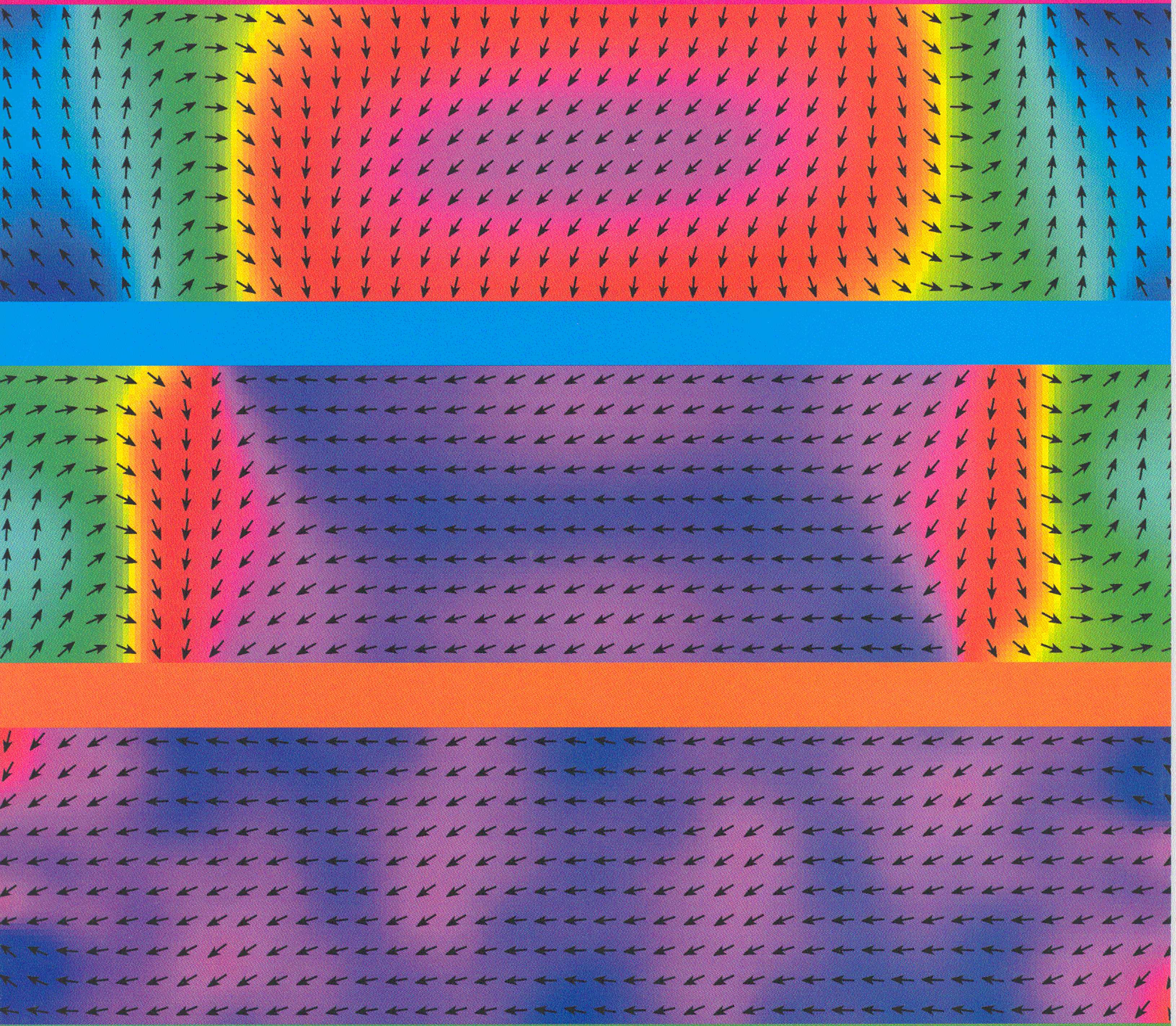
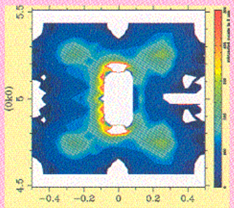
NIST

National Institute of Standards and Technology
Technology Administration,
U.S. Department of Commerce

Magnetic Data Storage at NIST



This is the best and worst of times for the magnetic data storage industry. Market potential is vast and growing, but global competition is intense, and the technical challenges extreme. Leading commercial magnetic disk drives today store about 25 gigabits of data per square inch. The National Storage Industry Consortium plans to demonstrate a recording density of 1 terabit per square inch—40 times today's level—by 2006.

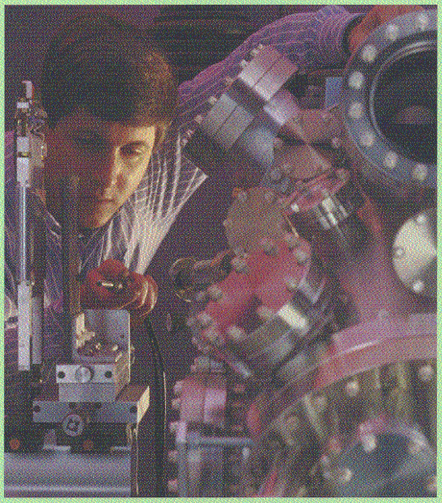


Cover image: A series of magnetization patterns computed for NIST Micromagnetic Standard Problem 4, an important benchmark for validating micromagnetic design tools.

New materials are needed that have smaller grain structures, can be produced as thin films, and can be deposited uniformly and economically. Recording heads must be designed to produce higher output signals and lower noise. Component dimensions must be made smaller, and the measurements more precise. New lubricants are needed to prevent wear as the spacing between the disk and head becomes smaller than the free path of air molecules. New methods are needed to standardize components and increase yields.

How to achieve those goals? The National Institute of Standards and Technology can help. For the past century, NIST has been helping U.S. industries invent and manufacture superior products reliably. It offers state-of-the-art technology, measurement tools, and standards—many of which cannot be found anywhere else—as well as a reputation for technical excellence and neutrality. Staff expertise spans all fields relevant to magnetic data storage, including materials science, electrical engineering, physics, mathematics and modeling, manufacturing engineering, chemistry, metrology, and computer science.

NIST is developing magnetic standards needed for quality control by the data storage and magnetic materials industries as well as instrument manufacturers. NIST has prepared "spin valve" recording heads with cutting-edge properties, measured magnetic switching dynamics, and pioneered methods for imaging magnetic materials in fine detail and rapidly fabricating infinitesimally small metallic structures. NIST measurement tools and expertise, which have helped the semiconductor industry keep doubling performance every 18 months, are equally relevant to data storage. And NIST has unique facilities, such as state-of-the-art neutron scattering facilities, an elaborately instrumented magnetic thin-film deposition laboratory, and *in situ* magnetic characterization and atomic-structure characterization equipment.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Molecular beam epitaxy chamber for *in situ* depth profiles of magnetic film surfaces and interfaces.

This brochure describes 13 areas of NIST research that may be useful to companies in the magnetic data storage industry and related fields, including electronics, semiconductors, and magnetic random access memories.

How to Tap NIST Resources

Companies can take advantage of NIST resources in many ways: by purchasing Standard Reference Materials or calibration services, attending workshops and seminars, participating in cooperative research, licensing patented technology, using NIST facilities, or requesting technical assistance with specific problems. Details can be found at *http://www.nist.gov*, click on "Work with Us."

Those interested in NIST research on the topics described in this brochure may contact the appropriate person listed in the sidebar. Arrangements may be made for research collaborations under a Guest Researcher Agreement or, if confidentiality of cooperative research results is desired, a cooperative research and development agreement. In some cases, NIST can provide free technical assistance or information that requires only a brief time to complete. Technical assistance may involve a written response, a telephone call, on-site discussions, visits to a non-NIST site, or a combination of these activities.

Current NIST Activities in Key Areas

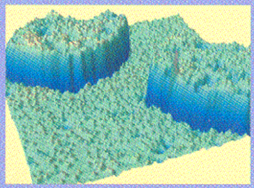
(Footnotes refer to contacts listed in the sidebar)

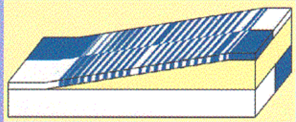
Magnetic Standards & Micromagnetic Modeling. NIST strives to meet industrial needs for new standards for both thin-film and bulk magnetic materials, as well as needs for new methods of measuring key properties.[9,11,16] The standards can be used to calibrate magnetometers and assess materials. In addition to micromagnetic software, NIST also has developed four standard problems to assist with comparisons of different micromagnetic software packages, computational techniques, and algorithms.[3,9]

Magnetic Imaging. NIST offers a variety of tools for imaging fine detail in magnetic materials. The facility for scanning electron microscopy with polarization analysis (SEMPA) is being upgraded to allow magnetic imaging below 10 nanometers (nm).[2,12,20] Another key tool is a scanning tunneling microscope with a special coating on the stylus tip.[4] Other equipment includes a magneto-optic Kerr microscope and magnetic force microscopes for studies of magnetic fields at surfaces, and atomic force microscopes for studies of topography at atomic scales.[10] For studies of magnetization dynamics in real time, NIST developed the magneto-optic indicator film technique, which is easy to use and requires only inexpensive equipment.[15,16] NIST also has devised new imaging methods for both data authentication and data recovery from damaged magnetic recording media.[11]

Nanoscale Metrology. Current efforts in nanoscale metrology focus on microelectronics manufacturing, but this expertise is also applicable to measurements of particle sizes and other elements of data storage devices.[13] Length measurements in the nanoscale regime are performed at and below 1 nm to 1 micrometer (µm).[13] Methods used include tunneling, atomic force, electron, visible, and ultraviolet microscopy. Among efforts to develop new metrology tools, NIST is designing sensitive but inexpensive magnetometers based on microelectromechanical (MEMS) systems.[10] New MEMS fabrication capabilities have been used to make imaging probes and microtorsional oscillators.

Structure of Magnetic Multilayers. NIST determines magnetic structures in thin films and multilayers in a variety of ways. Neutron reflectometry is used to probe both structural and magnetic density profiles.[1,8] High-angle neutron diffraction is among few techniques available for characterizing antiferromagnetic layers, which are important in exchange-biased structures. Electron microscopy and X-ray techniques can be used to study other structural aspects of films and develop methods for evaluating device performance. High-resolution X-ray diffraction is the method of choice for quantitative structure determination to elucidate the connection with function. Scanning tunneling microscopes are used to evaluate growth processes of layered thin films at the atomic scale.[2,19] NIST pioneered the use of wedge-shaped nonmagnetic spacer layers for studies of spacer thickness effects.[2,12,19,20]



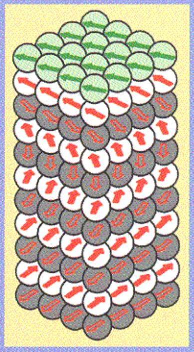


NIST also is developing the libraries and on-wafer metrology needed to apply combinatorial techniques to magnetic materials; automated measurements will enable researchers to map out complex phase diagrams in fractions of the time previously required.[14] In a related area, combinatorial techniques are used to investigate magnetic and elastic properties of giant magnetostrictive alloys, which have electronics applications.[14]

Magnetoresistive Materials. NIST is studying the growth, structure, and processing of giant and colossal magnetoresistive (GMR and CMR) materials to establish a scientific understanding of the manufacturing process and improve it.[4] Related studies focus on identifying and overcoming material flaws. NIST developed a new method for observing pinhole defects in metal and oxide thin films and is studying the thermal stability of GMR films with the aim of designing films with improved stability.[4]

Magnetic Dynamics. NIST research on magnetic dynamics seeks to evaluate material behavior, explain energy transfer processes, and find ways of manipulating these dynamics to enhance data transfer rate. NIST also performs research on high-speed switching (reversals in magnetic moment) in magetoresistive devices.[9,14,17] State-of-the-art instrumentation, such as femtosecond magneto-optics, is used to measure the dynamic response of head materials with picosecond time resolution.[7,14,17] Research is under way to find ways of controlling damping and to design microstructured materials with damping properties tailored to the application.[9,14] NIST was the first to demonstrate that pulse-shaping of current excitations used to switch magnetization can almost eliminate under-damped ringing in a magnetic switching event.[17]

Magnetization Control. The orientation of magnetic moments can be controlled through the use of certain materials and anisotropies (differences in magnetic properties based on orientation). NIST research has illuminated aspects of exchange bias, a quantum mechanical effect used to control magnetization in spin valve devices.[9,15,18] NIST models and techniques allow measurements of changes in certain materials as the magnetization rotates. NIST also is investigating novel nonmagnetic materials for use as pinning layers in spin valves. As a promising alternative to exchange bias, NIST developed a new technique based on anisotropy. Deposition techniques are used to induce shape anisotropy in thin films that, when used as pinning layers, may enable spin valves to operate at higher temperatures.[4,9]

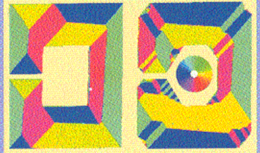


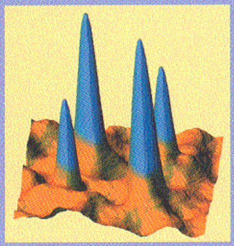
Magnetic Media. NIST offers unique measurement capabilities—generating information over length scales as small as 0.1 nm—for determining key structural and magnetic properties of materials. Neutron scattering, for example, is used to study the origins of CMR (offering 1 to 2 orders of magnitude more magnetoresistance than GMR) in materials that may be used in the next generation of recording and sensor technology.[1, 8] Other studies focus on the effect of surfactants on material properties.[6] NIST also is examining the hysteresis loops (energy dissipation as a magnetic field cycles) of recording media, in an effort to improve predictions so that media can be compared more reliably.[16] Other research is under way with industry to develop nanostructured materials with properties such as high moment and high resistivity and low damping and low coercivity (magnetic field required to switch magnetization) for use in magneto-electronic applications such as nonvolatile memories working at high frequencies.[14]

Soft Magnetic Materials. Soft magnetic materials, which are easily magnetized and demagnetized, are used in write heads. NIST is using neutrons to study these materials and is conducting the many experiments needed to test the theory that grain sizes in write head materials can be made small enough to achieve zero anisotropy and low coercivity; if the theory is correct, then manufacturers will have a method of creating ultrasoft materials. This work also will shed light on the relative importance of anisotropy and coercivity.[1, 8, 16]

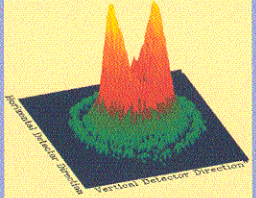
Nanotribiology. The control of stiction, friction, and wear at the head-disk interface is crucial as the distance between the head and disk continues to shrink. NIST studies the wear mechanisms at the interface, measures the surface forces, characterizes the surface structures, and provides basic theory for the organization of molecular assemblies at the 1 nm level to control surface properties.[6] NIST has a state-of-the-art laboratory to study the relationship between different media disks and different molecular assemblies deposited in various ways, and has developed an accelerated test method to improve the durability of thin organic films. NIST also explores ways of depositing monolayers of molecules into disk surfaces and develops methods to measure the shear strength of such films.

Spintronics. Future electronic devices might incorporate magnetic devices that alter and enhance performance. Such devices might be used one day to build quantum computers that could perform certain calculations much faster than digital computers ever could. However, the combination of magnetic metals with semiconductors raises the question of how to preserve the "spin state" of electrons. Ballistic injection might be fast enough to solve the problem. NIST is investigating the use of alumina thin films between a magnet and a semiconductor to allow the injection of ballistic, spin-polarized electrons into the semiconductor.[4, 11] Alternatively, coherent electron spin states (in which the electron is a quantum mechanical superposition of all possible orientations) may be used to transmit the spin momentum via dynamical channels. NIST is attempting to use spin momentum transfer mechanisms to manipulate spin states in semiconductors through the principle of angular momentum conservation.[10, 14, 17]





Neutron Probes. The NIST Center for Neutron Research operates unique facilities that provide essential measurement capabilities for determining key structural and magnetic properties of new materials and magnetic thin film multilayers—information that often cannot be obtained using any other technique.[1, 8] The instrumentation allows investigations of magnetic materials over a broad range of sizes, from 1 picometer to 1 micrometer, and dynamic ranges from 10^{-7} to 10^{-15} seconds.



Magnetic Measurements. NIST is developing improved methods for the measurement of magnetic properties and the characterization of magnetic materials.[5, 7, 14, 16]

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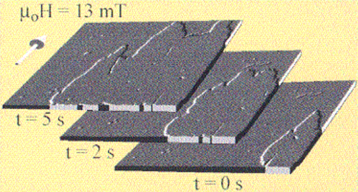
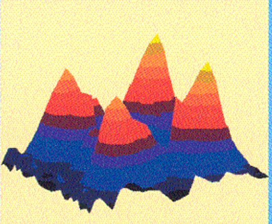
NIST is Involved in All Aspects of Magnetic Data Storage



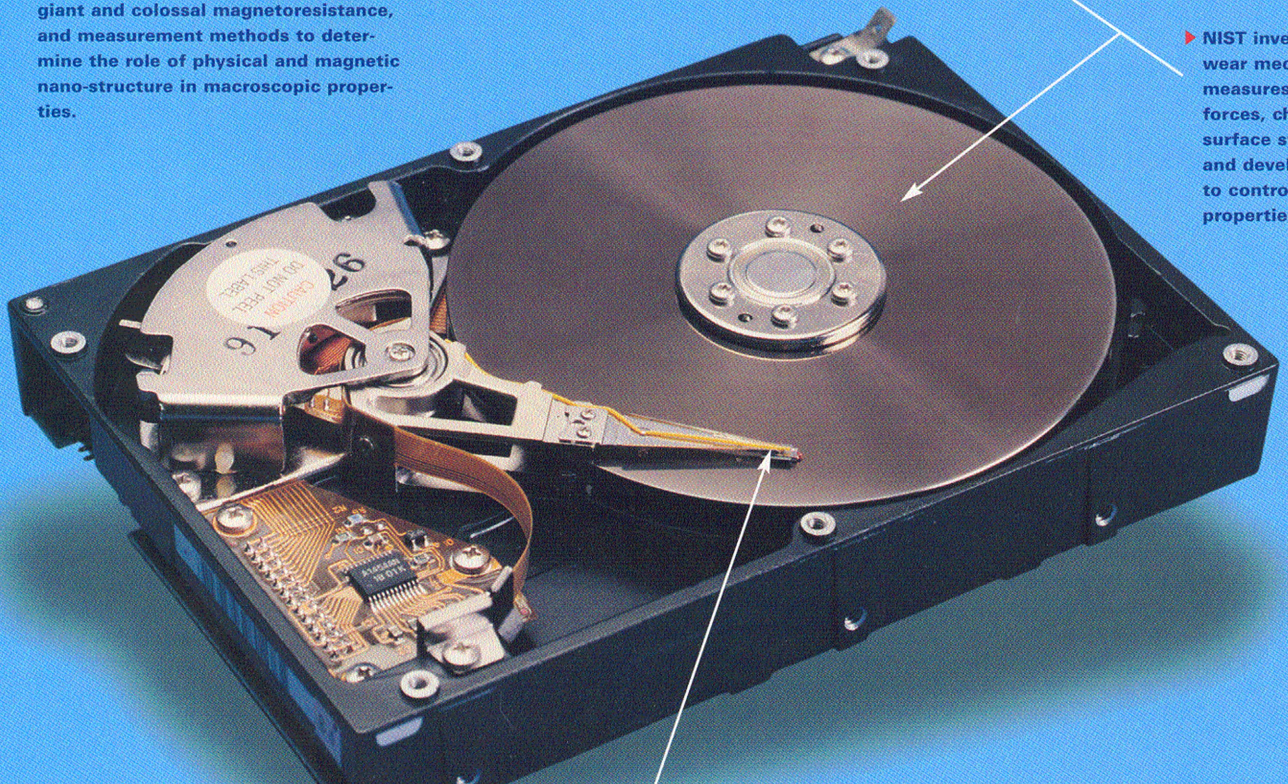
NIST develops materials and processing methods to exploit the benefits of giant and colossal magnetoresistance, and measurement methods to determine the role of physical and magnetic nano-structure in macroscopic properties.



NIST expertise in the measurement of nanometer-scale structures can help to provide accurate measurements of component structures.

- NIST imaging techniques help to correlate the magnetic, physical, and chemical structure of the individual grains in hard disk media.

- NIST investigates wear mechanisms, measures surface forces, characterizes surface structures, and develops ways to control surface properties.



- NIST has devised current probes to characterize the field rise time in write heads.

- NIST research may lead to new soft magnetic materials.

- NIST develops calibration standards for magnetometers and standards for bulk and thin film materials used in recording devices.

- NIST studies of material growth processes help to optimize methods for depositing very thin magnetic and nonmagnetic layers in read heads.

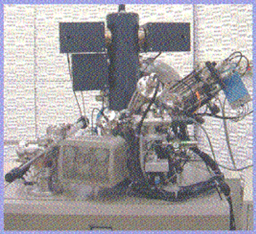
- NIST measurements, models, and other innovations have contributed to understanding of exchange bias, a primary method of controlling the magnetization in spin valve devices.

- NIST develops ways to measure and control magnetic ringing and damping.

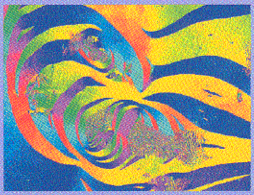
Illustrations of Selected NIST Capabilities

Magnetic Imaging

NIST pioneered the technique of scanning electron microscopy with polarization analysis (SEMPA), used to observe magnetic structures up to 100 times smaller than can be seen using optical techniques. SEMPA is unique in that it can directly image the magnitude and direction of a magnetization as small as that produced by 1,000 iron atoms. The technique assisted in the rapid development of high-density magnetic data storage systems. For example, in hard disk media, it was used to image the structure of digital bits to correlate the magnetic, physical, and chemical structure of the individual grains in the thin film.



NIST helped to improve magnetic force microscopy through the use of superparamagnetic tips and by fabricating magnetic imaging reference samples. NIST also developed new magnetic resonance force microscopes that combine the basic principles of scanned probe microscopy with magnetic resonance imaging to achieve quantitative field mapping at a spatial resolution of 1 μm, with an eventual goal of 20 nm.



NIST continues to work on new imaging methods. An example is ballistic electron magnetic microscopy, which can be used to image buried magnetic structure in sub-micrometer devices with 5 nm resolution, and to measure local spin-dependent transport properties such as spin relaxation lengths.

Magnetic Modeling

Micromagnetic computations can save time and money in the design and analysis of magnetic materials and devices, which are complex systems of alloys and multilayers containing up to 12 different components. NIST scientists and mathematicians developed a computer program called Object Oriented MicroMagnetic Framework. Its micromagnetic predictions can be compared with the predictions computed by other programs, enabling researchers to make more accurate models of many computer storage materials.

The user-friendly program has a well documented, flexible programmer's interface to allow outside researchers to swap their own code in and out. The software (available at *http://math.nist.gov/oommf*) has been downloaded more than 2,000 times since January 1999. It is used by leading U.S. firms as well as internationally. NIST has released an experimental three-dimensional version of the software that will enable researchers to model layered materials.

Giant Magnetoresistance

NIST is a leader in giant magnetoresistive (GMR) materials and technology, including the preparation of spin valves exceeding 20 percent GMR—a much higher value than the research standard. Read heads exhibiting a large GMR are ultrasensitive. NIST also developed methods to optimize the properties of GMR materials by producing them in the presence of a tiny amount of pure oxygen in a vacuum chamber. Studies of the thermal degradation of GMR films have shown that tantalum and tantalum oxide capping layers are much more robust than gold.

Research on GMR has been accelerated by NIST's Advanced Technology Program (ATP), which supports research on enabling technologies with the potential for high payoff in the national economy. Among its benefits, the ATP encourages the formation of research partnerships that otherwise would be unlikely or even impossible. A joint venture (under way from 1992 to 1997) led by the National Storage Industry Consortium to develop GMR recording heads brought together several leading U.S. firms.

More recently, high-speed measurements made by NIST and collaborators demonstrated the potential of GMR devices to work at frequencies up to 4 GHz, far greater than the 0.5 GHz typical today. The data clearly show the modifications needed for operation of recording heads and magnetic memory elements in the gigahertz regime, a level that must be attained soon if magnetic data storage is to maintain its technical advantage over competing formats.

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