was rotated over a range from 3.6 to 39 degrees away from the ambient magnetization direction along the easy axis. It was found that the magnetization response was linear over this response range, with the response for a pulse of 200 amperes per meter scaling onto the response for a pulse of 20 amperes per meter. The conclusion may be drawn that the damping measured with the PIMM system for such films is the result of linear relaxation processes.

This result is important because commonly used ferromagnetic-resonance **(FMR)** measurements of precessional response are limited to excitations that induce magnetization oscillations of less than a degree before the damping is dominated by nonlinear processes. These measurements suggest that nonlinear processes are suppressed when the magnetization is stimulated in such a manner that the precessional dynamics are allowed to decay before the application of the next excitation pulse.

External Recognition

- Tom Silva served as IEEE Magnetics Society Distinguished Lecturer. Presenting his talk entitled "Consideration of the Spherical Cow: The Realities of Magnetodynamics in an Imperfect World," he represented NIST's research and its impact at more than 20 research institutions throughout the world. Many attendees commented on the novel optical techniques for accurate time resolution of ultrafast spin dynamics.

Recent Publications

A. B. Kos, T. J. Silva, P. Kabos, M. R. Pufall, D. DeGroot, L. Webb, and M. Even, "Design and Performance of an Inductive Current Probe for Integration into the Trace Suspension Assembly," IEEE Trans. Magn., in press.

M R. Pufall and T. J. Silva, "Simultaneous Measurement of the Surface and Bulk Vector Magnetization Dynamics in Thin NiFe Films," IEEE Trans. Magn., in press.

N. X. Sun, S. X. Wang, J. J. Silva, and A. B. Kos, "Soft Magnetism and High Frequency Behavior of Fe-Co-N Thin Films," IEEE Trans. Magn., in press.

T. J. Silva, "Measurement of Dynamic Properties in Thin Films," in Physics of Ultrahigh Density Magnetic Recording, Springer Verlag, in press.

S. E. Russek, P. Kabos, T. J. Silva, F. B. Mancoff, D. Wang, Z. Qian, and J. M. Daughton, "High Frequency Measurements of CoFeHfO Thin Films," IEEE Trans. Magn. **37**, 2248-2250 (July 2001).

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).

A. Moser, D. Weller, N. D. Rizzo, and T. J. Silva, "Determination of Average Demagnetizing Fields in Longitudinal Magnetic Recording with Nanosecond Pulses," Appl. Phys. Lett. **77**, 1505-1507 (September 2000).

C. Alexander, Jr., J. Rantschler, T. J. Silva, and P. Kabos, "Frequency- and Time-Resolved Measurements of FeTaN Films with Longitudinal Bias Fields," J. Appl. Phys. **87**, 6633-6635 (May 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).

P. Kabos, A. B. Kos, and T. J. Silva, "Vectorial Second-Harmonic Magneto-Optic Kerr Effect Measurements," J. Appl. Phys. **87**, 5980-5982 (May 2000).

T. M. Crawford, P. Kabos, and T. J. Silva, "Coherent Control of Precessional Dynamics in Thin Film Permalloy," Appl. Phys. Lett. **76**, 2113-2115 (April 2000).

N. D. Rizzo, T. J. Silva, and A. B. Kos, "Nanosecond Magnetization Reversal in High Coercivity Thin Films," IEEE Trans. Magn. **36**, 159-165 (January 2000).

N. D. Rizzo, T. J. Silva, and A. B. Kos, "Relaxation Times for Magnetization Reversal in a High Coercivity Magnetic Thin Film," Phys. Rev. Lett. **83**, 4876-4879 (December 1999).

T. J. Silva, C. S. Lee, T. M. Crawford, and C. T. Rogers, "Inductive Measurement of Ultrafast Magnetization Dynamics in Thin-Film Permalloy," J. Appl. Phys. **85**, 7849-7862 (June 1999).

T. M. Crawford, T. J. Silva, C. W. Teplin, and C. T. Rogers, "Subnanosecond Magnetization Dynamics Measured by the Second-Harmonic Magneto-Optic Kerr Effect," App. Phys. Lett. **74**, 3386-3388 (May 1999).

S. E. Russek, T. M. Crawford, and T. J. Silva, "Study of NiFe/Al/Al2O3 Magnetic Tunnel Junction Interfaces Using Second-Harmonic Magneto-Optic Kerr Effect," J. Appl. Phys. **85**, 5273-5275 (April 1999).

G. M. Sandler, H. N. Bertram, T. J. Silva, and T. M. Crawford, "Determination of the Magnetic Damping Constant in NiFe Films," J. Appl. Phys. **85**, 5080-5082 (April 1999).

T. J. Silva and T. M. Crawford, "Methods for Determination of Response Times of Magnetic Head Materials," IEEE Trans. Magn. **35**, 671-676 (March 1999).

Tom Silva's technical insight and ability to effectively communicate ideas are always welcome attractions.

Dr. Randy Rannow
Chair, Rocky Mountain Chapter
IEEE Magnetics Society

Your lecture was really a tour de force.

Prof. Carl Patton
Department of Physics
Colorado State University

Nanoprobe Imaging

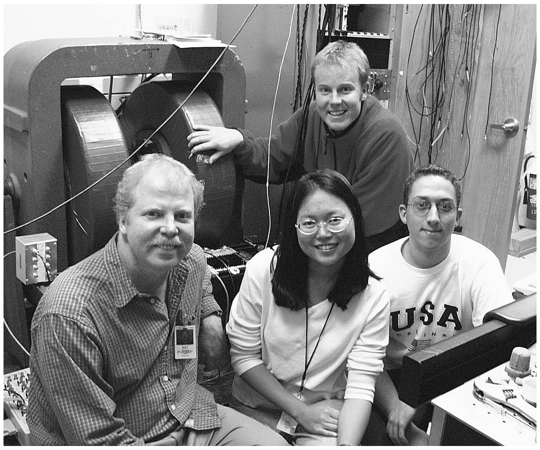
Project Leader:
John Moreland

Staff-Years (FY 2001):
1 professional
2 students

Funding Sources:
NIST (85 %)
Other (15 %)

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 develops ultra-small magnetic-force microscopy tips for imaging recording heads and media at a resolution of 20 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. In 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 **(FMR)** 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 single molecule manipulation and measurement techniques. Currently, there is a lack of tools for isolating and probing the behavior and structure of single molecules to determine the function of DNA, RNA, and proteins. This program will advance single-molecule metrology by developing a novel bio-nanoelectromechanical systems platform that integrates electrical, optical, and spectroscopic technologies.



Project Leader John Moreland, with students Qinzi Ji, Dan Porpora, and Todd Lammers (rear).

Customer Needs

The National Storage Industry Consortium **(NSIC)** 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.

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 force microscopy, 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 sub-micrometer magnetic resonance particles to ultra-sensitive cantilevers and to position particles a few nanometers from the sample surface.

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. We have broadened our clean-room fabrication capabilities to include MEMS bulk and surface micromachining of Si.

Technical Strategy

Our plans over the next five years are to demonstrate "magnetometers on a chip" based on MEMS devices that will enable us to create instruments that have superior performance compared to current magnetic-measurement methods. Our new micromachining facility, in association with the Electromagnetic Technology Division, is now operational. The facility is at the state of the art, providing the tools necessary for bulk and surface micromachining on Si wafers.

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.

MEMS Magnetometer Development

We will provide new instruments 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

In FY 2002, we will keep pace with the needs of industry in scanned probe microscopy and magnetometry. During FY 2002-2004, we will provide industry with new, inexpensive measurement systems that are calibrated within the SI system of units. During FY 2002-2006, we will develop techniques for visualization and comparison of fundamental magnetic phenomena at the quantum level.

Scanning Probe Development

- In FY 2002, we will achieve 20 nanometer MFM resolution.
- By FY 2004, we will achieve 1 nanometer magnetic resonance imaging resolution of thin-film ferromagnetic samples.

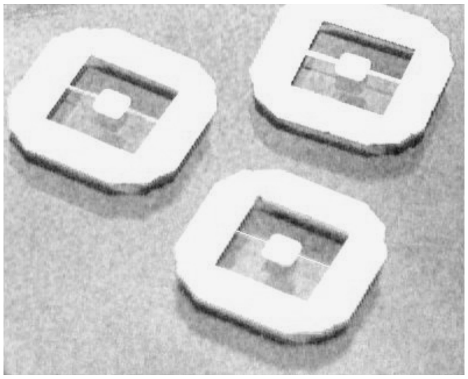
MEMS Magnetometer Development

- In FY 2002, we will fabricate fully integrated MEMS magnetometers.
- In FY 2002, we will develop active substrates, including disposable MEMS sensors, for monitoring magnetic thin films during deposition and processing to keep pace with the needs of industry.
- By FY 2004, we will develop a magnetic resonance spectrometer on a chip.
- By FY 2006, we will develop atomic scale magnetism instrumentation.
- By FY 2006, we will perform fundamental comparisons of spin systems on a single MEMS sensor.

Accomplishments

- Resonating Torque Microbalance Developed for *In-Situ* Measurements of Ferromagnetic Films with Sub-Monolayer 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 funded by the NIST Advanced Technology Program in response to the need to develop metrologies that will benefit the magnetic-disk-drive industry. In particular, measurements of thin-film properties critical to the development of read-head sensors and magnetic recording media are being investigated.

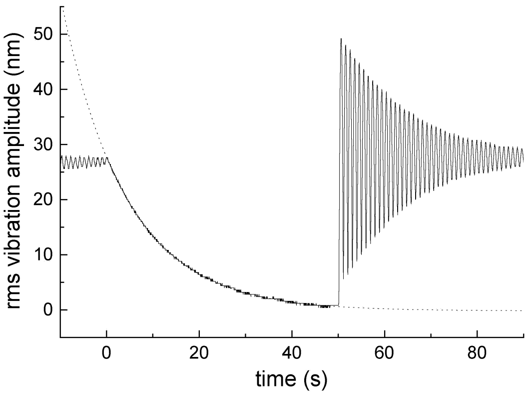
The production and development of many contemporary magnetic devices require that consistent growth conditions be maintained during thin-film deposition processing steps. Typically, film properties are determined *ex situ* with induction-field **(B-H)** loopers that measure the product of saturation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



High-Q silicon torsional oscillators fabricated in the NIST-Boulder MEMS fabrication facility.

fabricated, micromechanical substrates for quantitative measurements with sub-monolayer magnetic moment sensitivity.

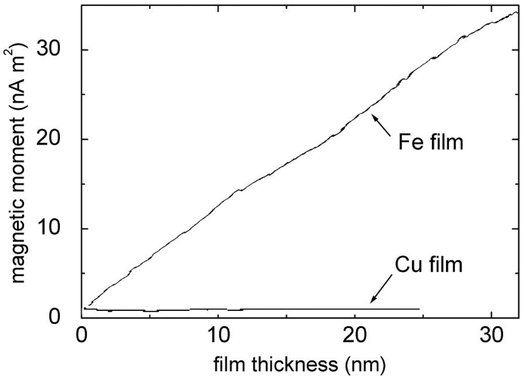
We have developed an instrument that measures the magnetic torque on a film as it is being deposited onto a single-crystal silicon microcantilever. An optical fiber interferometer is used to measure the deflection of the cantilever. Optical-fiber detectors work well in the high-noise environment typical of deposition systems. The magnetic torque is applied near the mechanical resonance of the cantilever to take advantage of the quality factor enhancement of the mechanical torque signal. 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 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 new NIST MEMS fabrication facility in Boulder.



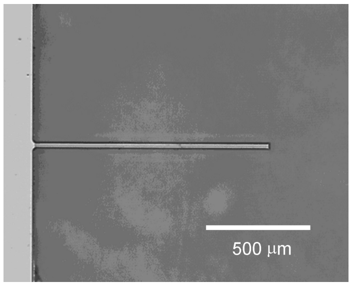
Free decay of high-Q micromechanical oscillators for *in situ* magnetometry.

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 0.02 nanometer thick ferromagnetic film with the current cantilever geometry.

- New Microscopic Scanning Microwave Power Meter — We have developed a micromachined bimaterial cantilever with a thin-film ferromagnetic resonance **(FMR)** sensor to probe RF fields near microwave devices. A patterned Permalloy 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 bimaterial cantilever. The deflection of the cantilever is measured with an optical lever. The small dimensions of the probe (20 micrometers × 20 micrometers × 0.05 micrometer) allow for measurements of RF magnetic fields near microwave devices with 20 micrometer resolution and minimal intrusion. The sensor is constructed of low-stress silicon nitride and low-temperature-deposited silicon oxide. The use of dielectric materials in the cantilever beam minimizes the background signal produced by eddy-current heating of the cantilever. Using this scanning FMR probe, we have measured vector-component-resolved microwave field distributions near a 500 micrometer wide stripline resonator driven at 9.15 gigahertz. The very tip of the cantilever was coated with the Permalloy probe. Absorption of microwave energy in the Permalloy tip is maximized when the microwave frequency matches the FMR condition determined by an externally applied DC magnetic bias

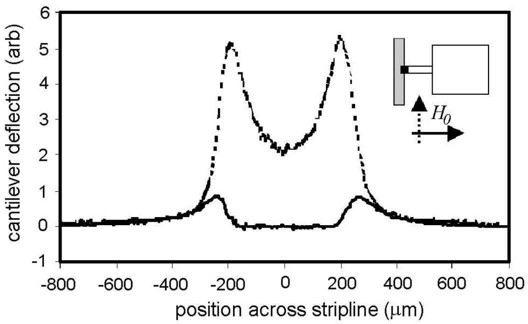


Magnetic moment versus thickness for an Fe film during deposition. The measurement was performed with a resonating torque microbalance developed at NIST.



All-dielectric bimaterial cantilever for calorimetric microwave field mapping.

field. The FMR frequency can be adjusted by changing the bias field, while different orientations of the bias field can be used to sense different components of the microwave field. Since the absorbed power is proportional to the local microwave intensity, this sensor can be used as a microscopic scanning microwave power meter. The probe currently has a lateral resolution of 20 micrometers (defined by the probe geometry), and a power resolution in the femtowatt range (limited by thermal excitation of the cantilever).



Cantilever response as a function of position across a microwave stripline. Dashed curve is with the FMR bias field H_0 parallel to the stripline. Solid curve is with H_0 transverse to stripline.

Recent Publications

A. Jander, J. Moreland, and P. Kabos, "All-Dielectric Micromachined Calorimeter for High-Resolution Microwave Power Measurement," submitted.

J. Moreland and T. J. Hubbard, "Resonating Torque Microbalance for In-Situ Measurements of Ferromagnetic Films," submitted.

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. **8**, 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).

T. G. Ruskell, M. Löhndorf, and J. Moreland, "Field Mapping with the Magnetic Resonance Force Microscope," J. Appl. Phys. **86**, 664-670 (July 1999).

Magnetic Thin Films and Devices

Project Leader:
Stephen Russek

Staff-Years (FY 2001):
1 professional
2 research associates
1 graduate student

Funding Sources:
NIST (65 %)
Other (35 %)

Goals

This project develops measurements and standards for magnetic thin-film materials and devices for the magnetic-data-storage and magneto-electronics industries. These measurements and standards assist industry in the development of advanced magnetic recording systems, magnetic solid-state memory, magnetic sensors, and magnetic microwave devices. The emphasis is on the performance of nanoscale devices, consisting of multilayer and multicomponent thin-film systems, 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 that will be required to develop quantum spin-based electronics for data storage and terahertz information processing.

Magnetic thin film deposition lab. From left to right: Stephen Russek, Fred Mancoff, Bill Bailey, and Shehzaad Kaka.

Customer Needs

Our project serves the needs of U.S. industries that use and develop magnetic thin-film and magnetic-device technologies. These industries include magnetic hard-disk recording, magnetic tape recording, magnetic random-access memory **(MRAM)**, and magneto-electronics (including sensors, isolators, and microwave devices). 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 measure and characterize these magnetic structures. Advances in technology are dependent on the discovery and characterization of new effects such as giant magnetoresistance 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.

Magnetic thin-film systems have become increasingly complicated, often containing quaternary alloys or multilayer systems with 4 to 10 elements that require atomic-level control of the layers. New techniques are required to efficiently and systematically develop and 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 a large region of parameter space.

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.

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 have fabricated test structures that allow the characterization of small magnetic devices at frequencies up to 10 gigahertz. The response of sub-micrometer magnetic devices, such as spin-valves, magnetic tunnel junctions, and giant-magnetoresistive devices with current perpendicular to the plane, 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. Measured data have been compared to numerical simulations of the device dynamics to determine the ability of current theory and modeling to predict the behavior of magnetic devices.

We are developing new techniques to measure the high-frequency noise and effects of thermal fluctuations in small magnetic structures. Understanding the detailed effects of thermal fluctuations will be critical in determining the fundamental limit to the size of magnetic sensors, magnetic data bits, and MRAM elements.

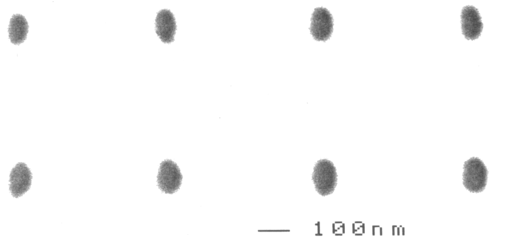
We are developing new techniques to measure the electronic and magnetic properties of magnetic thin-film systems *in situ* (as they are deposited). One such technique, *in-situ* magnetoconductance measurements, can determine the effects of surfaces and interfaces on spin-dependent transport in a clear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

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.

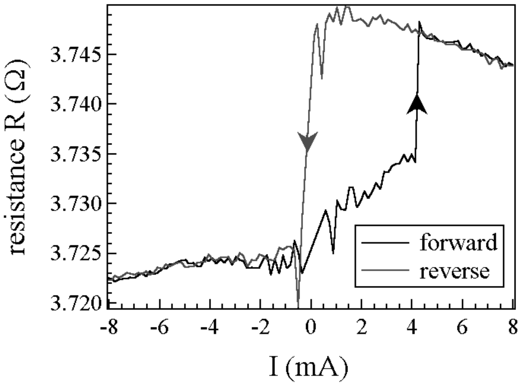
Finally, we are exploring new physical effects to create the foundation to develop entirely new technologies relying on spin-dependent transport at the quantum level. We are investigating the use of spin-momentum transfer to induce a dynamical response for microwave and high-speed signal processing systems. 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

- In 2002, we will fabricate spin valves, 100 nanometers in size, and measure switching and precession induced by spin-momentum transfer.



Micrograph of multi-layer, giant-magneto-resistive (GMR) perpendicular spin-valves, about 100 nanometers in size.

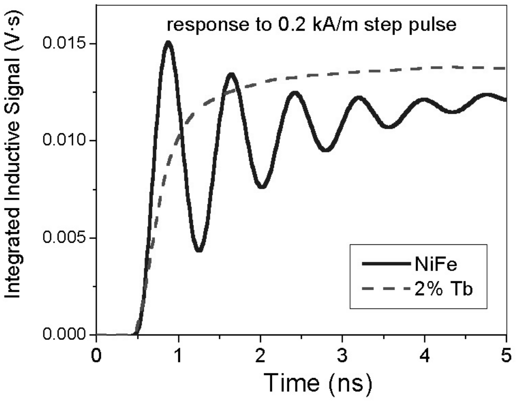


Plot showing the switching of the magnetization due to the injection of a spin-polarized current.

- During 2002, we will measure the high-frequency noise in submicrometer giant-magnetoresistive **(GMR)** devices to assess the fundamental size limits of GMR sensors.
- In 2002, we will design and fabricate a spin trap using GaAs heterostructures and develop measurement techniques to determine spin properties in small spin packets.
- In 2003, we will develop a practical on-wafer system to measure magnetostriction.
- In 2003, we will characterize the superparamagnetic transition in a single magnetic nanoparticle.

Accomplishments

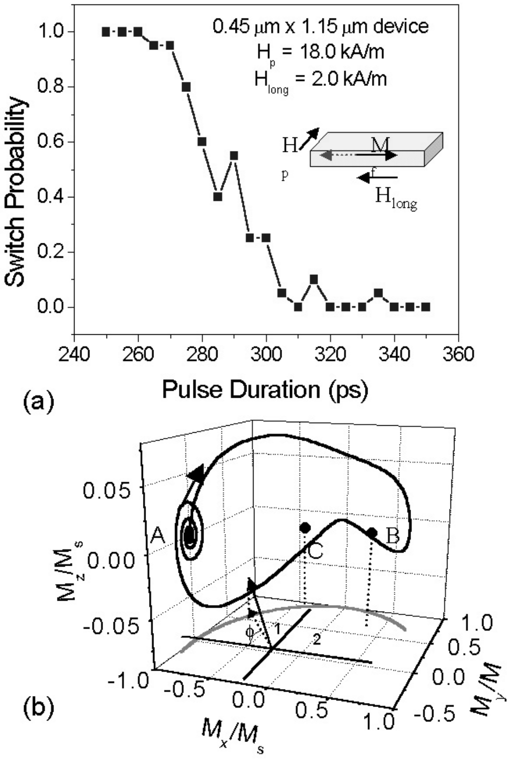
- Rare-Earth Doping Used to Control High-Speed Dynamics of Magnetic Data Storage Components — We have explored the use of rare-earth dopants to control the high-speed dynamics in magnetic thin films used in magnetic recording heads and magnetic random access memory **(MRAM)**. We discovered that a small amount of Tb dopant in Ni-Fe films can dramatically increase the magnetic damping without substantially changing the other magnetic properties. The films can be engineered to be underdamped, critically damped, or overdamped by varying the dopant concentration from 0 to 4 percent. High-speed measurements were made at frequencies up to 6 gigahertz by means of a pulsed inductive technique developed in the Magnetodynamics Project. Rare earths have long been known to increase magnetic damping in ferrite materials used in microwave devices. For microwave applications, damping is undesirable, and efforts have concentrated on eliminating rare-earth impurities. However, for magnetic-data-storage applications, critically damped behavior is desirable to prevent ringing and magnetic turbulence when magnetic elements are rotated or switched. For instance, a typical "spin-valve" read sensor, in response to a 250 picosecond pulsed field from a magnetic bit, will ring for approximately 2 nanoseconds after the applied bit field. Similarly, when an MRAM element is switched, the magnetic energy will cause the element to oscillate or break up into a disordered high-temperature magnetic state. The switching properties of the element will be dramatically altered until the magnetic energy is removed from the system. This can lead to undesirable switching in MRAM arrays if the clock speeds are faster than the magnetic cooling rate. Further temperature-dependent measurements and characterization of films doped with different rare earths indicate that the increased damping is due to local lattice distortions at the rare earth sites due to anisotropic orbitals that are strongly coupled to the film magnetization. The ability to engineer the high-speed dynamical properties of magnetic systems will become critical in the next few years when both magnetic recording and MRAM operation will be pushed into the gigahertz regime.



Plot of the magnetization response of a $Ni_{80}Fe_{20}$ film showing underdamped behavior and of a 2 percent Tb-doped $Ni_{80}Fe_{20}$ film showing critical damping.

- Precessional Switching in Magnetic Memory Devices Demonstrated — A particular type of thin-film magnetic device called a "spin-valve" 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 magnetic random access memory **(MRAM)**. Companies such as IBM, Motorola, and Honeywell are actively developing MRAM.

A primary technical requirement is precise control of the switching of individual devices. We have been studying the dynamics of magnetization reversal in spin-valves. 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.



(a) Switching probability of a 0.4 micrometer × 1.1 micrometer spin valve as a function of transverse field pulse width. The decrease in switching probability as the pulse width increases is an indication of precessional switching. (b) The trajectory of the magnetization: point A is the initial position; if the pulse is turned off between points B and C, the bit will switch.

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 have discovered a way to switch the devices using field pulses with durations of less than 300 picoseconds directed perpendicular to the easy axis. The magnetization is reversed due to large-angle precessional motion. For pulses of longer duration, 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.

- Combinatorial Libraries: Phase Diagrams on a Chip — The first NIST magnetic combinatorial thin-film libraries were fabricated and characterized in collaboration with the NIST Materials Science and Engineering Laboratory **(MSEL)** and Veeco Instruments. We fabricated Ni-Fe-Co-Tb compositional libraries and distributed them to collaborators for measurements. The libraries, fabricated on 7.6 centimeter wafers, contained 400 sites, each 2 millimeters on a side with a different elemental composition. MSEL performed X-ray diffraction measurements to determine microstructure, Veeco characterized the libraries with scanned magneto-optic Kerr effect **(MOKE)** magnetometry, and we measured the magnetic properties using alternating-gradient-field and superconducting-quantum-interference-device **(SQUID)** magnetometers. Additional libraries were provided to MSEL to assist in the development of on-wafer magnetostriction measurements. The libraries showed a complex phase diagram with several different microstructural and magnetic regions with dramatically different properties. The library contained regions of in-plane magnetization, out-of-plane magnetization, isotropic magnetic properties, and paramagnetic behavior.

The goals of this initial magnetic combinatorial program were to fabricate libraries of technological interest with a complex phase diagram, challenge the existing metrologies to determine whether they could efficiently and completely characterize the libraries, determine what type of new metrologies will be needed for successful application of combinatorial techniques to magnetic systems, and to create awareness in the magnetic technology and metrology community of the potential and requirements of magnetic combinatorial techniques. These goals have all been met and have set the stage for a more comprehensive program to develop the methodology and metrology required to implement combinatorial techniques to assist in the development of advanced magnetic data storage and magneto-electronic materials. Several magnetic-data-storage companies are interested in this program and have expressed the opinion that, due to the complexity of the magnetic materials being used, and the need to develop and implement these complex materials quickly, systematic materials development techniques will be essential.

- Effect of Surfaces and Interfaces on Magnetoresistance — Using a recently developed *in-situ* magnetoconductance technique, we completed an analysis of the effects of surfaces and interfaces on electron scattering in spin-valve devices. The measurements demonstrated the ability to precisely characterize changes in electron transport due to atomic-level changes in surfaces and interfaces. The spin-valves were similar to those being developed for magnetic-recording read heads, and consisted of multilayers of NiO/Ni-Fe/Co/Ru/Co/Cu/Co/X, where the top layer X was varied to included noble metals, transition metals, and oxides. The magnetoconductance was measured during deposition after every 0.25 monolayer of deposition. The variation of the conductance provides information on the scattering and added conductance channels of each added monolayer, while the magnetoconductance provides information on the spin-dependent scattering. It was found that the increase in magnetoconductance, as the thickness of the free layer was increased, could not be explained by simple semiclassical transport models that predict that the saturation length should be equal to the elastic mean free path in the free layer. Measurements of the effects of nano-oxide layers **(NOL)** further revealed that the increase in magnetoresistance due to the NOL did not, as predicted by simple transport models, scale with free-layer thickness. These models assume the magnetoresistance change can be described semiclasically by a changing surface specularity due to NOL formation. Our work has shown that more complete quantum-mechanical models are required for quantitative description of electron transport. These measurements provide a more accurate and precise characterization of spin-dependent transport in giant magnetoresistance systems than was previously available. This type of characterization is an essential first step in the development models that can quantitatively describe and predict the performance of magnetic devices being developed for magnetic-data-storage applications.

Recent Publications

S. E. Russek, P. Kabos, R. D. McMichael, C.-G. Lee, W. E. Bailey, R. Ewasko, S. C. Sanders, "Magnetostriction and Angular Dependence of FMR Linewidth in Tb-doped NiFe Thin Films," submitted.

R. D. McMichael, D. J. Twisselman, J. E. Bonevitch, P. J. Chen, W. F. Egelhoff, and S. E. Russek, "Ferromagnetic Mode Interactions in Periodically Perturbed Films," submitted.

S. E. Russek, P. Kabos, T. J. Silva, F. B. Mancoff, D. Wang, Z. Qian, and J. M. Daughton, "High Frequency Measurements of CoFeHfO Thin Films," IEEE Trans. Magn. **37**, 2248-2250 (July 2001).

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).

S. E. Russek, W. E. Bailey, G. Alers and D. L. Abraham, "Magnetic Combinatorial Thin-Film Libraries," IEEE Trans. Magn. **37**, 2156-2158 (July 2001).

W. E. Bailey, P. Kabos, F. B. Mancoff, and S. E. Russek, "Control of Magnetization Dynamics in $Ni_{80}Fe_{20}$ Thin Films Through the Use of Rare-Earth Dopants," IEEE Trans. Magn. **37**, 2248-2250 (July 2001).

S. E. Russek and S. Kaka, "Time and Frequency Domain Measurements of Ferromagnetic Resonance in Small Spin-Valves," IEEE Trans. Magn. **36**, 2560-2562 (September 2000).

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).

S. E. Russek, J. O. Oti, and Y. K. Kim, "Switching Characteristics of Spin Valve Devices Designed for MRAM Applications," J. Magn. Magn. Mater. **198-199**, 6-8 (July 1999).

S. E. Russek, T. M. Crawford, and T. J. Silva, "Study of NiFe/Al/Al2O3 Magnetic Tunnel Junction Interfaces Using Second-Harmonic Magneto-Optic Kerr Effect," J. Appl. Phys. **85**, 5273-5275 (April 1999).

P. Rice and S. E. Russek, "Observation of the Effects of Tip Magnetization States on Magnetic Force Microscopy Image," J. Appl. Phys. **85**, 5163-5165 (April 1999).

S. E. Russek, J. O. Oti, S. Kaka, and E. Y. Chen, "High Speed Characterization of Submicrometer Giant Magnetoresistive Devices," J. Appl. Phys. **85**, 4773-475 (April 1999).

Standards for Superconductor Characterization

Project Leader:
Loren Goodrich

Staff-Years (FY 2001):
1 professional
0.7 technician

Funding Sources:
NIST (90 %)
Other (10 %)

Goals

This project develops standard measurement techniques for critical current 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, and superconducting bearings. Project members assist in the creation and management of international standards for superconductor characterization covering all commercial applications, including electronics. The project is currently focusing on critical-current measurements of marginally stable superconductors, on temperature-variable critical-current measurements, and on measuring the irreversible effects of changes in magnetic field and temperature on critical current.

Ted Stauffer and Loren Goodrich performing a demonstration with a levitated model train at the NIST-Boulder Centennial Open House.

Customer Needs

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

The potential impact of superconductivity on electric-power systems makes this technology very 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.

Technical Strategy

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. Another activity is the measurement of the magnetic hysteresis loss in superconductors. 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)**.

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, specimen heating, from many sources during the measurement, can cause a wire to appear to be thermally unstable.

Deliverables

Standards

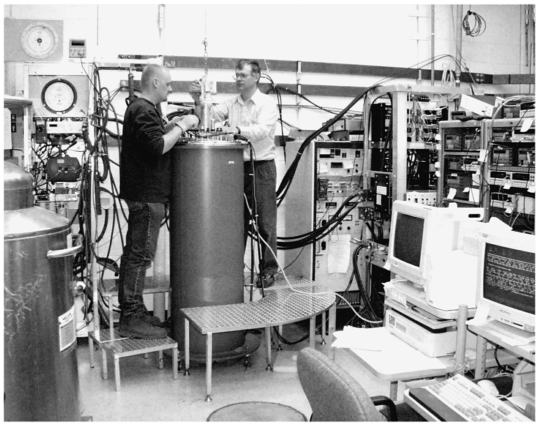
- During FY 2002, we will continue to solicit and incorporate comments from U.S. participants in IEC/TC 90 standards development. We will review, edit, and comment on draft standards in the 11 Working Groups in IEC/TC 90.
- During FY 2002, Loren Goodrich will continue to serve as Chairman of IEC/TC 90 and manage and coordinate the development of standards for superconductivity.

Characterization of Superconductors

- During FY 2002-2004, we will further develop our variable-temperature critical-current measurement capability and provide a critical-current database to the U.S. Department of Energy, Office of Fusion Energy Sciences program. The primary focus will be on Nb_3Sn wires.

- During FY 2002-2004, we will develop routine high-current testing of marginally stable Nb_3Sn conductors for the U.S. Department of Energy, Office of High Energy Physics program. The commonly used techniques have been shown to be inadequate for many of the latest conductors. More precise measurements are needed to evaluate conductor performance and provide reliable feedback to the development process. The development of testing will involve input from the other U.S. testing laboratories and will likely include interlaboratory comparisons.

- During 2002, we will continue to provide measurements of critical current, residual resistivity ratio, and hysteresis loss for U.S. companies and national laboratories.



Ted Stauffer and Loren Goodrich preparing to measure the electrical transport properties of a superconducting wire.

Accomplishments

Standards

- IEC Technical Committee, Led by NIST, Publishes Five New Superconductivity Standards — Five new international standards on superconductivity were recently published by the IEC/TC 90. The documents are:

  - IEC 61788-3 Superconductivity - Part 3: Critical current measurement - DC critical current of Ag-sheathed Bi-2212 and Bi-2223 oxide superconductors

  - IEC 61788-4 Superconductivity - Part 4: Residual resistivity ratio measurement – Residual resistivity ratio of Cu/Nb-Ti composite superconductors

  - IEC 61788-5 Superconductivity - Part 5: Matrix to superconductor volume ratio measurement - Copper to superconductor volume ratio of Cu/Nb-Ti composite superconductors

  - IEC 61788-6 Superconductivity - Part 6: Mechanical properties measurement - Room temperature tensile test of Cu/Nb-Ti composite superconductors

  - IEC 60050-815 International Electrotechnical Vocabulary - Part 815: Superconductivity

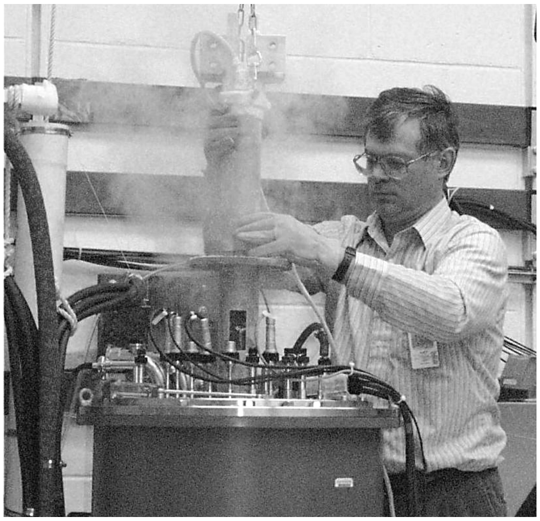
We have worked extensively on these documents and helped resolve many difficulties encountered during the development process. Loren Goodrich serves as Chairman of TC 90 and manages the international work. Thirteen countries participate in TC 90. The vocabulary was created under TC 90, but all vocabulary publications are listed under TC 1. This vocabulary contains 301 terms and their definitions. The standard on the critical current of oxide superconductors is the first IEC standard on the newer high-temperature superconductors. This brings the number of IEC TC 90 published standards to seven. Currently, seven more documents are at various stages of development within TC 90.

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

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

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

- Old Standards Withdrawn — The two American Society for Testing and Materials **(ASTM)** standards for superconductors were withdrawn, and Subcommittee B01.08 on superconductors was dissolved by Loren Goodrich, the former Chairman of B01.08. These two ASTM standards (B 713-82 and B 714-82) were used to draft parts of three IEC standards under TC 90. These two ASTM standards are now superseded by three IEC standards (IEC 61788-1, IEC 61788-2, and IEC 60050-815). The members of ASTM B01.08 had agreed that when these new IEC standards were published, then the above actions should be taken. These ASTM standards have served the superconductor industry well during the last 18 years, and they live on in the new IEC standards.



Loren Goodrich lowering a superconductor test fixture into liquid helium. The cloud at the top of the cryostat results from condensed moisture in air cooled by cold helium gas.

Characterization of Superconductors

■ Verified Performance of Conductor for Large Hadron Collider — A national laboratory involved in the U.S. program for the international Large Hadron Collider program asked NIST to conduct critical-current verification on several Cu/Nb-Ti strands. Loren Goodrich was a co-author on a paper that detailed the characterization of 2000 kilometers (about 18 tonnes) of superconducting strand for this program. The paper included an interlaboratory comparison among three laboratories on measurements of critical current, n-value, and residual resistivity ratio. This was the highest current comparison ever on a single strand (as opposed to a cable), with an average critical current of about 2000 amperes at 5 teslas and 4.2 kelvins.

In the conductor design, the amount of Cu stabilizer in the strand was kept to a minimum and additional high-purity Al and alloy Al were added to the cable to improve the stability and mechanical strength of the final product. However, the individual strands need to be tested before they are cabled in order to avoid introducing inferior strand into the cable, which would waste even more strand. This resulted in the need to develop new measurement procedures on strands that are designed to be marginally stable.

This type of work gives us the experience needed to develop future measurement standards and keeps us up to date on the latest conductors and measurements challenges. There is no good substitute for the experience and insight gained by performing routine measurements on the latest conductors in the advancing technology of superconductors. The unexpected scientific and practical discoveries continue to be reviewed by this work. The next accomplishment below, on a new source of misinterpretation in superconductor measurements, is one example.

■ New Source of Misinterpretation in Superconductor Measurements — As part of our program to develop standard measurement techniques for superconductors, we have identified and studied a new source of misinterpretation in critical-current measurements of superconductors. The critical current is the maximum current a conductor can carry before a quench, when it reverts to the normal, resistive state. Researchers can tell when the critical current is reached by measuring the resistive voltage on pairs of voltage taps soldered to the superconductor wires.

However, we discovered that anomalous inductive voltages can be induced in the loop formed by the voltage taps. The inductive voltages vary systematically with current, current sweep direction (increasing or decreasing), applied magnetic field, and whether the specimen was driven into the normal state in an immediately previous measurement. Furthermore, the decay time of the inductive voltage signal, after ending the current ramp, is longer near the onset of the resistive transition. These decay times are even longer during a superconductor's first current sweep after a quench.

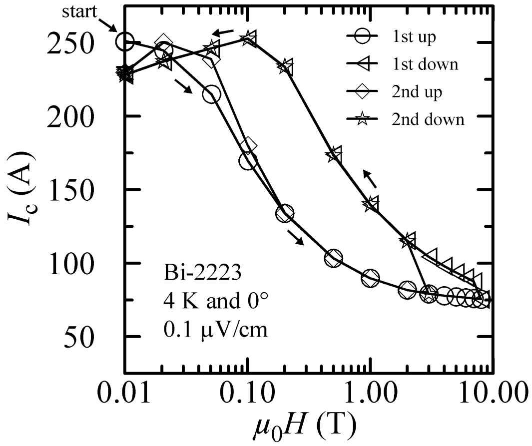
Many superconductor applications now require higher current densities, larger wire diameters, and less copper stabilizer, all of which results in marginally stable conductors with high critical currents above 1000 amperes. Variable induced voltages and long decay times become a concern when currents or current-ramp rates are high, or when voltage curves need to be extrapolated for measurements on marginally stable conductors. The resulting data can be mistakenly attributed to

(1) a bad conductor, (2) a damaged specimen, (3) an electrical ground loop, (4) a low critical current, or (5) specimen motion in the background magnetic field.

To avoid anomalous induced voltages, we recommend cycling the current before acquiring data after a quench, avoiding data acquisition while the current is being ramped, and allowing 3 seconds of settling time after current levels are changed before measurements are made near the critical current.

I think the new procedures developed and disseminated by Goodrich and Goldfarb have already allowed IGC-AS and the rest of the superconductor community to greatly improve their superconductor characterization.

Dr. Eric Gregory
Manager, Research and Development
IGC-Advanced Superconductors



Critical current versus magnetic field for Bi-2223 for various field-sweep directions. The order in the legend is the order in which these data were taken, and the arrows indicate the field-sweep direction.

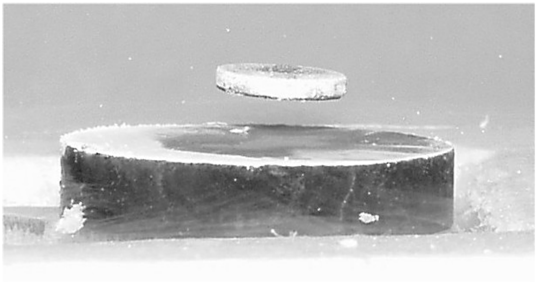
■ Critical-Current of Nb-Ti — We continue to provide critical current measurements of Cu/Nb-Ti samples for U.S. wire manufacturers. The current or magnetic field requirements are occasionally beyond their measurement capabilities. These measurements for a modest charge allow a small company to avoid the expense of maintaining specialized equipment and personnel.

■ Significant Paper on High Temperature Superconductors Published — We published a comprehensive paper on variable-temperature critical-current **(I_c)** measurement of oxide superconductors in the July-August 2001 issue of the NIST Journal of Research. This paper presents results on magnetic hysteresis in transport I_c measurements of Ag-matrix $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10-x}$ (Bi-2223) and AgMg-matrix $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) tapes. Magnetic hysteresis causes I_c to have a different value depending on the history of the magnetic field, the magnetic-field angle, and the temperature. This effect is completely reversible. The value of I_c at the same magnetic field, magnetic-field angle, and temperature can be different by as much as 74 percent, depending on what sequence of parameters the specimen experienced. Which value is *correct* is addressed in the context that the proper sequence of measurement conditions reflects the application conditions. The hysteresis in angle-sweep and temperature-sweep data is related to the hysteresis observed when the field is swept up and down at constant angle and temperature. The necessity of heating a specimen to near its transition temperature to reset it to an initial state between measurements at different angles and temperatures is discussed. A copy of this paper can be obtained at www.nist.gov/jres/ (NIST J. Res., vol. 106, no. 4, pp. 657-690).

■ Resistivity Measurement Problems Identified — We have been collaborating with a U.S. company and two U.S. universities on measurements of residual resistivity ratio **(RRR)** on high-purity Nb specimens. The RRR is typically defined as the ratio of the electrical resistivities measured at 273 kelvins (ice point) and 4.2 kelvins (in liquid helium). However, Nb is superconducting at 4.2 kelvins, so the low-temperature resistivity is defined as the normal-state resistivity *extrapolated* to 4.2 kelvins and zero magnetic field. 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. One future purchase is planned for 600 tonnes of high-purity Nb. There are two ways to obtain this extrapolated normal-state resistivity: measure the normal-state resistivity as a function of field at 4.2 kelvins and extrapolate to zero field, or measure the normal-state resistivity as a function of temperature in zero field and extrapolate to 4.2 kelvins. Both approaches have their difficulties, but it is generally thought that the extrapolation of the normal-state resistivity as a function of field at 4.2 kelvins has less uncertainty. Both approaches require the precise measurement of resistance as small as 0.5 micro-ohms on a specimen that resists wetting by solder.

We conducted an interlaboratory comparison of RRR measurements. The agreement and repeatability between results obtained at one university and NIST was within a few percent, which is quite acceptable. The difference between the average results obtained at another university and NIST was about 12 percent. That university's results also varied by more than 22 percent for five repeat measurements. We suggested seven changes to their procedure.

- Centennial Open House Demonstrations — We prepared new exhibits that demonstrate some of the properties of superconductors for the NIST-Boulder Centennial Open House on May 11-12, 2001. The demonstrations showed zero resistance, magnetic-flux expulsion (Meissner effect), a magnetic bearing, and levitated and suspended motion using high-temperature superconductors and Nd-Fe-B permanent magnets. An estimated 3000 visitors toured the NIST-Boulder site and we performed the demonstrations almost continuously for a total of about 12 hours. The suspended model train was received by the crowds with the most enthusiasm.



Demonstration of magnetic flux expulsion (Meissner effect) with a Y-Ba-Cu-O high-temperature superconductor cooled with liquid nitrogen. A Nd-Fe-B permanent magnet disk levitated when the superconductor cooled below its critical temperature.

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

B. Curé, B. Blau, D. Campi, L. F. Goodrich. I L. Horvath, F. Kircher, R. Liikamma, J. Seppälä, R. P. Smith, J. Teuho, and L. Vieillard, "Superconducting Strand for the Compact Muon Solenoid," IEEE Trans. Appl. Supercond., in press.

L. F. Goodrich and T. C. Stauffer, "Variable Mutual Inductance in Critical-Current Measurements," Adv. Cryo. Eng. (Materials), in press.

M. Takayasu, R. G. Ballinger, R. B. Goldfarb, A. A. Squitieri, P. J. Lee, and D. C. Larbalestier, "Multifilamentary Nb3Sn Wires Reacted in Hydrogen Gas," Adv. Cryo. Eng. (Materials), in press.

L. F. Goodrich, and T. C. Stauffer, "Hysteresis in Transport Critical-Current Measurements of Oxide Superconductors," NIST J. Res. 106, 657-690 (July-August 2001).

L. F. Goodrich and T. C. Stauffer, "Hysteresis in Transport Critical-Current Measurements of Oxide Superconductors," IEEE Trans. Appl. Supercond. 11, 3234-3237 (March 2001).

R. B. Goldfarb, L. F. Goodrich, T. Pyon, and E. Gregory, "Suppression of Flux Jumps in Marginally Stable Niobium-Tin Superconductors," IEEE Trans. Appl. Supercond. 11, 3679-3682 (March 2001).

L. F. Goodrich, L. T. Medina, and T. C. Stauffer, "High Critical-Current Measurements in Liquid and Gaseous Helium," Adv. Cryo. Eng. (Materials) 44, 873-880 (November 1998).

L. F. Goodrich, IEC/TC 90, "Superconductivity - Part 4: Residual Resistance Ratio Measurement - Residual Resistance Ratio of Nb-Ti Composite Superconductors," International Electrotechnical Commission International Standard IEC 61788-4 (July 2001).

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).

L. F. Goodrich, IEC/TC 90, "International Electrotechnical Vocabulary - Part 815: Superconductivity," International Electrotechnical Commission International Standard IEC 60050-815 (November 2000).

L. F. Goodrich, IEC/TC 90, "Superconductivity - Part 2: Critical Current Measurement - DC Critical Current of Nb3Sn Composite Superconductors," International Electrotechnical Commission International Standard IEC 61788-2 (March 1999).

L. F. Goodrich, IEC/TC 90, "Superconductivity - Part 1: Critical Current Measurement - DC Critical Current of Cu/Nb-Ti Composite Superconductors," International Electrotechnical Commission International Standard IEC 61788-1 (February 1998).

Superconductor Electromagnetic Measurements

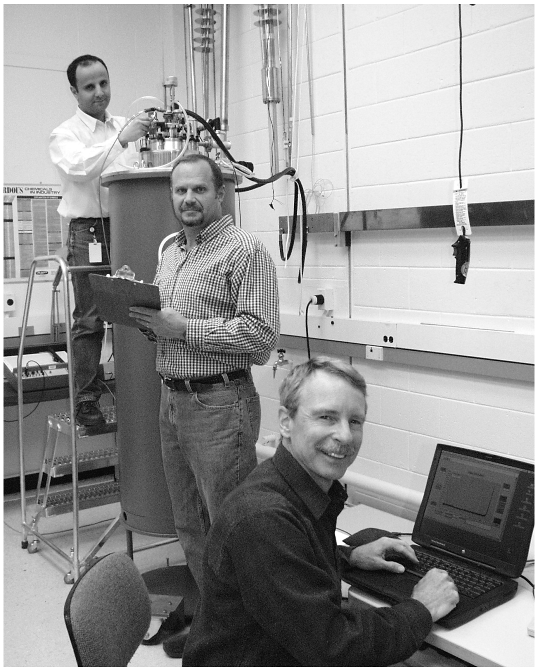
Project Leader:
Jack Ekin

Staff-Years (FY 2001):
1 professional
1 technician
1 research associate

Funding Sources:
NIST (25 %)
Other (75 %)

Goals

This project specializes in measurements of the effect of mechanical strain on properties of superconductors 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 on electrical contacts, which previously led to the first four-contact patents for high temperature superconductors, is being broadened to develop contacts with ultra-low interfacial resistivity for coated high-temperature superconductors.



Najib Cheggour, Cam Clickner, and Jack Ekin preparing to measure electromechanical properties of superconductor tape at 18.5 tesla field.

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 **(MRI)** industry, which provides invaluable medical data for health care, and contributes 2 billion dollars per year to the U.S. economy.

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 representing industrial suppliers, 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.

We have developed an array of specialized measurement systems to test the effects of mechanical stress 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. Among these measurement systems are apparatus for measuring the effects of axial tensile stress, the effects of transverse compressive stress, and the stress-strain characteristics, and a unique system for determining the electromechanical properties of reinforced superconducting composite coils.

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 and Y-Ba-Cu-O), 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.

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.

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

Electromechanical Performance of High-Temperature Superconductors

- In FY 2002, we will perform cryogenic mechanical testing of metal substrates for RABiTS and IBAD development.
- During FY 2002-2003, we will perform parametric *transverse* stress studies of YBCO coated IBAD and RABiTS conductors at 76 kelvins.
- During FY 2002-2003, we will perform parametric *axial* tensile strain studies of YBCO coated IBAD and RABiTS conductors at 76 kelvins.
- During FY 2002-2003, we will perform axial tensile strain and transverse stress measurements of new BSCCO conductors.
- In FY 2002, we will complete a preliminary survey of axial strain and transverse stress effects in recently discovered MgB_2 tape conductors.

Electromechanical Performance of Low-Temperature Superconductors

- In FY 2002, we will complete the data set of axial strain and transverse stress effects in two series of Nb_3Sn tape conductors, and measure the Young's modulus at 4 kelvins in these two samples in order to relate stress and strain for developing a multidimensional model.
- In FY 2003, we will complete the data correlation and determine the hydrostatic and deviatoric coefficients to generalize the Strain Scaling Law from one to three dimensions. Publish a generalized 3-dimensional model of strain effects in A-15 superconductors for use within finite-element strain designs of large superconducting magnet systems.
- In FY 2003, we will publish a paper on the results of the study testing the correlation of uniaxial strain effect with phonon anharmonicity in the A-15 superconductors.

Textbook on Cryogenic Measurement Apparatus and Methods

- During FY 2002, we will edit the introduction and chapters on heat transfer and on superconductor critical-current measurement techniques and analysis.
- In FY 2003, we will complete the appendix and send the book to the publisher.

Accomplishments

- Magnetic Substrates Shown to Reduce the Performance of Y-Ba-Cu-O Coated Conductors — Measurements on Y-Ba-Cu-O coating on buffered pure-nickel RABiTS revealed the first experimental evidence that the use of magnetic substrates can result in a significant and reversible reduction of the current-carrying capacity of the tape when the tape is arranged in a stack of two or more layers. This configuration is readily used in many potential applications where one tape is wound on top of another, or crosses over another as in a braided cable. When the Y-Ba-Cu-O layer is sandwiched between two magnetic nickel substrates, the interaction of the top and bottom nickel layers increases the perpendicular component of magnetic flux at the superconductor tape edges, and hence reduces the critical current density of the tape.

Absolutely essential data are being generated here.

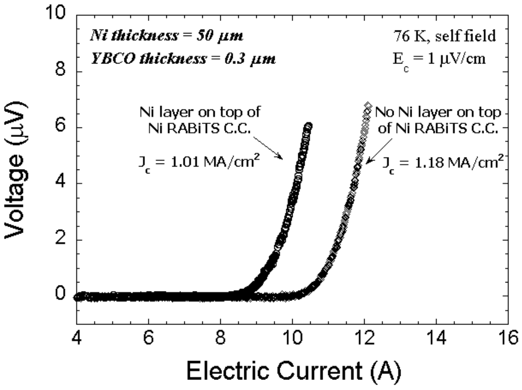
...

Excellent results. Such creation of basic engineering data is necessary for effective systems.

...

Important basic work, essential to successful system designs.

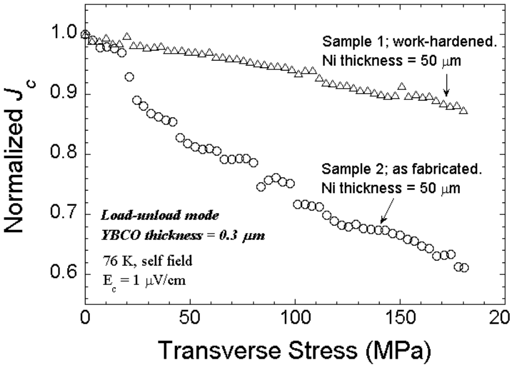
U.S. Department of Energy
Annual Peer Review
August 2001



First experimental evidence of a significant drop in J_c of coated conductors when a Y-Ba-Cu-O film is sandwiched between two magnetic substrates.

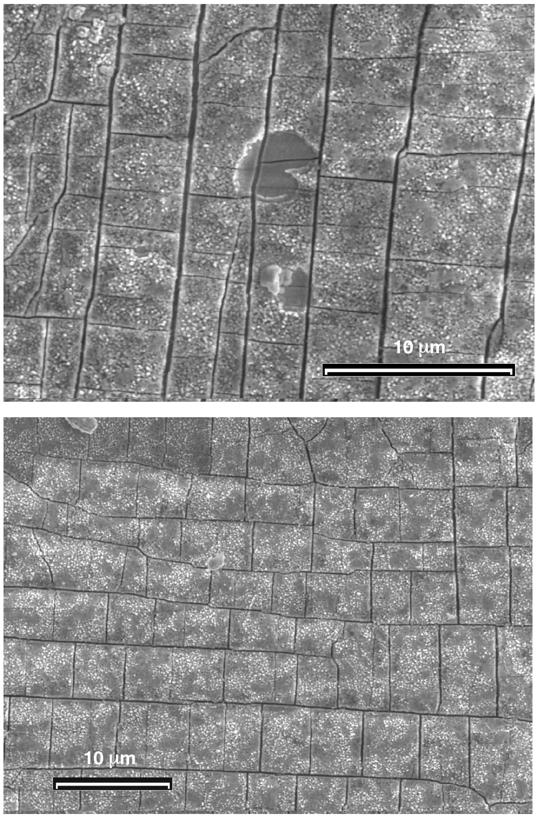
A model was successfully developed to quantify this phenomenon and showed that the reduction of the current-carrying capacity (**J_c**) depends on the geometry of the sample. The estimated drop in J_c can reach about 26 percent if the thickness of Y-Ba-Cu-O film is 1 micrometer and width is 3 millimeters, instead of 15 percent measured for tapes having a thickness of Y-Ba-Cu-O layer of 0.3 micrometer and width of 3 millimeters. The estimated drop in J_c for a thicker Y-Ba-Cu-O layer of 4 micrometers exceeds 40 percent. This information is highly relevant since the coated-conductors' manufacturers are developing tapes with thick Y-Ba-Cu-O layers (1 to 4 micrometers). This finding put more emphasis on the magnetic-substrate effect, which limits the potential use of Y-Ba-Cu-O coated conductors on magnetic buffered substrates, particularly in low-field applications such as underground power-transmission lines.

- Higher Yield-Strength Substrates Required for the Coated-Conductors to Achieve a Better Tolerance to Stress — Critical current measurements as a function of transverse compressive stress were made on Y-Ba-Cu-O coated conductors with textured pure nickel substrates. The results show that the tapes have much better tolerance to transverse stress when the soft nickel substrate is work-hardened. The samples tested under transverse compressive stress exhibit a degradation of the critical current density of about 28 percent at 100 megapascals. After work-hardening, however, the critical current density at 100 megapascals degraded by only 6 percent. This result lends support to the conclusion that substrate yield-strength is playing a major role. This suggests that in magnet applications using the coated conductors on soft substrates, a good practice would be to energize the magnet to its maximum magnetic field during the first run after manufacture in order to improve the robustness of the windings against transverse compressive stress. These results emphasize the need for development of non-magnetic substrates with higher yield-strength for RABiTS technology.



Effect of transverse stress on J_c in a Y-Ba-Cu-O film on pure nickel RABiTS. The results illustrate the role played by substrate work-hardening.

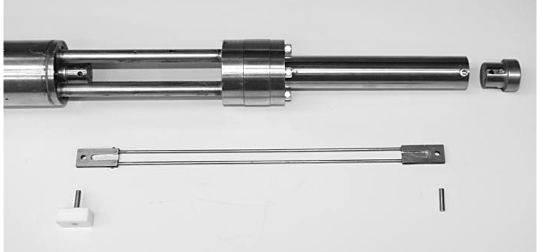
Microstructural characterization of the samples was carried out after static and cyclic transverse stress testing. Scanning electron microscopy **(SEM)** was used to examine the top Y-Ba-Cu-O layer of the samples. We found isolated regions of cracks both longitudinal and transverse to the direction of electrical current flow. The cracked regions are randomly distributed throughout the entire sample. These cracked regions cover areas in the sample that are a few micrometers to more than 600 micrometers wide. The total degradation of J_c correlates with the crack density in these defective regions. The cracks in the Y-Ba-Cu-O layer are found to extend through the buffer layers. The crack pattern, fundamentally different between RABiTS and IBAD samples we have studied previously, may reflect the influence of certain parameters on the robustness of the coated conductors, such as the mechanical properties of substrate material, the buffer layers, or the size of the Y-Ba-Cu-O grains.



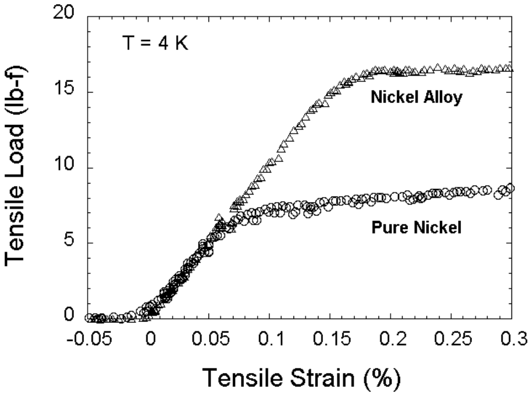
Scanning electron micrographs of the Y-Ba-Cu-O layer in RABiTS tape, after static and cyclic transverse-stress testing. Multi-patterned cracks in the Y-Ba-Cu-O and buffer layers are apparent. The vertical axis of the images coincides with the direction of the electric current applied to the sample.

■ A probe for measuring stress-strain characteristics developed — The mechanical test apparatus for axial stress-strain measurements required modifications to accommodate very thin, long and soft samples with very low yield strength.

We characterized mechanical properties of pure-nickel and nickel-alloy materials at room temperature, 76 kelvins and 4 kelvins. The two materials, which are candidates for use as substrates for Y-Ba-Cu-O coated superconductors, were compared in terms of yield strength, modulus of elasticity and proportional limit of elasticity. This information is important to the manufacturers in their selection of a suitable substrate material and in designing processing equipment for the manufacturing of the coated conductors.



Stress-strain measurements probe.



Stress-strain curves measured on pure nickel and nickel-alloy RABiTS materials, which are candidates for the fabrication of Y-Ba-Cu-O coated-conductors. The results show the benefit of developing nickel-alloy substrates for RABiTS technology.

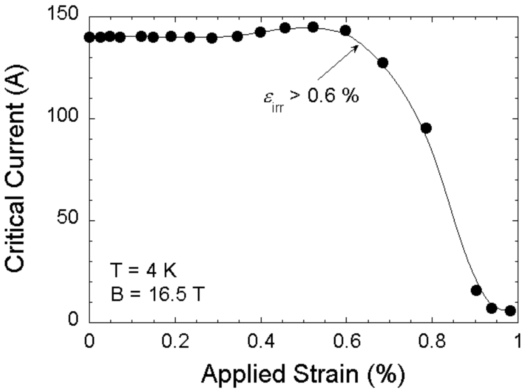
■ Superconductor Wire with High Niobium Content Has Unexpectedly Good Electromechanical Properties — The fabrication of the next generation of particle accelerators for high energy physics will require the development of new niobium-tin/copper superconductors able to carry extremely high current densities at high magnetic fields. One technique for accomplishing this is to push the density of superconductor in the composite wire to new limits. Such an experimental, high-niobium composite was recently fabricated by Oxford Superconducting Technology. A concern in the high-energy-physics community was that the conductor would have very low tolerance to mechanical strain. To test the conductor, we modified our axial electromechanical test apparatus and used a new 16.5 tesla, high-field magnet. Surprisingly, the conductor had electromechanical tolerance similar to standard Nb_3Sn composites. The irreversible strain, beyond which the conductor shows permanent degradation, had a relatively high value of 0.73 percent. The peak critical current was measured

The unique measurement services that Ekin, Cheggour, and Clickner have provided us and other U.S. wire manufacturers have allowed us to develop superconducting magnets of much higher field, helping our company compete in the international marketplace. Their critical current vs. strain instrument is one of very few in world, and their new, sensitive, stress vs. strain measurement apparatus at liquid-helium temperature is the only one in the U.S.

Dr. Seung Hong
Vice President, Engineering and Development
Oxford Superconducting Technology

at a strain of 0.29 percent. This result clears the way for wire manufacturers to push the niobium density to even higher values, which could provide a significant extension of the magnetic field limit of present accelerator magnets.

- Electromechanical properties of a new generation of Bi-2212 wires improved — The axial strain measurements carried out on a new generation of Bi-2212 multifilamentary wires at 16.5 teslas and 4 kelvins, revealed that the tolerance to strain of this conductor has been greatly improved. The irreversible strain at which the critical current density starts to degrade is found to be as high as 0.6 percent, representing an improvement by a factor of three with respect to early Bi-2212 wires made a decade ago. This new finding opens very promising perspectives for the use of Bi-2212 multifilamentary wires in fabricating large electromagnets for high-energy-physics accelerators. These new multifilamentary wires, developed by IGC, were designed so that the porosity of Bi-2212 powder is reduced. This resulted in a significant enhancement of both the critical current density and its tolerance to strain.



The tolerance to tensile strain of Bi-2212 multifilamentary wires has tripled compared to earlier Bi-2212 conductors made in the early 1990s. This improvement is a result of a substantial reduction in powder porosity.

Recent Publications

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), in press.

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

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).

Y. Xu and J. W. Ekin, “Tunneling Characteristics and Low-Frequency Noise of High-TC Superconductor/Noble-Metal Junctions,” Proc. 17th Symp. Energy Eng. Sci., U.S. Dept. of Energy, CONF-990001, 17-25 (November 1999).

P. E. Kirkpatrick, J. W. Ekin, and S. L. Bray, “A Flexible High-Current Lead for Use in High-Magnetic-Field Cryogenic Environments,” Rev. Sci. Instrum. **70**, 3338-3340 (August 1999).

Y. Xu, J. W. Ekin, and C. C. Clickner, “Low-Frequency Noise of YBCO/Au Junctions,” IEEE Trans. Appl. Supercond. **9**, 3990-3993 (June 1999).

Y. Xu, J. W. Ekin, C. C. Clickner, and R. L. Fiske, “Oxygen Annealing of YBCO/Gold Thin-film Contacts,” Adv. Cryo. Eng. (Materials) **44**, 381-387 (December 1998).

S. L. Bray, J. W. Ekin, and M. J. Nilles, “Fatigue-Induced Electrical Degradation of Composite High-Purity/High-Strength Aluminum Rings at 4 K,” Adv. Cryo. Eng. (Materials) **44**, 315-322 (December 1998).

Appendix A:
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Superconductor Electromagnetic Measurements

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Cam Clickner, 303-497-5441, clickner@boulder.nist.gov

Appendix B: Laboratory Facilities

Materials Preparation and Film Deposition

Computer-controlled, ultrahigh-vacuum deposition system
Computer-controlled, ultrahigh-vacuum, multi-target sputtering system with in-situ measurement of magnetoresistance and scanning tunneling microscope*
Ultrahigh-vacuum surface-analysis system
Laser-ablation system
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
Furnaces for reacting superconductors

Structural Characterization

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

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 system*
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*
Micro-resonating torque magnetometer*
Spin-resolved secondary-electron emission spectroscopy*
Optical cryostat with split-pair superconducting magnet
Time-resolved magneto-optic Kerr effect system with vector sensitivity*

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*

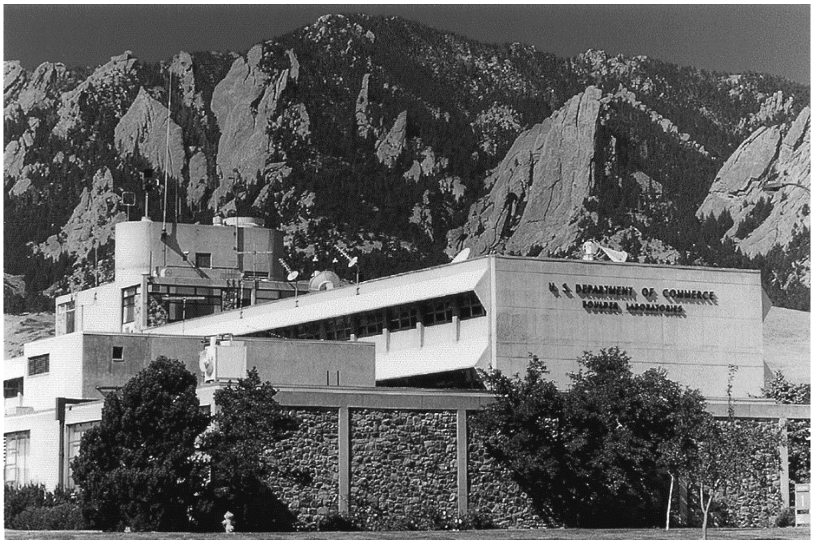
Characterization of Superconductors

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

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

Appendix C:
Postdoctoral Research Associateships

NIST offers postdoctoral 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 postdoctoral offerings are available at 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 postdoctoral 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 electric-power-utility applications and high-energy-physics accelerator magnets.

Measurements for Low-Critical-Temperature Superconductors

Contact: Jack Ekin, 303-497-5448

An interdisciplinary study of the physical, mechanical, and electrical properties of superconducting materials 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 for 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 ultrahigh-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 of, 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 ultrasensitive micro-cantilever. In principle, MRFM should have elemental identification capabilities with sub-angstrom 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 ultrasensitive 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 silicon 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.

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, ultrahigh 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.

Nanoscale Magnetic Structures

Contact: Stephen Russek, 303-497-5097

Ultrasmall 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 ultrasmall 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.

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-epsilon negative-mu (“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.

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 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-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, which includes mask generation facilities. Applicants are encouraged who have a strong experimental background in magnetism, especially in high-frequency magnetic phenomena such as ferromagnetic resonance.

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 preceding spins in a nanomagnet and direct diffusion across a forward-biased Shottky junction.

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 ultrahigh 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.

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 ultrahigh-vacuum sputtering system for the preparation of samples. Applicants with a strong experimental background in magnetism — especially magnetic thin-film preparation and characterization — are encouraged to apply.

Appendix D: 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 E:
Units for Magnetic Properties

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

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 F:
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		