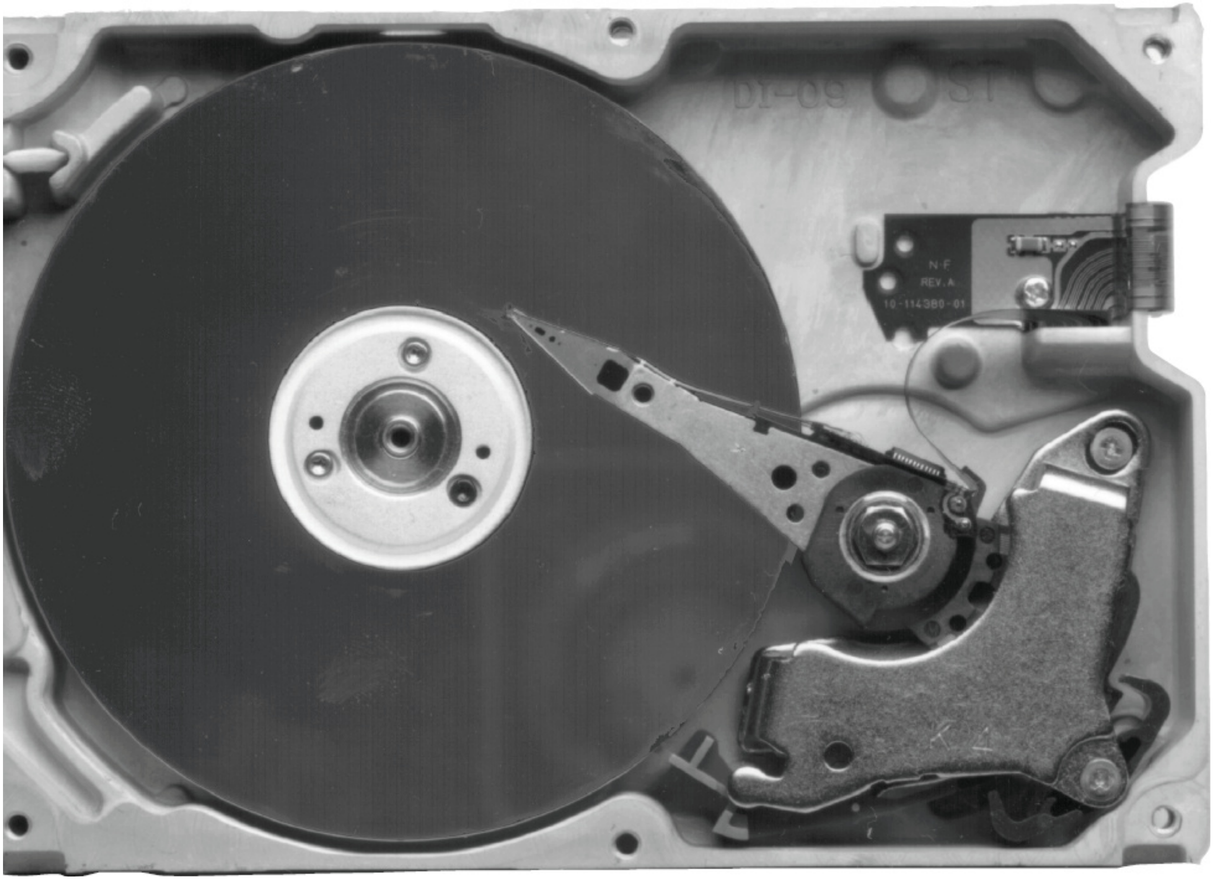
Magnetic Force Microscopy

MFM Imaging and Analysis of Magnetic Hard Disk

Goals / Tasks:

- Imaging of magnetic bit structure of a hard disk,
- Determination of the storage density and capacity,
- Magnetic contrast as a function of distance in MFM lift mode.

Provided samples: Hard disk drive



Additional Information (downloads)

- Information on HDD
- Information on MFM Cantilever
- SPM Training Notebook
- Unser Manual for Gwyddion Image Processing Software (freeware)

Please watch **SPM training video from DVD** before the experiments. This can be obtained and handed out from the instructor

Experimental Tasks:

1. Set-up AFM instrument:

- set AFM to MFM mode
- mount MFM tip
- magnetize the MFM tip,
- tune cantilever frequency
- set-up lift mode to desired lift height

2. Disassemble the HDD.

- Take photographs of the HDD for documentation.
- **Mount the HD** in the AFM stage.
- Set xy stage coordinates to zero at disk center.

3. Record AFM+MFM images at three different positions of HD

(inner, middle and outer edge of data region).

- Image size in the range of 10-50 µm
- the horizontal image axis should be aligned parallel to the data tracks.
- determine the inner and outer radii of written data regions to be able to calculate the effective storage area of HD.

4. Storage density.

- Determine the local bit size and track distance of the three regions.
- Measure, plot and compare the MFM profiles measured from the images.
- Calculate the average bit density and total storage capacity of HD from the smallest bit size in the images

5. Magnetic contrast versus lift height.

- Select a certain region of HD with high density of bit patterns, if possible a regular pattern
- Record a sequence of MFM images with 1:8 aspect ratio of the same surface region at increasing lift heights starting from z =10 nm until the magnetic contrast totally disappears.
- Note: It is advisable to increase the increments in z with increasing distance.

Contrast Analysis:

- Plot and compare the MFM images at different lift height. Explain what is seen. What is the maximum lift height at which individual bits can still be resolved?
- Extract profiles of the same surface region at different lift height z and plot them o n top of each other to see how the profiles change.
- Determine amplitude ΔC of MFM contrast as a function of z.
  Plot the contrast as a function of z on a linear scale and on a log-log scale.
  How does the contrast decrease as a function of z ?

Written Report (Protokoll):

1. Task description (Aufgabenstellung)

2. Basic principle of NC AFM and MFM and instrumentation.

3. (a) Experimental parameters
Cantilever specifications (parameters) and its video microscope picture, screenshot of resonance spectrum, list resonance frequency and FWHM of resonance curve, imaging conditions.

(b) Sample description and specifications

Written Report - Results

4. Characterization of Hard Disk

4.1 Presentation and *description* (text!) of MFM and AFM images.
Compare AFM and MFM image.
Discuss difference between MFM of different regions and explain origin.

4.2 Present, describe and compare the **MFM profiles** of the different regions.

Show how bit size and bit density is determined.
Table of results for three regions: bit width, length, local bit density + error estimate
Plot bit width and local bit density versus radius.
Calculate the average bit density and from the effective area the total storage capacity and compare it to the nominal value.

5. Magnetic contrast versus distance (lift height)

Compile figure with MFM images recorded at different lift height and compare them with each other. What is the maxima lift height at which individual bits can still be resolved ?
Plot MFM profiles for different lift heights on top of each other. Describe how they change.
Plot amplitude and RMS value of profiles versus lift height on a linear and log-log scale.
Discuss how it changes (trends, scaling behavior- exponential, power law, etc…. as a function of lift height.

⇨ **Important aspect for data presentation:**
For all figures, the ***figure captions*** should include ***all*** essential information about what is displayed. Example: "MFM images of xxx HD recorded at a lift height of ●z = … using an xxx coated MFM cantilever (type …..)". Image size: … ."
"Contrast amplitude ●C plotted versus …. extracted from the profiles shown in Fig. … , for a xxx HD with bit size of xxx µm … "

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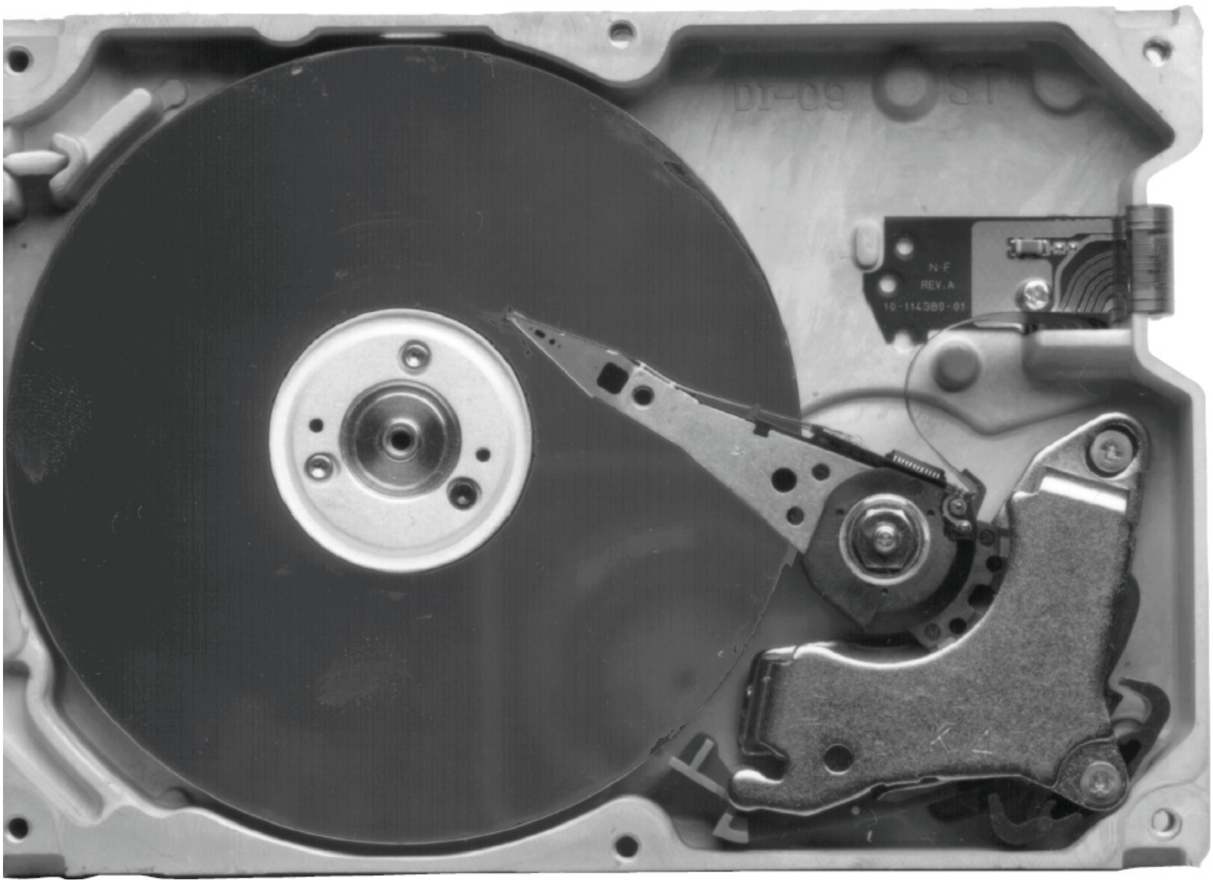

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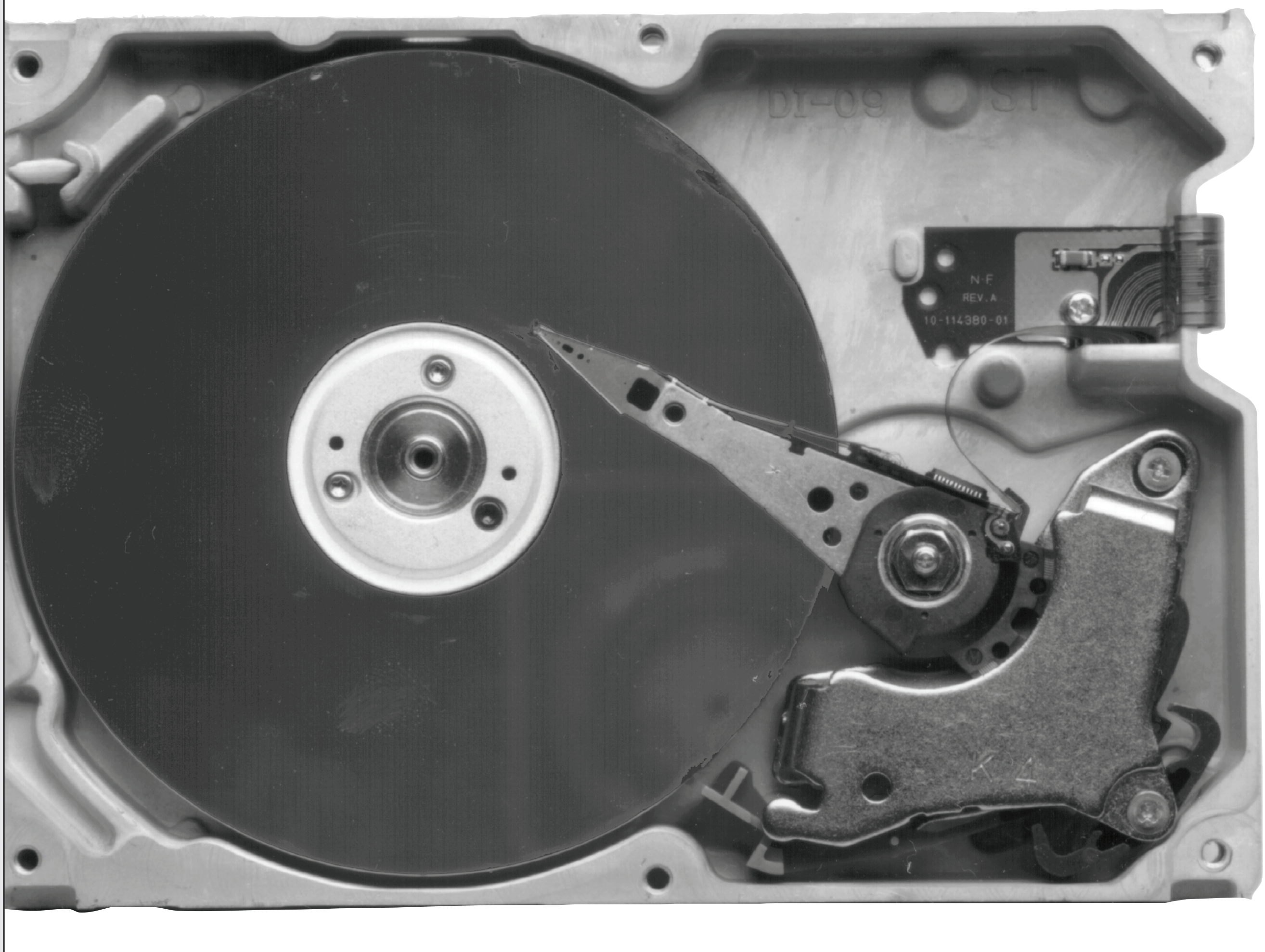
”Contrast amplitude □C plotted versus …. extracted from the profiles shown in Fig. … , for a xxx HD with bit size of xxx µm … “

CHAPTER 10

Hard Disk Storage



Definition of a Hard Disk

To many users, the hard disk drive is the most important and yet the most mysterious part of a computer system. A *hard disk drive* is a sealed unit that a PC uses for nonvolatile data storage. *Nonvolatile*, or semi-permanent, storage means that the storage device retains the data even when no power is supplied to the computer. Because the hard disk drive is expected to retain data until deliberately erased or overwritten, the hard drive is used to store crucial programming and data. As a result, when the hard disk fails, the consequences are usually very serious. To maintain, service, and upgrade a PC system properly, you must understand how the hard disk functions.

A hard disk drive contains rigid, disk-shaped platters, usually constructed of aluminum or glass (see Figure 10.1). Unlike floppy disks, the platters cannot bend or flex—hence the term *hard disk*. In most hard disk drives, you cannot remove the platters, which is why they are sometimes called *fixed* disk drives. Removable hard disk drives are also available. Sometimes this term refers to a device in which the entire drive unit (that is, the disk and the drive) is removable, but it is more commonly used to refer to cartridge drives, where the platters are contained in a removable cartridge.

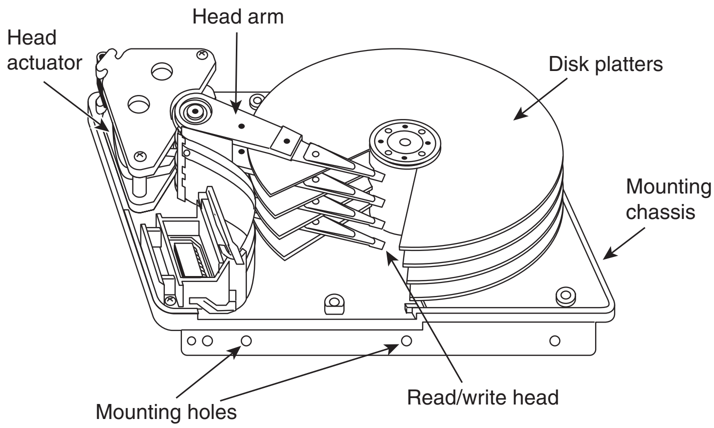


Figure 10.1 Hard disk heads and platters.

Note

Hard disk drives are sometimes referred to as *Winchester drives*. This term dates back to 1973, when IBM introduced the model 3340 drive, which had 30MB of fixed platter and 30MB of removable platter storage on separate spindles. The drive was codenamed Winchester by project leader Ken Haughton, because the original capacity designation (30-30) sounded like the popular .30-30 (caliber-grains of charge) cartridge used by the Winchester 94 rifle introduced in 1895. The original 3340 "Winchester" drive was the first to use a sealed head/disk assembly, and the name has since been applied to all subsequent drives with similar technology.

Hard Drive Advancements

In the almost 20 years that hard disks have commonly been used in PC systems, they have undergone tremendous changes. To give you an idea of how far hard drives have come in that time, I've outlined some of the more profound changes in PC hard disk storage:

- Maximum storage capacities have increased from the 5MB and 10MB 5 1/4-inch full-height drives available in 1982 to 180GB or more for even smaller 3 1/2-inch half-height drives (Seagate Barracuda 180), and 32GB or more for notebook system 2 1/2-inch drives (IBM

Travelstar 32GH) that are 12.5mm (or less) in height. Hard drives smaller than 10GB are rare in today's desktop personal computers.

- Data transfer rates from the media (sustained transfer rates) have increased from 85KB to 102KB/sec for the original IBM XT in 1983 to an average of 51.15MB/sec or more for the fastest drives today (Seagate Cheetah 73LP).
- Average seek times (how long it takes to move the heads to a particular cylinder) have decreased from more than 85ms (milliseconds) for the 10MB XT hard disk in 1983 to 4.2ms or less for some of the fastest drives today (Seagate Cheetah X15).
- In 1982, a 10MB drive cost more than $1,500 ($150 per megabyte). Today, the cost of hard drives has dropped to one-half cent per megabyte or less!

Hard Disk Drive Operation

The basic physical construction of a hard disk drive consists of spinning disks with heads that move over the disks and store data in tracks and sectors. The heads read and write data in concentric rings called *tracks*, which are divided into segments called *sectors*, which normally store 512 bytes each (see Figure 10.2).

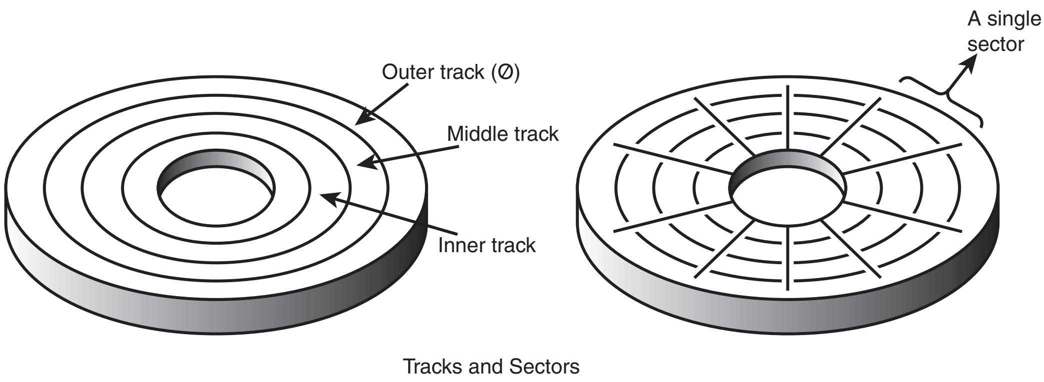


Figure 10.2 The tracks and sectors on a disk.

Hard disk drives usually have multiple disks, called *platters*, that are stacked on top of each other and spin in unison, each with two sides on which the drive stores data. Most drives have two or three platters, resulting in four or six sides, but some PC hard disks have up to 12 platters and 24 sides with 24 heads to read them (Seagate Barracuda 180). The identically aligned tracks on each side of every platter together make up a cylinder (see Figure 10.3). A hard disk drive normally has one head per platter side, with all the heads mounted on a common carrier device or rack. The heads move radially across the disk in unison; they cannot move independently because they are mounted on the same carrier or rack, called an *actuator*.

Originally, most hard disks spun at 3,600rpm—approximately 10 times faster than a floppy disk drive. For many years, 3,600rpm was pretty much a constant among hard drives. Now, however, most drives spin the disks even faster. While speeds can vary, most modern drives spin the platters at 4,200; 5,400; 7,200; 10,000; or 15,000rpm. High rotational speeds combined with a fast head-positioning mechanism and more sectors per track are what make one hard disk faster than another.

The heads in most hard disk drives do not (and should not!) touch the platters during normal operation. When the heads are powered off, however, in most drives they land on the platters as they stop spinning. While the drive is running, a very thin cushion of air keeps each head suspended a short distance above or below the platter. If the air cushion is disturbed by a particle of dust or a shock, the head can come into contact with the platter while it is spinning at full speed. When contact with the spinning platters is forceful enough to do damage, the event is called a *head crash*. The result of a head crash can be anything from a few lost bytes of data to a completely ruined drive. Most drives have special lubricants on the platters and hardened surfaces that can withstand the daily "takeoffs and landings" as well as more severe abuse.

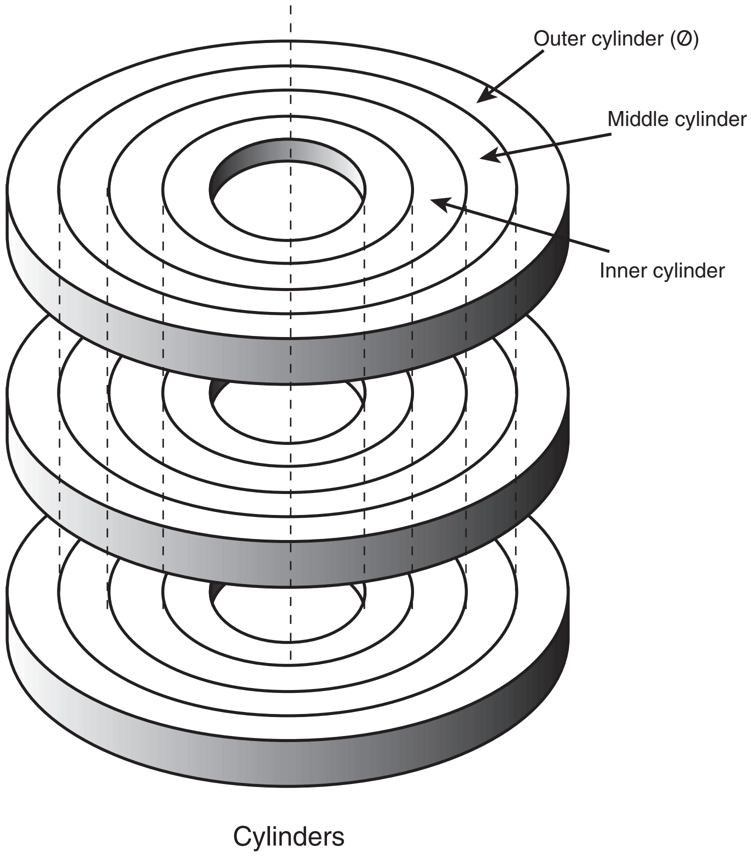
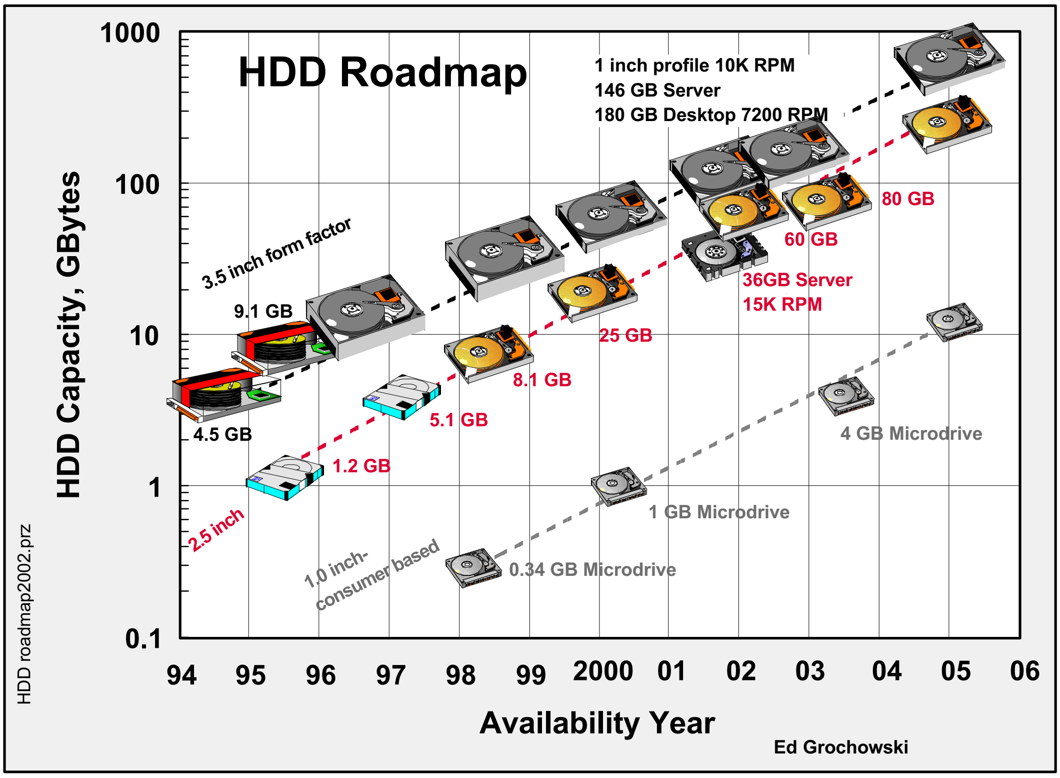


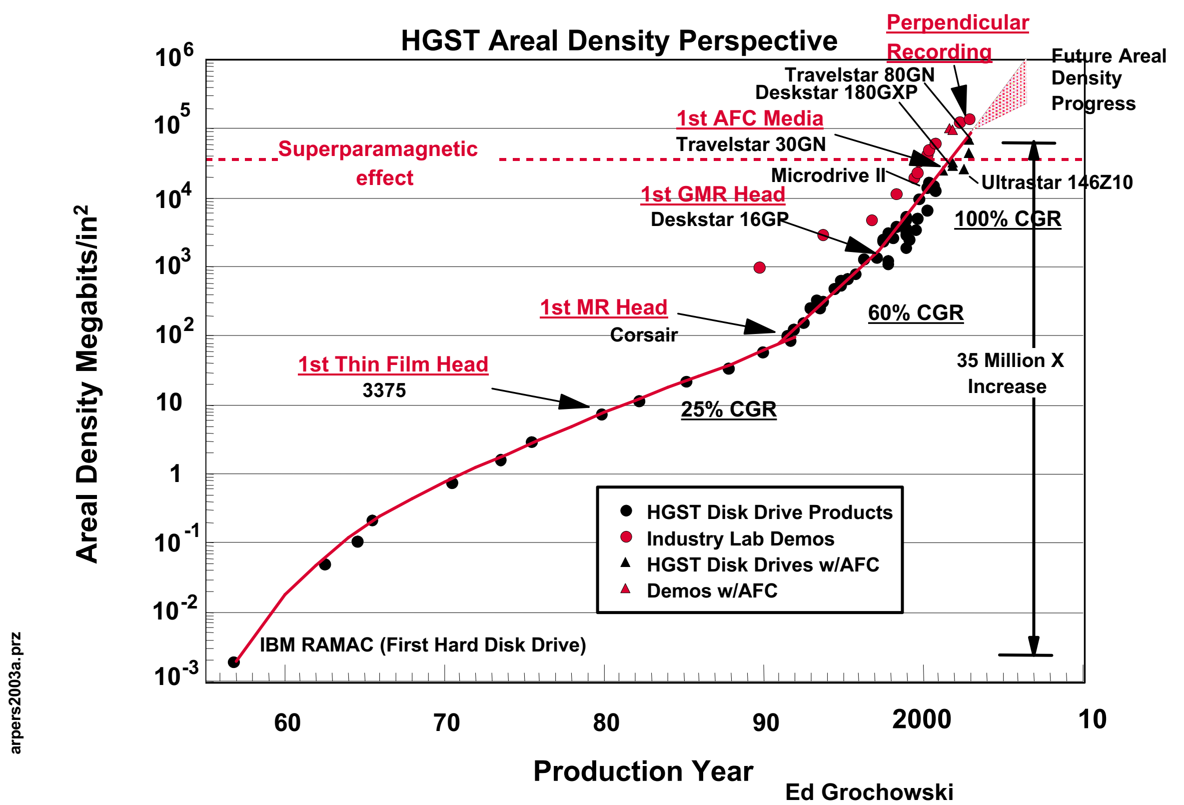
Figure 10.3 Hard disk cylinders.

Because the platter assemblies are sealed and nonremovable, the track densities on the disk can be very high. Hard drives today have up to 38,000 or more TPI (tracks per inch) recorded on the media (IBM Travelstar 30GT). Head Disk Assemblies (HDAs), which contain the platters, are assembled and sealed in clean rooms under absolutely sanitary conditions. Because few companies repair HDAs, repair or replacement of the parts inside a sealed HDA can be expensive. Every hard disk ever made eventually fails. The only questions are when the failure will occur and whether your data is backed up.

Caution

It is strongly recommended that you do not even attempt to open a hard disk drive's HDA unless you have the equipment and the expertise to make repairs inside. Most manufacturers deliberately make the HDA difficult to open, to discourage the intrepid do-it-yourselfer. Opening the HDA almost certainly voids the drive's warranty.


HDD Roadmap
1000
100
10
1
0.1
HDD Capacity, GBytes
1 inch profile 10K RPM
146 GB Server
180 GB Desktop 7200 RPM
3.5 inch form factor
9.1 GB
4.5 GB
80 GB
60 GB
36GB Server
15K RPM
25 GB
8.1 GB
5.1 GB
1.2 GB
2.5 inch
4 GB Microdrive
1 GB Microdrive
1.0 inch-
consumer based
0.34 GB Microdrive
94
95
96
97
98
99
2000
01
02
03
04
05
06
Availability Year
Ed Grochowski
HDD roadmap2002.prz


HGST Areal Density Perspective
Areal Density Megabits/in2
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
Perpendicular
Recording
Future Areal
Density
Progress
Travelstar 80GN
Deskstar 180GXP
1st AFC Media
Travelstar 30GN
Superparamagnetic
effect
Microdrive II
Ultrastar 146Z10
1st GMR Head
Deskstar 16GP
100% CGR
1st MR Head
Corsair
60% CGR
1st Thin Film Head
3375
35 Million X
Increase
25% CGR
HGST Disk Drive Products
Industry Lab Demos
HGST Disk Drives w/AFC
Demos w/AFC
IBM RAMAC (First Hard Disk Drive)
60
70
80
90
2000
10
Production Year
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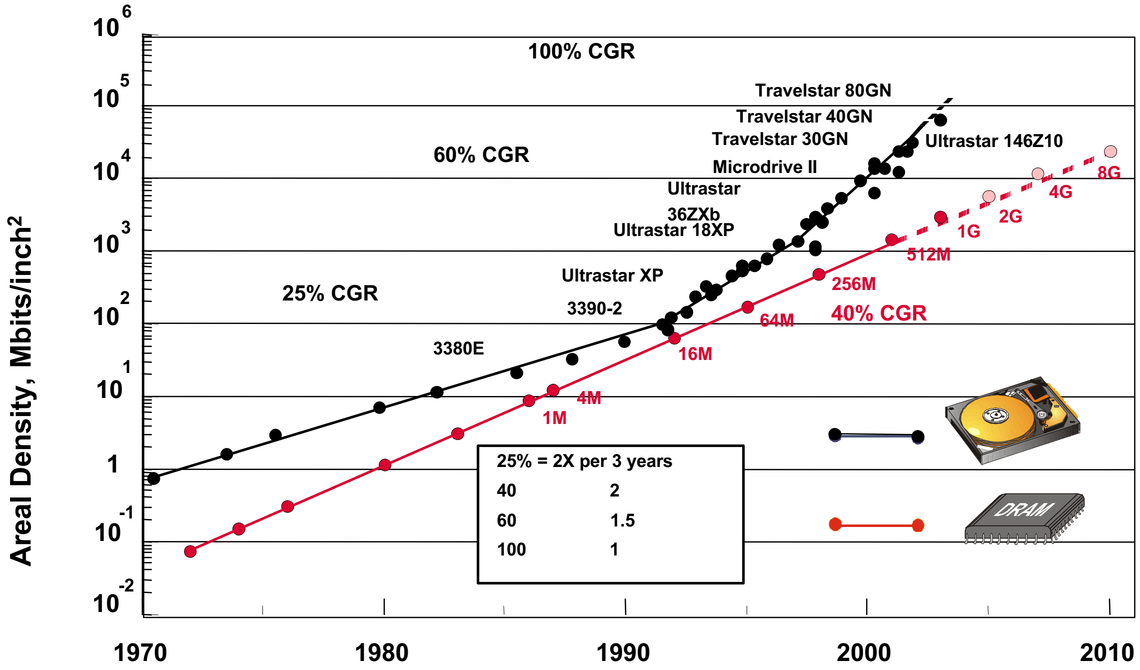
arpers2003a.prz

Areal Density of Magnetic HDD and DRAM



DRAM projections after 2001 are based on industry capacities and constant chip area

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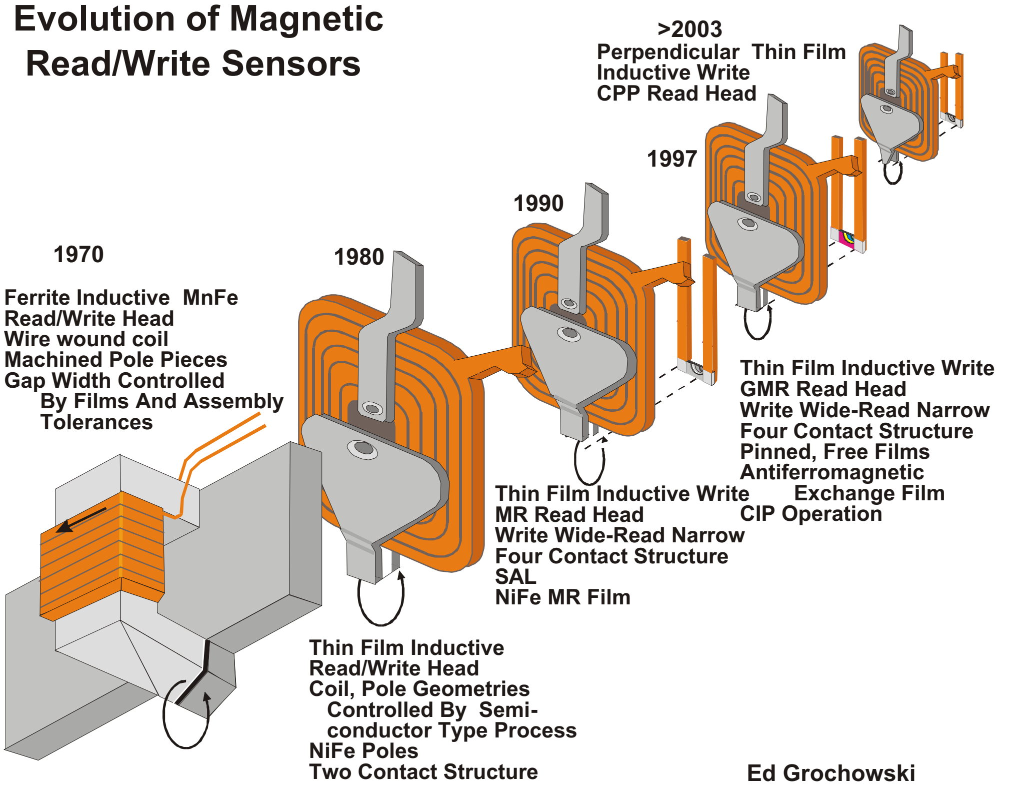
Evolution of Magnetic Read/Write Sensors



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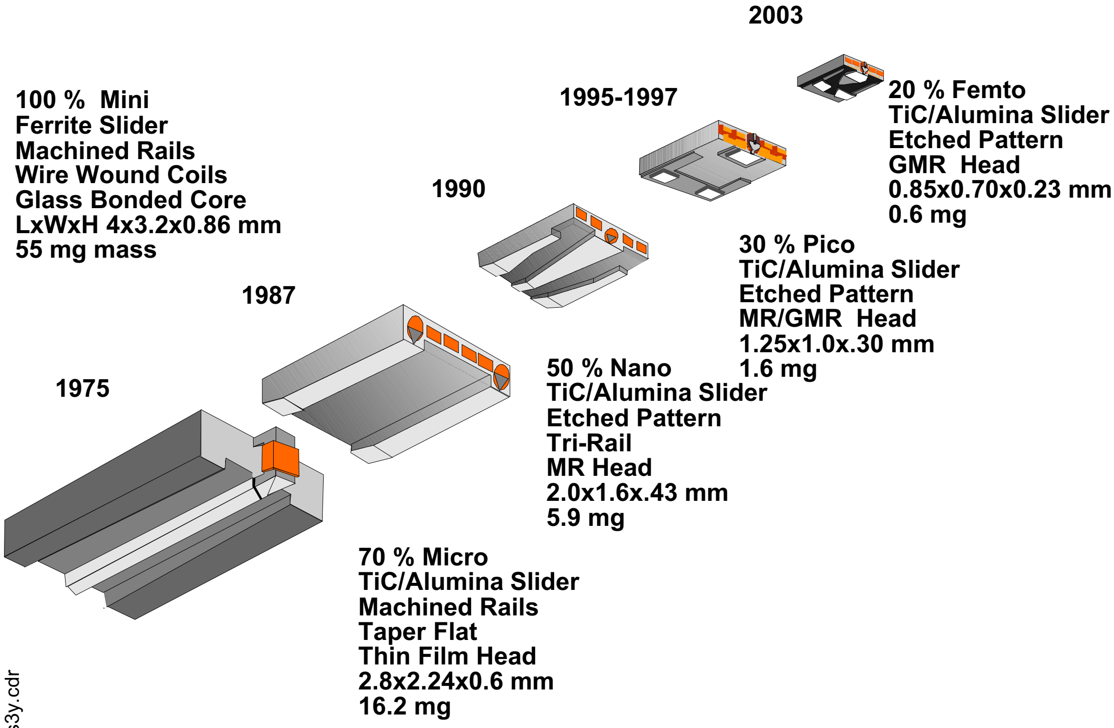
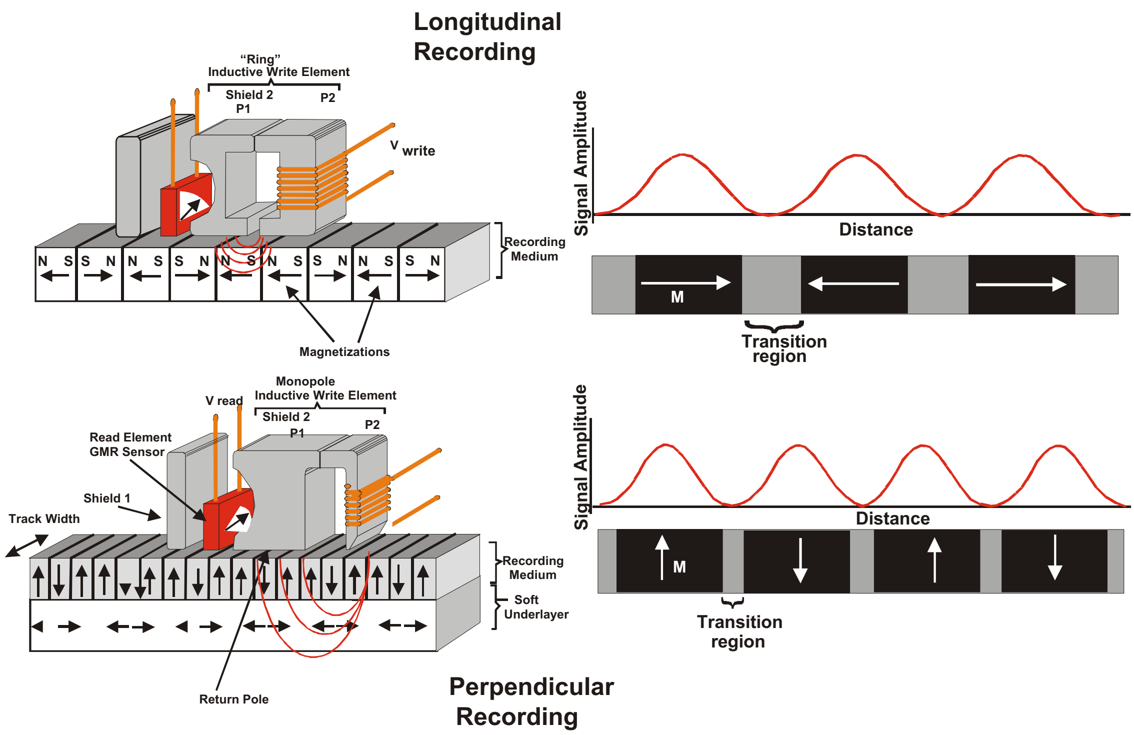
Evolution of Slider/Air Bearing Surface



Abs3y.cdr



Recording Technologies

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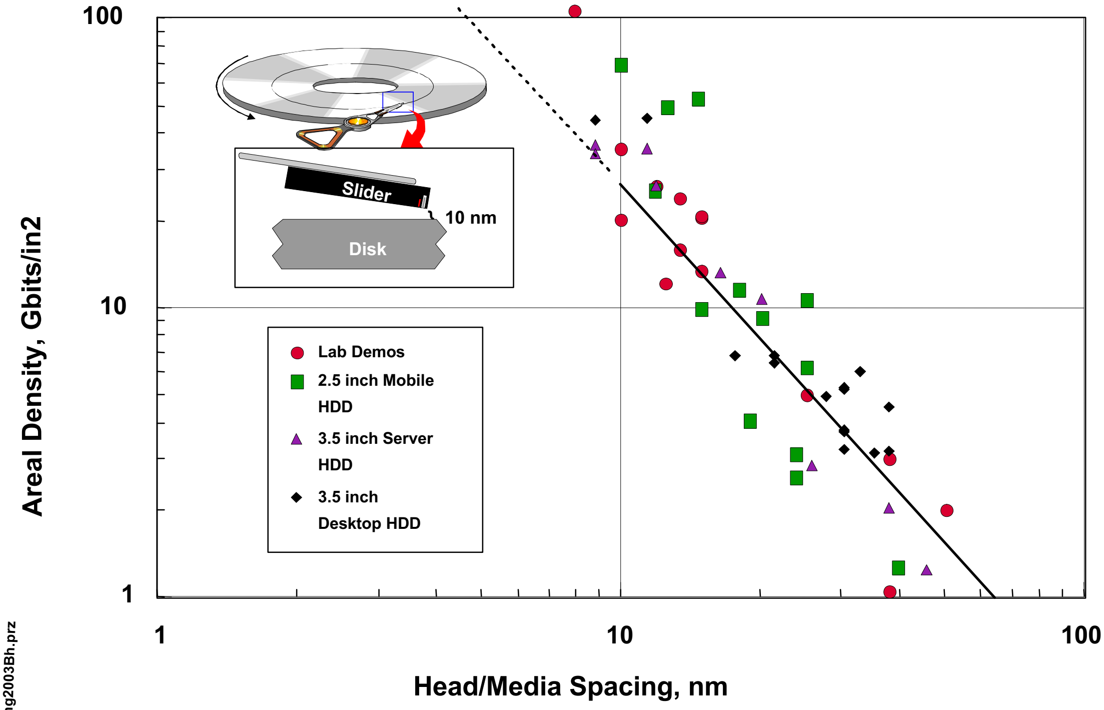
Spacing-Areal Density Perspective



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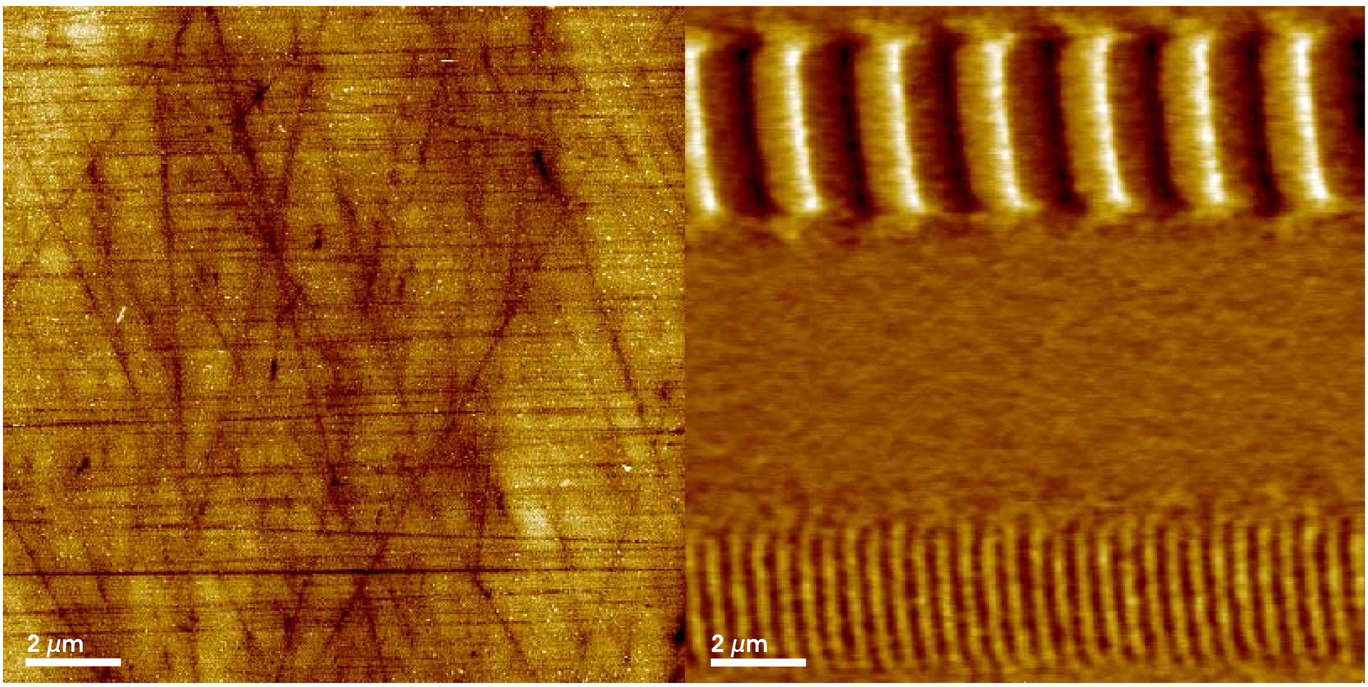
Magnetic Force Microscopy

Silicon-MFM-Probes

For visualisation of magnetic domains by Scanning Probe Microscopy different Magnetic Force Microscopy probes are offered. They are designed to match the demands of a wide range of applications defined by the variety of magnetic samples with different properties. All the different magnetic coatings of the probes have proven an excellent long-term stability.



Topography (left) and magnetic frequency shift image (right) of an experimental hard disk (courtesy of IBM) measured with a PPP-MFMR probe (z-range topography: 72nm, magnetic image scale: 22.5Hz).

In general, the measurement performance of Magnetic Force Microscopy is a compromise between sensitivity, resolution and sample disturbance. High sensitivity to magnetic signal requires a strong magnetic moment of the tip. However, this high magnetic moment may disturb the domain structure of the sample itself and usually the lateral resolution drops with increasing magnetic moment of the tip. For improvement of the lateral resolution sharp High Aspect Ratio tips and thin magnetic coatings are required. Because of the low magnetic moment of such thin magnetic films the sensitivity is decreased. An optimum trade-off between lateral resolution and sensitivity is necessary.

The magnetic domains of low coercivity samples are predominately "wiped out" by hard magnetically coated tips. This kind of sample can only be visualised by low coercivity probes which, on the other hand, may change their magnetization under the influence of a magnetic sample with higher coercivity. Therefore, in order to achieve optimum results, the MFM probe has to be chosen carefully and in accordance with the particular sample under investigation.

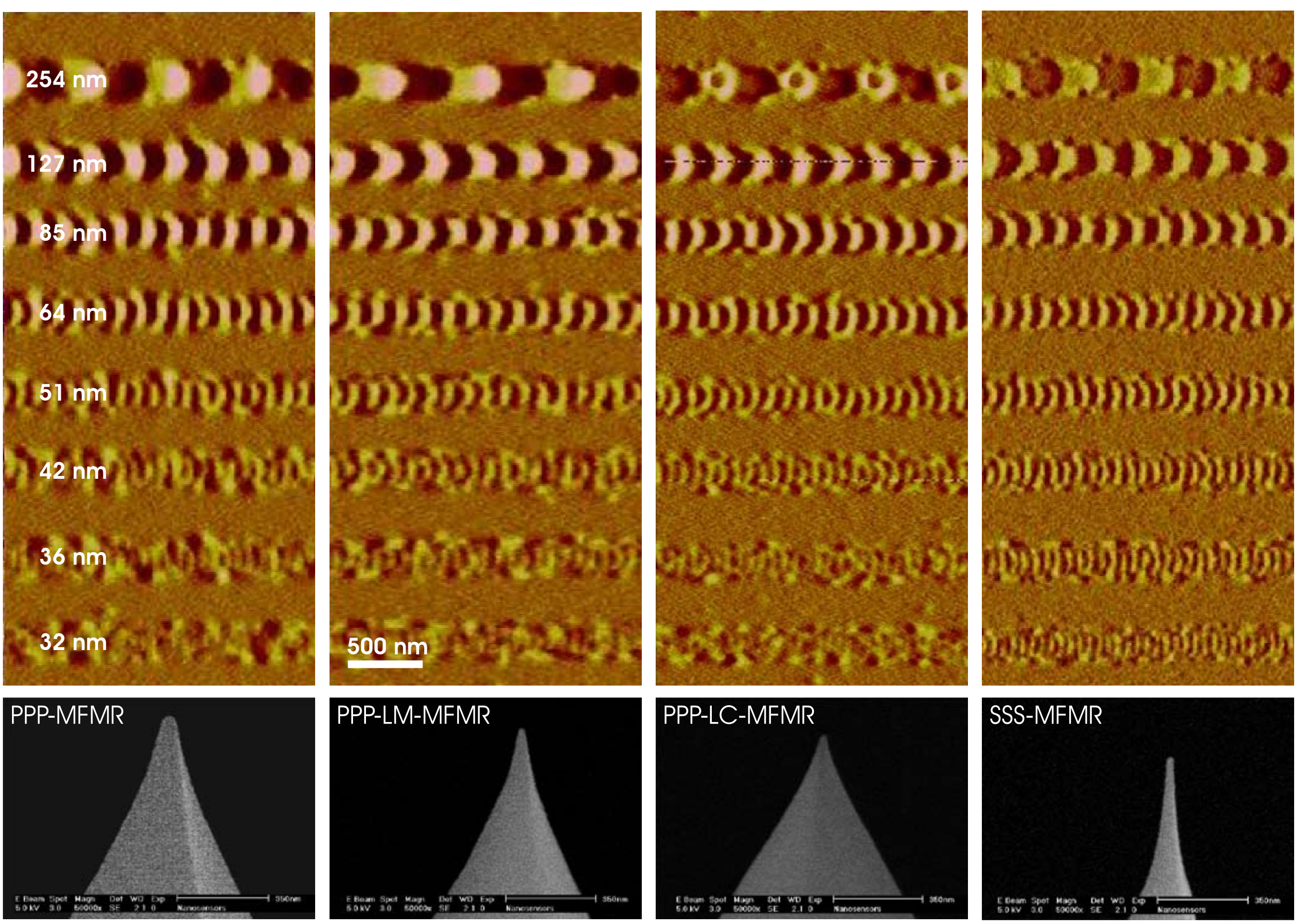
General Features

The NANOSENSORS™ Magnetic Force Microscopy probes are based on a well-established cantilever type that is specially tailored for the Magnetic Force Microscopy yielding high force sensitivity while simultaneously enabling Tapping Mode, Non-Contact and Lift Mode operation in air. In particular, the stiffness of the cantilever is a trade-off between preventing the tip snapping to the surface during Tapping Mode or Non-Contact Mode operation and sensitivity to magnetic forces during Lift Mode operation.

Technical Data (Cantilever)	Nominal Value
Thickness [µm]	3
Width [µm]	28
Length [µm]	225
Force Constant [N/m]	2.8
Resonance Frequency [kHz]	75

The detector side of the cantilever is covered with a reflex coating to enhance signal of the optical read-out and, thus, reducing the noise of the optical detection system. The reflex coating is an approximately 30 nm thick aluminum coating on the detector side of the cantilever which enhances the reflectivity of the laser beam by a factor of about 2.5.

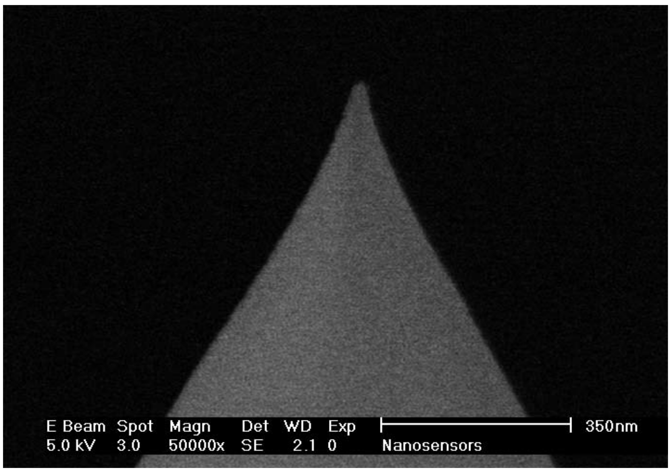
Comparison of Lateral Resolution



Magnetic images (phase shift) of an experimental hard disk with varied bit length (courtesy of Maxtor).

PointProbe® Plus Low Coercivity Magnetic Force Microscopy Probe (PPP-LC-MFMR)

The PPP-LC-MFMR probe is coated with a soft magnetic thin film enabling the measurement of magnetic domains within soft magnetic samples. Due to the low coercivity of the tip coating the magnetization of the tip will easily get reoriented by hard magnetic samples.
The soft magnetic coating on the tip has a coercivity of app. 0.75 Oe and a remanence magnetization of app. 225 emu/cm^3 (these values were determined on a flat surface).



SEM image of a PPP-LC-MFMR tip (close-up).

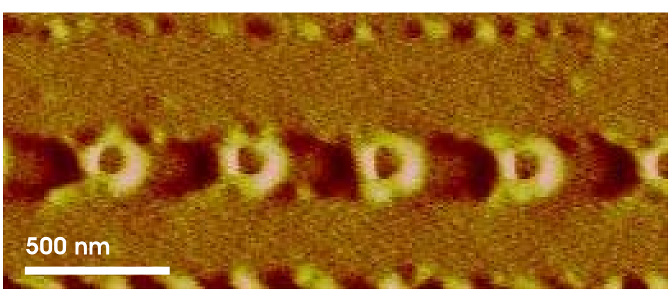
Probe Features at a Glance

- Coercivity of app. 0.75 Oe
- Remanence magnetization of app. 225 emu/cm^3
- Effective magnetic moment 0.75x of standard PPP-MFMR probes
- Guaranteed tip radius of curvature < 30 nm
- Magnetic resolution better than 35 nm
- Reflex coating on detector side of cantilever

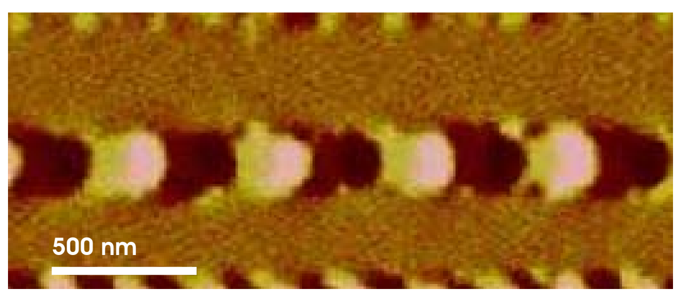
Application Example

Magnetic bits of a hard disk

The magnetization of the tip is easily reversed by the stray field of magnetic bits written into a hard disk. As a consequence attractive magnetic forces are detected at both halves of the bits. Although this effect makes the interpretation of results more difficult, it can be used to examine extremely hard magnetic samples. Instead of a random reorientation of the tip magnetization the magnetic moment of the LC-MFMR probes will always be directly opposed to the magnetization of the sample.



Magnetic image (frequency shift) of a hard disk with 254 nm long written bits (sample courtesy of Maxtor) acquired with a PPP-LC-MFMR probe.



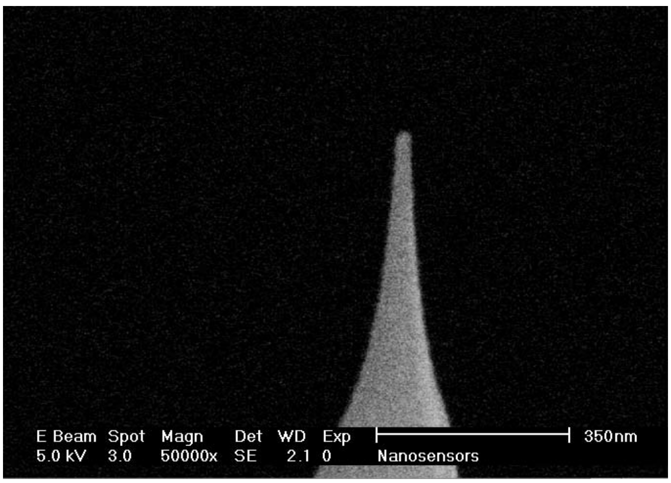
Comparison magnetic image (frequency shift) of the identical sample acquired with a standard PPP-MFMR probe.

SuperSharpSilicon™ High Resolution Magnetic Force Microscopy Probe (SSS-MFMR)

The SSS-MFMR probe is optimized for high resolution magnetic imaging. The SuperSharpSilicon™ tip basis combined with a very thin hard magnetic coating result in an extremely small radius of the coated tip and a high aspect ratio on the last few hundred nanometers of the tip apex – the essential requirements for high lateral resolution down to 20 nm in ambient conditions.

Due to the low magnetic moment of the tip the sensitivity to magnetic forces is decreased if compared to standard PPP-MFMR probes, but the disturbance of soft magnetic samples is also reduced.

The hard magnetic coating on the tip is characterized by a coercivity of app. 125 Oe and a remanence magnetization of app. 80 emu/cm³ (these values were determined on a flat surface).



SEM image of a SSS-MFMR tip (close-up).

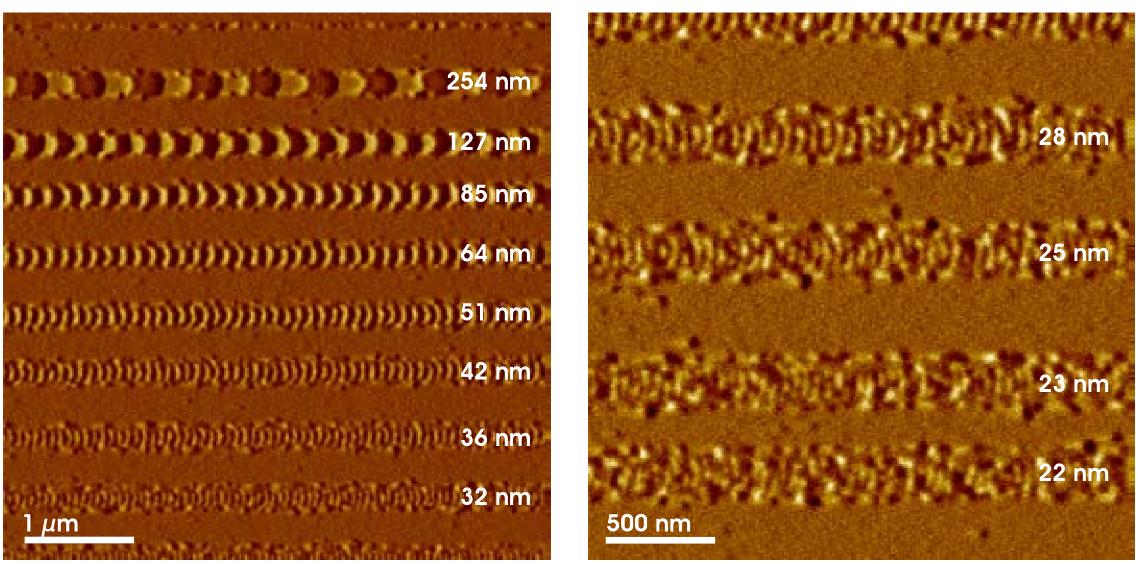
Probe Features at a Glance

- Coercivity of app. 125 Oe
- Remanence magnetization of app. 80 emu/cm³
- Effective magnetic moment 0.25x of standard PPP-MFMR probes
- Guaranteed tip radius of curvature < 15 nm
- Magnetic resolution better than 25 nm
- Reflex coating on detector side of cantilever

Application Example

High density hard disk

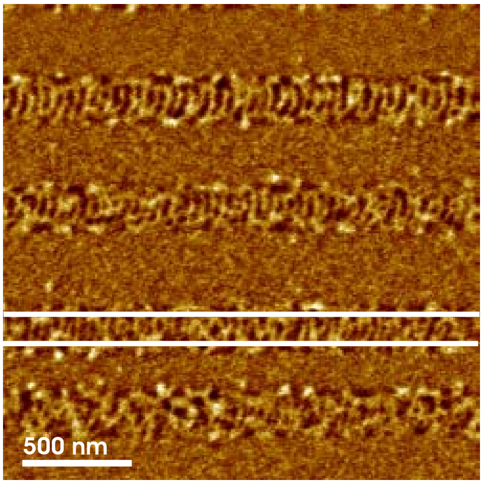
Magnetic bits on a hard disk can be characterized with the high resolution Magnetic Force Microscopy probe SSS-MFMR down to a bit length of 25 nm. This resolution capability is demonstrated by means of an experimental hard disk with varied bit length ranging from 254 nm to 22 nm.

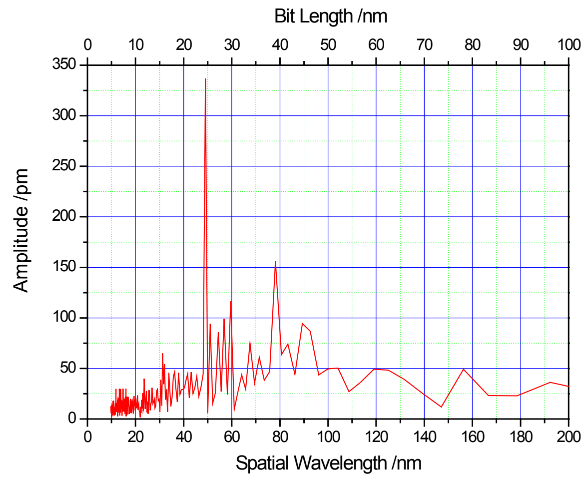


Magnetic images (phase shift) of an experimental hard disk with varied bit length (courtesy of Maxtor) measured with a SSS-MFMR probe.

Resolution Perfomance Demonstration (SSS-MFMR)

The spatial resolution of the magnetic image can be determined by fourier analysis of measured magnetic bits at the experimental hard disk sample. In case of resolved bits the spectrum contains a clear peak corresponding to the length scale of the magnetic bits. Due to the definition of bit length as distance between opposite magnetization directions (maximum flux change) the determined spatial wavelength is exactly twice the bit length.



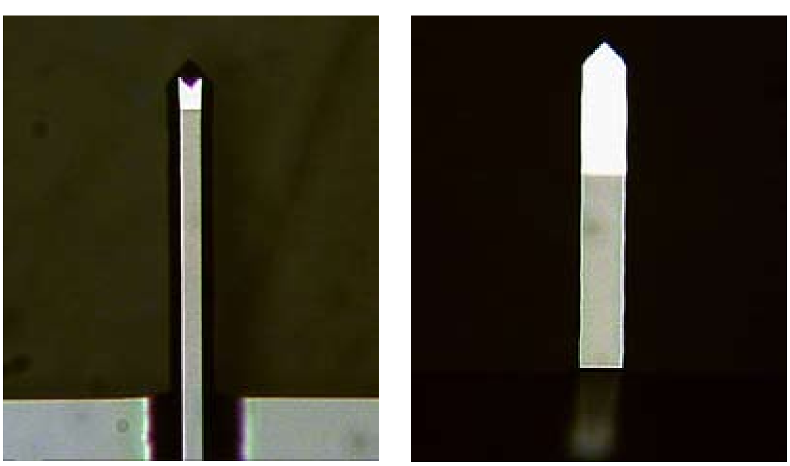


Fourier analysis of the 23 nm bit track (average profile between white lines of the left MFM image showing a significant peak at a spatial wavelength of 48 nm corrsponding to a bit length of 24 nm.

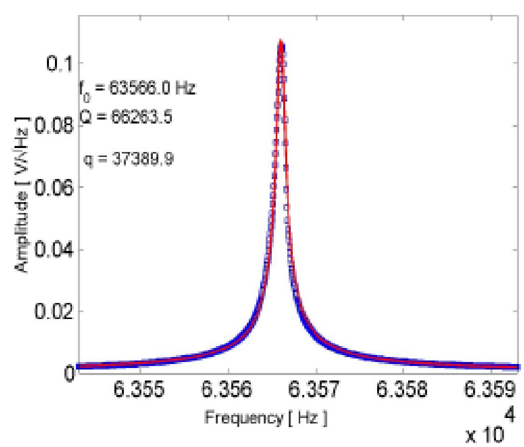
High Quality-Factor Magnetic Force Microscopy Probes (SSS-QMFMR and PPP-QLC-MFMR)

The high resolution MFM probes and the low coercitivity MFM probes are also available in a special version for applications under ultra high vacuum conditions. The SSS-QMFMR and PPP-QLC-MFMR probes are designed to achieve a Q-factor in UHV higher than 30,000.

The magnetic characteristics are identical to the properties of the SSS-MFMR and PPP-LC-MFMR probes, respectively. The typical Q-factor of over 35,000 under UHV conditions and the aluminum coating on the detector side secure excellent resolution and an enhanced signal to noise ratio.



Photographs of high quality factor MFM probes with partially coated cantilever (left: tip side, right: detector side).



Resonance curve of a typical high Q-factor MFM probe.

Probe Features

	PPP-MFMR (standard)	PPP-LM-MFMR (low momentum)	PPP-LC-MFMR (low coercivity)	SSS-MFMR (high resolution)
Force Constant (nominal)	2.8 N/m	2.8 N/m	2.8 N/m	2.8 N/m
Resonance Frequency (nominal)	75 kHz	75 kHz	75 kHz	75 kHz
Tipside Coating	Hard Magnetic	Hard Magnetic	Soft Magnetic	Hard Magnetic
Coercivity*1	300 Oe	250 Oe	0.75 Oe	125 Oe
Magnetization*1	300 emu/cm³	150 emu/cm³	225 emu/cm³	80 emu/cm³
Magnetic Tip Moment*2	≈ 10^{-13} emu	x0.5	x0.75	x0.25
Guaranteed Tip Radius*3	< 50 nm	< 30 nm	< 30 nm	< 15 nm
Achievable Lateral Resolution*4	< 50 nm	< 35 nm	< 35 nm	< 25 nm
Coating on Detector Side	Reflex	Reflex	Reflex	Reflex

High Quality Factor Version			PPP-QLC-MFMR (low coercivity)	SSS-QMFMR (high resolution)
UHV Quality Factor*5			> 30 000	> 30 000

*1 coating properties measured on planar substrates
*2 estimation based on assumed effective magnetic volume at tip apex
*3 radius of curvature including magnetic coating
*4 achievable resolution at optimized measurement conditions
*5 measured under UHV conditions

For more details please refer to the product datasheet on our website
www.nanosensors.com

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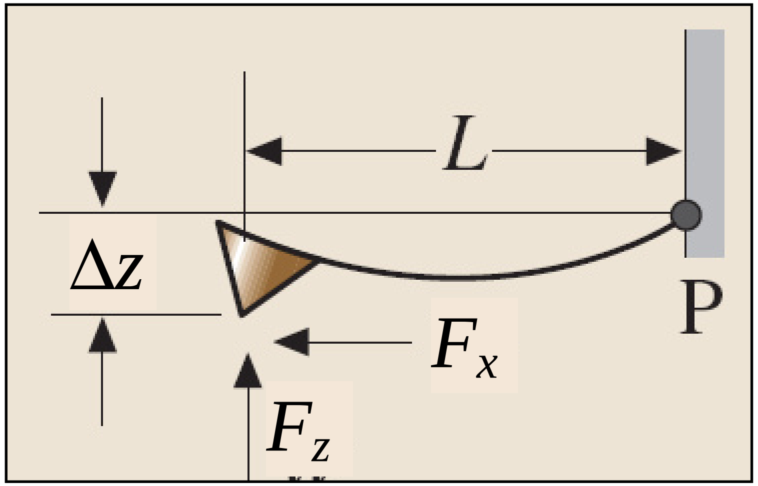
info@nanosensors.com

Force Sensors: Micromechanical Cantilevers

Generally, forces are measured using a ***spring sensor***, in which case the force F_z acting on a spring leads to a length change or deflection *dz* of the spring.



In AFM, not a spiral spring but a ***cantilever*** spring is used due to the simpler fabrication.

The relation between the force acting on the cantilever end and cantilever deflections is given by the **Hook's law:**

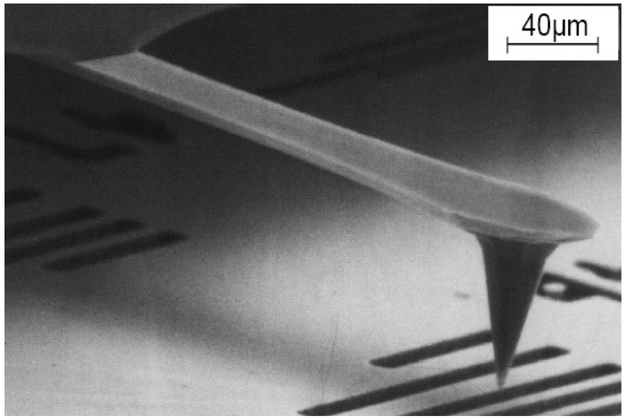
$\boxed{F_z = k_{c,z} \cdot \Delta z}$ with k_{cz} = cantilever force constant

⇨ Thus, the measurement of vertical cantilever deflection Δz yields magnitude of the vertical force acting between tip and sample surface.

Typical interatomic force constants are of the order of 10 N/m, depending on bonding type).

Typical cantilever force constants for contact mode AFM: k_{cz} = 0.01 – 10 N/m

Magnitude of deflection: For ΔF_z = 0.1 nN » Δz = 10 Å for k_{cz} = 0.1 N/m (in NC mode).



Basic considerations:

(a) *Small k*: Large deflection for small ΔF
» high sensitivity, important for soft samples.
But: High sensitivity to environmental noise.

(b) *Large k*: Smaller sensitivity but higher stability.
(also higher resonance frequencies).

Cantilever Design

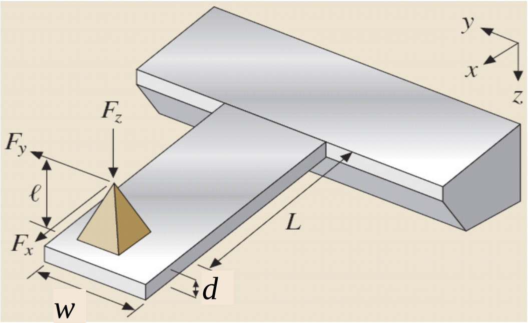
1. Spring constant in the range of 0.01 – 100 N/m:

The force constant k_{cz} of a cantilever is determined by its geometry, i.e., length L, thickness d and width w, as well as by the elastic constants (elastic modulus E) of the cantilever material.

For simple cantilever geometries with constant cantilever cross section, the force constant can be calculated analytically using elasticity theory .

Rectangular beam of width w, length L, and thickness d, elasticity module E and and a tip at a distance Δs from the end:

$$\boxed{k_{cz} = E \cdot \frac{w \cdot d^3}{4 \cdot (L - \Delta s)^3}}$$



⇨ By choice of the geometry the spring constant can be tuned arbitrarily over a wide range !

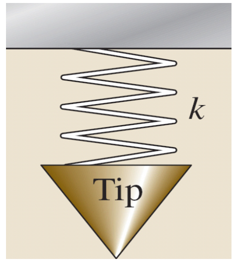
Common cantilever and tip materials:

Property	Young's Modulus (E) (GPa)	Density (ρg) (kg/m^3)	Microhardness (GPa)	Speed of sound ($\sqrt{E/\rho}$) (m/s)
Diamond	900–1,050	3,515	78.4–102	17,000
Si_3N_4	310	3,180	19.6	9,900
Si	130–188	2,330	9–10	8,200
W	350	19,310	3.2	4,250
Ir	530	–	∼ 3	5,300

2. Resonance Frequency ω_{res} of the Cantilever

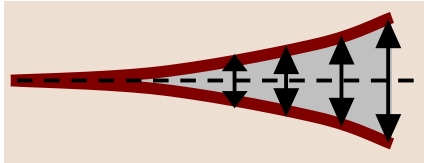
The fundamental resonance frequency a simple spring-type ***harmonic oscillator*** (mass load attached to a spring) is given by:

$$\omega_{res} = \sqrt{k/m}$$



For a **cantilever s**the situation is somewhat different because the cantilever *mass is distributed* along the cantilever beam.

Thus, different cantilever parts oscillate with different amplitude and velocity.



Rayleigh solution: = Equating the maximum kinetic energy and maximum strain energy of the cantilever, where: $z(x,t) = z_0(x^4 - 4x^3L^2 + 6x^2L^2)/L^4 \cdot \sin(\omega t)$ for the free ended cantilever.

By integration from $x = 0$ to L , one obtains: $E_{strain} = 1/2 \cdot (1.6 \cdot k_c) z_0^2$ and $E_{kin} = 1/2 \cdot (0.256 \cdot m_c) \cdot \omega^2 z_0^2$

Lowest frequency mode:
(vertical bending mode)

$$\boxed{\omega_{res} = \sqrt{\frac{k_c}{0.24 \cdot m_c}}}$$

or with additional tip mass m_{tip}:

$$\boxed{\omega_{res} = \sqrt{\frac{k_c}{0.24 \cdot m_c + m_{tip}}}}$$

Higher order modes:

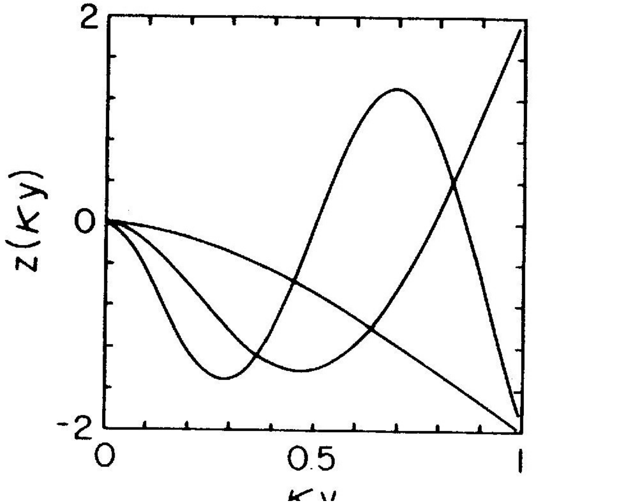
$$\boxed{\omega_n = \frac{\kappa_n^2}{L^2}\sqrt{\frac{E \cdot I}{\rho \cdot A}}}$$

with κ_n = 1.875, 4.694, 7.855, 10.996, ... and

$m_c = \rho \cdot V = \rho \cdot A \cdot L$ and $k = 3EI/L^3 = E \cdot w \cdot d^3/4L^3$

V-shaped cantilever:

$$\boxed{\omega_{res} \approx \sqrt{\frac{k_c}{0.163 \cdot m_c + m_{tip}}}}$$



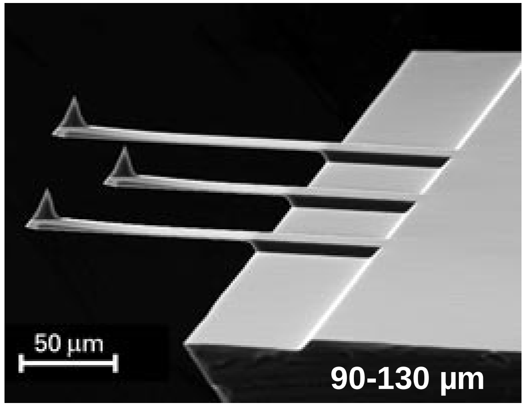
The first three modes of vibration of a lever.

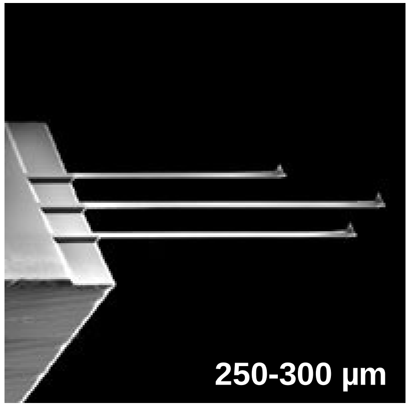
From the equations above it follows that for a given *k*-value, defined by the geometry and shape of the beam, a high resonance frequency can be achieved by ***reducing the cantilever mass***.

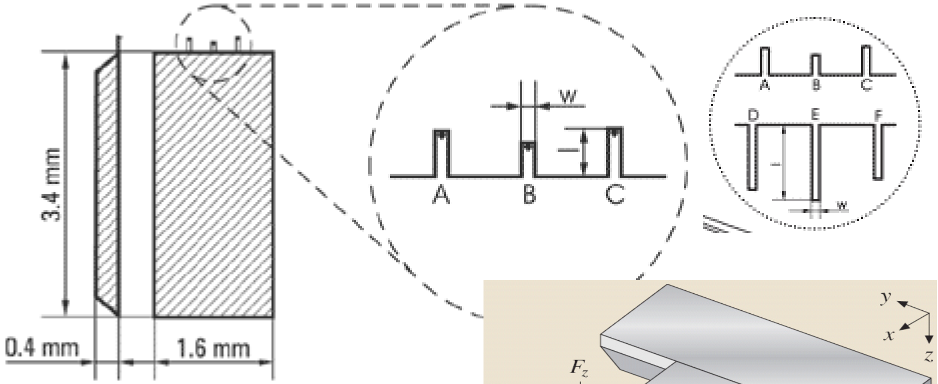
This means ***miniaturization of the cantilever beams*** to achieve a high resonance frequency !

⇨ If *w* and the *d*/*L* ratio is fixed, then *k* is constant and ω_{res} increases if *L* is made very small.

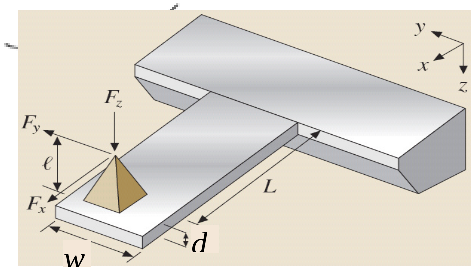
Example: Rectangular bar-shaped cantilevers made of silicon







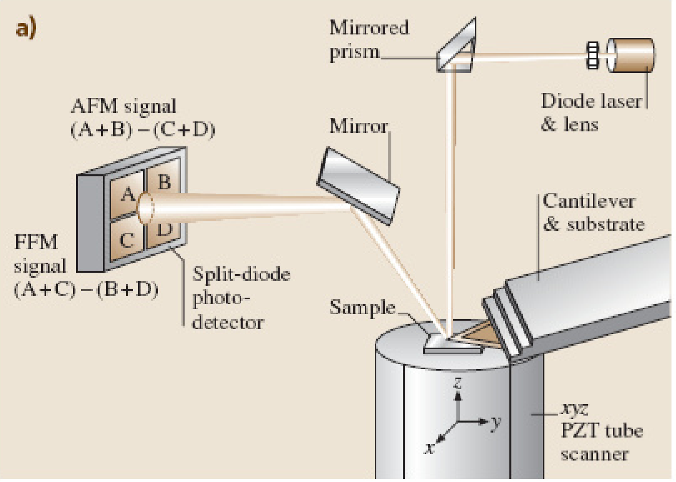
SEM images of 3 rectangular silicon cantilevers (A, B, C) with two different length series.

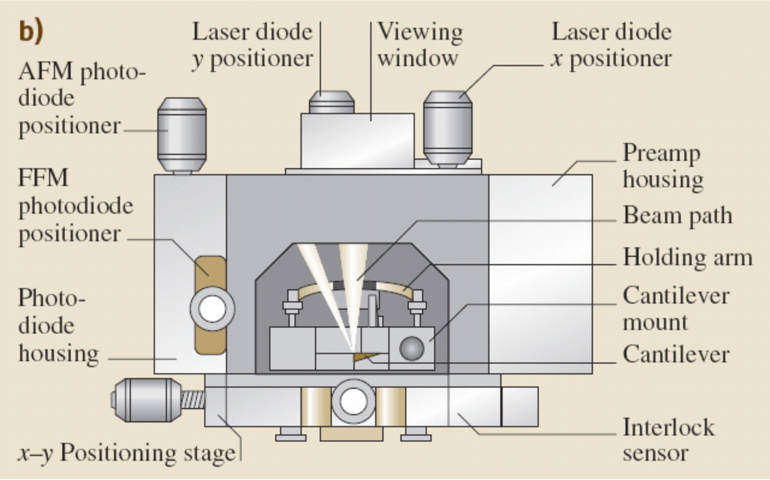


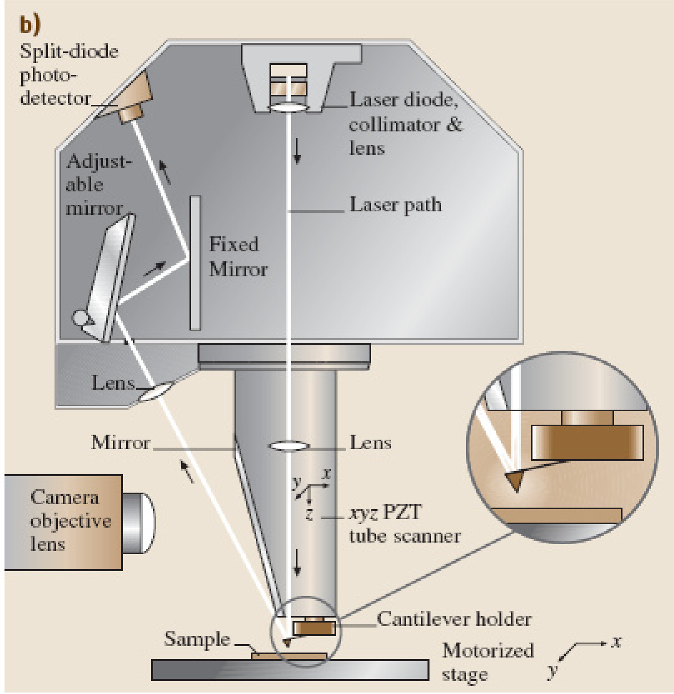
Specifications for different cantilever parameters

Cantilever Type	Length, $L\pm5$ µm	Width, $w\pm3$ µm	Thickness, d µm	Resonant Frequency, kHz	Force Constant, N/m
A	110±5%	35±8%	2.0±10%	210±20%	7.5±30%
B	90	35	2.0	315	14.0
C	130	35	2.0	150	4.5
A	110	35	1.0	105	0.95
B	90	35	1.0	155	1.75
C	130	35	1.0	75	0.60

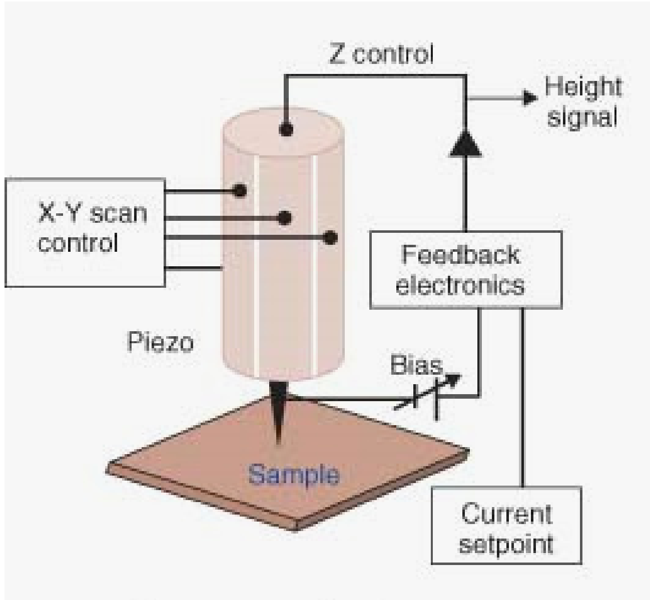
Optical Beam Deflection Measurement Systems





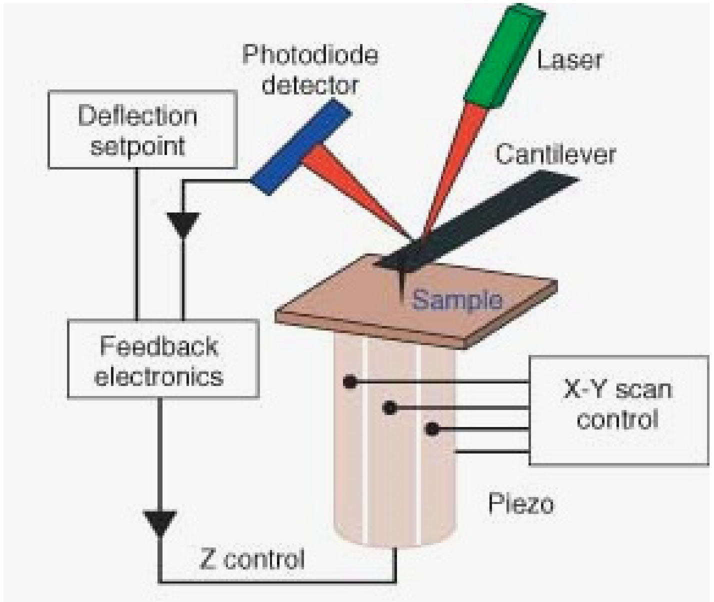


(a) Tip-scanning systems



Most common for STM

(b) Sample scanning systems



More common for AFM

Tip-scanning systems

Advantages:

» **Low inertial mass**, high resonance frequency.
» Faster scanning.
» **No limitation for sample size**.
» Free sample access, e.g., for heating, cooling etc..

Disadvantages:

» Moving tip makes optical measurement more difficult to implement

Sample scanning systems

Advantages:

» **No lateral tip movement**; more easy implementation of optical detection

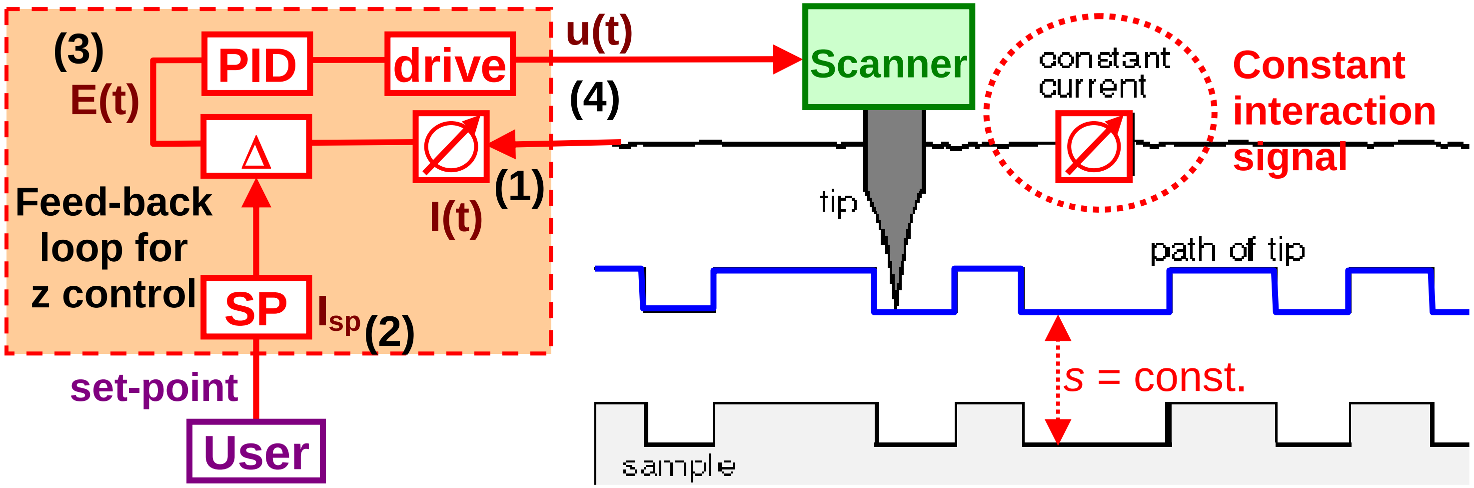
Disadvantages:

» Higher inertial mass, slower scanning.
» Limited sample size and weight.

Other combinations: (x,y) sample scanning, z-movement of tip, etc. …

Feedback Loop and Scan Control

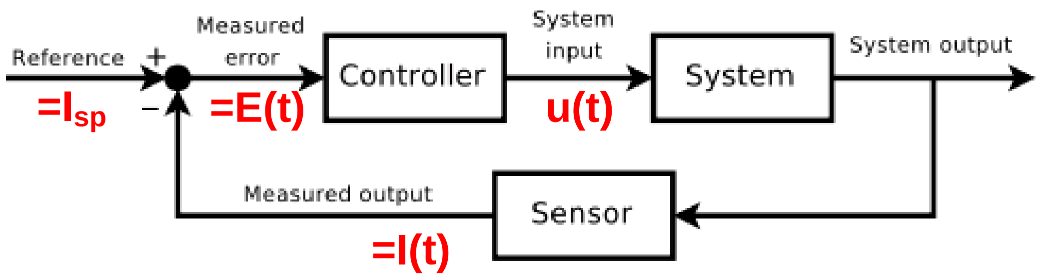
For the constant interaction mode, an electronic ***feed-back control* loop** is needed to keep the *tip-sample distance constant* during the scanning process and to reconstruct the surface topography.



Working principle of the feed-back Loop:

- **(1)+(2):** In the feed-back loop, the measured ***interaction signal*** ***I(t)*** **(1)** is constantly compared to the user chosen ***set-point*** ***interaction*** I_{sp} ***value*** **(2)**.
- **(3)** The difference between signal and set-point yields the so-called ***error signal*** $\boxed{E(t) = I(t) - I_{sp} \quad (3)}$
- **Case #1**: When the ***error signal is zero***, the interaction strength is equal to the desired set point. Thus, the tip-sample distance has the correct value and the z- extension should be unchanged.
- **Case #2**: If the ***error signal is non zero***, a **drive voltage** $\boxed{u(t) = f(E(t))}$ **(4)** must be generated and applied to the scanner to change the z-position of the tip until the measured interaction signal again reaches the desired set point value, i.e., until the error signal again goes to zero.
- If the error signal E(t) is always ~ zero during the scanning process, then the tip follows *exactly* the surface topography $z_{sf}(x,y)$. The topography is then simply given by: $z_{scanner}(x,y)$

Generic block-diagram of a feed-back control system



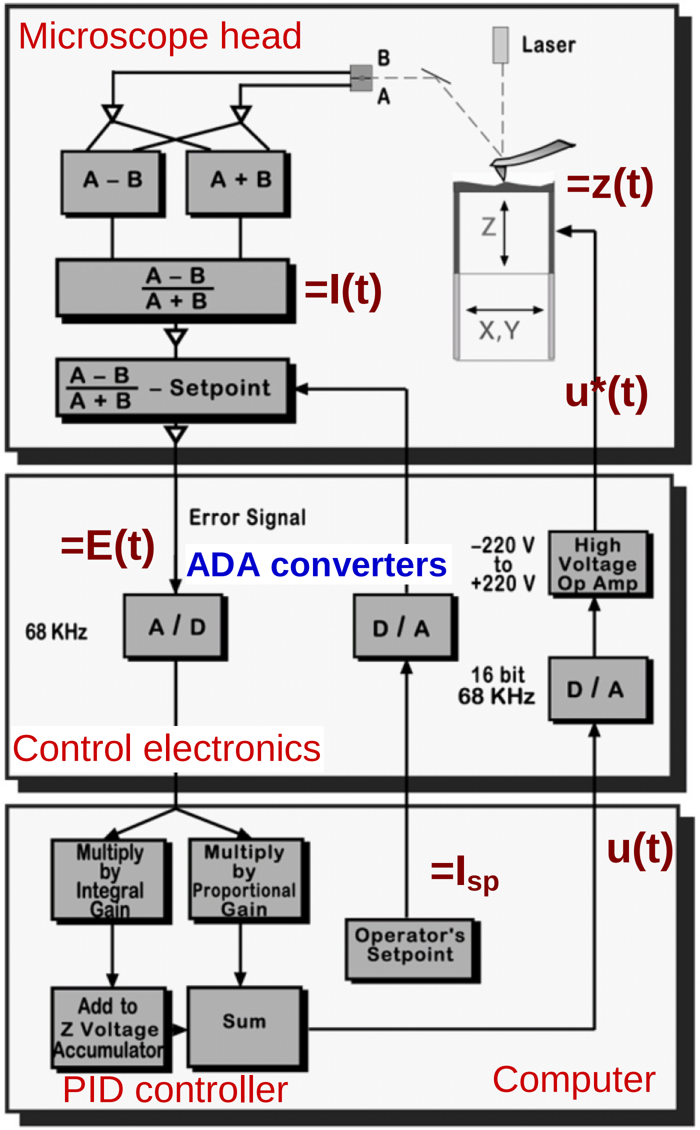
In general, a feed-back control loop consist of:

1. The ***system*** of which the state should be controlled. It is constantly driven by the drive signal but is also exposed to perturbations from the environment (e.g. vibrations) and by the sample topography (SPM).
2. a ***sensor*** that measures the status ***I(t)*** of the system,
3. a reference channel that inputs the set-point value ***I_{sp}***,
4. a ***comparator*** that generates the ***error signal E(t)***,
5. a feed-back ***loop controller*** that generates (or calculates) from the error signal a ***drive signal u(t)***
6. an input of the drive signal to the ***system*** to change its state towards the desired set-point value ***I_{sp}***.

Examples:

Temperature controller, pressure controller, velocity controller, position controller, ...

Example: Block diagram for AFM



PID Feed-Back Controller

The design and optimization of a feed-back loop and the control algorithms is the main issue of **control theory,** which is used in many different fields of engineering.

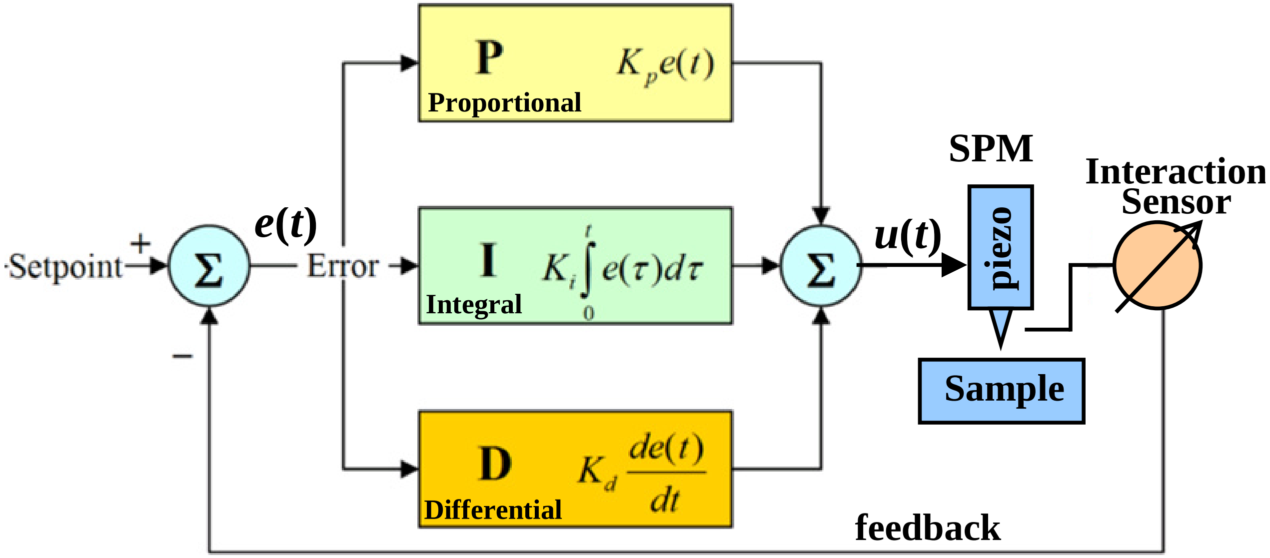
The **task** is to generate a drive signal *u*(*t*) that adjusts the piezo extension based on the *known quantities* of the system, i.e., the momentary error signal *e*(*t*) and the output drive *u*(*t*-*Δt*) at time *t*-*Δt*.

PID controller

The most common feedback control design is the "Proportional-Integral-Derivative" (PID) controller. In this system, the control (drive) signal u(t) is derived from the measured error signal *e*(*t*) using the sum of three different components ***u*(*t*) = *P*(*t*) + *I*(*t*) + *D*(*t*)** with the weighing factors K_P, K_I and K_D:

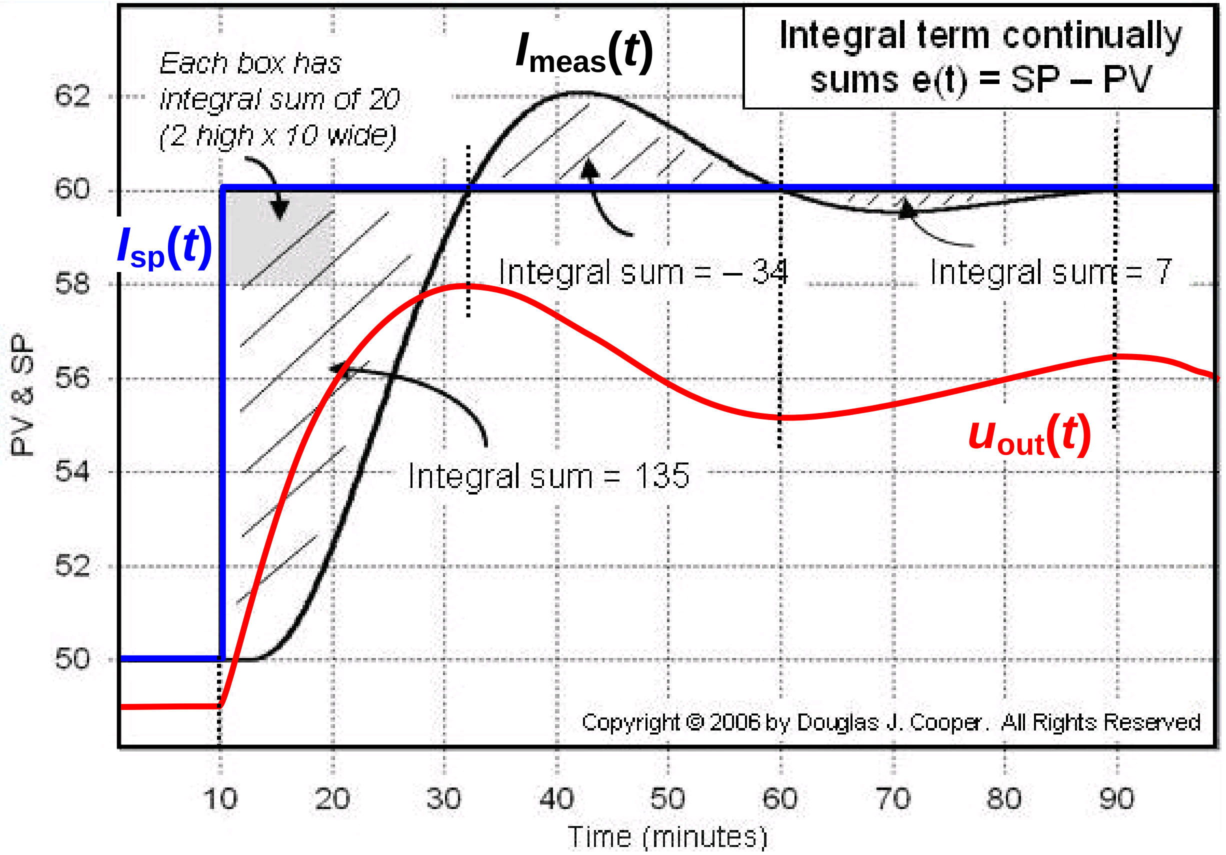
$$\boxed{u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{d}{dt} e(t)}$$

Here: *u*(*t*) is the voltage applied to the SPM scanner



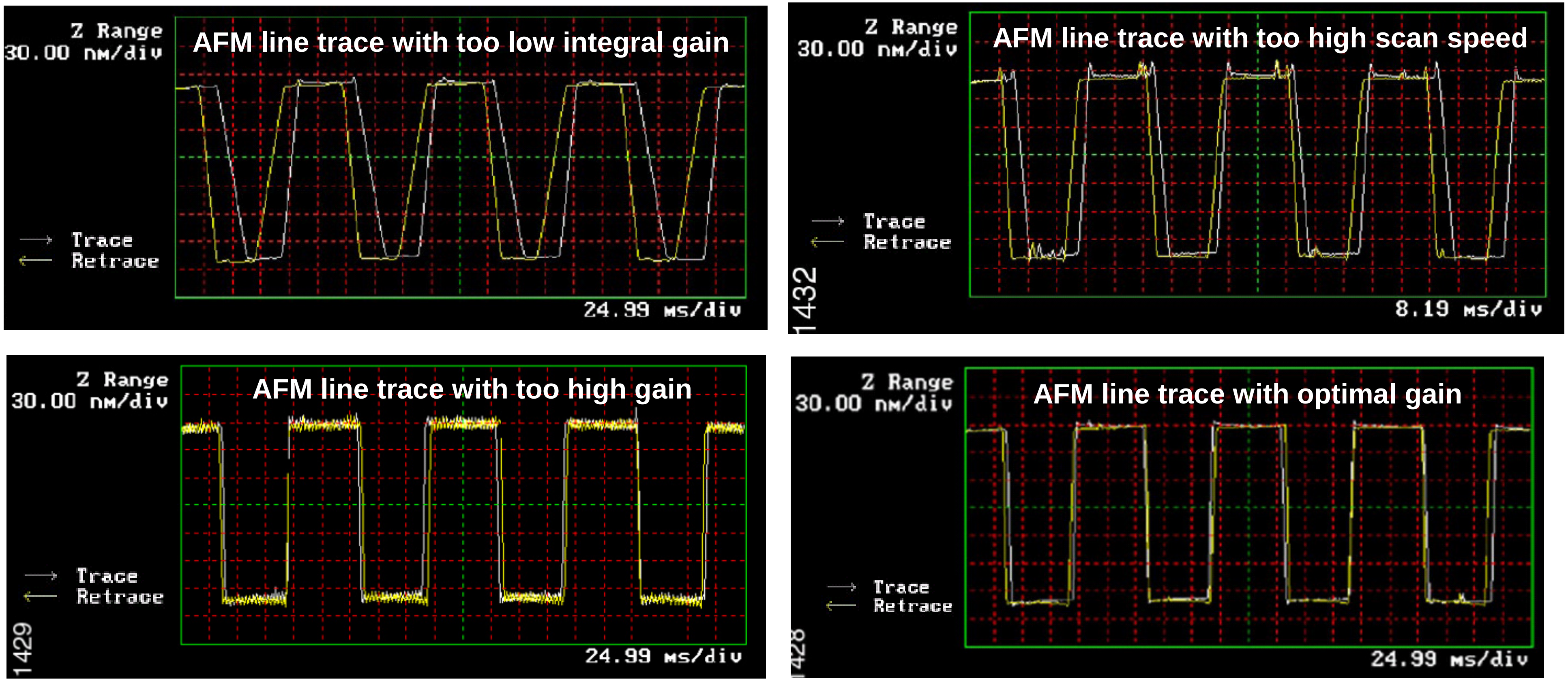
Example for the action of a PI controller:

$$\mathrm{u(t)} = \mathrm{MV(t)} = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau$$



Practical Examples: AFM line scans of a calibration grating with different scan parameters

White lines: Forward scan direction (”trace”). Yellow lines: Backward scan direction (“retrace”)



- **General conclusion:** Optimum feedback parameters depend on
  (a) SPM scan head construction (resonance frequency)
  (b) Scanning speed,
  (c) the sample topography (lateral size and height of surface features)
  (d) AFM: Force constant of cantilever force sensor
- Must be optimized for a given sample and scan conditions.

Non-Contact/Tapping Mode AFM

Basic Principle: The cantilever is used as a driven harmonic oscillator (***tuning fork***) excited into a high frequency vibration by an piezo actuator mounted underneath the cantilever chip.

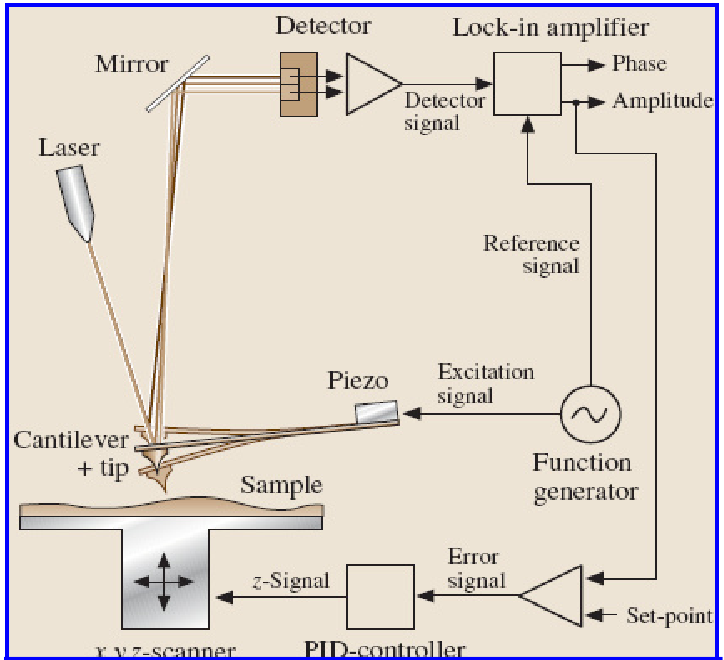
Interaction sensing: When the tip interacts with the sample surface the oscillator properties such as resonance frequency, amplitude and phase are slightly changed. These changes (frequency shift, phase shift or amplitude change) are detected and are used as a measure of tip/sample interaction instead of the force itself.

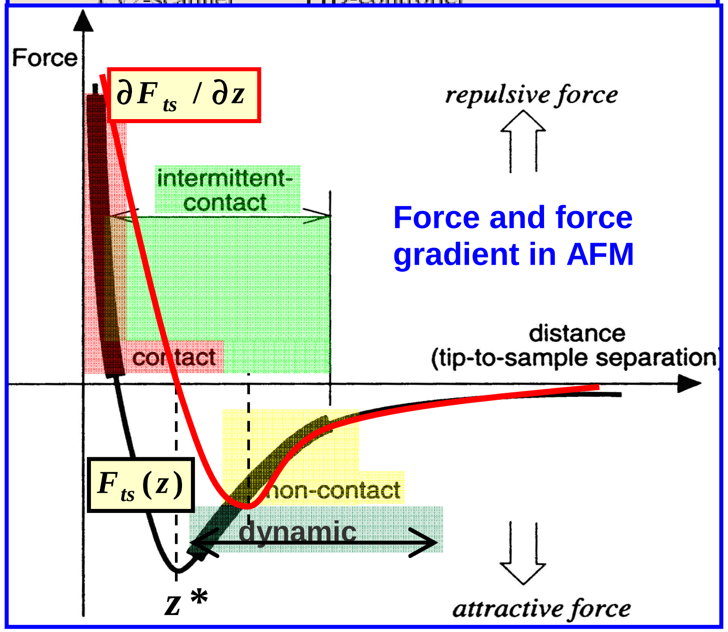
Main operation modes:

- **Tapping/intermittant contact mode** (large amplitude, intermittent contact between tip and sample)
- **Non-contact mode AFM** (large tip-sample distance)
- **Derivative force imaging** (small oscillation amplitudes)

Detection schemes for the interaction:

- **Amplitude modulation** (excitation with fixed excitation frequency): Measurement of change of amplitude.
- **Phase detection** (fixed frequency excitation): Measurement of the phase difference between the AC excitation current and the detector oscillation.
- **Frequency modulated detection** (variable excitation frequency tuned to the resonance frequency): Measurement of frequency shift due to interaction.





Oscillating Cantilever Interacting with a Sample Surface

When the tip interacts with the sample, an additional force F_{ts} acts on the tip when it is in close vicinity of the sample surface. As a result, the ***oscillation properties slightly change***.

- ⇨ This means that interaction strength can be sensed by measuring the **changes** in the ***resonance frequency*** $\Delta\omega$ and/or ***changes in the oscillation amplitude*** ΔA ***and phase*** $\Delta\varphi$ as shown below. These changes can be used alternatively for the measurement of the cantilever deflection.
- ⇨ These scanning modes are called tapping or intermittent contact or noncontact scan modes

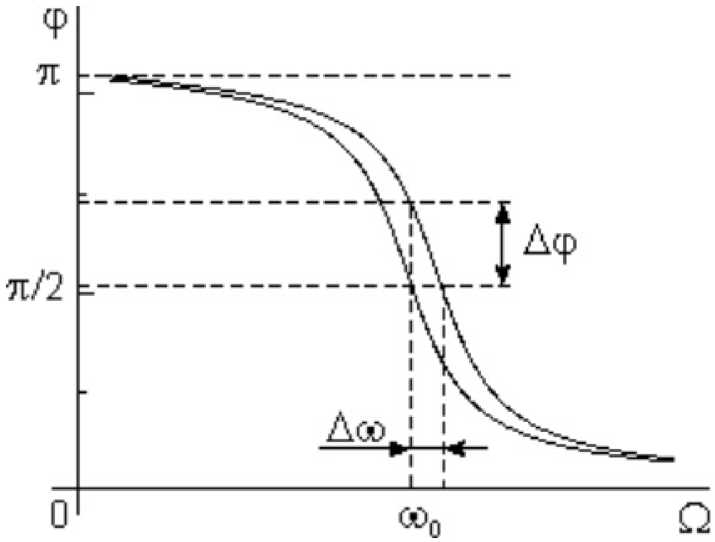


Fig. 4.2. Variation of the oscillations phase with resonant frequency.

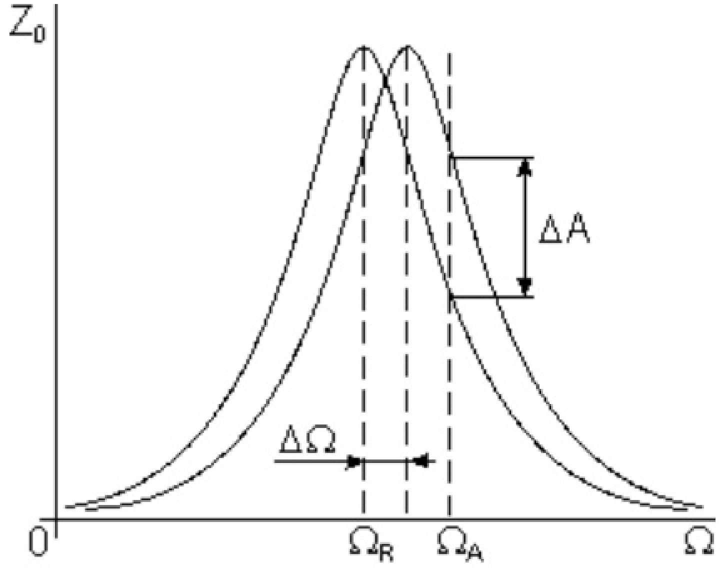


Fig. 4.3. Variation of the oscillations amplitude with resonant frequency.

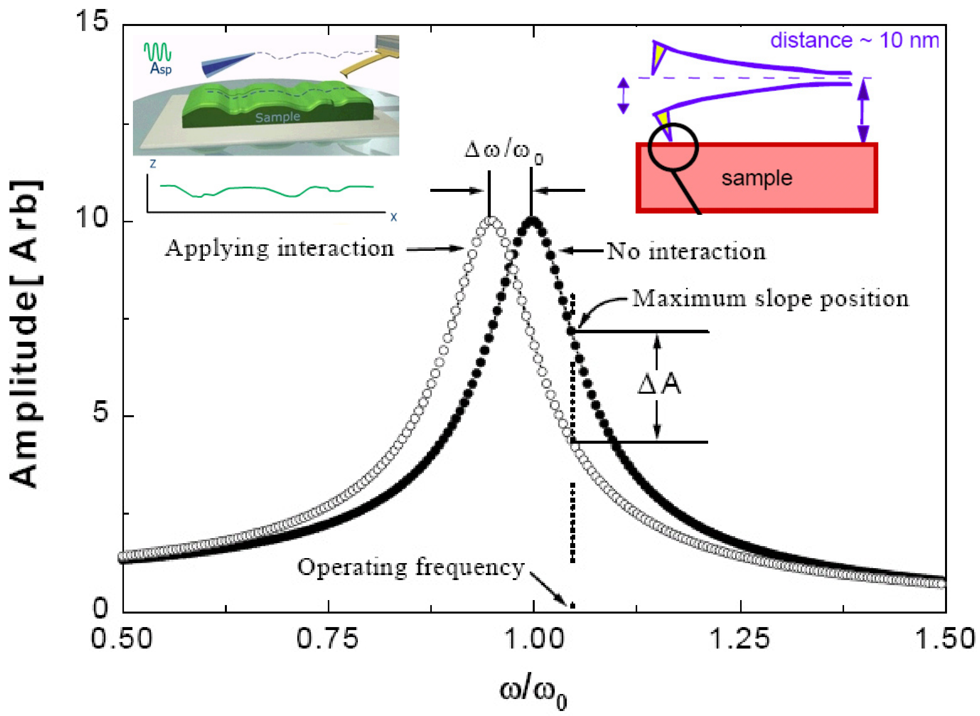
- ⇨ In general, if the interaction is dominated by repulsive forces, the resonance frequency ***increases*** because the cantilever is pushed back more strongly to the zero position.
- ⇨ On the contrary, when attractive forces dominate the resonance frequency is ***lowered***.

f_{inter} f_0

Detection Modes: Amplitude versus Frequency Detection

(a) Amplitude Detection: Excitation at constant excitation frequency f_{exc} close to f_{res}
Measurement of *amplitude change ΔA* using lock-in technique.

(b) Frequency modulation mode: Excitation frequency is kept tuned to resonance and amplitude kept constant. Measurement of *frequency change* **Δf** relative to free-air resonance frequency



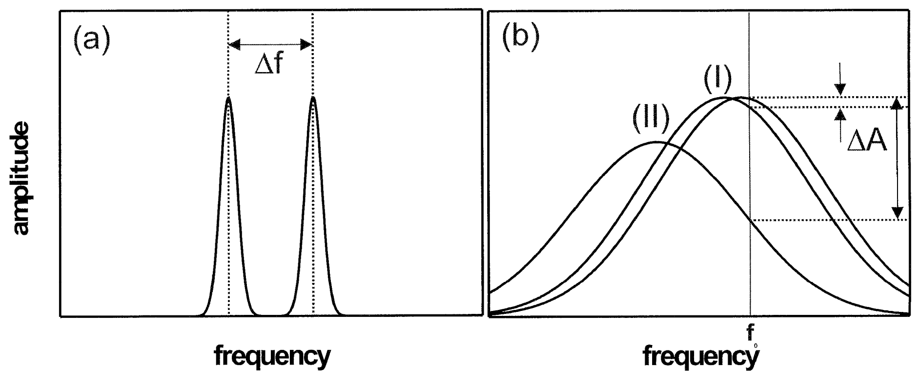


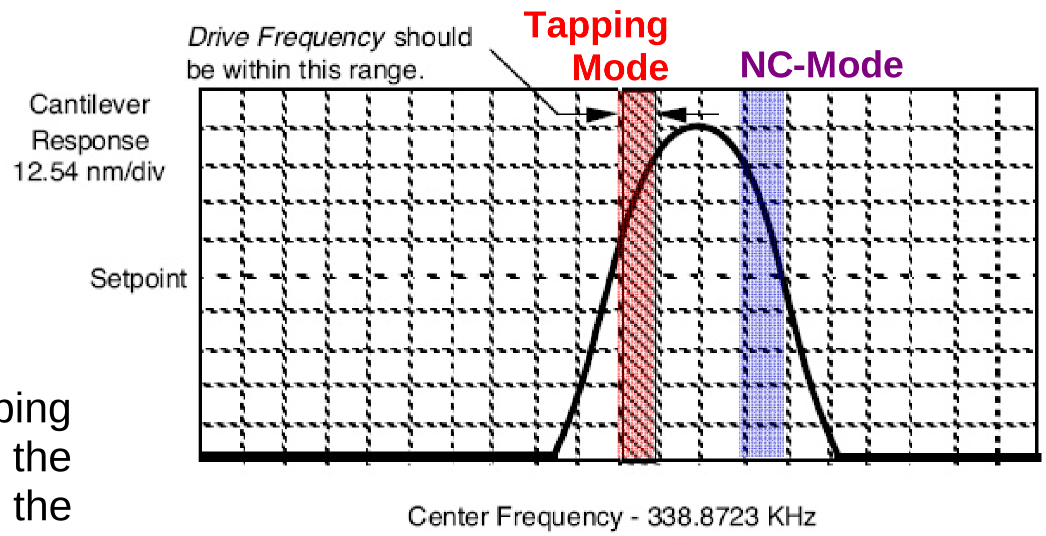
Fig. 3.7. Two dynamic modes for the detection of tip–sample interactions. In dynamic force microscopy (**a**), the shift in frequency caused by the tip–sample interaction is detected. The oscillation is driven at the actual eigenfrequency of the cantilever. This mode is mainly applied in vacuum, where high Q-factors allow a precise determination of the resonance frequency. In the intermittent contact mode (**b**), the change in amplitude is detected at a fixed frequency f_0. This mode is suitable for systems with low Q-factors, where the amplitude changes fast enough upon tip–sample interactions. The decrease in amplitude at f_0 may be due either to a frequency shift (I) or to an additional decrease in the total amplitude due to damping (II)

Intermittent Contact (Tapping) versus True Non-Contact Mode

<u>Tapping mode</u> (= intermittent contact) AFM

In this operation mode, the ***excitation frequency*** is ***set slightly below the resonance frequency*** of the free cantilever and the amplitude set-point for scanning at a value lower than the amplitude of the free cantilever at the excitation frequency.

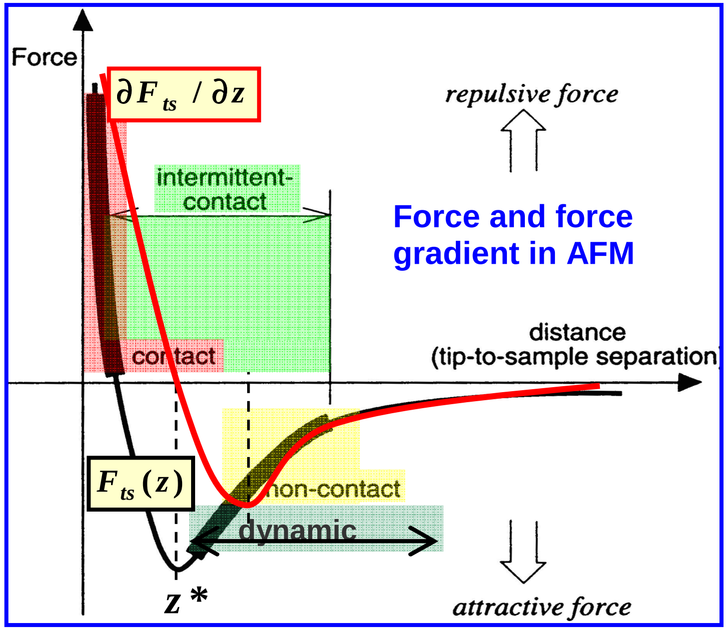
As the tip comes into the ***contact regime*** (tapping on the sample), the resonance curve shifts to the right hand side to higher frequencies and thus, the cantilever amplitude at the drive frequency is reduced until the set-point value is reached.



<u>Non-contact mode</u> (far distance attractive force regime)

In NC-mode AFM, the ***excitation frequency*** is ***set slightly above the resonance frequency*** of the free cantilever and the amplitude set-point for scanning at a value lower than the amplitude of the free cantilever at this excitation frequency.

As the tip comes in the non-contact regime, the resonance curve shifts to the left hand side to lower frequencies because the attractive force retards the cantilever oscillation. Thus, at the fixed excitation frequency, the cantilever amplitude is reduced until the set-point value is reached.



Comparison of the different AFM Imaging Modes

Table: Operation modes in atomic force microscopy

Mode	Advantages	Disadvantages
Contact Mode *Static* (DC)	High lateral resolution (A) simple operation simple interpretation	Large tip wear due to strong tip-sample interaction, limited force resolution
Contact Mode *Dynamic* (AC) intermittent or tapping mode	Highest spatial resolution (atomic) and sensitivity, high force resolution (pN) low noise, high stability reduced sample damage	More advanced instrumentation
Noncontact Mode-*Static* (DC)	Nondestructive: No tip wear, and no sample damaging, sensitivity to long range forces (MFM)	Poor spatial and force resolution (~10nm) unstable operation very sensitive to drifts
Noncontact *Dynamic* (AC)	Nondestructive higher sensitivity as DC, sensitivity to long range forces (MFM)	Poor spatial resolution (~10nm)