MAGNETIC FORCE MICROSCOPY:
Methods and Applications in Data Storage

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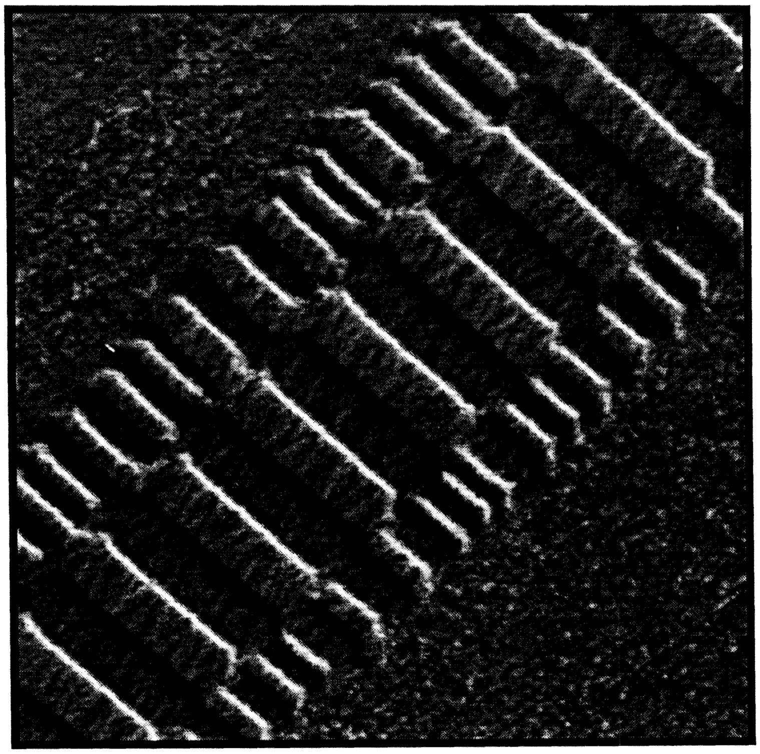
Magnetic Force Microscopy: Methods and Applications in Data Storage



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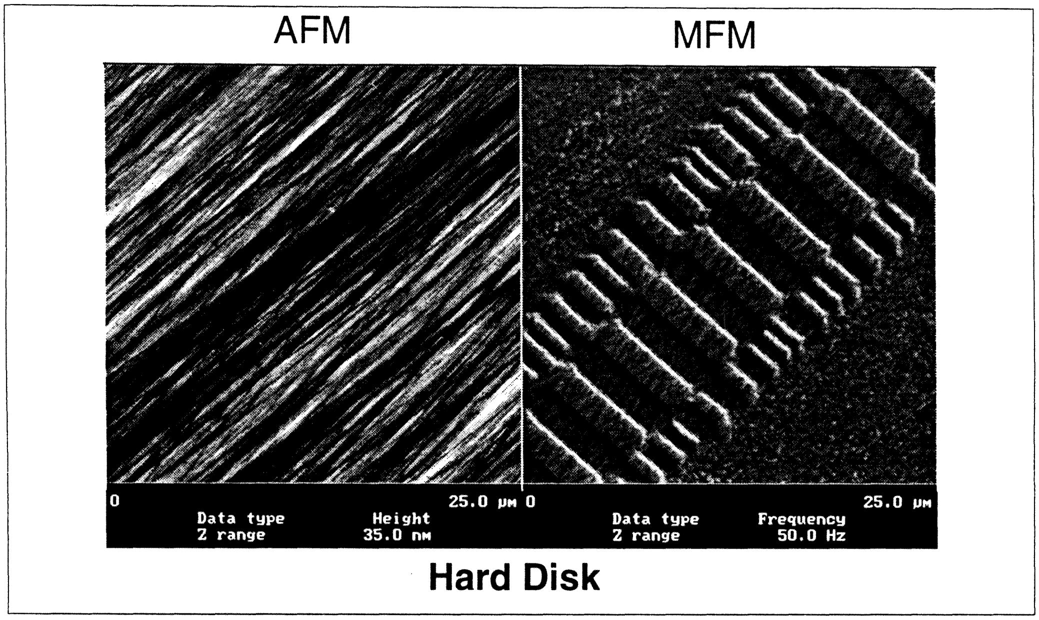
Digital Instruments, Inc.

Santa Barbara, CA

V. 1
March, 1996

Introduction



Magnetic force microscopy (MFM) combines a familiar property of magnetism - the attraction or repulsion of two magnets - with the power of *scanning probe microscopy* (SPM). MFM works by scanning a tiny ferromagnetic probe over a sample and detecting the extremely small forces exerted on the probe by the sample's stray magnetic fields. MFM produces images such as the hard disk tracks shown above (right), with resolution down to the 10 nanometer scale. Imaging is done in ambient conditions, and requires little or no sample preparation.

A companion of MFM is *atomic force microscopy* (AFM). AFM maps and measures surface topography down to the nanometer and even Å scale, with no sample damage; see the image of hard disk texture shown above (left). AFM and MFM are normally performed together, and comparison of the two types of data can reveal the influence of morphology on magnetic structure.

Use of MFM and AFM in the data storage industry is exploding, with installations at virtually every manufacturer in the United States and overseas. This is due in part to recent advances in instrumentation which have improved reliability, ease-of-use, and compatibility of SPM with industrial needs. Meanwhile, data densities have surpassed the 1 Gbit/in^2 benchmark, and magnetic and structural features on devices have shrunk accordingly. MFM provides valuable feedback on media and head performance by allowing direct visualization of features such as track width and skew, transition spacing and irregularities, media noise, servo patterns, magneto-optical bit edge roughness, elements of magneto-resistive heads, fringing fields in active heads, and others. These applications often require resolution beyond the diffraction limit of optical imaging methods (eg., Kerr), and demand ease-of-use not available with electron-based imaging (SEM,TEM, SEMPA). AFM gives quantitative measurements of disk texture and roughness, recording head topography (contamination, polishing, pole tip recession), defect analysis, and other applications.

In addition to the data storage industry, MFM and AFM are finding widespread use in the development of novel magnetic materials and in fundamental magnetism.

Course Goals and Outline

This course gives a practical introduction to the fundamentals of MFM and AFM, describes widely-used instrumentation, and surveys current data storage applications. No prior experience with SPM is assumed.

AFM and MFM fall under the umbrella of *scanning pobe microscopy* (SPM), which encompasses these and other microscopies that map the interactions between a sharp, microscopic probe and a sample. An understanding of MFM first requires an introduction to the more general principles of SPM.

Topics to be covered include:

- a brief introduction to scanning probe microscopy, including fundamental principles and instrument overview
- topographical imaging with AFM
- fundamental principles and capabilites of MFM
- interpretation of AFM and MFM images
- examples of specific applications in data storage, including media and recording heads
- discussion of emerging techniques such as MFM imaging in applied fields
- a brief introduction to other SPM techniques such as thermal imaging and nanoindentation

The "classroom" discussion will be accompanied by demonstrations of AFM/MFM operation

Contents (partial)

I. Introduction to SPM and AFM

II. Magnetic Force Microscopy

III. Data Storage Applications

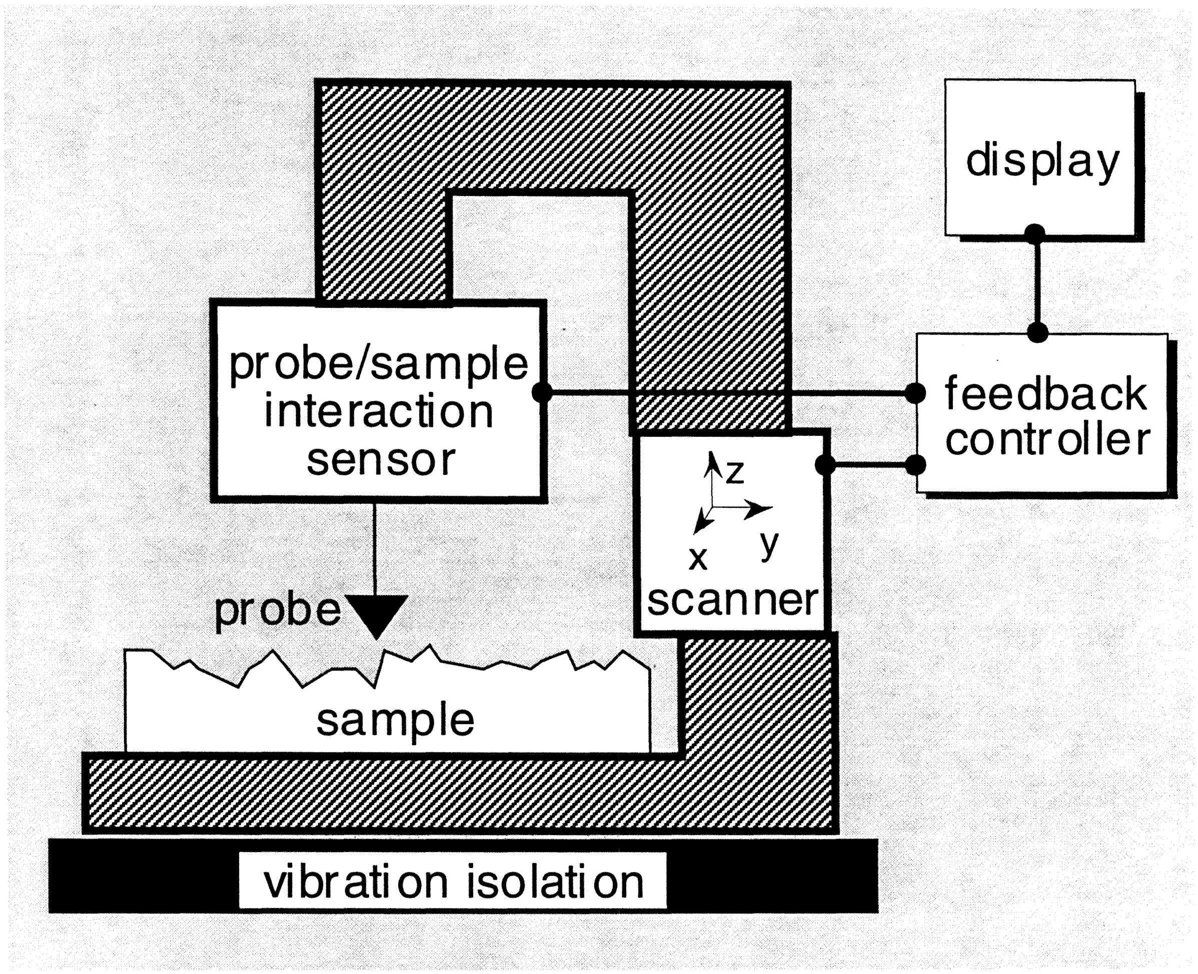
IV. Probes Revisited

Appendices

I. Introduction to Scanning Probe Microscopy

SPM Schematic

a general cartoon...



A SPM consist of 4 key components:

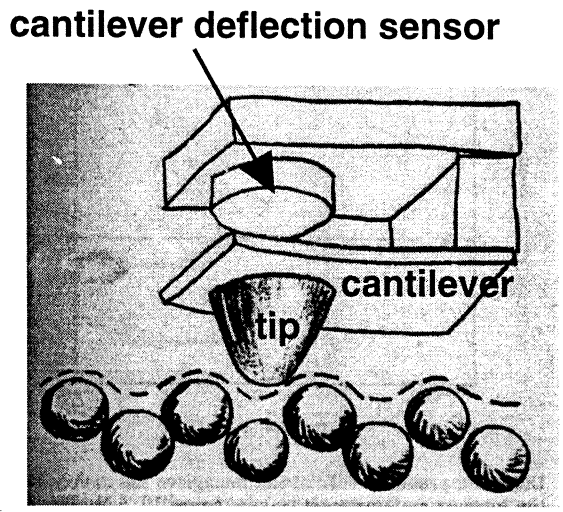
- **sharp probe**
- **three-axis scanner**
- **detector of probe-sample interactions**
- **feedback loop**

The probe is scanned relative to the sample while the detector monitors probe/sample interactions. Feedback controls vertical scanner motion z so as to keep the probe (and detector) response constant. $z(x,y)$ is recorded to produce an image of the surface.

AFM and MFM

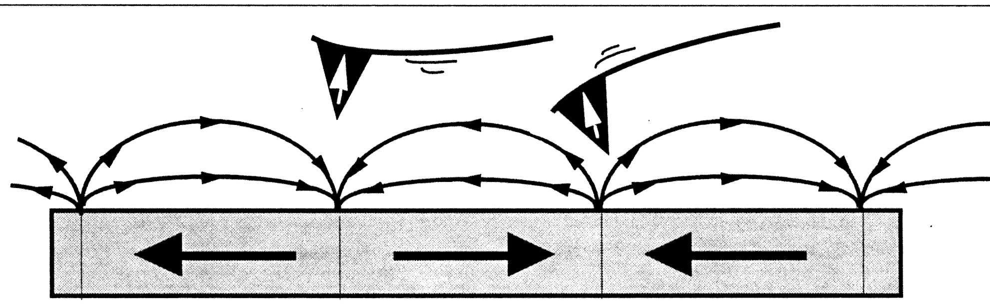
AFM

- AFM= one type of SPM
- probe = mechanically sharp tip mounted on a weak cantilever spring
- cantilever deflected by interactions between the tip and surface; sensor detects the deflection
- a feedback loop keeps the cantilever deflection constant during scanning
- can be generalized to oscillating cantilevers (TappingMode)
- atomic resolution possible with sharp probes and a great deal of care
- majority of AFM applications in the range from a few nanometers to ~100 μm
- can be done in ambient conditions
- provides quantitative lateral *and* height data, with no sample damage
- remarkably wide range of industrial and research applications



MFM

- extends these ideas to the mapping of magnetic fields
- probe is magnetically sensitized, typically by applying thin films of magnetic alloy
- sample's stray fields exert a force on the tip, deflecting the cantilever
- with some refinements, this technique gives direct visualization of magnetic structure down to the 10 nm scale.



Other SPM Modes

The SPM family includes a number of other modes that map sample properties at high resolution. Time allows us to touch on only a few of these toward the end of the course. A list:

Scanning Tunneling Miscroscopy (STM)

Lateral Force Microscopy (LFM)

Force Modulation Microscopy

Electric Force Microscopy (EFM)

Surface Potential Microscopy

Phase Imaging

Force Volume

Electrochemical STM and AFM (ECM)

Scanning Capacitance Microscopy (SCM)

Scanning Thermal Microscopy (SThM)

Near-field Optical Microscopy (NSOM or SNOM) — also Kerr effect

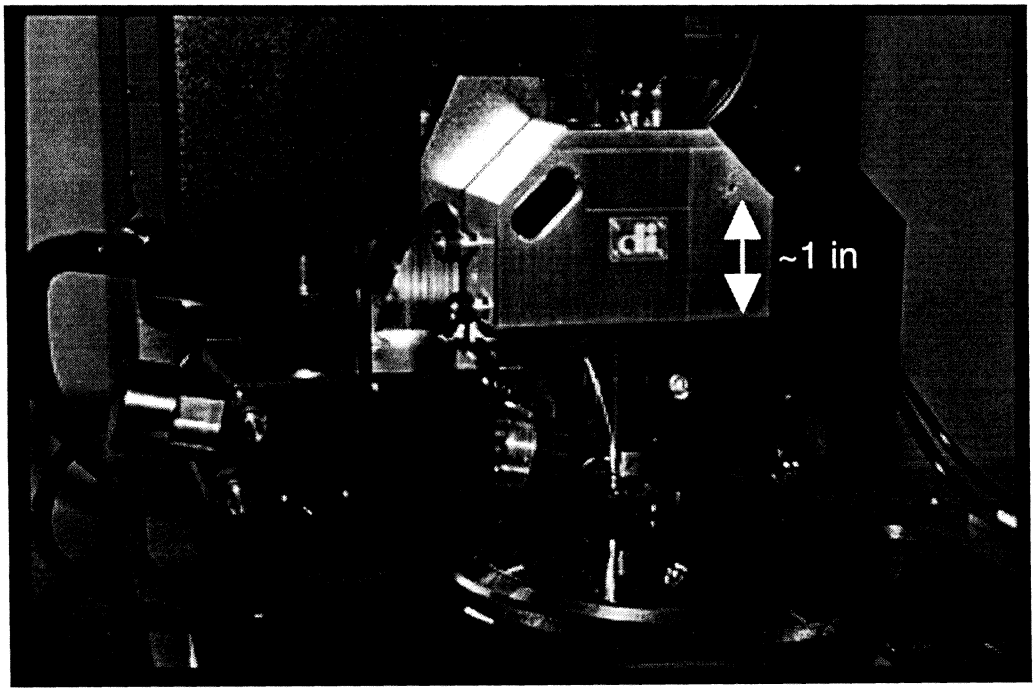
Photon Scanning Tunneling Microscopy (PSTM)

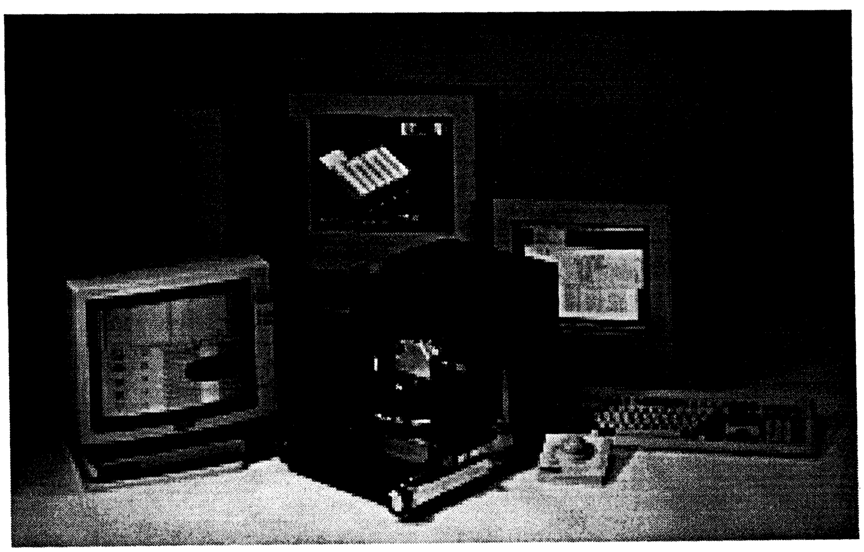
Ballistic Electron Emission Microscopy (BEEM)

Bl... elec. microscopy.

Realization of SPM

The remainder of this section will show how these concepts are put into practice. Pictured below is instrumentation widely used in industrial applications of AFM and MFM:



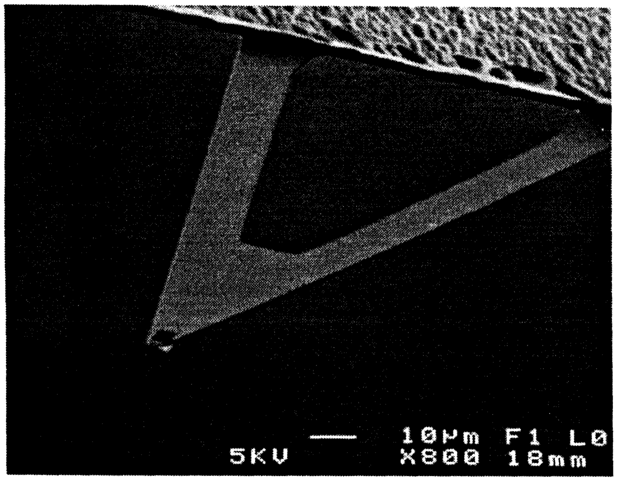


Begin by looking at SPM components in detail...

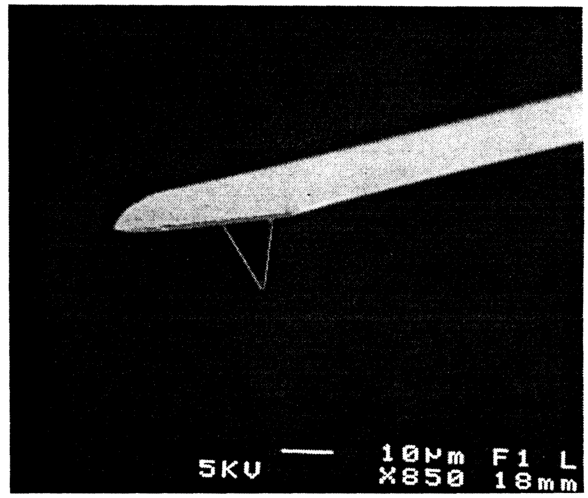
AFM Probes

Si N

S.C. Si



Si_3N_4



single-crystal Si

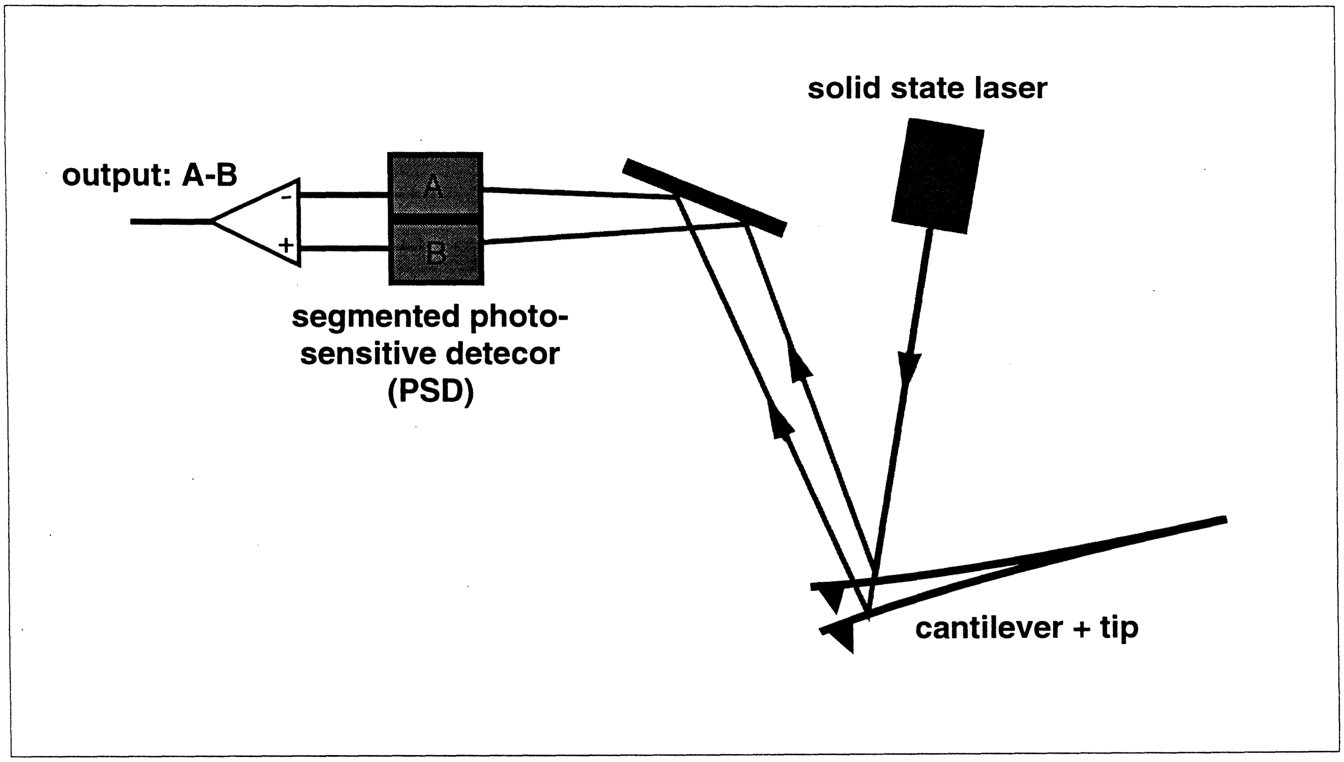
400
100 μm long
typical

- batch fabricated using lithography and etching techniques
- pyramidal tips are extremely sharp: end radii 5-10 nm.
- cantilevers 50-500 μm long
- cantilever spring constants ~0.1 - 50 N/m
- resonant frequencies 10 kHz - 1 MHz

~1 N/m energy ~~spring~~ between 2 atoms

We will be concerned mostly with "*ac*" measurements in which the cantilever is driven into oscillation like a diving board. Silicon cantilevers are most commonly used for this.

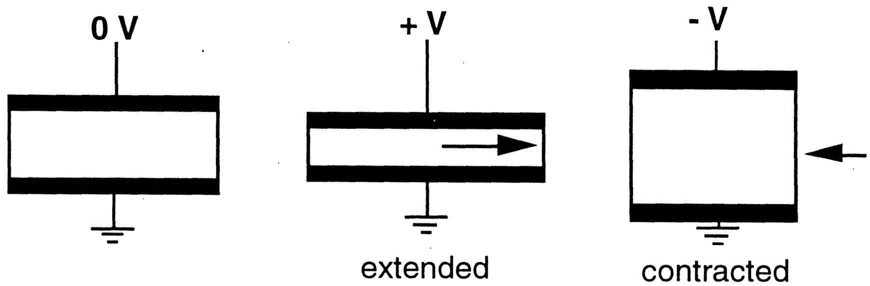
Detectors: "optical lever" or "beam deflection" technique



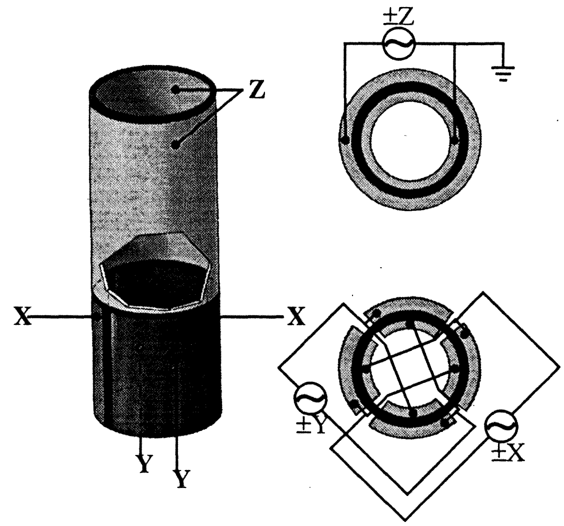
- long beam path (several cm) amplifies changes in beam angle
- can detect cantilever deflections < 1 Å (thermal noise limited)
- most widely used technique (cf., interferometers)

Scanners

Usually made from the piezoceramic "PZT" = $Pb(Zr,Ti)O_3$, which changes dimension when an electric field is applied

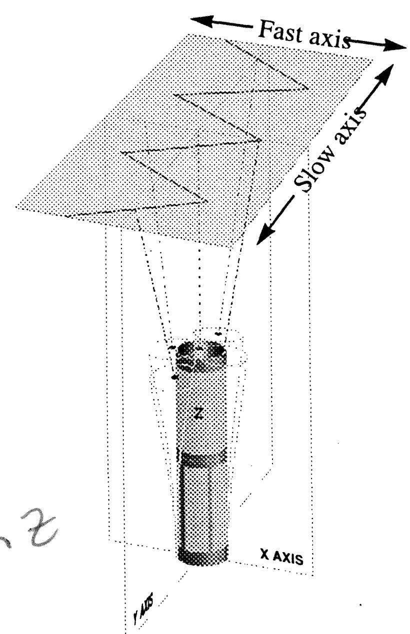


configure as a tube scanner to give three-axis motion



100's of V used

- application of appropriate x-y voltage waveforms gives raster scan motion in *x,y*
- vertical motion tracks surface topography



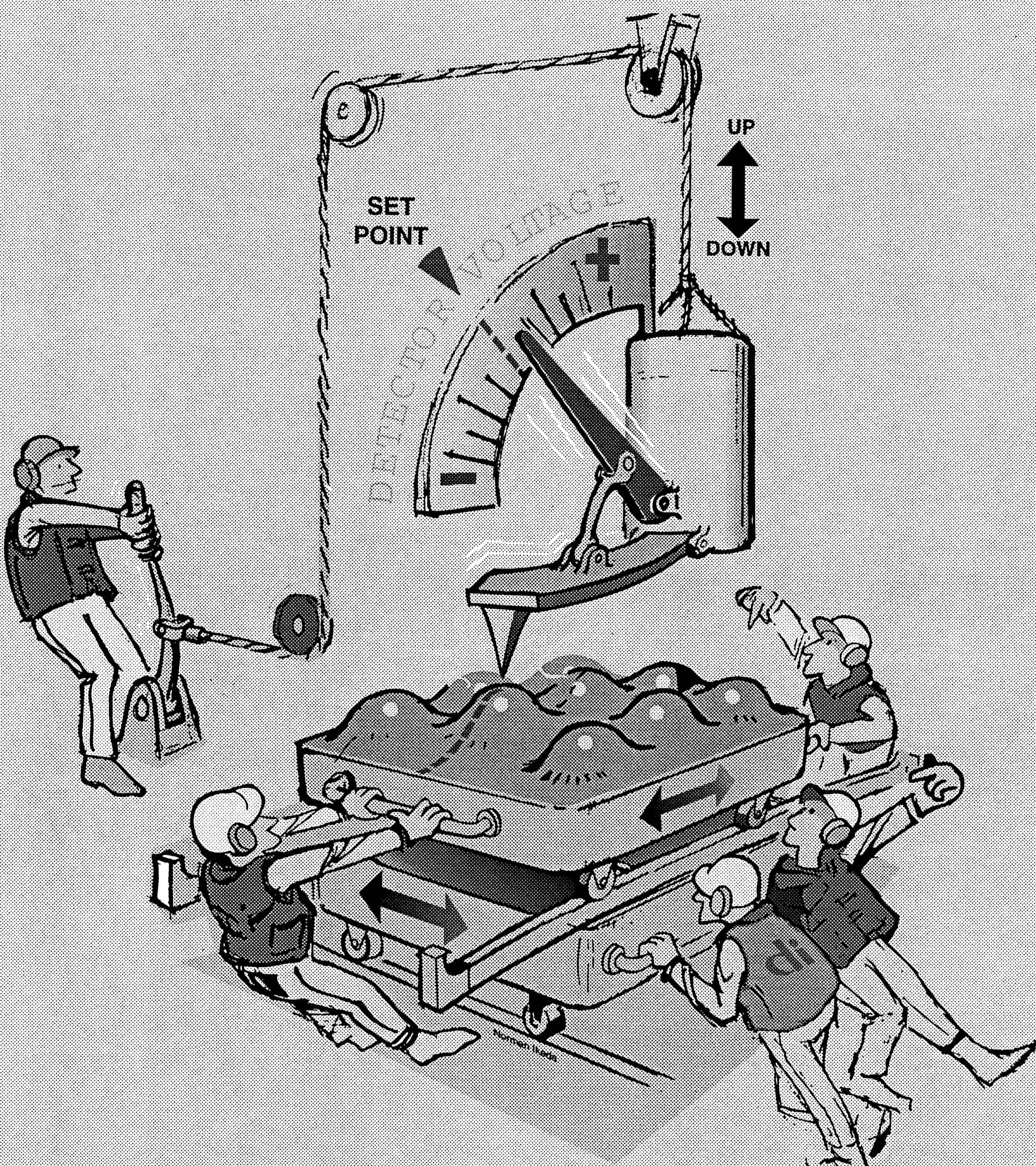
typical scan range:

x,y: 0-100 μm

z: 0-5 μm

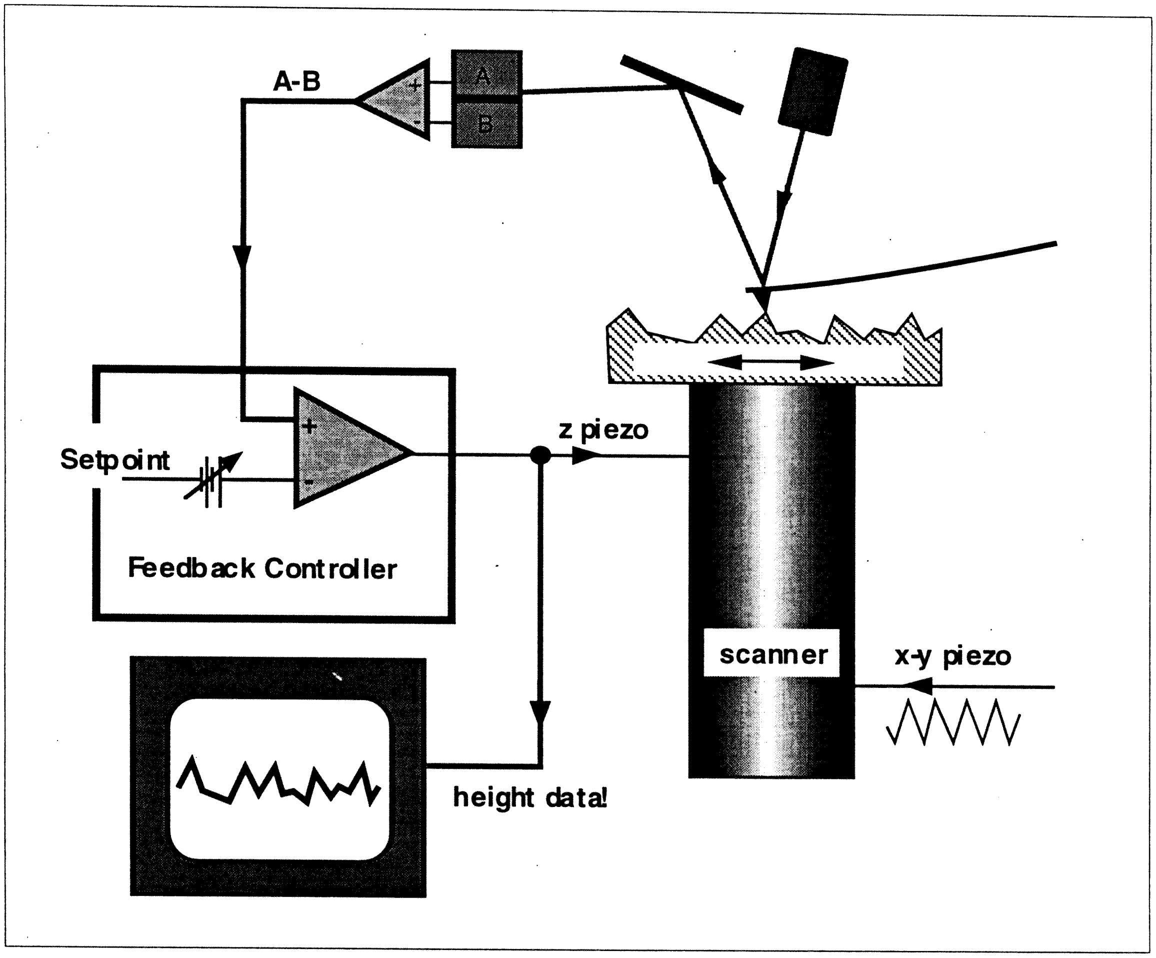
up to 10 μm Z

Scanner design is a major part of SPM engineering. PZT's nonlinear and hysteretic extension *vs.* voltage characteristics must be corrected for to give a linear, calibrated scan.



FEEDBACK BASICS

Feedback: Contact Mode AFM



- Output is voltage goes to sample tip

- sample is scanned relative to the tip in a raster pattern

- feedback controller loop continually adjusts the vertical scanner position z to keep the PSD output, and hence cantilever deflection, at a selectable, constant value (the *setpoint*)

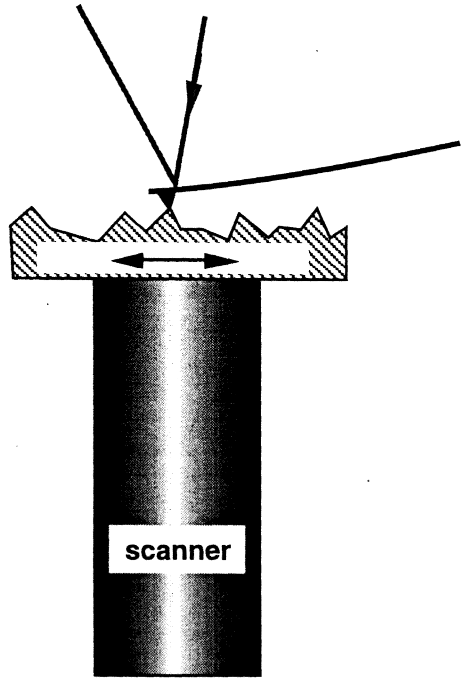
- by maintaining a constant cantilever deflection, a constant force be tween tip and sample is maintained.

- force is calculated by Hooke's Law: $F=-kz$, where F=force, k= spring constant, z=cantilever deflection. Forces are typically in the nN to μN range.

-recording and displaying $z(x,y)$ gives an image of the surface topography.

Actual SPMs typically use digital feedback. The analog signal from the PSD is digitized, and the feedback loop is controlled by a digital signal processor (DSP) and computer. The digital feedback output is then converted to analog voltages and sent to the scanner.

SPM Configurations



Scanned Sample

For simplicity, the previous illustrations have shown this configuration, where the tip is held fixed and the sample mounted on the scanner.

Advantages: allows very short, rigid mechanical path between tip and sample, and optimal noise floor, and excellent imaging at atomic scales

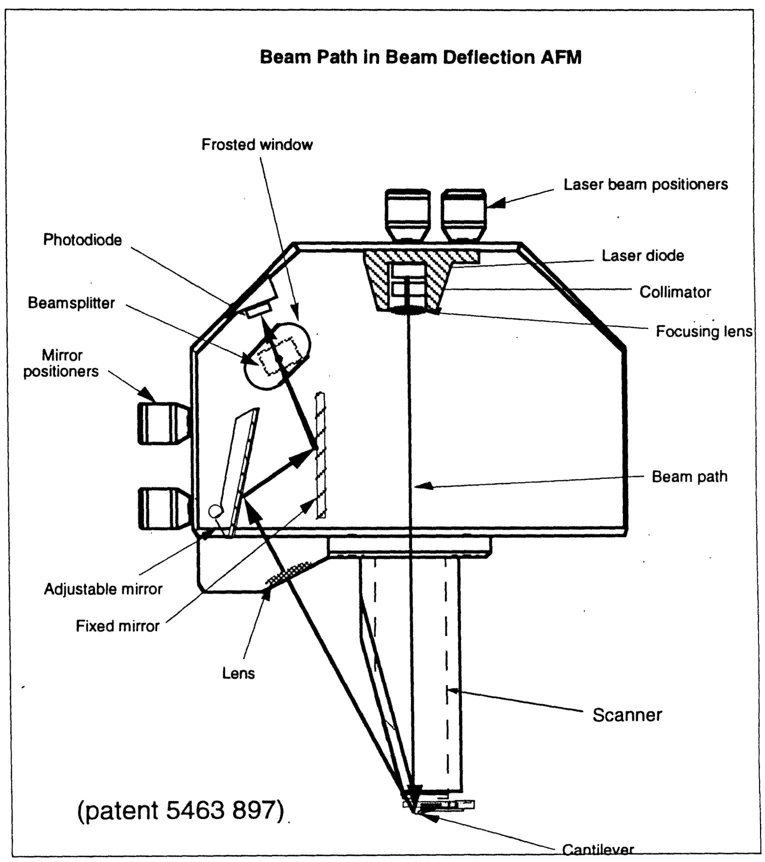
Disadvantages: limited to small samples

better for atomic scale

Scanned Tip

Tip mounted on scanner; sample supported below. The sketch shows this configuration with an incorporated beam-deflection detector.

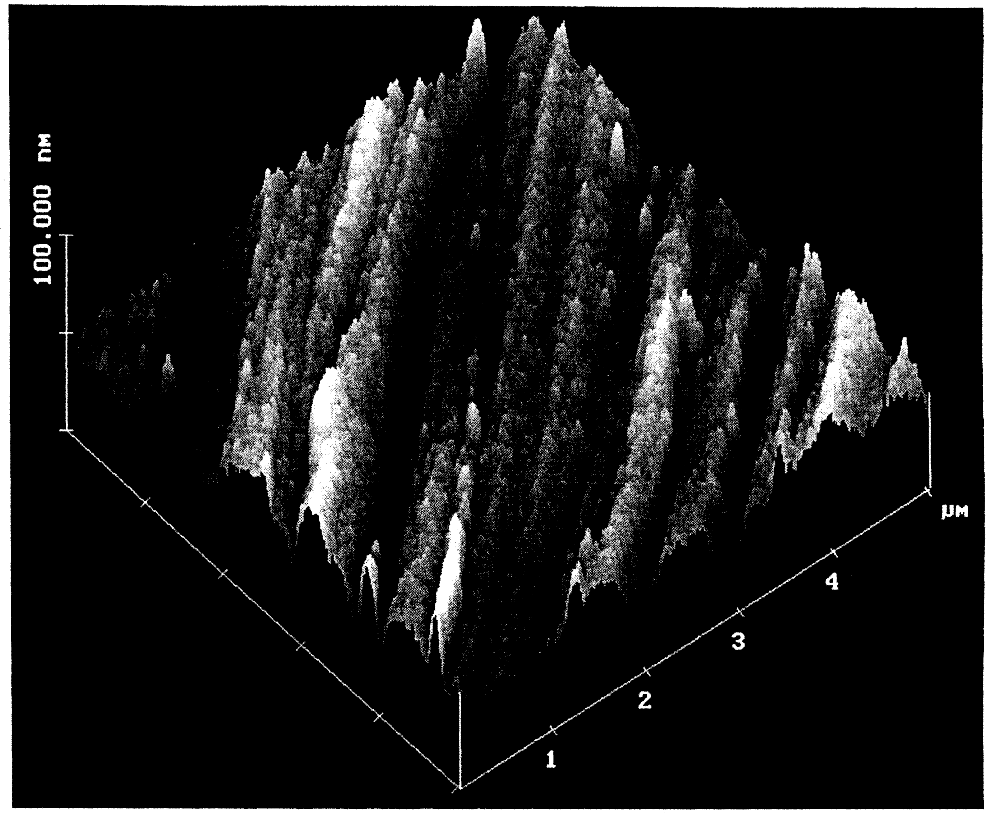
- allows large samples to be fixed below the tip, mounted, for example, on course positioning stages. Top-view optics can also be incorporated.
- even with the longer mechanical path between tip and sample, a well-designed instrument can give vertical noise floors below 0.5 Å *RMS*.
- the preferred configuration for industrial SPM applications.



- may be lateral drift due to thermal drift (relative w/ acoustic enclosure)

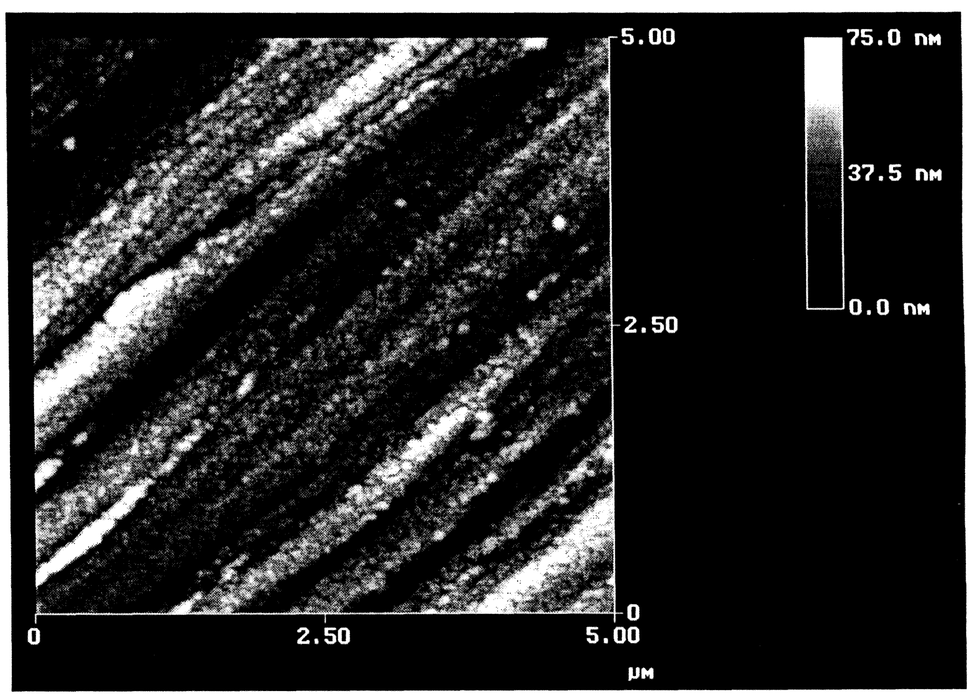
AFM image representation

An AFM image is composed of height data $z(x,y)$, and can be shown as a surface



Textured hard disk. Also seen is the fine scale grain structure of a carbon overcoat

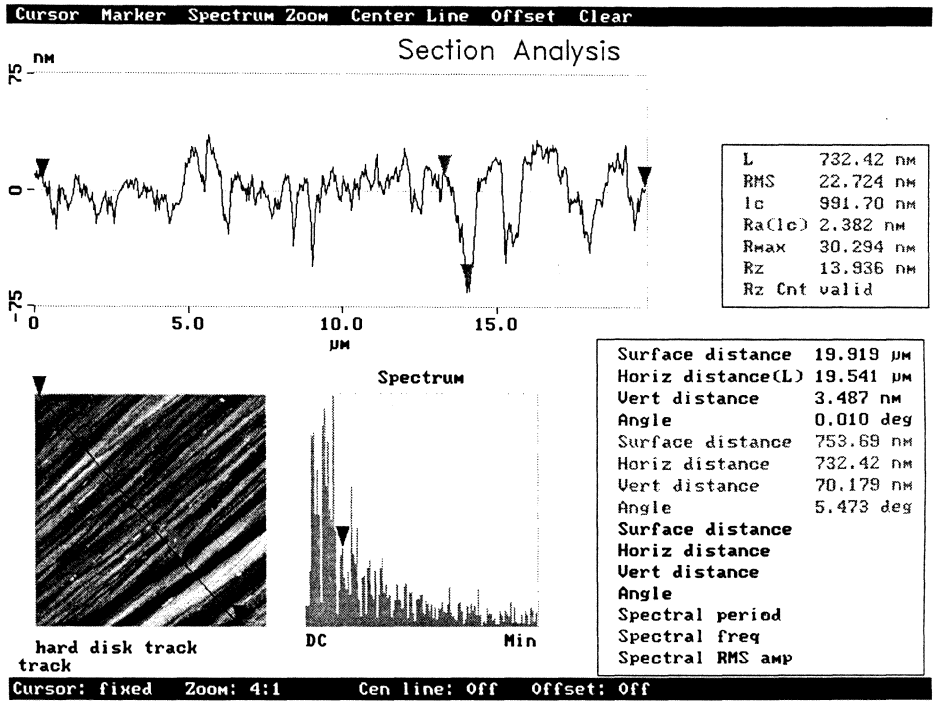
AFM data can also be shown "flat" by mapping height onto a color table. "Low" areas are generally shown as dark, "high" spots as light.



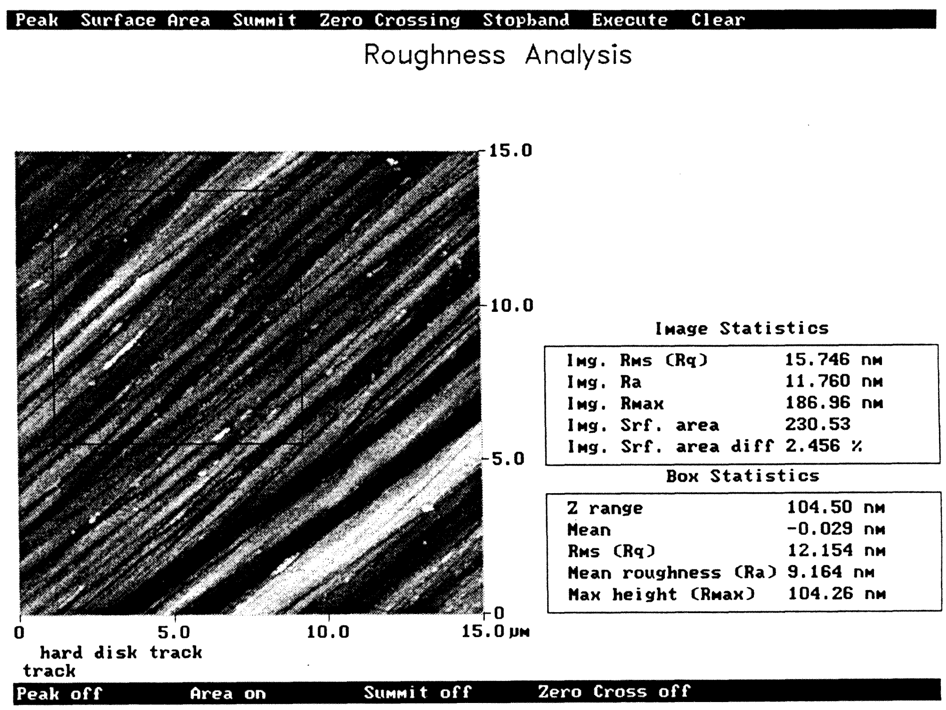
Analysis of Height Data

z-axis exploded

A number of standard image processing tools can be used to analyze SPM data. For example, section data shows details of a profile across the disk, and gives information about peak-to-valley and *RMS* roughness.



In this example, *RMS* and other roughness measurements are taken across the entire image, and within a selected sub-area. Other tools: 2–D FFT, power spectral density, grain size, etc.

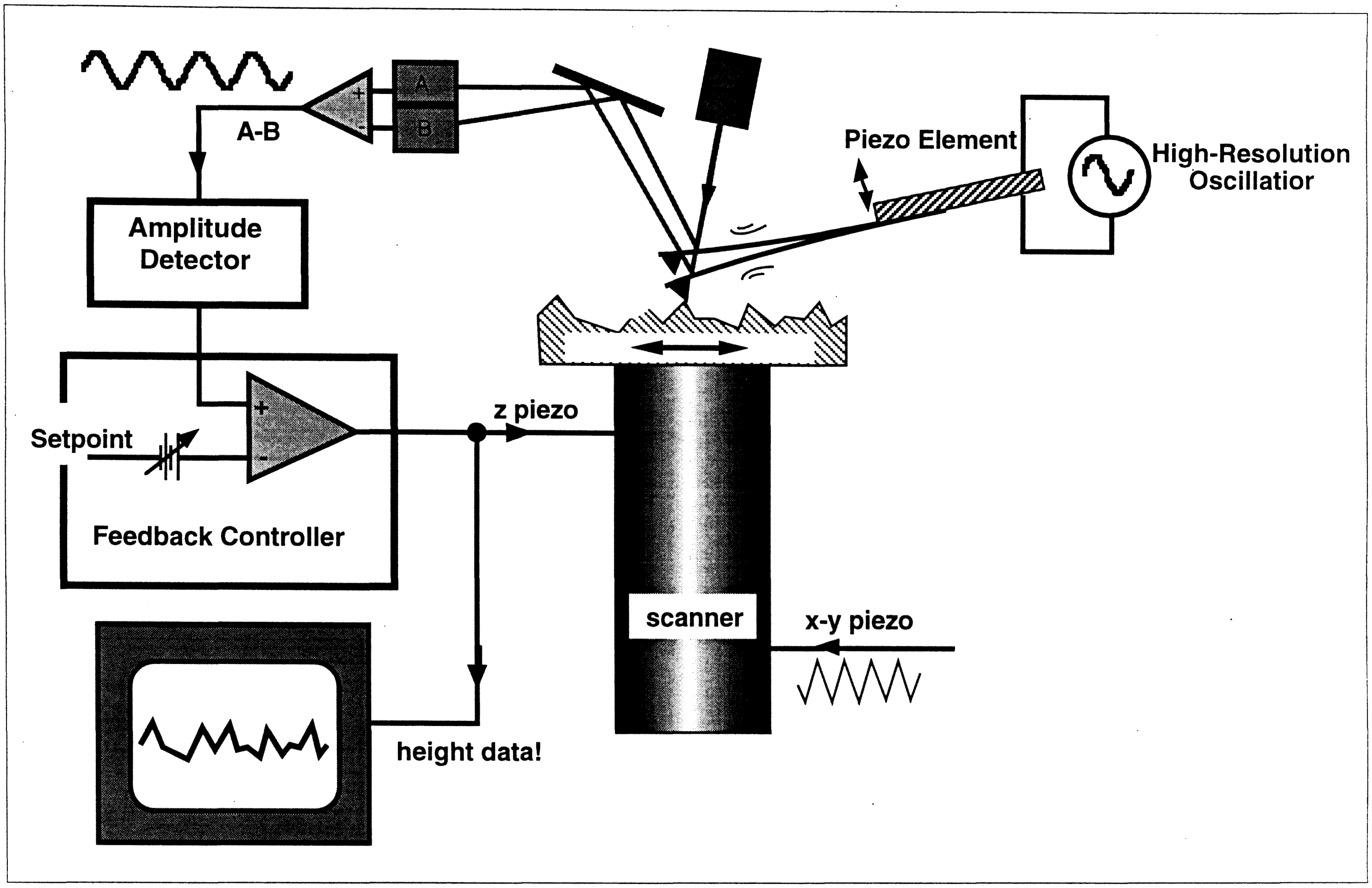


TappingMode AFM

- oscillate cantilever at its resonant frequency with a miniature piezo element

- the tip lightly taps the sample surface, reducing the oscillation amplitude relative to "free air"

- feedback maintains a fixed oscillation amplitude

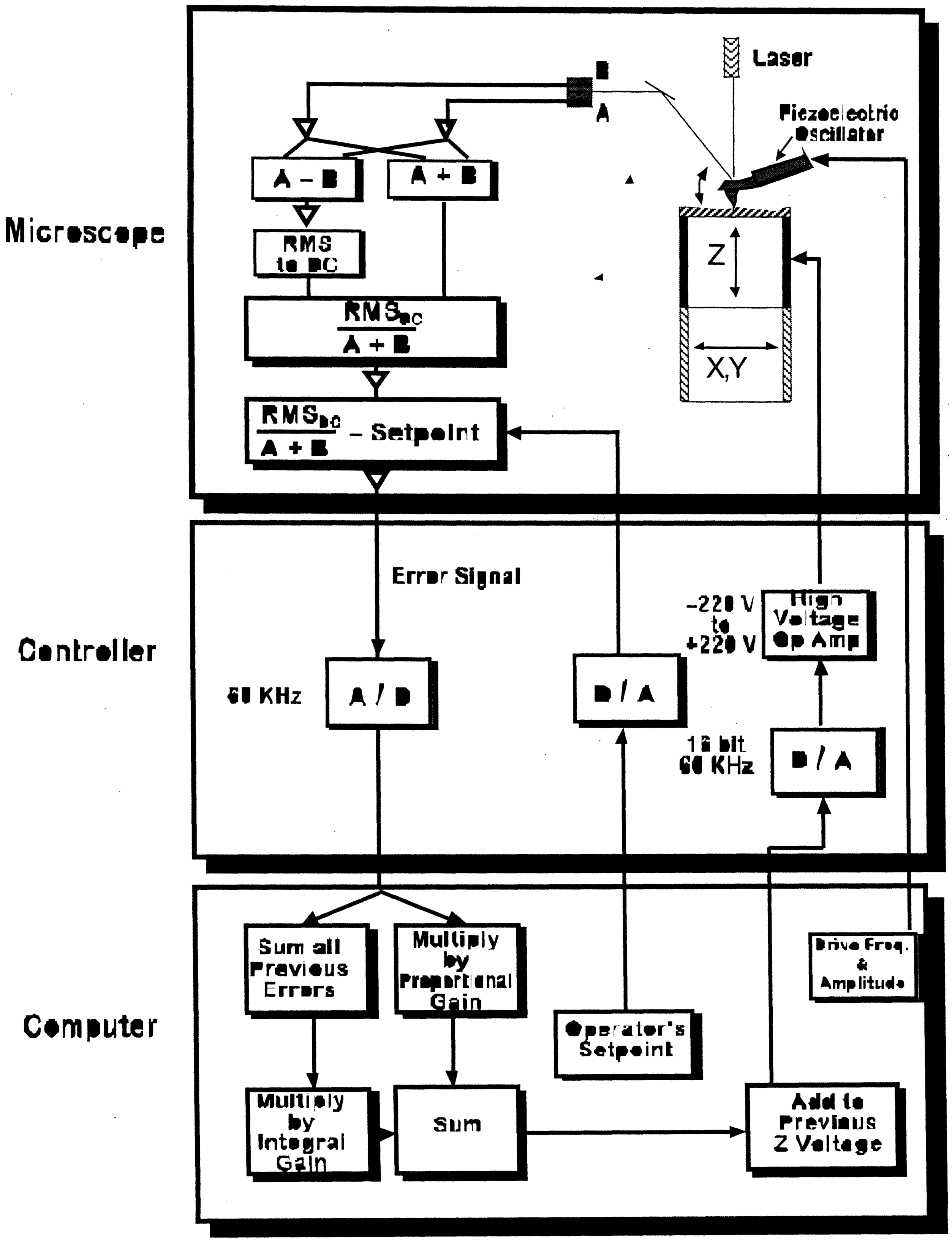


• Cantilevers are high-quality resonators. A few *nm* of "shaking" by the piezo element can give ~100 nm of amplitude at the tip.

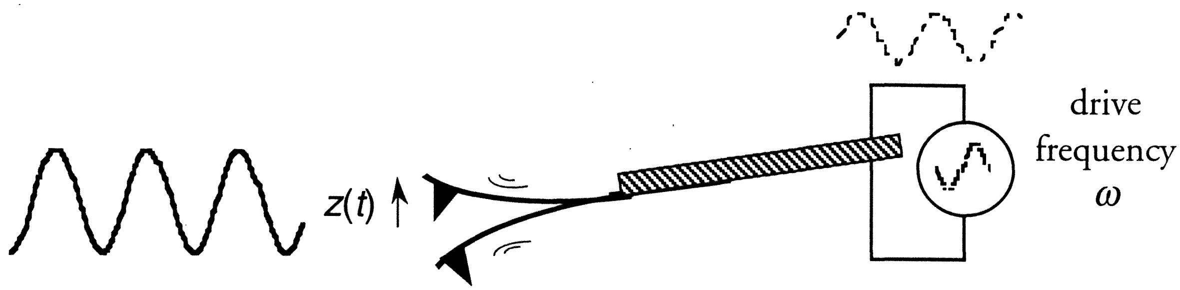
• typical tip amplitudes 20-100 nm.

• with 100 kHz cantilevers, the tip "taps" the surface more than 100 times for each image data point (pixel)!

TappingMode Instrumentation Block Diagram

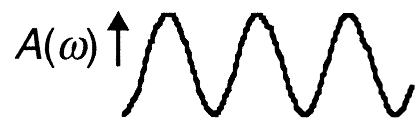


Cantilever Resonance

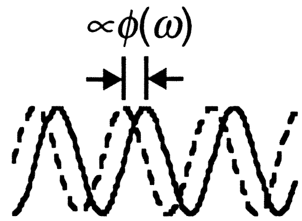


In "free air" (tip far from sample), the tip executes harmonic motion $z(t) = A\cos(\omega t + \varphi)$ characterized by 2 parameters:

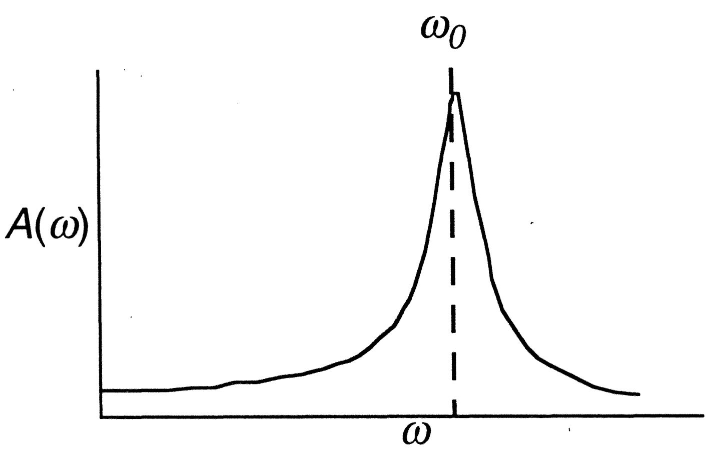
1) oscillation amplitude:

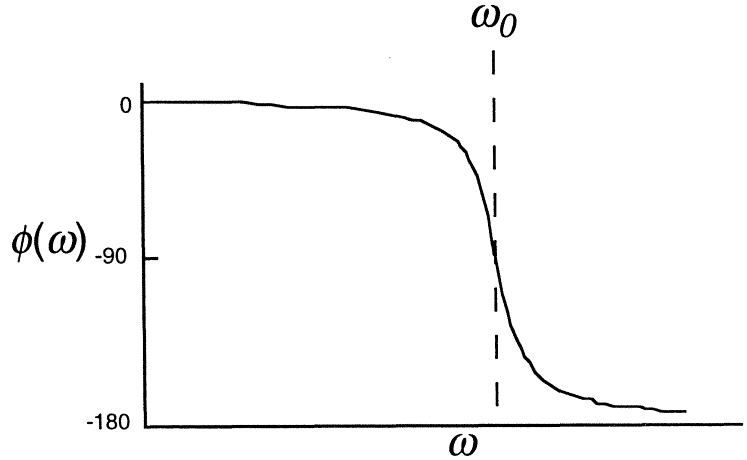


2) phase lag realtive to drive:



- A increases with the drive strength.
- as function of drive frequency ω, A and ϕ have the characteristic forms of a driven, resonant oscillator (see Appendix C):



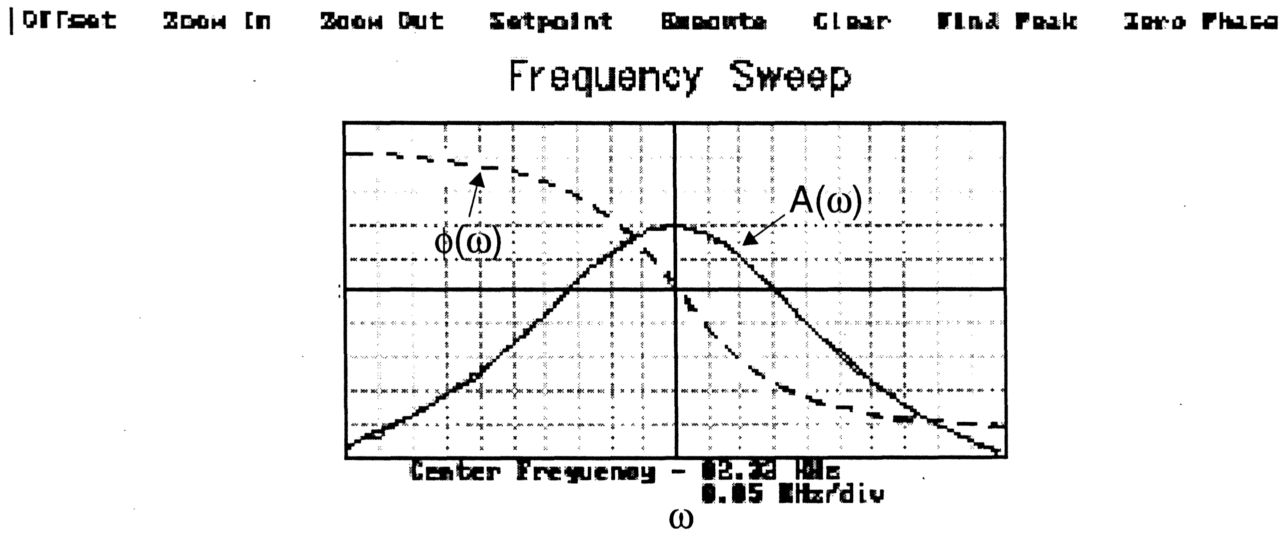


- TappingMode is usually done with a drive frequency at or near resonance ($\omega \approx \omega_0$). This yields a usable oscillation amplitude, while minimizing the energy transferred to the sample with each "tap"

- these resonant properties can also be exploited for sensitive detection of magnetic interactions

Cantilever "Tuning"

"Tuning" the cantilever for TappingMode requires adjustment of the drive frequency and amplitude to the driving piezo. This can be done in instrument software:



Precision measurement requires precise frequency control (better than 0.1 Hz at 100 kHz). Drive signals are often digitally synthesized.

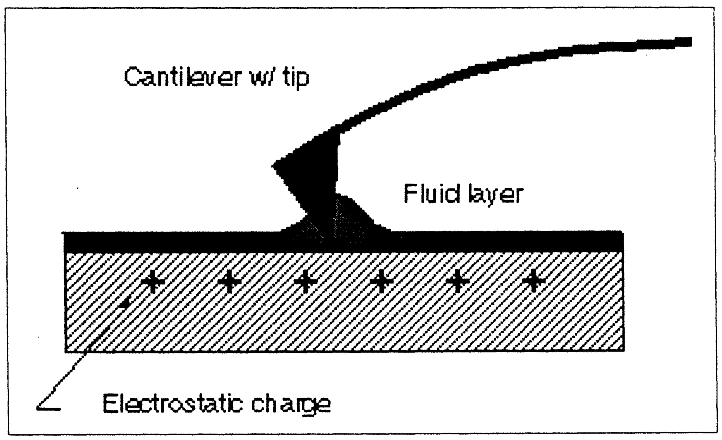
Contact Mode AFM

Advantages:

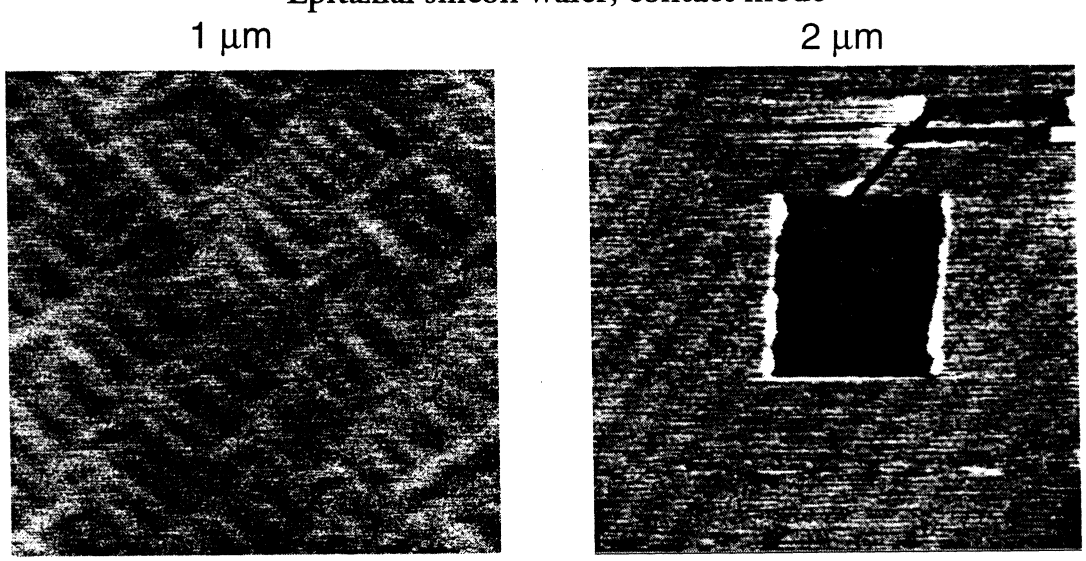
- high speed scans (throughput)
- only AFM mode that can obtain "atomic resolution" images

Disadvantages:

- lateral (frictional) forces can distort features in image
- capillary forces due to the adsorbed fluid layer on the sample surface, or electrostatic forces, can cause large normal tip-sample forces (in ambient conditions, adsorbed gases and water vapor are always present to varying degrees; 10 to 30 monolayers are typical)



Epitaxial silicon wafer; contact mode



Disks mostly imaged in tapping mode. Faster imaging

Atomic terraces and fingers ~2 Å high are visible. After the 1 µm scan, however, "zooming out" and imaging a 2 µm area reveals damage done during in first scan.

TappingMode

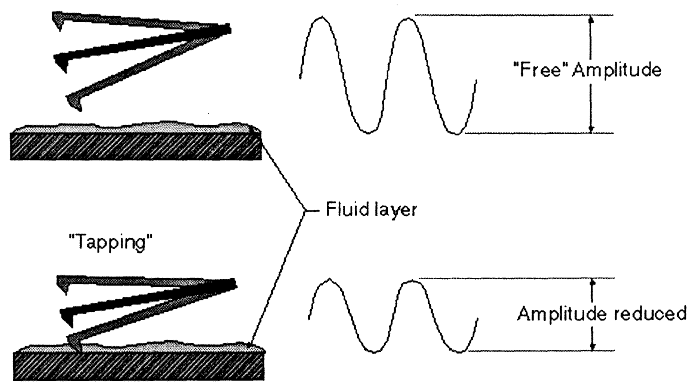
Advantages:

- higher lateral resolution on most samples (1-5 nm)
- lateral forces eliminated
- lower forces and less sample damage in air

Disadvantages:

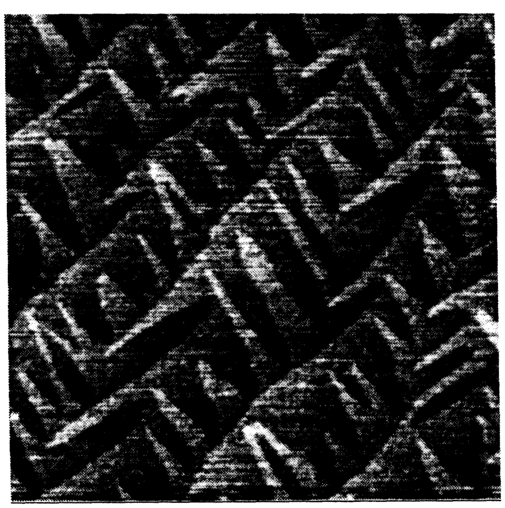
- slightly slower scan speed than contact mode AFM

- tip penetrates fluid layer; no meniscus forces
- tip is lifted between each "tap", eliminating the lateral, frictional forces that can cause damage
- tip "taps" the sample > 100 times for each data point (pixel)

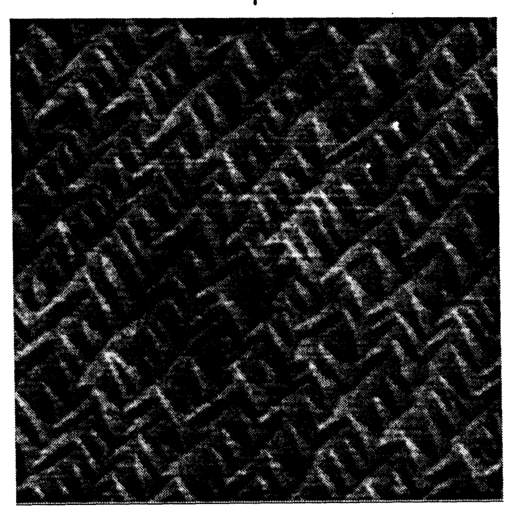


Epitaxial silicon wafer: TappingMode

1 µm



2 µm



Adsorbed layers don't have time to form meniscus. Don't generally see fluid.

The same sequence using TappingMode reveals better lateral resolution and no sample damage.

AFM capabilites

vertical resolution:	< 0.5 Å (with vibration isolation)
lateral resolution:	2-10 nm (tip-dependent)
scan speed:	~1-2 Hz (scan line); 1-5 min/scan

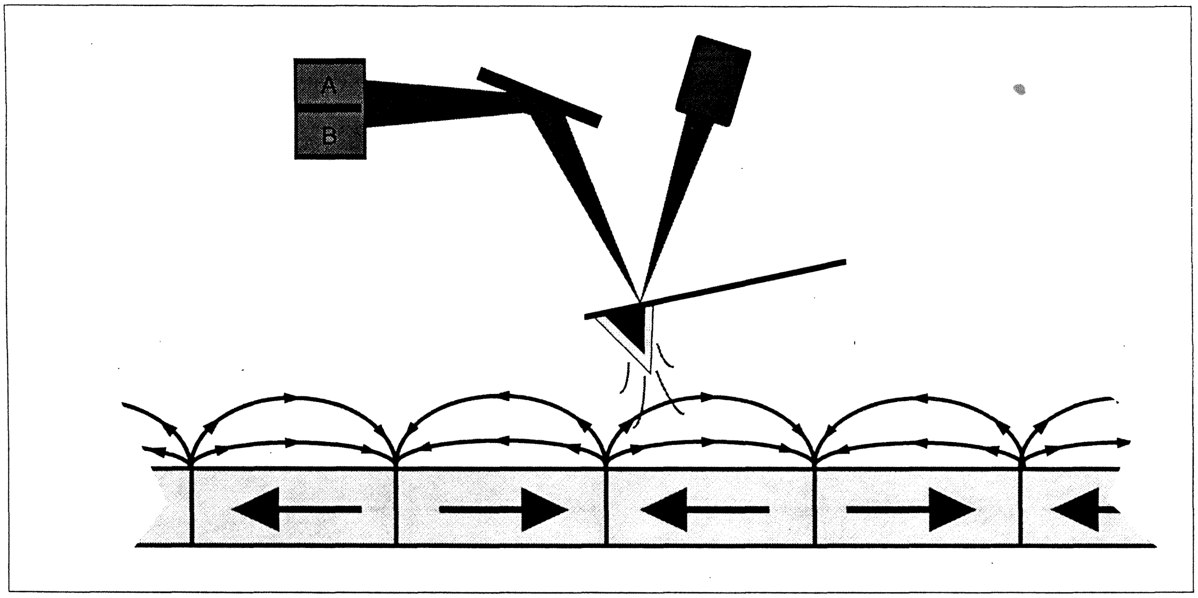
There are AFM methods other than contact and TappingMode. For example, *non-contact* imaging uses the weak "Van der Waals" attraction between a tip and sample for feedback. Tip-sample forces are minimized. Resolution in noncontact mode is, however, generally lower than in contact or TappingMode, since it is dependent on the tip-sample separation and oscillation amplitude. Noncontact scanning is also usually slower, since the tip must avoid the fluid layer, and is not as robust for general purpose imaging.

~10 nm spacing (shifts res. freq.

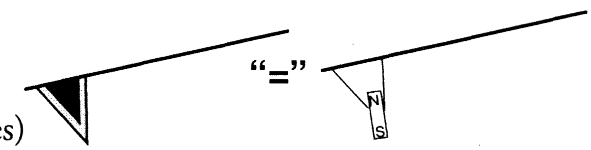
For the remainder of the course we will consider primarily TappingMode.

II. Magnetic Force Microscopy

MFM=SPM with a magnetized tip



- model tip as point dipole:
  (an approximation that works well in most cases)



- magnetize vertically; magnetic moment: $\vec{m} = m_z \hat{z}$
- force on tip proportional to field *gradient*: $F_z = m_z \dfrac{\partial H_z}{\partial z}$
  where H is the stray field from the sample

Simple magnetic force detection maps these forces to produce an image. We will discuss refinements used in actual instruments to improve sensitivity.

Ex) **cantilever deflection:** $\Delta z = \dfrac{F_z}{k}$, k=cantilever spring constant

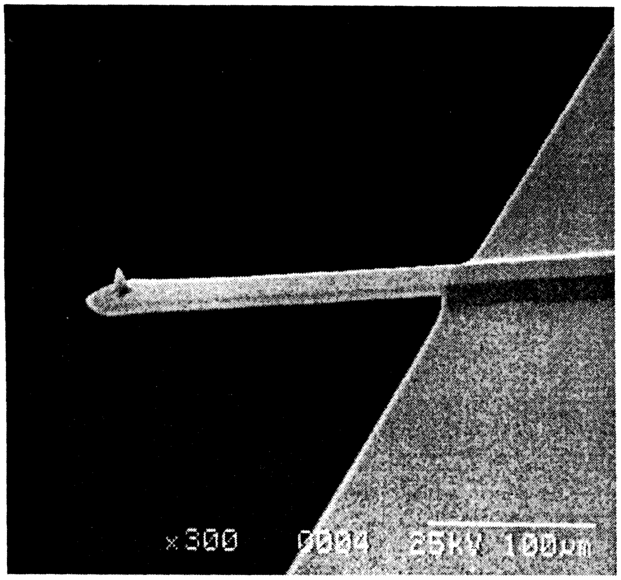
sample: hard disk, 1 μm transition spacing, M_r=500 emu/cc ⇒ $\dfrac{\partial H_z}{\partial z} \approx 10^7\, Oe/cm$

z

tip: k= 1 N/m, m_{tip}=10^{-11}emu ⇒

Δz= 1 nm, easily detected with beam deflection

MFM Probes



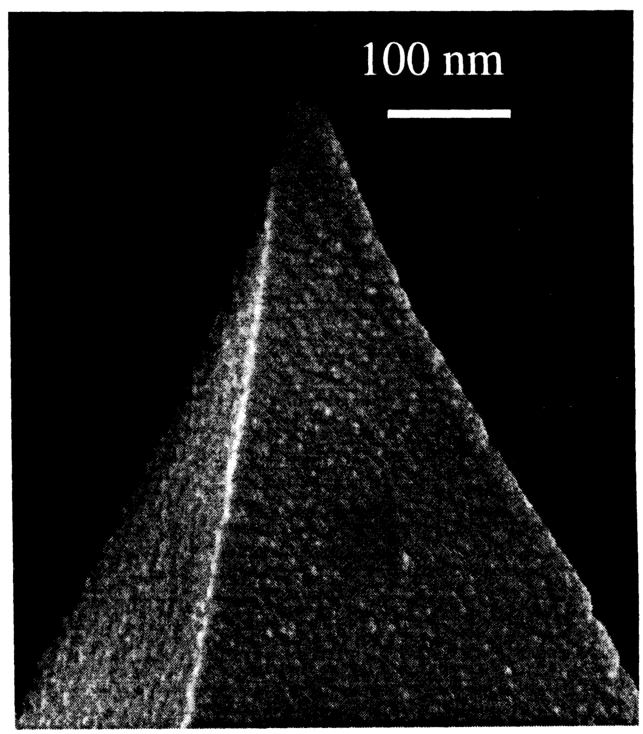
As in all SPM modes, probes are a crucial component of MFM. The same cantilevers are used for TappingMode AFM and sensitive MFM detection.

Left:

- 225 μm cantilever
- resonant frequency f_0~80 kHz
- spring constant k~2 N/m

This configuration gives good speed in TappingMode AFM imaging, and excellent MFM sensitivity.

- sputter-coat probes with a magnetic alloy (thickness 100-1000 Å).
- coated tips have slightly larger end radii (typ. 20-40 nm) than uncoated tips.
- can sputter several hundred probes at once.
- MFM resolution roughly limited by the size of the magnetic volume at the tip apex.
- magnetic properties (moment, sensitivity, coercivity) can be adjusted by tailoring the sputtered alloy and its thickness.
- typical choices are Co-based alloys much like those used on rigid media.
- coated tips can be magnetized to give a net vertical magnetic moment
- matching the MFM probe to a given sample can be important, as discussed in detail later.

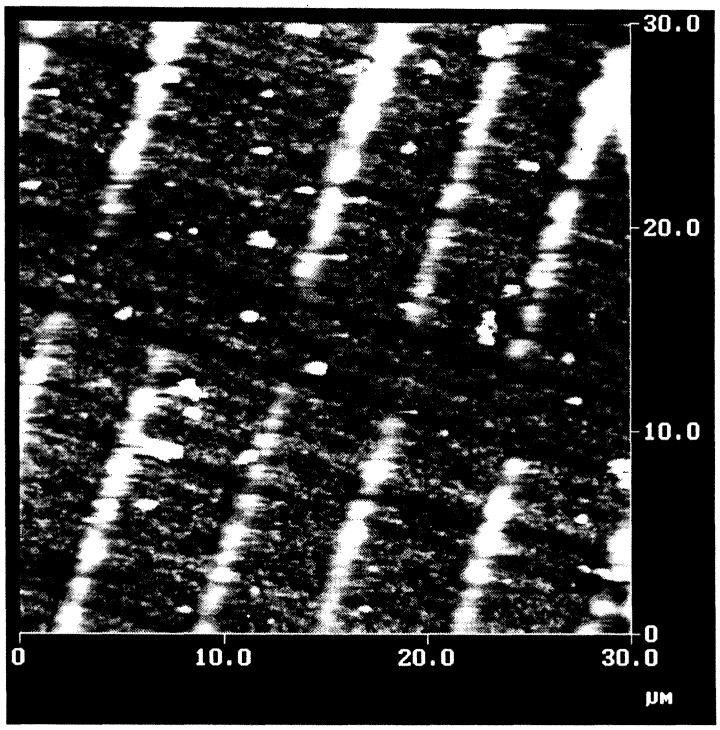


MFM Techniques

- Magnetic forces are weak - must lift the tip off surface to avoid interference from relatively strong contact forces

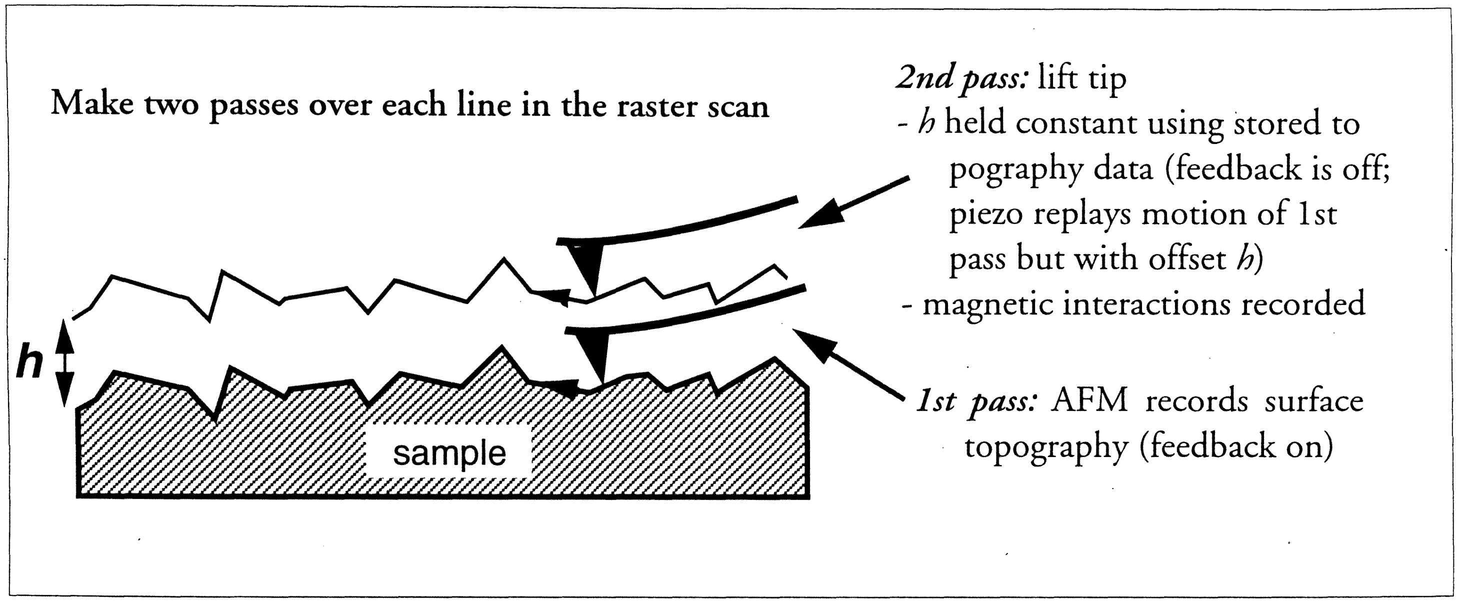
- Early MFM used magnetic interactions (and perhaps others) in the control loop.

- Drawback: images show a mixture of topographic and magnetic data; also prone to "tip crashes"



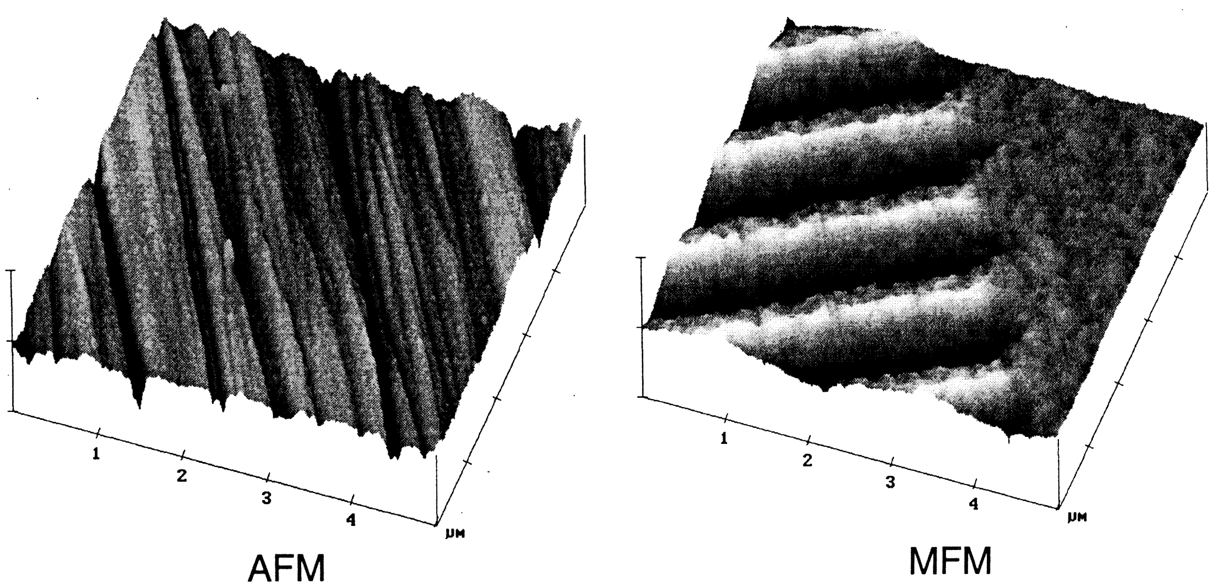
Ex) this AFM scan sensed both surface and magnetic forces on the tip, revealing transitions on a hard disk where the magnetic forces dominated This is an extreme example, but similar "cross-contamination" exists whenever magnetic interactions influence the feedback.

LiftMode

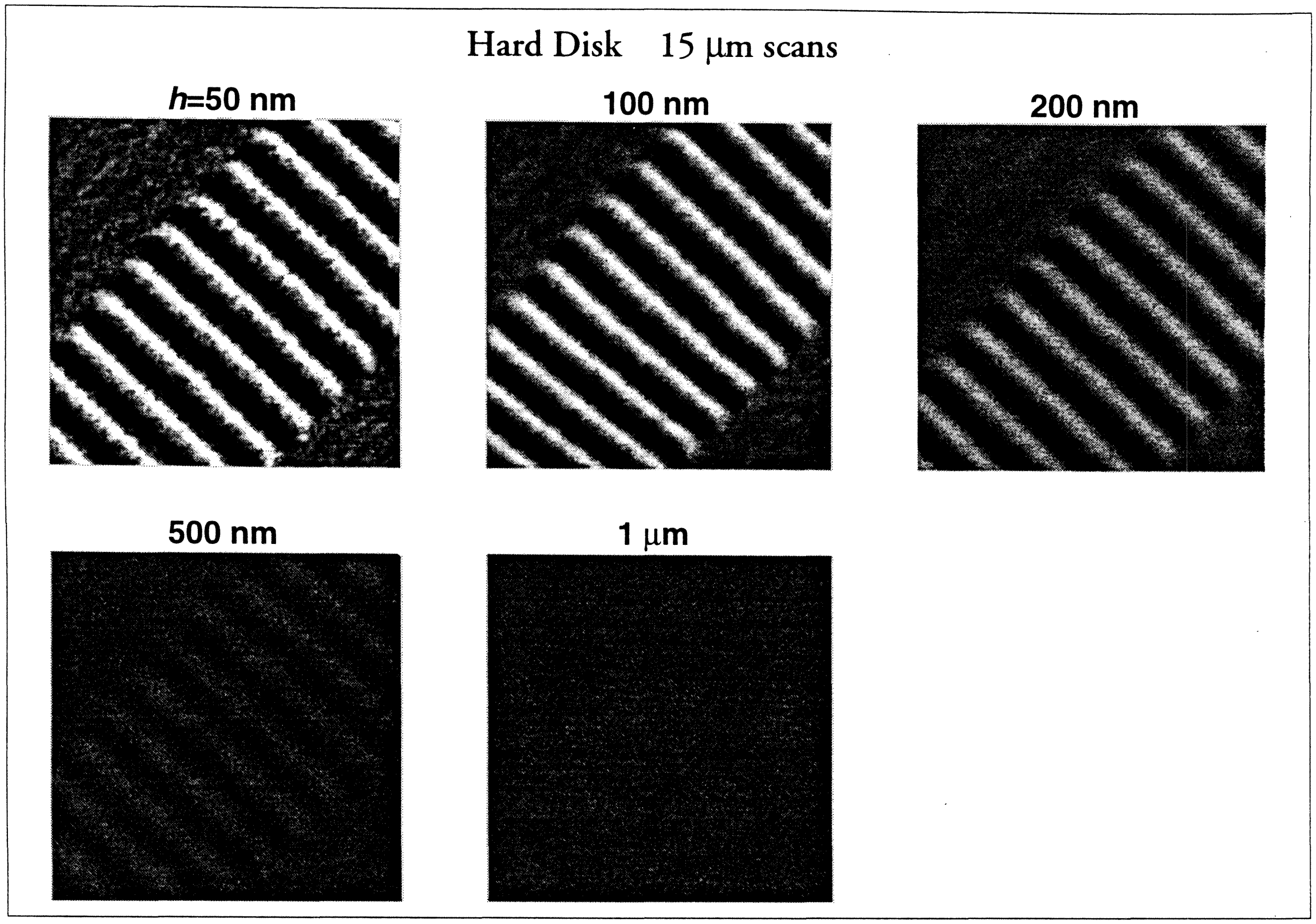


- repeat for each scanline to produce separate AFM and MFM images of the same area
- little or no cross-contamination between AFM and MFM images
- feedback not required during lift pass; can record any desired signal
- *h* can be set as desired (typ. 10-100 nm) to examine interactions at various heights
- small lift heights (10 nm or even less) give maximum resolution
- robust: liftmode can image any sample that allows AFM imaging, even rough samples

LiftMode images of a hard disk track



MFM Resolution *vs.* Lift Height



With increasing lift height:
- fields weaken; contrast decreases
- fields "blur", apparent resolution decreases

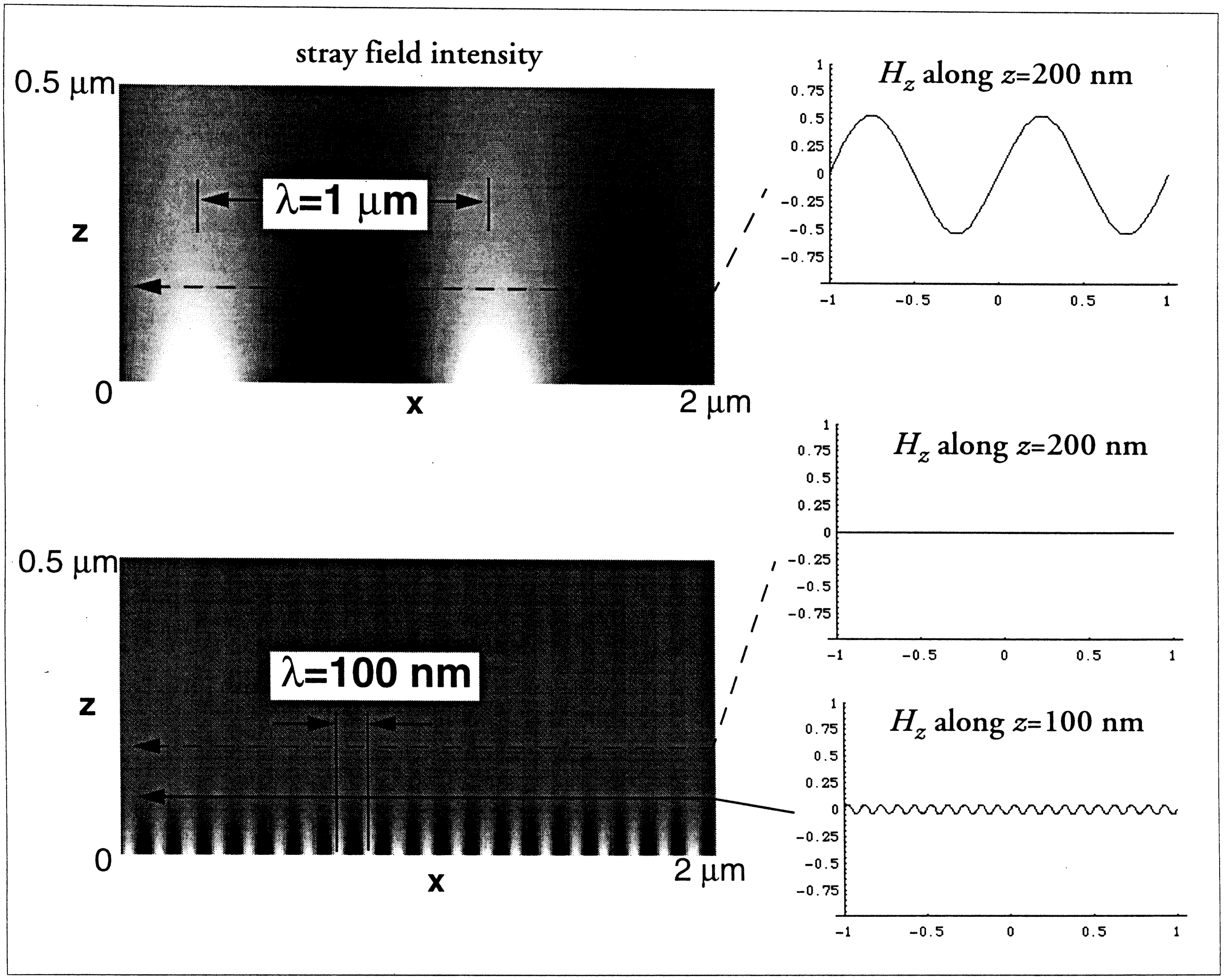
- MFM is "focused" by bringing the tip close to the sample
- Lateral resolution is roughly equal to the tip-sample spacing h
- Resolution< 50 nm; ultimately limited by the probe (as $h \rightarrow 0$)

MFM Resolution *II:* Sample Stray Fields

For domain pattern with length scale λ, stray fields decay exponentially with distance above the surface, with a characteristic length approximately equal to λ.

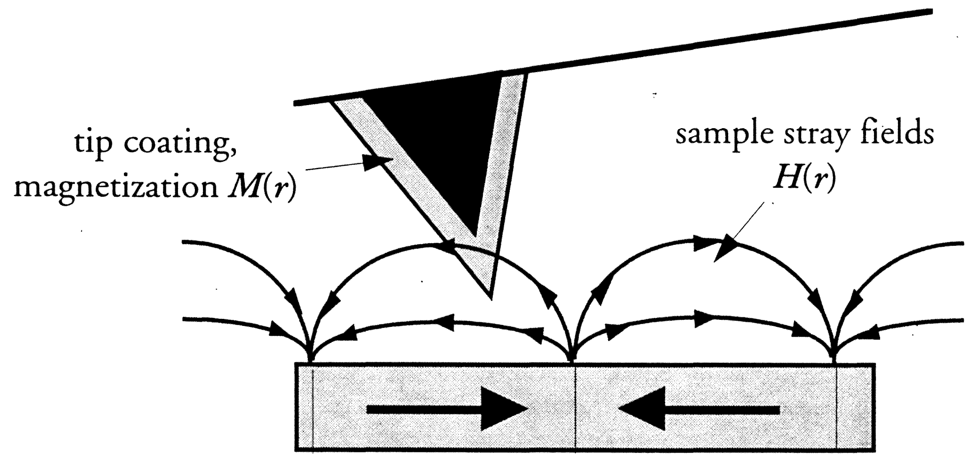
Ex) compare periodic patterns with length scales 1 µm and 100 nm. Model stray fields as:

$$H_z(x,z) = sin(\frac{2\pi x}{\lambda})e^{-\pi z/\lambda}$$



- so, to resolve magnetic features having length scale λ, must keep the tip within z= λ of the sample surface.
- this is an observation about the character of stray fields, not instrumental resolution

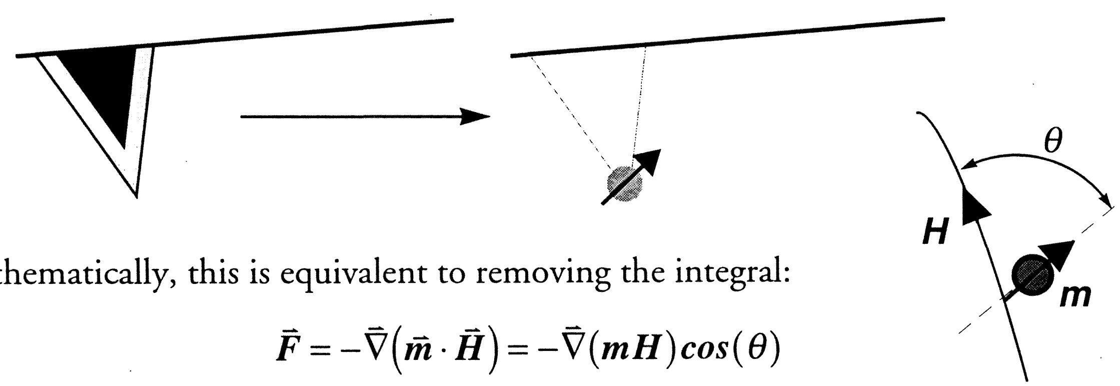
Forces on MFM Probes: Some Really Basic Stuff



Rigorously, must account for the interaction of the field *H* with each bit of the magnetic coating. Mathematically:

$$\vec{F} = -\int_{tip} \vec{\nabla}\left(\vec{M}(r)\cdot\vec{H}(r)\right) d^3 r$$

Approximate the probe as a point dipole *m* located at the tip



Mathematically, this is equivalent to removing the integral:

$$\vec{F} = -\vec{\nabla}\left(\vec{m}\cdot\vec{H}\right) = -\vec{\nabla}(mH)\cos(\theta)$$

where θ is the angle between the tip moment *m* and the sample field *H*.

- this approximation works well for explaining most aspects of MFM, and the great majority of MFM applications
- it is *not* sufficient for precise, quantitative field measurements (a difficult problem)

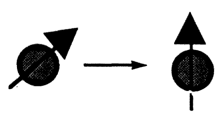
Forces on MFM Probes: Some Really Basic Stuff II

Consider only force perpendicular to the cantilever (F_z) (others have no effect)

$$F_z = -\frac{\partial}{\partial z}\left(\vec{m}\cdot\vec{H}\right) = -\frac{\partial}{\partial z}\left(m_x H_x + m_y H_y + m_z H_z\right)$$

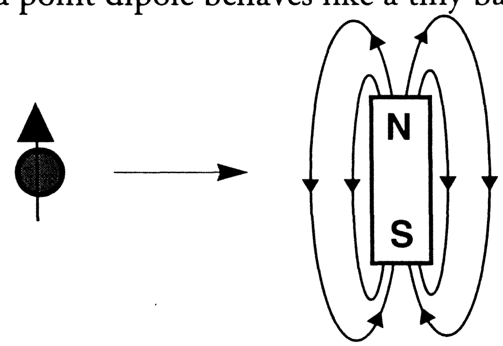
(also ignore *torques* on the tip's magnetic moment)

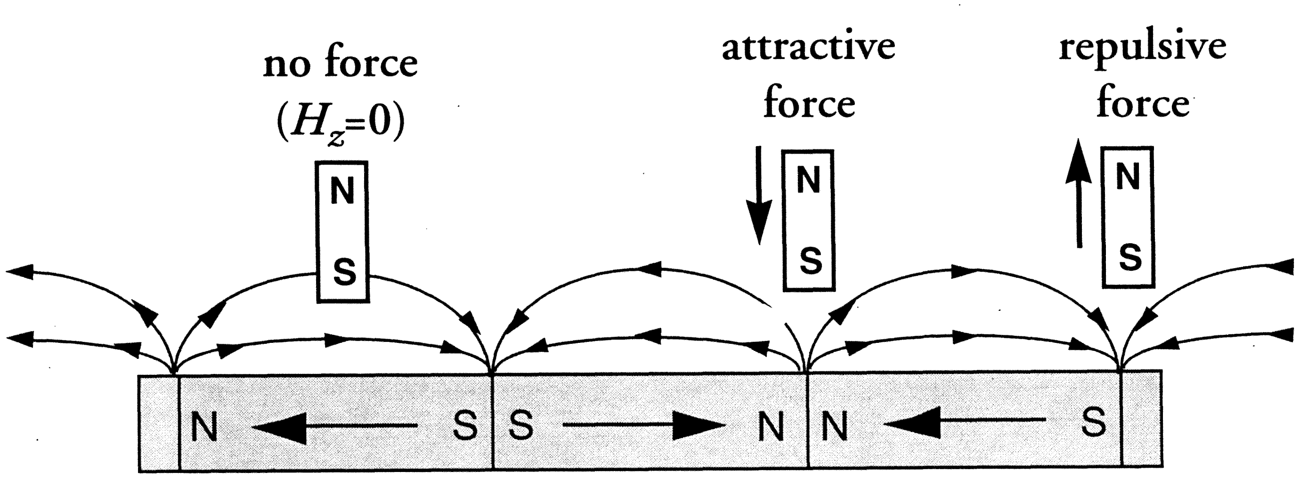
Now assume a tip that's been magnetized along z: $m=m_z z$, $m_x=0=m_y$



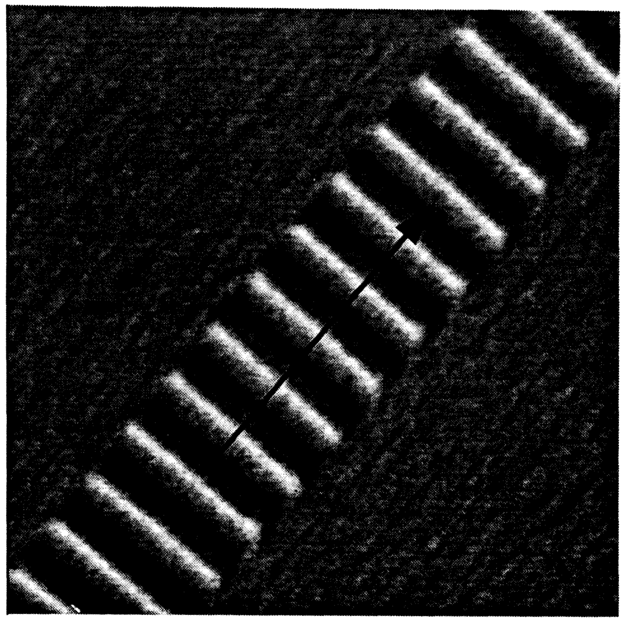
$$F_z = -m_z \frac{\partial H_z}{\partial z}$$ ☆

more intuitively... a point dipole behaves like a tiny bar magnet:

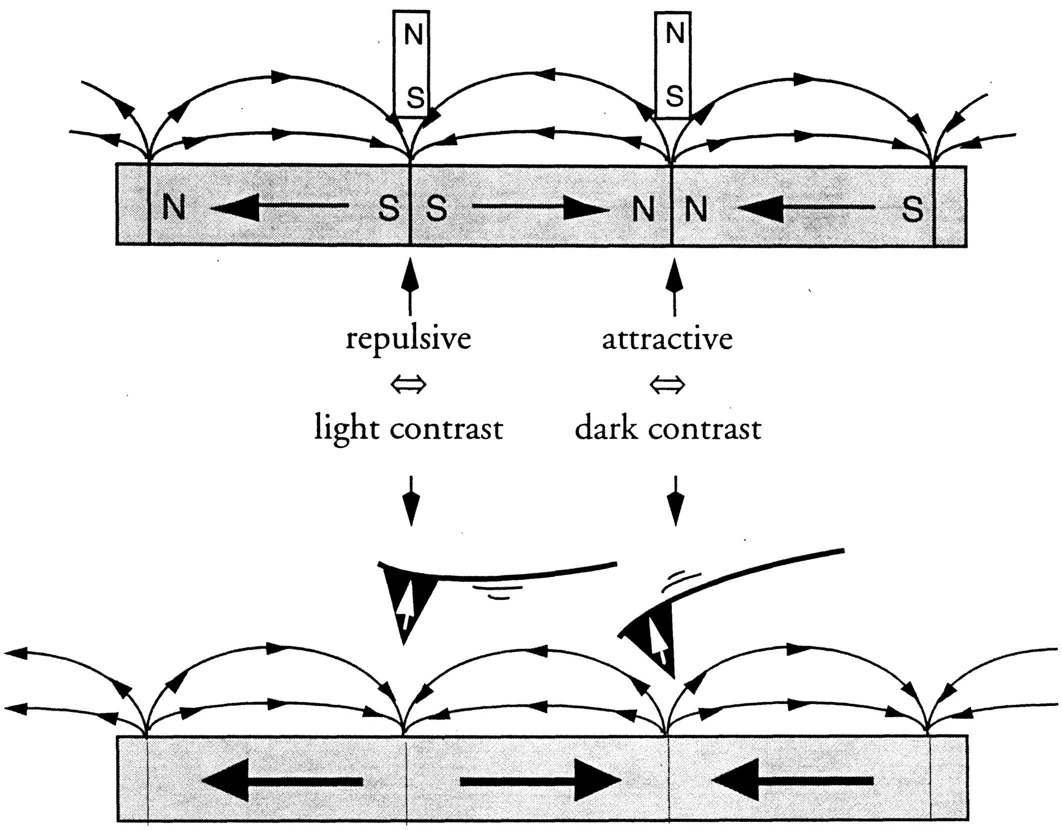




MFM Image Interpretation I: Hard Disk Model



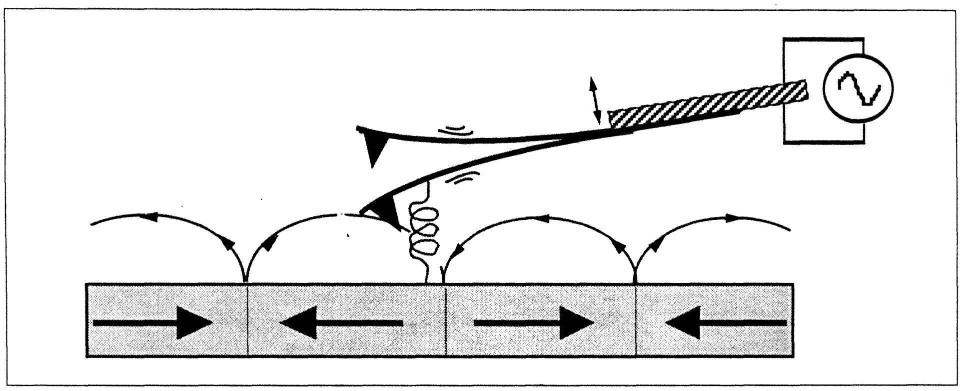
25 µm



Force Gradient Detection I

(how MFM detection is usually done)

- oscillate tip near its resonant frequency (in LiftMode)
- model magnetic forces as a spring between tip and sample

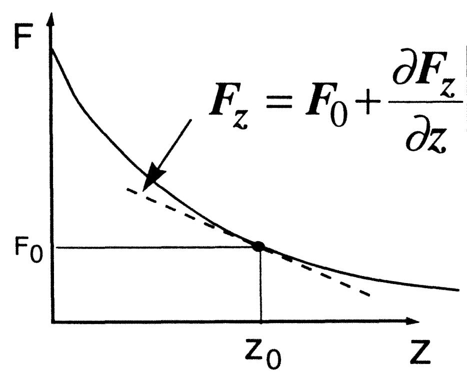


this "spring" changes the effective cantilever spring constant: $$k_{eff} = k - \frac{\partial F_z}{\partial z}$$

where $\frac{\partial F_z}{\partial z}$ is the vertical gradient in the magnetic force on the tip

<u>why the force gradient?</u>

for a tip at mean height z_0, the magnetic force *vs.* z can be approximated as linear - the characteristic of a simple spring



$$F_z = F_0 + \left.\frac{\partial F_z}{\partial z}\right|_{z=z_0} (z - z_0) + \ldots$$

The cantilever resonant frequency is: $\omega_0 = \sqrt{\frac{k_{eff}}{M}} = \sqrt{\frac{k - \frac{\partial F_z}{\partial z}}{M}}$

(M is an effective mass)

Relative to the case of no magnetic forces: $F = 0, \ \omega_0 = \sqrt{\frac{k}{M}}$

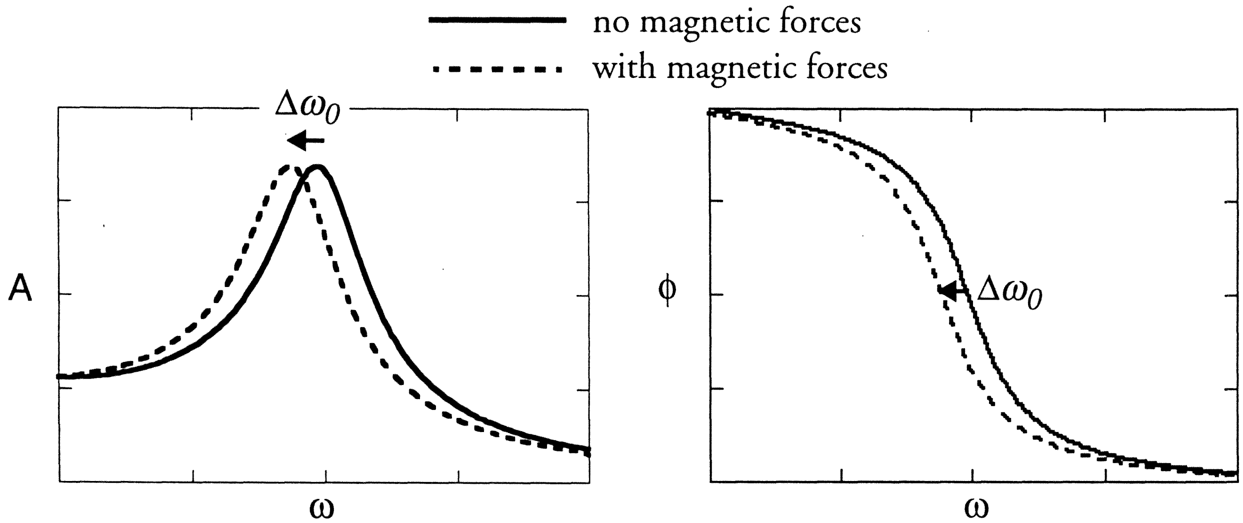
the resonant frequency is shifted by:
(see Appendix for details):

$$\Delta\omega_0 = -\frac{\omega_0}{2k}\frac{\partial F_z}{\partial z}$$

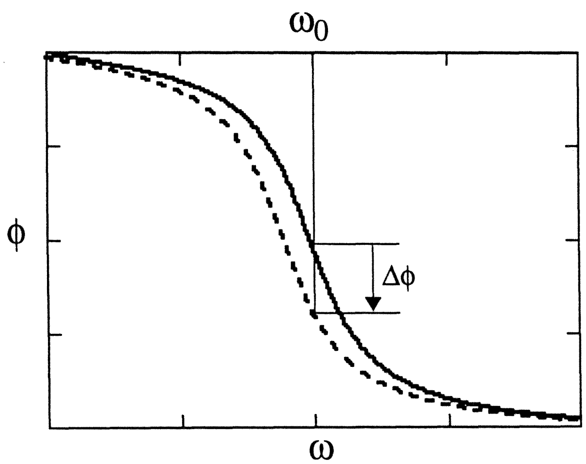
This frequency shift is the physical basis of force gradient detection

Force Gradient Detection II: Detecting Resonance Shifts

A shifted resonance frequency will shift the amplitude- and phase *vs.* frequency response of the cantilever:



Slope Detection of $\Delta\omega_0$: drive the cantilever at its "free" resonant frequency ω_0. A shift in resonance frequency then gives a shift in the phase lag ϕ:



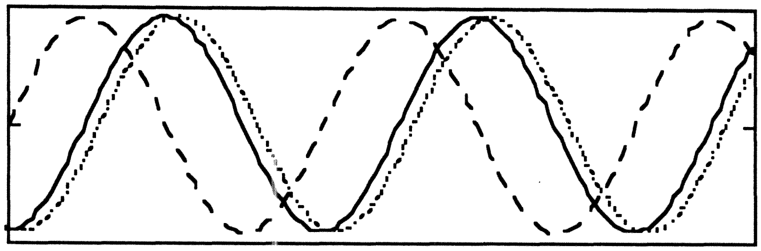
The sensitivity is proportional to the slope of the phase *vs.* frequency curve:

$$\Delta\varphi = \Delta\omega_0 \left.\frac{\partial\varphi}{\partial\omega}\right|_{\omega_0} = -\frac{Q}{k}\frac{\partial F_z}{\partial z}$$

High sensitivity is obtained because the cantilevers have a large "quality factor" ("Q"); see Appendix.

Force Gradient Detection III: Phase Detection

... in the time domain:

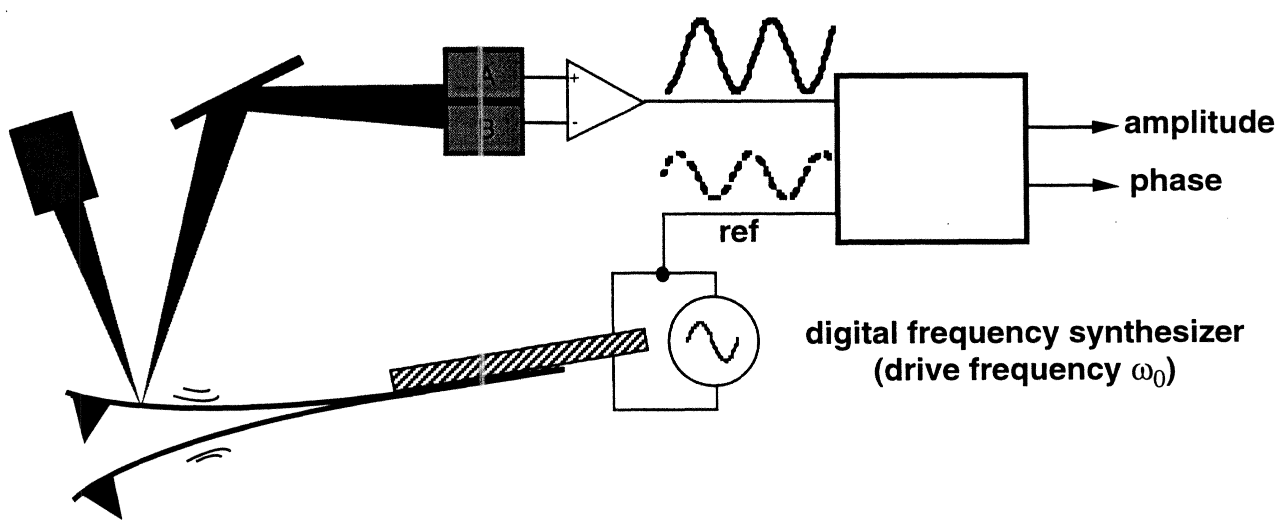


- — -	piezo drive	$D\cos(\omega_0 t)$
——	response with fields absent	$A\cos(\omega_0 t - \varphi_0)$ (ϕ_0=90°)
·······	response with fields present	$A\cos(\omega_0 t - \varphi_0 - \Delta\varphi)$

$\Delta\varphi = -\frac{Q}{k}\frac{\partial F_z}{\partial z}$ is mapped to give a force gradient image

Instrumentation

- compares phase of PSD output to that of piezo drive
- mapping variations $\Delta\phi$ gives a force gradient image



An alternative: Frequency Detection:

- drive frequency continually adjusted to keep phase "on resonance" (90 deg behind drive) (phase is used as error signal in feedback loop)
- resulting drive frequency is $\omega_0 + \Delta\omega_0$; mapping variations $\Delta\omega_0$ gives a force gradient image

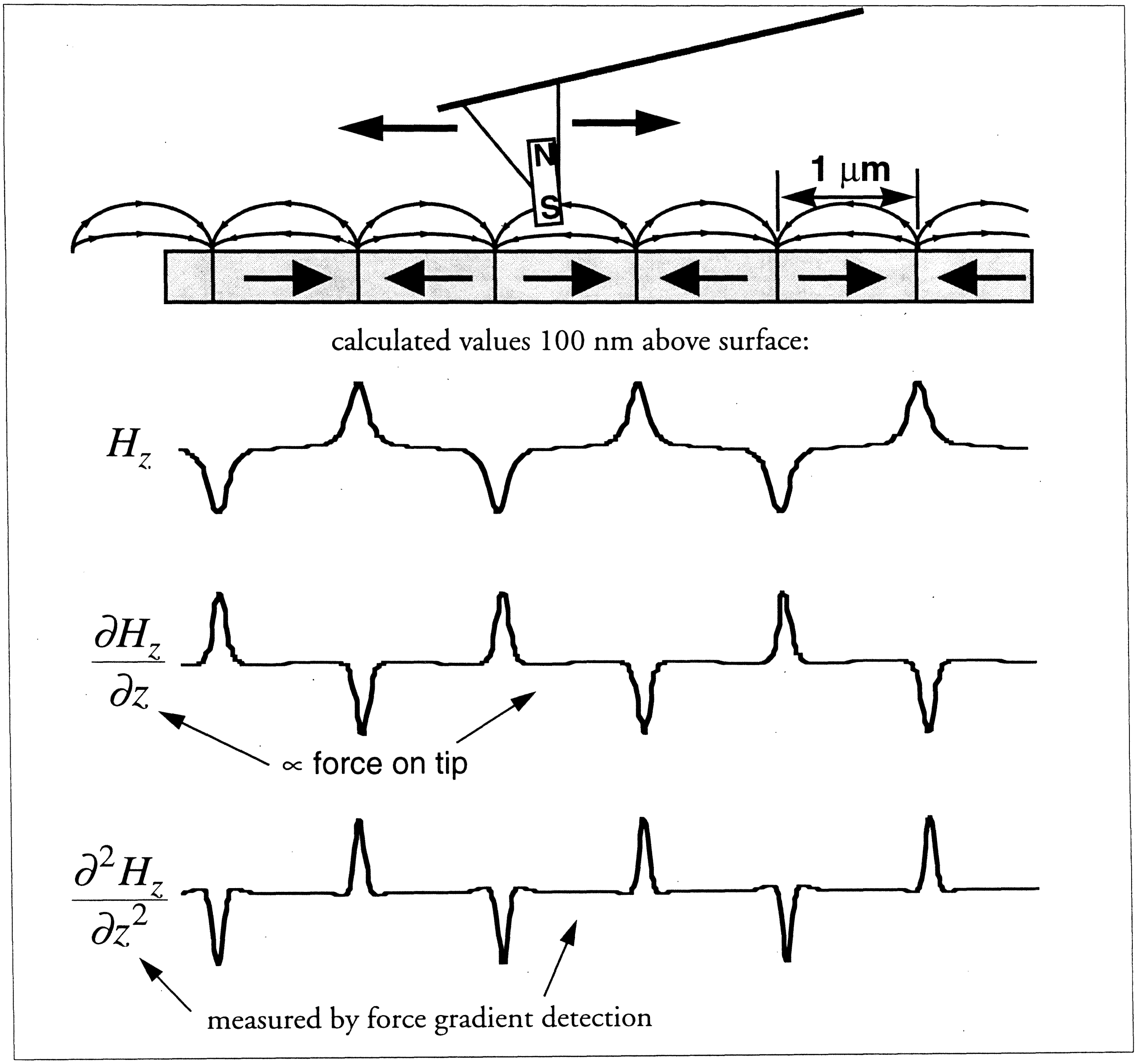
MFM Image Interpretation II: Force *vs.* Force Gradient

Simple "force detection" senses $F_z = m_z \dfrac{\partial H_z}{\partial z}$

Force gradient detection measures $\dfrac{\partial F_z}{\partial z} = m_z \dfrac{\partial^2 H_z}{\partial z^2}$

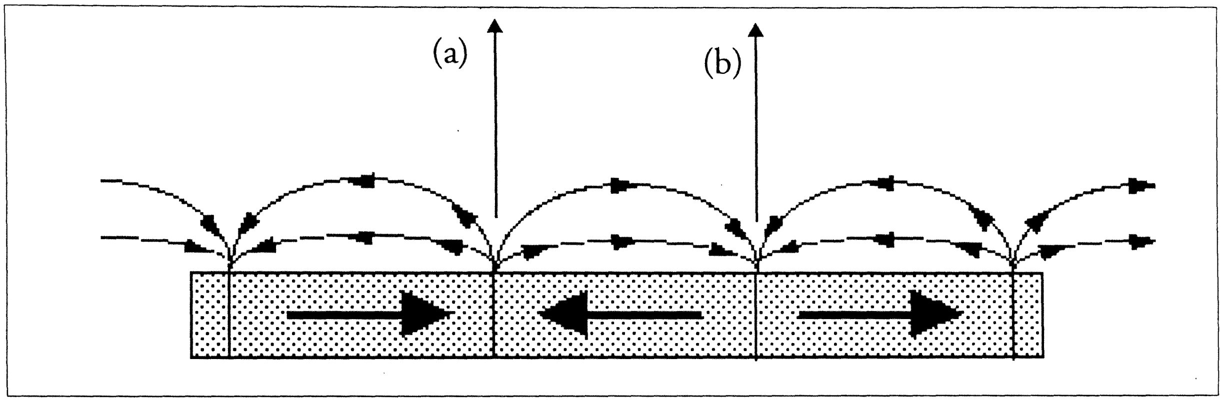
(again, these expressions assume the point dipole moment approximation for the tip)

How do the resulting images compare?

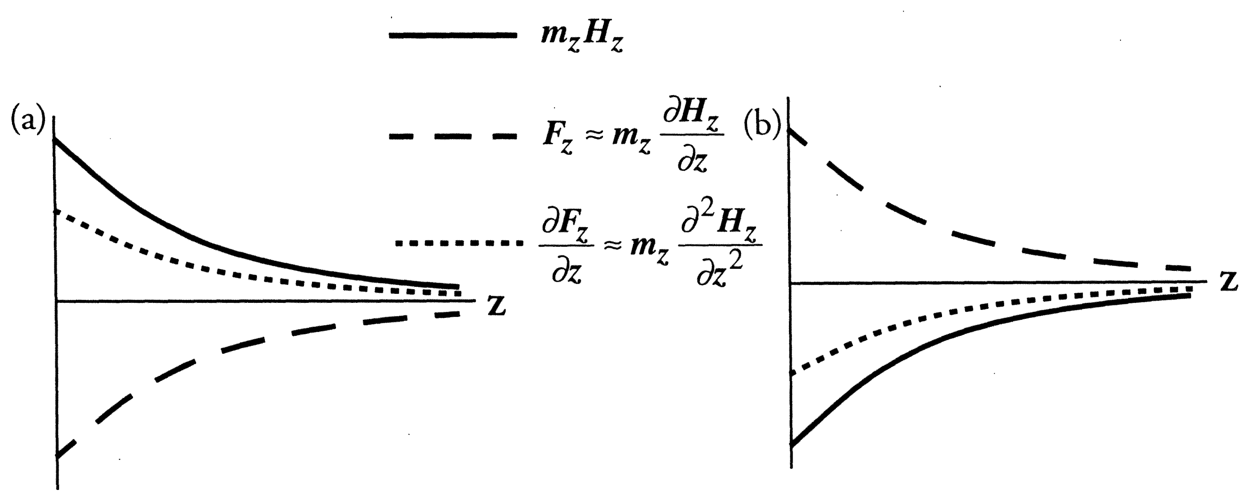


Maps of force and force gradient are similar, except for fine details.

MFM Image Interpretation III: "Thinking Vertically"



vertical field dependence along paths (a) and (b):



Contrast Convention

Case (b): light contrast | **Case (a): dark contrast**

$$\Delta\omega_0 = -\frac{\omega_0}{2k}\frac{\partial F_z}{\partial z} > 0$$

reverse!

monotonic decay ⇒ sign reversed at each step:

$$\frac{\partial F_z}{\partial z} < 0$$

$F_z > 0$ (repulsive force)

$m_z H_z < 0$ (tip aligned opposite to field)

Note that all of the above quantities are $\propto m_z$; reversing the tip moment (by re-magnetizing it) will reverse the signs, and hence the image contrast.

Compare "thinking laterally": when dF_z/dz changes sign (e.g., when crossing a domain or domain wall), so do F_z and H_z. This is another reason maps of H_z, F_z, and dF_z/dz are similar.

MFM Image Interpretation IV:
Longitudinal *vs.* Perpendicular Media

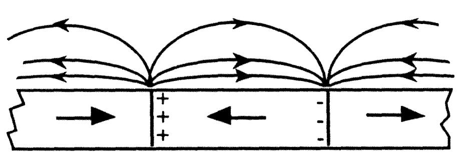
Stray fields produced by magnetic materials:

$$\vec{H} = -\vec{\nabla}\varphi \qquad \varphi(r) = -\int_{vol} \frac{\vec{\nabla}' \cdot \vec{M}(r')}{|r - r'|} d^3r' + \int_{surf} \frac{\hat{n} \cdot \vec{M}(r')}{|r - r'|} dA$$

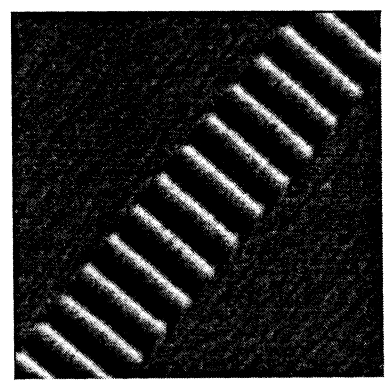
where M is the magnetization of the material. So, the sources of H are
1) divergences in M. These occur at domain walls and transitions (bits) in longitudinal recording media.
2) normal intersection of M with a surface

($\vec{\nabla} \cdot \vec{M}$ and $\hat{n} \cdot \vec{M}$ are analogous to electrostatic charge densities)

Longitudinal Media: Magnetization in-plane. Stray field sources: $\vec{\nabla} \cdot \vec{M}$
Transitions are highlighted in MFM contrast.*

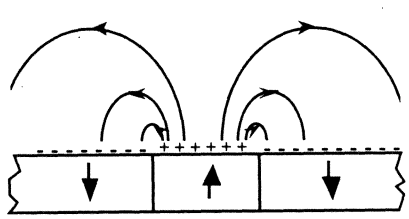


Transitions on a hard disk

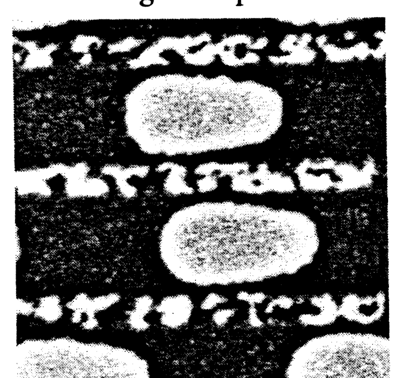


25 μm

Perpendicular Media: Magnetization perpendicular to sample plane. Stray field sources: $\hat{n} \cdot \vec{M}$ Occurs at intersections of magnetization with surface. MFM contrast highlights *bits* or *domains* *



Bits on magneto-optical media

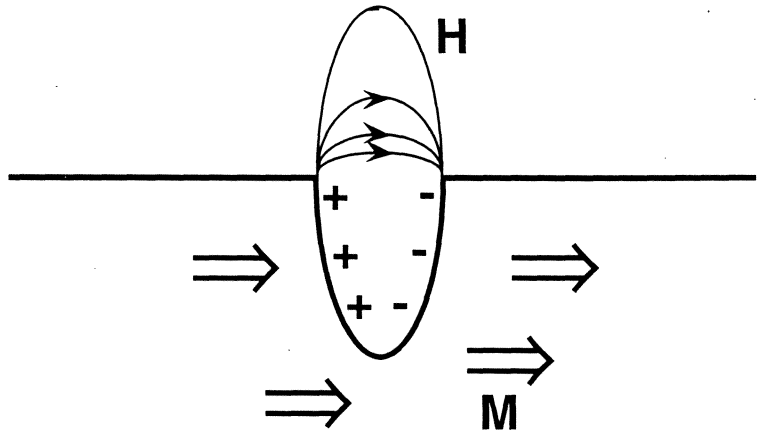


5 μm

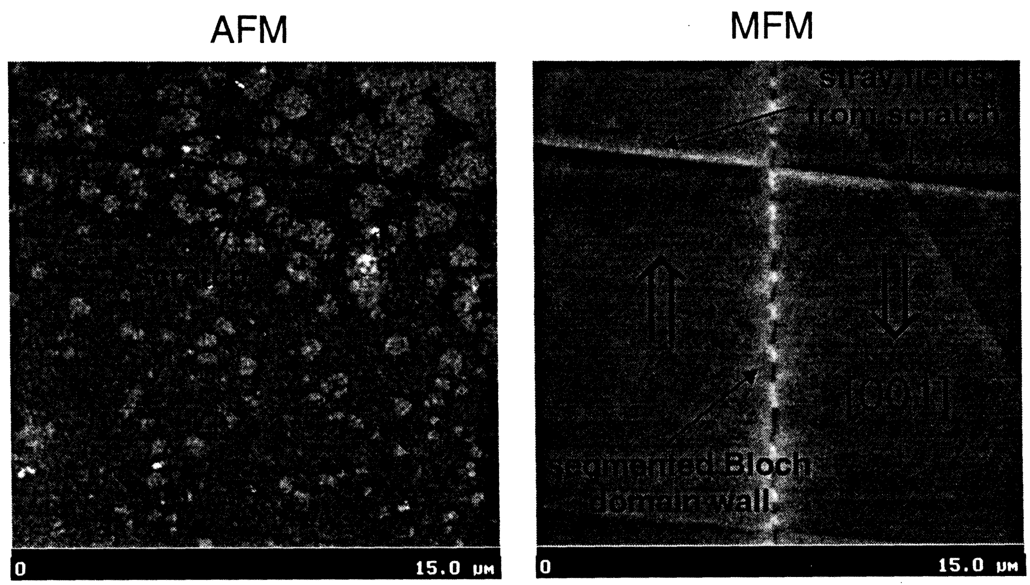
* assumes a vertically magnetized tip $m = m_z z$

MFM Image Interpretation III:
Influence of Topography on Magnetics

ex) pits, bumps, or scratches in longitudinal magnetization produce stray fields which can be detected with MFM



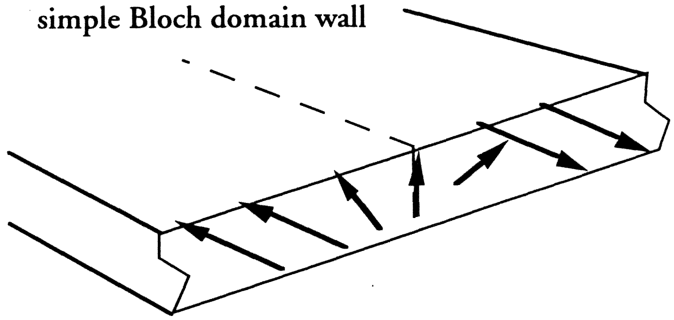
Ex) Crystalline Iron (110 Fe)



Images courtesy of Roger Proksch

- scratch stray field “polarity” reverses across domain wall
- surface corrosion visible in topography produces no stray field

simple Bloch domain wall



Similar considerations arise when examining defects on recording media

AFM/MFM Capabilities Summary

AFM

vertical resolution: < 0.5 Å (with vibration isloation)

lateral resolution: 5-10 nm

MFM

lateral resolution: <50 nm (small tip-sample sepration)

sensitivity: < 0.1 Hz @ 80 kHz(FGD); ample for submicron single-domain particles

Probes

typ. single-crystal Si, 225 µm cantilever, 80 kHz, 2-5 N/m

pyramidal tip; end radius: 5-10 nm (uncoated); 20-40 nm (coated for MFM)

magnetic properties variable

(magnetically "hard" or "soft", selectable moments)

time to change probe: ~ 1 min

tip lifetime: from 1 scan - 2 weeks (mostly sample/dirt dependent)

Other

scan range: 0-100+ µm

Z range: ~6 µm

scan time: 1-5 min

ambient imaging

no sample prep

high ease of use

built in optical microscopy

course positioning stage for large samples

software: real-time parameter control (?), image analysis

automation options: site mapping, pattern recognition, auto data analysis..

Comparison with Other Imaging Techniques

Topography: AFM vs:

Optical Microscopy

imaging only - no height calibration
resolution down to ~200 nm

SEM

SEM faster and has greater depth of field (~mm vs. ~6μm for SPM)
Requires vacuum
imaging only - no height calibration

TEM

TEM requires thin sections

For high resolution in ambient conditions, AFM can't be beat

Magnetic: MFM vs:

TEM, SEMPA

TEM requires thin sections; can alter magnetic properties from bulk
MFM: far greater ease-of-use, no sample prep

Kerr/MOKE and related

resolution is diffraction limited
typically faster than MFM
can't see through most overcoats
some instruments require soft samples
overall speed? ease-of-use?

AFM/MFM also cost effective

III. Applications of MFM and AFM in Data Storage

A Sampler of Current Applications in R&D and Fab

Rigid Media

roughness/texture/asperities/defects
wear tracks
track characteristics: width, skew, spacing, erase band
transition irregularies (due to head)
visualization of servo patterns
media noise: S/N vs. frequency via MFM
tribology, lube?

Measure force gradients so measure relative strengths not actual field values

MFM persists where head re-sponse rolls off

Also get SNR from MFM (MFM may get higher since higher freq noise)

Other Media

bit roughness on MO media
video/DAT/other tape

MR Heads

on ABS

AFM of wear, contaminants, and "local" pole tip recession
visualization of components through overcoats: sensor, poles, shields
"sensitivity function" mapping

wafer level

imaging of domain structure in MR sensor, bias

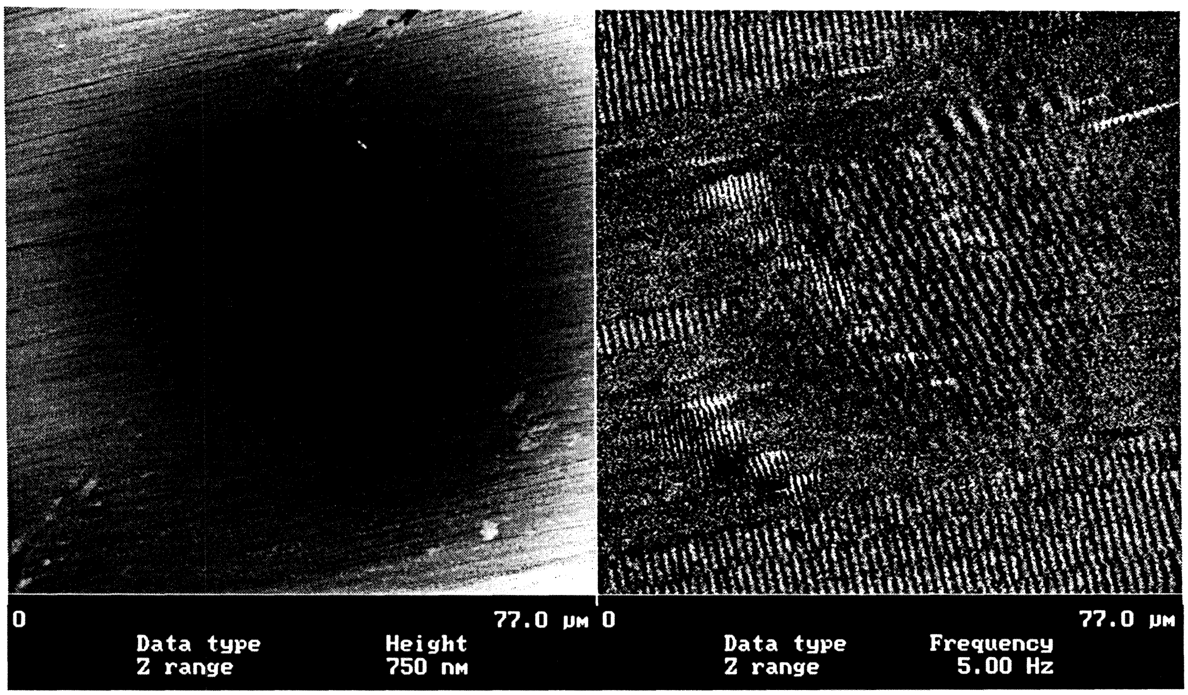
Inductive Heads

imaging of fringing fields of active write poles
measurement of saturation in high M_s heads

Examples....

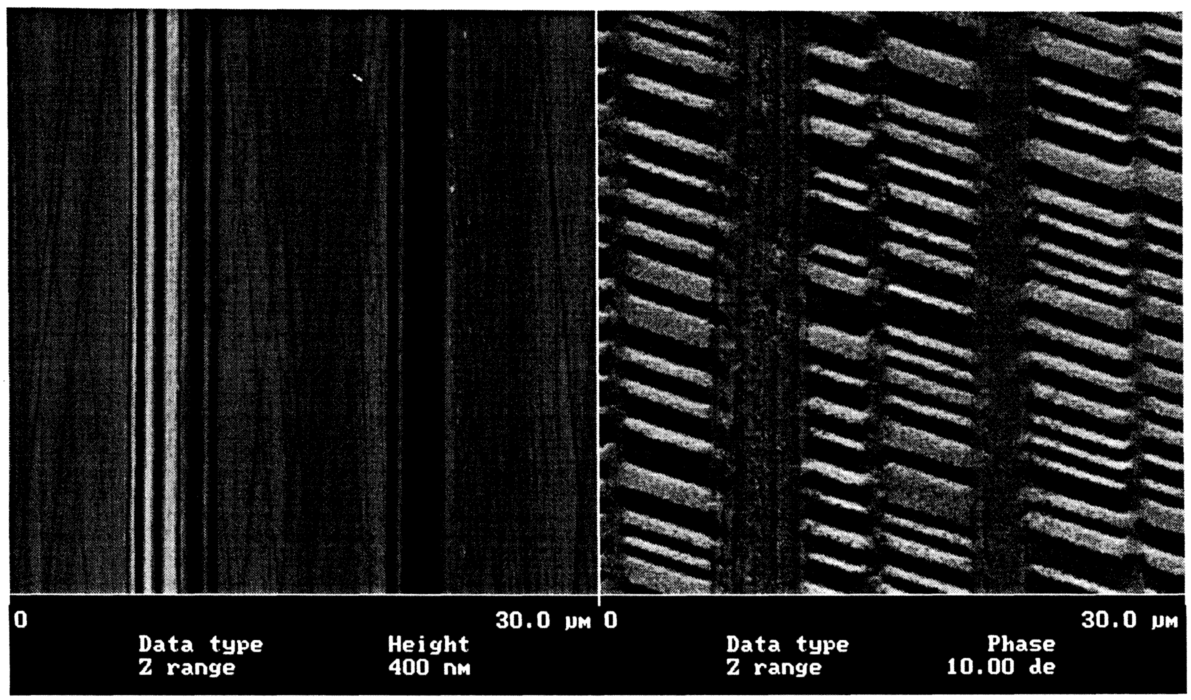
Defect Analysis

Numerous read/write areas in one sector were easily traced to this large topographical defect (70 µm wide x 100 nm deep). The magnetic image shows that (not surprisingly!) essentially no data could be written or read in the vicinity of the defect.



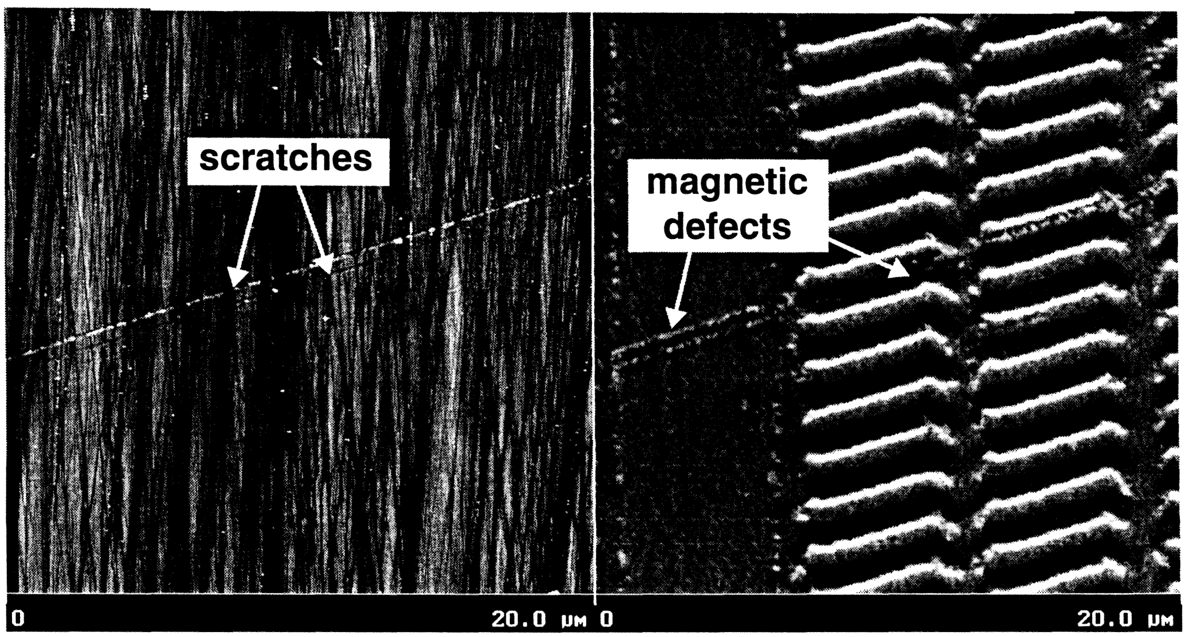
Wear Tracks

The TappingMode image (left) shows wear tracks where a defective head repeatedly passed in contact with the disk surface. The wear also" chopped off" the edges of two tracks, as can be seen in the MFM image (right).

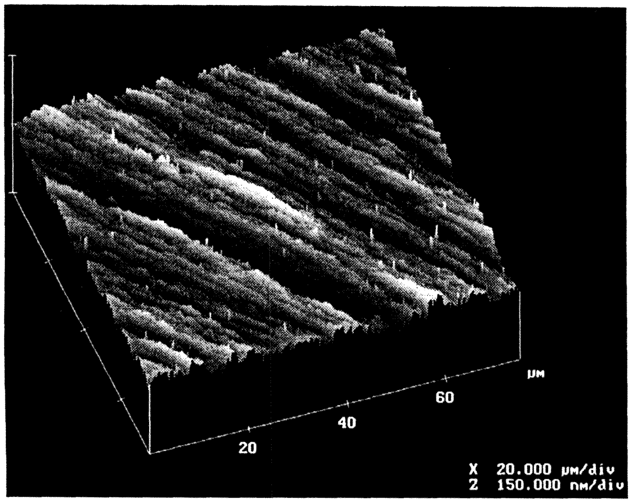


Scratch Defect

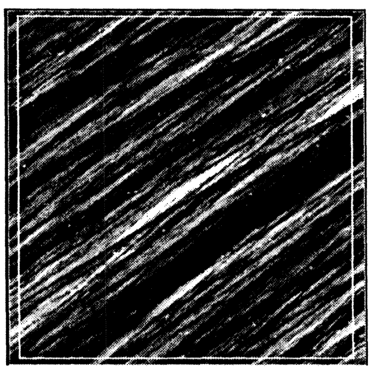
Two scratches are visible in the topography (left). The resulting stray fields produced by the longitudinal media can be seen in the MFM image (right). Read errors can sometimes be traced to such defects.



Asperities (AFM)

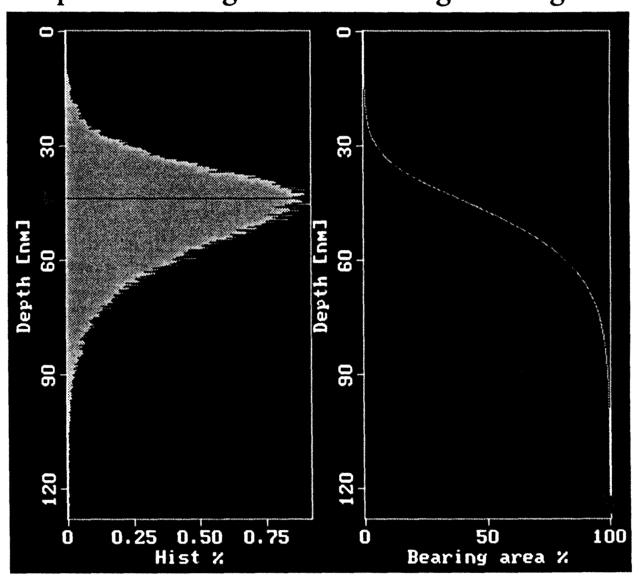


AFM reveals asperities on a hard disk surface (left) which result in poor head/media tribology. These and similar topographical features can be characterized with "bearing analysis", which gives a histogram of areas at various heights.

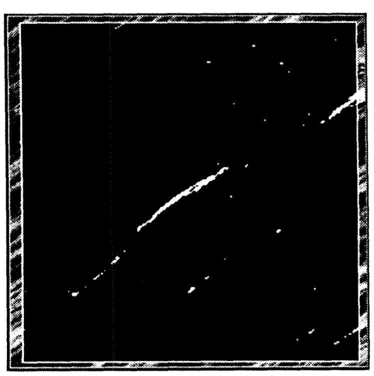


histogram of # data points vs. height

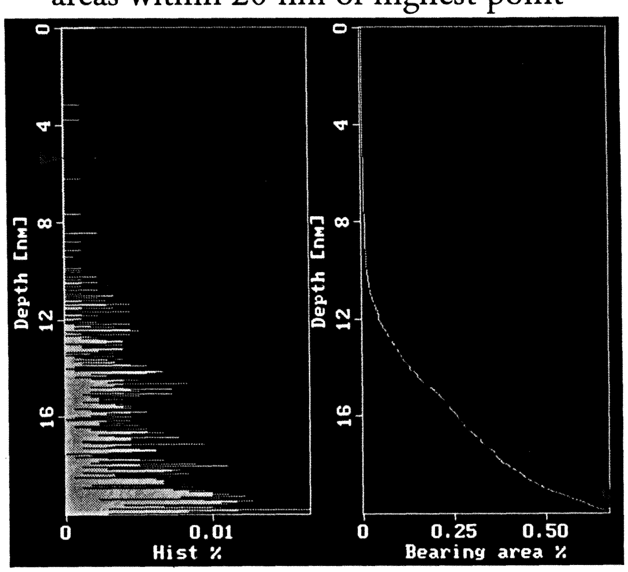
percentage of points above given height



Highlight highest regions:

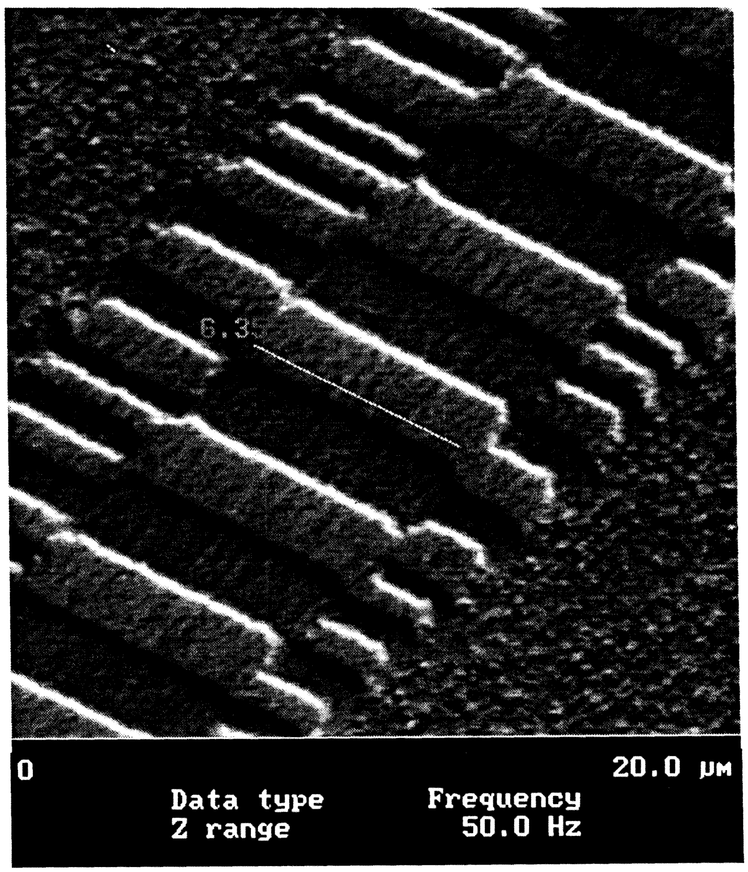


areas within 20 nm of highest point



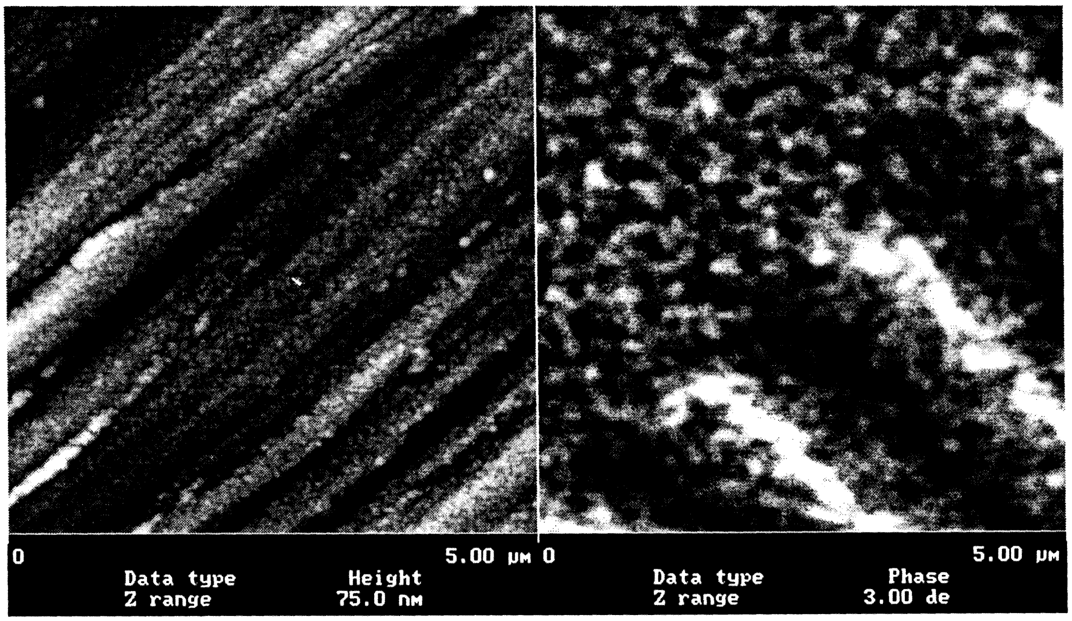
Track Characteristics

This MFM image shows the results of an overwrite test: two "data tracks" were written side-by-side, then a lower-frequency "all-1's" track was overwritten, down the center. Such images allow immediate meaurements of track characteristics such as track width, skew, erase-band width, and transition fringing and other irregularities caused by head defects.

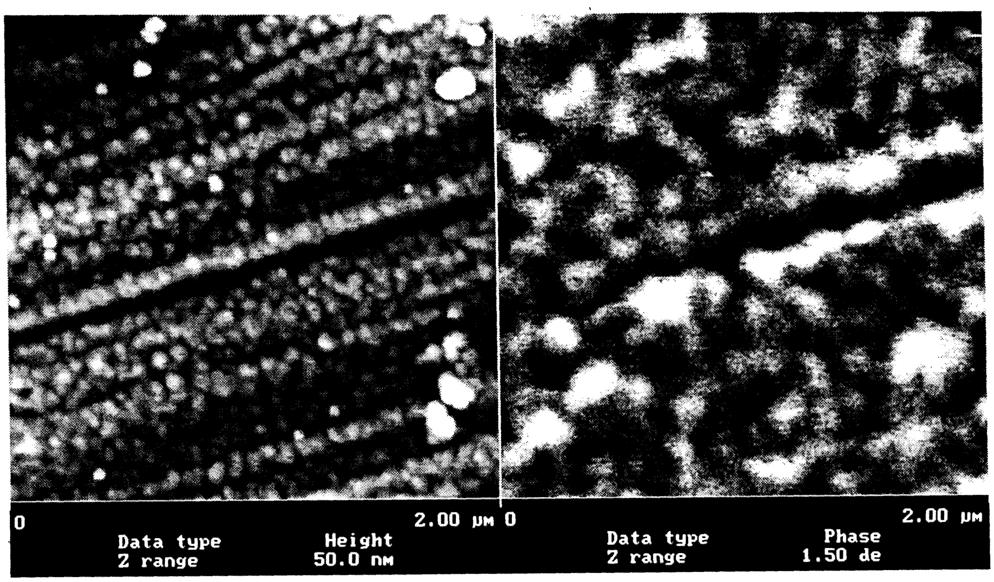


Transition Details

High resolution MFM images show that transitions on longitudinal media are comprised of individual magnetic "clusters" or "interaction domains". This structure leads to irregularities in transition shape which increase noise ("media noise"). Transition bending at track edges due to head fringing fields can also be seen at this scale.



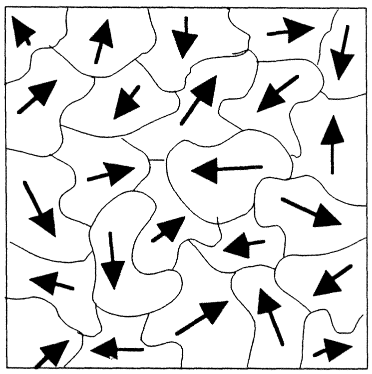
Similar image showing cluster alignment near a deep texture "valley".

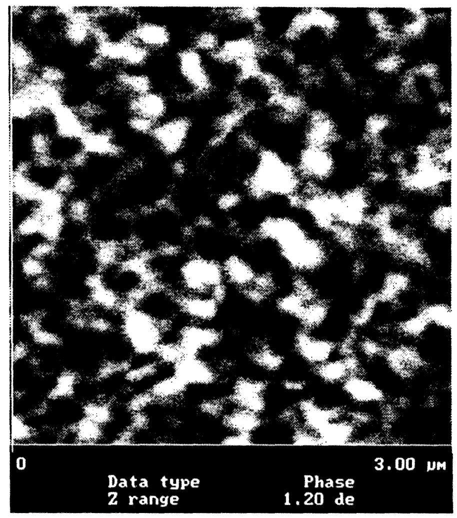


Media Noise

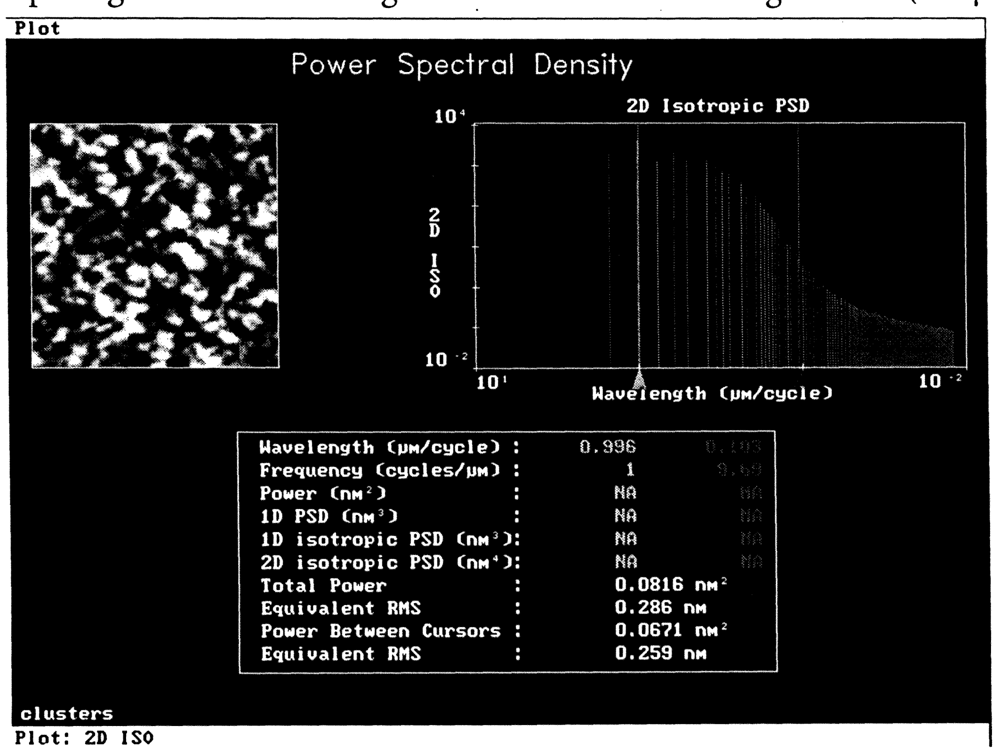
"Media noise" arises because the media's magnetic state is a conglomeration of individual magnetic "clusters". The cluster length scale is a key media parameter, since it sets a limit on how close transitions can be spaced, and thus on data density.

DC Demagnetize Relate to noise.

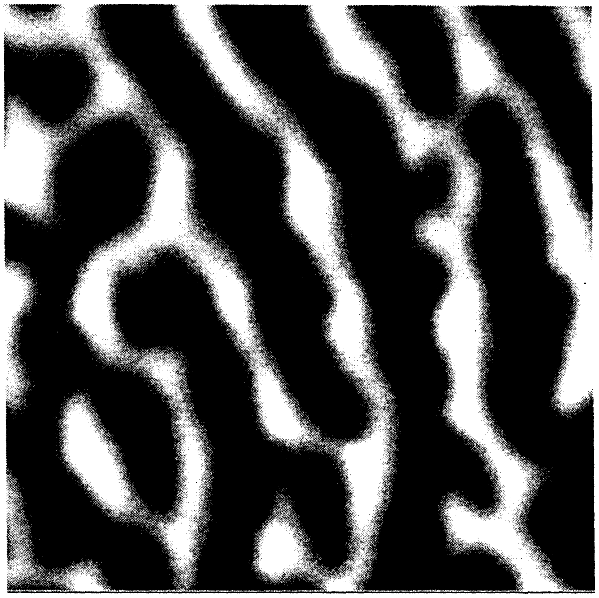




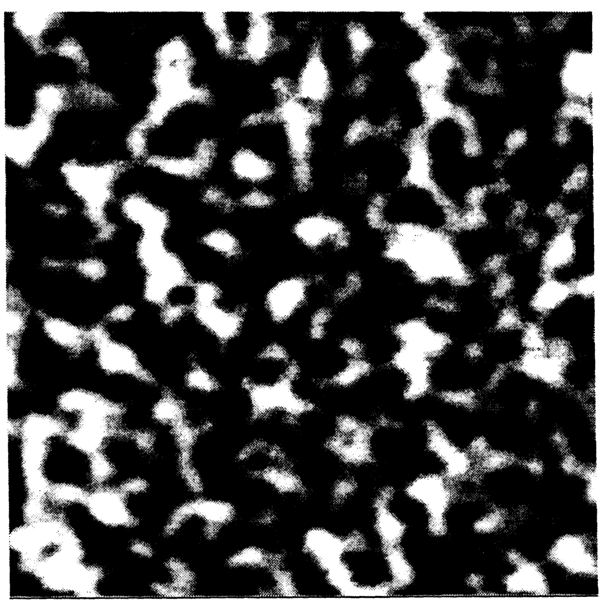
Power Spectral Density (PSD) analysis shows that most of the image "power" for this media is concentrated in length scales greater than 100 nm; this may be taken as a measure of cluster size, and hence a bound on minimum transition spacing. There are also significant fluctuations at larger scales (~ 1 µm).



Media Development


2 μm

CoCr alloy sputtered at room temperature. The film is compositionally homogeneous, and supports "continuous" domains whose walls are free to cross grain boundaries, a characteristic unsuitable for data storage.


2 μm

CoCr alloy sputtered at 200 deg C. At high temperature, yhe alloy phase seprates into Co-rich amd Co-depleted regions. The latter reduces magnetic coupling between grains, producing small-scale, discontinous domain structure suitable for high-density storage.

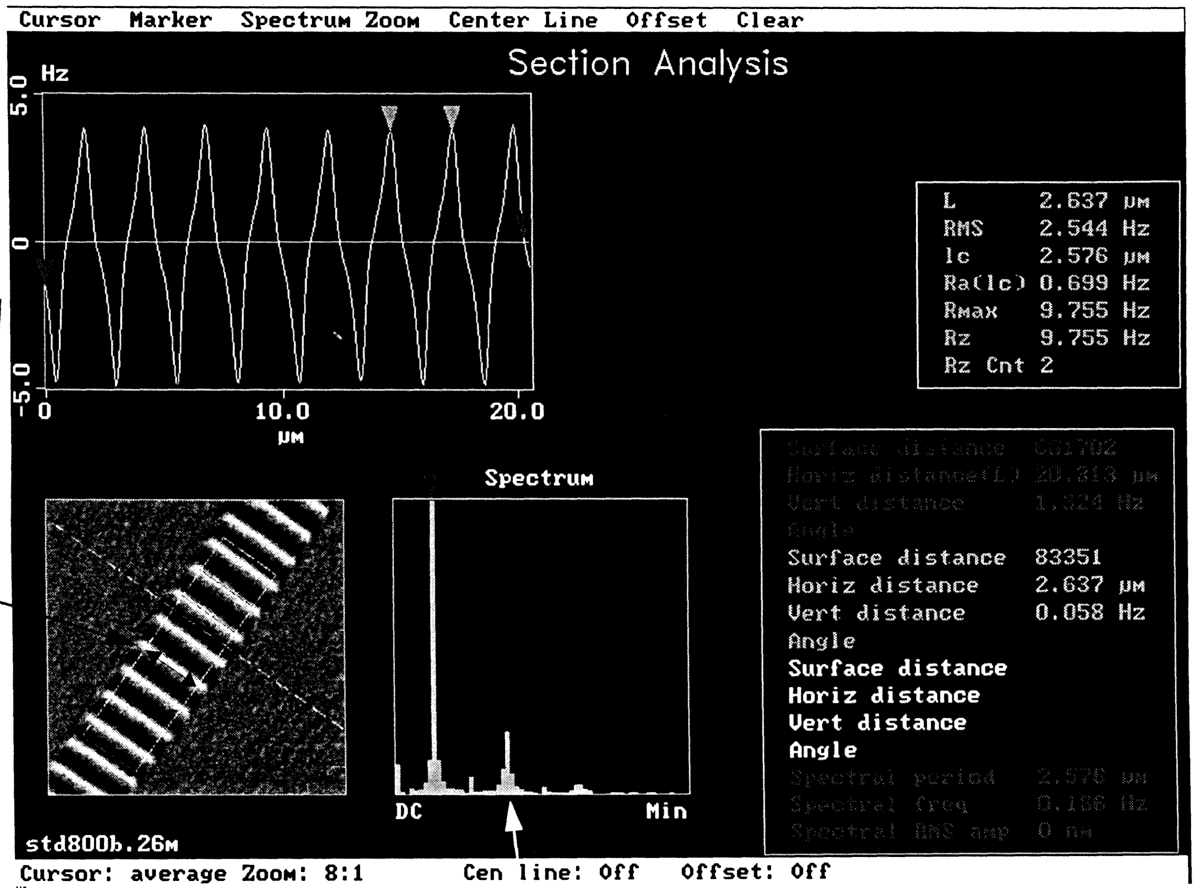
from Y. Maeda, T. Ohkubo, K. Takei, D.J. Rogers, and K.L. Babcock, J. Mag. Soc. Japan **19**, 706 (1995).

NTT perp. media

Magnetic "Track Profiles"

Taking a section through the MFM data gives a "magnetic profile" of a written track. Averaging laterally simulates the signal that would be given by a recording head. The Power Spectrum of the section gives information such as signal strength, noise, and harmonic content.

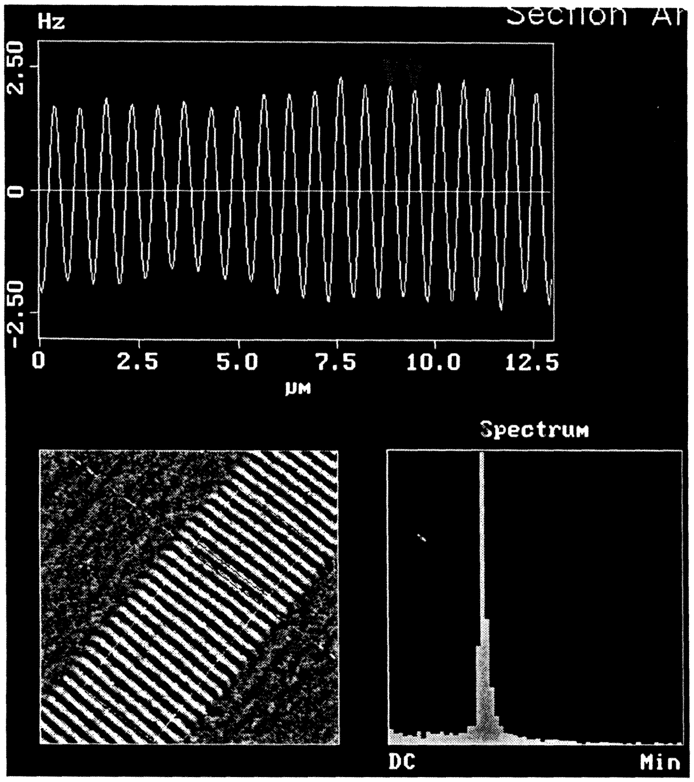
section obtained by averaging across track



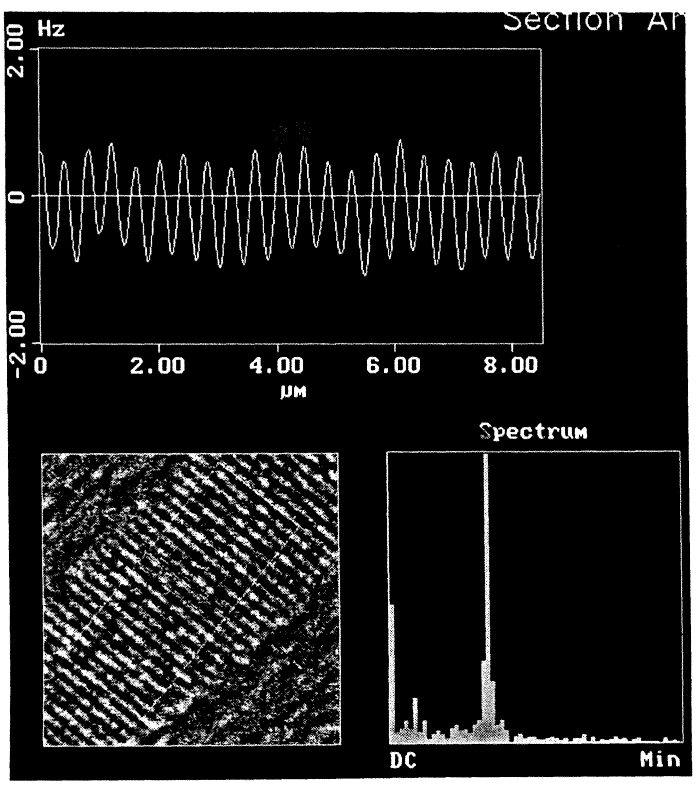
this track at 800 reversals/mm shows a strong 2nd harmonic typical of widely-spaced transitions (relative to transition width).

Signal/Noise *vs.* Frequency

Similar analysi can give an estimate of signal-to-noise ratio.



This track at 3200 reversals/mm shows a harmonic profile typical of high-frequencies

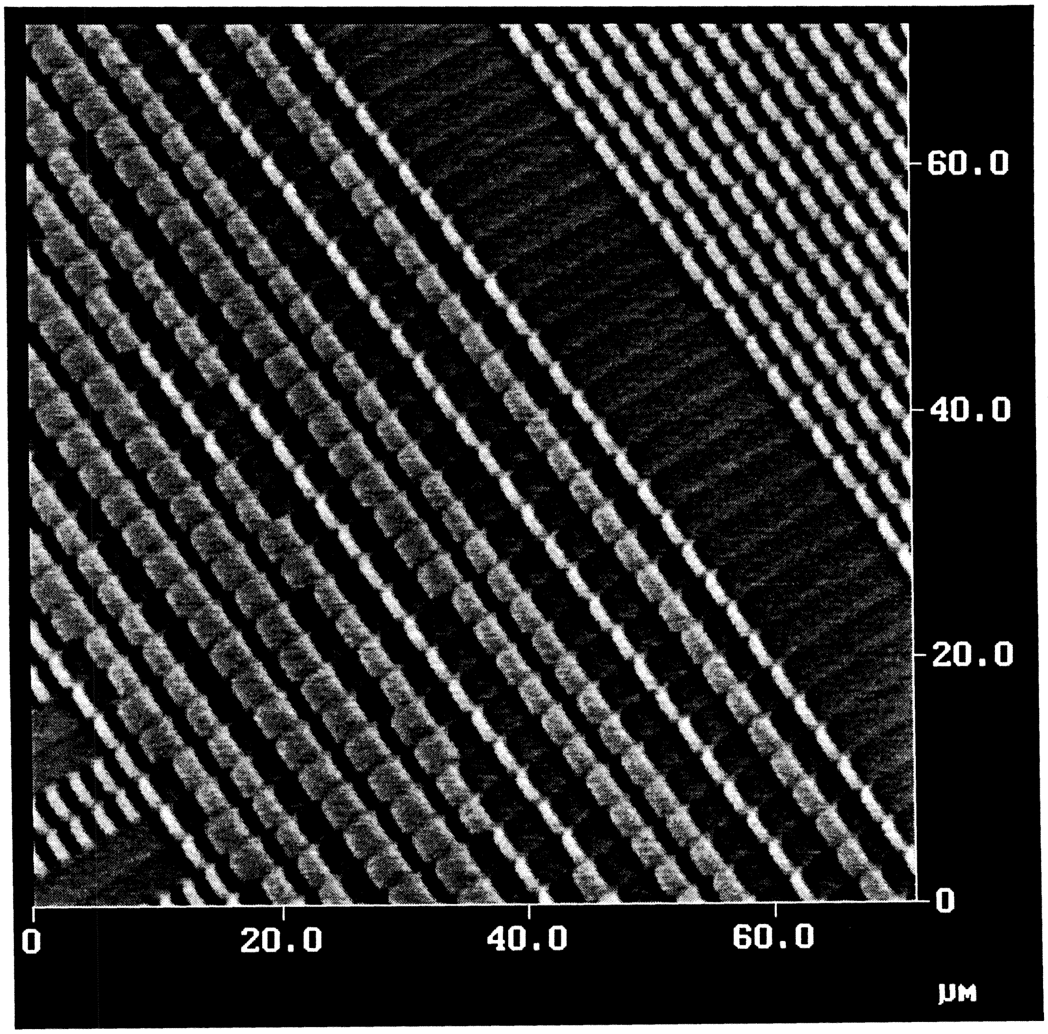


An even higher frequency (5000 rev/mm) track shows increased low frequency noise. The S/N can be taken as the ratio of the power in the fundamental peak to the integrated power outside th e peak. The results show the expected decrease in S/N at high frequencies, and follow closely the results from conventional experiments using heads. (The noise estimated by MFM is a few dB higher since it senses small-scale noise not detected by heads).

See P. Glijer, J.M. Sivertsen, J.H. Judy, C.S. Bhatia, M.F. Doerner, and T. Suzuki, "Magnetic Recording Measurements of High-Coercivity Longitudinal Media using MFM", to be published in J. Appl. Phys.

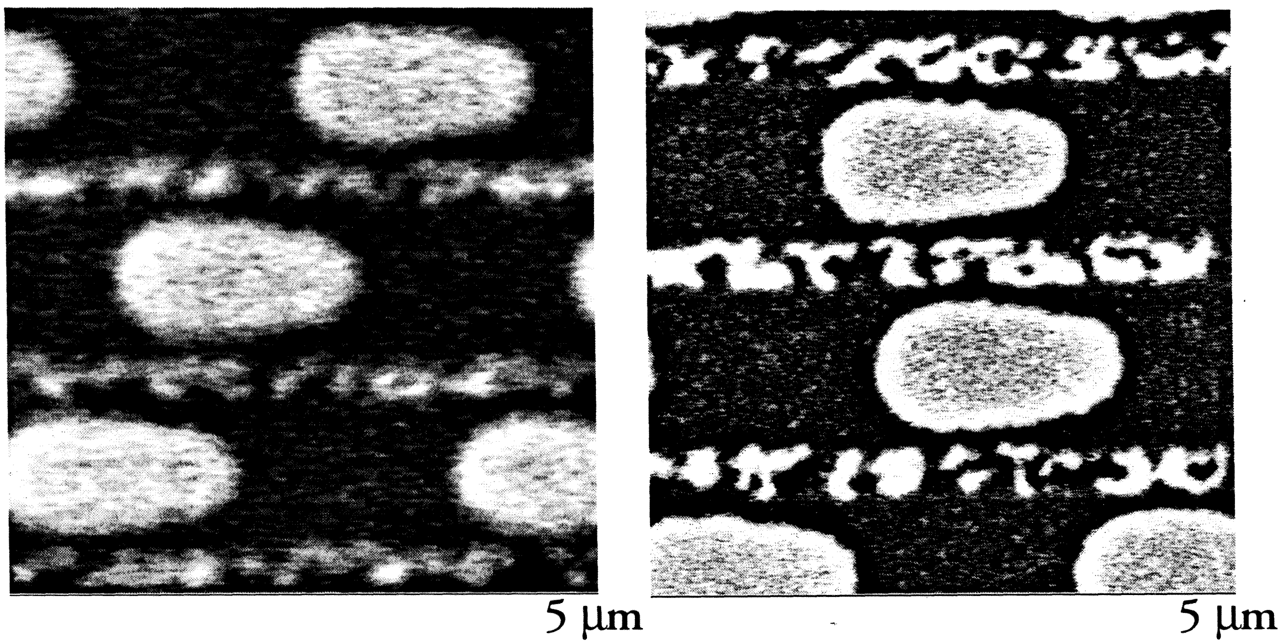
Servo Patterns

MFM gives direct visualization of servo performance by showing transition and track alignment in servo "All-1's" and "burst" patterns.



Magneto-optical Media

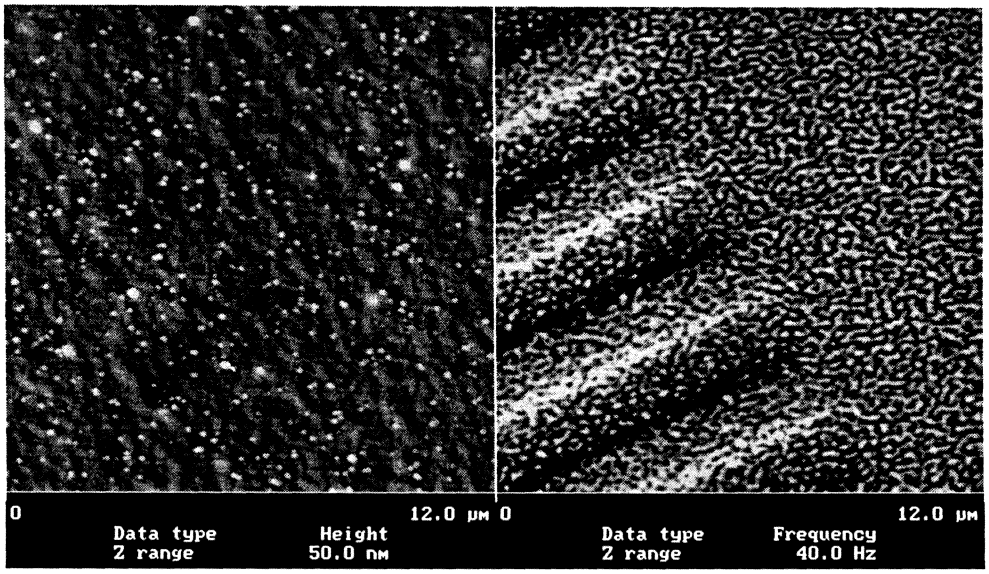
Noise on magneto-optical media is affected by bit shape, which is determined by the media and the conditions (laser power and pulse duration) under which they are written. The MFM images below show roughness on the bit peripheries. In both cases, the lift height was 30 nm. The left image was scanned in an area having a 60 nm nonmagnetic overcoat, so the tip was a total of 90 nm from the magnetic layer. The right image was captured in an area having no overcoat; the smaller tip-sample spacing (30 nm) gives higher apparent resolution, and shows magnetic features as small as 50 nm in the virgin domain structure between the tracks.



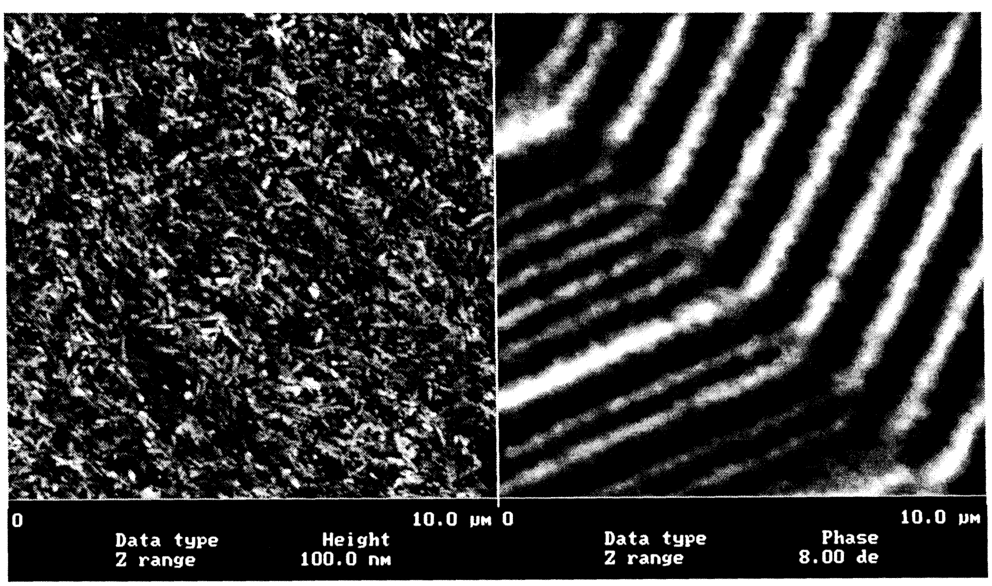
sample courtesy of WIlliam Challener, 3M Corp.

Other Media

Metal-evaporated recording tape (Sony Hi-8). "Lubrication nodules" which set the head-media gap and improve tribology are shown in the topography (left). The MFM image (right) shows transitions and virgin domain structure on the 100 nm scale.



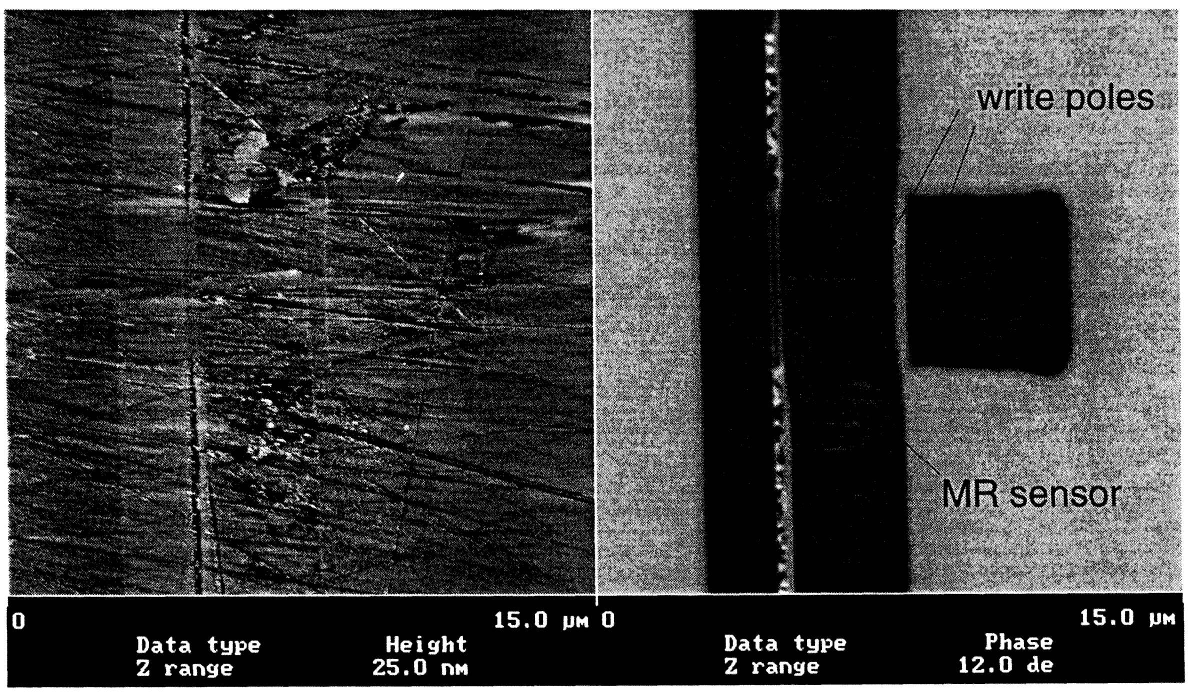
Digital audio tape, showing particulate structure (left) and a track boundary (right).



Magnetoresistive Recording Heads

AFM reveals polishing scrtaches, wear, and contamination on the ABS, and can also measure local pole-tip recession to sub-nm accuracy. MFM delineates magnetic components such as poles, shields, MR sensor, and hard magnetic bias films even when they are not apparent in the topography,, and can image through carbon overcoats.

speckle is hard bias layer



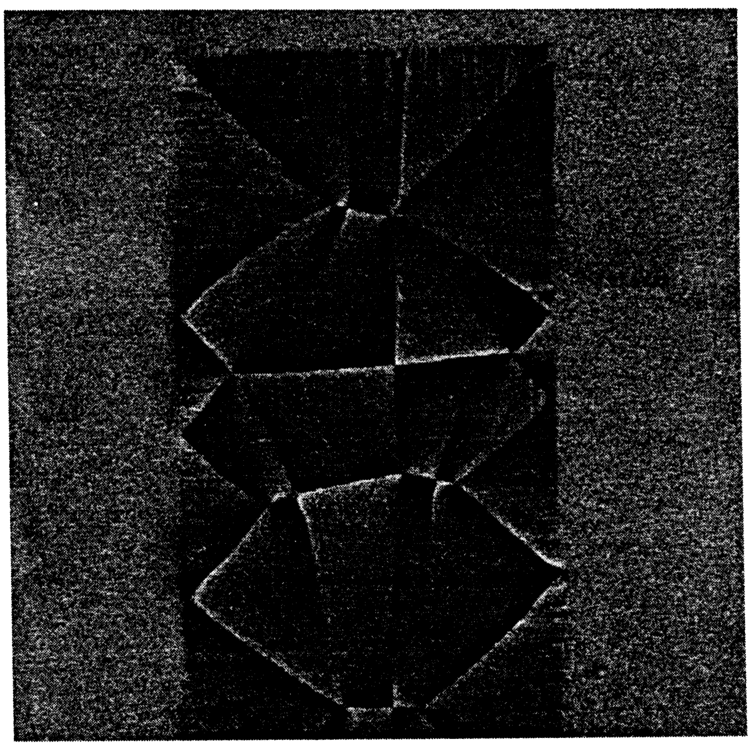
nonenergized

soft mag. mat'l - dark

“Soft” Films: MR Heads at the Wafer Level

Magnetoresistive sensors are typically made of “soft” (low-coercivity) magnetic films. At the thin-film processing level (“wefer-level”), these films can be imaged using MFM to determine domain structure, which can affect noise and sensitivity, as well as the effects of “hard” magnetic bias features on the MR sensor’s magnetic state. Domain structure is also a concern in flux guides in inductive heads.

Below is an MFM image of domains in CoZrNb (“C-Z-N”), a soft film used in recording heads. Visible are closure and cross-tie domains, and the effects of edge roughness. This image was captured using a tip with a weak magnetic moment. Although this reduces sensitivity, it also minimizes perturbation of low-coercivity samples by the tip’s magnetic stray field; we will discuss this topic further.

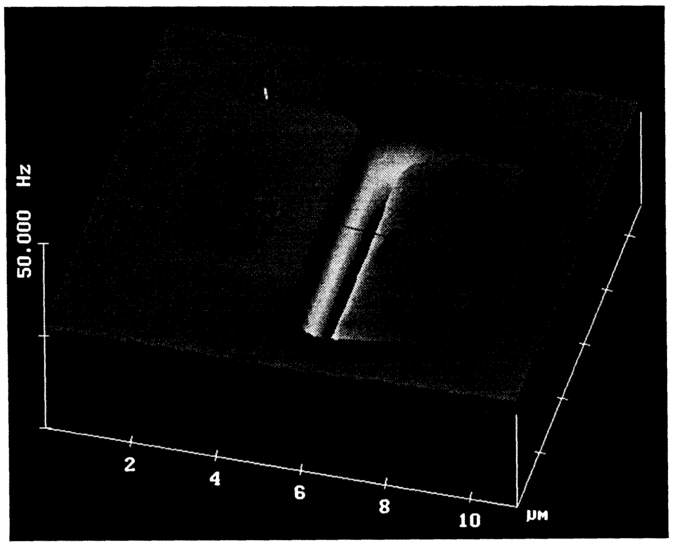


50 μm

note - wrinkles long length scale texture dependence of soft films.

Fringing Fields of Activated Write Poles

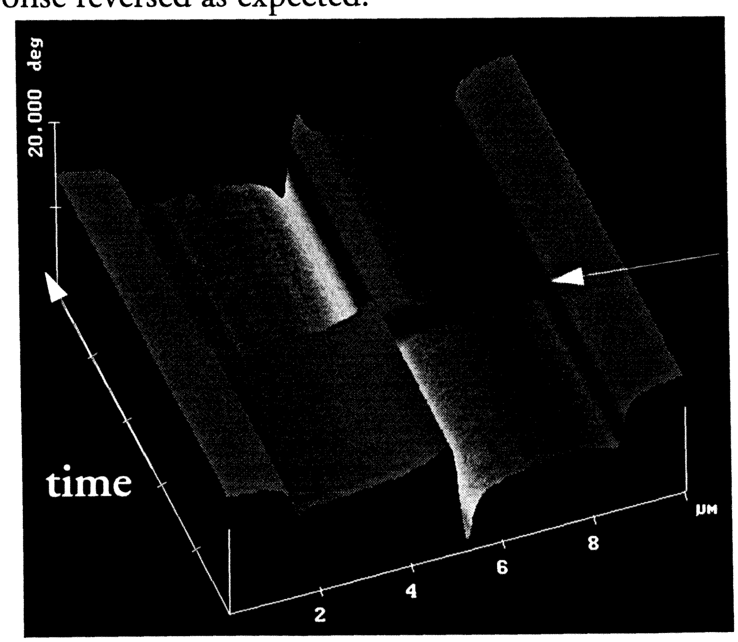
MFM scans of heads activated for writing map the "Karlquist" fields emananting from the pole tips. Sufficiently strong write currents (stronger than those used below) produce fields sufficint to "erase" the tip during each scanline; the tip moment is then always aligned with the head field, producing an interaction which is attarctive everywhere. Measuring MFM response *vs.* write current can reveal head saturation, even in high-M_S heads.



2 mA

Note applied fields can change probe sensitivity.

The image below was produced by scanning repeatedly across the poles in the same position (i.e., the "slow" motion of the raster scan was turned off). Half way through the scan, the write current was reversed; the bipolar response reversed as expected.



write current reversed

⊥ head field

Note overall depression of poles

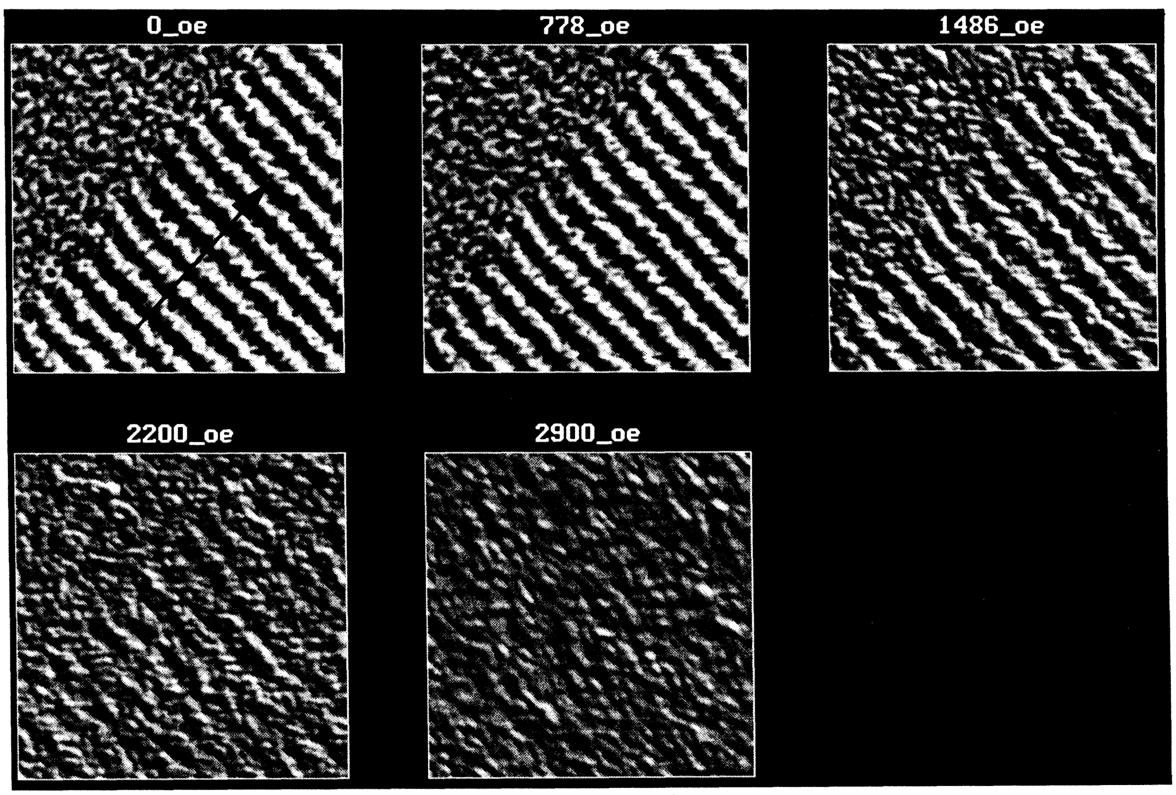
MFM Imaging in Applied Fields: Erasure of Recording Media

- Can't look @ processes much faster than 1msec,

MFM imaging can be performed in the presence of a uniform applied field. A uniform field does not interfere with imaging since the probe senses field *gradients*. As shown below, this procedure can reveal the microscopic mechanisms by which media becomes "dc erased".

Sufficiently strong applied fields can affect the magnteic state of the tip, which will alter image contrast. One must distinguish changes in the magnetic state of the tip from thoes of the sample.

Metal-evaporated video tape. Field applied along track.



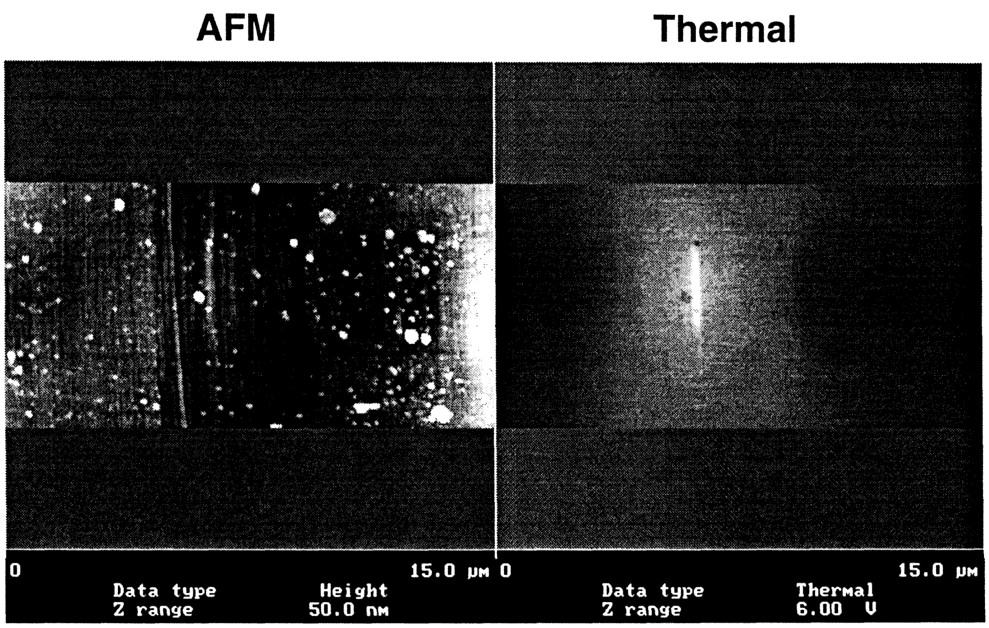
see also: R.D. Gomez, I.D. Mayergoyz, and E.R. Burke, IEEE Trans. Magn. **31**, 3346 (1995), and R. Proksch, E.Runge, S. Foss, B. Walsh, and P. Hansma, J. Appl. Phys. **78**, 3303 (1995).

But need to compensate for probe sensitivity change w/ field

Other SPM Techniques: Thermal Imaging

- fabricate probe with thermoresistive or thermocouple element at tip
- scan in contact mode while mapping thermal response

Ex) MR head with current-biased biased MR sensor
18 mA bias

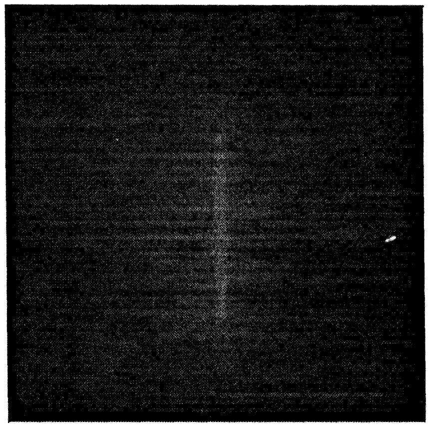


in contact – map electronic output of thermocouple tip.

The "hot spot" corresponds to the MR sensor, which sustains very high current densities when biased. Uneven heating can signify film breakdown due to electromigration or other effects.

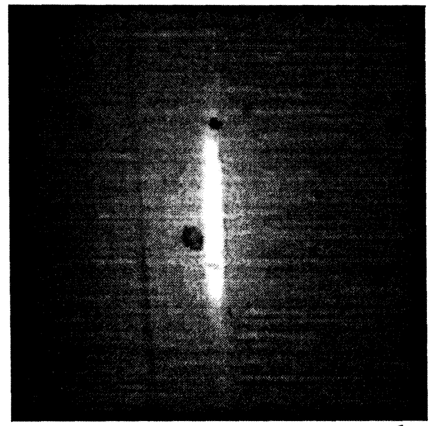
Thermal Imaging II

12 mA



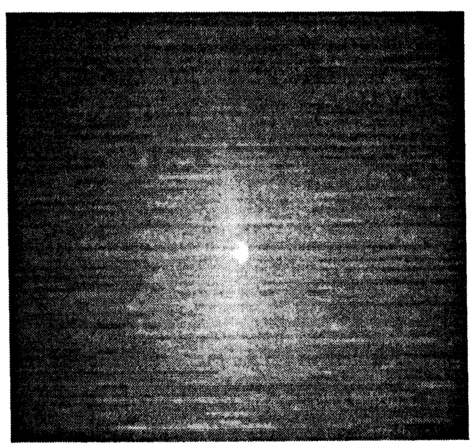
6 µm

18 mA



6 µm

A large increase in thermal response is seen with only a moderate increase in bias.



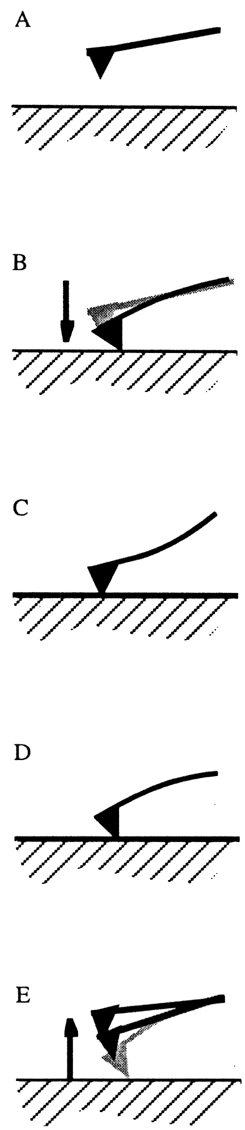
6 µm

A "hot spot" in a different head.

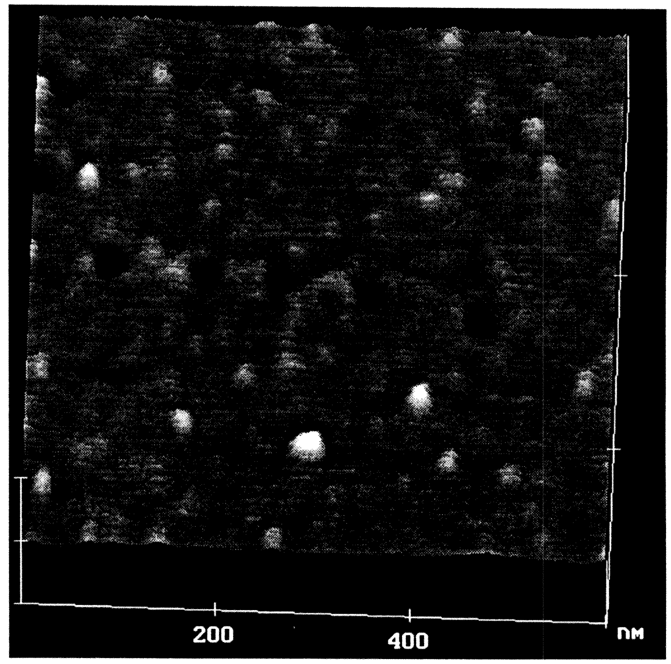
Other SPM Techniques: Nanoindentation

- stiff cantilever
- μN forces

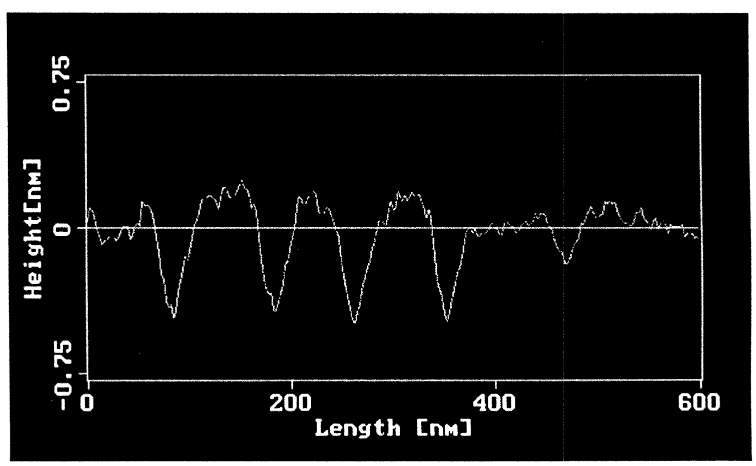
- push diamond tip into surface with *z* scanner
- total force known *via* cantilever spring constant and measured deflection
- image results with same probe using TappingMode



Ex) indentations in 10 nm DLC coating



Section analysis: indentations are ~ 5 Å deep

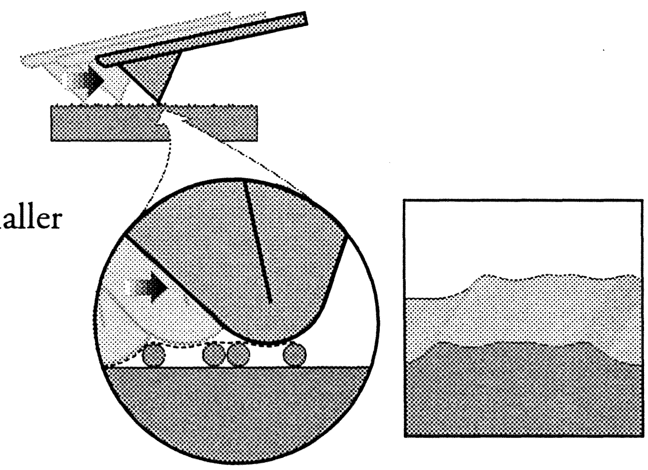


IV. Probes Revisited

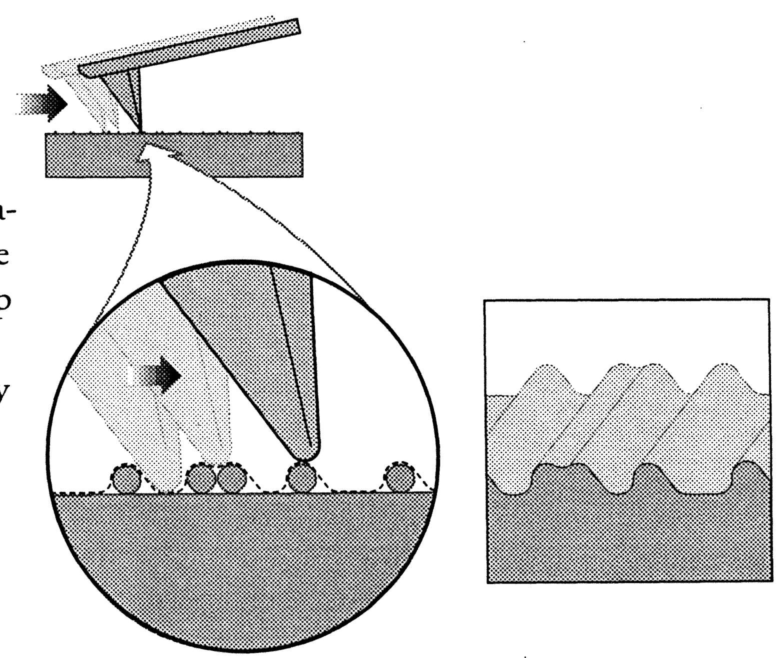
Tip Shape in AFM Imaging

A number of probe characteristics can affect SPM imaging. Probe shape determines lateral resolution in AFM, and tips which are mishapen or contaminated with dirt can produce image artifacts. Magnetic characteristics of MFM probes determine their sensitivity and their interaction with magnetic samples.

A tip cannot resolve features smaller than its end radius.

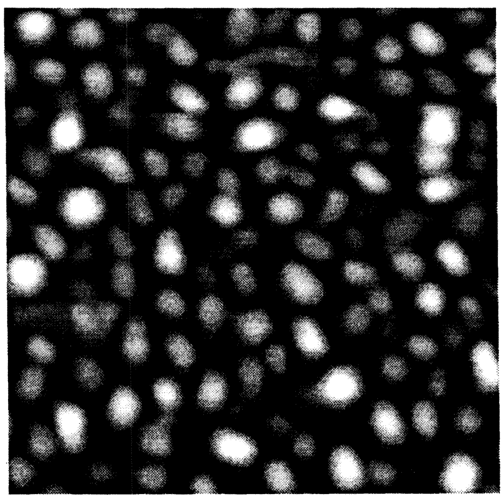


A sharper tip can resolve the same features. The apparent lateral size of the spheres is increased by roughly the tip diameter. Note, however, that the *height* measurement is not affected by the tip size.

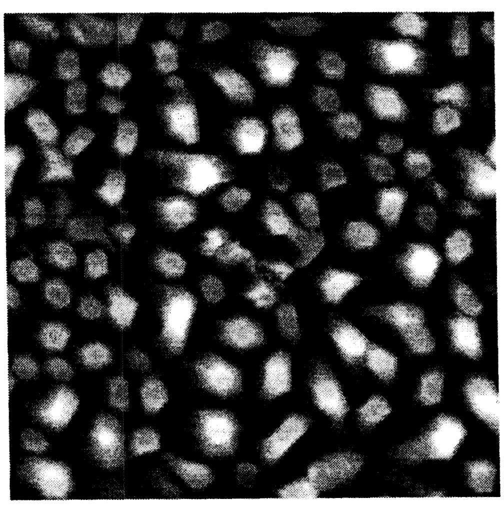


Ex): Coated (MFM) vs. Uncoated Si Probes

Coating MFM probes with a magnetic alloy increases their end radius by an amount roughly equal to the coating thickness (typ. 10-50 nm). This slightly decreases the resolution obtainable with AFM.



Grains in CoCr alloy imaged with coated MFM tip (TappingMode).

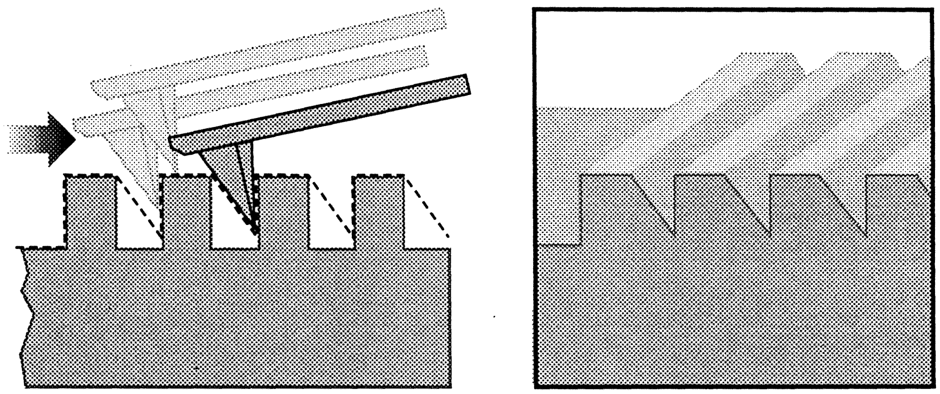


Grains in same film imaged with an uncoated Si tip, showing fine detail and polygonal shape not visible with the coated tip.

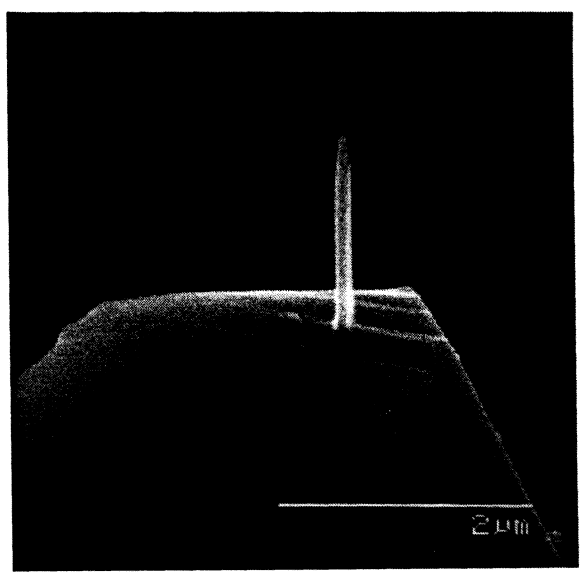
Exercise: Imagine a perfectly sharp, straight, infnitely thin needle sticking perpendicular to a flat surface. What would its AFM image look like?

Probe Geometry

When imaging tall, steep-walled objects, the overall probe geometry can affect the image. Below the pyramidal tip cannot track the vertical walls on the left of the trenches.



Alternative probe geometries allow more accurate imaging of wall angles. This high aspect ratio probe was made by milling away parts of a pyramidal probe with a focused ion beam.

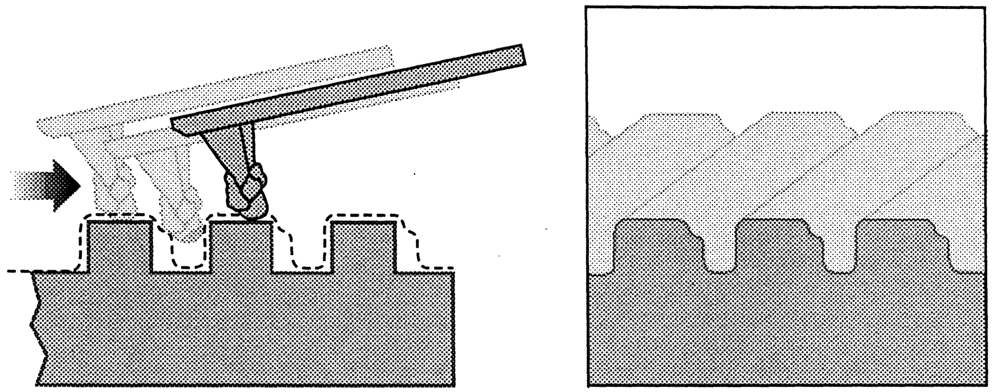


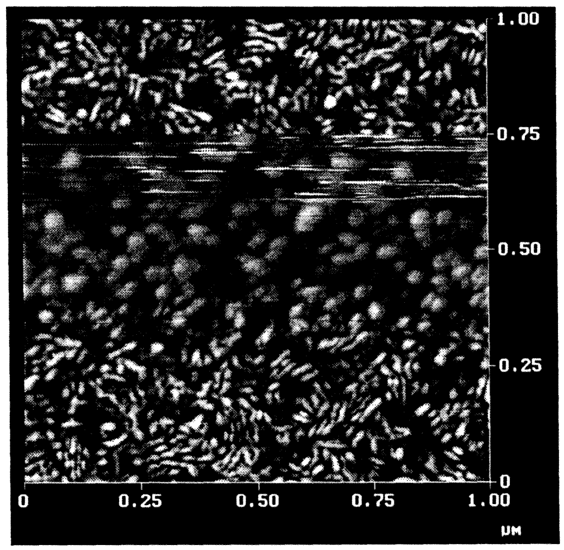
-no sharper tip, may be duller

Current research in SPM is attempting to account for tip shape effects.

Probe Contamination

Dirt particles attached to the tip can change the effective tip shape and affect the image.

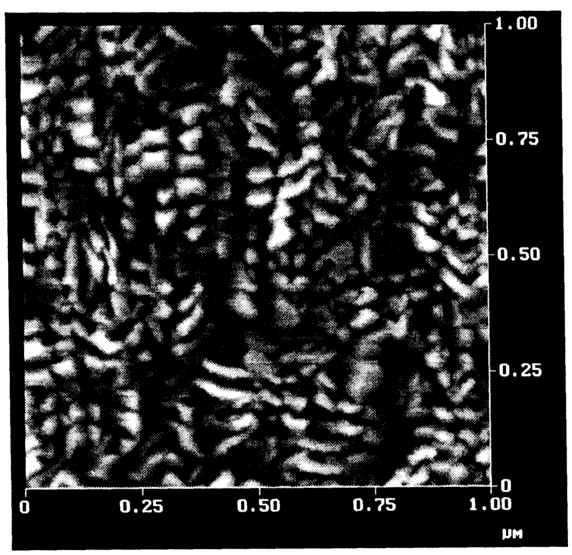




contamination detaches

tip contaminated

images courtesy of Phil Russell, NCSU



"double" tip

Probe contamination is uncommon in clean environments and with non-particulate samples. Similar artifacts occur with damaged or worn tips. An alert the SPM user will be able to recognize most tip artifacts.

Magnetic Probe Characteristics

Need to discharge samples if a prob[lem]
Can also image electrical fields.

Properties of MFM probes :

- magnetic moment magnitude m_z (which determines sensitivity)
- coercivity
- moment orientation

- these properties are critical in determining image contrast, and in determining how a probe interacts with a sample
- they can be tailored by adjusting the sputtered alloy and sputtering conditions, and how the tip is magnetized

<u>So far we have assumed that</u>:

- the tip's own stray field has no effect on the sample being imaged
- the moment magnitude m_z remains fixed as it scans through the sample's stray fields - i.e., the tip's coercivity is large compared to the stray field it is imaging
- the tip orientation is fixed in the z direction; this makes the probe sensitive to vertical field components

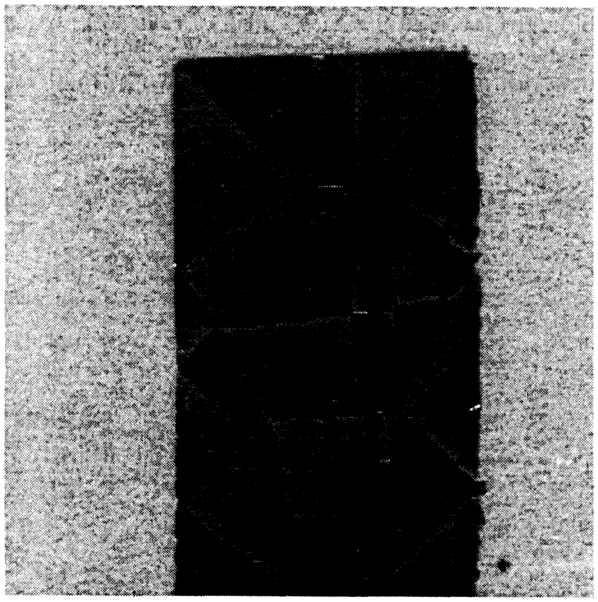
<u>We consider now cases where these assumptions no longer hold, specifically</u>

- imaging artifacts, and how they can be avoided by using appropriate probes
- how tip properties can be adjusted to give more information, e.g., by detecting different stray field components

Also suggestion to use Kerr to look at transitions

He recommends low moment probes to look @ soft layers,
He says thin soft mag. films, may have rapidly moving domains?!

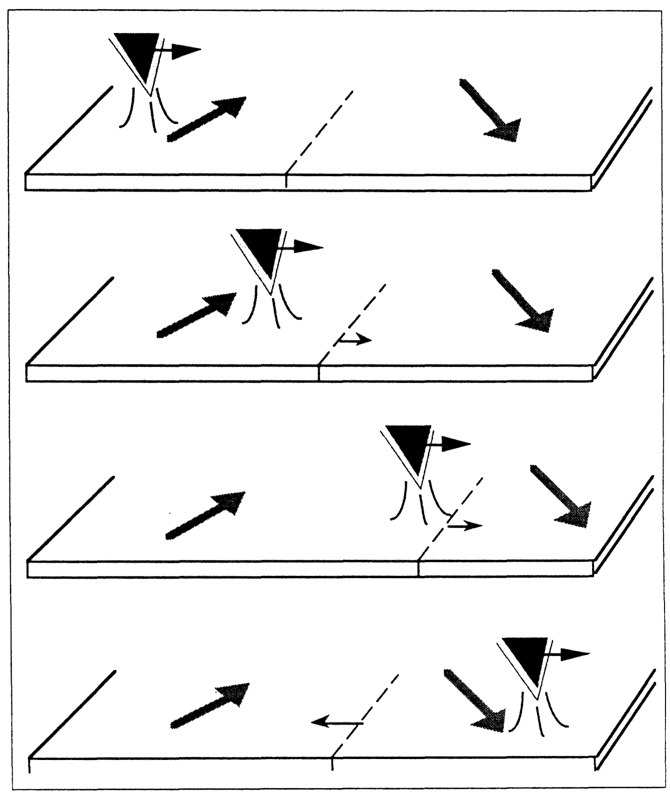
Imaging "Soft" (Low-Coercivity) Samples



50 μm

In this MFM image of a 60 nm CoZrNb film on a glass substrate, there is evidence that the tip's stray field perturbed the magnetization and domain structure during scanning

Jaggedness in the domain walls is caused when the tip's stray field "shoves" the domain walls back and forth as it scans over them.



Right:

- tip approaches domain wall
- influence of tip's stray field pushes the wall in front of it
- the tip finally passes over the wall, and "magnetic restoring forces" cause the wall to snap back

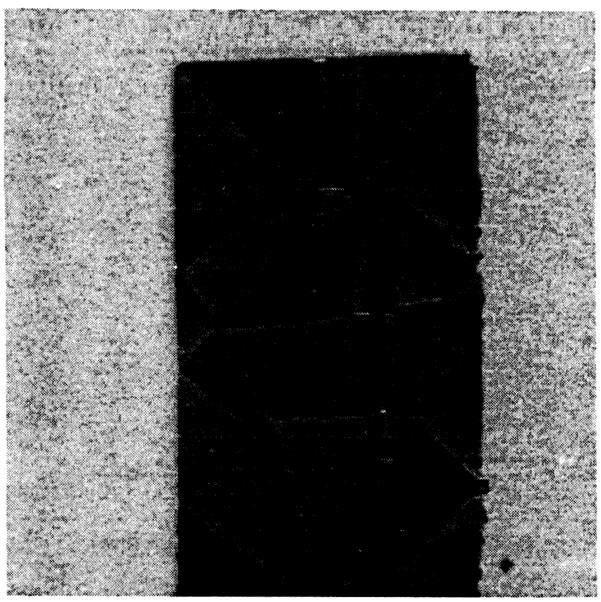
The wall does not return to the exact original position; hence the jaggedness in the image

Such perturbation can be severe on extermely soft samples (e.g., films of soft alloy < 20 nm thick).

Imaging "Soft" Samples II

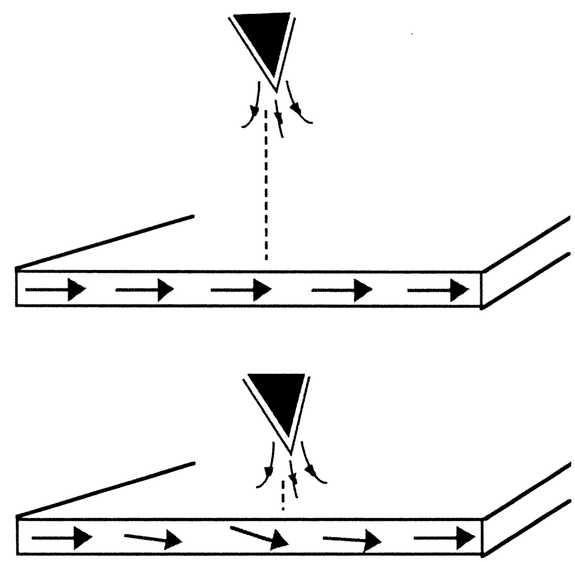
artifact

Another effect:
overall dark contrast compared to the nonmagnetic background



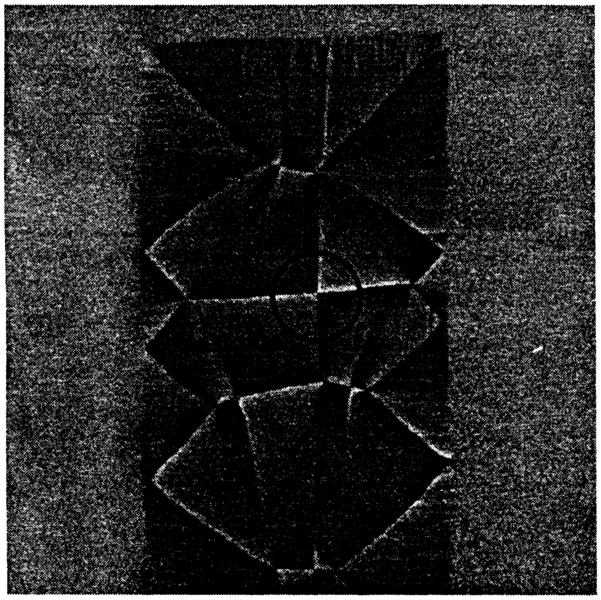
50 µm

- sample magnetization is initially in-plane.
- tip is brought close to the sample, and magnetization tilts slightly out of plane
- magnetization then has component aligned with the tip's stray field
- tip is attracted to sample, giving "dark" contrast



This effect is commonly seen when imaging soft films in recording heads.

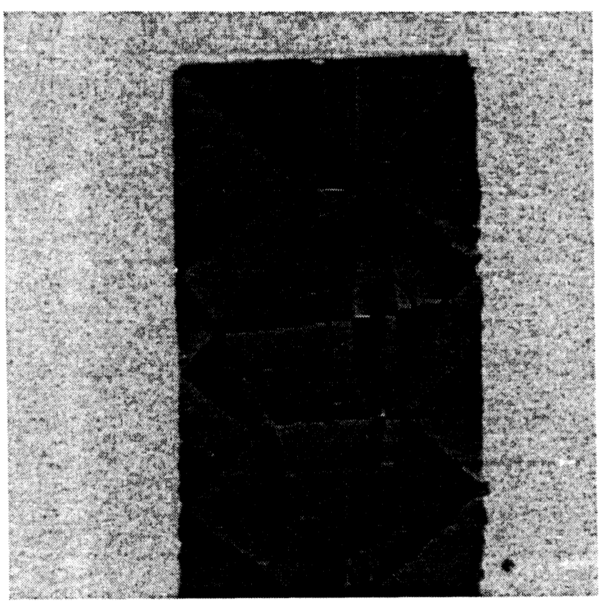
Imaging "Soft" Samples III



50 µm

These effects can be minimized by using a probe with reduced magnetic moment m_z, which reduces the tip's stray field. The image at left shows less domain wall perturbation and overall attraction.

A drawback: reducing the tip moment also reduces sensitivity. Tip moments therefor cannot be made arbitrarily weak, and extremely soft samples (e.g., soft films < 10 nm thick) are difficult to image well with MFM.



50 µm

This image was captured *after* the above image. The circled area shows where an additional cross-tie domain was generated by the "strong" tip's stray field.

Such *irreversible* changes in domain structure are perhaps the most severe tip effect on soft samples.

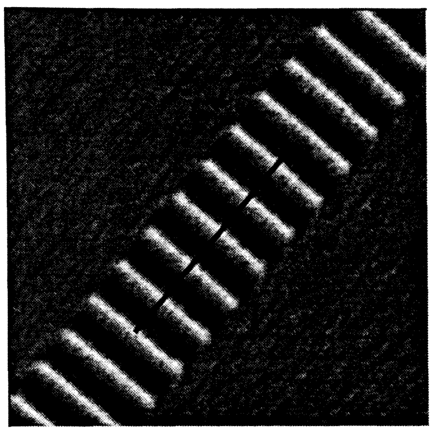
Tip Sensitivity

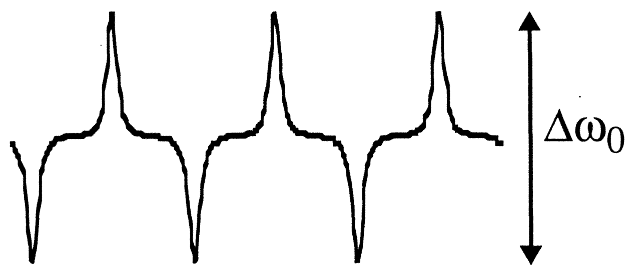
Tip sensitivity increases with magnetic moment:

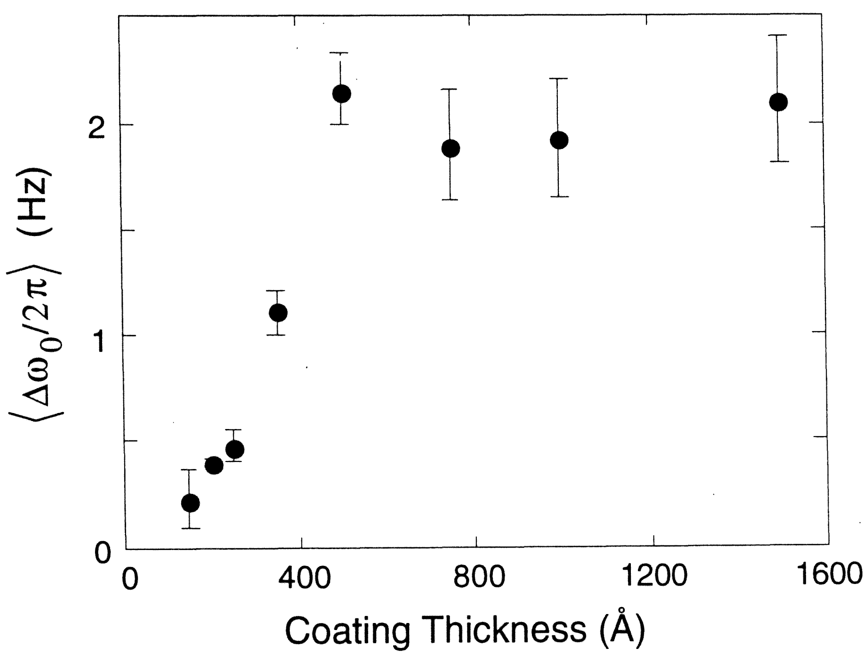
$$\frac{\partial F_z}{\partial z} \cong m_z \frac{\partial^2 H_z}{\partial z^2} \quad \text{(dipole approximation)}$$

The moment m_z increases with the thickness of the sputtered film

Ex) Sputtered CoCr. Meaasure sensitivity *via* peak-to-valley MFM contrast excursions in images of hard disk transitions



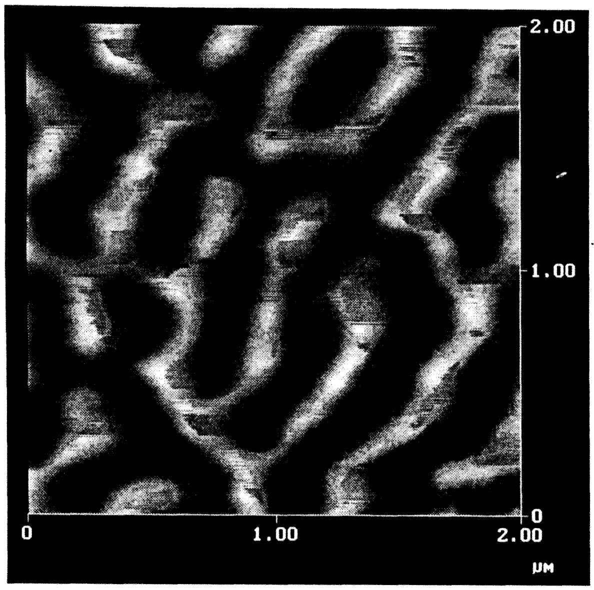




from K. Babcock, M. Dugas, V. Elings, and S. Loper, IEEE Trans. Magn., 30, 4503 (1994)

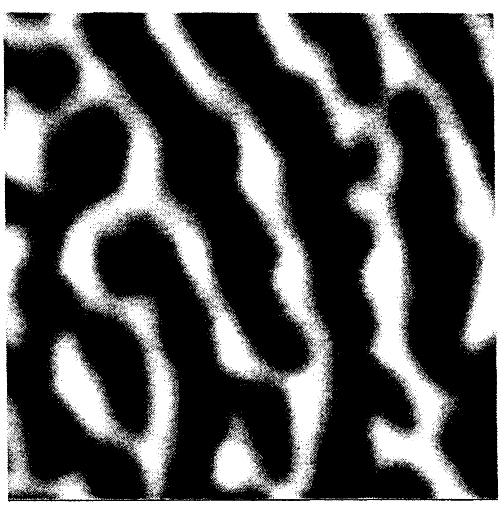
Tip Coercivity: "Hard" Tips

On the previous example, the tip affected the sample. In some cases the sample can affect the tip. For example, if the sample's stray fields are very strong, or the tip coercivity very low, the tip can be repeatedly "erased" (partially) then remagnetized as it passes through the sample stray fields.



Ex) MFM of CoCr film

- note changes in contrast in "light" areas
- recall that in these regions the sample field is aligned opposite to the tip moment.- contrast changes are due to tip being partly remagnetized
- tip would then be remagnetized when it entered areas of dark contrast, where the field is algine with tip
- demagnetization/remagnetization occurs in semi-random fashion



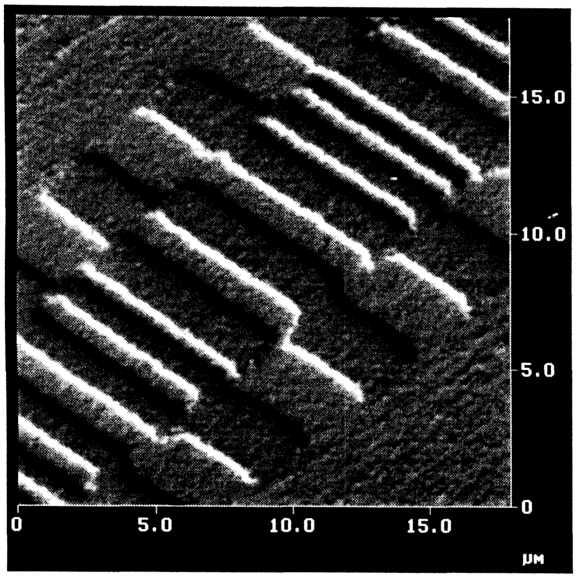
A Solution: high-coercivity tips

- by using a high-coercivity tip coating
- tip moment,a nd sensitivity, then stays fixed during scanning, giving clean images
- for optimal scanning, need tip coercivity greater than sample stray fields
- good tips can withstand most media fields
- difficult to obtain sufficient coercivitity for demanding samples; e.g., permanent magnets, or fringing fields from recording heads - after all, they are designed to erase media, and "media" is what's on the tip!

Tip Coercivity II: "Soft" Tips

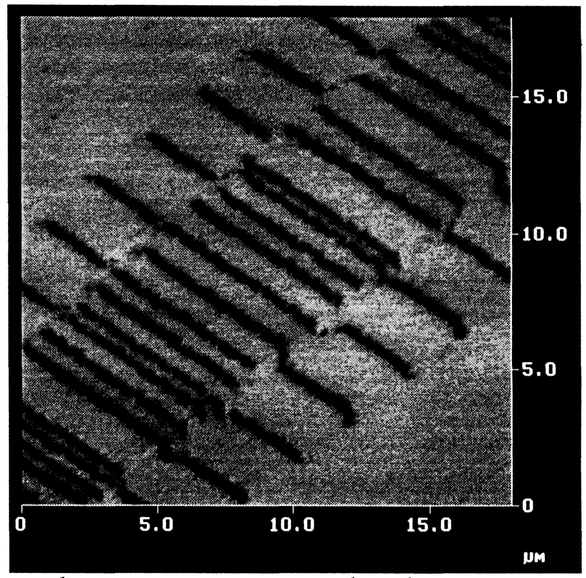
Another approach: low-coercivity tips

Image of hard disk trask using a fixed-moment (high-coercivity) probe.



Probe is repelled by some transitions (light contrast), and attracted to others

Image of same track imaged with "soft" (low-coercivity) probe.



- probe moment constantly adjusts so as to stay aligned with the sample stray field

- interaction is then always attractive, with magntitude increasing with field strength

since probe mag. modified

Soft Probe Math

- vertical force on probe (dipole approximation): $F_z = -\frac{\partial}{\partial z}(\vec{m} \cdot \vec{H}) = -\frac{\partial}{\partial z}(|\vec{m}||\vec{H}|cos(\theta))$

  (θ is angle between tip moment and sample field)

- soft probe: m always aligned with H: $\cos(\theta)=1$; $\vec{m} \cdot \vec{H} = |\vec{m}||\vec{H}|$

- force (and force gradient) on probe is always attractive (< 0), and depends only on field magnitude:

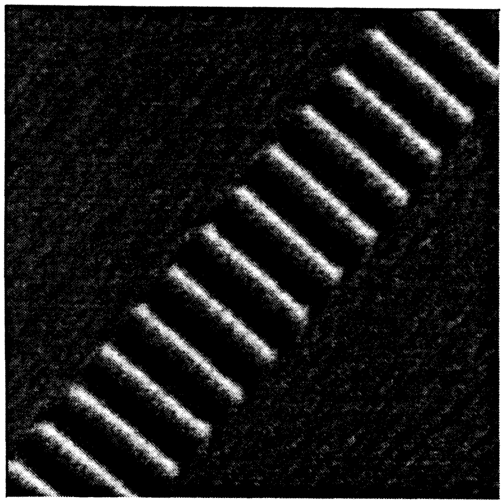
$$F_z \approx -|m| \frac{\partial |H|}{\partial z}$$

(we've assumed that the tip's moment m is independent of its orientation)

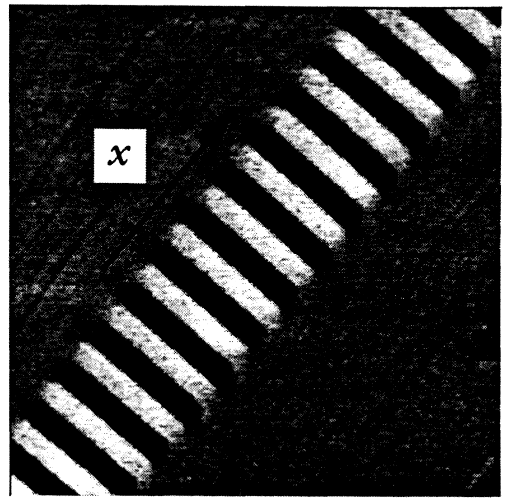
Component-wise Sensititivy of MFM probes

So far we have considered probes magnetized vertically: $\boldsymbol{m}=m_z\boldsymbol{z}$. This gives sensitivity to vertical field components H_z and their derivatives, and highlights, e.g., hard disk transitions.

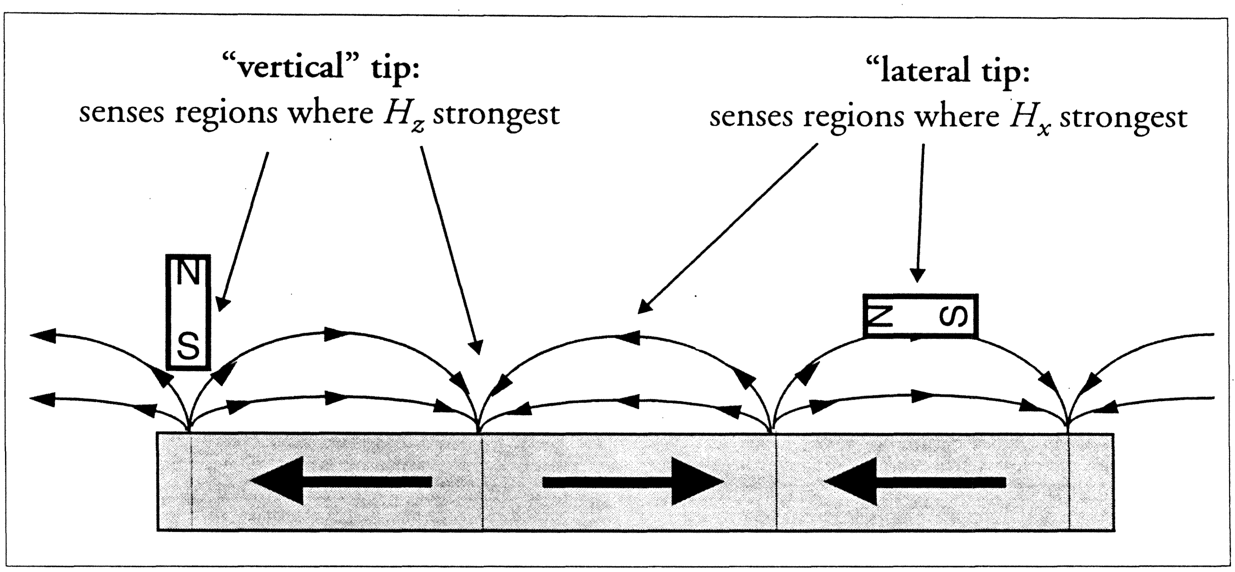
Instead, magnetizing probes laterally ($\boldsymbol{m}=m_x\boldsymbol{x}$) gives sensitivity to lateral field components H_x.. (Here, $\boldsymbol{x}$ is the direction along the track).This will highlight the "domains" between transitions:



25 μm



25 μm



- requires a "high-coercivity" probe that can be magnetized using strong field
- most "hard" thin-film probes will take a "set" either along $\boldsymbol{z}$ or $\boldsymbol{x}$, depending on the orientation of the magnetizing field
- when magnetizing in $\boldsymbol{x}$, the tip will often retain some $\boldsymbol{z}$ component to the moment, and will sense a mix of H_x and H_z.

Can set cantilever ⊥ to tracks to image

Component-wise Sensititivy of MFM probes II

Probe Component Math

- vertical force on probe (dipole approximation):

$$F_z = -\frac{\partial}{\partial z}\left(\vec{m} \cdot \vec{H}\right) = -\frac{\partial}{\partial z}\left(m_x H_x + m_y H_y + m_z H_z\right)$$

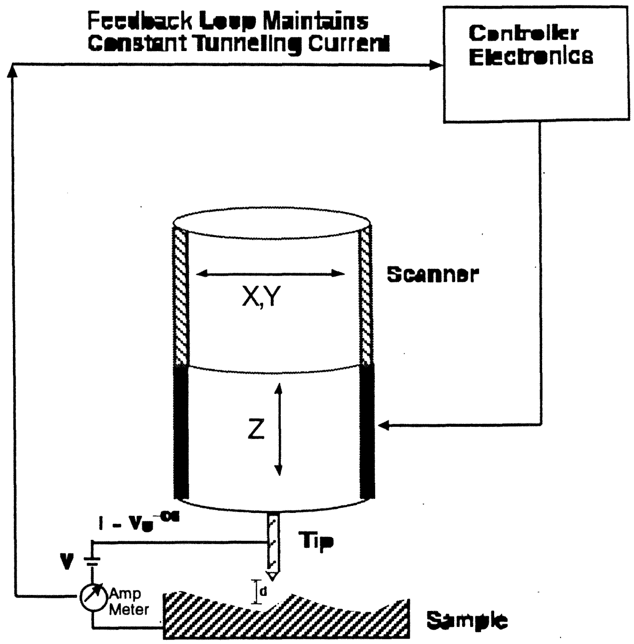
- vertically-magnetized tip: $m=m_z z$, $F_z = -m_z \frac{\partial H_z}{\partial z}$

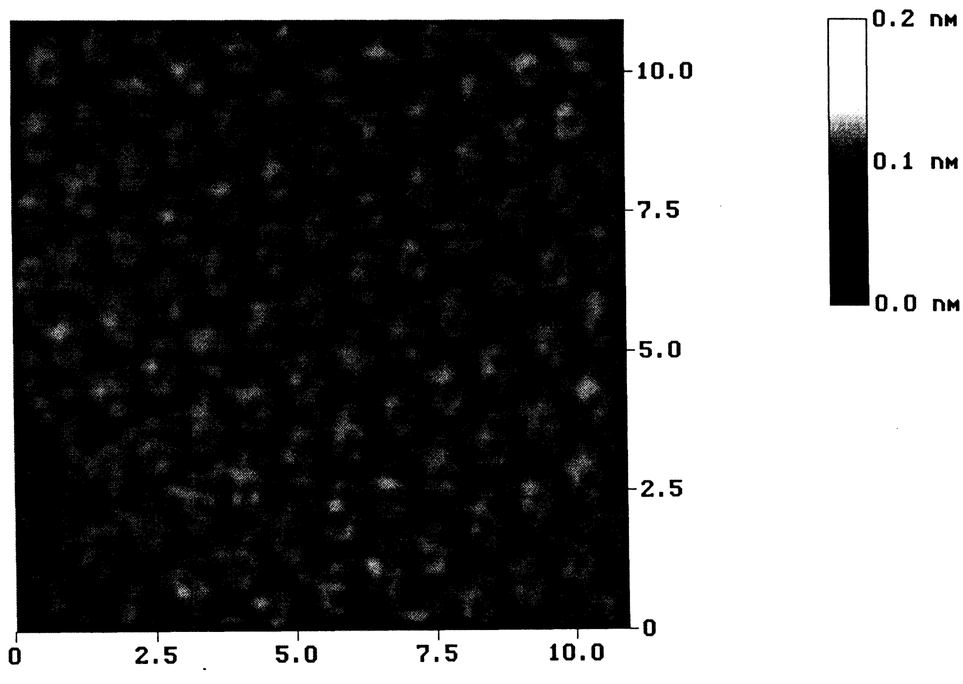
- laterally-magnetized tip: $m=m_x x$, $F_z = -m_x \frac{\partial H_x}{\partial z}$

Appendix : A very brief history of early SPM

STM The original SPM was the scanning tunneling microscope (STM), invented in 1982 (Binnig, Rohrer, Gerber, Weibel), and winning the Nobel Prize in 1986 (Binnig and Rohrer).

STM monitors the quantum tunneling current between tip and a conducting sample held at a a potential difference. STM shocked the world with its ability to image individual atoms (especially in UHV), opening up new realms of surface science.



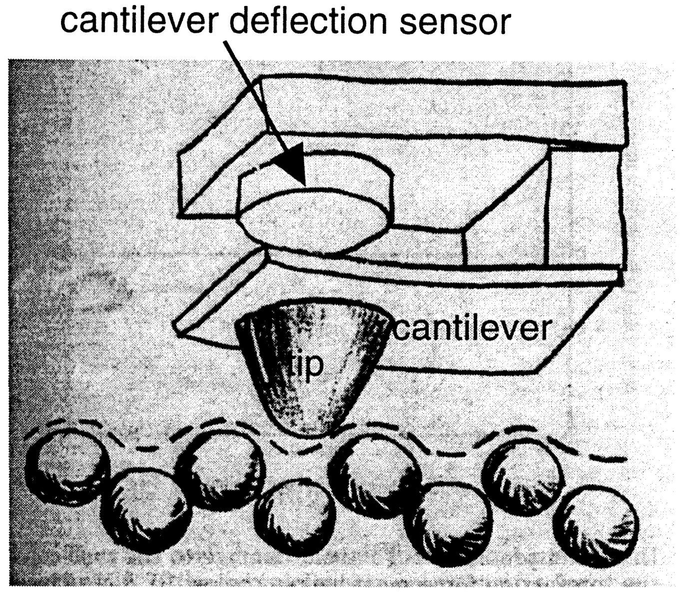


12 nm STM scan of self-assembled Silicotungstate anions ($SiW_{12}O_{40}$) on Ag(111)

Image courtesy of Dr. Larry Ge

Appendix : A very brief history of early SPM II

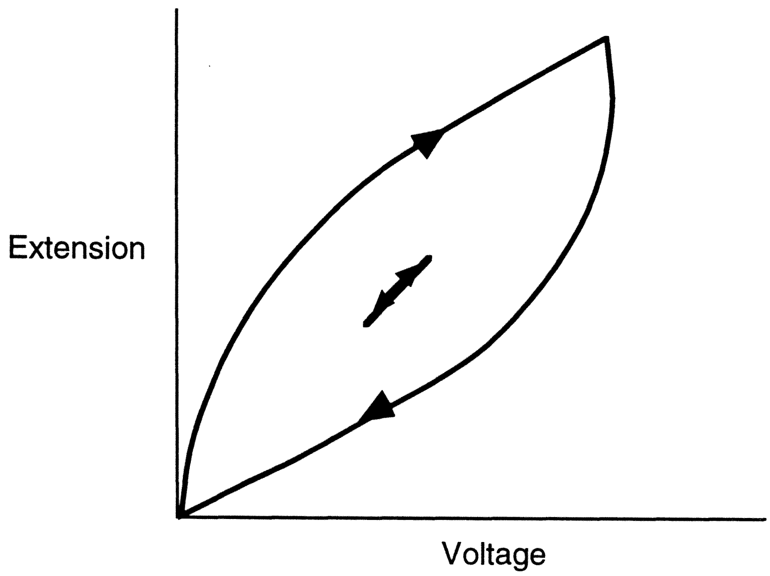
AFM Atomic force microscopy followed STM (Binnig, Quate, and Gerber, 1986). AFM uses a mechanically sharp tip mounted on a weak cantilever spring which is scanned over a surface. Interactions between the tip and surface cause the cantilever to deflect, and this is detected with a sensor. Typically, the sensor output is used in a feedback loop which continually adjusts the vertical position of the tip (*via* a three-axis scanner) so as to keep the cantilever deflection constant.



AFM extended ultra-high resolution imaging to nonconductiong samples, and today is used far more than STM. It is possible to make extremely sharp tips, and cantilever springs weaker than interatomic bonds. Atomic resolution has been demonstrated, but is not straightforward. While atomic-scale surface science continues with STM and AFM, the bulk of today's SPM applications concern length scales in the range 10 nm-100 μm. SPM's basic concepts are very simple, but a significant amount of engineering underlies todays instruments.

Appendix: More About Scanners

PZT allows relatively large scan ranges. At larger scan sizes, however, their extension *vs.* voltage is nonlinear and hysteretic; at sufficiently small displacements, motion remains linear.



Various approaches attempt to correct for this behavior and give an accurate scan

"open loop"

Appropriate nonlinear waveforms are applied to give a linear, calibrated raster scan in *x* and *y*. Waveform coeffcients are determined by scanning a grid of known spacing.

"closed loop"

Separate sensors (eg., interferometers, strain gauges) detect scanner positions, and feedback dictates the appropriate applied voltage.

For vertical (*z*) motion: The relatively small range (~ 5 μm) required in *z* allows more linear piezo materials, which can be calibrated for a given height range. A closed-loop approach can also be used.

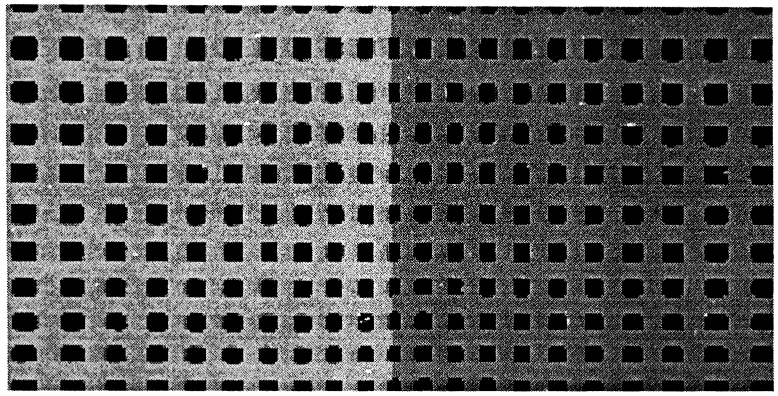
This discussion is far from complete, and other design issues also arise with scanners. Scanner and control loop design is a major part of SPM engineering. The bottom line is:

A well-designed scanner and control loop will give linear, calibrated scans over a wide scan range.

Appendix: Yet More About Scanners

check calib. ~every 6 mo.

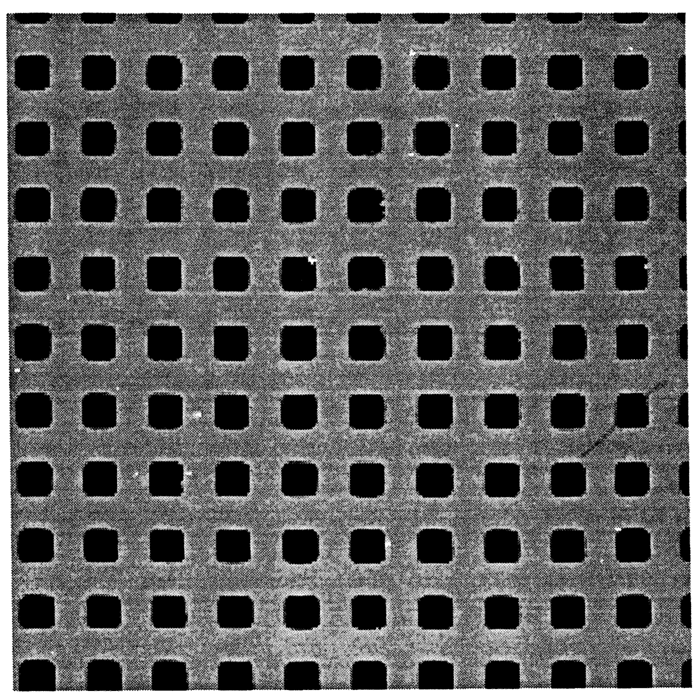
without proper linearity correction:



Trace → ← Retrace

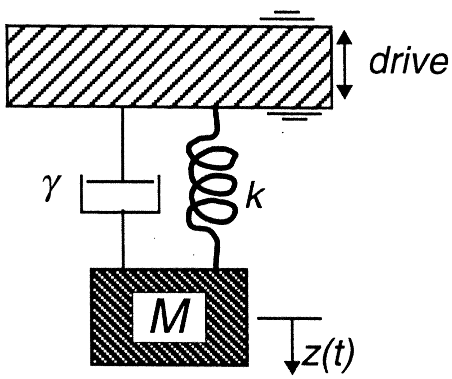
100 μm x 100 μm scans in the trace and retrace directions of a 10 μm pitch grating, showing nonlinearity and hysteresis. Note the apparent variations in spacing, size, and shape of the pits.

with proper correction:

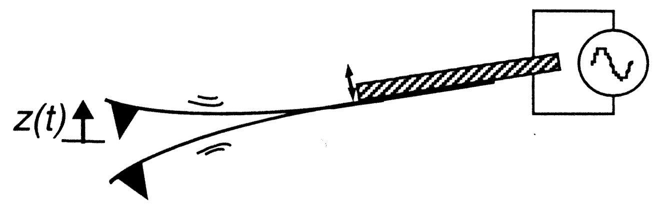


Same grating imaged with a corrected and calibrated scanner (open loop correction).

Appendix: Damped, Driven Oscillator Model of Cantilever Oscillation



"="



- good freq. control needed

with no magnetic forces, motion of tip *z(t)* governed by:

$$M\ddot{z} + \gamma\dot{z} + kz = D\cos(\omega t) \qquad \ddot{z} + \frac{\omega_0}{Q}\dot{z} + \omega_0^2 z = \frac{D}{M}\cos(\omega t)$$

M = effective cantilever mass
γ models damping (mostly air damping)
k = cantilever spring constant
D represents drive due to piezo oscillation
Q = "quality factor"

$$\omega_0 = \sqrt{\frac{k}{M}}$$ = resonant frequency

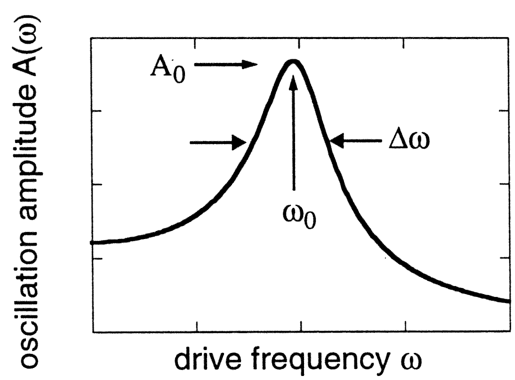
substitute harmonic solution
(ignore transients)

$$z(t) = A\cos(\omega t - \phi)$$

$$A(\omega) = \frac{A_0(\omega_0/\omega)}{\sqrt{1 + Q^2(\omega/\omega_0 - \omega_0/\omega)^2}}$$

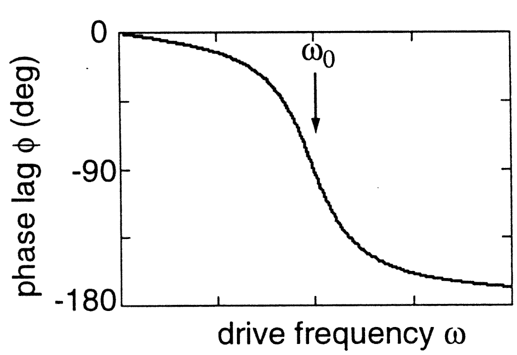
$$A_0 = \frac{QD}{M}$$

- amplitude a maximum at $\omega \approx \omega_0$
- Q=(total energy)/(energy lost/cycle) $=\omega_0/\Delta\omega$
  - ~ 200 in air
  - ~ 10,000 in vacuum

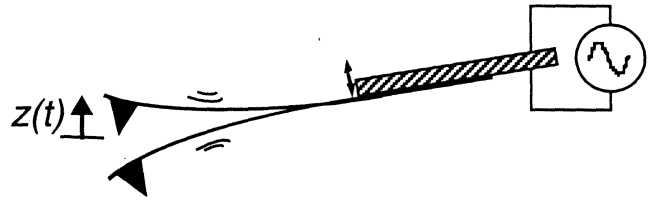


$$\phi(\omega) = \tan^{-1}\left(\frac{\omega\omega_0/Q}{\omega_0^2 - \omega^2}\right)$$

- no phase lag at low ω, 90 deg (1/4 of an oscillation) at $\omega=\omega_0$.
- slope increases with Q



Appendix: Force Gradient Detection Math



In MFM, the cantilever motion obeys:

$$M\ddot{z} + \gamma\dot{z} + k\,z = F$$

where F represents magnetic forces. Linearly expanding F around the cantilever's equilibrium position:

$$F(z) = F(z=0) + \frac{\partial F}{\partial z}(z) + \ldots$$

gives

$$M\ddot{z} + \gamma\dot{z} + (k - \frac{\partial F}{\partial z})z = D\cos(\omega t)$$

where we have dropped $F(0)$ since it causes only a static deflection, and added a periodic drive. The effective spring constant is clearly

$$k_{eff} = k - \frac{\partial F}{\partial z}$$

so the resonant freqeuncy in the presence of F is

$$\omega_0 = \sqrt{\frac{k - \frac{\partial F}{\partial z}}{M}} = \sqrt{\frac{k}{M}}\sqrt{1 - \frac{1}{k}\frac{\partial F}{\partial z}} \approx \sqrt{\frac{k}{M}}\left(1 + \frac{1}{2k}\frac{\partial F}{\partial z}\right)$$

and the shift from the case of no forces $\left(\omega_0 = \sqrt{\frac{k}{M}}\right)$

is

$$\boxed{\Delta\omega_0 = -\sqrt{\frac{k}{M}}\frac{1}{2k}\frac{\partial F}{\partial z} = -\frac{\omega_0}{2k}\frac{\partial F}{\partial z}}$$