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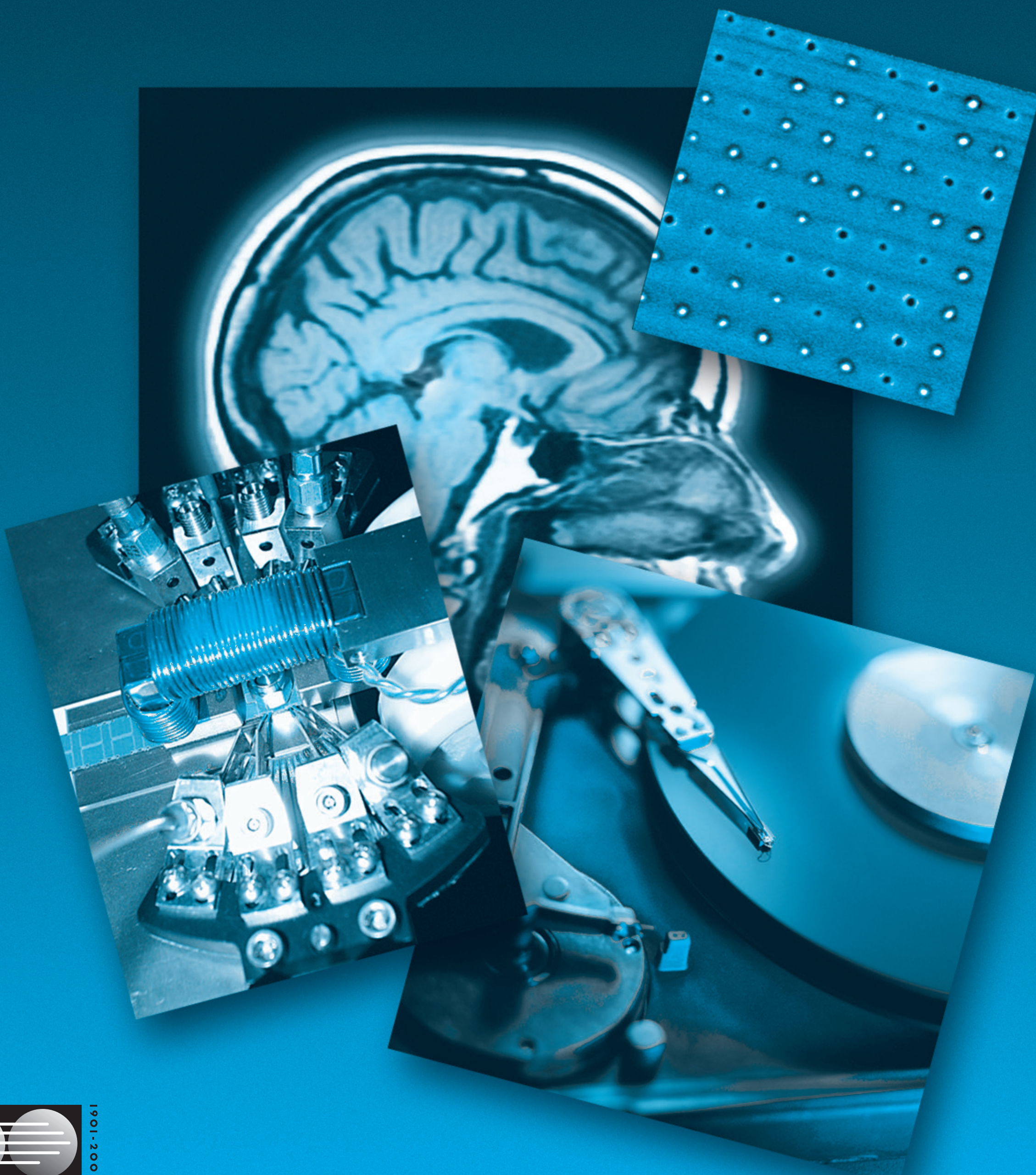
January 2001

Electronics and Electrical Engineering Laboratory

Magnetics Group

Programs, Activities, and Accomplishments



NIST CENTENNIAL 1901-2001

The cover illustrates some of the research areas of the EEEL Magnetics Group: magnetic calibration standards (magnetic-force microscope image of single-domain Co-Pt multilayer dots, 100 nanometers in diameter, upper right), improvements in data storage density and data-transfer rate (internal view of a computer hard disk, lower right), new measurement tools for the magnetic recording industry (inductive current probe for testing write heads, lower left), and metrology for the superconductor industry (magnetic-resonance image for medical diagnostics, background).

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EEEL Magnetics Group
National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80305-3328

Telephone: 303-497-5477
Facsimile: 303-497-5316
On the Web: http://www.eeel.nist.gov/magnetics

Contents

Welcome

The **Magnetics Group** develops and disseminates unique measurement technology for industries concerned with magnetic information storage and superconductor power. The group is located in Boulder, Colorado, part of the Electronics and Electrical Engineering Laboratory at NIST. It collaborates with the Magnetic Materials Group in Gaithersburg, Maryland, part of the Materials Science and Engineering Laboratory, in developing magnetic calibration standards and in the study of magnetodynamics.

Each of the group's projects is led by a senior scientist, often assisted by an engineer, technician, postdoctoral research associate, graduate or undergraduate student, or guest research scientist. The group has six projects:

- Magnetic Recording Measurements
- Magnetodynamics
- Nanoprobe Imaging
- Magnetic Thin Films and Devices
- Standards for Superconductor Characterization
- Superconductor Electromagnetic Measurements

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

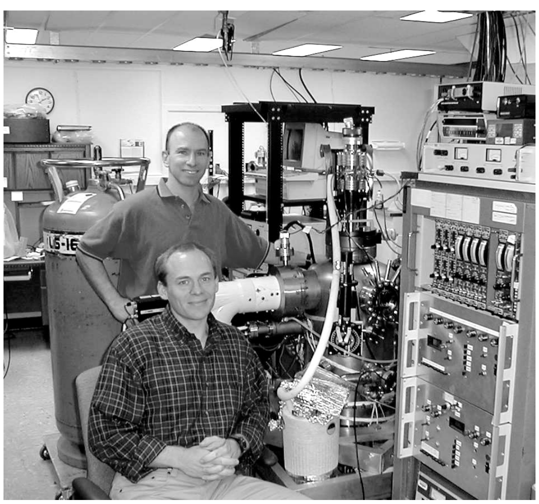
For additional information about the EEEL Magnetics Group, please visit our Web site at http://www.eeel.nist.gov/magnetics. Thanks for your interest in the EEEL Magnetics Group.

— Ron Goldfarb, Acting Group Leader

Magnetic Recording Measurements

Project 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 active inductive standards for magnetometers to standards for the determination of the absolute magnetic moment of thin magnetic films. 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 magnetic reorientation transition of ultra-thin (two atomic layers) films of iron on gadolinium as well the magnetic phase transition of the atomically clean gadolinium surface.



David Pappas and Steve Arnold in the Magnetic Recording Measurements lab.

Customer Needs

Magnetic data storage has been a growing industry this entire century. With the advent of widespread 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 has pushed quality assurance to its limit. This extends to a wide range of magnetic properties and requires magnetometers that are calibrated over many orders of magnitude in sensitivity. We are currently working on a number of novel methods to standardize 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 utilized. 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, three 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, an inductive magnetic-flux standard, and a zero-coercivity standard.

MILESTONE: In 2001, fabricate planarized magnetic/superconducting samples.

MILESTONE: By 2002, measure and standardize flux in integrated magnetic/superconducting samples.

Project Leader:
David Pappas

Staff-Years (FY 2000):
1 professional
1 contractor
1 student

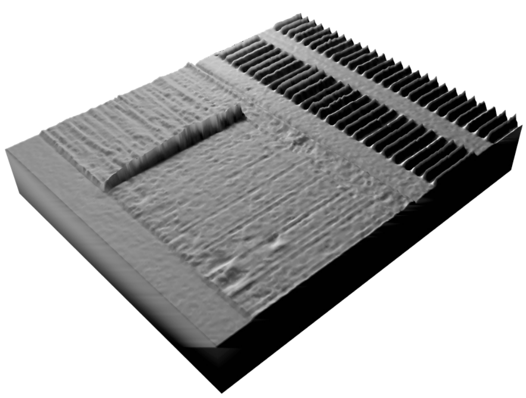
Funding Sources:
NIST (70%)
Other (30%)

Parent Program:
Magnetics

Three-dimensional perspective view of magnetic bits on recording tape. A section of the tape was erased and then "NIST" was written.

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.

MILESTONE: In 2001, develop high-speed, high-resolution metrology for magnetic recording tape.

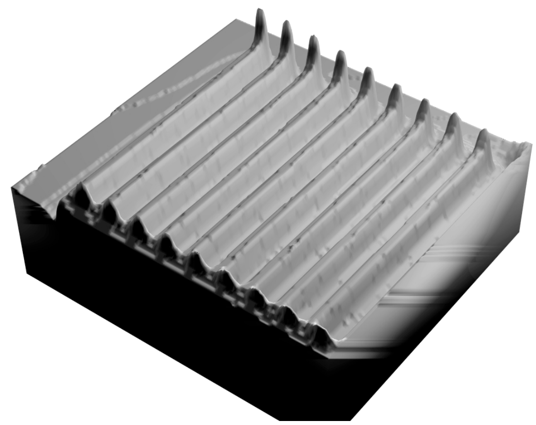


Magnetic fields above a sample of recording tape. A test tone was recorded from the left and right channels of a stereophonic system (rear, right). On the same tape, a stop mark from the write head of a monaural telephone-answering machine is imaged (front, left).

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

MILESTONE: In 2001, measure field distributions of current leakage in VLSI chips.



Three-dimensional plot of the magnetic fields 100 micrometers above a photolithographed meander line carrying 10 milliamperes of current.

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 characterize band structure.

MILESTONE: By 2002, measure spin-polarized electron excitations in magnetic quantum wells, both metallic and semiconducting.

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.

MILESTONE: By 2002, measure surface magnetism of magnetic semiconductors.

Accomplishments

- New Technique for Recovering Data — In collaboration with the National Telecommunications and Information Administration's Institute for Telecommunication Sciences, we developed a new technique for recovering audio and digital data from mangled tapes or other storage media that allows for much more complete and accurate analysis. Termed "second-harmonic magnetoresistive microscopy" (SH-MRM), this technique makes use of high-resolution magnetic sensors developed for modern computer hard-disk drives. These sensors are used to map the microscopic magnetic fields across samples, thereby allowing investigators to reconstruct the original signal and gain insight into the recording process and history. To forensics analysts, this can provide critical information regarding the authenticity of evidence. We have imaged a number of samples from other government laboratories. A demonstration of this technique was the recovery of audio data from a tape fragment provided by the NTSB laboratory. We showed that raw digital data can be read from a very short segment of tape from a flight data recorder. Small bits of tape are occasionally all that can be recovered from a major accident. While such segments may hold the key to the investigation, they are unreadable in a conventional tape deck. Images from sample audio cassette recordings provided by the FBI's Engineering Research Facility Audio Laboratory revealed magnetic marks produced by the erase and record heads during the recording process. In the hands of experts, these data may allow for authenticity verification. It was shown that the audio data from test tracks can be reconstructed and played back directly from the SH-MRM images. This information is independent of the normal inductive read process, and can be critical in the evaluation of recorded evidence produced for federal criminal-law cases.

- IDEMA Task Force — In collaboration with the International Disk Drive Equipment and Materials Association (IDEMA), we participated in a task force to (a) write a standard method for measuring magnetic properties and (b) design a new interlaboratory comparison to test the written standard. The study will include industry and instrument manufacturers and is targeted at understanding the needs of the industry and how NIST and the instrument manufacturers can accommodate them.

- Magnetic Thin-Film Standards — We manufactured wafers comprised of thin-film magnetic coupons with integrated superconducting flux measurement loops. These samples will be tested for use as thin-film magnetic Standard Reference Materials. The effects of planarization of the spacer layers between the magnetic and superconducting films is ongoing.

- Solenoid Flux Standards — A process was developed for fabricating thin-film solenoid flux standards. This involved fabricating two layers of Cu wires separated by an insulating polyimide layer, with via conductors between the two layers. Special lithographic features were incorporated for accurate determination of the solenoid dimensions, such as the thicknesses of the Cu and polyimide layers. The first flux prototypes have been completed, and tests are underway.

- Models for Flux Standards — Mathematical models were conducted for the active magnetometer calibration sample that showed that field accuracy of better than 1 percent is feasible in a 1 nanoweber standard. The models showed that, within 1 percent, the flux was relatively insensitive to typical errors in solenoid positioning in the magnetometer. It was found that Dy_2O_3-based paramagnetic samples would satisfy the requirements of a zero-coercivity standard. The key material properties are high paramagnetic permeability, high chemical purity, and low electrical conductivity. The target flux for the present standard is 10 milliwebers per tesla while producing less than 1 picoweber in remanence due to eddy-current artifacts in a field of 0.02 tesla. Tests on the first prototype zero-coercivity reference sample are underway.

- Surface Studies of Ultrathin Fe Layers on Thin Gd(0001) — We showed that this system has a two-step reorientation transition as the temperature is increased. At low temperatures, the Fe remains in-plane, antiferromagnetically coupled to the Gd. At the intermediate temperature, the Fe/Gd surface undergoes a continuous rotation to a canted direction. Because the exchange coupling in Gd is small, domain walls are narrow, and we expect an inhomogeneous magnetization depth profile in the Gd thin films in this intermediate temperature range. Available models in ultrathin films assume a homogeneous magnetization and exclude the coexistence of continuous and discontinuous behavior within one 90 degree reorientation. The inclusion of a magnetization depth profile is probably necessary to reveal the underlying physics in this system.

- Surface Magnetization of Rare Earths Measured — It has long been believed that some rare-earth metals (e.g., Gd and Tb) have a surface that is so much more magnetic than the bulk that the critical temperature, where long-range order vanishes, is higher than that in the bulk. Some studies indicated possible enhancements of 30 to 80 degrees. We have concluded an extensive study of the Gd surface and find that there is no enhanced surface critical temperature. The study required temperature measurement, the analysis of spins of electrons emitted from the surface, and the measurement of light ellipticity from the sample with unprecedented accuracy. This startling result illustrates some of the pitfalls and shortcomings of existing techniques, including interpretations of electron spectroscopy data.

Recent Publications

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,” Conf. on Law Enforcement Technology, Proc. SPIE, in press.

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, “Second and First Order Phase Transitions in the Magnetic Reorientation of Fe/Gd,” Phys. Rev. Lett., **83**, 3305-3308 (October 1999).

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).

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).

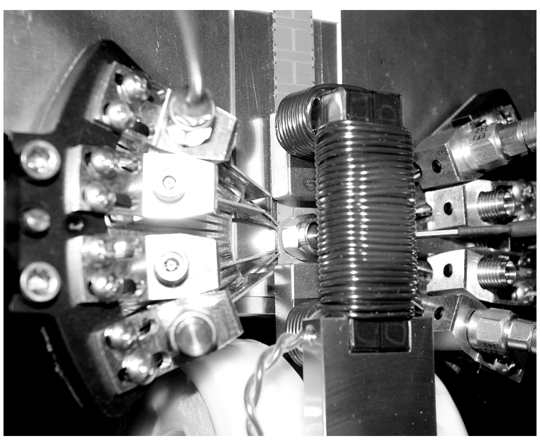
C. S. Arnold, M. Dunlavy, D. Venus, and D. P. Pappas, “Magnetic Susceptibility Analysis of the Relaxation-Time for Domain-Wall Motion in Perpendicularly Magnetized, Ultrathin 1.5 ML Fe/2 ML Ni/W(110) Films,” J. Magn. Magn. Mater. **198-199**, 465-467 (June 1999).

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 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 memories **(MRAM)**, and the growing spintronics community. Recent results 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.



Inductive current probe in microwave test station.

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 gigabits 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 then develop electronic components (e.g., heads, disks, or MRAM) that can fully exploit the bandwidth potential of the material. We are also 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.

MILESTONE: During 2001-2003, improve understanding of ferromagnetic switching processes.

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.

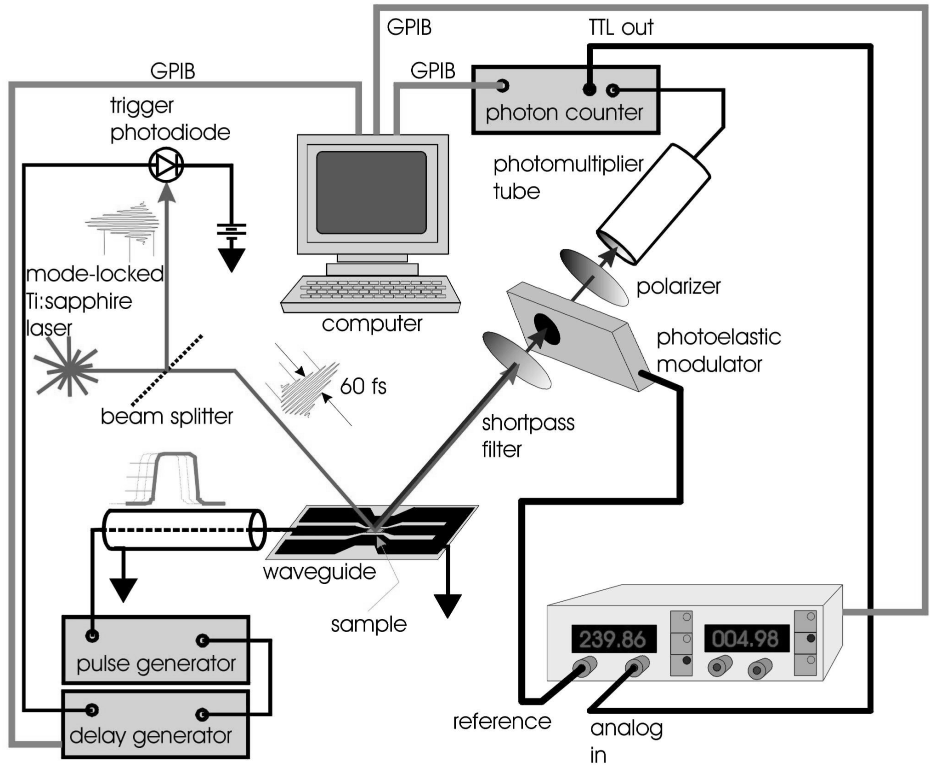
Data-transfer rates are increasing at 40 percent per year (30 percent from improved linear bit

Project Leader:
Tom Silva

Staff-Years (FY 2000):
2 professionals
1 postdoctoral associate
1 guest researcher

Funding Sources:
NIST (80%)
Other (20%)

Parent Program:
Magnetics



Simplified schematic of the TRe-SHMOKE system. This system can be used to evaluate the switching response of thin films to 7 gigahertz excitations.

Your experiments on very fast switching in magnetic films are well designed and incisive. They are exactly the right kind of experiments that should be done at an institution like NIST. It advances the science of metrology, and requires facilities, both human and economic, which will coexist in no other kind of institution.

Prof. Robert L. White
Director
Center for Research on Information Storage Materials
Stanford University

density and 10 percent from greater disk rotational speed). The maximum data-transfer rate is currently 50 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?"

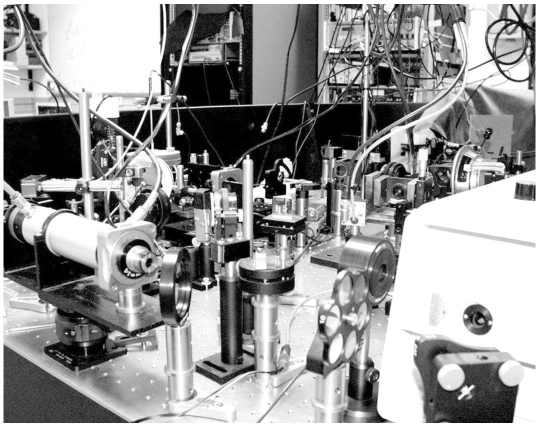
MILESTONE: By 2002, continue development of noninvasive inductive current probe for measurement of current rise-times in trace-suspension interconnects between disk-drive heads and write-current drivers.

MILESTONE: During 2001-2003, develop methods for the quantitative study of high-speed switching in ferromagnetic films.

The current laboratory demonstration record for storage density is 9 gigabits per square centimeter (60 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.

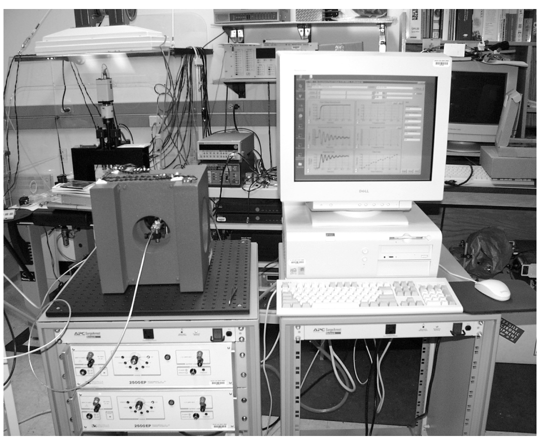
We have sought to extend magneto-optics for the quantitative measurement of magnetization dynamics in practical ferromagnetic films. Methods include time-resolved generalized magneto-optic ellipsometry **(TRe-GME)**, time-resolved second-harmonic magneto-optic Kerr effect **(TRe-SHMOKE)**, and quantitative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

- The magneto-optic Kerr effect **(MOKE)** makes use of the rotation of polarization of light upon reflection from a magnetized film. We have used MOKE with an optical microscope to measure equilibrium and nonequilibrium decay of magnetization in recording media.
- The second-harmonic magneto-optic Kerr effect **(SHMOKE)** is especially sensitive to surface and interface magnetization. We have used SHMOKE for time-resolved, vectorial measurements of magnetization dynamics and to demonstrate the coherent control of magnetization precession.



TRe-SHMOKE system for the measurement of magnetization dynamics with time resolution of 20 picoseconds.

▪ 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.



Pulsed inductive magnetometer for measuring the switching dynamics of thin magnetic films.

MILESTONE: Upgrade the PIMM to a self-contained user facility for use by industrial collaborators to measure switching speeds of standard and proprietary 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 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.

MILESTONE: By 2002, measure precessional dynamics in spintronic components using time-resolved magneto-optics.

MILESTONE: By 2003, investigate practical applications of spin-momentum transfer effect in magnetic heterostructures.

Accomplishments

▪ New Field Sources — We built two computer-controlled field sources that allowed our inductive current-probe measurements to be automated and improved the accuracy and consistency of our measurements. We have made dozens of measurements in a tenth of the time previously required. A bandwidth of 6 gigahertz has been achieved in the deconvolved results for the step-current rise time when using a supplemental bias field to improve the Ni-Fe response.

▪ New Theory for Damping in Ferromagnetic Resonance — We have developed a theoretical framework for understanding damping in ferromagnets. We analyzed the damping mechanism in the case of direct coupling between the electron spins and the crystal lattice within the context of the quantum-mechanical magnetodynamic

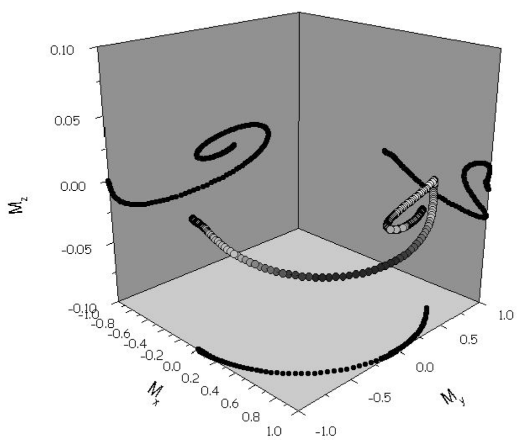
I am very impressed by the results that Tom Silva obtained with the high speed current probe that he designed, fabricated and tested. I was skeptical that any ferromagnetic material could be used in this context, but he did it and it works. This will be a valuable tool for diagnosing the write current in high-speed drive applications.

Dr. Mike Mallary
Quantum Fellow
Quantum Corporation

I have been especially impressed by the novel optical techniques for accurate time resolution of ultrafast spin dynamics. They provide, for the first time, clear experimental evidence for appreciable deviation from magnetization magnitude conservation for ultrafast magnetic switchings.

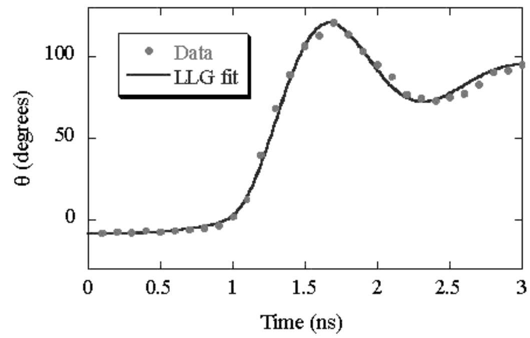
Prof. Isaak Mayergoyz
University of Maryland

equation originally proposed by Herbert Callen in 1958. Callen's landmark work analyzed the process of ferromagnetic relaxation as the sum of three distinct processes: direct coupling between the uniform precession and the lattice, dissipation via spin wave generation, and coupling of spin waves to the crystal lattice. We found that one can calculate the direct coupling term in the relaxation equation using conservation of angular momentum and a quantum-mechanical description of the fundamental spin relaxation process. An implication of the calculation is that the direct relaxation process is a function of the magnetization angle relative to the crystalline anisotropy axis. For magnetization oriented along the easy axis, direct relaxation is a maximum. For orientation along the hard axis, direct relaxation is forbidden by simple symmetry considerations. Thus, relaxation (damping) is dominated by spin-wave generation when the magnetization is orthogonal to the anisotropy axis.



Vector evolution of magnetization after application of field pulse along +x direction. The spiral-like path is the result of precessional dynamics for ferromagnetic spins.

■ Damping Theory Applied to Magneto-Optic Data — We used our new theoretical description of damping to interpret our recent SHMOKE data where we found that the magnitude of the magnetization can be strongly reduced immediately after application of a strong field pulse. The reduction occurred only if the magnetization was initially oriented along the hard axis prior to application of the pulse. We determined that the Callen model can be used to fit the time dependence of the magnetization reduction with a single fitting parameter: the quantum-mechanical rate of spin-wave generation. We found that the rate of spin-wave generation greatly increases for large pulses in excess of 560 amperes per meter. This has profound implications for the disk drive industry, where very large field pulses are routinely used in the operation of a recording head.



Time-evolution of magnetization after application of field pulse. Material is 50 nanometer thick Ni-Fe, a common magnetic alloy in disk-drive recording heads. The measured switching time of 500 picoseconds implies an intrinsic bandwidth of 700 megahertz. The solid curve is a fit to the data based on the Landau-Lifshitz-Gilbert equation.

■ Spins at a Surface: Are They Faster? — We are comparing surface and bulk magnetodynamics in thin films of Ni-Fe. Using second-harmonic and conventional forms of the magneto-optic Kerr effect (SHMOKE and MOKE) and measuring the response to a field pulse, we found that the surface and bulk dynamics are almost indistinguishable from each other. The ability to measure both effects simultaneously using the same pulsed laser source removes many possible sources of systematic error. Our error analysis will set quantitative bounds on the similarity of surface and bulk magnetodynamics. This study should be of great interest to those modeling dynamics in recording-head materials, where there is general disagreement as to the role of eddy currents.

■ Assessing the Performance of Chaff at RF — We extended our work on measurements of the resistance of carbon fibers to high frequencies. We are using two approaches: The first is a direct measurement of resistance calibrated against known resistors specified for 20 gigahertz operation. The second is a method using Fourier analysis of time-domain reflectometry measurements to extract resistance versus frequency. This method is simpler experimentally but requires more difficult analysis.

■ Amplifying the Electron Spin: A Proposed Spintronics Device — In collaboration with the Magnetic Thin Films and Devices Project, Cornell University, and Motorola Corporation, we developed a novel spintronics device concept: the spin amplifier. It is based on the recent experimental results at Cornell, where a resonant enhancement of the giant magnetoresistance was observed in nanoscale devices in the presence of large magnetic fields. According to the theory, the spins that constitute a ferromagnet enter a massively degenerate excited state at the bottom of the spin-wave spectrum under conditions of sufficiently large dc current, reminiscent of the stimulated emission process that drives a laser. We plan to use such a device for the injection and detection of coherently precessing spins in a semiconductor host. As a spin injector, a "SWASER" (spin-wave amplification by stimulated emission of radiation) is unique in that it prepares spins in a coherent superposition of "up" and "down" states (parallel and antiparallel to an applied magnetic field) before injection into a semiconductor. Such a coherent superposition has intrinsic, statistical advantages compared to a polarized spin current.

- Advanced High-Moment Head Material Benchmarked — In collaboration with the Materials Science and Engineering Department at Stanford University, we measured the switching speed of Fe-Co-N films with the PIMM system. Our collaborators at Stanford discovered that they can greatly improve the uniaxial orientation of sputtered, high-moment, iron nitride films through use of Permalloy ($Ni_{0.8}Fe_{0.2}$) as a seed layer. We found that the materials exhibit an intrinsic switching speed of 200 picoseconds, more than a factor of two faster than conventional head materials. The highest-quality films were surprisingly well damped in their precessional response. Such desirable response is coincident with the observation of an anomalous second-harmonic component in the time-resolved data that may contribute to the large damping. The physics of this effect are still under investigation.

- Flux Propagation Speed Measured in Recording Head Material — The spatial propagation of magnetic flux pulses launched in thin-film Ni-Fe were measured using TRe-SHMOKE. The energy propagation velocity, or "group velocity," was found to be 10^5 meters per second in a film that was 400 nanometers thick. Such a fast speed is consistent with the predictions of Damon and Eshbach's magnetostatic spin-wave theory. It was also found that the decay of the flux pulse was consistent with a damping parameter of 0.02. Such a value for damping is typical for Ni-Fe films. These results suggest that the usual quasi-static calculations for the recording efficiency of disk-drive heads may be erroneous in the limit of precessional dynamics.

Recent Publications

T. J. Silva and P. Kabos, "Non-Linear Magneto-Optical Observation of Transient Spin-Wave Excitation in a Ferromagnetic Film Undergoing Large-Angle Switching," IEEE Trans. Magn., in press.

P. Kabos, S. Kaka, S. E. Russek, and T. J. Silva, "Metastable States in Large Angle Magnetization Rotations," IEEE Trans. Magn., in press.

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).

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).

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/Al_2O_3 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).

We need the NIST sub-nanosecond switching, experimental, real-materials viewpoint.

Dr. Gordon Hughes
Associate Director
Center for Magnetic Recording Research
University of California at San Diego

Nanoprobe Imaging

Project Leader:
John Moreland

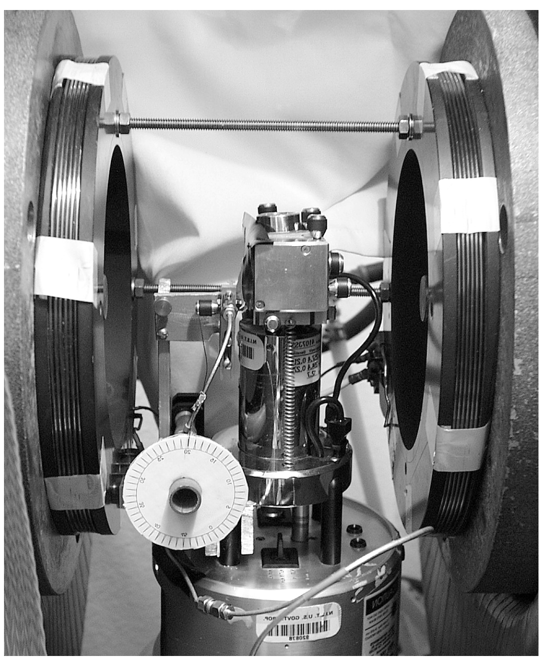
Staff-Years (FY 2000):
1 professional
1 postdoctoral associate

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

Parent Program:
Magnetics

Project Goals

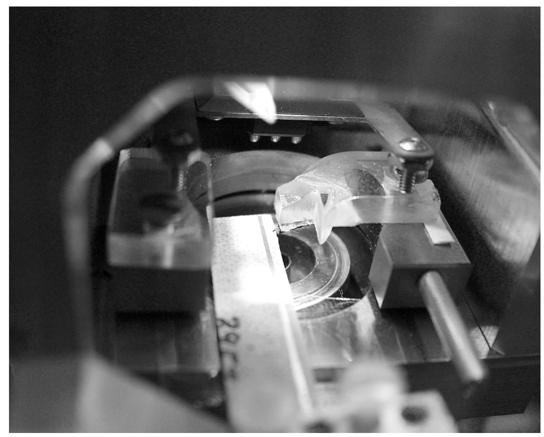
This project develops scanned-probe microscopy **(SPM)** and micro-electromechanical systems **(MEMS)** for nanometer-scale magnetic measurements in support of the magnetic data storage industry. Project members perform research to understand and relate SPM images and MEMS magnetometer measurements to the performance of magnetic materials and devices for future recording technologies. The project is currently focusing on ultra-small magnetic-force microscopy tips for imaging recording heads and media at a resolution of 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. Over the next few years, the project will work on a "magnetic resonance spectrometer on a chip" to achieve magnetic-resonance imaging resolution of 1 nanometer on ferromagnetic thin films. Recent research includes the development of new ferromagnetic resonance **(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.



Atomic-force microscope (AFM) head adapted for MEMS magnetometry. The head is placed in a precision dipole magnet for magnetic-moment measurements of magnetic films deposited onto the flat surface of an AFM cantilever. Measurements can be made at fields up to 1.2 teslas.

Customer Needs

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



Cantilever chip mounted near a microstrip resonator. The cantilever, fabricated in the new MEMS laboratory in Boulder, consists of a bilayer of silicon nitride and glass with a Ni-Fe FMR sensor deposited at the tip. Calorimetric detection of FMR occurs when the microwave heat absorption causes the bilayer to bend.

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 submicrometer magnetic resonance particles to ultrasensitive 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 ultrasensitive cantilevers and position the particles a few nanometers from the sample surface for field mapping with 1 nanometer resolution.

MILESTONE: High-frequency scanning probes — In 2001, compare capabilities of calorimetric, magnetic-moment, and spin-decay scanning ferromagnetic-resonance **(FMR)** probes.

MILESTONE: High-frequency scanning probes — In 2001, develop low-insertion-loss glass/nitride bimaterial cantilever FMR probes for high-resolution microwave power imaging.

MILESTONE: Recording studies — By 2002, develop micromachined nitride-membrane substrates for new magnetic imaging standard.

MILESTONE: Magnetic resonance imaging based on MRFM — By 2002, demonstrate force sensitivity at the 10^{-18} newton level with cantilevers fabricated in the MEMS fabrication facility.

MILESTONE: New MFM technology — In 2001, demonstrate sample-on-cantilever MFM.

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.

MILESTONE: Fabrication and integration — In 2001, optimize micro-torsional oscillator fabrication process for quantitative measurements with the micro-resonating torque magnetometer.

MILESTONE: Fabrication and integration — In 2001, demonstrate magnetic force and torque sensors with a sensitivity of 10^{-18} ampere meter squared per root hertz.

MILESTONE: Magnetic moment measurements — In 2001, demonstrate *in-situ* monitoring of thin-film magnetic moment during deposition.

MILESTONE: Magnetic moment measurements — By 2002, demonstrate *in-situ* monitoring of thin films with sub-monolayer (tenth nanometer) sensitivity.

MILESTONE: Spin-decay measurements — In 2001, develop torsion oscillators with isolated sub-micrometer magnetic dots.

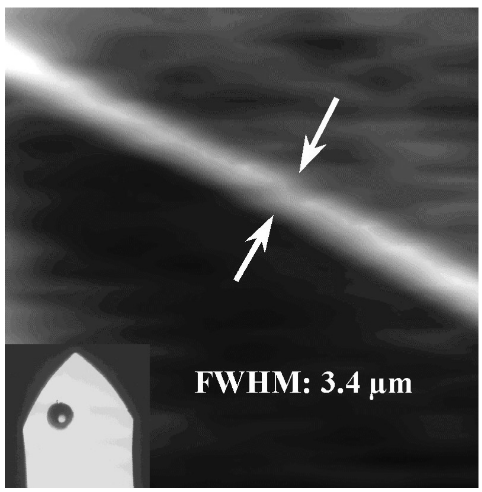
MILESTONE: Magnetic resonance imaging based on a MEMS sensor — By 2003, develop high-gradient, miniature electromagnets and rf coils.

I have been impressed by the research on ferromagnetic resonance imaging and development of multipurpose scanning probes. These probes can be used for high accuracy magnetometry and the measurement of angular momentum of rf magnetic fields.

Prof. Isaak Mayergoyz
University of Maryland

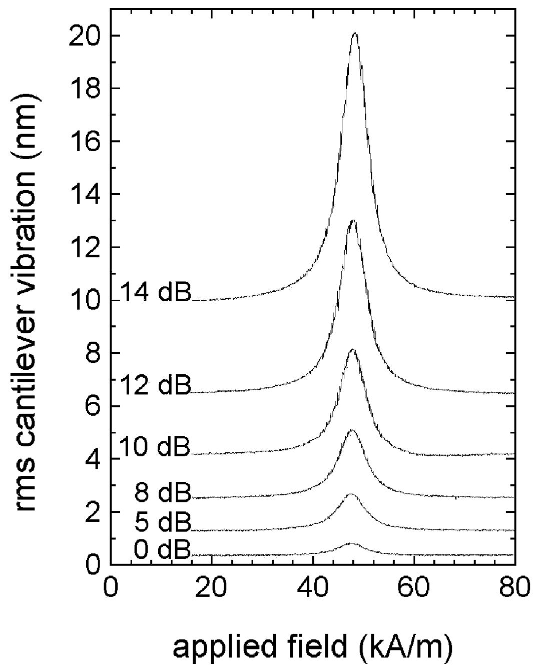
Accomplishments

■ New Scanning-Probe Microscope for Quantitative High-Resolution Imaging of Magnetic Fields in Magnetic Recording — The technique is based on technology recently developed in several laboratories in the U.S. and abroad for a new type of probe microscopy referred to as "magnetic-resonance force microscopy" (**MRFM**). High-resolution field mapping with an MRFM instrument relies on the combination of a small magnetic-resonance particle mounted on an atomic force cantilever that constitutes a very sensitive probe of local magnetic fields near a magnetic device. Magnetic-resonance phenomena are the basis for the most accurate measurements of magnetic fields.



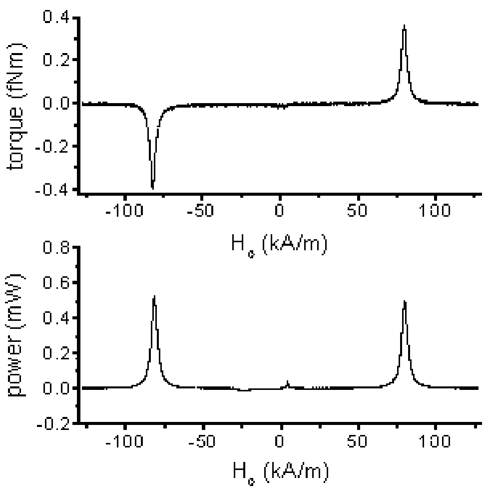
MRFM image of a magnetic field contour line above a small permanent magnet. The dimensions of the scanning probe (shown in the inset at the lower left) determine the resolution of the contour line image (3.4 micrometers). The probe is a diphenyl-picrylhydrazyl (DPPH) particle with a strong, narrow electron-spin resonance (ESR) absorption line. The scanned area is 40 micrometers by 40 micrometers.

■ New Ferromagnetic Resonance (**FMR**) Spectrometers Based on Micromechanical Sensors for Measurements of Magnetic Thin Films — The MEMS FMR spectroscopy probes are based on calorimetry, torque, and angular-momentum absorption. The sensors can be integrated into an atomic-force microscope for imaging local dc and rf magnetic fields. Spectra show a peak in the cantilever deflection as a function of applied magnetic field. This corresponds to a peak in the absorbed microwave power that occurs under FMR conditions for a given ferromagnetic film. The techniques are being investigated as potentially superior ways to make quantitative measurements of the saturation magnetization of thin-film samples with very small total magnetic moments.



Cantilever vibration caused by heating versus applied field for a 30 nanometer Co film at different relative input microwave power levels. Detection is based on the different thermal expansion coefficients of the Co film and the Si cantilever that cause the cantilever to bend when heated. The microwave power is chopped at 1 kilohertz in order to vibrate the cantilever. The data show the characteristic Lorentzian absorption line expected for FMR in Co.

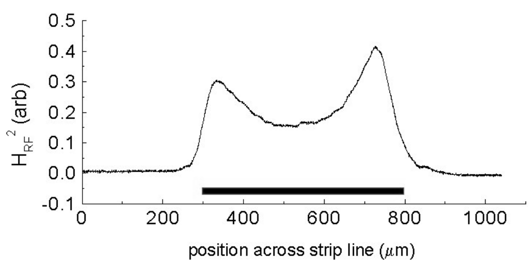
■ Micromechanical Detection of Energy and Angular Momentum Transfer in Ferromagnetic Resonance — A spinning top in a gravitational field undergoes precession. Similarly, a magnetization vector in a magnetic field precesses. For the precession to persist, microwave energy perpendicular to the static magnetic field must be supplied to the ferromagnetic material. In FMR, the natural damping of the precessional motion of magnetic spins in FMR results in a transfer of both energy and angular momentum to the crystal lattice of the ferromagnetic specimen. Absorption of the energy results in heating of the material, whereas transfer of the spin angular momentum results in a torque on the material. The source of the energy and angular momentum can be traced to the energy and angular momentum of the microwave photons that induce the resonance. This is one example of new micro-cantilever-based methods of magnetic metrology developed at NIST and the first demonstration of torque detection from angular momentum absorption in FMR.



Cantilever torque and power absorption as a function of applied field for a 30 nanometer Ni-Fe film deposited onto a Si cantilever. The torque is caused by the decay of spin angular momentum when FMR occurs in the film. By measuring the power-torque ratio as a function of resonance field, it may be possible to directly measure the saturation magnetization of a magnetic film without *a priori* knowledge of the gyromagnetic constant or the volume of the material.

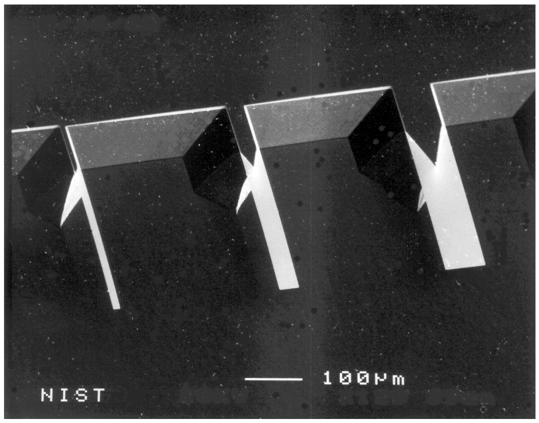
▪ Static Magnetic Field Imaging Based on FMR Scanning Probe — A Ni-Fe thin film probe patterned on the end of an atomic-force-microscope **(AFM)** cantilever is excited by FMR with microwaves from a stripline. Mechanical detection of FMR allows for the quantitative determination of local fields as the probe is scanned over the sample surface. The NIST instrument has demonstrated calibrated, two-dimensional magnetic-field mapping with lateral resolution of approximately 20 micrometers and field sensitivity of 50 amperes per meter. Several scanned-probe magnetic-imaging techniques based on the principles of AFM have been developed in the past decade. The most popular of these has been the magnetic-force microscope, because of its high resolution, simplicity, and robustness. However, it has proven difficult to quantify MFM results because the instrument images field gradients rather than fields. A calibration source with well-characterized field gradients on a 10 nanometer scale is needed to calibrate the response. Other scanned-probe techniques have been developed that are directly field sensitive. These use magnetoresistors, superconducting quantum interference devices, and Hall-effect sensors that can be calibrated with uniform magnetic fields. However, these sensors do not scale easily to sub-micrometer dimensions, and they require electrical connections, which makes it difficult to integrate them to the tip of a cantilever. Techniques that use mechanical detection eliminate the need to fabricate complex structures on the end of a cantilever.

▪ Microwave Scanning Probe Based on Mechanical Detection Ferromagnetic Resonance — The probe described above for static magnetic field measurements can also be used to measure microwave magnetic fields near microwave components. The local field measurements can be used to determine the current distribution in such devices. The probe is based on the bimaterial calorimeter affect. A special cantilever has been developed in our MEMS fabrication facility designed specifically for these measurements. It is a rectangular beam, 1 micrometer by 50 micrometers by 500 micrometers, consisting of glass and silicon-nitride films deposited by low-pressure chemical-vapor deposition **(LPCVD)**. These cantilevers have low rf losses compared to their Si predecessors and are therefore less intrusive as field probes.



Line scan over a microstrip resonator showing the variation of a 10 gigahertz microwave field H_{RF} as a function of position. Resolution is determined by the size of the FMR Ni-Fe probe, about 10 micrometers.

▪ First Micromachined Structures in New MEMS Facility — We have fabricated cantilevers and beams using a surface micromachining processes in which structures are made by patterning a low-stress nitride film on a sacrificial low-temperature oxide film grown on Si wafers. The cantilevers and beams are used to measure nonuniform and linear residual stress in the films to make sure the furnace reactor deposition process is within specifications. In addition, we fabricated Si cantilevers with a bulk micromachining process based on a silicon-nitride etch mask for anisotropic potassium-hydroxide etch. A series of cantilevers and T-bar torsional oscillators were fabricated for MEMS magnetometer applications. The furnace reactors provide the basic tools for both surface and bulk micromachining on Si wafers. The furnaces are capable of five processes, including dry and wet oxidation, boron doping, silicon-nitride deposition, polysilicon deposition, and low-temperature silicon-oxide deposition. Thermal oxides are useful as wet etch masks, insulators, and as structural material for cantilevers. Boron doping is useful as an etch stop for bulk micromachining. Silicon nitride is useful as an etch mask and as a structural material. The nitride process can be adjusted by varying the ratio of the reactive gases dichlorosilane and ammonia.



Scanning-electron micrograph of a series of silicon-nitride cantilevers for MEMS magnetometer. Processes available for surface and bulk micromachining include wet and dry oxidation, boron diffusion doping, and LPCVD of silicon nitride, polysilicon, and low-temperature oxide (glass).

Films of silicon nitride have very low residual stress and are useful for making extremely thin cantilevers (less than 50 nanometers thick) required for applications such as the MRFM, where force sensitivity at the 10^{-18} newton level is needed. Polysilicon films are useful as sacrificial layers for surface micromachining of silicon nitride. Polysilicon is also the choice for structural material in micromachined actuators such as electrostatic comb drives. Finally, the furnaces can grow sacrificial films of low-temperature oxide that are etched relatively quickly in hydrofluoric acid.

Recent Publications

A. Jander, J. Moreland, and P. Kabos, "Angular Momentum and Energy Transferred through Ferromagnetic Resonance," submitted.

A. Jander, P. Kabos, and J. Moreland, "Magnetic Field Imaging with a Scanning Ferromagnetic Resonance Probe," submitted.

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).

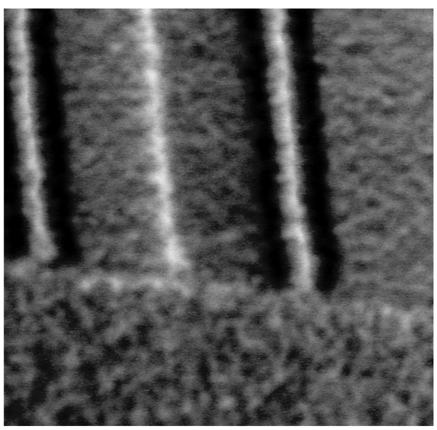
M. Löhndorf, J. Moreland, and P. Kabos, "Ferromagnetic Resonance Detection with a Torsion-Mode Atomic-Force Microscope," Appl. Phys. Lett. **76**, 1176-1178 (February 2000).

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 Goals

This project develops measurements and standards for magnetic thin-film materials and devices for the magnetic data storage and magneto-electronics industries, with applications in magnetic recording, magnetic solid-state memories, magnetic sensors, and magnetic microwave devices. The emphasis is on the performance of nanoscale devices, consisting of multilayer and multicomponent thin-film systems, at microwave frequencies. Project members have successfully devised ways to control the dynamical properties of magnetic devices. In addition, they fabricate magnetic nanostructures to determine the resolution of magnetic imaging systems and develop new combinatorial materials and on-wafer metrology. Recently, the project has begun to develop new techniques to measure spin-dependent electron transport at surfaces and interfaces in advanced magnetic device structures. 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.



High-resolution magnetic force micrograph of bits in the magnetic imaging reference standard. The area of the image is 4 micrometers on a side.

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 memories **(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 recording 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.

MILESTONE: During 2001-2002, develop ballistic electron magnetic microscopy **(BEMM)** to characterize magnetic devices at 10 nanometer length scales.

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 non-linear switch-

Project Leader:
Stephen Russek

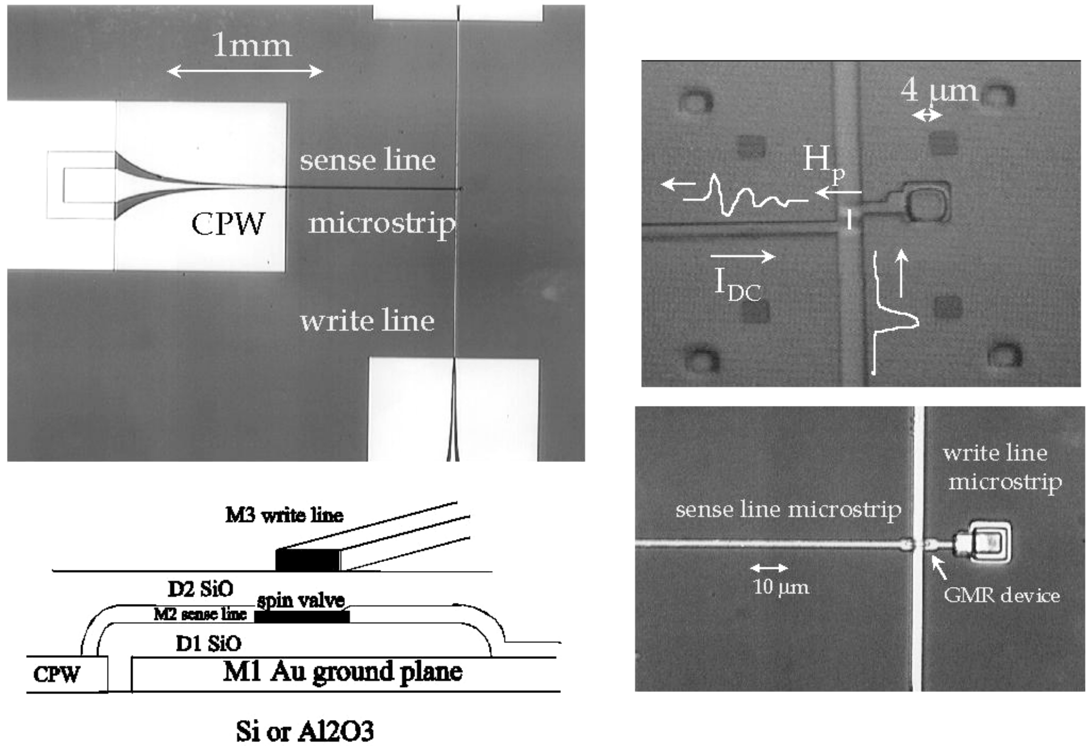
Staff-Years (FY 2000):
1 professional
1 postdoctoral associate
1 graduate student

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

Parent Program:
Magnetics

Our association with your group has been highly successful. Your work on magnetic switching is extensive and important. The measurements and analysis on the samples we sent was very much appreciated.

Dr. Jim Daughton
President
Nonvolatile Electronics, Inc.



High-speed test circuits are used to measure the performance of giant-magnetoresistance and spin-dependent tunneling devices at frequencies up to 10 gigahertz.

ing 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 to predict the behavior of magnetic devices.

MILESTONE: In 2001, characterize gigahertz noise and thermal-fluctuation-induced dynamics in 100 nanometer spin valves and tunnel junctions.

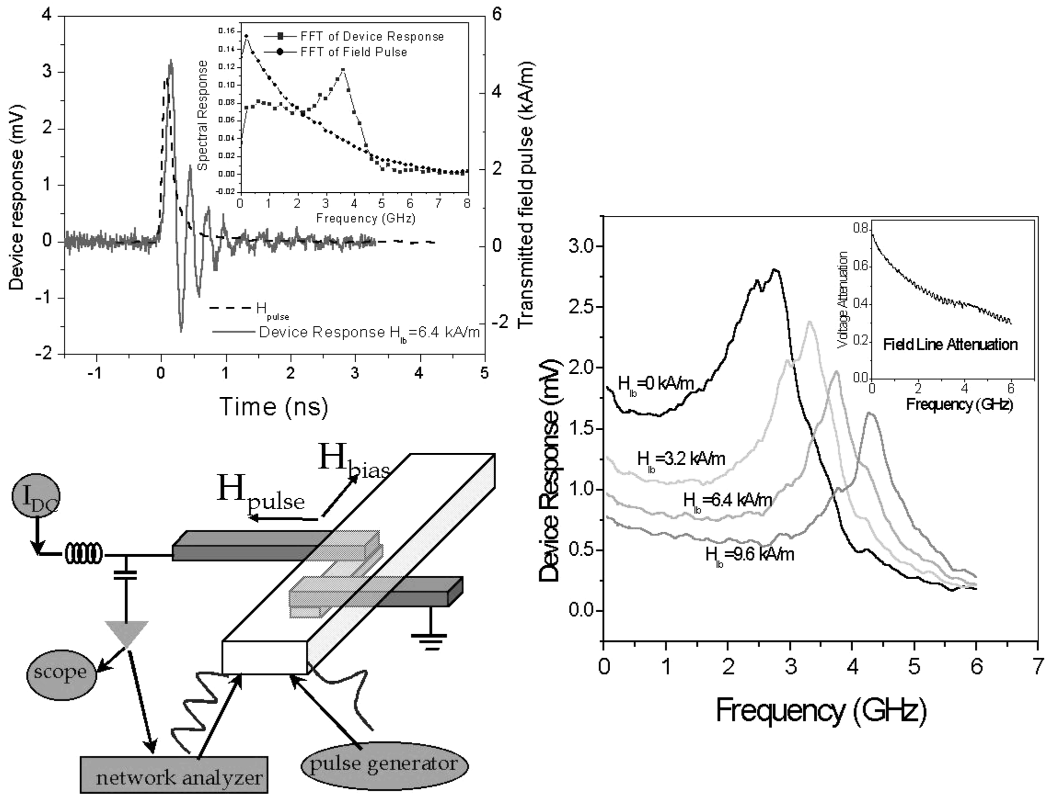
We are developing new techniques to measure the electronic and magnetic properties of magnetic thin-film systems *in situ* (as they are deposited). One such technique, *in-situ* magneto-conductance measurements, can determine the effects of surfaces and interfaces on spin-dependent transport in a clear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

MILESTONE: During 2001-2002, investigate the electronic scattering from nano-oxides in giant magnetoresistive **(GMR)** systems and determine if electron confinement techniques can significantly enhance read-head sensor performance.

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 with a large number of sites with systematic variation of materials properties such as composition, or process parameters such as growth temperature. In addition to library fabrication, the combinatorial process involves the development of high-throughput on-wafer metrologies that can systematically characterize the libraries and scan for desirable materials properties.

MILESTONE: By 2002, develop techniques to make on-wafer measurements of saturation magnetization and magnetostriction.

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 an essential ingredient to the development of methods to control and



Time- and frequency-domain measurements of the ferromagnetic resonance in a micrometer-sized spin-valve device.

manipulate small numbers of spins in a spin circuit.

MILESTONE: By 2002, measure spin-transfer-induced dynamics in nanoscale current-perpendicular-to-plane **(CPP)** devices in collaboration with Cornell University and Motorola.

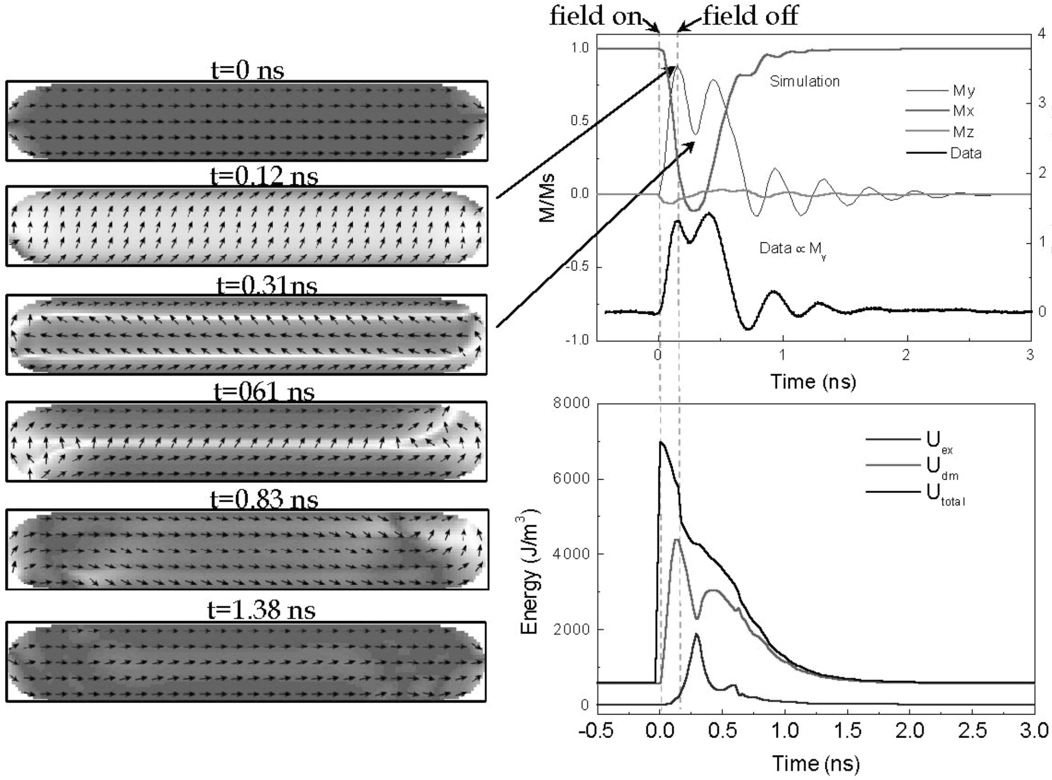
MILESTONE: In 2001, measure electron spin resonance **(ESR)** in sub-micrometer spin-polarized two-dimensional degenerate electron-gas devices.

Accomplishments

■ We have measured the ferromagnetic resonance in micrometer-sized spin-valve devices. The ferromagnetic resonance was measured using both time-domain and frequency-domain magnetoresistance techniques. This work represents the measurement of ferromagnetic resonance in the smallest single particle to date. The work provides a clear measurement of the response of magnetic sensors similar to those used in magnetic recording read heads, up to 6 gigahertz. Knowledge of the high-frequency performance of these devices will be required in the next few years when the data transfer rates exceed 1 gigahertz. This work has further stimulated the use of these sensors in other magneto-electronic applications such as high-speed isolators working in the gigahertz regime.

■ We have completed a study of switching probabilities in small spin-valve devices designed for MRAM applications. The switching probability was measured as a function of magnetic field pulse height and pulse width. At long pulse widths (above 1 nanosecond) reproducible switching, with unity switching probability, was observed. As the pulse width was decreased, a rapid transition occurred in which the switching probability decreased from 1 to 0 over a span of 100 picoseconds. Metastable states were observed in this transition region. The metastable states were found to have a very wide spread in lifetimes, ranging from a few nanoseconds to several milliseconds.

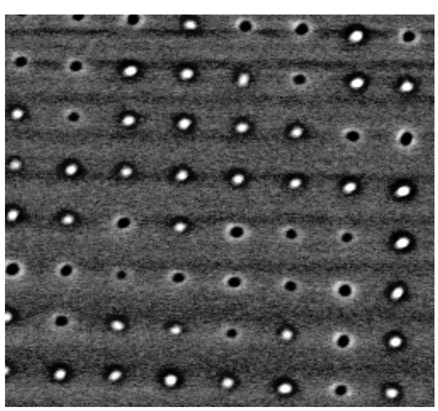
■ Using micromagnetic simulations of rotations in spin-valve devices, we have shown that the inclusion of disorder causes a non-uniform damping, which agrees qualitatively with the measured data from small spin-valve devices. The simulations showed that during the initial



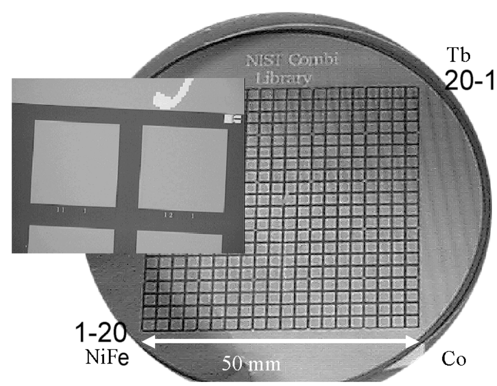
Micromagnetic simulation of response of 0.8 micrometer by 4.8 micrometer spin-valve device to a 150 picosecond, 80 millitesla, transverse field pulse.

large-angle motions there was a larger transfer of energy, mediated by the disorder, from the uniform mode to short-wavelength magnetic modes. As the motion amplitude decreased, fewer spin waves were produced and the damping decreased. The exact type of the disorder in giant-magnetoresistive devices remains to be determined. Possible candidates include edge roughness, Néel coupling with the pinned layer, variations in local anisotropy, or stress.

- We discovered a new method of engineering the high-speed dynamical properties of technologically relevant magnetic thin films. Doping Ni-Fe films with a few percent of Tb will increase the damping of the films by an order of magnitude while not appreciable changing other magnetic properties. Gd doping was also explored and showed less increase in damping. Gd has only a spin moment whereas Tb has both a spin and an orbital moment. The results are



Magnetic force microscope image of Co-Pt multilayer dots, 100 nanometers in diameter.



Magnetic combinatorial library showing 2 millimeter sites with identification numbers.

consistent with the hypothesis that the orbital moment of Tb, in combination with the high anisotropy of the orbitals, allows the magnetization to directly couple to the lattice. Both uniform and modulation doping were explored. Temperature-dependent measurements of the magnetization and damping were made, along with high-resolution x-ray measurements, to determine the correlation of the damping to the magnetic properties and microstructure. This work represent the first effort to engineer the intrinsic dynamical properties of materials used in magnetic data storage applications.

- We measured magnetic-force microscope line scans of 100 nanometer Co-Pt dots and compared them with calculated field and field-gradient profiles. The calculations show that there should be sharp features in the field gradients at the edge of the dots if the dots were ideal, with uniform perpendicular magnetization. The features should have peak widths of about 20 nanometers, which were not resolved in our measurements. Therefore, the calculations indicate that these samples may be useful for magnetic imaging reference samples, since they should have features at or beyond the resolution of current magnetic-force microscopes.

- We completed fabrication of the first set of magnetic combinatorial libraries in collaboration with the Materials Science and Engineering Laboratory. The libraries cover a large range of the Tb–Ni-Fe–Co phase diagram and contain several magnetic and crystalline phases. The magnetic structure ranges from in-plane ferromagnetic to perpendicular ferrimagnetic to isotropic ferrimagnetic, to paramagnetic. These libraries were designed to explore giant-magnetostrictive materials and to provide test systems for developing on-wafer magnetic metrology.

- We completed a study of the high-speed magnetic switching properties of Co-Fe-Hf-O in collaboration with Nonvolatile Electronics, Inc. Co-Fe-Hf-O is a new material developed by NVE with potential applications in high-speed magnetic devices. Co-Fe-Hf-O has a tunable resistivity and anisotropy and has dynamic properties that exceed those of Ni-Fe for thicknesses greater than 100 nanometers.

Recent Publications

S. E. Russek, P. Kabos, T. J. Silva, F. B. Mancoff, D. Wang, Z. Qian, and J. M. Daughton, "High Frequency Measurements of CoFeHfO," submitted.

S. E. Russek, W. E. Bailey, and G. Alers, "Magnetic Combinatorial Thin-Film Libraries," submitted.

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., to be published.

S. E. Russek and S. Kaka, "Time and Frequency Domain Measurements of Ferromagnetic Resonance in Small Spin-Valves," IEEE Trans. Magn., in press.

S. E. Russek and W. E. Bailey, "Magnetic Domain Structure and Imaging of Co-Pt Multilayer Thin-Film Nanostructures," IEEE Trans. Magn., in press.

P. Kabos, S. Kaka, S. E. Russek, and T. J. Silva, "Metastable States in Large Angle Magnetization Rotations," IEEE Trans. Magn., in press.

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/Al_2O_3 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 2000):
1 professional
1 technician

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

Parent Program:
Power

Project 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.

Magnetic resonance imaging (MRI) system in a hospital setting. A superconducting magnet is used to produce a high magnetic field, which is one of the necessary components for imaging without using ionizing radiation. The inset shows a cross section of the patient's knee. Photo courtesy of Philips Medical Systems.

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 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

This project's primary activities are critical-current measurement metrology, interlaboratory comparisons, and development of international standards. 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.

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)**.

MILESTONE: During 2001-2003, continue to manage and help create international standards for superconductivity.

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 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.

MILESTONE: In 2001, study the effect of extrinsic parameters on overall stability of Nb_3Sn wires during routine testing to 1000 amperes in a magnetic field of 12 teslas.

MILESTONE: By 2002, determine a procedure for routine critical-current measurements up to 1500 amperes at fields of 12 teslas.

MILESTONE: In 2001, complete a detailed report on variable-temperature critical-current measurements of high-temperature superconductors.

Accomplishments

- Critical-Current Tutorial — We gave an invited tutorial during the 2000 Applied Superconductivity Conference on critical-current measurements for power applications. The procedure consists of measuring the voltage-current characteristic and applying a criterion to determine the critical current. The figure below shows an illustration of the voltage-current characteristic and two criteria. Typical criteria are electric-field strength of 10 microvolts per meter and resistivity of 10^{-14} ohm meters.

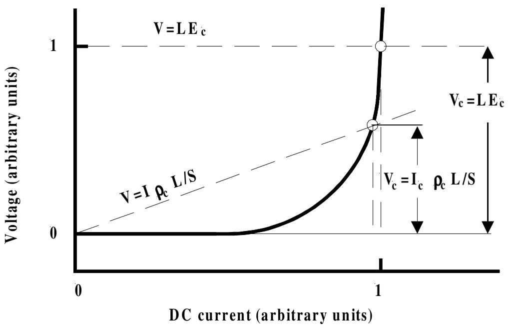
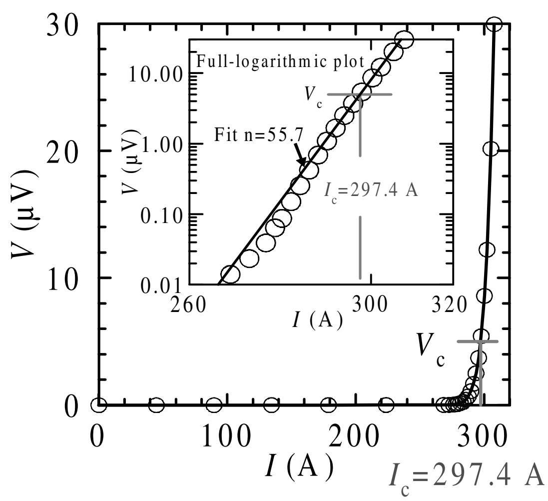


Illustration of a superconductor's voltage-current characteristic with two common criteria applied.

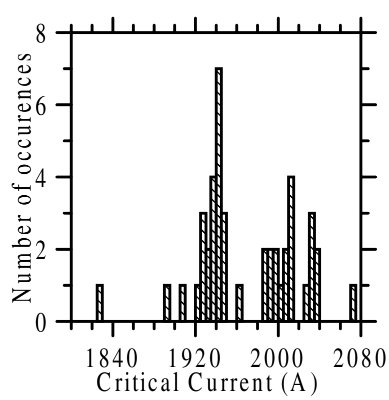
An actual voltage-current characteristic for a Nb-Ti wire is shown below.



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

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

- Performance of Wire Verified — A national laboratory involved in the U.S. effort for the international Large Hadron Collider program asked us to conduct critical-current verification on several Cu/Nb-Ti wires. The critical-current specification was 1925 amperes at 5 teslas. The current density in the Nb-Ti is over 3000 amperes per square centimeter. These wires were designed with only the minimum amount of Cu stabilizer, which made them difficult to measure. The application will use a cable constructed of these wires and additional high-purity aluminum stabilizer will be added to the cable to make the application more stable. We tested 44 specimens from about 528 km of wire so far in the program. The distribution of critical currents is shown in the plot below. Most of the specimens tested above the specification. The lowest value on one specimen was found to be caused by an end effect. Our resistivity measurement at room temperature indicated that the copper fraction of this specimen was higher than in all the other specimens, which is consistent with a lower critical current. With this observation, the manufacturer was able to crop one end of the wire. A new specimen was tested and found to be above the critical-current specification, which saved about 11 kilometers of wire from rejection. This is one example of how we help solve some of the measurement problems facing the U.S. superconductor wire industry. Our experience with such measurements will help in making future standards more practical.



The distribution of critical-current measurements on 44 specimens of Nb-Ti wire at 10 microvolts per meter, 5 teslas, and 4.2 kelvins.

We are in debt to Loren Goodrich for his work with our conductor samples, and we have profited greatly from his general knowledge of materials of this type.

Dr. Richard P. Smith
Fermilab

■ Variable-Temperature Measurements of Critical Current — We recently developed and tested a new variable-temperature critical-current measurement system. We used this system to measure commercially produced Ag-sheathed $Bi_2Sr_2Ca_1Cu_2O_x$ and $Bi_2Sr_2Ca_2Cu_3O_x$ multi-filamentary tapes to currents over 250 amperes. The critical currents of these high-temperature superconductor tape samples depend on the angle of the applied magnetic field relative to the *c*-axis of the material.

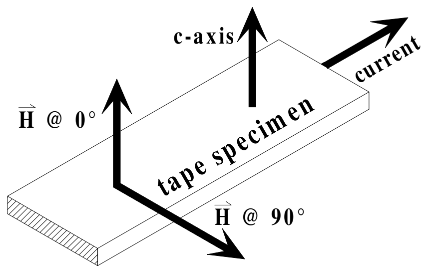
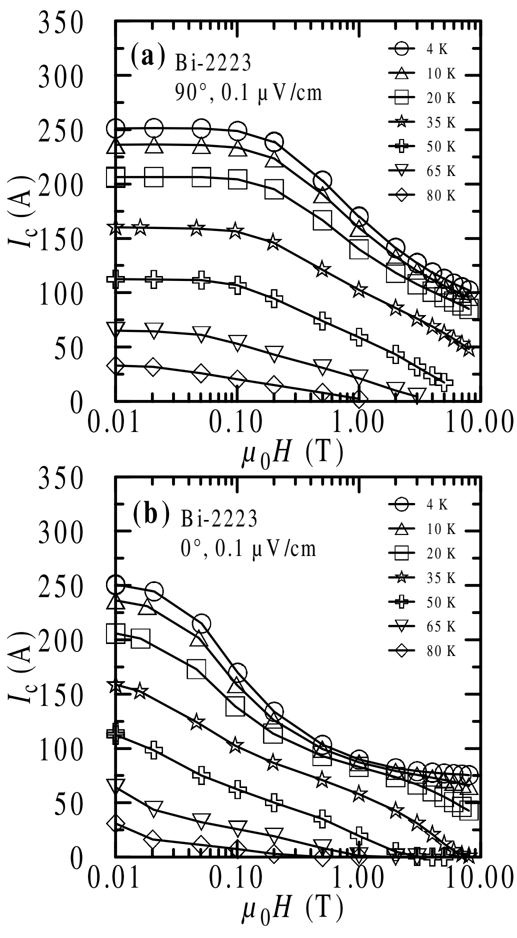


Illustration of the definition of magnetic field angle relative to the c-axis of the material.



Critical current as a function of magnetic field sweep for an $Ag/Bi_2Sr_2Ca_2Cu_3O_x$ tape at various temperatures and two angles: (a) 90°, (b) 0°.

The definition of this angle is given in the illustration. The data plots show the measured critical current of a $Bi_2Sr_2Ca_2Cu_3O_x$ specimen as a function of field and at various temperatures and two angles. A short paper on these results was presented at the 2000 Applied Superconductivity Conference. A longer paper is currently in the review process.

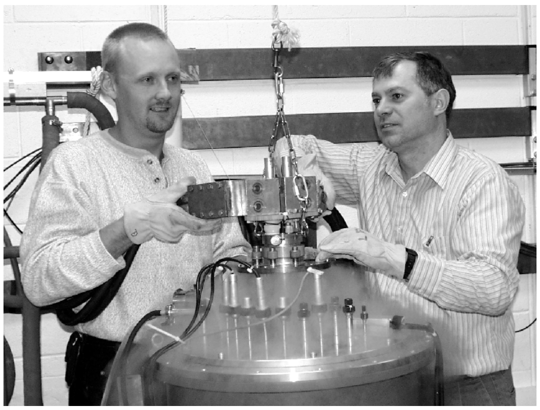
■ Sixth IEC Meeting on Superconductivity — We organized, hosted, and participated in the sixth meeting of IEC Technical Committee 90 (TC 90) on superconductivity in Boulder, Colorado. The meeting allowed experts from around the world to come together and work to advance the draft international standards in six Working Groups. In addition, results from pre-standards research and interlaboratory comparisons were presented on four new working drafts and on six future drafts. To date, two IEC measurement standards have been published and a third standard on superconductivity vocabulary is being published. As a result of this meeting, three more draft standards are now ready for the final voting stage. Information about the IEC TC 90 activities can be found at http://www.IEC.ch/ dashbd-e.htm (enter "90" for the committee number). An outline of the organization is given below.

IEC Technical Committee 90	
Secretariat	Japan
Chairman	L. F. Goodrich
Secretary	K. Sato
Participating Countries	11
Observing Countries	18

TC 90 Working Groups	
1	Terms and Definitions (301 terms, 110 pp., in press)
2	Critical-Current Measurement of Cu/Nb-Ti (43 pp., published)
3	Critical-Current Measurement of Bi-Based Superconductors
4	Residual Resistivity of Cu/Nb-Ti
5	Room Temperature Tensile Tests of Cu/Nb-Ti
6	Matrix Composition Ratio of Cu/Nb-Ti
7	Critical-Current Measurement of Nb_3Sn (57 pp., published)
8	Electrical Characteristic Measurements, Surface Impedance
9	AC Losses in Cu/Nb-Ti

■ Resistivity of High-Purity Cu — We measured residual resistivity ratio **(RRR)** measurements of four high-purity Cu samples (for a total of 35 for this program) from an aerospace company. The RRR measurements are used to estimate the low temperature thermal conductivity of thermal straps to be used in several instruments for the Space Infrared Telescope Facility.

- Critical Current of Nb-Ti — We measured critical currents of three Nb-Ti conductors from a U.S. wire manufacturer. The currents required were beyond the capabilities of their measurement facilities. The company has an occasional need for some measurements at high current (2000 amperes) or high field (12 teslas). Ours is one of the few labs in the country that can do these measurements.



Ted Stauffer and Loren Goodrich lowering a test fixture into a critical current measurement cryostat. The cloud at the top of the cryostat results from the boiling cryogen.

- Suppression of Flux Jumps — We demonstrated that flux jumps could be suppressed during the measurement of hysteresis loss by immersing marginally-stable Nb_3Sn conductors in liquid He. The increased thermal conduction affords dynamic stability against flux jumps, which allows ac losses to be estimated from the area of the magnetization-versus-field loop.

- Standards Committees — Loren Goodrich was 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, and WG6, and the secondary U.S. Expert to WG1, WG3, and WG7. Ted Stauffer was Administrator of the U.S. Technical Advisory Group to TC 90.

Recent Publications

L. F. Goodrich and T. C. Stauffer, "Hysteresis in Transport Critical-Current Measurements of Oxide Superconductors," IEEE Trans. Appl. Supercond., in press.

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., in press.

L. F. Goodrich "III-2: Intercomparison Program in USA. Part 1: I_c Comparison," submitted to Cryogenics, VAMAS Supplement.

L. F. Goodrich "III-2: Intercomparison Program in USA. Part 2: Simulator Round Robin Test," submitted to Cryogenics, VAMAS Supplement.

L. F. Goodrich "II-4: Critical Current Measurement Methods for Oxide Superconductor Tapes and Wires. Part 1: Transport Current Method," submitted to Cryogenics, VAMAS Supplement.

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).

IEC/TC 90, "Superconductivity – Part 2: Critical Current Measurement – DC Critical Current of Nb_3Sn Composite Superconductors," International Electrotechnical Commission, International Standard IEC 61788-2 (March 1999).

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

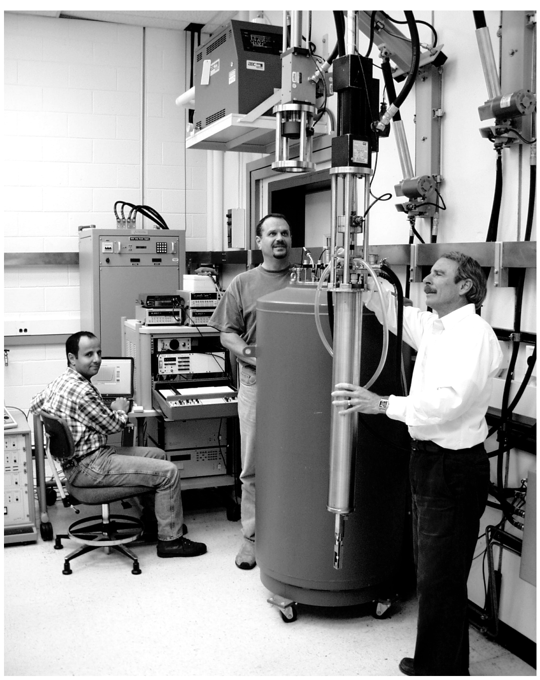
Staff-Years (FY 2000):
1 professional
1 technician
1 guest scientist

Funding Sources:
NIST (40%)
Other (60%)

Parent Program:
Power

Project Goals

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



Najib Cheggour, Cam Clickner, and Jack Ekin preparing to measure the electromechanical properties of a superconductor tape.

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 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, both from industry and from 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 a new set of 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 contributed 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 and transverse compressive stress, 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), as well as high-temperature superconductors (Bi-Sr-Ca-Cu-O and Y-Ba-Cu-O). The purpose of the database produced from these measurements is to allow the magnet industry to design reliable superconducting magnet systems.

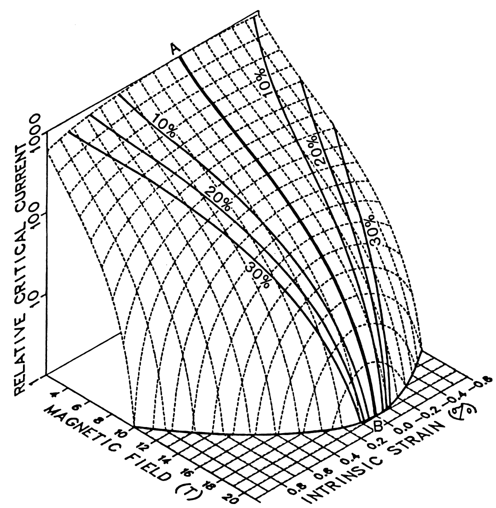
MILESTONE: By 2003, perform parametric studies of axial and transverse stress effect on the electrical performance of second-generation high-temperature superconductors.

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, superconducting 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.

MILESTONE: By 2002, create the first data base of mechanical properties of coated superconductor substrates at cryogenic temperatures.

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 more than a decade 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 that this assumption is invalid. We are now developing a measurement system for carefully determining the three-dimensional strain effects in A-15 superconductors. The potential financial consequences of these measurements for very large accelerator magnets are considerable.

MILESTONE: By 2003, develop the measurement techniques and obtain the data needed to generalize the Strain Scaling Law from one to three dimensions.



Critical current-field-strain surface for the A-15 superconductor Nb_3Sn at 4 kelvins.

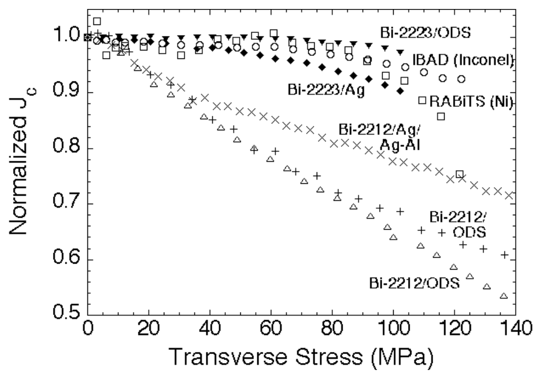
Accomplishments

▪ Measurements of Transverse Stress on Coated High Temperature Superconductors — We completed the first measurements of transverse stress effects in second-generation high temperature superconductors, Y-Ba-Cu-O-coated, rolling-assisted, biaxially-textured substrates **(RABiTS)** and ion-beam-assisted deposition **(IBAD)** tapes. The critical current of these materials is over 1 000 000 amperes per square centimeter at 77 kelvins, making possible magnet and power transmission-line applications at liquid-nitrogen temperature. Our measurements program is the only one looking at the electromechanical performance of these new materials. Before these measurements, the available electromechanical data on these conductors were limited to a few measurements of bending strain versus critical current. The electromechanical performance of the RABiTS conductor, which consists of brittle superconductor and buffer layers deposited on a substrate of soft, pure Ni, was particularly suspect. The results showed that the ion-beam-textured material behaves well under stress, but the deformation-textured con-

The NIST-Boulder labs have several specialized and unique systems for measuring the effects of mechanical stress and strain on superconductor performance. NIST enabled ASC to demonstrate that our Bi-2223 conductor has a transverse compressive stress tolerance greater than 100 megapascals.

Dr. L. J. Masur
Senior Manager
American Superconductor Corporation

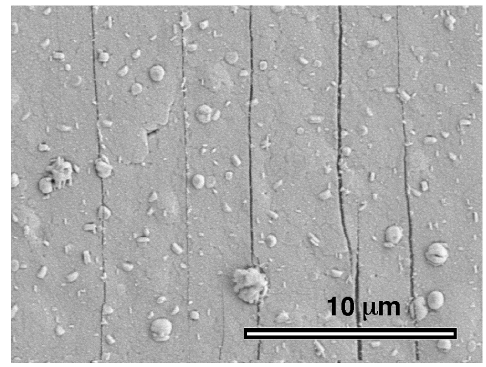
ductor, which is currently made using pure Ni, may have to be constructed from stronger Ni alloys to withstand the magnetic stress encountered in commercial magnet applications. Our data are being sought both to guide government funding decisions for new conductor development, as well as to provide feedback to industry on the technical development of these new conductor materials.



Comparison of the effect of transverse stress (in megapascals) on the critical-current density J_c of various high-temperature tape superconductors: Y-Ba-Cu-O on an Inconel IBAD substrate, Y-Ba-Cu-O on a pure Ni RABiTS, $Bi_2Sr_2Ca_2Cu_3O_x$ with Ag and oxide dispersion strengthened Ag matrices, and $Bi_2Sr_2Ca_1Cu_2O_x$ with oxide-dispersion-strengthened Ag matrix and double sheathed with Ag and Ag-Al matrices.

The timing is particularly important for the upgrading of electric power service to urban areas, as well as for new magnet technology being developed for stabilizing electric power grids operating at high capacity levels. Using our recently developed fatigue testing facility, we also made the first high-cycle fatigue measurements on $Bi_2Sr_2Ca_2Cu_3O_x$ superconductors. The initial results indicate there may be significant accumulated damage on mechanically cycling these materials, such as they would experience in repeatedly charged electromagnets.

■ New Class of Superconductors Shown to Tolerate Stress — Our measurements on a new class of flexible high-temperature coated superconductors have shown that the use of frictional support from a high-yield structural material co-wound with the superconductor can greatly improve their transverse stress tolerance. This should allow these new superconductors to be used in high-field magnet applications. The effects of static and cyclic transverse stress on the critical current of Y-Ba-Cu-O coated tapes of textured Ni were carried out at 76 kelvins. When subjected to monotonic loading, critical current degraded by about 1 percent. However, when samples were tested with frictional support removed between each measurement, critical current degraded by 7 percent to 26 percent. Microstructural data also show that improvement in stress tolerance may be achieved by providing lateral transverse support to the superconductors in magnet applications.



Scanning electron micrograph of the Y-Ba-Cu-O on an Inconel IBAD substrate after static and cyclic transverse stress testing to 122 megapascals, showing the pattern of longitudinal cracks along the length of the tape near the tape edge.

Scanning electron microscopy of ion-beam-textured tapes subjected to transverse stress show a series of thin longitudinal cracks (along the direction of the transport current) near the tape edges; the center of the tape, however, was free of any observable cracks. This indicates that the failure is due to in-plane transverse tensile strain.

■ Stress Effects on Nb_3Sn Produced by Chemical-Vapor Deposition — As part of an investigation of three-dimensional stress effects in Nb_3Sn superconductors, the effect of transverse stress was measured in several specimens of a Nb_3Sn tape produced using a chemical-vapor deposition process. This conductor was selected for its relatively simple structural geometry, which lends itself to mechanical modeling. Previous measurements of numerous other Nb_3Sn conductors have shown large degradation of critical-current density (about 40 percent) with transverse stress; however, the degradation of this conductor was less than 1 percent at 170 megapascals. Understanding this unexpected and seemingly remarkable behavior will be an important step in extending the existing Strain Scaling Law from two to three dimensions.

■ New Monograph on Contact Techniques — We completed a monograph on contact techniques for high-temperature superconductors. The information is particularly relevant for critical-current measurements of the new coated superconductors, where films carrying 500 amperes of current are now being fabricated. The higher currents have resulted in severe contact heating problems in critical-current tests, usually resulting in vaporization of the samples. This chapter details techniques for reducing the contact resistivity of such contacts by up to two orders of magnitude. Many requests were received for this chapter at a recent Department of Energy peer review on superconductor development for electric-power utilities.

Recent Publications

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

Appendix A: Laboratory Facilities

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

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

Characterization of Magnetic Materials

- Vibrating-sample magnetometer
- AC susceptometer
- SQUID magnetometer
- Alternating-gradient force magnetometer
- Induction-field looper
- Magneto-optic Kerr effect magnetometer
- *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*

Characterization of Magnetic Devices

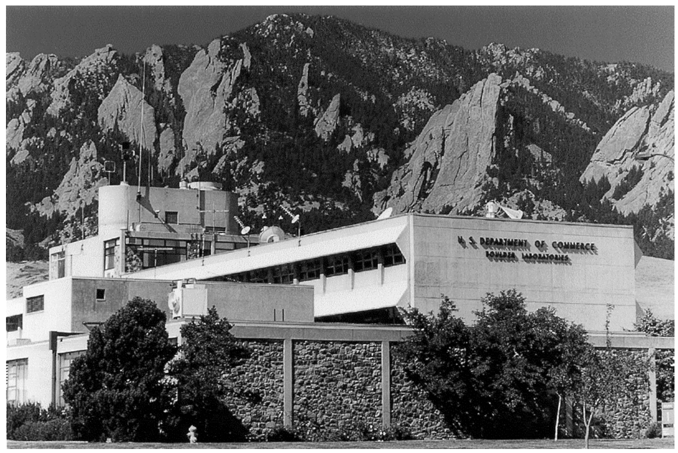
- Local magnetoresistance scanning-probe station
- *Time-resolved magnetoresistance of magnetic random-access memory devices*
- Variable-temperature microwave probe station
- Industry-standard spin stand
- *Scanning magnetoresistance probe for forensic analysis of recording media*

Characterization of Superconductors

- Large-bore superconducting magnets up to 18 teslas
- *Measurement of critical current up to 2500 amperes*
- Low-resistance (1 nano-ohm) measurements of stabilizer materials
- *Simulation of 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)*
- Measurement of electrical transport and noise in superconductor interfaces
- Magnetic measurement of ac losses in superconductors

Appendix B:
Postdoctoral Research Associateships

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



Fabrication and Properties of High-T_c Superconducting Films and Interfaces

Contact: Jack Ekin, 303-497-5448

Research is conducted on the electromagnetic and transport properties of high-T_c superconductor thin films and multilayer structures in the Y-, Bi-, and T1-based material systems. Particular emphasis is given to understanding and controlling interfaces for junction applications, as well as developing methods for making reliable electrical connections to the oxide superconductors. Our work also focuses on modeling and understanding the transport and noise characteristics of oxide/normal-metal interfaces.

High-T_c 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.

Low-T_c Superconductor Measurements

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. We study conventional superconductors, Nb-Ti and Nb_3Sn, and the newer high-transition-temperature materials. We conduct fundamental studies of the superconducting-normal transitions and 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 Measurements for the Data Storage Industry

Contact: Ron Goldfarb, 303-497-3650

We invite proposals for the development of new, quantitative, metrological techniques to characterize the magnetic properties of small magnetic structures. Examples of such structures include recording and giant-magnetoresistive read heads at various stages of production, patterned recording media, and magnetic random-access memory elements. Ideally, the measurement methods would be transferable to industry for use in quality control and production.

Magnetostriction Measurements in Thin Film

Contact: Ron Goldfarb, 303-497-3650

Magnetostriction refers to the dimensional change in a ferromagnetic material when it is magnetized in an applied field. We are interested in developing tools to measure magnetostriction (and inverse magnetostriction) in thin films and multilayers of high permeability magnetic alloys used in recording heads. Applicants should have an interest in magnetic metrology and the data-storage industry. Available characterization tools include vibrating-sample, alternating-gradient, and SQUID magnetometers; x-ray diffraction; and atomic-force, magnetic-force, and electron microscopes. Thin-film deposition chambers and a fully equipped cleanroom are also available.

Properties of Nanometric Magnetic Particles and Ultrathin Films

Contact: Ron Goldfarb, 303-497-3650

This project develops magnetic measurement techniques and phenomenological models for the characterization of magnetic particles, molecules, and thin films on the order of 1-10 nm. Research proposals are invited to measure and understand such materials for use in the areas of ultrahigh-density recording media, biomagnetism, medical therapeutics, microwave absorbers, radio-frequency transformers, magnetic inks, and extruded permanent magnets. Collaborations are encouraged.

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 and fundamental recording processes in different kinds of storage media.

Magnetic Resonance Force Microscopy

Contact: John Moreland, 303-497-3641

Magnetic-resonance force microscopy (MRFM) is a promising imaging technique based on the magnetic coupling between magnetic spins and an ultra-sensitive 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 issues must be addressed before an atomic-scale apparatus of this kind can work: (1) fabrication of high-sensitivity cantilevers, (2) development of computer-based MRI imaging schemes for a scanning probe, and (3) construction of an ultra-sensitive AFM 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 clean room facility is equipped for bulk micromachining of silicon and LPCVD 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.

Magnetism in Thin Films and Surfaces

Contact: David Pappas, 303-497-3374

Research efforts on magnetic thin films and multilayers have been redoubled as the need for higher density storage media increases. Opportunities are available to work in a wide range of topics. Areas of interest include developing measurements such as *in-situ* SQUID Magnetometry, magneto-optic Kerr effect (MOKE) susceptibility measurements, and spin-polarized electron spectroscopy. In addition, there is ongoing work to generate standard samples for magnetic force microscopes with nanoscale-patterned magnetic media, as well as a strong interest to incorporate MOKE and magnetostrictive devices into micro-electromechanical systems.

Nanoscale Magnetic Structures

Contact: Stephen Russek, 303-497-5097

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

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 phenomena. Giant magnetoresistive (GMR) devices and magnetic tunnel junctions (MTJ) are being developed for use in magnetic recording heads, magnetoresistive random-access memory, and industrial magnetic sensors. The market for these devices is enormous, in the tens of billions of dollars. 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 their interfaces. Research involves the fabrication of novel GMR, MTJ, and novel magnetic semiconductor devices using a state-of-the-art 8-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 K to 500 K and dc to 40 GHz. Device level measurements will be compared with spin-polarized transport measurements using an *in-situ* UHV scanning tunneling microscope.

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- ("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-GHz sampling oscilloscope, a 50-fs 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. Applications are encouraged from those who have a strong experimental background in magnetism, especially in high-frequency magnetic phenomena such as ferromagnetic resonance.

Nonlinear Magneto-Optics

Contact: Tom Silva, 303-497-7826

The second harmonic magneto-optic Kerr effect (SHMOKE) is under investigation as a tool for the study of interfacial magnetism. SHMOKE shows strong sensitivity to the magnetization at optically accessible interfaces between ferromagnetic and non-ferromagnetic films, yet SHMOKE does not require exotic facilities, such as 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% in some sample systems. Extensive resources for the study of SHMOKE exist, including a mode-locked 50-fs Ti:sapphire laser, coincident-photon detection electronics, photoelastic modulators, lock-in amplifiers, and sample translation stages. Samples may be produced on site with a state-of-the-art 8-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, which 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 8-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 C:
EEEL Magnetics Group Staff

Alan Cookson, EEEL Acting Deputy Director, 301-975-2220, alan.cookson@nist.gov
Fred Fickett, Acting Division Chief for Boulder, 303-497-3785, fickett@boulder.nist.gov
Ron Goldfarb, Acting Group Leader, 303-497-3650, goldfarb@boulder.nist.gov
Linda Derr, Administrative Officer, 303-497-4202, derr@boulder.nist.gov
Ruth Corwin, Secretary, 303-497-5477, corwin@boulder.nist.gov

Magnetic Recording Measurements

David Pappas, Project Leader, 303-497-3374, pappas@boulder.nist.gov
Steve Arnold, Contractor, 303-497-3381, arnoldcs@boulder.nist.gov
Gideon Shalev, PREP Student, 303-497-4283, shalev@boulder.nist.gov
(Also contributing in FY 2000: Carla Eunice, David Stevenson)

Magnetodynamics

Tom Silva, Project Leader, 303-497-7826, silva@boulder.nist.gov
Tony Kos, 303-497-5333, kos@boulder.nist.gov
Matt Pufall, Postdoctoral Associate, 303-497-5206, pufall@boulder.nist.gov
Fabio da Silva, Guest Research Scientist, 303-497-3873, fcss@boulder.nist.gov
(Also contributing in FY 2000: Pavel Kabos, Kevin Pettit, Nick Rizzo, Gordon Yee)

Nanoprobe Imaging

John Moreland, Project Leader, 303-497-3641, moreland@boulder.nist.gov
(Also contributing in FY 2000: Albrecht Jander, Peter Johnson)

Magnetic Thin Films and Devices

Stephen Russek, Project Leader, 303-497-5097, russek@boulder.nist.gov
Bill Bailey, Postdoctoral Associate, 303-497-3701, baileyw@boulder.nist.gov
Shehzaad Kaka, PREP Graduate Student, 303-497-7365, kaka@boulder.nist.gov
Fred Mancoff, Postdoctoral Associate, 303-497-4987, mancoff@boulder.nist.gov
Bill Rippard, Postdoctoral Associate, 303-497-3882, rippard@boulder.nist.gov
(Also contributing in FY 2000: Terry Gafron)

Standards for Superconductor Characterization

Loren Goodrich, Project Leader, 303-497-3143, goodrich@boulder.nist.gov
Ted Stauffer, 303-497-3777, stauffer@boulder.nist.gov

Superconductor Electromagnetic Measurements

Jack Ekin, Project Leader, 303-497-5448, ekin@boulder.nist.gov
Najib Cheggour, Guest Research Scientist, 303-497-3815, cheggour@boulder.nist.gov
Cam Clickner, 303-497-5441, clickner@boulder.nist.gov
(Also contributing in FY 2000: Steve Bray, Tim Collins, Roland Sesselmann, Yizi Xu)

— December 1, 2000

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

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

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For additional information contact:
Telephone: (303) 497-5477
Facsimile: (303) 497-5316
On the Web: http://www.eeel.nist.gov/magnetics