Surface analysis

Lecture 4: functional AFM/SFM techniques

KPFM (Kelvin Probe) and other electrical force sensing techniques

MFM (magnetic force microscopy)

Nano-lithography

Nano - indentation

SNOM,

SThM, TERS

SICM

- Summary

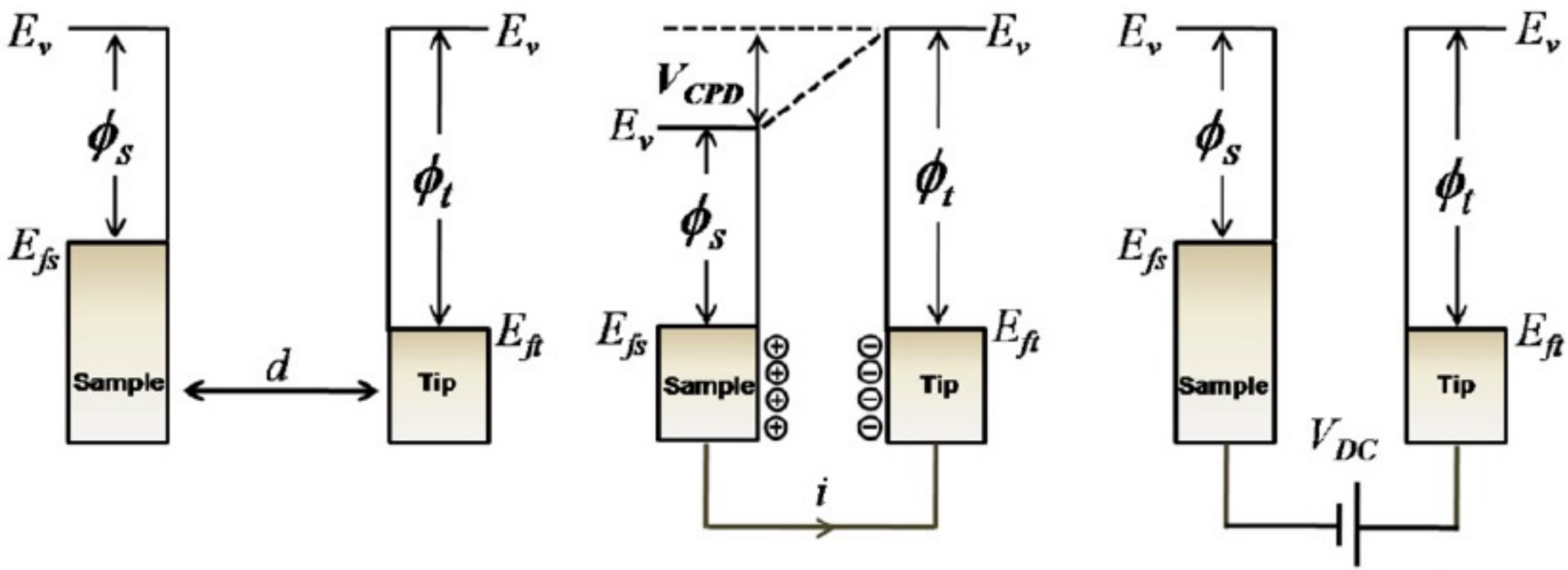
exam: Friday 23.01 (please verify later, changes are possible!)

Kelvin probe force microscopy (KPFM)

• KFPM is a NC-AFM technique that measures the local potential difference between the sample and probe. This can be used for mapping work function or surface potential

• The fundamentals of KPFM are illustrated by energy level diagrams below, where ϕ_s and ϕ_t stand for workfunctions of sample and tip, separating corresponding Fermi levels and vacuum levels.

- Left image: the tip and sample are separated and electrically disconnected
- Central image: Equilibrium is established, which means the Fermi levels of tip and sample are aligned. The tip and sample surfaces are charged, there is Contact Potential Difference (CPD) – called hereafter V_{CPD}
- Right image: An external bias is applied in order to nullify V_{CPD}



Kelvin probe force microscopy (KPFM)

• *By applying to the sample AC + DC voltage one can measure and map the work function of the sample.*

The electrostatic force between the tip and sample is: $F_{es}(z) = \frac{1}{2}\Delta V^2 \frac{dC(z)}{dz},$

where $\frac{dC(z)}{dz}$ is capacitance gradient and ΔV is the potential difference

When $V_{AC}\sin(\omega t) + V_{DC}$ is applied to the tip: $\Delta V = (V_{DC} \pm V_{CPD}) + V_{AC}\sin(\omega t)$

$$F_{es}(z,t) = -\frac{1}{2}\frac{\partial C(z)}{\partial z}\left[(V_{DC} \pm V_{CPD}) + V_{ac}\sin(\omega t)\right]^2$$

This equation can be divided into three parts:

$$F_{DC} = -\frac{\partial C(z)}{\partial z}\left[\frac{1}{2}(V_{DC} \pm V_{CPD})^2\right]$$

- Static deflection

$$F_{\omega} = -\frac{\partial C(z)}{\partial z}(V_{DC} \pm V_{CPD})\,V_{AC}\sin(\omega t)$$

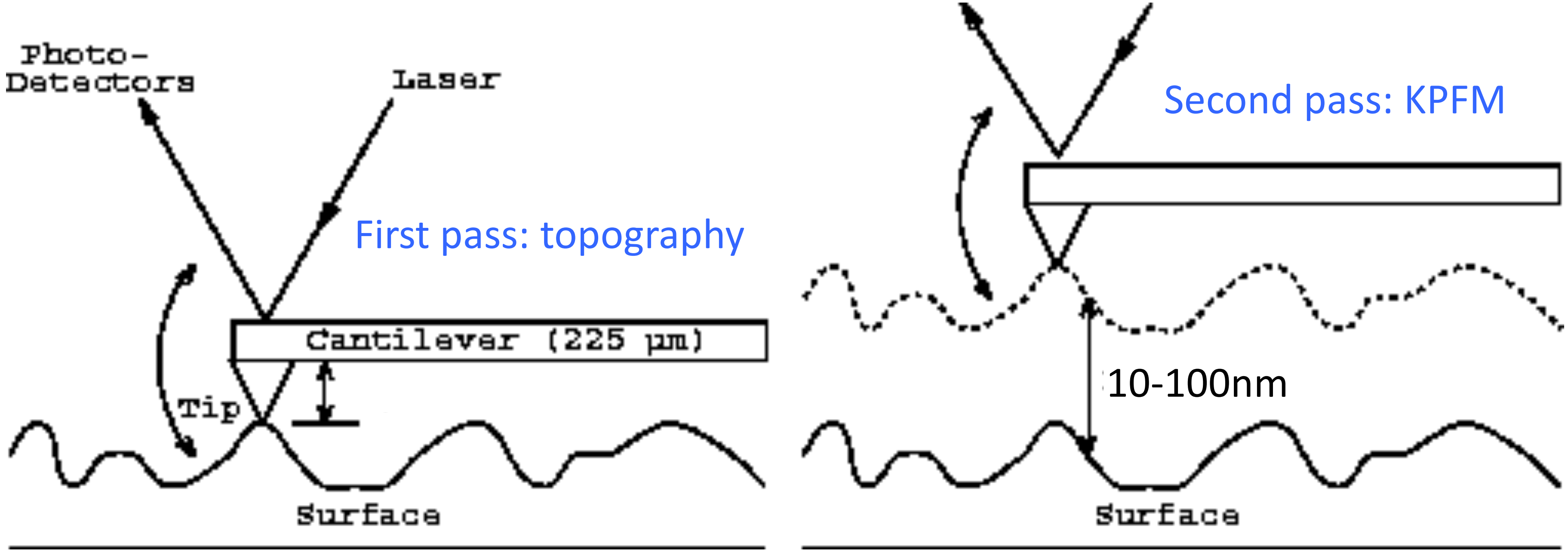
- Response at ω is proportional to $(V_{DC} \pm V_{CPD})$ - nullified by adjusting V_{DC}

$$F_{2\omega} = \frac{\partial C(z)}{\partial z}\frac{1}{4}V_{AC}^2\left[\cos(2\omega t) - 1\right].$$

- Response at 2ω used for capacitive microscopy

KPFM: two pass approach

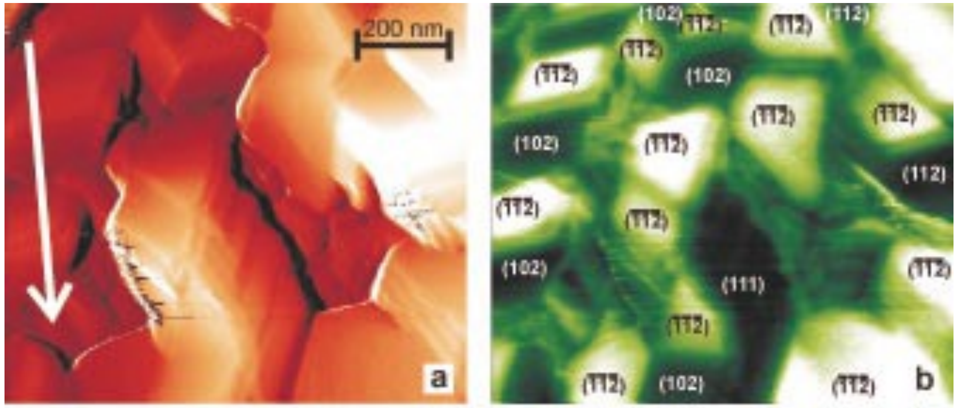
KPFM is generally performed in combination with topography imaging. Two-pass scan is a useful technique to avoid crosstalk between two sets of data.
For accurate KPFM data the tip-sample distance should be unchanged
Technically it is implemented as follows:
AFM operates in non-contact or tapping mode. Initially a line is scanned in topography mode and the height profile h(x) is collected. Then the tip is retracted by some 10-100 nm and same line is traced again. During the second trace the scanner continuously adjust the tip height in order to follow the height profile



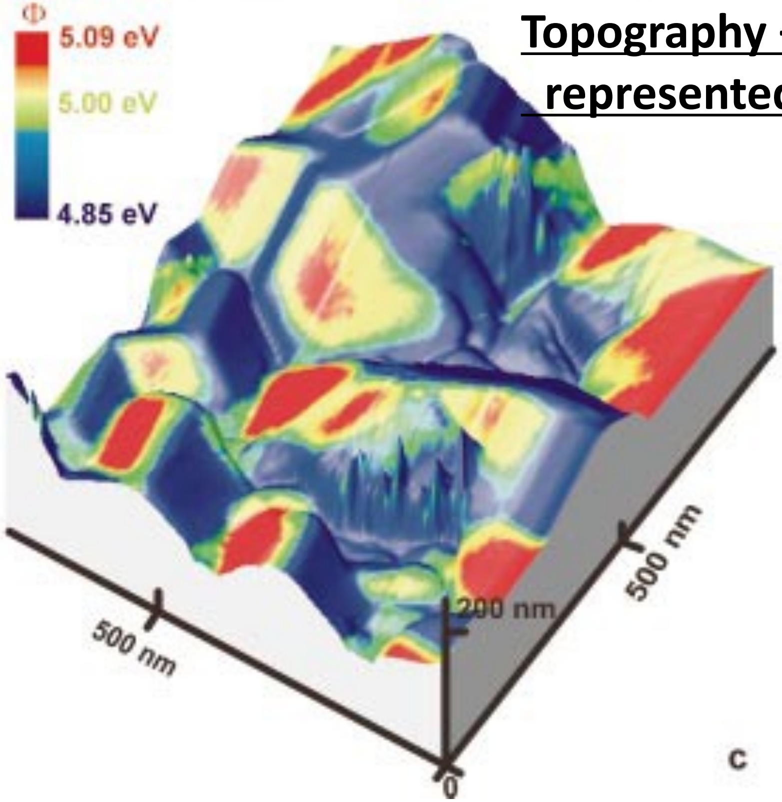
The two-pass approach is not necessary for atomically flat substrate. In this case instead of getting detailed topography the slope of the surface in X and Y direction is detected. Then the tip is retracted to required distance and KPFM data are collected

Kelvin probe force microscopy (KPFM): examples

<u>**topography**</u> <u>**Topography + Φ**</u>

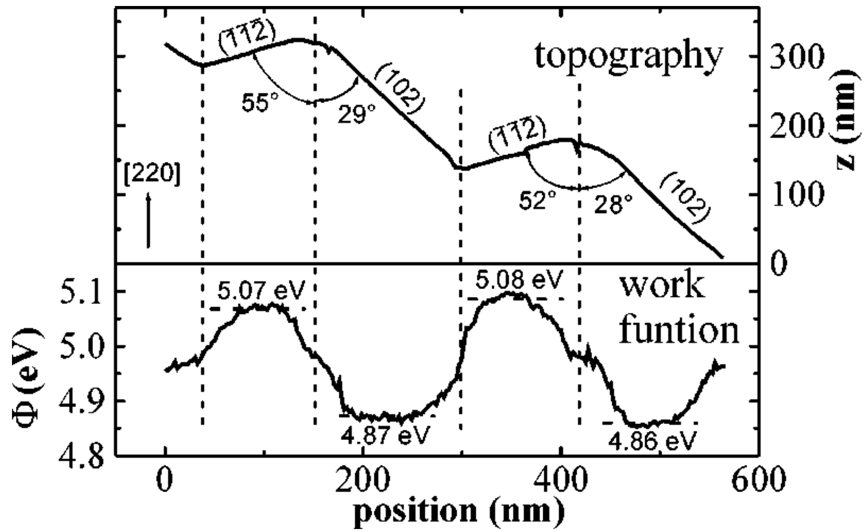


<u>**Topography + Φ represented in 3D**</u>



In this example the tetragonal solar cell material $CuGaSe_2$ has been studied by KPFM in order to measure the work function variation between differently oriented crystal facets.
This difference is of high practical importance since it influences the band bending of solar cell heterostructures and impacts the solar power conversion efficiency

<u>**The topography and work function profiles**</u>



S. Sadewasser et al., Appl. Phys. Letters, 80, 2979 (2002)

Kelvin probe force microscopy (KPFM)

• KPFM is a NC-AFM technique where the electrostatic force is measured at frequency ω. A lock-in amplifier is used in order to extract the signal at this frequency, which is proportional to (V_{DC}-V_{CPD})

• Thus V_{AC} generates oscillating electrical forces between the AFM tip and sample surface and V_{DC} nullifies the forces originating from CPD between the tip and sample. So scanning the surface with ***Kelvin feedback*** results in a map of V_{dc} (x,y) , which reflects distribution of the surface potential along the sample surface.

$$V_{CPD} = \frac{\phi_{tip} - \phi_{sample}}{-e}$$

• Knowing the work function of the tip one can calibrate the map in order to obtain the workfunction of the material

• The work function is highly sensitive to surface change (contamination, oxidation, band bending due to surface states…). Work in ultra-high vacuum and special tip preparation help precise measurements of work function.

• Apart from measurements at ω, one can use the conventional topographic scan methods at the resonance frequency (independently of the above). Thus, in one scan, the topography and the contact potential of the sample are determined simultaneously.

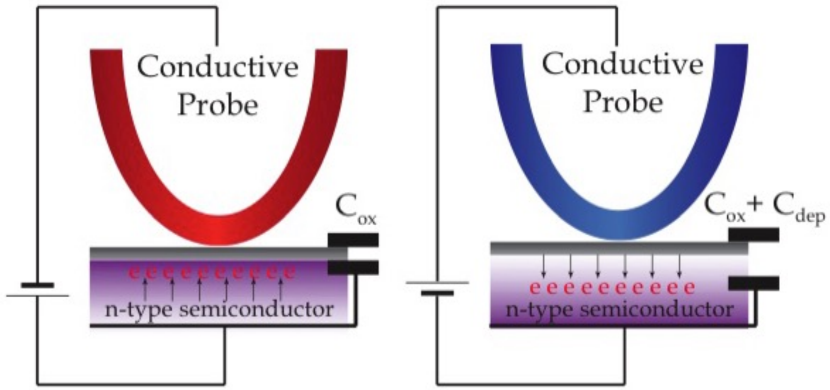
Explanation of KPFM from Park systems: https://www.youtube.com/watch?v=54OG7Yi-iMw

Scanning Capacitance Microscopy

SCM mode: **characterizes the surface of the sample using information obtained from the change in electrostatic capacitance between the surface and the probe. It is used for imaging dopant variations in semiconductor devices; quantification of local dielectric properties.**

$$F_{2w} = \frac{1}{4}\frac{dC}{dz}V_{ac}^{2}\cos(2wt)$$

2nd harmonic depends only on *dC/dz* and V_{ac}

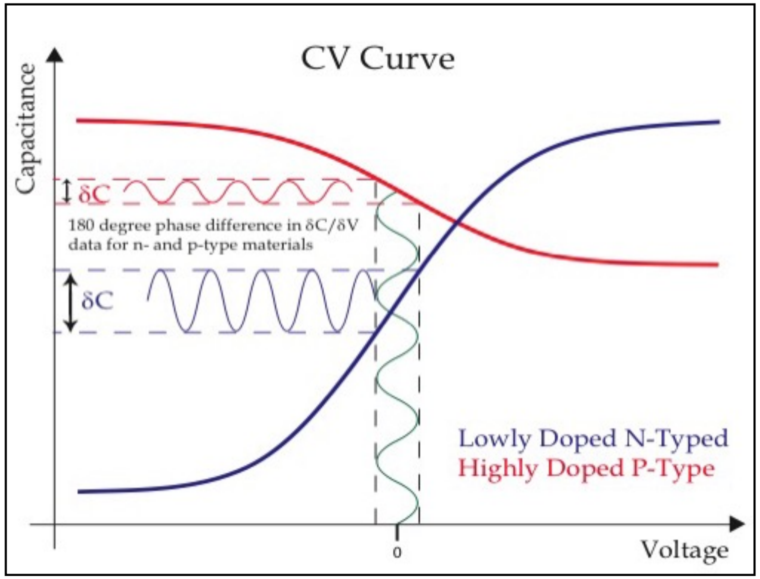


The capacitance measured by the SCM sensor varies as the carriers move towards (accumulation) and away from (depletion) the probe.

Scanning Capacitance Microscopy

The magnitude of capacitance change with the applied AC bias gives information about the concentration of carriers (SCM amplitude data), whereas the difference in phase between the capacitance and the applied bias carries information about the sign of the charge carriers (SCM phase data)

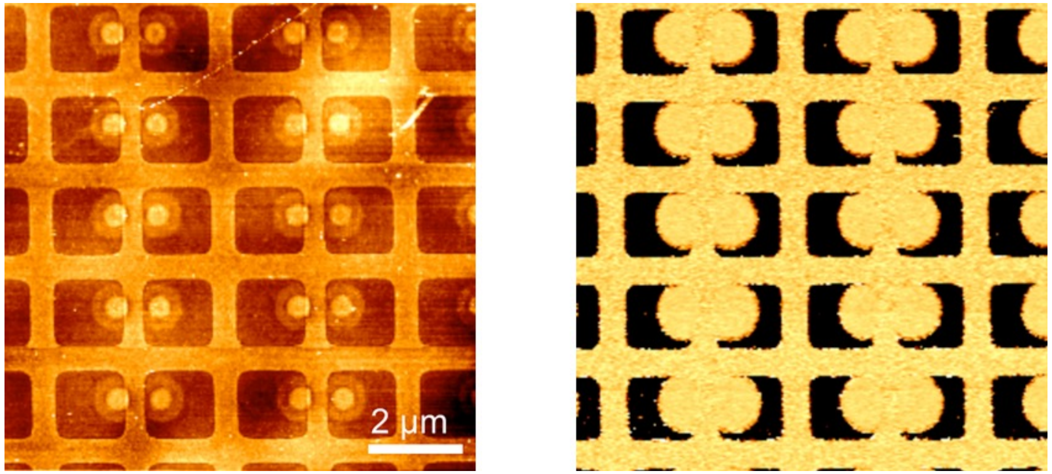
Capacitance vs voltage (p, n-doping)



The C-V curve and dC/dV for both n- and p-type materials. Notice both the change in amplitude as a function of doping concentration and the phase shift with dopant species.

Scanning Capacitance Microscopy

topography phase



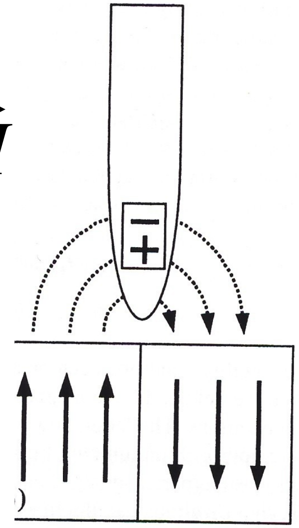
Ion implanted pattern on Si wafer (low p-doping) is imaged by SCM.

Left - topography, right - SCM phase map showing the dopant polarity (n-doping)

Magnetic force microscopy: an overview

In MFM measurements, the magnetic force between the sample and tip can be expressed (in point dipole approximation) as:

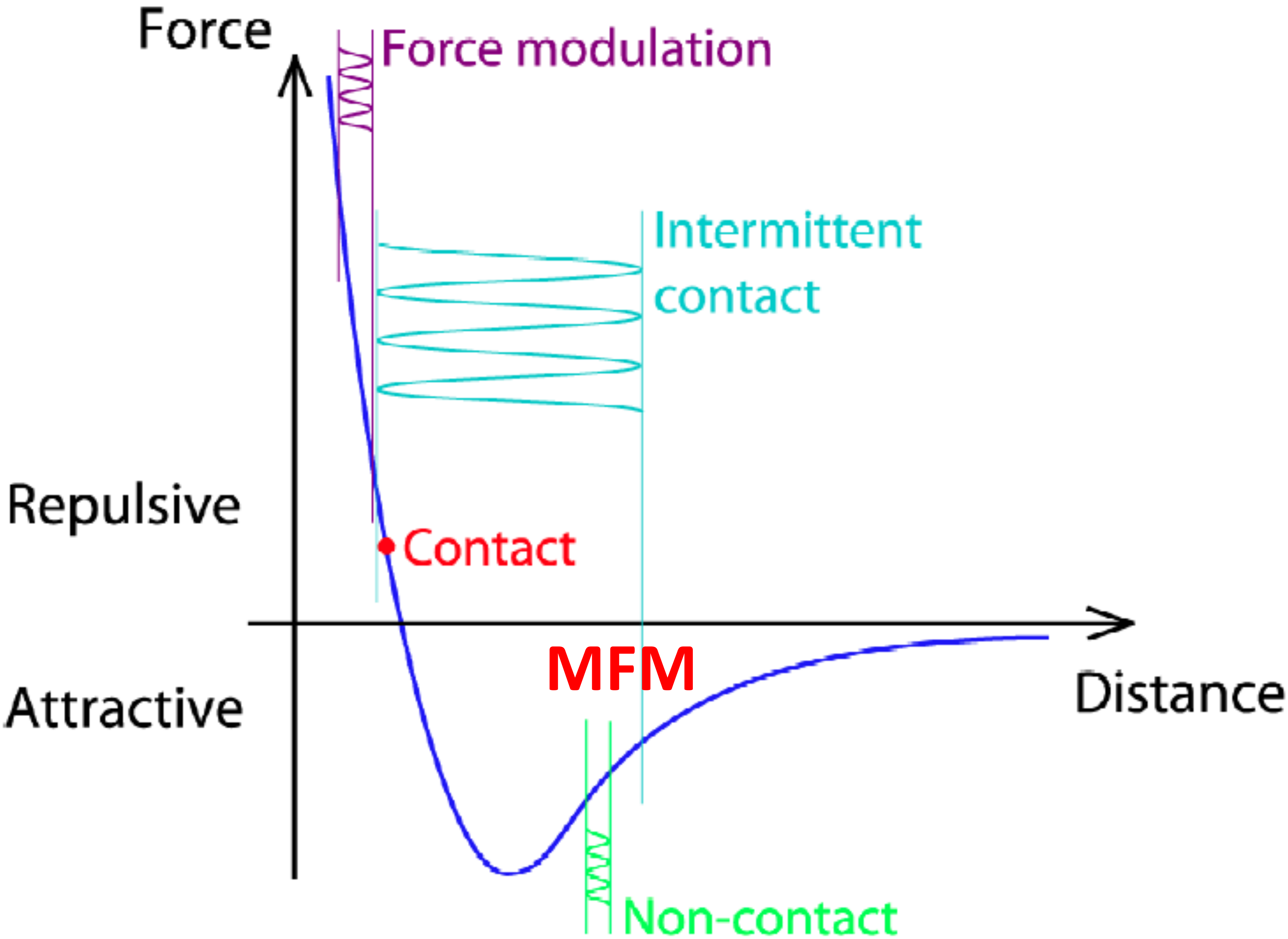
$$\vec{F} = \mu_0 (\vec{m} \cdot \nabla) \vec{H}$$



Here $\vec{m}$ is the magnetic moment of the tip approximated as a point dipole, ***H*** is the magnetic stray field from the sample surface.
For calculating the total force the integration has to be performed over the volume and the magnetic domain configuration needs to be known.
MFM relies on long-range interactions, hence the resolution is limited (generally about 50-100nm, some state-of-art results show 10-20 nm)

Despite the difficulties with quantitative analysis MFM is a widely used and attractive technique for imaging magnetic domains. Its essential features can be summarized as follows:

- The sample does not need to be electrically conductive.
- Measurement can be performed at wide temperature range, in liquid environment, or in air
- Measurement is nondestructive (if domains are not affected by magnetic field of the tip)
- Long-range magnetic interactions are not sensitive to surface contamination.
- No special surface preparation or coating is required (measurements through coating are also possible)
- Deposition of thin non-magnetic layers on the sample does not alter the results.
- MFM is a non-contact technique. It is often done in combination with topography mapping to avoid crosstalk between the topography and magnetic features.

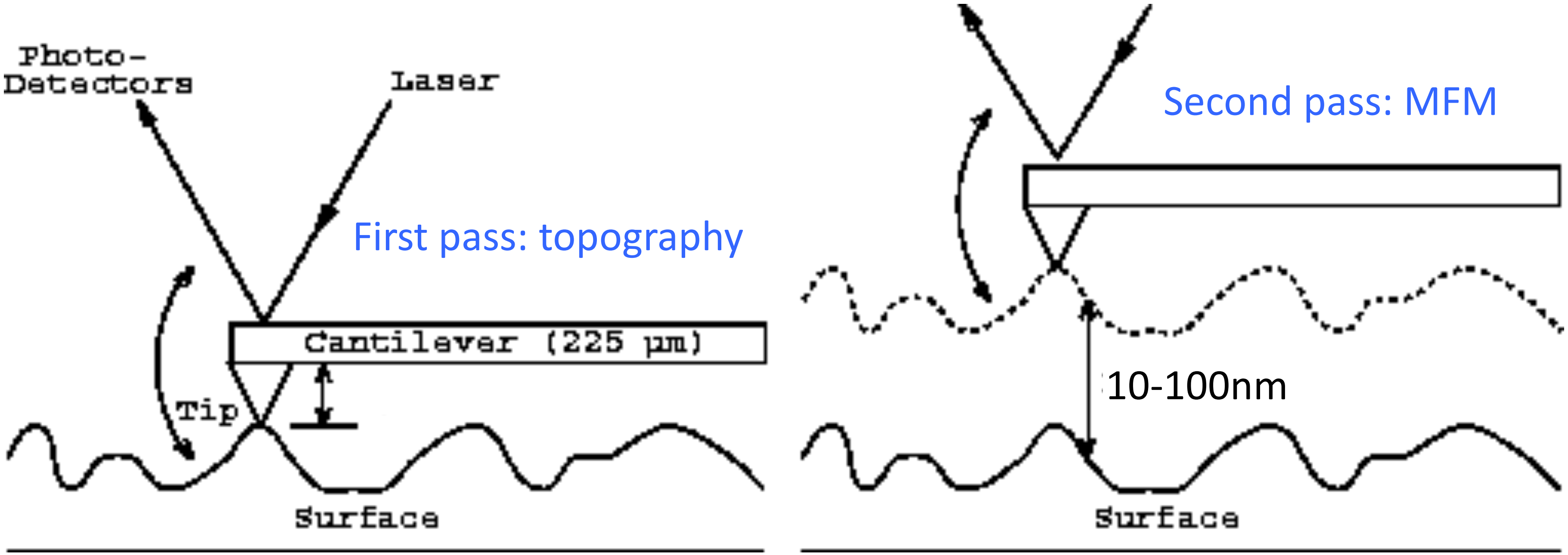

Force
Force modulation
Intermittent
contact
Repulsive
Contact
MFM
Attractive
Distance
Non-contact

Magnetic force microscopy

MFM is generally performed in combination with topography imaging. Two-pass scan is a useful technique to avoid crosstalk between two sets of data.

Technically it is implemented as follows:

AFM operates in non-contact or tapping mode. Initially a line is scanned in topography mode and the height profile h(x) is collected. Then the tip is retracted by some 10-100 nm and same line is traced again. During the second trace the scanner continuously adjust the tip height in order to follow the height profile

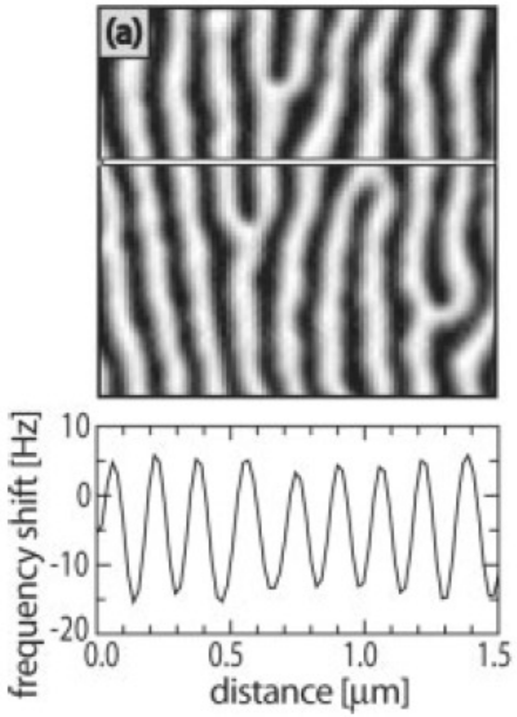


The two-pass approach is not necessary for atomically flat substrate. In this case instead of getting detailed topography the slope of the surface in X and Y direction is detected. Then the tip is retracted to required distance and MFM data are collected

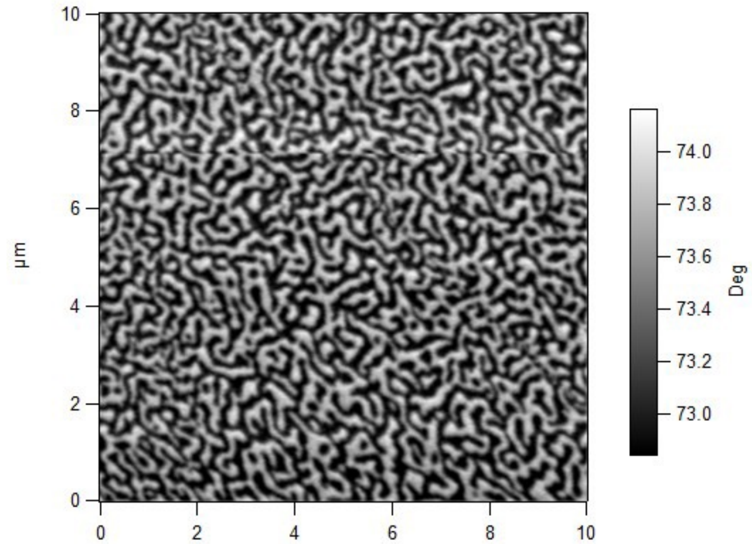
Magnetic force microscopy: examples

Magnetic domain structure of
Co/Pt multilayered sample

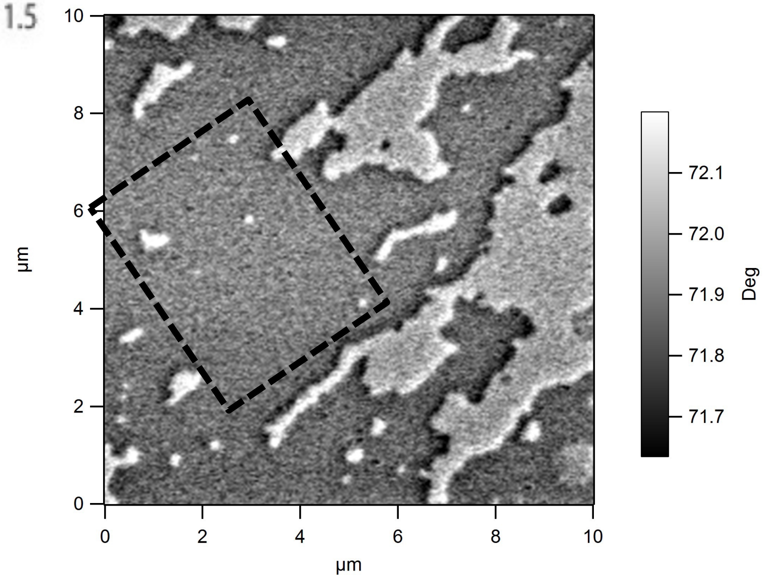
P. Kappenberger et al., Adv. Eng. Materials, 7, 332 (2005)



Magnetic domain structure of
FePt ultrathin layer (2nm), RT



Co 1nm + PVDF



Magnetic domain structure of ultra-thin Co layer (1 nm), RT
20 nm of PVDF polymer is deposited on top of Co,
MFM is taken at the distance of 60nm

Black rectangular: the magnetic domains are erased by inducing electrical polarization charge in the marked area

Magnetic force microscopy: probes

Tip Schematic

Geometry:	Standard (Steep)
Tip Height (h):	10 - 15μm
Front Angle (FA):	25 ± 2.5°
Back Angle (BA):	15 ± 2.5 °
Side Angle (SA):	22.5 ± 2.5 °
Tip Radius (Nom):	35 nm
Tip Radius (Max):	50 nm
Tip SetBack (TSB)(Nom):	15 μm
Tip Set Back (TSB)(RNG):	5 - 25 μm
Tip Coating:	Magnetic

Cantilever Specification

Cantilever schematic

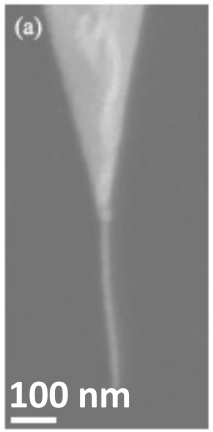
Material:	0.01 - 0.025 Ωcm Antimony (n) doped Si
Geometry:	Rectangular
Cantilevers Number:	1
Cantilever Thickness (Nom):	2.75 μm
Cantilever Thickness (RNG):	2.0 - 3.5 μm
Front Side Coating:	Magnetic CoCr
Back Side Coating:	Reflective CoCr

https://www.brukerafmprobes.com/p-3948-mesp-v2.aspx

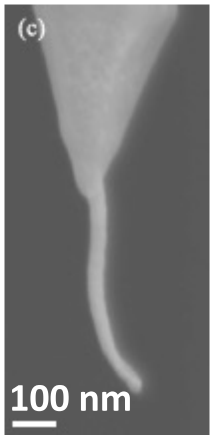
- Magnetic tips with different magnetic coating (e.g. Cr-Co) are commercially available.
- The tip radius is relatively large (30 – 100 nm)
- There is a choice of tips with different magnetic moments and coercive fields (from <10 Oe to 1000 Oe)

- The tips typically need to be magnetized before measurements
- In-situ magnetic coating is used for some special measurements in UHV

5 nm Co



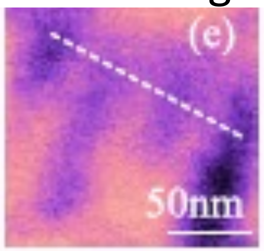
15 nm Co



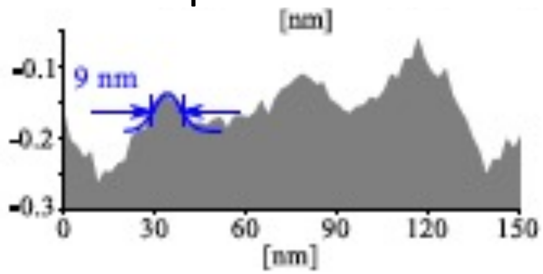
- Special solution for high-resolution MFM: Co-coated carbon nanotube

Y. Lisunova et al. Nanotechnology, 24, 105705 (2013)

MFM image



Line profile

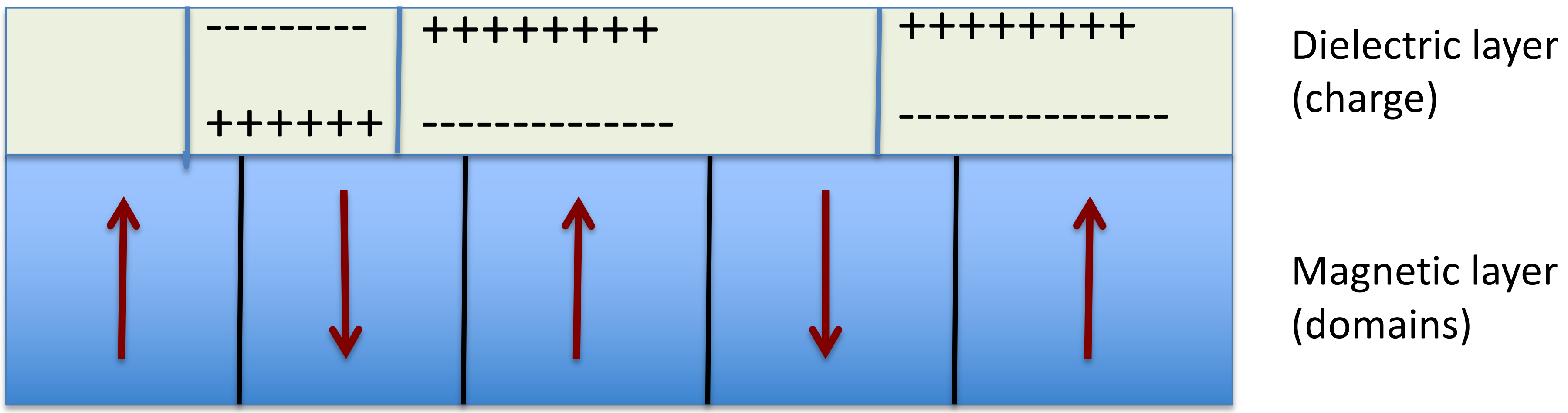


Practical question: MFM in multilayer structure with electrostatic interaction

In this example a thin magnetic layer is covered with a ferroelectric polymer layer
The polymer layer accumulates and retains for long time electrostatic charge
(this charge can be introduced during polarization switching or due to the temperature change)

Because of this charge the electrostatic forces mask magnetic domain contrast picture.

- Propose an experimental technique to see magnetic domains by MFM



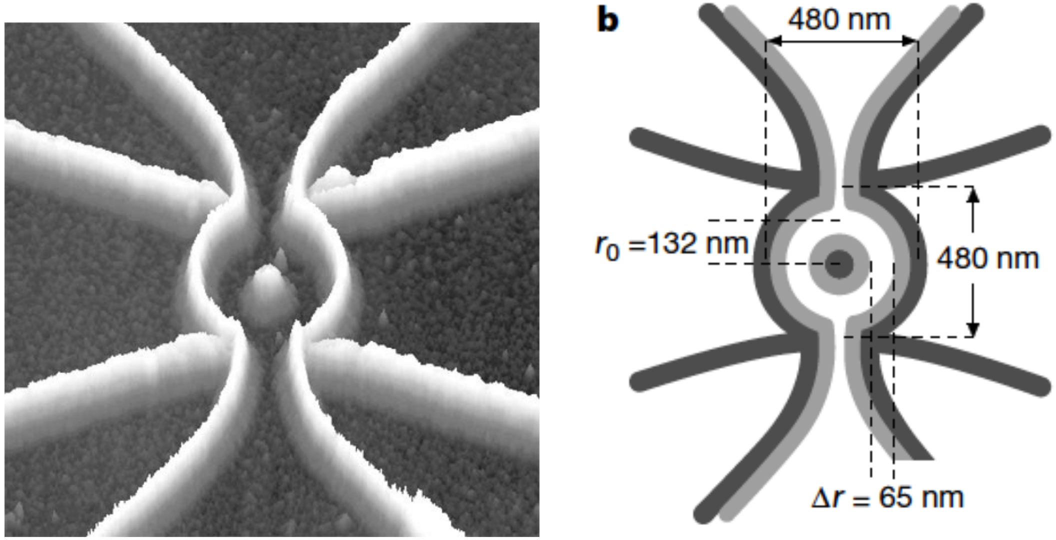
Lectures on YouTube, PFM, KPFM and other related techniques

Useful lectures from ORNL team

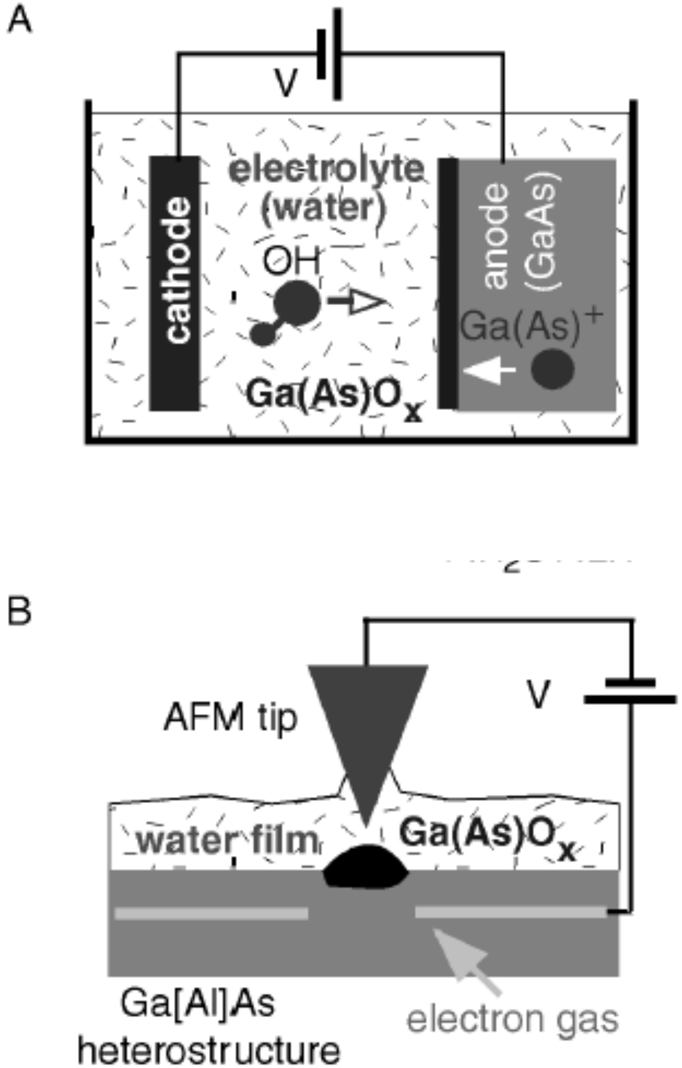
- PFM
  - https://www.youtube.com/watch?v=UsyRW2_Kp-Y
  - https://www.youtube.com/watch?v=BDmXUt4OOuY
  - And others in the series
- KPFM and other electrical methods
  - https://youtube.com/watch?v=WB0s9cwIuxM
  - https://youtube.com/watch?v=PjjjXij7930
  - And others in the series

These lectures provide insights into various aspects of functional SPM methods
(Not required for the exam)

AFM lithography: local oxidation using surface water layer



A. Fuhrer et al. NATURE | VOL 413, 822 (2001)



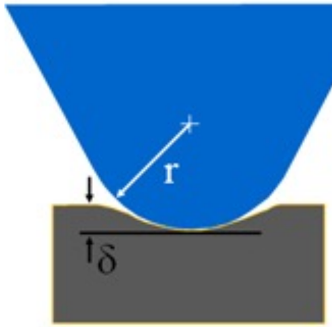
Superlattices and Microstructures, Vol. 31, No. 1, 2002

• AFM can be used by patterning surface with nanoscale resolution. The example above shows a quantum ring patterned on GaAs/AlGaAs 2D electron gas by local oxidation. (The tip leaves behind a trace of oxide that depletes 2D electron gas).

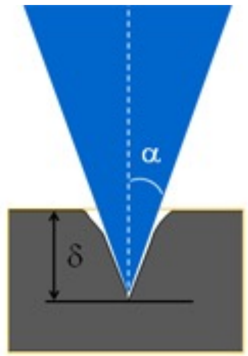
• Right image: **A**, scheme of anodic oxidation: a negative voltage applied between cathode and anode (GaAs in this case), immersed in an electrolyte (e.g. water), leads to oxidation of the anode surface.

B, Scheme for local oxidation on a Ga[Al]As heterostructures with an AFM. Here, the voltage is applied between the AFM tip and the electron gas, resulting in oxidation of the GaAs cap layer, and depletion of the electron gas underneath. The electrolyte is formed by the water film present under ambient conditions

AFM-based Indentation and local elasticity measurements



E_s : Sample modulus
ν_s: Poisson's ratio
r: tip radius of curvature
α: opening angle
δ– indentation depth



$$F = \frac{4}{3} \cdot \frac{E_s}{1-\nu_s^2} \cdot \sqrt{r} \cdot \delta^{\frac{3}{2}}$$

Hertz Model

$$F = \frac{2}{\pi} \cdot \frac{E_s}{1-\nu_s^2} \cdot \tan\alpha \cdot \delta^2$$

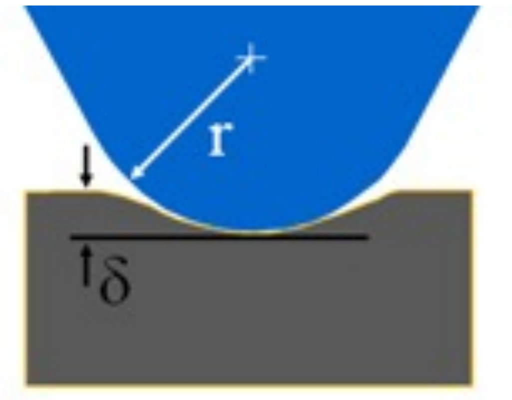
Sneddon Model

• In previous examples the sample surface was considered rigid, and the effect of indentation was neglected. However for a wide range of "soft" materials like polymers, lipids or other biological materials the effect of indentation have to be taken into account. Furthermore indentation is useful for extracting information about the material e.g. elastic (Young) modulus.

• Elastic modulus is obtained from the force curve using one of contact mechanics models. The Hertz model describes the indentation of an infinitely hard spherical indenter on an elastic cylinder (the sample). It is used when the indentation depth is much less than the radius of curvature of the probe.

• When the indentation depth is close to or exceeds the radius of curvature of the probe, the Sneddon model of contact between an infinitely hard conical indenter and an elastic cylinder is more appropriate.
A major strength of AFM-based indentations is that it is a true nanoscale approach, where the forces and deformations remain "nano" in scale. In allows for true nanoscale resolution and helps avoiding permanent deformation of the sample.

Indentation and local elasticity measurements



A question:
How to measure the elastic modulus from nano-indentation data? propose a method

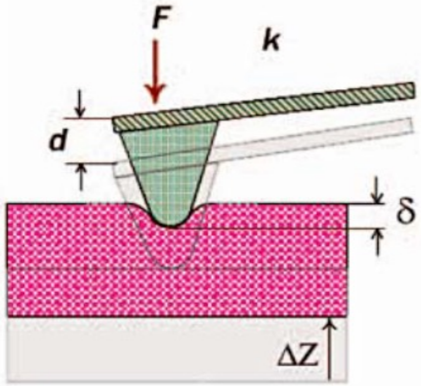
Indications:
Analyse « Deflection – distance » curves (known also as force-distance curve) for two cases :
1) hard surface - indentation is negligible – use it as a reference
2) soft surface (indentation occurs) – studied case
Draw both curves together on the same graph.

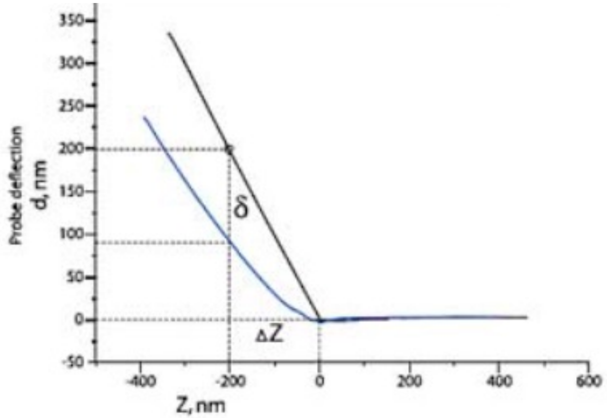
Show graphically and explain how to use these two curves in order to obtain necessary input parameters for calculation of elastic (Young) modulus.
Use Hertz model:

$$F = \frac{4}{3} \cdot \frac{E_s}{1 - \nu_s^2} \cdot \sqrt{r} \cdot \delta^{3/2}$$

Assume that the Poisson ratio of the material ν=0.3 , radius of the tip r = 50nm , and cantilever spring constant k=1N/m

Answer: Indentation and local elasticity measurements



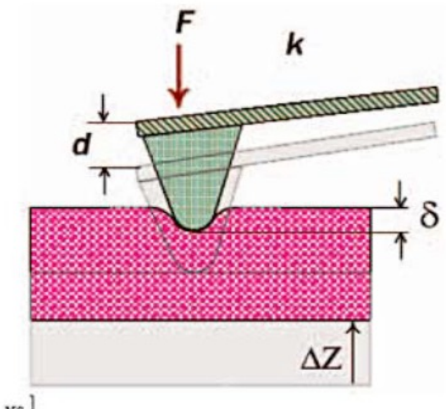


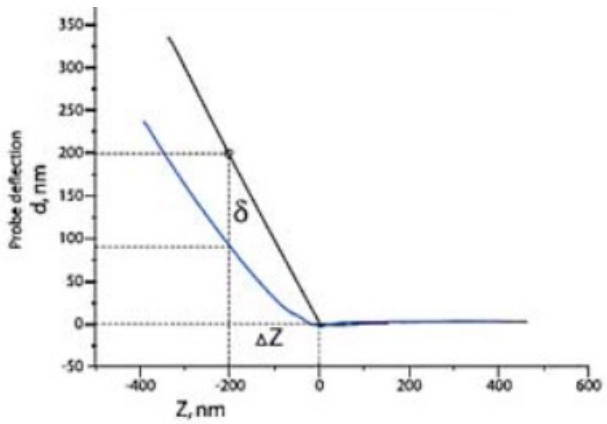
$$F = \frac{4}{3} \cdot \frac{E_s}{1 - \nu_s^2} \cdot \sqrt{r} \cdot \delta^{3/2}$$

The « Deflection – distance » curves for hard and soft surface are shown in the graph (right).
The indentation depth δ can be extracted directly from these curves.

The cantilever deflection d can be extracted from the curve as well (see the drawing). Knowing the spring constant of the cantilever one readily calculates the force ***F*** that will be substituted to the formula above.

Exercise : Indentation and local elasticity measurements





$$F = \frac{4}{3} \cdot \frac{E_s}{1 - \nu_s^2} \cdot \sqrt{r} \cdot \delta^{3/2}$$

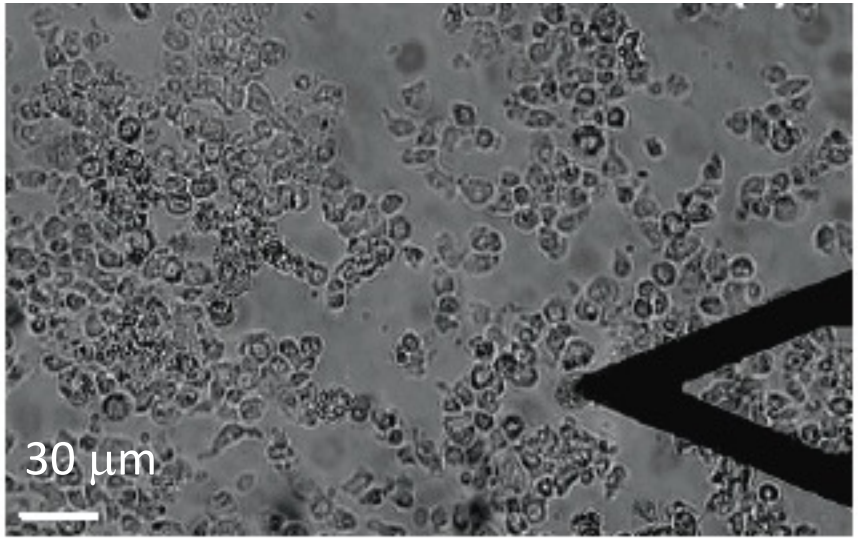
Solution:

The « Deflection – distance » curves for hard and soft surface are shown in the graph (right).
The indentation depth δ can be extracted directly from these curves. (δ= 120nm)

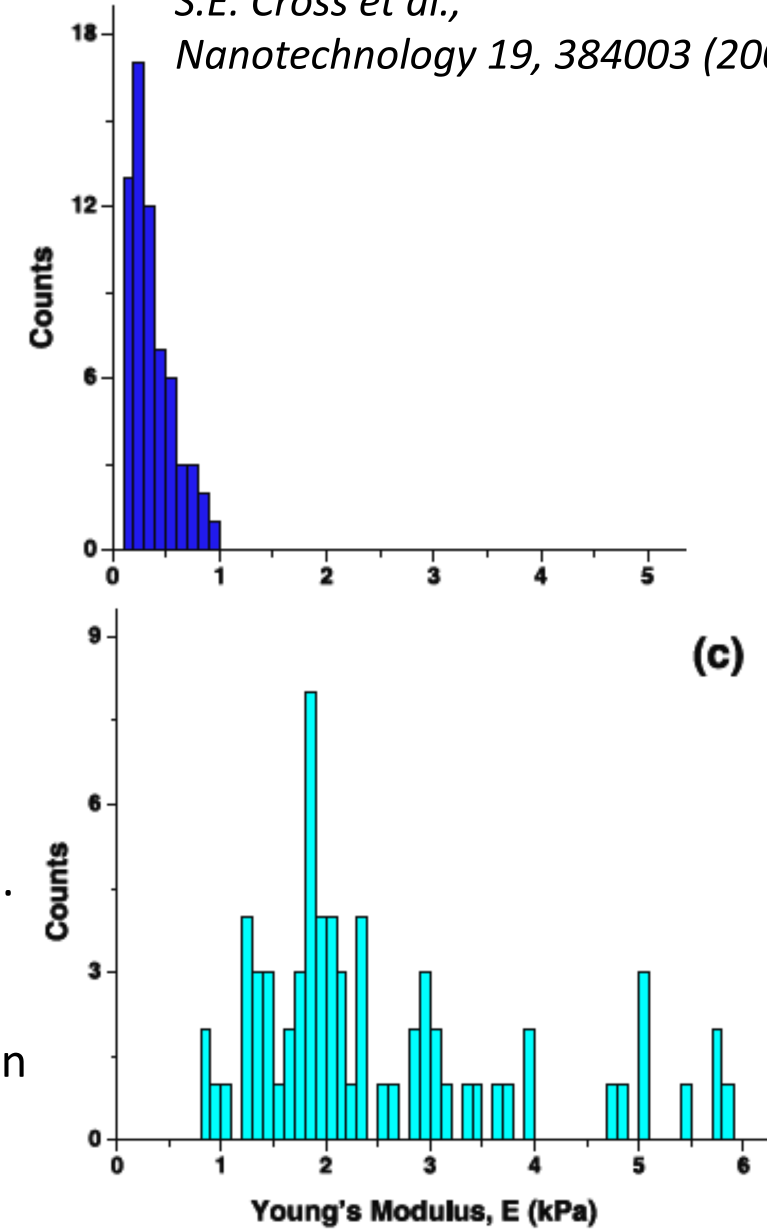
The cantilever deflection d can be extracted from the curve as well (see the drawing, d=80nm).
Knowing the spring constant of the cantilever k=1N/m one readily calculates the force ***F=80nN*** that has be substituted to the formula above.

Therefore, $\boldsymbol{E_s = 2.25 \times 10^7\ Pa}$

Example 1. AFM-based nano-indentation for biological applications: using AFM to diagnose cancer



S.E. Cross et al., Nanotechnology 19, 384003 (2008)

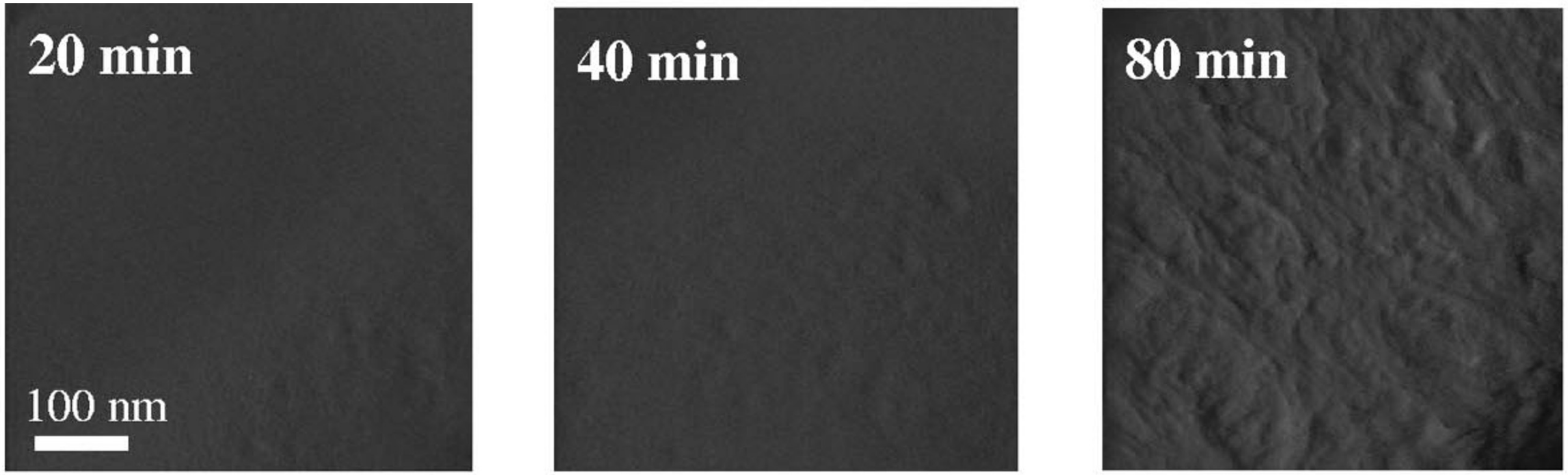


This example represents nanomechanical measurements of live cells. Left side: optical view of an AFM cantilever probing mixed healthy and tumourous cells. Right: Young's modulus of tumor cells (upper diagram) and healthy cells (lower image).

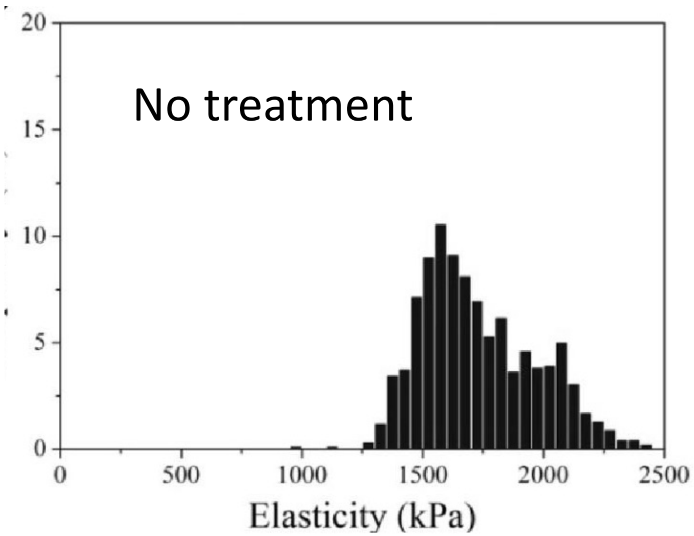
AFM-based nano-indentation shows that the tumor cells are much less stiff, enabling cell motility in the body.

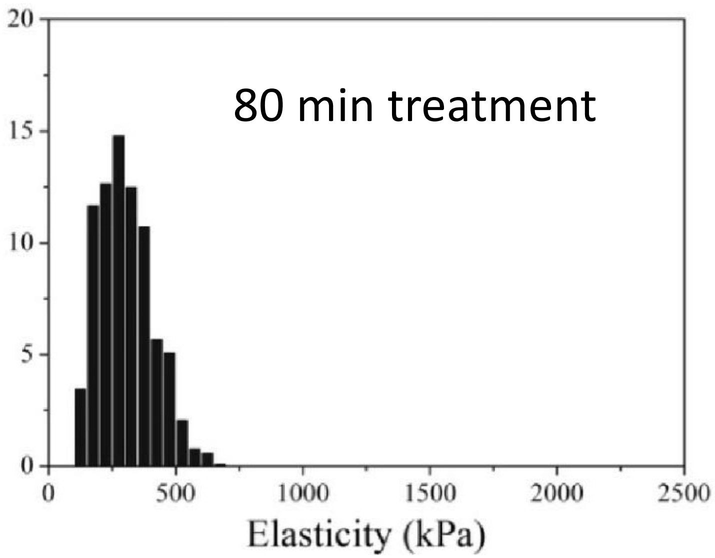
Example 2. AFM for biological applications: mechanical measurements of bacterial response to antibiotics

Cell wall roughening in ***Staphylococcus aureus*** after treatment with antibiotic lysostaphin (topography, contact mode in liquid). After 80 min the cell wall is severely degraded



The effect of antibiotic treatment on the cell wall stiffness

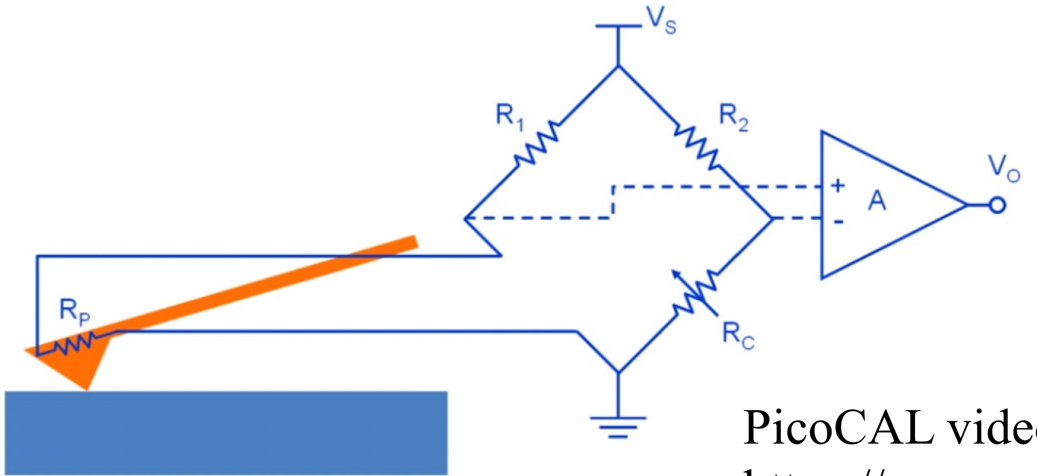




G. Francius et al., J. of Bacteriology, Dec.2008, p. 7904

Scanning thermal microscopy (SThM)

Sensor: functionalized AFM cantilever (e.g. resistive heat detection)



$$V_O = AV_S\left(\frac{R_P}{R_P+R_1} - \frac{R_C}{R_C+R_2}\right)$$

$$S = \frac{\Delta V_0}{\Delta R_P} = AV_S\frac{R_1}{(R_P+R_1)^2}$$

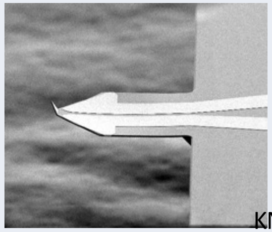
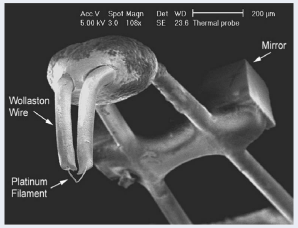
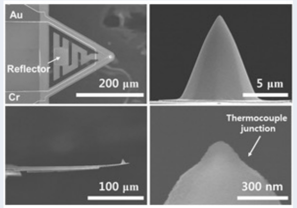
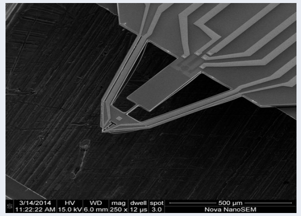
PicoCAL video
https://www.youtube.com/watch?v=TZb5D_T3xLo

• SThM is a technique to map the heating of a sample, such the Joule heating of an electrical device during operation, or to qualitatively map local differences in thermal conductivity. With careful calibration, one can extract actual values for temperature.

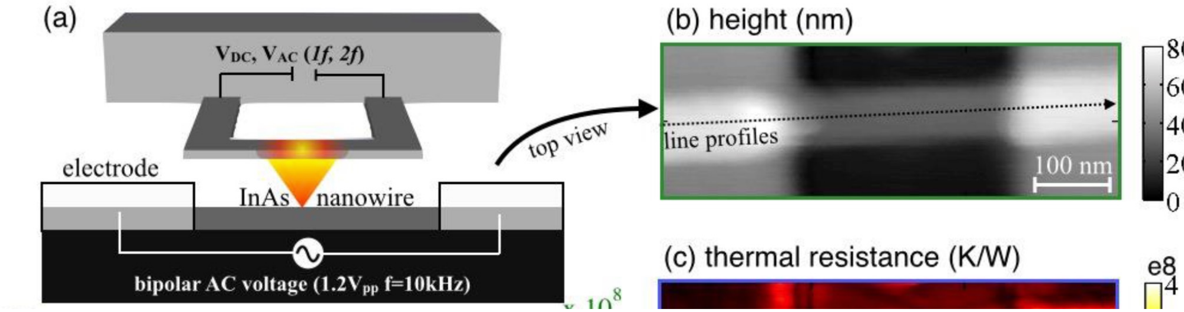
• The change in resistance due to heating is detected using a wheatstone bridge, generating a map of heating

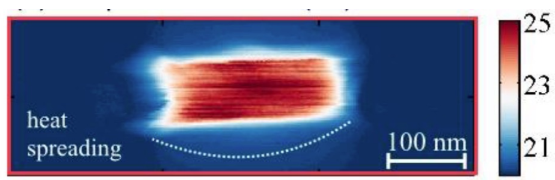
Scanning thermal microscopy (SThM)

Sensor: functionalized AFM cantilever (e.g. resistive heat detection)

			
Kelvin Nanotechnology **-optical monitoring** -tip radius <100 nm -price 350 Euro -resistive detection	Park Systems **-optical monitoring** -wire radius < 1µm -price 400 USD -resistive detection	TSP Nanoscopy **-optical monitoring** -tip radius ~ 100 nm -price (?) -thermocouple	NANOHEAT **-piezoresistive monitor.** -tip radius ~ 100 nm -price ~ 300 Euro -resistive detection

Example of use: mapping of heat distribution on nanowire FETs



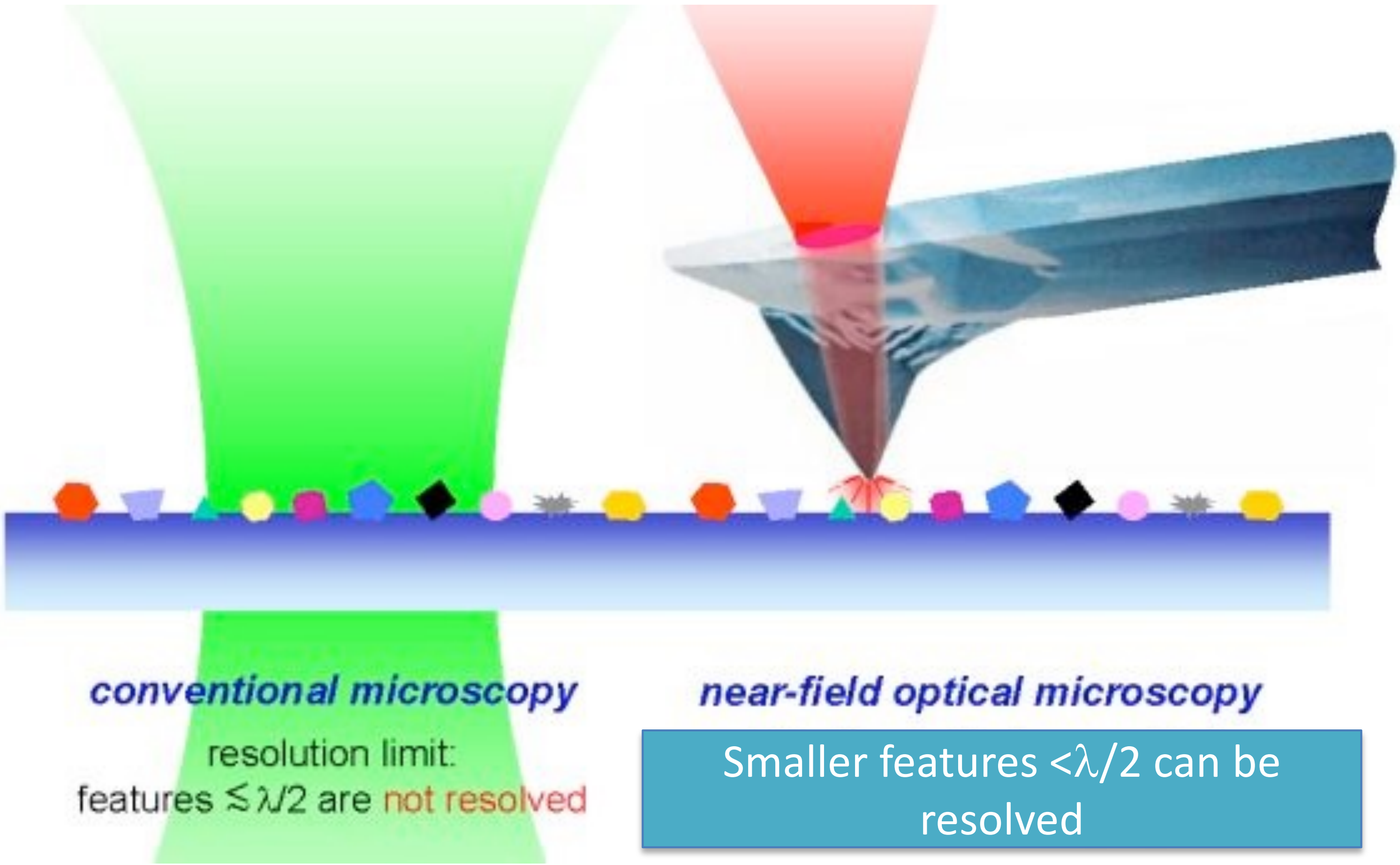


Data from IBM , Zurich

High vacuum greatly enhances measurements of heat distribution

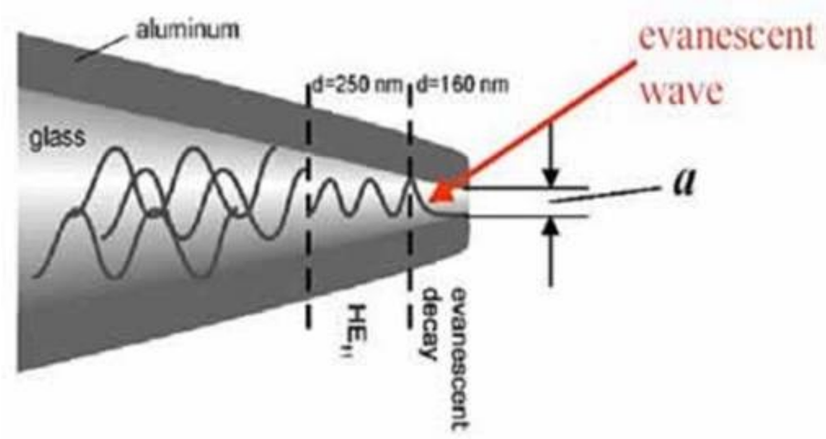
Scanning near-field optical microscopy (SNOM)

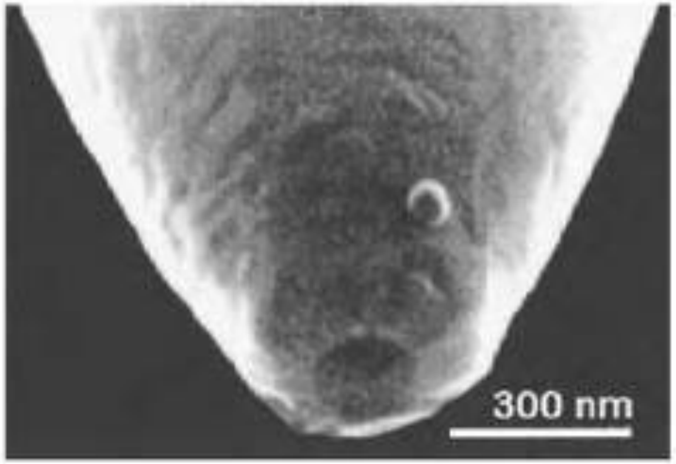
- Scanning near-field optical microscopy (SNOM or NSOM) is an optical microscopy technique capable of imaging objects with a resolution below the diffraction limit of conventional (far-field) microscopy; i.e., below approximately half the wavelength of the light used.
- The propagation associated with near-field light is limited to very short distances from its source (less than $\lambda/2$). It is often called an evanescent wave to express its confined character.
- The near field and radiative far field coupling signals are always coupled (whenever an object interacts with an optical near-field, the far-field radiation changes). This effect is exploited in SNOM

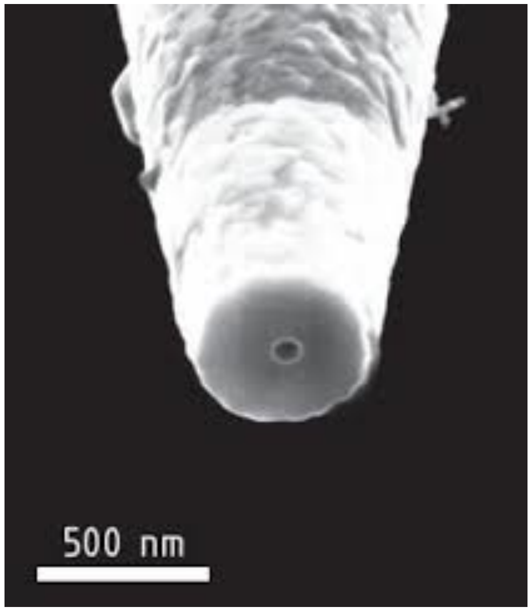


Smaller features $<\lambda/2$ can be resolved

Scanning near-field optical microscopy (SNOM): probes





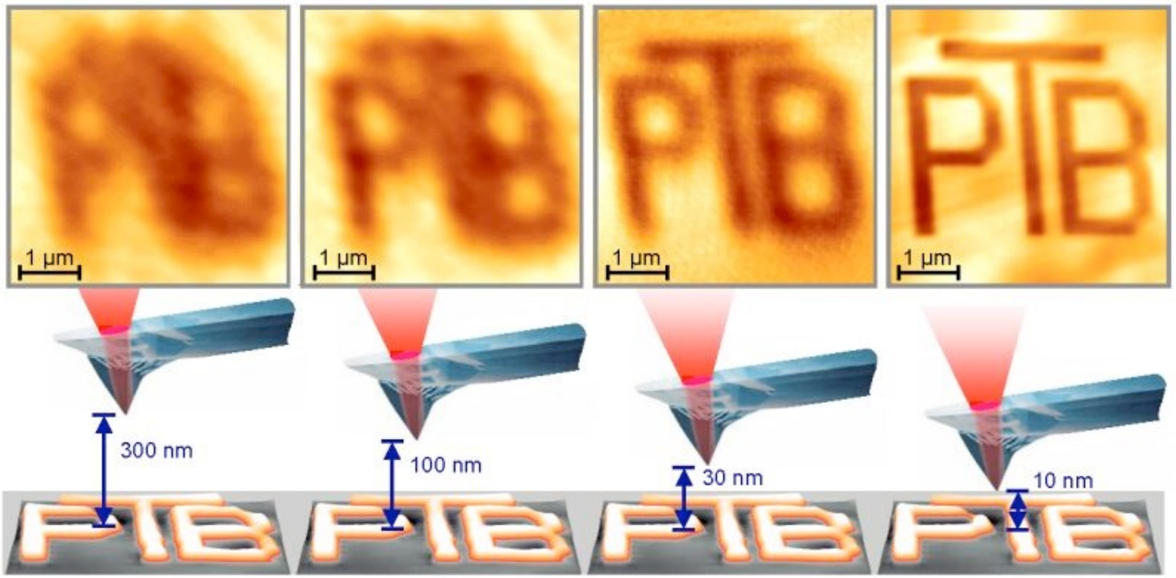


Well-controlled aperture is an essential part of a SNOM probe.
Tapered optical fibers are commonly used for SNOM probe fabrication. The fibers have to be covered with metal coating in order to confine the light and prevent light leaking out of tapered end.
Then a sub-wavelength aperture have to be made in the metal coating.

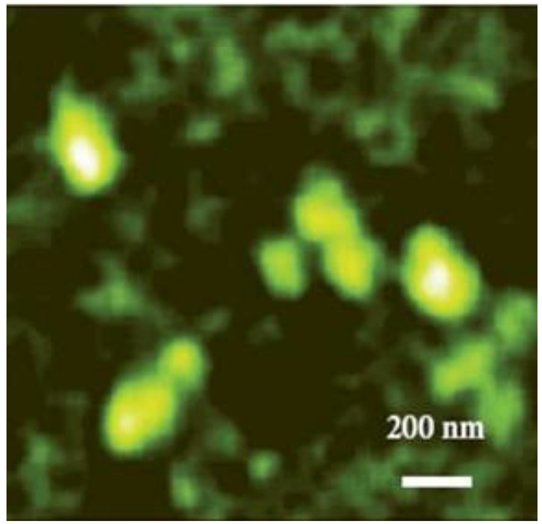
SNOM: resolution, regulation and feedback

• Unlike in conventional microscopy, the resolution does not depend on the wavelength of the radiation but mainly on the geometry of the probe, in particular the aperture diameter and distance to the sample.

• Images below show distance dependence of near-field optical resolution: series of scanning transmission images recorded at test structures on a silicon wafer. The scan height is subsequently reduced from approx. 300 nm (left image) to approx. 10 nm (right image), thus reaching a lateral resolution of about 80 nm (the wavelength of 1064 nm is used here). The ultimate resolution of 10 nm has been reported in most advanced SNOM experiments.

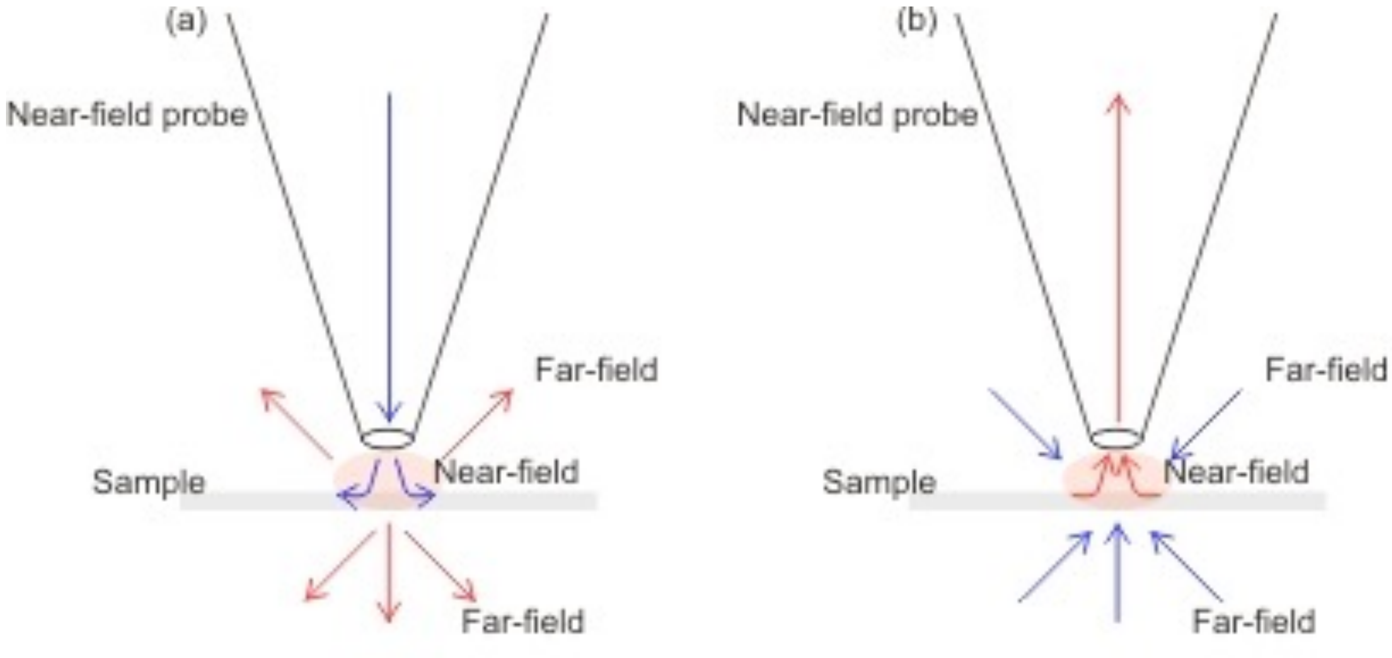


SNOM image of mitochondria



The distance control is more complicated than in conventional STM because light intensity vs. distance curve is rather complicated. Instead the damping of a lateral oscillation of the probe due to the shear forces is exploited (kind of NC-AFM). The probe is excited by means of a small quartz tuning fork. Alternatively a normal AFM tip (with light aperture) can be used. In this case the distance can be precisely controlled by detecting the laser deflection.

Scanning near-field optical microscopy (SNOM): probes



The above figures show the possible operational configurations of the near-field microscope.

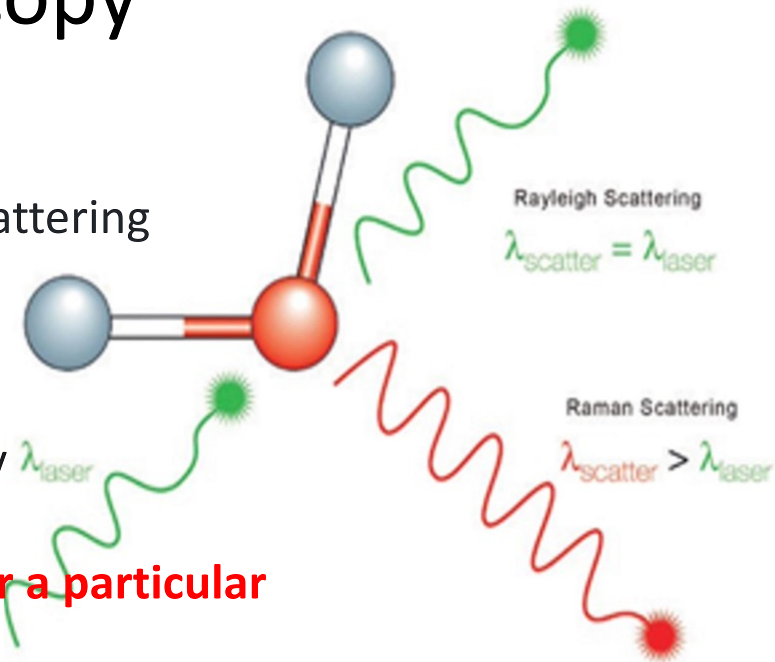
• In left image an aperture probe illuminates a small area of a sample surface (reddish area under the SNOM probe). The resulting signal from the interaction with the sample is then collected in the far-field both in transmission on in reflection. This configuration can be also used to excite a photoluminescent signal of a sample in the near-field regime and then collect the luminescence in far-filed.

• In right image far-field light (conventional light) illuminates the sample and the near-field signal is then collected by the probe. This particular technique is commonly used for the direct detection of localized field on the sample as in the previous configuration, can be exploited for photoluminescence measurements.

Optical SPM methods without fiber-type probe: Tip Enhanced Raman Spectroscopy

What is Raman spectroscopy?

- inelastic scattering of photons, known as Raman scattering
- used to determine vibrational modes of molecules
- A source of monochromatic light
- The laser light interacts with molecular vibrations, phonons or other excitations – shift of photon energy



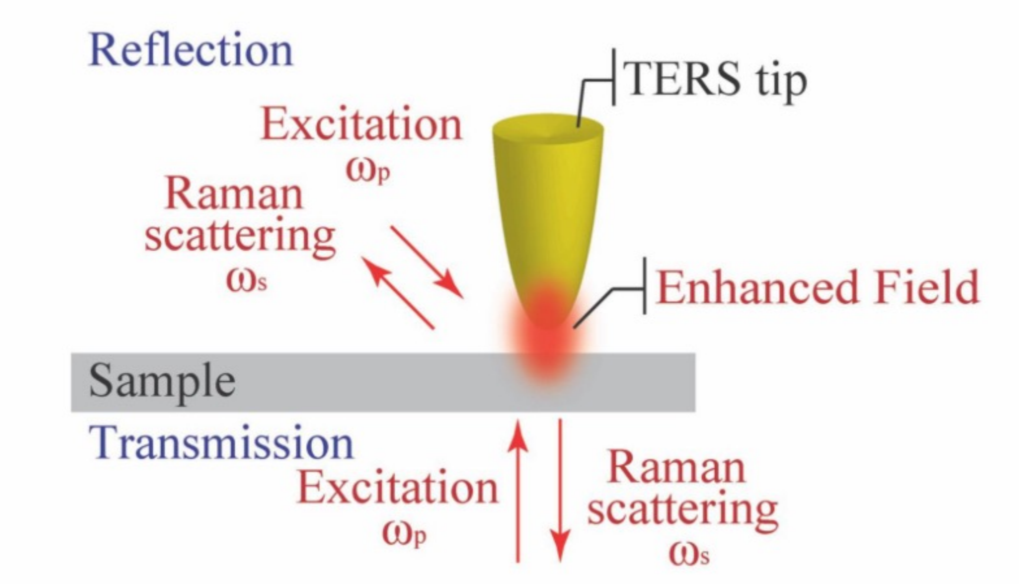
Raman principle

Raman spectrum is a distinct chemical fingerprint for a particular molecule or material

Raman Spectroscopy is a non-destructive chemical analysis technique which provides detailed information about chemical structure, phase and polymorphy, crystallinity and molecular interactions. It is based upon the interaction of light with the chemical bonds within a material.

- Chemical structure and identity
- Phase and polymorphism
- Intrinsic stress/strain, Contamination and impurity

Tip Enhanced Raman Spectroscopy



TERS: Tip-enhanced Raman spectroscopy

• The reflection configuration can be used for any kind of samples (opaque and transparent)

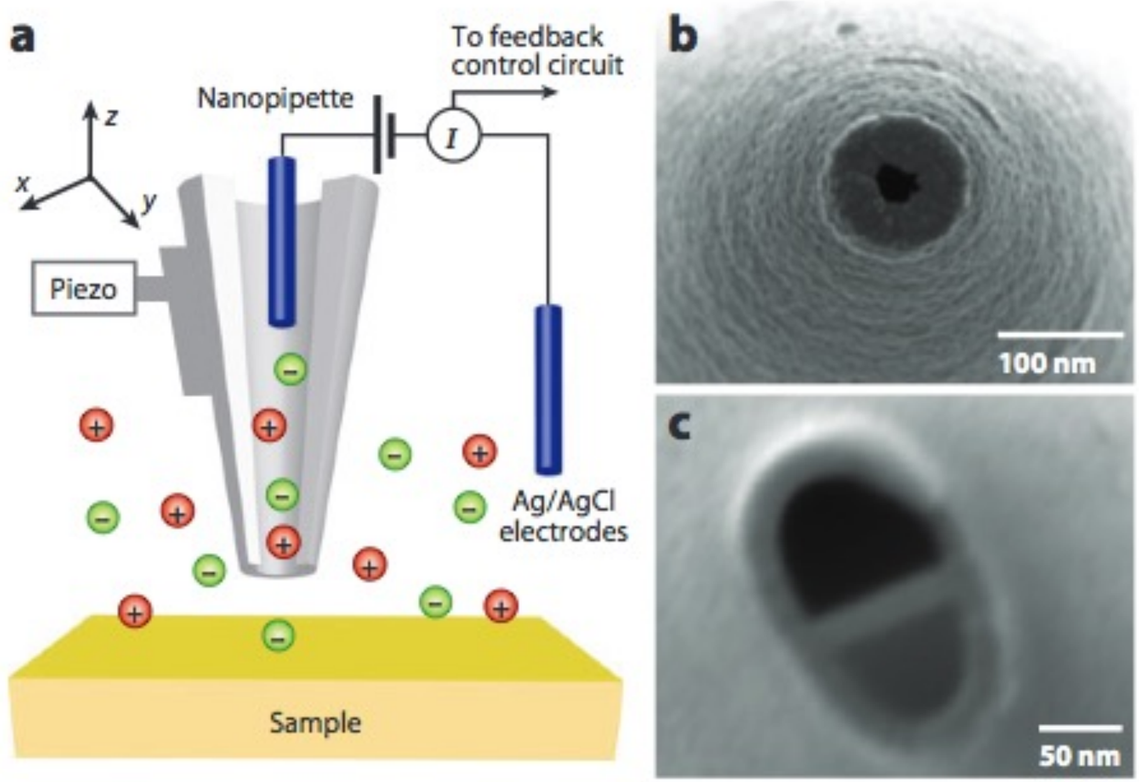
• The transmission configuration allows for best resolution but can only be used for transparent samples

A TERS system is based on a metallic tip (generally made of gold or silver) employed to concentrate the incident light field at the apex. The tip acts as a nano-source of light and local field enhancer, greatly improving the Raman sensitivity (by a factor of 10^3 - 10^7) and reducing the probed volume to the “nano” region immediately below the tip.

A resolution down to 10nm (or even higher) can be achieved

More information: https://www.horiba.com/

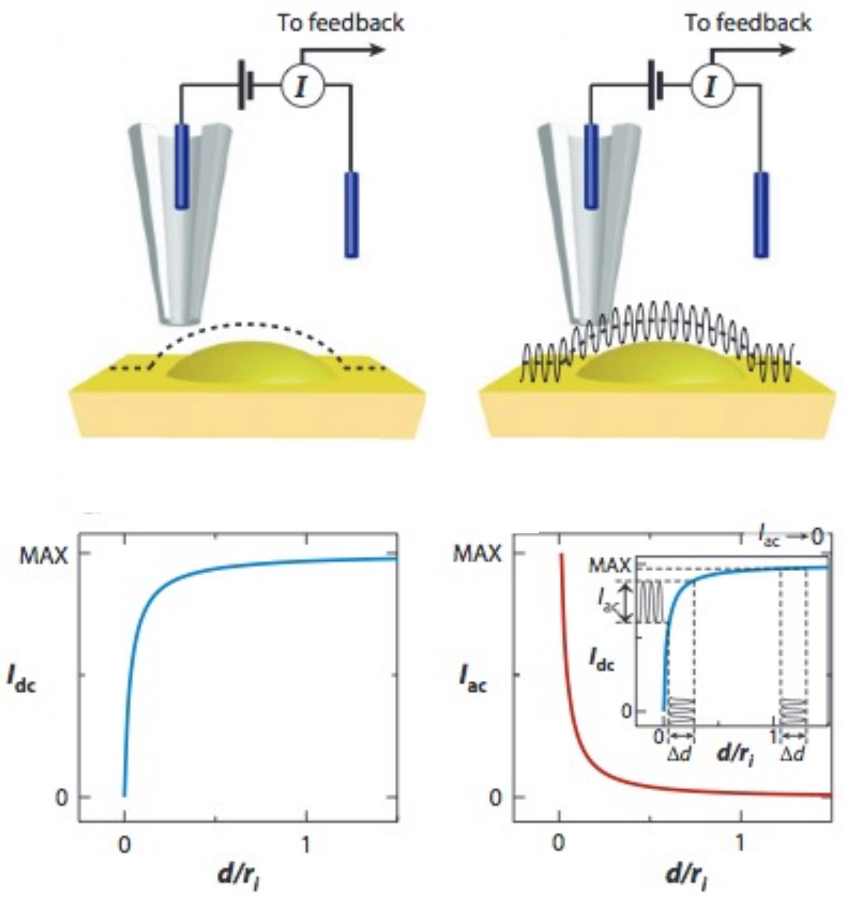
Scanning ion conductance microscopy (SICM)



• Scanning ion conductance microscopy (SICM) is a scanning probe technique that utilizes a nanopipette to scan samples bathed in electrolytic solutions. The operation of SICM relies on an ion current that flows between an electrode inside a pipette and another electrode in an external bath solution.

• This ion current, which is highly dependent on the tip-sample separation, is utilized as a feedback signal to maintain the tip-sample separation and to allow the pipette to follow surface contours, which generates topographic information. SICM has attracted significant attention due to potential applications with living cells, in which high-resolution, noncontact imaging proves beneficial.

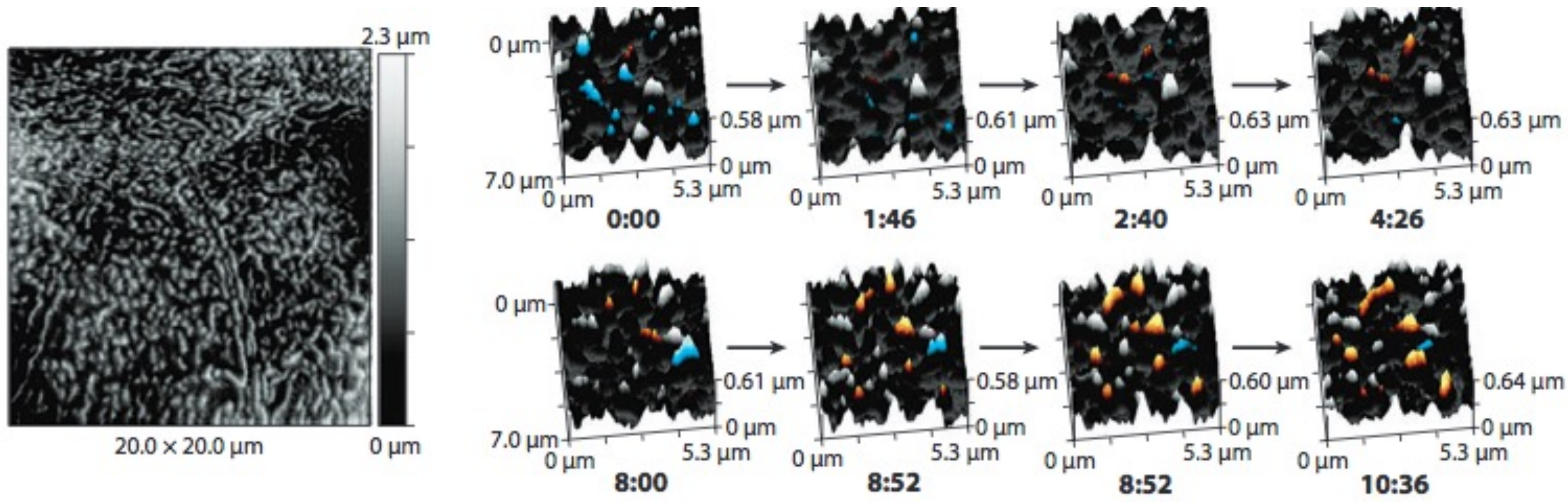
Scanning ion conductance microscopy (SICM): feedback



• Left image: nonmodulated feedback control. In this mode, the dc ion current is sensitive to the tip-surface distance, as represented by the curve below (the tip-sample distance normalized to the pipette inner radius). This curve is used directly to control the position of the nano-pipette.

• Right image: Distance-modulated feedback control. In this mode, the pipette height is modulated with a distance Δd which results in a modulated ion current. In this mode, the ac component of current is used to maintain the tip-surface distance.

Scanning ion conductance microscopy (SICM): example



Dynamics of individual microvilli in a living epithelial cell.
(Microvillus is a very tiny hair-like membrane in the body cells. The microvillus greatly increase the amount of surface area for a cell, found on tongue, intestines etc).

Left image: Topographical scanning ion conductance microscopy image of cells with well-formed microvilli.
Sequence of smaller images: of High-resolution time-lapse imaging of microvilli. Microvilli that are forming, retracting, and relatively stable are highlighted in orange, blue, and white, respectively.

C. Chen et al., Annual Review of Analytical Chemistry 2012, 5, 207-228

Where to order probes

NANOANDMORE GMBH
The World of Scanning Probes and More

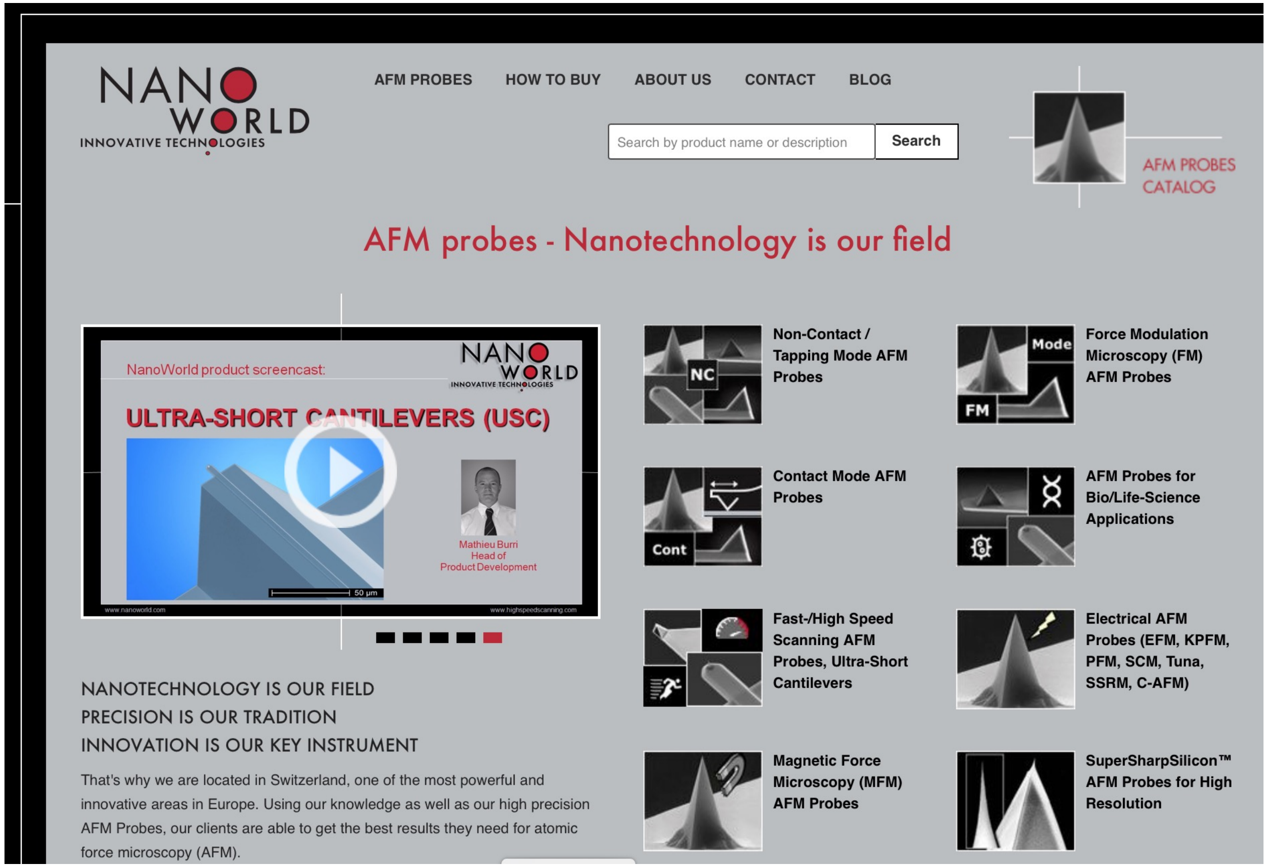
https://www.nanoandmore.com

BRUKER

https://www.brukerafmprobes.com

OXFORD INSTRUMENTS

https://afmprobes.asylumresearch.com/probes



Scanning probe methods: checklist

Methods:

STM:

- **-constant current**
- **-constant height**
- **-STS**
- **-spin-polarized STM**

AFM:

- **-topography – contact mode**
- **-topography – non-contact mode, tapping (intermittent) mode**
- **-force-distance curves**
- **-conductive AFM**
- **-piezo-force microscopy**
- **-KPM**
- **-MFM**
- **-nano-indentation and elasticity measurements**
- **-SNOM**
- **-TERS**
- **-SICM**

Scanning probe methods: checklist

Fundamentals:

- **-phenomenon of tunneling, tunneling current**
- **-force vs. distance (range usable for different techniques)**
- **-principal interactions probed in different techniques**

Technical aspects:

- **-feedback loop**
- **-lock-in techniques**
- **-piezoelectric effect, scanners**
- **-force detection (deflection, interference, amplitude/frequency shift)**

Physical properties measured using scanning probe

(be sure to understand what parameter is kept constant and what is measured/mapped)

Be sure you are aware of realistic values: measurable forces, measurable/controllable displacement, realistic work function values…