MAE649

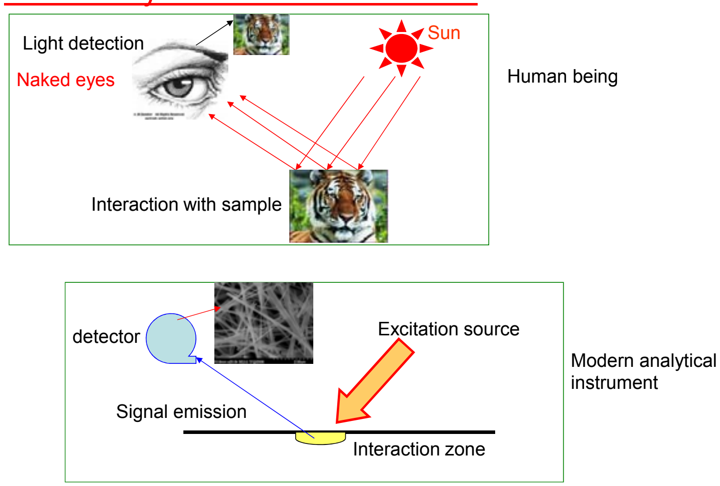
Chapter 1

Scanning Probe Microscopy (SPM)

Scanning Probe Microscopy (SPM)

- Introduction of basic principle and instrumentation
- Contact-mode AFM
- Lateral force microscopy (LFM)
- Tapping mode AFM
- Electrostatic force for microscope (EFM)
- Magnetic force microscope (MFM)
- Scanning tunneling microscope (STM)
- Nanoscale force measurement by AFM (including pull-off force and nano-indentation)

How analytical instruments work



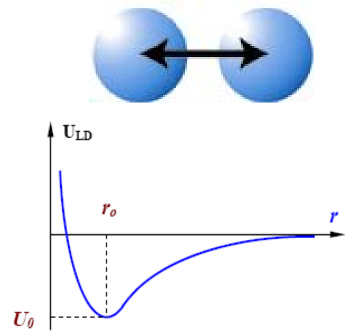
Basic concept of microscope

- Spatial resolution
- Limit of detection
- Sampling depth (penetration)
- Interaction zone

AFM

- Introduction of basic principle and instrumentation
- Contact-mode AFM
- Lateral force microscopy (LFM)
- Tapping mode AFM

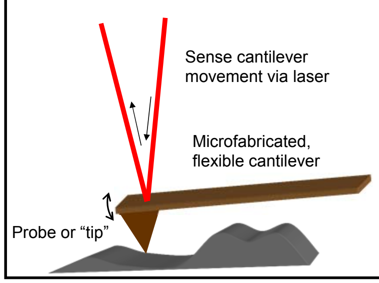
AFM operation principle



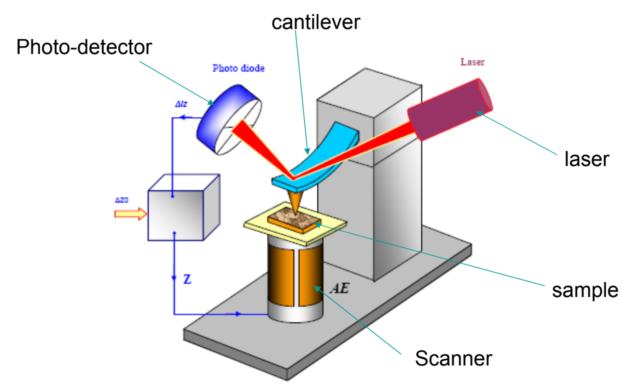
Lennard-Jones potential energy dependent on inter-atomic distance

Scanning or "Atomic" Force Microscopy (SFM/AFM)

- Image 3D surface topography digitally (measure heights, quantify roughness)
- Image material composition via tip/sample interfacial forces (e.g., friction force)
- Characterize distance-dependent interfacial forces (e.g., mechanical stiffness, molecular bonding)

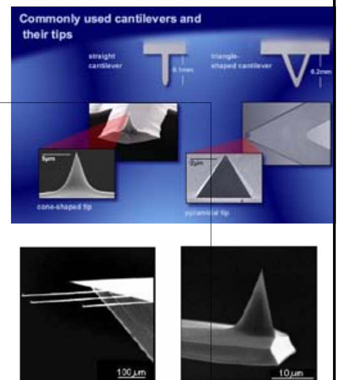


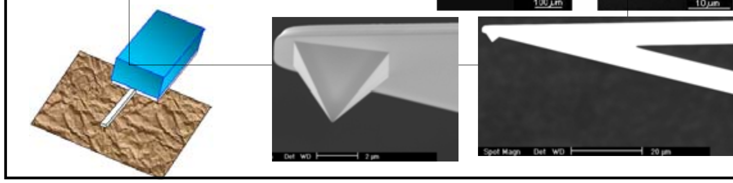
Configuration of AFM



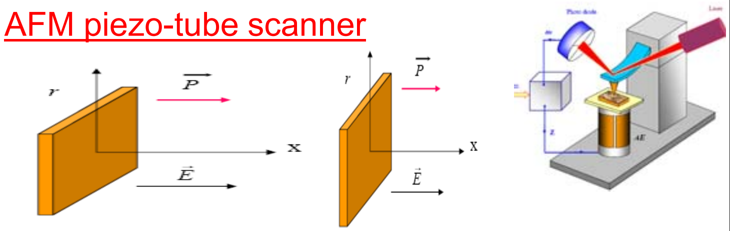
AFM tip and cantilever

- Cantilever bending and twisting modes cause reflected laser spot to be displaced on a position sensitive photodiode array
- Laser spot is actually focused down to ~20 μm size onto a section of the cantilever (that is a bit larger).
- Tip is extremely sharp (2-15 nm in radius of the tip end curvature), but cantilever spring constant is small enough to keep forces at nN level, such that the force per unit contact area (pressure) does not exceed the yield strength of the material





AFM piezo-tube scanner



Dimension change of piezo-ceramics induced by the external electric field

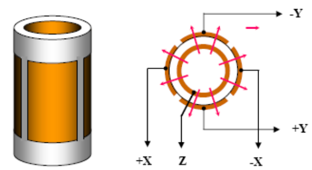


Fig. 5. Tubular piezo-scanner

SPM's commonly employ piezoelectric tube scanners with X-Y-Z electrical configurations.

Nonlinearity and creep of piezo-tube scanner

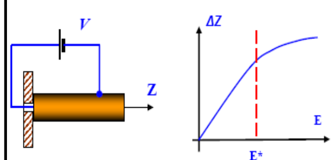
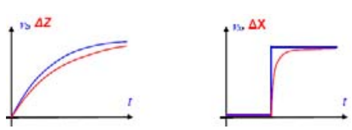


Fig. 9. Schematic representation of dependence of ceramics shift on the size of applied electric field

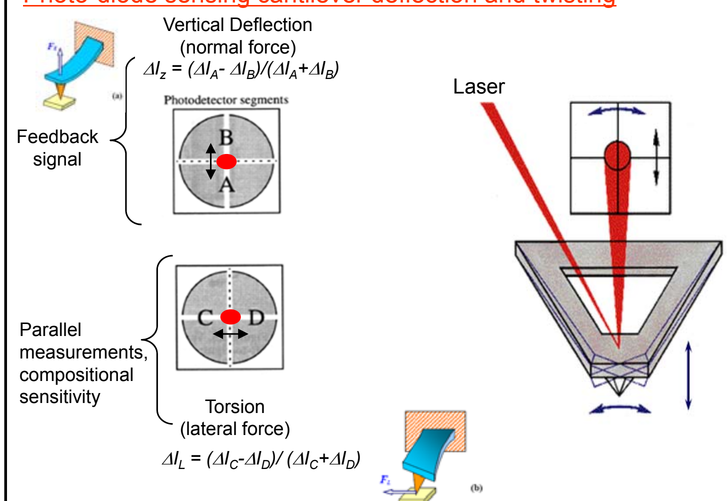
Typical values of E* fields, at which nonlinear effects start to affect, make about 100 V/mm. Therefore for the correct work of scanning elements the control fields are usually used in the area of ceramics linearity (E <E*).



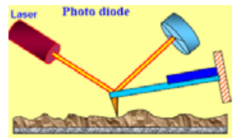
time diagrams of change of a control field on a Z-electrode in a feedback circuit and on an X-electrode during scanning (shown in dark blue color). Red color schematically shows the dependences corresponding to reaction of the scanner on change of control voltages

The creep results in appearance of geometrical distortions in SPM images due to this effect. Specifically strong influence of the creep occurs when the scanner is moved to a reference point for conduction of local measurements and on initial stages of the scanning process. Time delays are used to reduce the ceramics creep influence on the specified processes, allowing partially to compensate the scanner delay.

Photo-diode sensing cantilever deflection and twisting

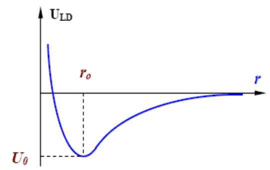


AFM operation principle



AFM tip-sample interaction can be qualitatively explained in terms of van der Waals forces. Most frequently the van der Waals interactions energy of two atoms, located on the *r* distance from each other, is approximated by the exponential function: Lennard-Jones potential

$$U_{LD}(r)=U_0\left\{-2\left(\frac{r_0}{r}\right)^6+\left(\frac{r_0}{r}\right)^{12}\right\}$$



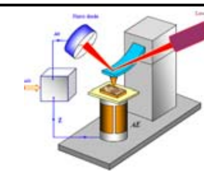
Lennard-Jones potential qualitative form

The first term describes the long-distance attraction caused, basically, by a dipole-dipole interaction of atoms.

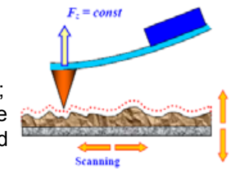
The second term takes into account the atoms repulsion on small distances. r_o is the equilibrium distance between atoms, - energy value in the minimum.

Real interaction of a tip with a sample has more complex character; however, the basic features of the given interaction are the same – the AFM tip experiences attraction from the sample on big distances and repulsion on small ones

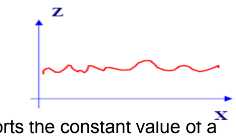
Contact mode-AFM



AFM contact mode is operated either at a constant interaction force of a tip with a surface or at a constant distance between the probe base and the surface of a sample



In the constant distance mode, the probe moves on some average height Z=constant above the sample; during this the cantilever bend ΔZ, proportional to the force influencing the tip from the surface is registered in every point.



During force constant mode, the feedback system supports the constant value of a cantilever bend, and consequently, the interaction force of a tip with a sample as well. Thus the control voltage in a feedback loop, applied on a Z-electrode of the scanner, will be proportional to the sample surface topography.

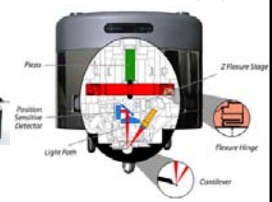
AFM Instrument

Digital multidemode IV AFM, Veeco

Bioscope II AFM, Veeco

PICO SPM II, Molecular imaging

Scanner, Molecular imaging

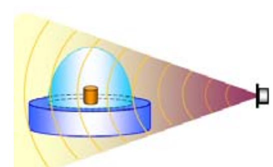


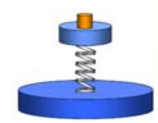
MFP-3D™, Asylum Research

Isolation of AFM from environment interference

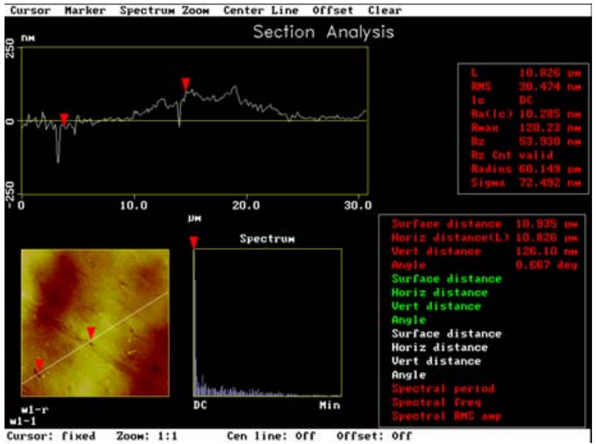
- Mechanical vibration
- Acoustic noise
- Electromagnetic interference

Electric and magnetic shield cage





Contact mode AFM images

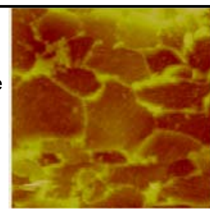


X-52 pipeline steel polished sample before corrosion

Surface roughness measured by AFM images

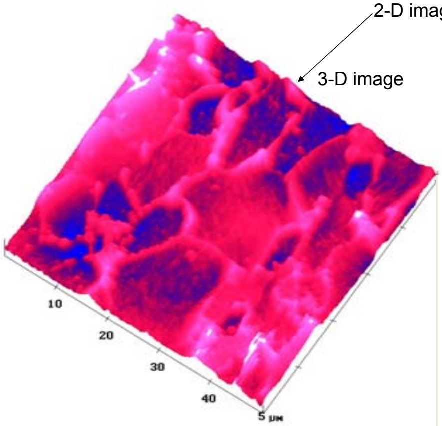
Term	Definition	Calculation	Use
R_a	Roughness average is the main height as calculated over the entire measured length or area. It is quoted in micrometers or micro-inches. R_a is calculated per the ANSI B46.1 standard.	Two-dimensional R_a $R_a=\frac{1}{n}\sum_{i=1}^{n}\lvert Z_i-Z\rvert$ Three-dimensional R_a $R_a=\frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M}\lvert Zij\rvert$ where M and N = number of data points in X and Y, and Z is the surface height relative to the mean plane.	R_a is typically used to describe the roughness of machined surfaces. It is useful for detecting general variations in overall profile height characteristics and for monitoring an established manufacturing process.
R_q	The Root means square (rms) average between the height deviations and the mean line/surface, taken over the evaluation length/area. The parameters "RMS" and "R_q" are equivalent in Wyko® Vision® and are computed using the same equation.	Two-dimensional R_q $R_q=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z_i-Z)^2}$ Three-dimensional R_q $R_q=\sqrt{\frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M}Z^2(x_i,y_j)}$	RMS roughness describes the finish of optical surfaces. It represents the standard deviation of the profile heights and is used in computations of skew and kurtosis.
R_p , R_v	Maximum profile peak height and Maximum profile valley depth are the distances from the mean line/surface to the highest/lowest point in the evaluation length/area.	Measured	Peak height provides information about friction and wear on a part. Valley depth provides information about how a part might retain a lubricant.
R_t	Maximum height is the vertical distance between the highest and lowest points in the evaluation length/area.	$R_t=R_p+R_v$	Maximum height describes the overall roughness of a surface.
R_z	The Average maximum profile of the ten greatest peak-to-valley separations in the evaluation area. Vision excludes an 11 x 11 region around each high (H) or low (L) point such that all peak or valley points won't emanate from one spike or hole.	$R_z=\frac{1}{10}\left[\sum_{i=1}^{10}H_i-\sum_{j=1}^{10}L_j\right]$	R_z is useful for evaluating surface texture on limited-access surfaces such as small valve seats and the floors and walls of grooves, particularly where the presence of high peaks or deep valleys is of functional significance.
R_{sk}	Skewness is a measure of the asymmetry of the profile about the mean line. Negative skew indicates a predominance of valleys, while positive skew is seen on surfaces with peaks.	$R_{sk}=\frac{1}{nR_q^3}\sum_{i=1}^{n}(Z_i-Z)^3$	R_{sk} illustrates load carrying capacity, porosity, and characteristics of non-conventional machining processes. Negative skew is a criterion for a good bearing surface.
R_{ku}	Kurtosis is a measure of the distribution of spikes above and below the mean line. For spiky surfaces, $R_{ku} > 3$; for bumpy surfaces, $R_{ku} < 3$; perfectly random surfaces have kurtosis 3.	$R_{ku}=\frac{1}{nR_q^4}\sum_{i=1}^{n}(Z_i-Z)^4$	Kurtosis describes machined surfaces and is rarely used for optical surfaces. It is sometimes specified for the control of stress fracture.

Contact mode AFM images

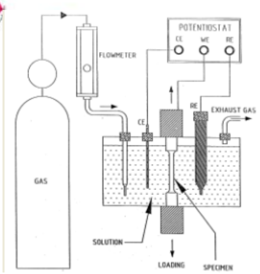


2-D image

3-D image

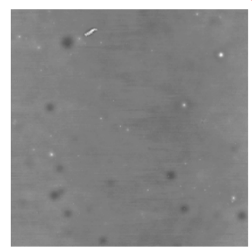


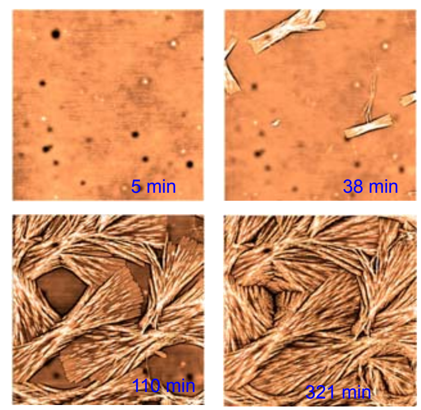
2-D image, height mode



3-D AFM image of X-52 pipeline steel after corrsion corrosion

In-situ AFM images





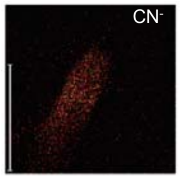
In situ observation cystallization of polypropylene,

Syndiotactic polypropylene melted to 160°C, and left to crystalize at 105°C

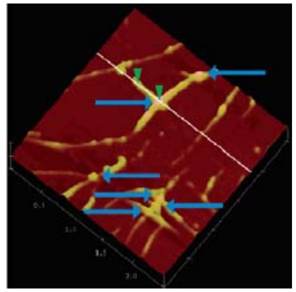
http://www.asylumresearch.com/CUSyndio.shtml

Application of AFM and SIMS in biology

AFM image of dip-pen pattern of peptide amphiphiles fibers, scale: 10um, by courtesy of H. Jiang



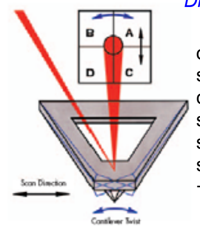
SIMS image of peptide amphiphiles pattern



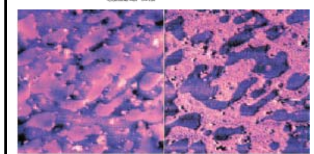
AFM image of peptide amphiphiles fibers

Lateral force microscopy (LFM) images

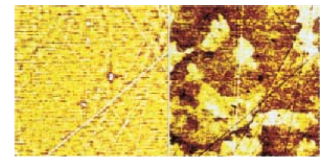
Distinguish the different phases in materials by LFM



or LFM, the probe is scanned sidewise, and the friction signal is calculated. The degree of torsion of the cantilever supporting the probe is a relative measure of surface friction caused by the lateral force exerted on the scanning probe. Note that for contact mode, the deflection signal is calculated as laser spot intensity for quadrants (A + B) - (C +D).



Topographic (left) and LFM (right) images of a natural rubber/EDPM blend. 12µm scans, by M.G. Heaton, et al



Topographic (left) and LFM (right) images of the surface of a polished polycrystalline silicon carbide film. The polishing process obscures in the topography image the grain structure, which is clearly visible in the LFM image. 30µm scans. by M.G. Heaton, et al

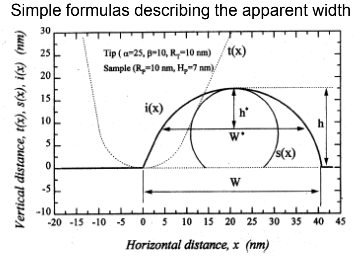
Lateral force microscopy (LFM) images

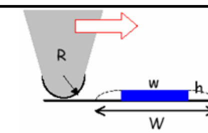
A specialized use of LFM is Chemical Force Microscopy (CFM), where the tip is functionalized with a chemical species, and scanned over a sample to detect adhesion differences between the species on the tip and those on the surface of the sample

(1). CFM scan of well-defined regions that terminate in either methyl or carboxylic acid groups.
(2). When a carboxylic acid-terminated tip is used for imaging (left), the carboxylic acid terminated regions exhibit greater frictional force (lighter color) than the methyl-terminated regions.
(3). When a methyl terminated tip is used (right), the friction contrast is reversed. No differences are revealed by the topographic AFM scan (not shown) since the functional groups are structurally quite similar. (50µm images, Image courtesy of Dr. C. Lieber, Harvard University).

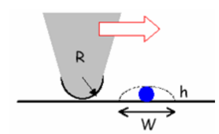
Broadening of features by tip

Simple formulas describing the apparent width of objects





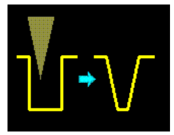
$W = w + 2\sqrt{h(2R-h)}$



$W = 2\sqrt{2Rh}$

- The shape traced by the tip is in essence a superposition of spheres (neglecting mechanical deformation, a later topic).
- Imaged lateral size is much larger than true size.
- Vertical size is approximately correct.
- Independent measurement of sphere size (e.g., via electron microscopy) or distribution of sphere sizes (e.g., via scattering) can provide a calibration specimen: a means of determining the true shape of the tip via a nanoparticle.

Tip Effects on AFM image

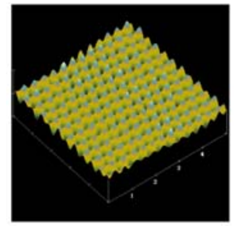



broadening---Tip broadening arises when the radius of curvature of the tip is comparable with, or greater than, the size of the feature to be imaged. As the tip scans over the specimen, the sides of the tip make contact before the apex, and the microscope begins to respond to the feature. This is what we may call tip convolution

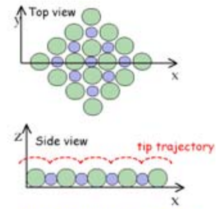
compression-- Compression occurs when the tip is over the feature trying to be imaged. It is difficult to determine in many cases how important this affect is, but studies on some soft biological polymers (such as DNA) have shown the apparent DNA width to be a function of imaging force. It should be born in mind that although the force between the tip and sample may only be nN, the pressure may be MPa

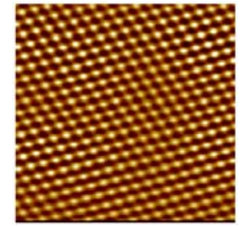
interaction forces--- Interaction forces between the tip and sample are the reason for image contrast with the AFM.

Can AFM gives atomic resolution?



Mica



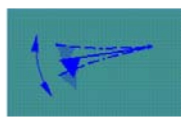


5x5 nm of graphite

- True atomic resolution is very difficult to obtain.
- In most claimed cases of atomic resolution in air, it is now understood to be *lattice* resolution, where the underlying lattice is sensed due to the periodicity of the friction force, but a single-atom point contact is not achieved.
- Atomic point defects are the hallmark of true atomic resolution.
- True atomic resolution is only possible under stringent circumstances:

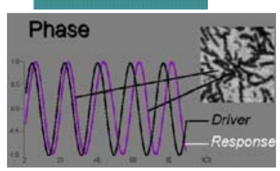
  in liquid or in ultrahigh vacuum,
  with a “good” tip (very sharp),
  provided the forces are very carefully controlled.

Tapping mode AFM



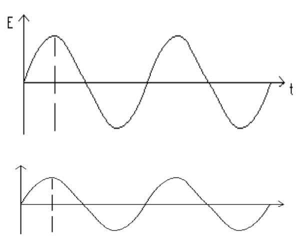
A tip is vibrating when the tip is far away form the sample surface

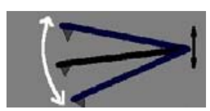
$$Z = A_0 \cdot \cos(\omega t + \varphi_0)$$

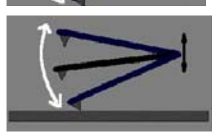


A tip is vibrating when the tip is close to the sample surface, amplitude will vary and phase will shift

$$Z = A_1 \cdot \cos(\omega t + \varphi_1)$$







Tapping mode AFM

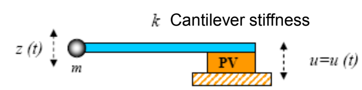
Let the piezo-vibrator harmonically oscillate with the ω frequency:

$$u = u_o Cos(\omega t)$$

Then the movement equation of such oscillatory system will be written down as

$$m\ddot{z} = -k(z-u) - \gamma\dot{z} + F_0$$

where the term, proportional to the first $\gamma\dot{z}$ derivative, takes into account the forces of viscous friction from the air, and by means of the gravity F_0 and other possible constant forces is designated.



Tapping mode AFM

The cantilever makes forced oscillations with a small amplitude about 1 nm. During approach of a tip to a surface the cantilever is affected by an additional force F_{ps} acting from the sample. If the AFM tip is located on distance Z_0 from a surface, then small oscillations can be expressed by

$$F_{PS} = F_{PS0} + \frac{\partial F}{\partial z}(z_0)\cdot z(t)$$

It results to that in the right part of the equation describing oscillations in such system, additional terms appear:

$$m\ddot{z} = -k(z-u) - \gamma\dot{z} + F_0 + F_{PS0} + F_z^{'} z$$

Having divided the equation by *m* and having introduced the parameter of good quality of the system:

$$Q = \frac{\omega_0 m}{\gamma}$$

ω_0 is the frequency of forced oscillation of the tip when the tip is far far from a surface

Tapping mode AFM

By solving the equation, the amplitude-frequency characteristic of a system:

$$A(\omega) = \frac{u_0\omega_0^2}{\sqrt{(\omega_0^2 - \omega^2 - \frac{F_z^{'}}{m})^2 + \frac{\omega^2\omega_0^2}{Q^2}}}$$

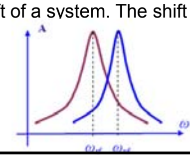
And, accordingly, the phase response: $\varphi(\omega) = arctg\left[\frac{\omega\omega_0}{Q\left(\omega_0^2 - \omega^2 - \frac{F_z^{'}}{m}\right)}\right]$

ω is the frequency of the cantilever as the tip is close to the sample surface.

In this case, the tip has a resonance frequency, ω_{rf}. ω_{rf} is different from the the resonance frequency ω_{rd} . ω_{rd} is corresponding to the case that the tip is far away from the sample surface.

The interaction force of a tip with a surface of a sample results in additional bias of the amplitude-frequency characteristic and the phase shift of a system. The shift of resonant frequency can be presented as

$$\Delta\omega = \omega_{rd} - \omega_{rf} = \omega_{rd}\left(1 - \sqrt{1 - \frac{F'_z}{m\omega_{rd}}}\right)$$



Tapping mode AFM

When the forcedly oscillating tip is approaching the sample surface, the tip-sample interaction resulting in phase shift, consequently leading to dissipation of energy:

$$E_{PS} = \frac{\pi\, k\, u_0 A}{Q} Sin(\varphi) - \frac{\pi\, k\omega\, A^2}{\omega_0 Q}$$

This equation is re-written:

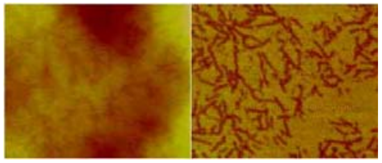
$$Sin\varphi = \frac{\omega\, A}{\omega_0 u_0} + \frac{QE_{PS}}{\pi\, k u_0 A}$$

Phase imaging under tapping mode AFM

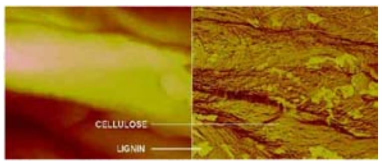
There has been much interest in **phase** imaging. This works by measuring the phase difference between the oscillations of the cantilever driving piezo and the detected oscillations. It is thought that image contrast is derived from image properties such as stiffness and viscoelasticity. Thus the phase imaging mode features:

- Phase lag measures composition, adhesion, friction and viscoelastic properties;
- Identifying two-phase structure of polymer blends;
- Identifying surface contaminants that are not seen in height images;
- Distinguishing the regions of high and low surface adhesion or hardness;
- Less damaging to soft samples than lateral force microscopy;

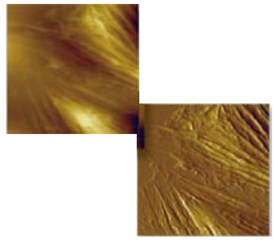
Phase imaging under tapping mode AFM



Topography (left) and phase image (right) of a copolymer surface



Topography (left) and phase image (right) of a wood pulp fiber



Height (left) and amplitude (right) images of living endothelial cells in culture, 50 µm scan, by M. Wright

http://www.asmicro.com/phase.htm

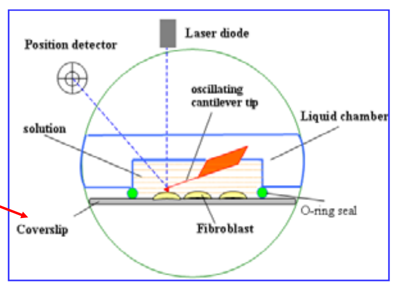
Tapping mode AFM in fluid

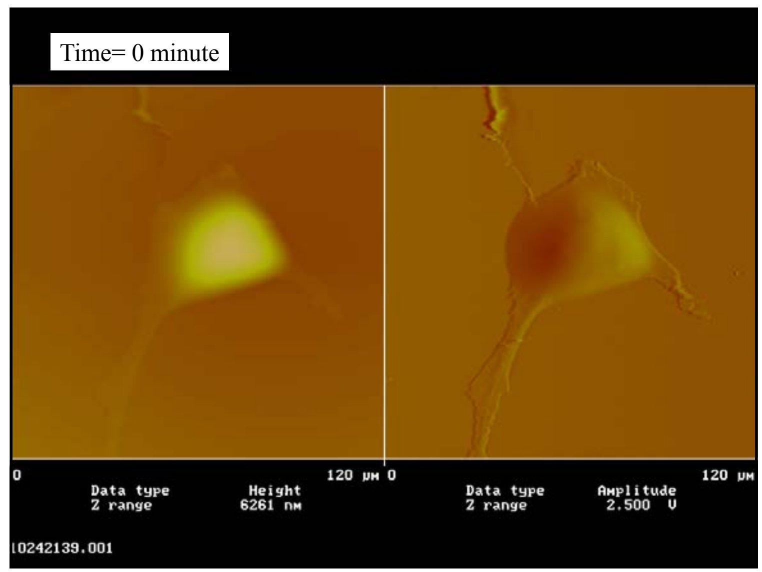
- Tapping mode operation in fluid has the same advantages as in the air or vacuum.
- When an appropriate frequency is selected (usually in the range of 5,000 to 40,000 cycles per second), the amplitude of the cantilever will decrease when the tip begins to tap the sample, similar to Tapping Mode operation in air.
- imaging in a fluid medium tends to damp the cantilever's normal resonant frequency. In this case, the entire fluid cell can be oscillated to drive the cantilever into oscillation.
- Alternatively, the very soft cantilevers can be used to get the good results in fluid. The spring constant is typically 0.1 N/m compared to the tapping mode in air where the cantilever may be in the range of 1-100 N/m

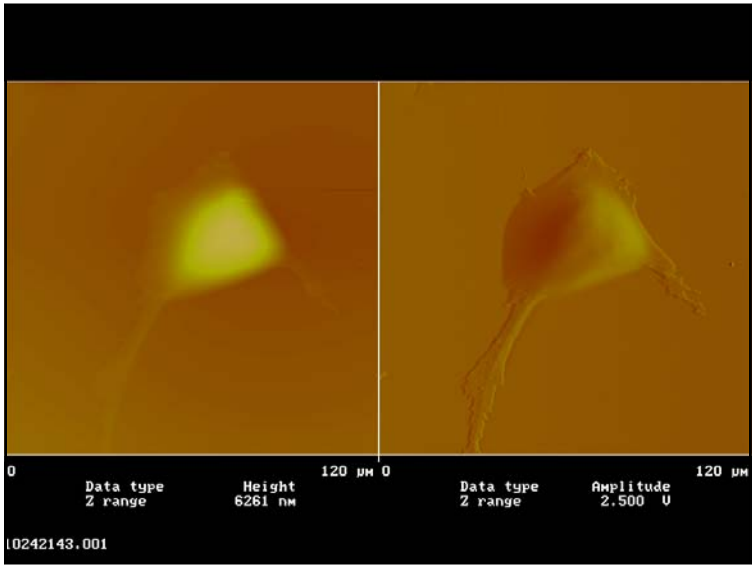
MOVIE

Time-resolved AFM images of a living cell in physiological environment

- Cell: 3T3 fibroblast
- Solution: phosphate buffer solution (PBS), 7.2PH
- real-time image obtained by tapping mode AFM in liquid cell
- Left image: height mode
- Right image: deflection mode



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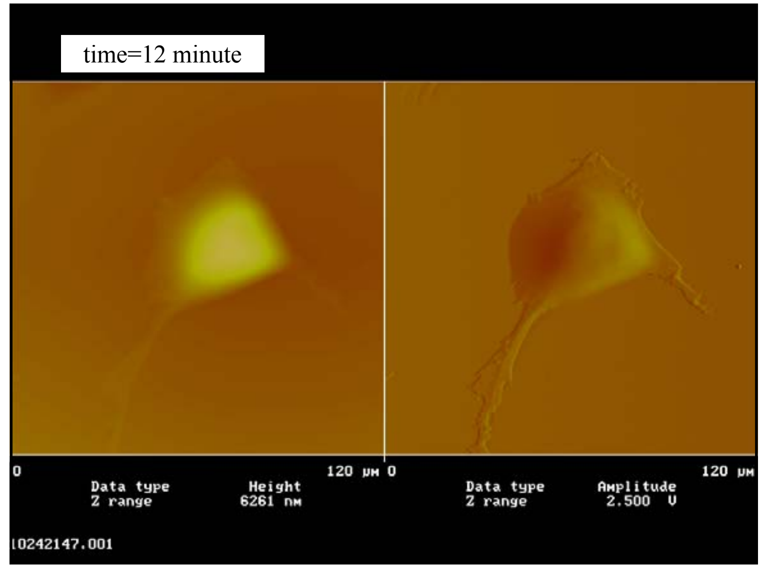
120 µm 0
Data type
Z range
Amplitude
2.500 V
120 µm
10242143.001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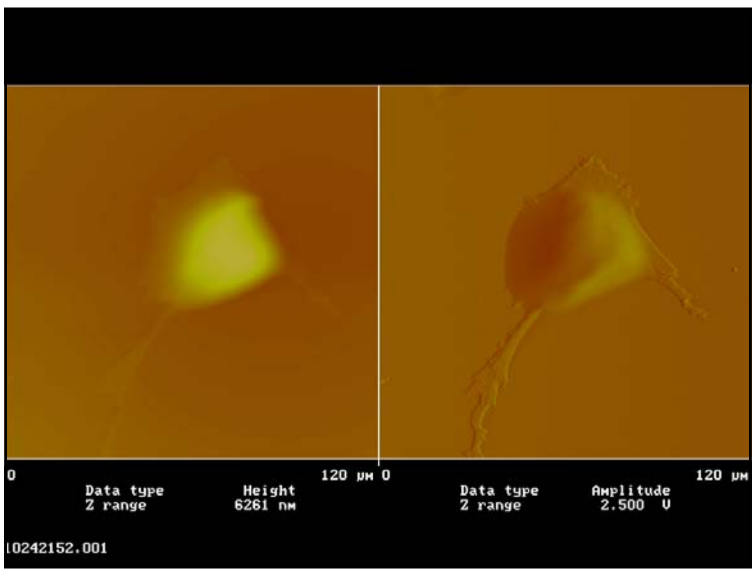
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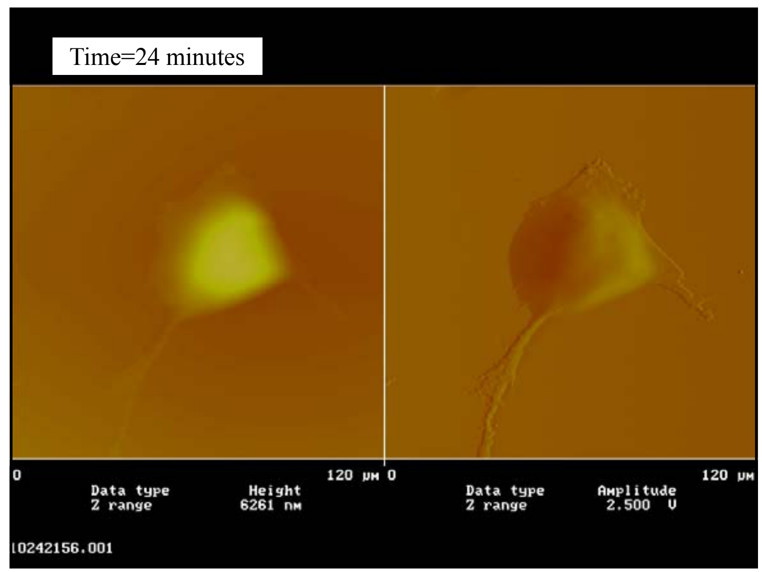
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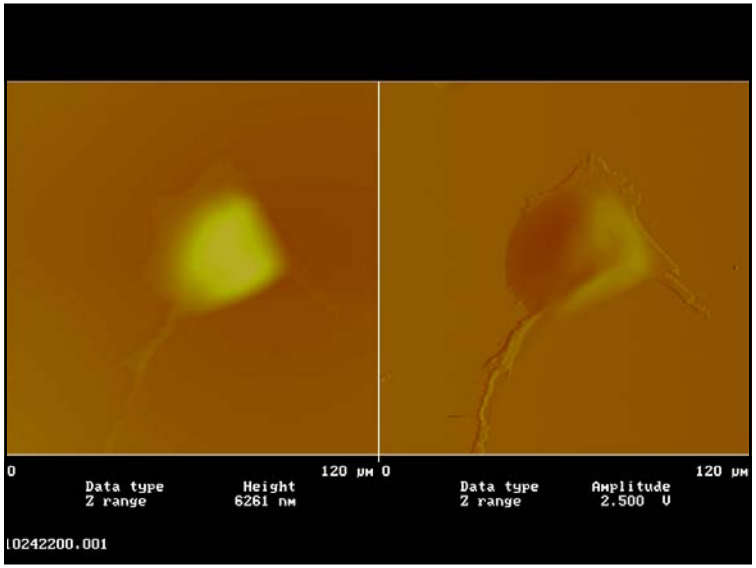
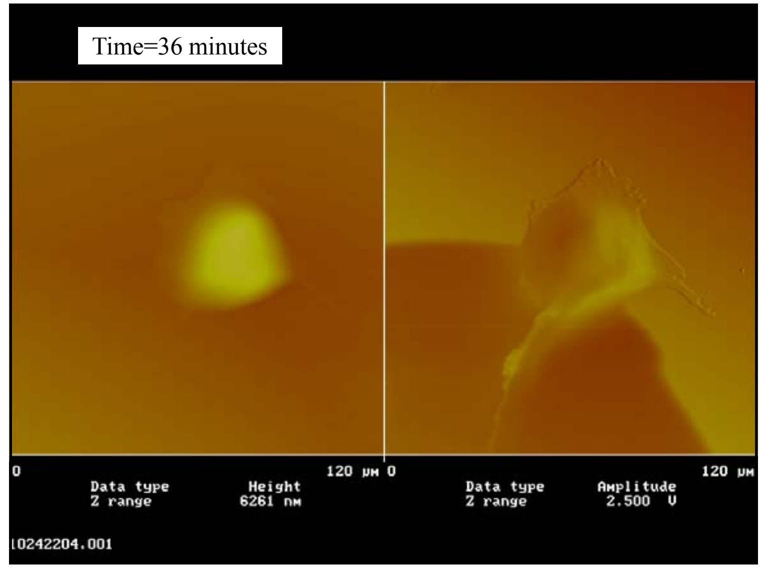
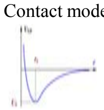
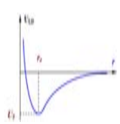




Summary different AFM imaging modes

Imaging mode	Interaction force	Comments
Contact mode 	Strong repulsion-constant force or constant distance	The force on the tip is repulsive with a mean value of ~nN.
Lateral force	Friction force-torque on cantilever	
Non-contact 	Weak attraction-vibrating probe	the tip hovers 5 – 10nm above the sample surface, the fluid contaminant layer is substantially thicker than the range of the Van der Waals force gradient and therefore, attempts to image the true surface with non-contact AFM fail as the oscillating probe becomes trapped in the fluid layer or hovers beyond the effective range of the forces
Tapping mode	Strong repulsion--vibrating probe	

Comparison of contact mode with tapping mode

Contact Mode AFM

- Operation is easy, High speed scanning rate.
- Suitable for the relatively hard surface
- Use of tips with low spring constant cantilever can improve the sensitivity
- In addition, a large class of samples, including semiconductors and insulators, can trap electrostatic charge (partially dissipated and screened in liquid). This charge can contribute to additional substantial attractive forces between the probe and sample.
- Problems with contact mode are caused by excessive forces applied by the tip to the sample

Tapping Mode AFM

- allow high resolution topographic imaging of sample surfaces that are easily damaged, loosely hold to their substrate, or difficult to image by other AFM techniques, in particular, tapping mode is extensively used for biological sample such as DNA, proteins and living cells;
- the high frequency (50k - 500k Hz) makes the surfaces stiff (viscoelastic), and the tip-sample adhesion forces is greatly reduced;
- topography image and phase image can be acquired simultaneously. And Phase image is used to distinguish two components with different stiffness or viscoelasticity;
- Lower speed scanning rate compared with contact mode

Imaging modes under Scanning Probe Microscopy umbrella

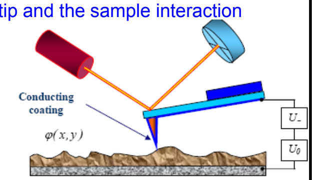
Our course will cover the techniques highlighted in blue

- Contact mode AFM
- friction (lateral) force microscopy (FFM or LFM)
- force modulation microscopy (FMM)
- dynamic or AC atomic force microscopy (tapping mode, noncontact)
- electrostatic force microscopy (EFM),
- magnetic force microscopy (MFM)
- scanning Kelvin Probe microscopy (SKPM)
- scanning tunneling microscopy (STM)
- conducting AFM (C-AFM)
- scanning near field optical microscopy (SNOM or NSOM)
- scanning acoustic or ultrasonic force microscopy (SAFM),
- scanning thermal microscopy (SThM)
- scanning electrochemical microscopy (SECM)
- scanning ion conductance microscopy (SICM)

Electrostatic force microscope (EFM)
Scanning Kelvin probe microscope (SKPM)

Measurement of electric interaction between the tip and the sample interaction

- A dielectric film on the conducting substrate;
- A conducting substrate;
- AC bias $U_{\sim}$ is applied between the tip and the sample;
- Surface potential $\varphi(x,y)$ is built on the surface of the dielectric film.



Let the U_0 constant and $U_{\sim} = U_1 \cdot Sin(\omega t)$ variable voltages be applied, the voltage between a tip and a sample surface can be presented as

$$U = U_0 + U_1 Sin(\omega t) - \varphi(x,y)$$

The tip-sample system has some electric capacity C so that the energy of such system can be presented in the following form:

$$E = \frac{CU^2}{2}$$

EFM and SKPM

Then electric force of tip-sample interaction is equal to

$$\vec{F} = -grad(E)$$

its Z-component can be presented as

$$F_z = -\frac{\partial E}{\partial z} = -\frac{1}{2}U^2\frac{\partial C}{\partial z}$$

Thus, the Z-component of the electric force is equal to

$$F_z = -\left\{\frac{1}{2}\left((U_0 - \varphi(x,y))^2 + \frac{1}{2}U_1^2\right) + [U_0 - \varphi(x,y)] \cdot U_1 Sin(\omega t) - \frac{1}{4}U_1^2 Cos(2\omega t)\right\} \times \frac{\partial C}{\partial z}$$

First term: constant component $F_{z(\omega=0)} = -\left\{\frac{1}{2}\left((U_0 - \varphi(x,y))^2 + \frac{1}{2}U_1^2\right)\right\} \times \frac{\partial C}{\partial z}$

Second term: component with ω frequency $F_{z(\omega)} = -[(U_0 - \varphi(x,y)) \cdot U_1 Sin(\omega t)] \times \frac{\partial C}{\partial z}$

-- SKPM

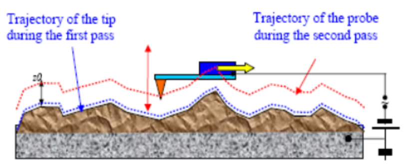
Third term: component with 2ω frequency $F_{z(2\omega)} = \left\{\frac{1}{4}U_1^2 Cos(2\omega t)\right\} \times \frac{\partial C}{\partial z}$

--EFM

EFM

$$F_{z(2\omega)} = \left\{\frac{1}{4}U_1^2 Cos(2\omega t)\right\} \times \frac{\partial C}{\partial z}$$ Dependent on 2ω frequency

Detecting of the cantilever oscillation amplitude with 2ω frequency allows to investigate the surface distribution on the nanoscale - a capacity derivative with respect to the z-coordinate (so-called capacitance microscopy). it is to study local dielectric properties of subsurface layers of samples.

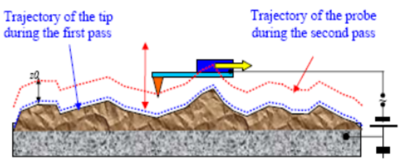


During the first pass cantilever oscillations are excited by the piezo-vibrator with a frequency close to the resonant frequency ω, and the topography AFM profile is obtained .
Then the probe is retracted from a surface to the distance, a variable voltage is applied, and scanning is repeated. During the second pass the probe moves above a surface with a trajectory repeating the topography of a sample. changes of cantilever oscillation amplitude with the 2ω frequency will be connected to the change of a tip-sample system capacity due to the change of dielectric properties of a sample

SKPM

$$F_{s(\omega)} = -[(U_0 - \varphi(x,y)) \cdot U_1 Sin(\omega t)] \times \frac{\partial C}{\partial z}$$ Component dependent on ω frequency

The signal detection with the ω frequency allows to study the distribution of surface potential ϕ *(x,y)* (so-called Kelvin Probe)

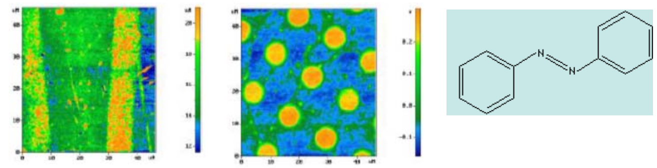


$$U_O = \varphi(x,y)$$

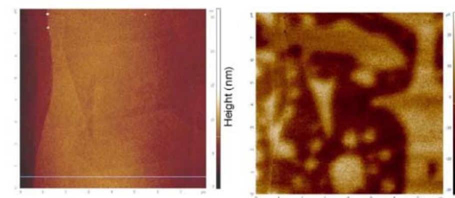
During the first pass cantilever oscillations are excited by the piezo-vibrator with a frequency close to the resonant frequency ω, and the topography AFM profile is obtained.

Then the probe is retracted from a surface to the distance, a variable voltage is applied, and scanning is repeated. With the help of a readjusted source the constant U_0 voltage value is selected so that the cantilever oscillation amplitude with the ω frequency becomes equal to zero. It occurs if $U_0 = \phi(x,y)$ in the given point of a surface.

SKPM and EFM images



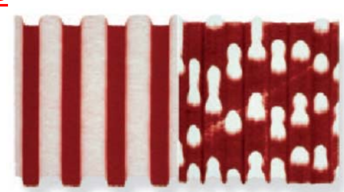
Surface topography (left) and distribution of superficial potential (right) of a azobenzene film, By Stiller



Topography (left) and EFM (image) of graphite
By Yonghua Lu, P. Esquinazi, and M. Muñoz, etal

SKPM and EFM images

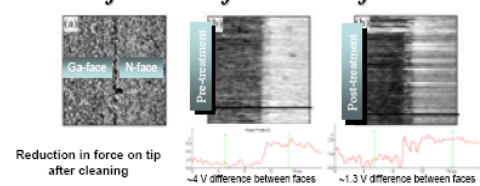
Topography (left) and Surface Potential (right) images of a nanowire between two metal contacts with biased applied between them. 2µm x 1µm scans. Sample courtesy of Philips Corp., The Netherlands.



Topography (left) and Kelvin probe image (right) of a CD-RW, locating the position of the bits. by Yasudo Ichikawa, Toyo Corporation, Tokyo, Japan. 5µm scans.

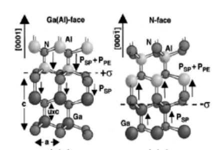
EFM images

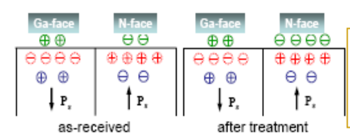
EFM before and after HCl surface treatment

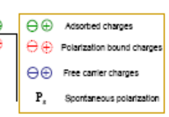


Surface topography (left), and EFM images (right),

by Brian J. Rodriguez, Alexei Gruverman,







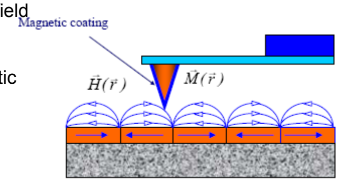
O. Ambacher, JAP, 87, 334,

For Ga-face, both charge and potential are the same before and after the treatment.

The change in potential must come from an increase in adsorbed charge on the N-face.

Magnetic force microscopy (MFM)

Generally the interaction of the MFM tip with a field of a sample represents a considerably complex problem. We shall consider the MFM tip as a single magnetic dipole described by the magnetic moment, $\vec{m}$, as the simplest model. Potential energy of such system is equal to:



$$w = -(\vec{m}\vec{H})$$

The magnetic dipole is influenced in the $\vec{H}$ field by the following force:

$$\vec{f} = -grad(w) = \vec{\nabla}(\vec{m}\vec{H})$$

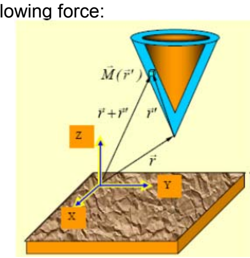
and the moment of forces is equal to

$$\vec{N} = [\vec{m}\vec{H}]'$$

Then full energy of magnetic interaction of a tip and a sample can be presented in the following form:

$$W_{\text{маг}} = -\int_{\vec{r}_p} \vec{M}(\vec{r}')\cdot\vec{H}(\vec{r}+\vec{r}')dV'$$

where $\vec{M}$ is specific magnetization of a magnetic covering, dV is elementary volume.



Magnetic force microscopy (MFM)

the interaction force of a tip with a field of a sample is equal to

$$\vec{F} = -grad(W_{\text{маг}}) = \int_{\vec{r}_p} \vec{\nabla}(\vec{M}\vec{H})dV'$$

Accordingly, the Z-component of a force is as follows:

$$F_z = -\frac{\partial W_{\text{маг}}}{\partial z} = \int_{\vec{r}_p}\left(M_x\frac{\partial H_x}{\partial z} + M_y\frac{\partial H_y}{\partial z} + M_z\frac{\partial H_z}{\partial z}\right)dV''$$

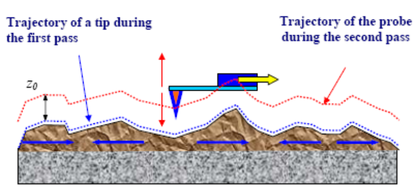
Magnetic force microscopy (MFM)

The two-pass technique is applied for MFM researches of magnetic samples with a considerable topography of a surface.

On the first pass the AFM image of a topography in a contact mode is obtained.

Then the tip is retracted from a surface to a distance, and the scanning is repeated.

The distance is selected so that the van der Waals force is less than the magnetic interaction force.

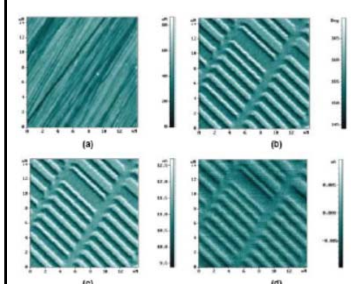


Since the local distance between the tip and a surface in every point is constant in this case, changes of a cantilever bend during scanning are connected to the heterogeneity of the magnetic forces affecting the tip from a sample.

MFM-tapping mode

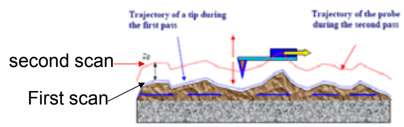
Application of oscillatory techniques in the MFM allows to implement high sensitivity and to receive better MFM images of samples.

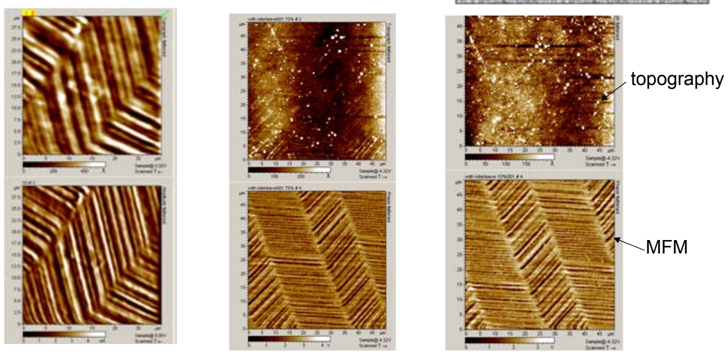
Presence of a force gradient results in the resonant frequency change, and consequently, in the amplitude variation and phase response shift in a tip-sample system.



MFM image of a magnetic disk surface:
(a) AFM topography;
(b) MFM phase contrast;
(c) MFM amplitude contrast;
(d) MFM image of distribution of tip-surface force interaction

MFM





First scan far away from surface

First scan close to surface

Acknowledgement

References

- V. L. Mironov, Fundamentals of scanning probe microscope,