DATA STORAGE
TECHNOLOGY & MANUFACTURE OF STORAGE DEVICES

Magnetic force microscopy: High-resolution imaging for data storage

THE INCREDIBLY HIGH BIT DENSITIES OF TODAY'S HARD DISKS AND OTHER STORAGE DEVICES DEMAND USE OF THIS ADVANCED MAGNETIC IMAGING TECHNIQUE.

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Measurements of magnetic features become increasingly difficult as the bit densities of storage media continue their climb to higher levels. Reaching the gigabit/in^2 benchmark has produced magnetic features smaller than the wavelength of light. As a result, extremely high-resolution magnetic imaging is becoming a requirement for the design and manufacture of most data-storage devices [1]. Typical applications for high-resolution magnetic imaging include measurements of the head performance on hard disks, the bit shape and roughness for magneto-optical disks, and the domain behavior of emerging thin-film and magnetoresistive heads.

Magnetic force microscopy (MFM) brings the power of scanning probe microscopy (SPM) [2,3] to a convenient and cost-effective imaging tool that is ideal for many data-storage device applications. By scanning a tiny ferromagnetic probe over a sample, MFM maps the stray magnetic fields close to the sample surface (Fig. 1).

MFM boasts many capabilities that complement existing imaging methods. Resolution is routinely better than 50 nm—far surpassing that of optical techniques such as Kerr microscopy. Also, sensitivity is sufficient to image individual submicron particles. Fields can be imaged through the nonmagnetic and opaque overcoats often applied to hard disks and magneto-optical media. Compared to electron-based scanning methods (i.e., Lorenz microscopy and SEMPA), MFM offers convenience and ease of use. Imaging is done under ambient conditions, requires little or no sample preparation, and gives results in a few minutes. With its dual identity as a magnetic and atomic force microscope, an MFM instrument can also characterize media topography (such as hard-disk roughness) with sub-angstrom vertical resolution. Though not the main topic of this article, these topographic measurements are extremely valuable for evaluating surface characteristics and defects for the full range of data storage devices.

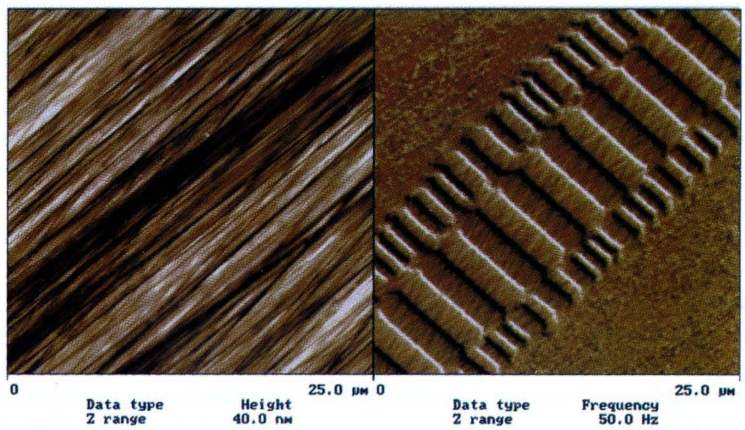

Figure 1. MFM images of overwritten tracks on a textured hard disk. The topography (left) was imaged using TappingMode; the magnetic force image of the same area (right) was captured with LiftMode (lift height 35 nm) by mapping shifts in cantilever resonant frequency. Acquisition time was about five minutes. Track width and skew, transition irregularities, and the difference between erased and virgin areas are visible.

In the past few years, MFM has advanced from a research curiosity to a valuable diagnostic tool for hard-disk and thin-film manufacturing, and for related research into the basic physics of micromagnetism. State-of-the-art performance is now available in commercial instruments, and the use of MFM in the data-storage industry is spreading rapidly.

OPERATING PRINCIPLES FOR MFM

To understand the principles of MFM, we must first look at SPM, from which the technique is derived [2,3]. An SPM probe consists of a sharp tip mounted on a weak cantilever spring. The tip is brought close to the sample and a piezoelectric scanner moves the probe in a raster pattern. Interactions between the tip and sample

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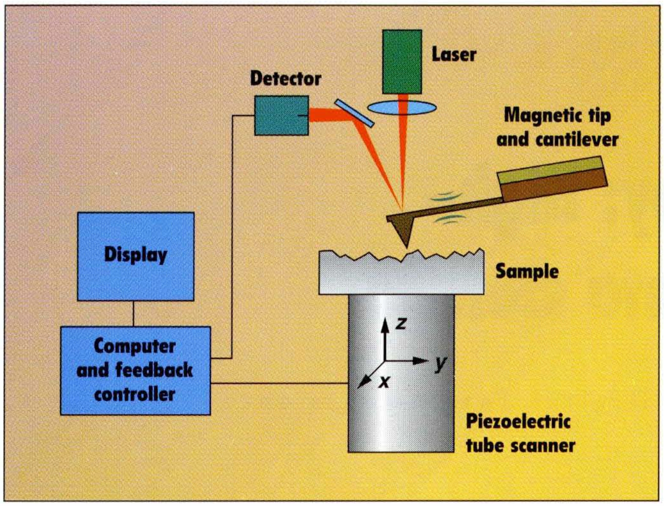

Figure 2. Schematic of a scanning probe microscope (MultiMode design). For magnetic imaging, the probe has a magnetic tip. The sample is moved in a raster pattern by the piezoelectric scanner, and the sample's stray fields cause shifts in the resonance of the cantilevered probe that are measured by laser detection.

Figure 3. The advanced MFM imaging system used to produce the images in this article includes the Digital Instruments NanoScope III SPM controller and a Dimension 3000 atomic-force/magnetic-force microscope. Also shown are the computer and displays used for real-time video, system control, and signal processing.

deflect the cantilever. The deflection is monitored by reflecting a laser beam off the cantilever into a segmented photodiode (Fig. 2) and an image is formed by mapping this laser-detected deflection while scanning.

In its simplest form, SPM brings the tip into direct contact with the sample. Feedback continually adjusts the z (vertical) position of the sample to keep the cantilever deflection at a constant value while scanning. The resulting vertical offset $z(x,y)$ is displayed as a three-dimensional image of the surface topography (see the hard-disk texture shown in the left of Fig. 1). Cantilever springs can be made weaker than interatomic bonds (about 1 Newton/meter), thus allowing imaging with atomic resolution [2].

For MFM, batch-microfabricated silicon probes are magnetically sensitized by sputter coating with a ferromagnetic material. The tip is scanned several tens or hundreds of nanometers above the sample, avoiding contact. Magnetic-field gradients exert a force on the tip's magnetic moment, and monitoring the tip/cantilever response gives a magnetic-force image.

To enhance sensitivity, most MFM instruments oscillate the cantilever near its resonant frequency (around 100 kHz) with a piezoelectric element. Gradients in the magnetic forces on the tip shift the resonant frequency of the cantilever (see "Resonant Enhancement" sidebar) [3,4,5]. Monitoring this shift, or related changes in oscillation amplitude or phase, produces a magnetic-force image. The right frame of Fig. 1 shows a frequency-shift map of an overwritten hard-disk track captured in this manner.

All images shown in this article were produced using the Digital Instruments NanoScope III SPM controller, 486/66 computer, monitors, and either the Dimension 3000 SPM (Fig. 3) or the MultiMode SPM. In addition to the magnetic imaging featured here, these instruments fill several other roles. They can perform topographic measurements by atomic force microscopy (with sub-angstrom vertical resolution), operate with samples in ambient conditions or in fluid, and can double as scanning tunneling microscopes on conducting samples. For MFM applications, NanoProbe silicon probes are specially sputter-coated by Advanced Research Corp. of Minneapolis, MN.

SEPARATING TOPOGRAPHIC AND MAGNETIC DATA

One long-standing problem in MFM has been the contamination of magnetic data by the influence of topography [4,5,6]. Ideally, the magnetic and topographic data types should be kept separate in order to give a more accurate magnetic image and to reveal correlations between magnetic and structural features.

A recent breakthrough in topographic/magnetic separation was achieved with the development of LiftMode. In this technique, each line in the raster scan pattern is passed over twice (Fig. 4). On the first pass, topographical information is recorded using TappingMode, in which the oscillating cantilever lightly taps the surface. An image of the topography is obtained by using the oscillation amplitude as a feedback signal for the tip-sample spacing. Magnetic force data is acquired during a second pass, for which the tip is raised to a user-selected "lift height." The lift height (typically 20–200 nm) is added point-by-point to the stored topographical data, thus keeping the tip-sample separation constant and preventing the tip from interacting with the surface. These two-pass measurements are taken for every scan line to produce separate topographic and magnetic force images of the same area.

Other methods for topographic/magnetic separation either apply an oscillating potential between the tip and a conducting sample, or

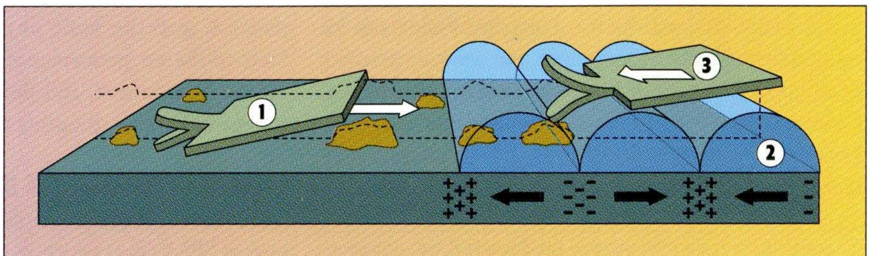

Figure 4. Magnetic imaging using LiftMode. For each scanline, the surface topography is first determined with TappingMode, in which the tip lightly taps the sample (1). The tip is then raised to the lift height (2), and a second pass is made to acquire magnetic force data (3) while keeping the tip-to-sample spacing constant.

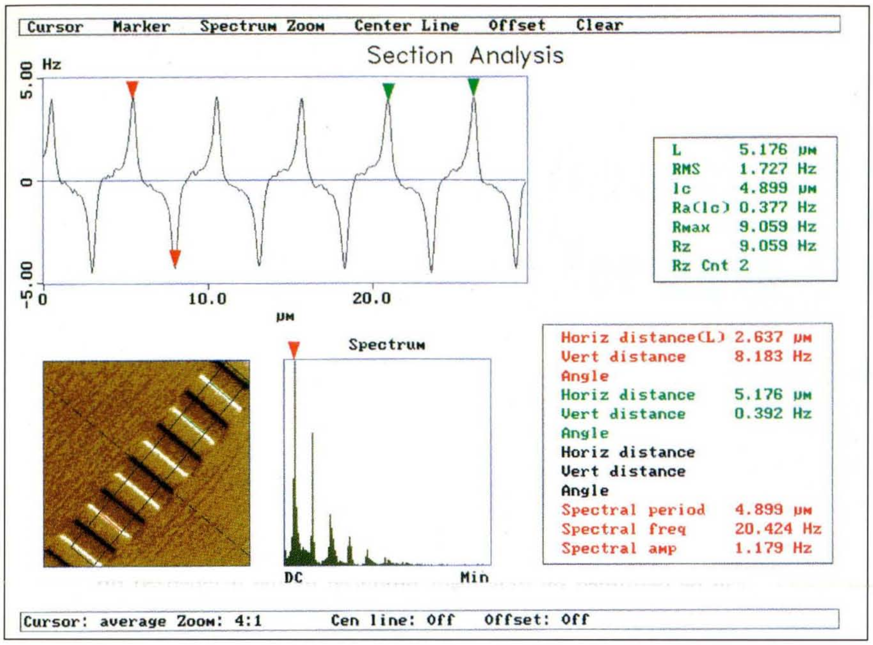

Figure 5. Section analysis of a hard disk track. The magnetic signal (top) is an average across the rectangular box centered on the track (lower left). Also shown are the power spectrum and various statistical measures of the magnetic signal.

they use feedback to keep the probe in a "non-contact" region very close (<30 nm) to the surface, without the benefit of previously recorded topographic information [6]. Both those methods have been used with some success on a limited number of samples.

LiftMode, however, has advantages in both flexibility and reliability, including the ability to image nonconducting or patterned samples as well as conducting samples. Because the tip oscillates and follows a path predetermined by the topography, LiftMode is not prone to "tip crashes"— destructive contact that noncontact methods often experience. Also, frequency, phase, or amplitude shifts can be recorded as desired. Small lift heights (<50 nm) exploit the full potential of MFM for high-resolution imaging. Specific lift heights can also be chosen to image the fields experienced by disk-drive heads at different flying heights. Furthermore, large lift heights can allow magnetically "soft" samples (such as Permalloy) to be imaged.

APPLICATIONS TO DATA STORAGE TECHNOLOGY

MFM can provide valuable information about nearly any recording medium. For example, width, skew, and spacing of hard-disk tracks (Fig. 1) can be precisely measured to evaluate head performance. Section analysis (Fig. 5) shows how the MFM signal appears when laterally averaged across the track. Such data reflect the response of a read head, and appropriate settings of the lift height can mimic different head fly heights. The high resolution of MFM also allows evaluation of disk media themselves. For example, images of demagnetized media show the magnetic cluster size, a critical parameter thought to correlate with media noise. Sub-nanometer scale roughness analysis of the topography can be done simultaneously.

MFM is also useful for imaging perpendicular media, such as the magneto-optical disk tracks shown in Fig. 6. Bit shape, position, and edge roughness are readily visible. This partially-processed disk has demagnetized areas in the grooves, and the 30-nm lift height allowed 50-nm features to be resolved.

A track edge of metal-evaporated video tape is shown in Fig. 7. The topography image (left) shows lubrication nodules and surface roughness. Meanwhile, the magnetic-force gradient map (right) shows how written transitions are related to the virgin domain structure that is visible off-track.

For particulate media, such as digital audio recording tape, separating the topographic and magnetic information can show how particle characteristics affect the recorded information. Orientation of the particles becomes visible, and the magnetic signal weakens considerably as the bit spacing approaches the particle size. Related research on the magnetics of individual submicron particles can also benefit from MFM's high sensitivity.

These examples demonstrate that MFM can image magnetic structure in recording media. More challenging is the imaging of magnetically "soft" materials commonly used in thin-film inductive

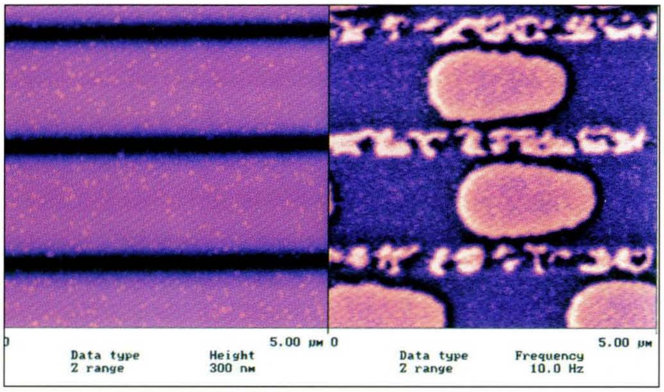

Figure 6. Bits on a magneto-optical disk. The left image shows surface topography with the tracks delineated by grooves. The magnetic force image on the right used LiftMode (lift height 35 nm). Bit edge roughness is visible, as is the virgin domain structure in the grooves (with features as small as 50 nm).

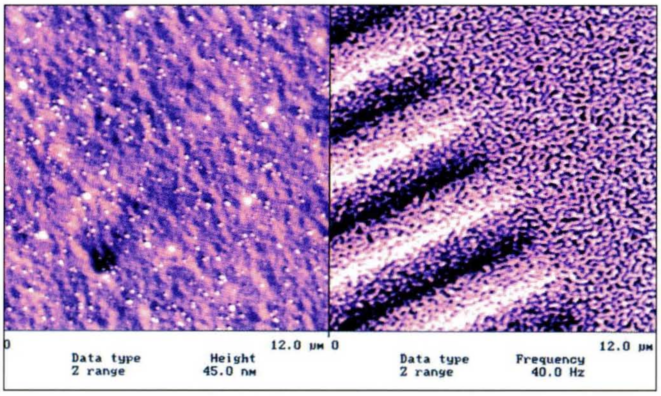

Figure 7. Track edge on metal-evaporated recording tape. Lubrication nodules and surface structure are visible in the topography image (left). The magnetic force image (right) used a lift height of 30 nm, and shows how the bit transitions are related to the virgin magnetic structure.

RESONANT ENHANCEMENT

As mentioned in this article, most MFM instruments exploit the resonant properties of the cantilever to improve the signal-to-noise ratio [3,4,5]. A typical MFM cantilever can be characterized as a weakly damped driven oscillator with a resonant frequency, f_o, of around 100 kHz and a quality factor (Q) of 100 or more. To harness the signal magnification resulting from the high Q at resonance, the base of the cantilever is mounted on a piezoelectric element and excited into oscillation near the resonant frequency, and with amplitudes in the range of 10–100 nm.

The sample's magnetic fields or, more precisely, the gradients (F') of the magnetic force on the probe tip, alter the effective spring constant (k). That, in turn, shifts the resonant frequency by an amount:

$$\Delta f_o \approx \frac{f_o}{2k} F'$$

This shift is tracked by laser detection to give a map of the force gradient. Associated shifts in the cantilever amplitude or phase can also be mapped. In a simplified picture, the tip has a fixed magnetic dipole moment in the vertical direction ($\mathbf{m}=m\hat{z}$). The vertical component of the force is thus

$$m \frac{\partial H_z}{\partial z} \qquad (1)$$

and resonant enhancement is sensitive to the second derivative of the sample's stray field

$$F' = m \frac{\partial^2 H_z}{\partial z^2} \qquad (2)$$

where H is the stray field from the sample. The improvement in signal-to-noise ratio is roughly equal to the Q of the mechanical resonance which can be a significant factor. For a simple MFM instrument without resonant enhancement, the tip deflection would be about 1 nm (for a sample of recording media with 1-µm magnetic features and 100-Oe magnetization). That order of deflection would be detectable. But with samples having small magnetization and weak stray fields, the straight "dc" measurement of deflection does not provide sufficient sensitivity for good imaging. Also, the simple dc techniques are prone to tip crashes when one attempts high-resolution imaging that requires bringing the tip very close (<100 nm) to the sample. Of course, such problems are avoided with the higher sensitivities provided by resonant enhancement. ▲

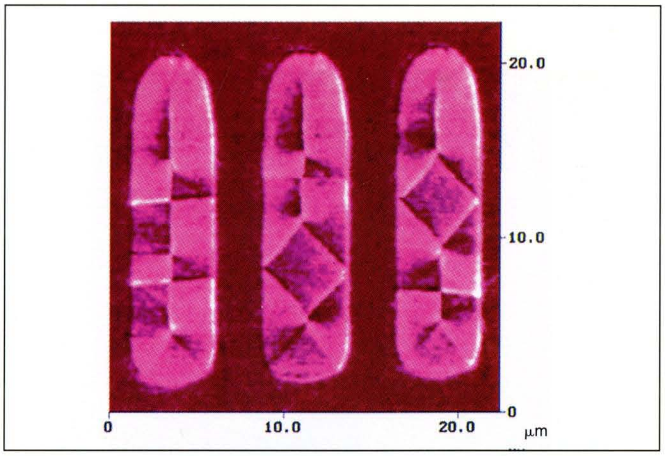

Figure 8. Magnetic domains in three topographically identical regions of 50-nm Permalloy ($Ni_{80}Fe_{20}$) film. Magnetically "soft" materials such as Permalloy are widely used in such components as magnetic recording heads.

and magnetoresistive heads. Domains in magnetically soft materials can be perturbed by stray fields produced by the magnetized tip. The image of magnetic domains in thin Permalloy film (Fig. 8) shows that suitable choices of tip characteristics and lift height can give good images without destroying the domain structure.

Thick (several µm) films such as those used in head yokes can also be imaged. In that application, weak stray fields cause cantilever frequency shifts as small as 0.1 Hz, relative to an 80-kHz resonance. Such small signals put a premium on precision, low-noise scanning and signal detection.

Garnet films are another group of magnetically soft materials that have many technological applications. In an interesting MFM example, remarkable "flower" domains are revealed in a garnet designed as a magneto-optic isolator (Fig. 9). A large lift height (200 nm) used for that measurement produced minimal domain

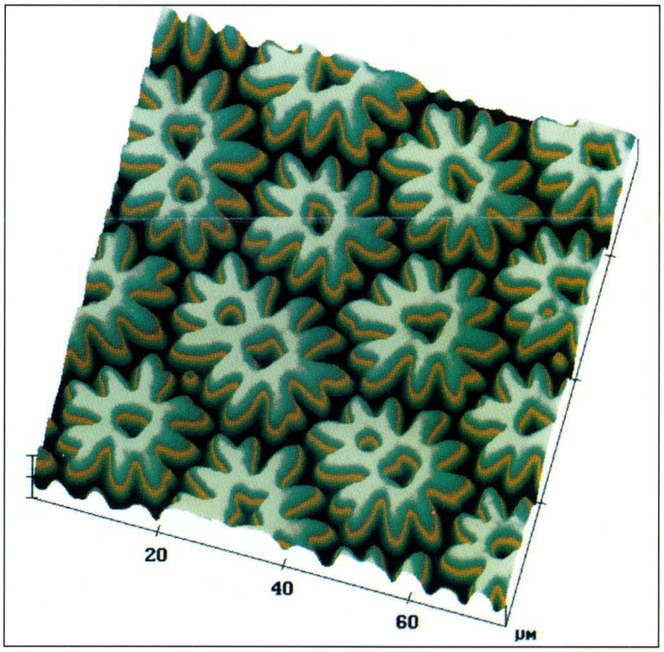

Figure 9. MFM reveals picturesque "flower" domains in a 60-µm garnet film used in magneto-optic isolators. Similar garnet films are also used for magnetic bubble memories and are proposed for data storage devices based on micromagnetic structures (Bloch lines) at the walls of bubble domains. (Sample courtesy of Vincent Fratello and Raymond Wolfe, AT&T Bell Laboratories.)

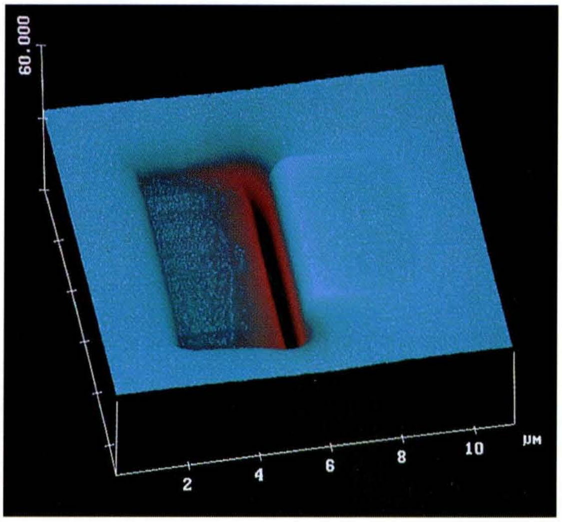

Figure 10. Magnetic force gradient map of fields from an active inductive head; lift height 50 nm. The magnetic gap appears as the sharp color change between the pole tips.

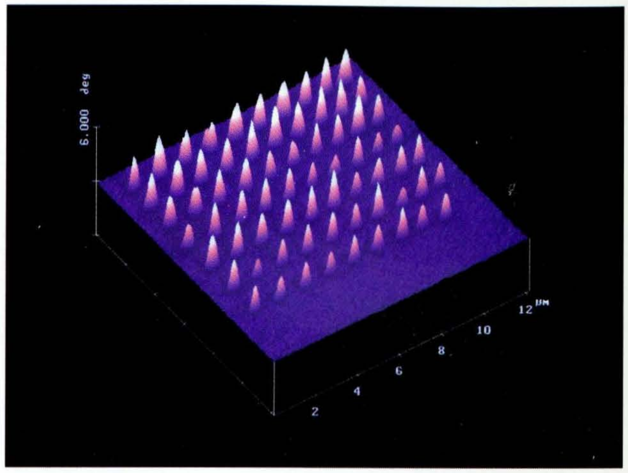

Figure 11. Bits written on TbFeCo magneto-optical media with a thin-film MFM probe. The same probe was used for imaging. The total applied field was decreased in successively nearer rows until no bits were written, giving a measure of the media's point coercivity. Sample courtesy of William Challener, 3M Corp.

perturbation. Garnet films were originally developed for bubble-memory systems in which the presence or absence of mobile cylindrical domains ("magnetic bubbles") is treated as information. Current research focuses on using micromagnetic structures (Bloch lines) in the domain walls to achieve information densities higher than those allowed by the relatively large domains themselves.

MFM can also directly assess the performance of recording heads. An MFM image of an active inductive head (Fig. 10) maps the head fields and gives a measure of the magnetic gap. Corresponding topographic images allow the most accurate possible measurements of the mechanical gap and pole tip recession. Similar images of magnetoresistive heads show how domain structure in the MR element is influenced by surrounding magnetic and conducting elements.

In addition to imaging, MFM probes can be used to write and sense "bits" of reversed magnetization in perpendicular recording media (Fig. 11) [7,8]. Bits are written by momentarily adding an external magnetic field to the stray field of the probe. When the total field exceeds the local media coercivity, magnetization is reversed and a bit is written. The results can be imaged immediately with the same probe. Bits as small as 120 nm and densities > 5 Gbit/in^2 have been demonstrated [8]. "Data" rates are very slow, however, and the technique perhaps shows more promise for media analysis than for data storage. For example, the shape and size of the written bits directly assesses media response to very localized fields. Recent work [8] has shown that the local, or *point*, coercivity of the media can be measured on a 100 nm scale by varying the external field strength (Fig. 11). The results complement bulk hysteresis measurements attained by standard techniques such as vibrating sample magnetometry. In addition, spatial variations in nucleation fields can be evaluated [8], demonstrating the potential for probing submicron structure that affects media performance.

TRENDS IN MFM TECHNOLOGY

MFM has several applications outside of the data storage measurements described in this article. Some important examples include: imaging of micromagnetic structure in iron, magnetite, and other materials [9]; failure analysis of ICs by imaging the magnetic fields produced by active circuits [10]; imaging of biological samples such as magnetotactic bacteria [9]; and geophysical applications, such as the mapping of different magnetic phases in andesite [4,5].

MFM technology is still young, and the list of applications is expanding rapidly. Images discussed in this article demonstrate the power and versatility of MFM. Sensing of stray fields can be particularly useful when examining recording media, because the tip is exposed to exactly the same fields as a read head. In most cases, domain structure is easily inferred from MFM images. Recent work [4,5,9] has pushed MFM into the realm of analytical micromagnetism and quantitative analysis. With the best instruments and tips currently available, MFM resolution is routinely 50 nm or better. That represents an order-of-magnitude improvement over optical techniques (e.g., Kerr microscopy), and images can be acquired in just a few minutes without sample preparation.

Since MFM's recent commercial debut, numerous media and thin-film manufacturers have recognized its performance and have adopted it as a diagnostic and quality control tool. Improvements in the design and coating of tips and the development of the LiftMode technique have further increased power and reliability. MFM is clearly destined to play an important role in the push toward higher storage densities. ▲

Acknowledgments
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