Surface analysis
part I: local probe techniques

Lecture 3: functional AFM

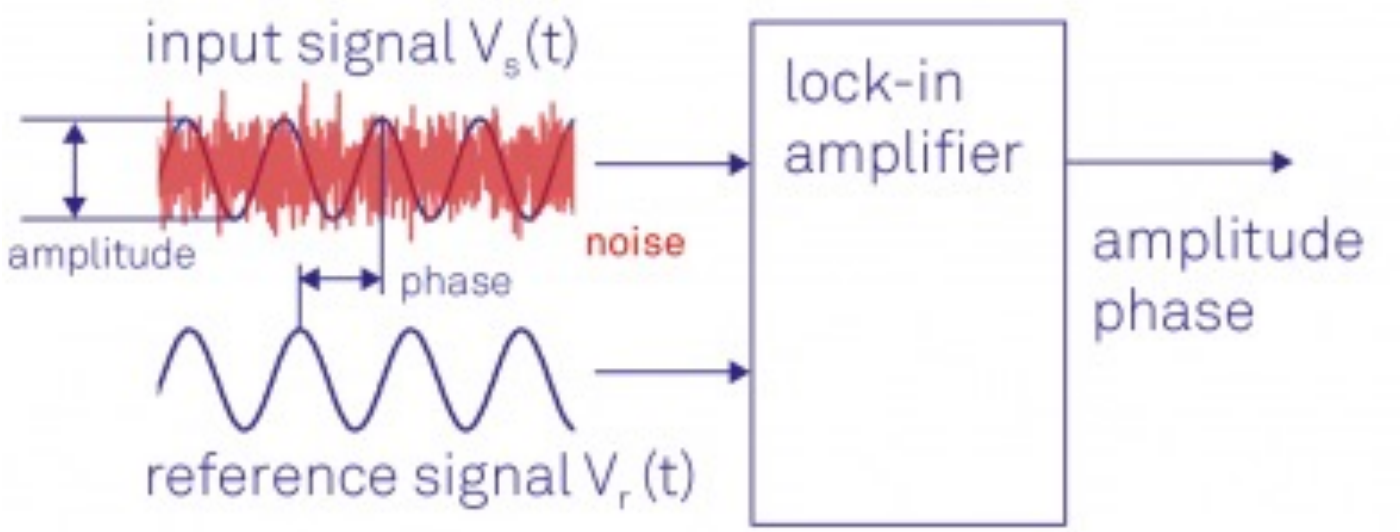
AFM techniques for probing functional properties
- ***electrical***
- ***electromechanic interactions***
- ***magnetic***

technical note:

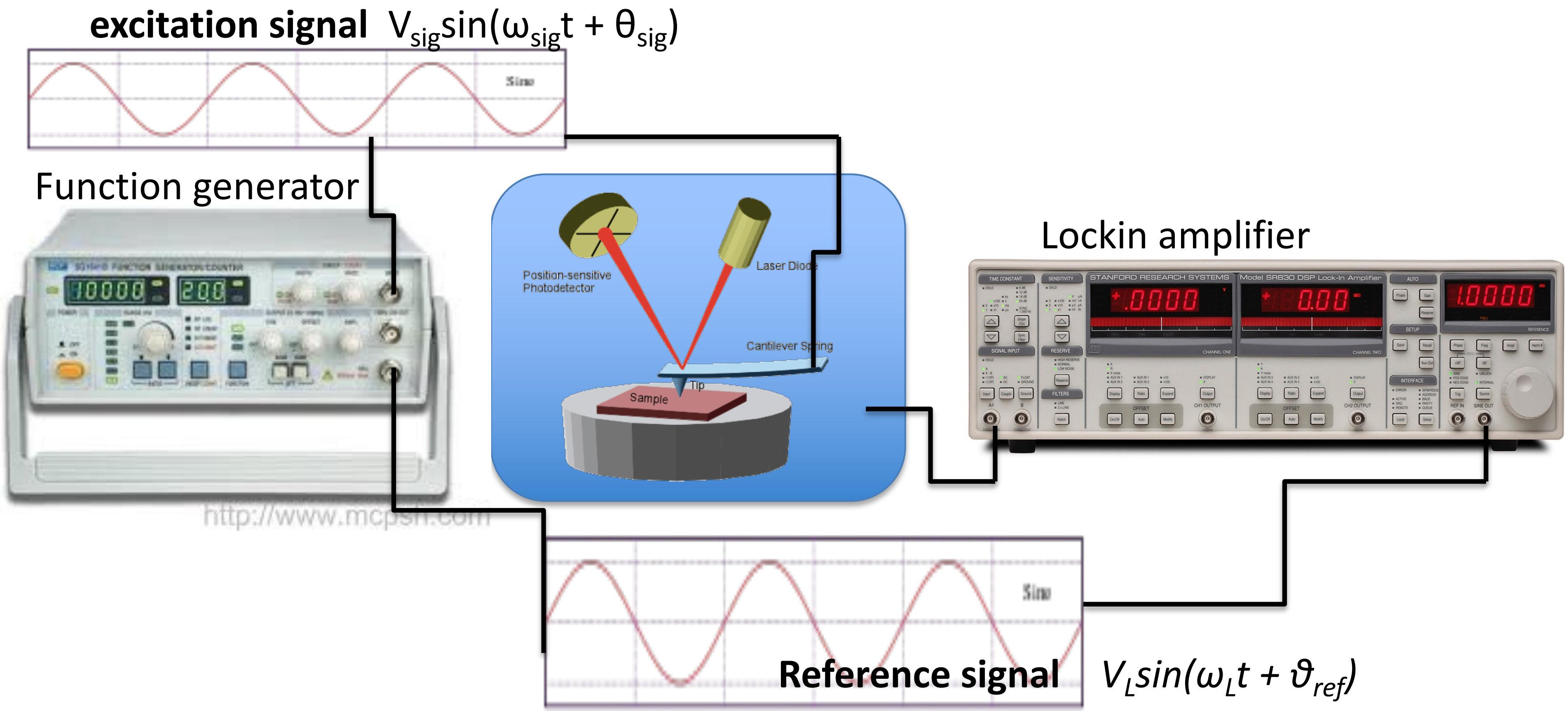
Lock-in amplifiers: essential hardware for different functional AFM / STM modes

• Many methods rely on sample excitation at a chosen frequency and extracting the response at the same frequency (or superior harmonics)

• A lock-in amplifier can be considered as an extremely sensitive filter capable of extracting an AC signal at given frequency even if this signal is masked by a noise, which is orders of magnitude stronger than the signal



Hardware for functional AFM modes: Lock-in amplifiers



The Lock-in amplifier implements phase-sensitive detection (PSD). The output of PSD is the product of two sine waves:

$$V_{psd} = V_{sig}\sin(\omega_{sig}t + \theta_{sig}) \ \text{x} \ V_L\sin(\omega_L t + \theta_{ref}) =$$

$$= 1/2 V_{sig}V_L\cos([\omega_{sig} - \omega_L]t + \theta_{sig} - \theta_{ref}) - 1/2 V_{sig}V_L\cos([\omega_{sig} + \omega_L]t + \theta_{sig} + \theta_{ref})$$

Hence the output of PSD consists of two AC signals: one is proportional to cos $[\omega_{sig} - \omega_L]$ and the other is proportional to cos $[\omega_{sig} + \omega_L]$

Lock-in amplifiers: concept of measurements

• The output of PSD consists of two AC signals: one is proportional to cos $[\omega_{sig} - \omega_L]$ and the other is proportional to cos $[\omega_{sig} + \omega_L]$

• If the PSD output is passed through a low pass filter, the AC signals are removed. What will be left? In the general case, nothing. However, if ω_{sig} equals ω_L, the difference frequency component will be a DC signal. In this case, the filtered PSD output will be:

$V_{psd} = 1/2 V_{sig} V_L \cos(\theta_{sig} - \theta_{ref})$

This is a DC signal proportional amplitude of the signal that we need to detect.

• In general case instead of a pure sine wave, the input is made up of signal plus noise. The PSD and low pass filter only detect the signal with frequencies very close to the lock-in reference frequency. Noise signals, at frequencies far from the reference, are attenuated at the PSD output by the low pass filter

• Noise at almost same frequency as the reference will result in very low frequency AC outputs from the PSD ($\omega_{noise} - \omega_{ref}$) is small). Their attenuation depends upon the low pass filter bandwidth (a trade-off between the speed and sensitivity)

• The phase dependence of the detected signal can be eliminated by adding a second PSD. If the second PSD multiplies the signal with the reference oscillator shifted by 90°. From these two outputs the amplitude and phase of detected signal can be extracted.

Lock-in amplifiers: concept of measurements - summary

• A lock-in amplifier, because it multiplies the signal with a pure sine wave, measures the single Fourier (sine) component of the signal at the reference frequency.

• A lock-in amplifier can be considered as an extremely sensitive filter capable of extracting an AC signal at given frequency even if this signal is masked by a noise, which is orders of magnitude stronger than the signal

• A lock-in is a very powerful tool that allows detection of very low-amplitude signals. Its use relies on excitation of the system with AC signal (or just periodic signal) at given frequency and use this frequency as a reference

technical note end

Density of states measured by STM - a lock-in technique

The DOS is a very useful quantity to be able to measure since it can be used to derive a wealth of information about the crystal's properties.
The DOS can vary as a function of position in the crystal which means that one can define a local density of states (LDOS). LDOS is then a quantity which depends on both energy and on position, LDOS(*x*, *y*, *E*).

$$I = I_0 \int_{-eV}^{0} \rho_s(\varepsilon) d\varepsilon$$

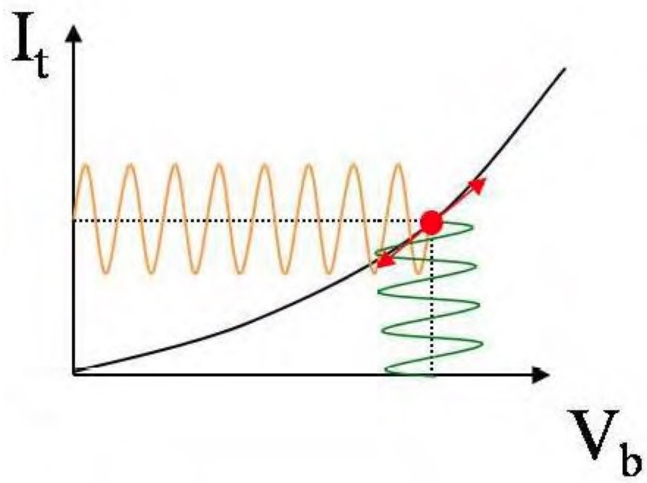
For a negative bias voltage on the sample, the electrons are tunneling from sample to tip, and we are measuring the integrated density of full states below the Fermi level in the sample.

How to get DOS (rather than integrated DOS)? By taking derivative numerically one gets a lot of noise. However derivative can be measured directly by modulating bias voltage.

$$\frac{dI}{dV} \propto DOS$$

To measure DOS one has to modulate the bias voltage by ***dV*** and measure current modulation ***dI***

Technically this in done using ***lock-in amplifier***, which is a very sensitive tool that permits to extract a signal at a given frequency and filter out noise that can be much (orders of magnitude) stronger than the signal.



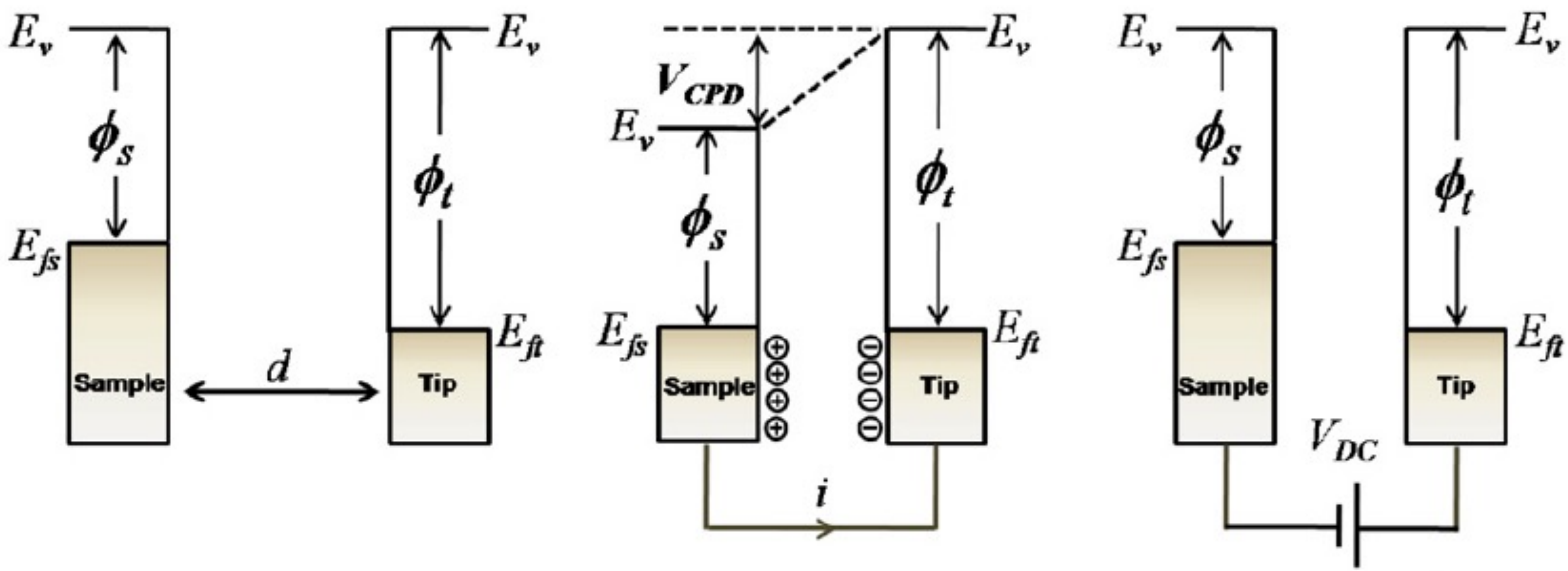
The resolution of DOS measurements is determined by ***dV***. The resolution limit is imposed by the amplitude of thermal wiggle (when the modulation becomes less than $K_B T$ = 0.36 meV at T = 4.2 K). However in real experiments the modulation can be as small as 2-3mV

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

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

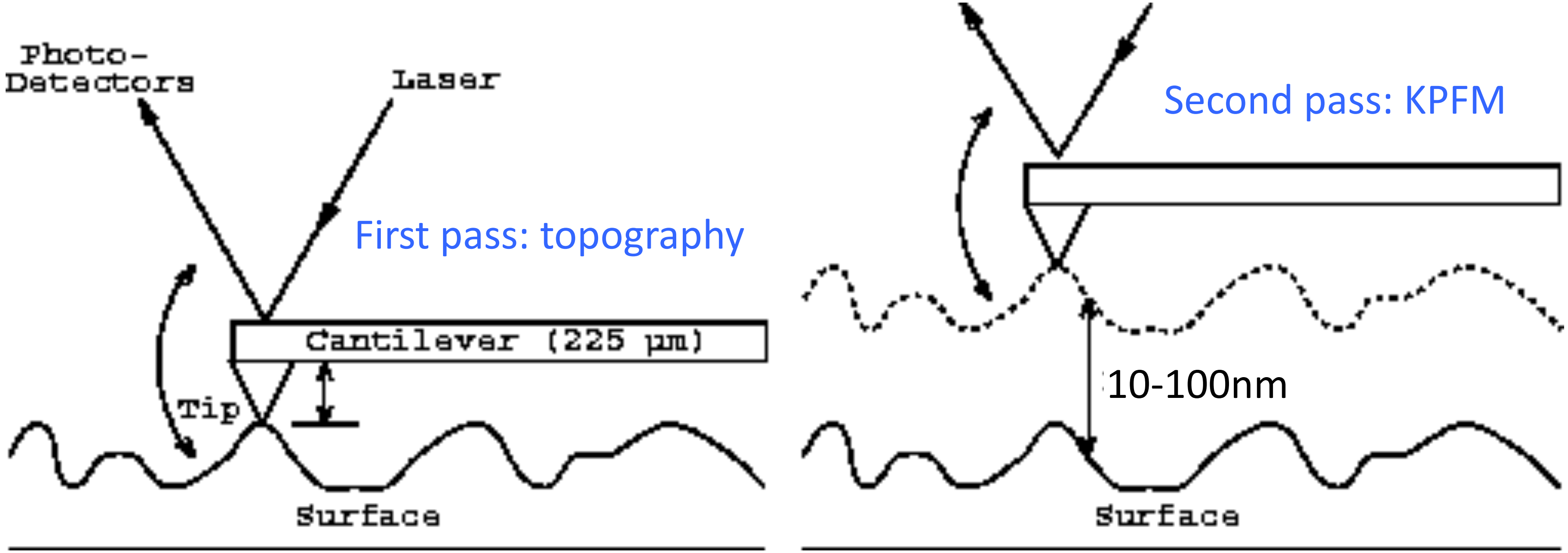
- **Response at ω is proportional to ($V_{DC}\pm V_{CPD}$) - nullified by adjusting V_{DC}**

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

- Response at 2ω used for capacitive microscopy

KPFM: two pass approach

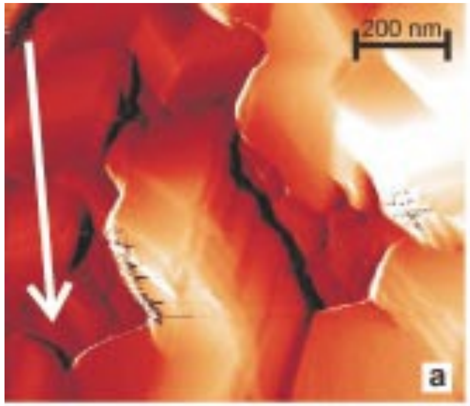
KPFM is generally performed in combination with topography imaging. Two-pass scan is a useful technique to avoid crosstalk between two sets of data.
For accurate KPFM data the tip-sample distance should be unchanged
Technically it is implemented as follows:
AFM operates in non-contact or tapping mode. 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



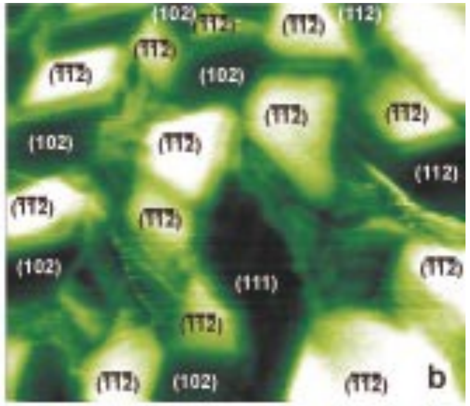
The two-pass approach is not necessary for atomically flat substrate. In this case instead of getting detailed topography the slope of the surface in X and Y direction is detected. Then the tip is retracted to required distance and KPFM data are collected

Kelvin probe force microscopy (KPFM): examples

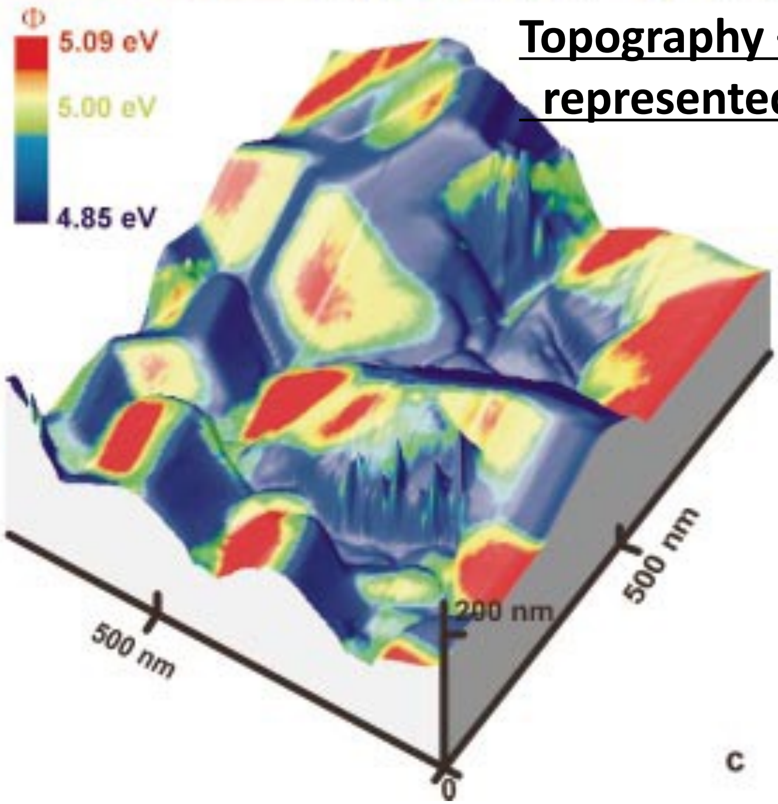
topography



Topography + Φ



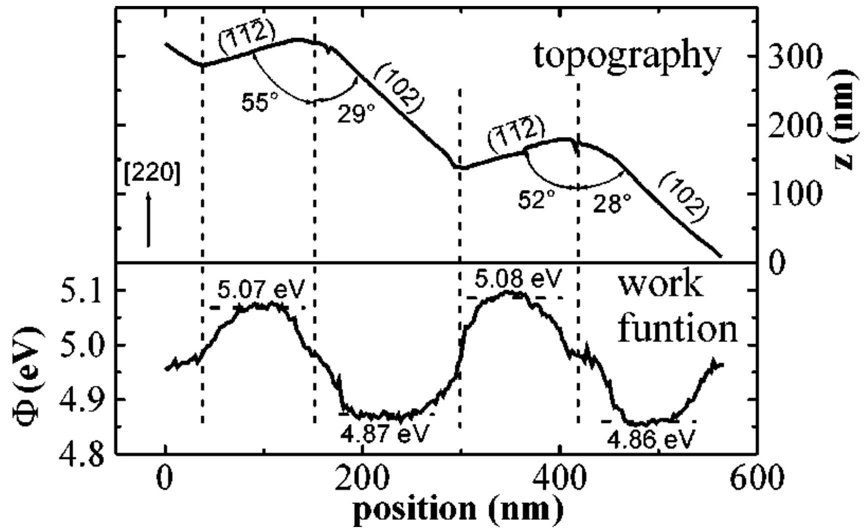
Topography + Φ represented in 3D



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

The topography and work function profiles



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.

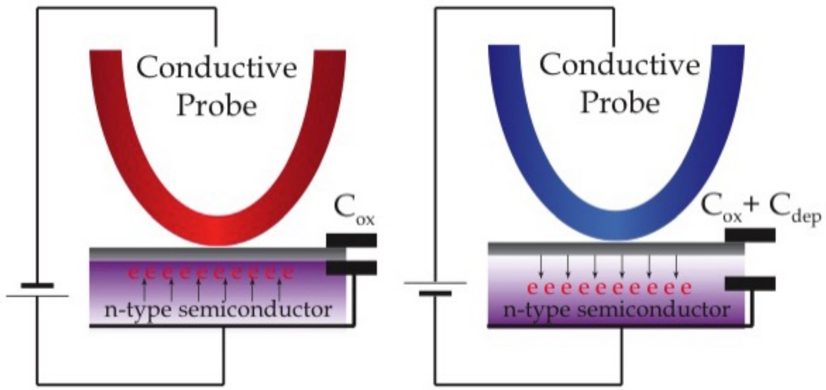
Explanation of KPFM from Park systems: https://www.youtube.com/watch?v=54OG7Yi-iMw

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}

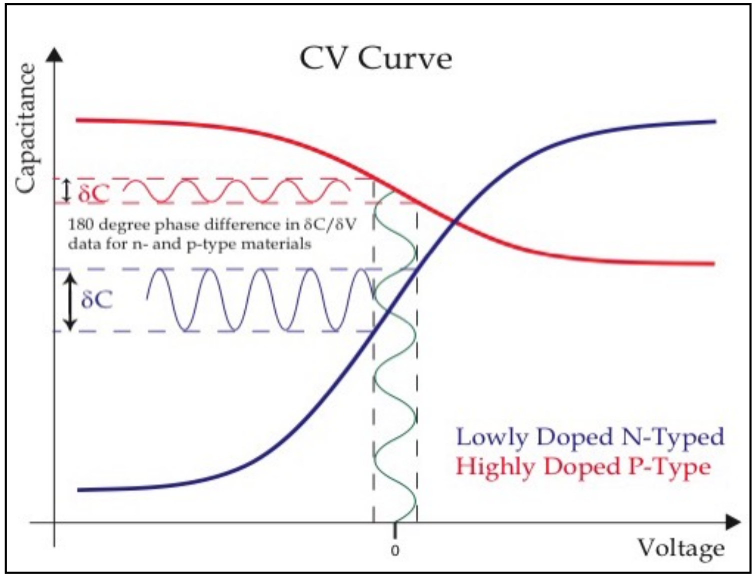


The capacitance measured by the SCM sensor varies as the carriers move towards (accumulation) and away from (depletion) the probe.

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)

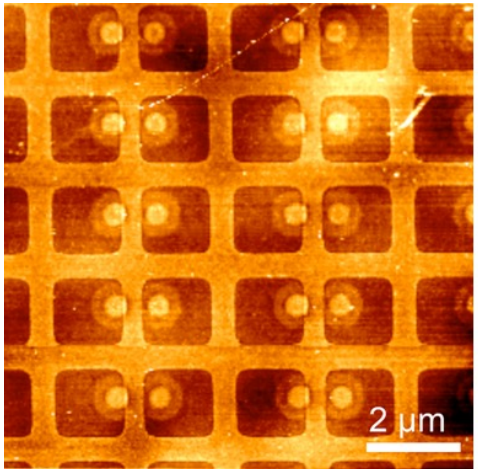
Capacitance vs voltage (p, n-doping)



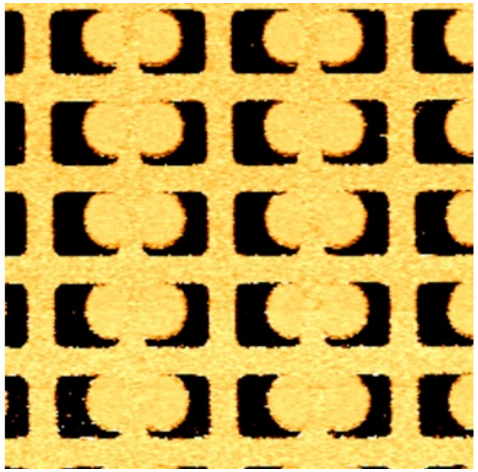
The C-V curve and dC/dV for both n- and p-type materials. Notice both the change in amplitude as a function of doping concentration and the phase shift with dopant species.

Scanning Capacitance Microscopy

topography



phase

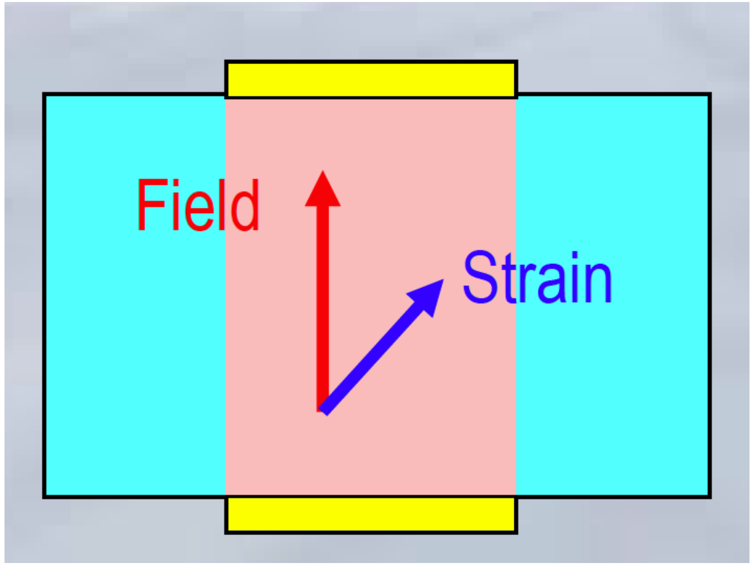


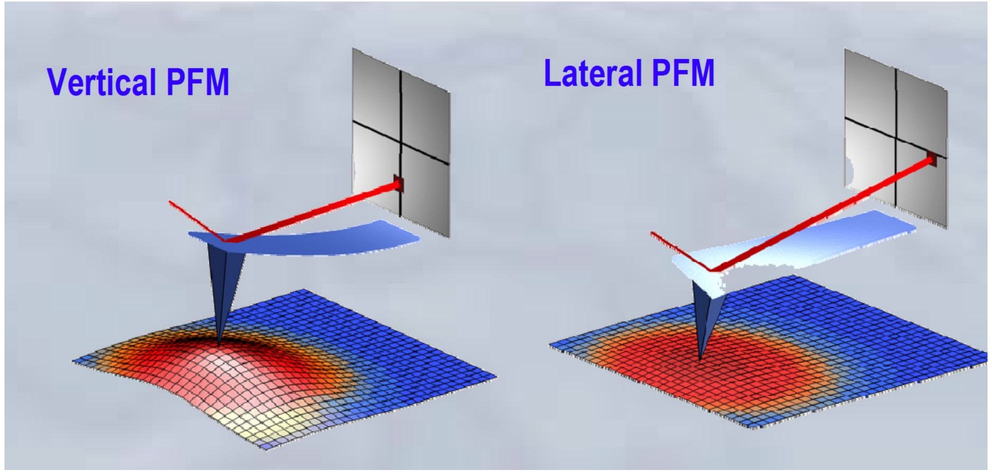
Ion implanted pattern on Si wafer (low p-doping) is imaged by SCM.

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

Probing nanoelectromechanics
Piezoelectric response force microscopy (PFM)

In macroscopic systems, we measure response to the uniform external field (e.g. by interferometry)





Interpretation:
In general case the strain ***x*** is linked to the polarization ***P*** through the equation $\boldsymbol{x=QP^2}$

Piezoresponse Force Microscopy:
electromechanics can be probed locally

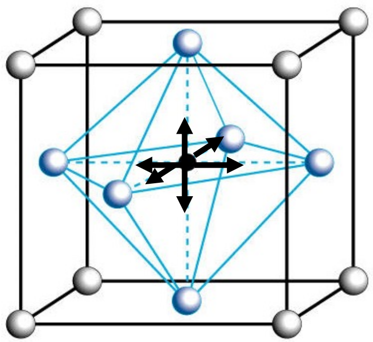
Application of AC + DC bias to the tip

$V_{tip} = V_{dc}+V_{ac}\cos(\omega t)$

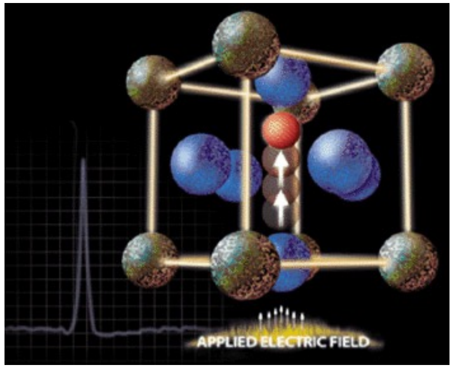
$d = d_0+A(\omega,V_{dc})V_{ac}\cos(\omega t+\varphi)$

Ferroelectric materials: a strong electromechanical response

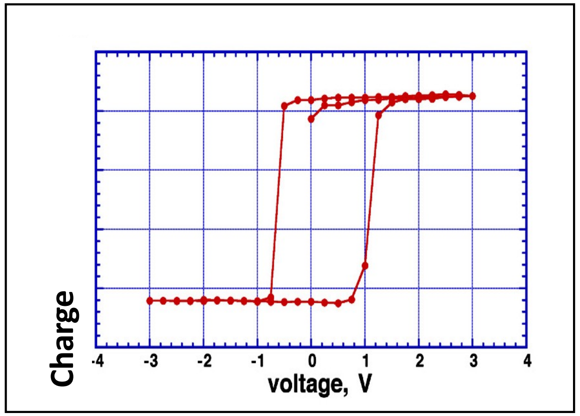
Possible polarization directions in a perovskite ferroelectric in tetragonal phase



Control of polarization direction by an external electric field



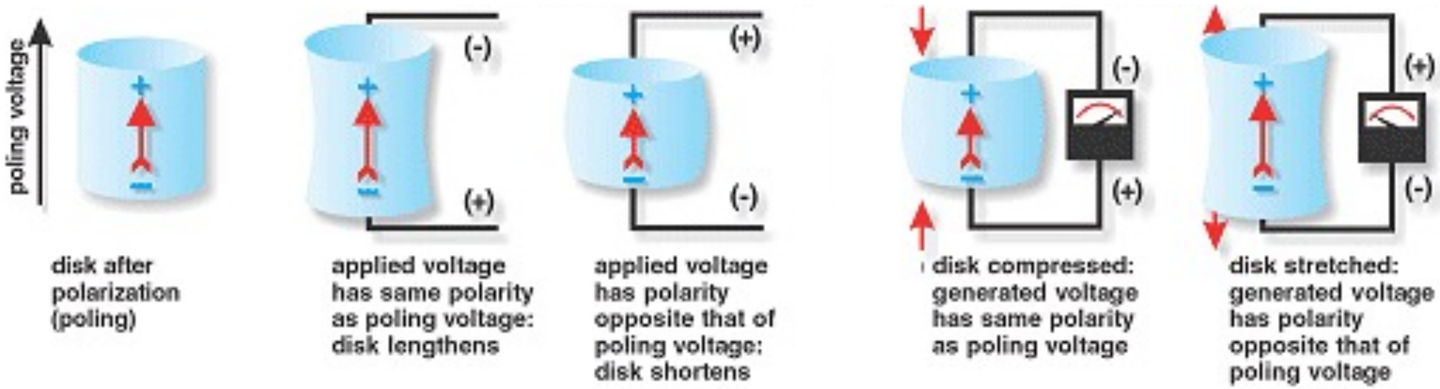
Hysteresis of polarization



Piezoelectric effect

Converse piezoelectric effect

Direct piezoelectric effect



$\Delta d = d_{33}V$, for PZT ceramics ***d_{33}***=500pm/V , e.g. by applying 1V you can get a displacement of 5Å

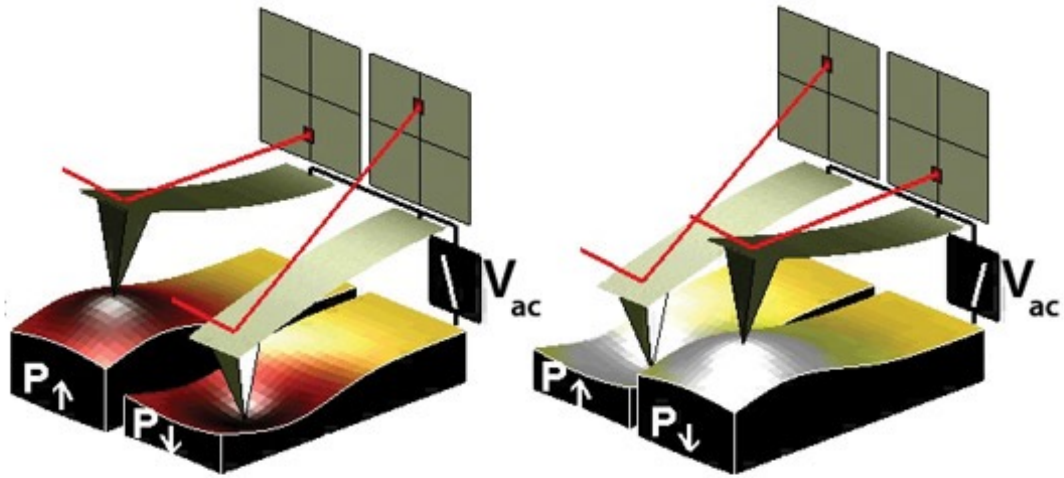
Piezoelectric response force microscopy (PFM)

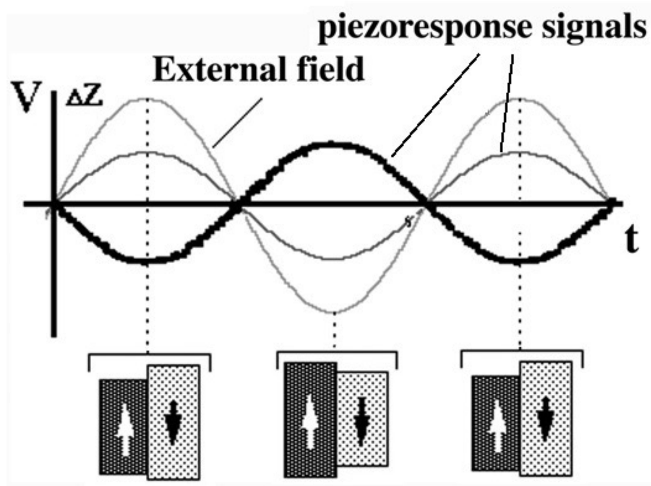
Measurements of strain in dc mode are often very difficult, PFM is much more practical

• The most efficient way to probe local piezoelectric response is to drive the conductive tip with a small ac voltage $\boldsymbol{V_{ac} = V_0 \sin(\omega t)}$
The mechanical displacement at the same frequency (both amplitude and phase) is detected – ***lock-in***

• in many materials typical piezoelectric response is of order of magnitude of $\boldsymbol{d_{33}}$=10 pm/V. The driving ac voltage for thin films and nanostructures is typically kept below 1V in order to avoid polarization switching, high conduction and other undesired effect. Hence the expected response amplitude may be below 10 pm (<0.1Å)

• lock-in technique permits filtering out such a small response even if the high-nose environment





• If the material consists of polarization domains (regions where the polarization points in different directions), which is typically observed in ferroelectrics the map of phase of local piezoelectric response corresponds to the map of ferroelectric domains

Piezoelectric response force microscopy (PFM)

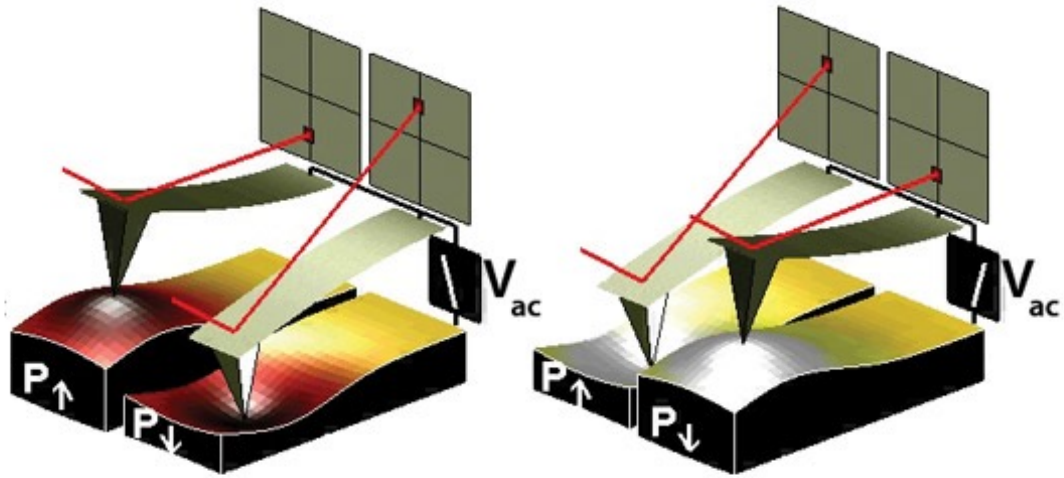
PFM background: where does the linear piezoresponse come from?

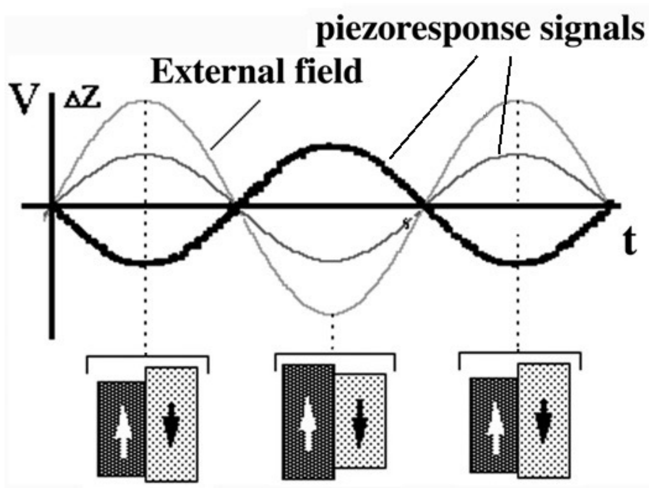
In most general case the strain $\boldsymbol{x}$ is linked to the polarization $\boldsymbol{P}$ through the equation $\boldsymbol{x=QP^2}$, where Q is the electrostrictive coefficient. In presence of spontaneous polarization $\boldsymbol{P}$ slightly modified by a small external AC signal $\boldsymbol{P\pm\delta P}$ we get for strain :

$$x = Q(P\pm\delta P)^2 = QP^2 + 2QP\delta P + \cancel{Q\delta P^2} = QP^2 + 2QP\varepsilon\varepsilon_0 E$$, ***where E is small ac electric field***

$2QP\varepsilon\varepsilon_0$ is a piezoelectric coefficient (m/V), realistic values for ferroelectrics are 10-100 pm/V

Thus a small AC signal linearizes the electromechanical response, so the phase of the response shows the polarization direction



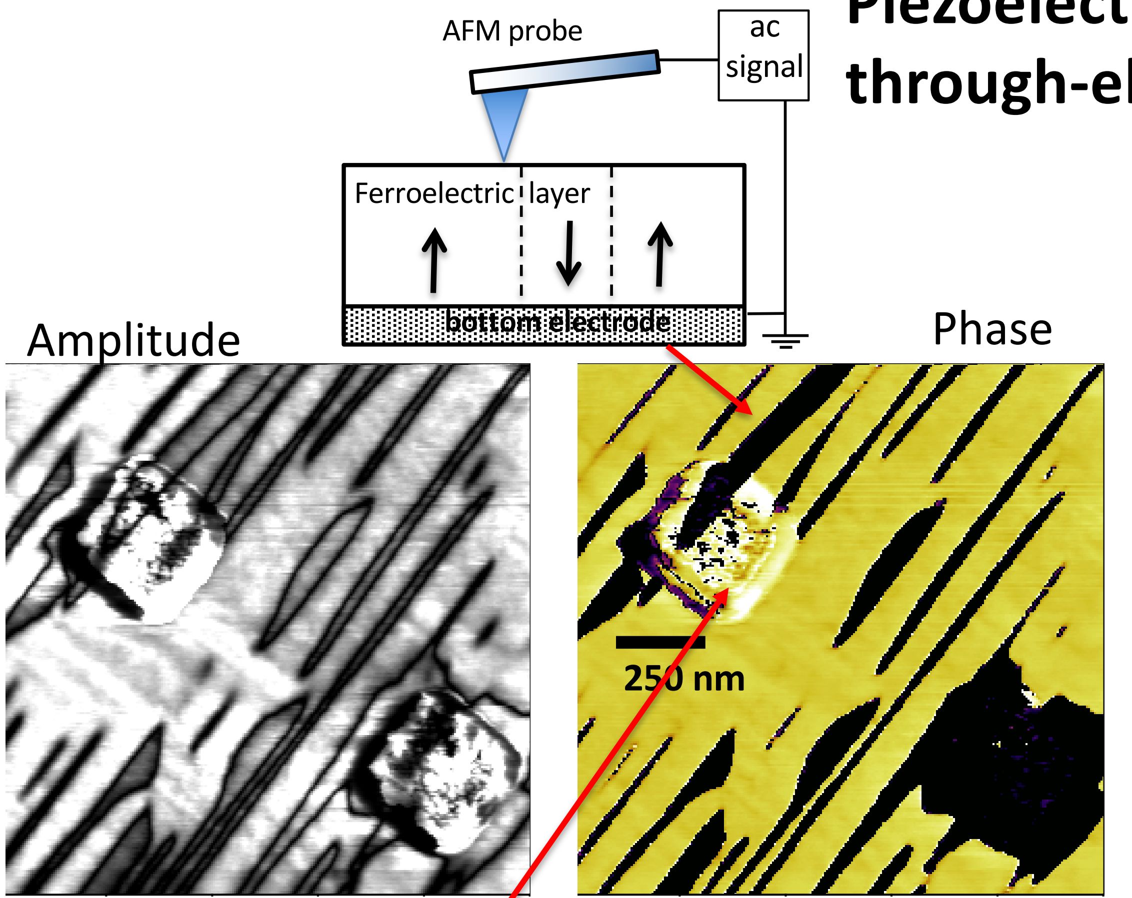


- If the material consists of polarization domains (regions where the polarization points in different directions), which is typically observed in ferroelectrics the map of phase of local piezoelectric response corresponds to the map of ferroelectric domains

PFM: principles

- Drive: Eac of Eac+Edc, detect mechanical displacement (x or Z)
- E_{ac} must be small (does not switch or destroy – just probe)
- Contact technique, conductive probe
- Lock-in technique – signal is normally hidden by noise (pm range)
- DC-deformation is difficult to measure, ac displacement – pm resolution
- Displacement can be quantified – measure piezoelectric coefficient

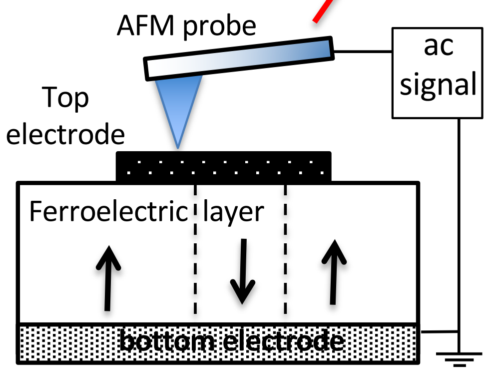
Piezoelectric response mapping, through-electrode imaging



This example shows amplitude and phase of local piezoresponse measured on a thin (50 nm) film of ferroelectric bismuth ferrite ($BiFeO_3$).

In the phase image the domains with the spontaneous polarization pointing up are represented by bright color while the domains with polarization pointing down are black.

In the amplitude image the boundaries of domains are black (zero amplitude)



Rectangular Au electrodes are deposited on the film surface for electrical measurements.
Remarkably the domains can be sensed through the thick (50 nm) gold layer. Lower image shows a sketch of the electrical configuration used for probing piezoelectric response through the electrode

Another rectangular electrode have been poled and then mechanically removed by the probe. The area underneath is fully poled (big black spot)

PFM: ultimate limit of sensitivity: fractions of pm

Genuinely Ferroelectric Sub-1-Volt-Switchable Nanodomains in $Hf_xZr_{(1-x)}O_2$ Ultrathin Capacitors

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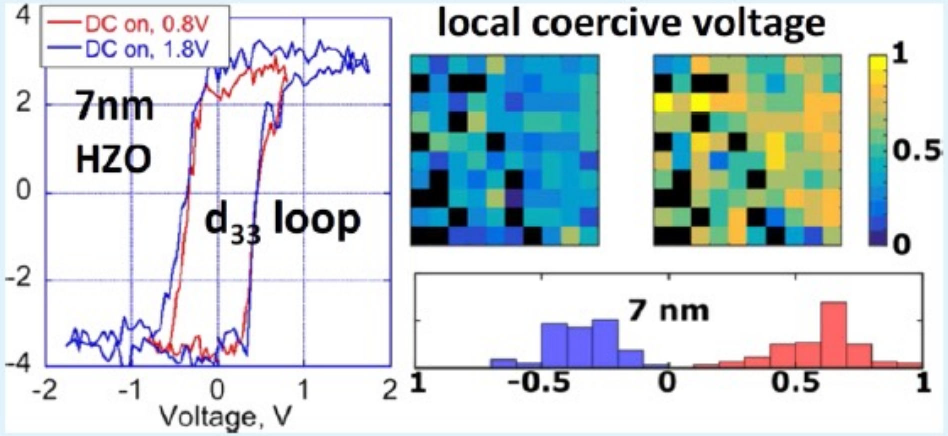
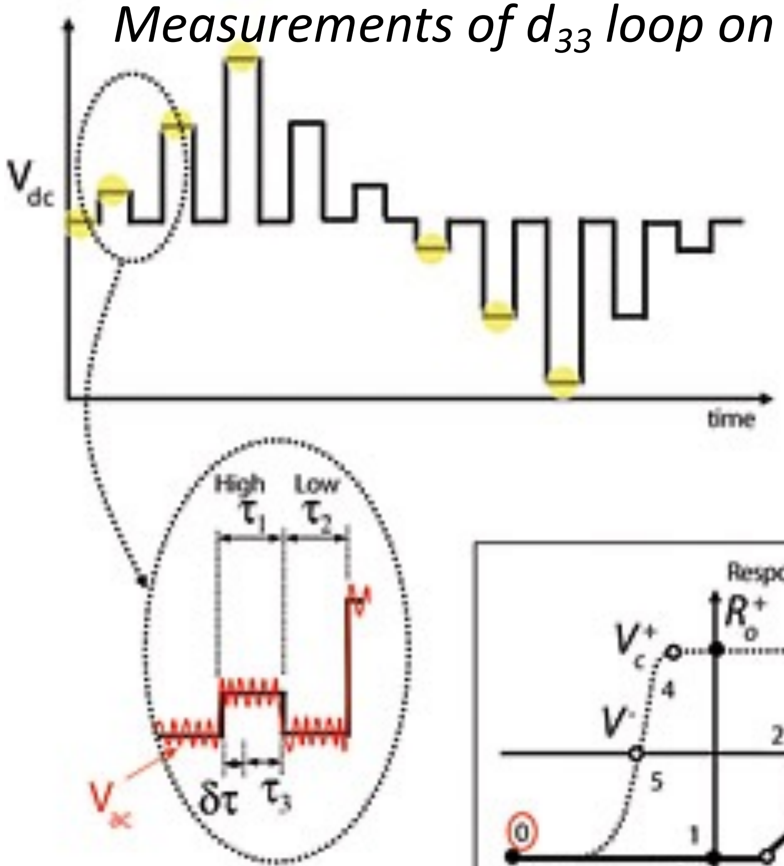
Supporting Information

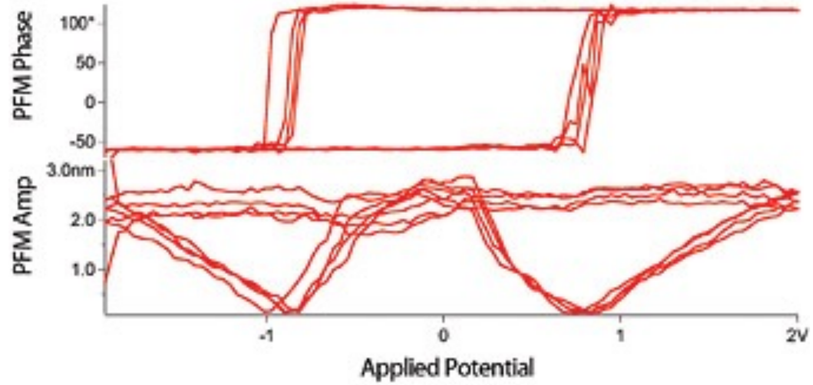
ABSTRACT: The new class of fully silicon-compatible hafnia-based ferroelectrics with high switchable polarization and good endurance and thickness scalability shows a strong promise for new generations of logic and memory devices. Among other factors, their competitiveness depends on the power efficiency that requires reliable low-voltage operation. Here, we show genuine ferroelectric switching in $Hf_xZr_{(1-x)}O_2$ (HZO) layers in the application-relevant capacitor geometry, for driving signals as low as 800 mV and coercive voltage below 500 mV. Enhanced piezoresponse force microscopy with sub-picometer sensitivity allowed for probing individual polarization domains under the top electrode and performing a detailed analysis of hysteretic switching. The authentic local piezoelectric loops and domain wall movement under bias attest to the true ferroelectric nature of the detected nanodomains.

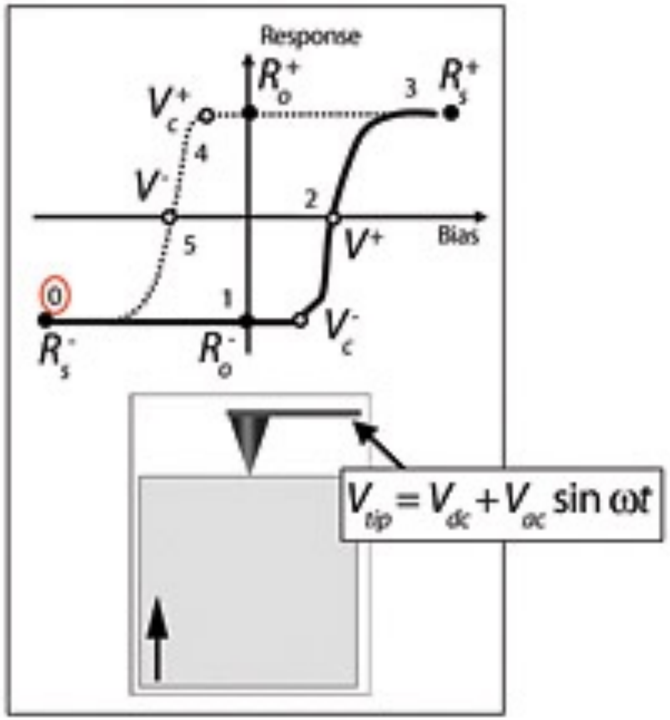


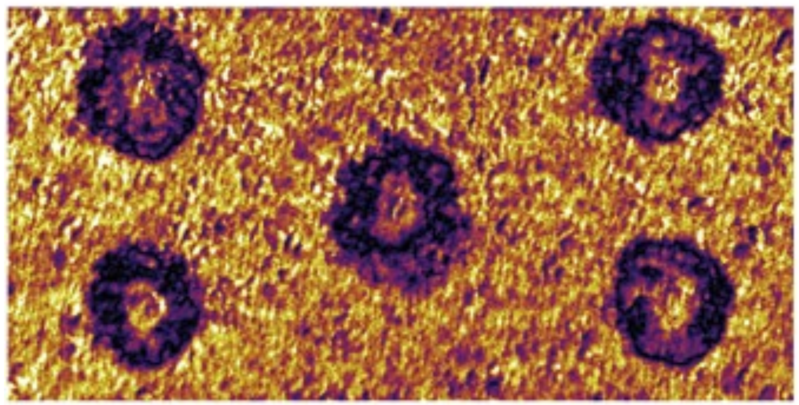
Piezoelectric response force (PFM) spectroscopy

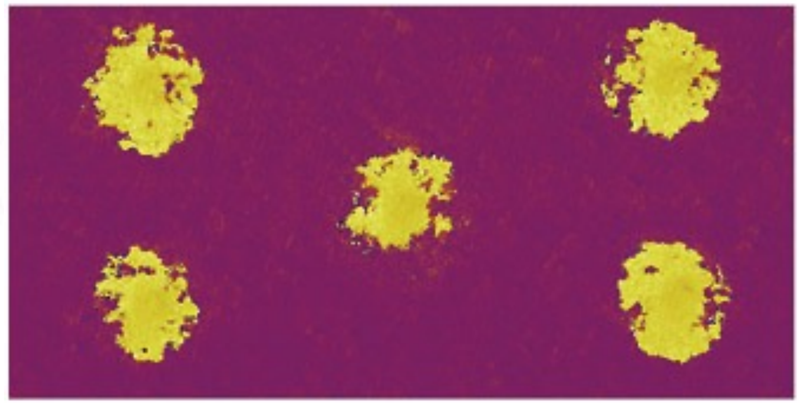
Measurements of d_{33} loop on a single point









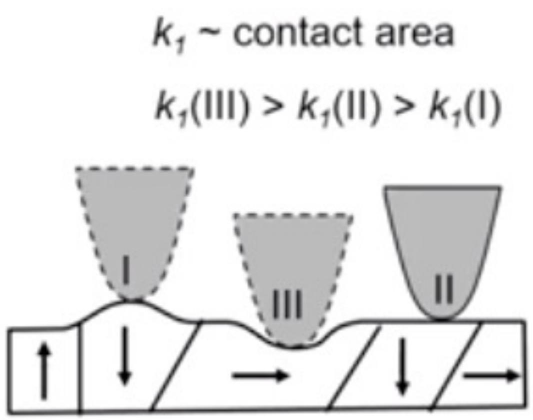


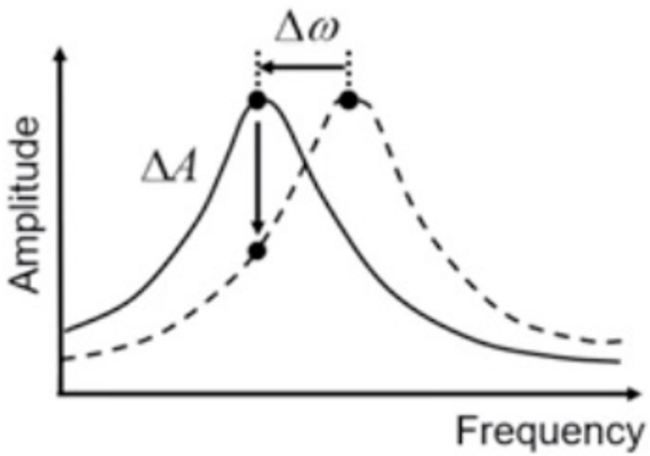
Loop measurement: the tip position is fixed, dc voltage is applied by steps; ac signal is permanently applied, the amplitude and phase of the mechanical response is plotted vs. V_{DC}

Cantilever resonance and frequency effects in PFM

- In PFM measurements the use of frequencies close to the tip resonance is very attractive – you can amplify the mechanical response by order(s) of magnitude

- There are difficulties – the resonance frequency may shift , this causes artifacts!
- The resonance frequency needs to be tracked and adjusted during PFM





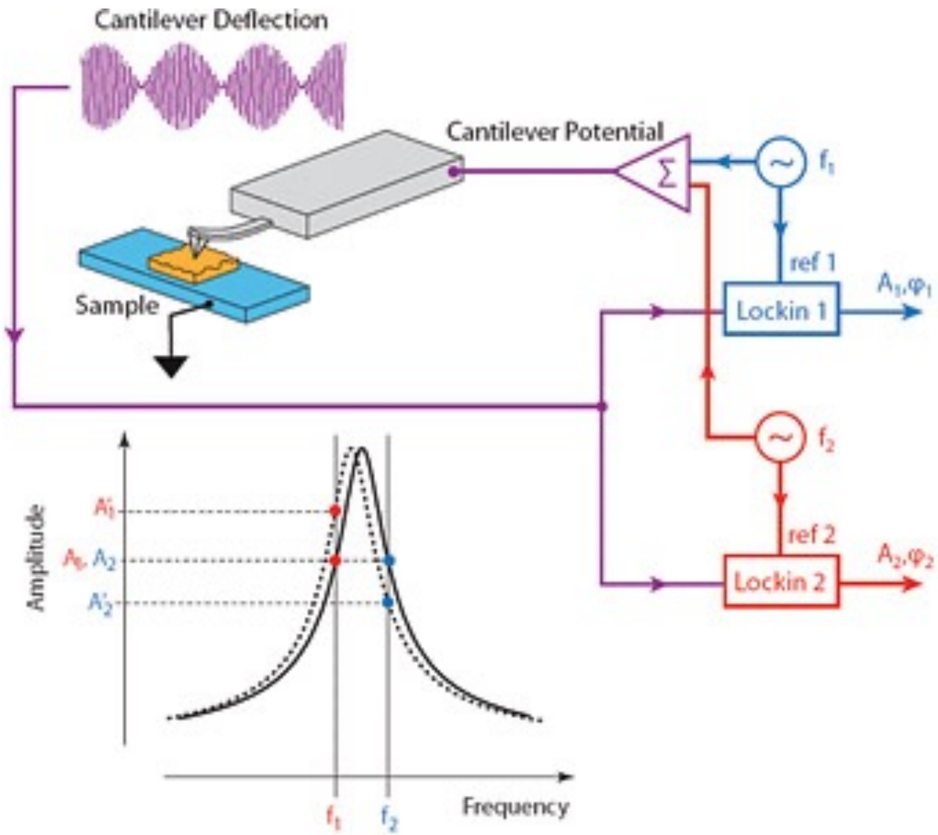
Problem 1: Resonance frequency depends on the topography
(and not on the electromechanical response)

Problem 2: Standard PLL frequency tracking loops are unstable

Piezoelectric response force microscopy (PFM):

Enhancing sensitivity by using cantilever resonances

Dual AC Resonance Tracking (DART)



• Driving cantilever with ac voltage at resonance frequency enhances sensitivity by an order of magnitude

• How to maintain the resonance while scanning the surface?

• the most common kind of resonance-tracking feedback loop is called a phase-locked loop (PLL) – does not work (phase changes)

By measuring the amplitudes at two frequencies, it is possible to measure changes in the resonance behavior and track the resonant frequency. Specifically, by driving at one frequency below resonance (A1), and another above (A2), A2-A1 gives an error signal used as a feedback

A powerful technique to track resonance: band excitation

Instead of tracking the resonance frequency like DART, a band of frequencies is generated in order to characterize the resonance peak at each point

Application note from Asylum research says:

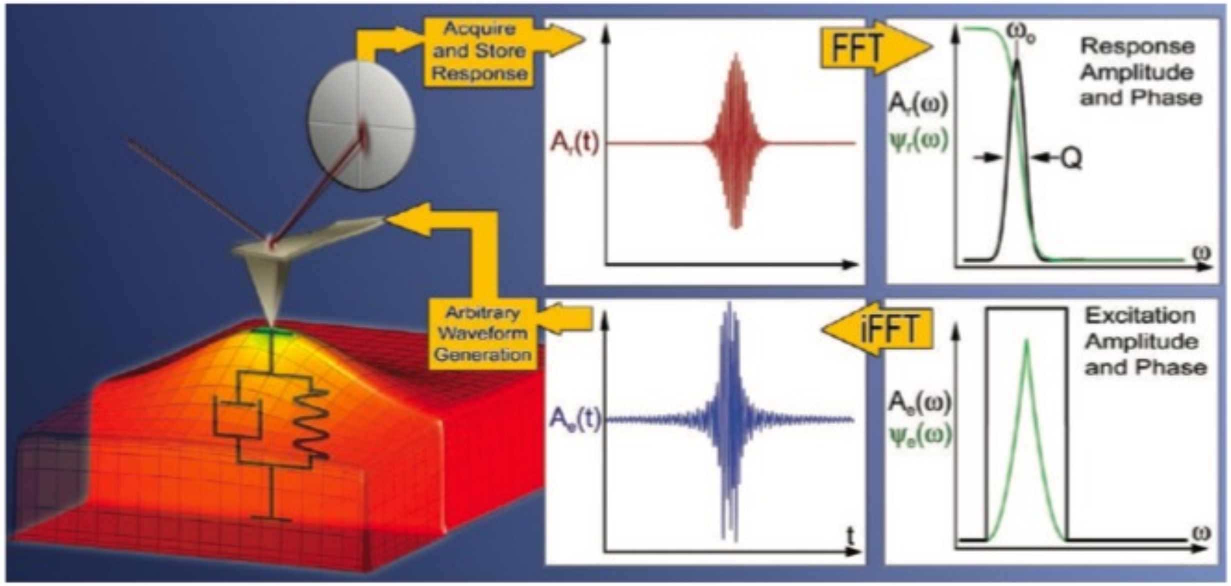
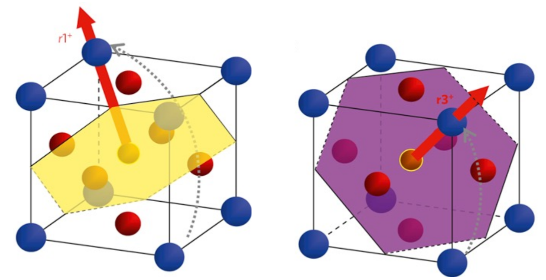


Figure 1: Principle of BE SPM. The excitation signal is digitally synthesized to have a predefined amplitude and phase in the given frequency window. The cantilever response is detected and Fourier transformed at each pixel in an image. The ratio of the fast Fourier transforms of response and excitation signals yields the cantilever response (sometimes also called the "transfer function"). Fitting the response to the simple harmonic oscillator yields amplitude, phase, resonance frequency, and Q-factor, plotted as 2D images or used as feedback signals.

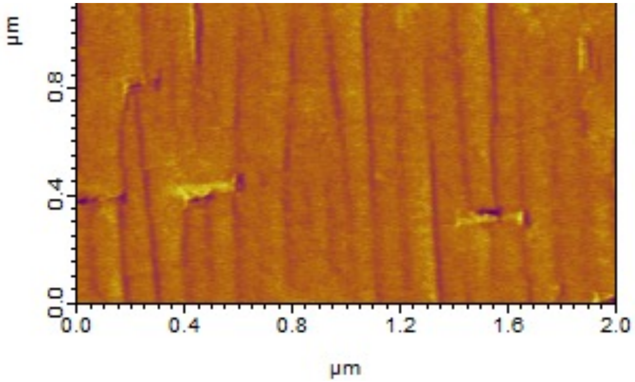
Lateral PFM



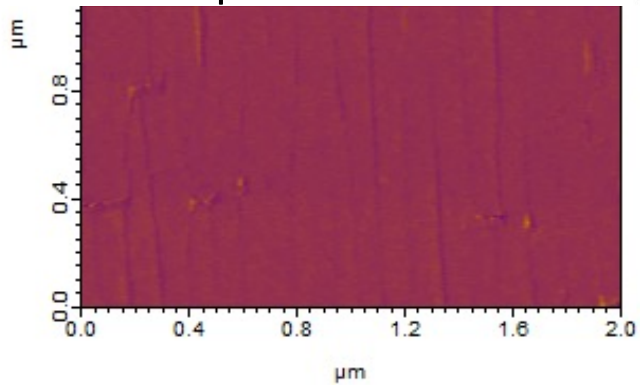
domain structures with unchanged vertical component of polarization do not show any contrast in standard (vertical) PFM images. However lateral PFM response shows clear amplitude and phase contrast

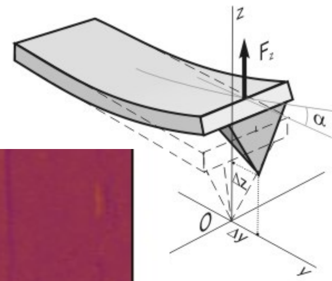
Vertical PFM

amplitude



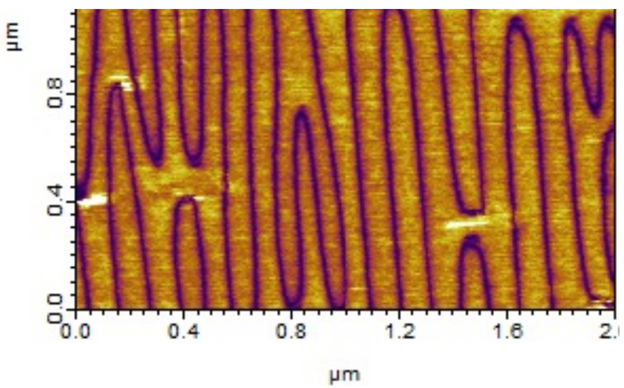
phase



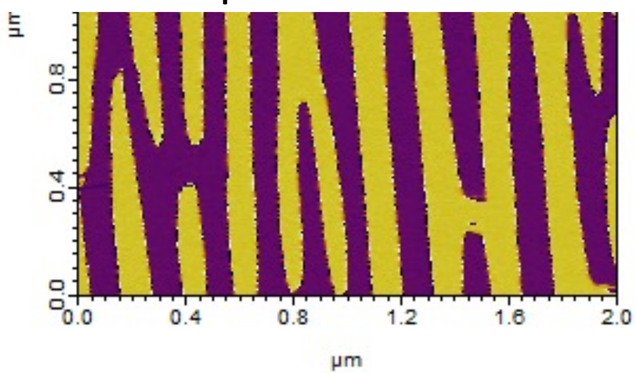


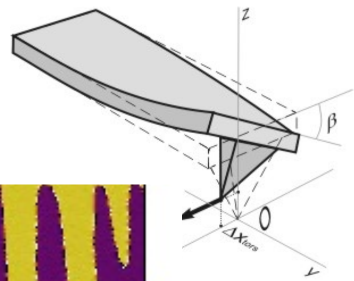
Lateral PFM

amplitude



phase





-Substrate: DSO/SRO(5nm)

-Thickness 60 nm

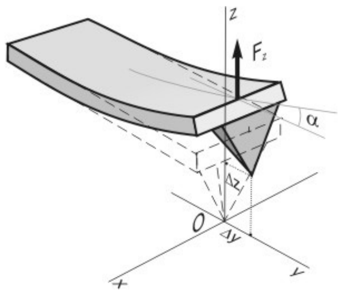
-Very smooth $BiFeO_3$ ferroelectric film (regular monolayer terraces)

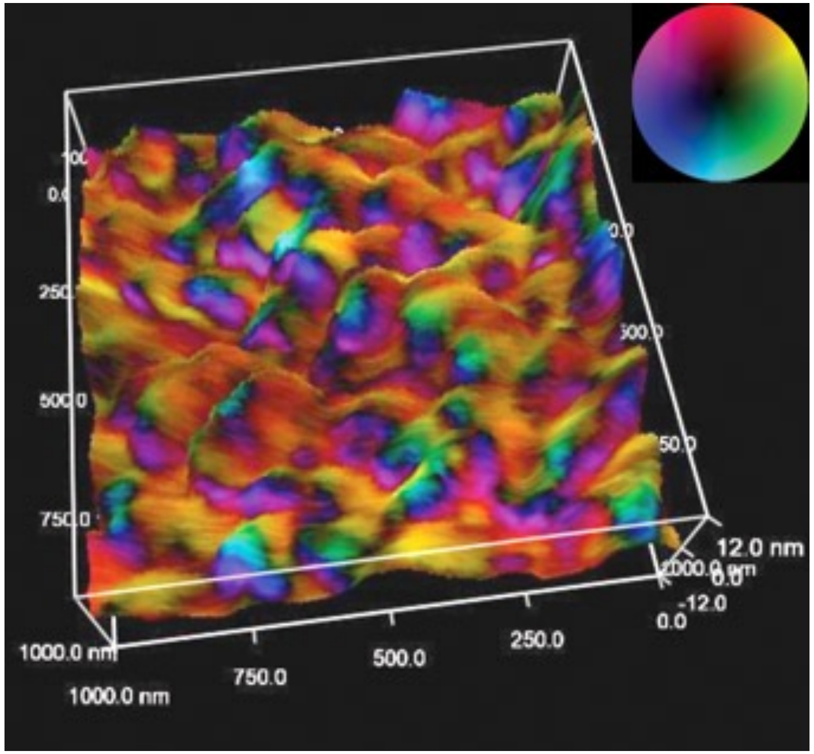
-Arrays of regular domains with 71° DWs (vertical polarization component unchanged)

Vector PFM

In vector PFM, the real space reconstruction of polarization orientation comes from three components of piezoresponse: vertical PFM plus at least two orthogonal lateral PFM. The picture shows an example of a vector PFM image of a barium strontium titanate film (BST), permitting qualitative inspection of the correlation of grain size, shape and location with local polarization orientation. Here, the color wheel permits identification of the local orientation of the polarization. Regions colored as cyan (darker blue/green) possess polarizations which are oriented predominantly normal to the plane of the film, whereas regions that appear magenta-blue or light green possess polarizations which are oriented predominantly within the plane of the film. The intensity denotes the magnitude of the response.

Vertical PFM





Lateral PFM

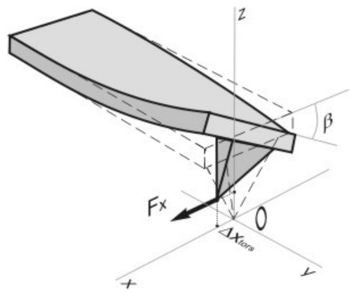
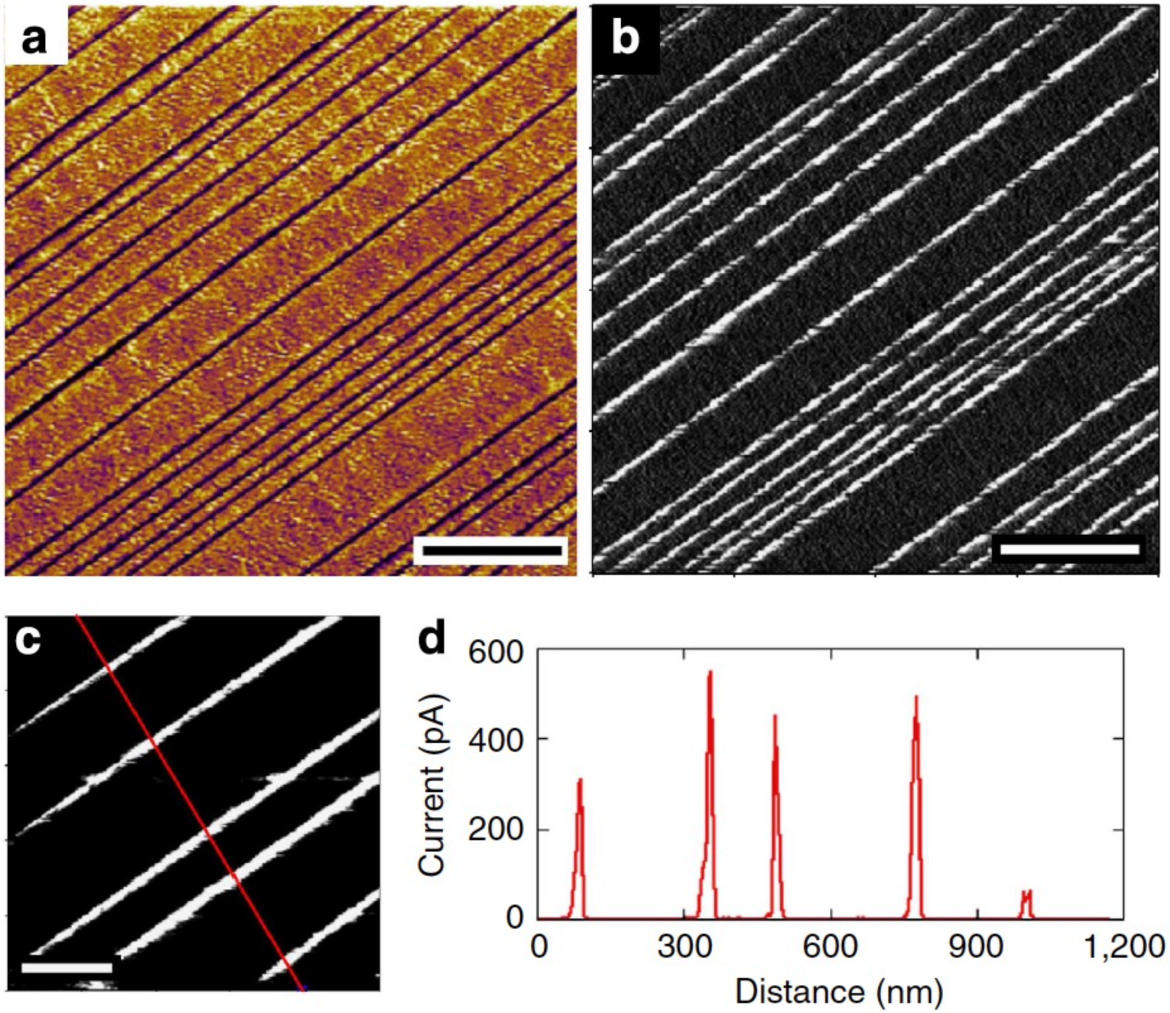


Image from Asylum Research website

Multi-functional AFM: combination of PFM and Conductive AFM (c-AFM)

PZT film with 1D array of ferroelectric domains (90° domains)
Combination of PFM and c-AFM: narrow 90° domains provide conductive channels



Nature Communications 5, 4677 (2014)

a) PFM amplitude, 4x4 μm scan

b) c-AFM, constant V=4V, same area

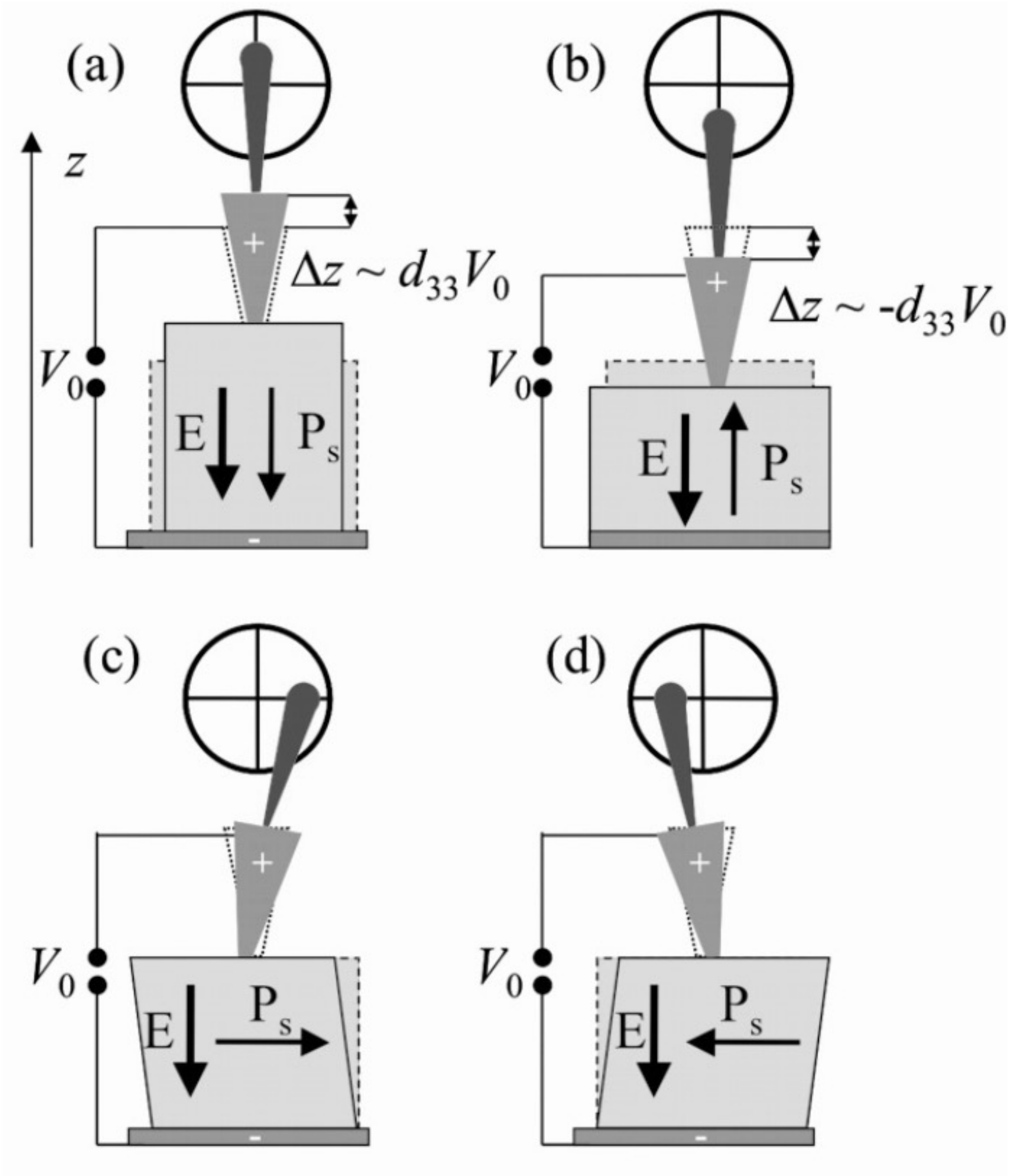
c) Zoom in: 1x1 μm c-AFM

d) Current profile, cross-section

Is it possible to use PFM if the polarization is in-plane?

Vertical mode:
Piezo coefficient $d_{33} = d_{333}$

Shear mode:
Piezo coefficient $d_{15} = d_{113}$



Exercise

- Download from moodle the paper cited below and supplementary materials
- Analyze the PFM measurements presented in this work
- Make sure you understand how the PFM experiment has been carried out
- Answer why angle-resolved measurements have been undertaken
- Answer why both vertical and lateral PFM are used (and what way they complement each other)

COMMUNICATION

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In-Plane Ferroelectricity in Thin Flakes of Van der Waals Hybrid Perovskite

Lu You, Fucai Liu, Hongsen Li, Yuzhong Hu, Shuang Zhou, Lei Chang, Yang Zhou, Qundong Fu, Guoliang Yuan, Shuai Dong, Hong Jin Fan, Alexei Gruverman, Zheng Liu, and Junling Wang**

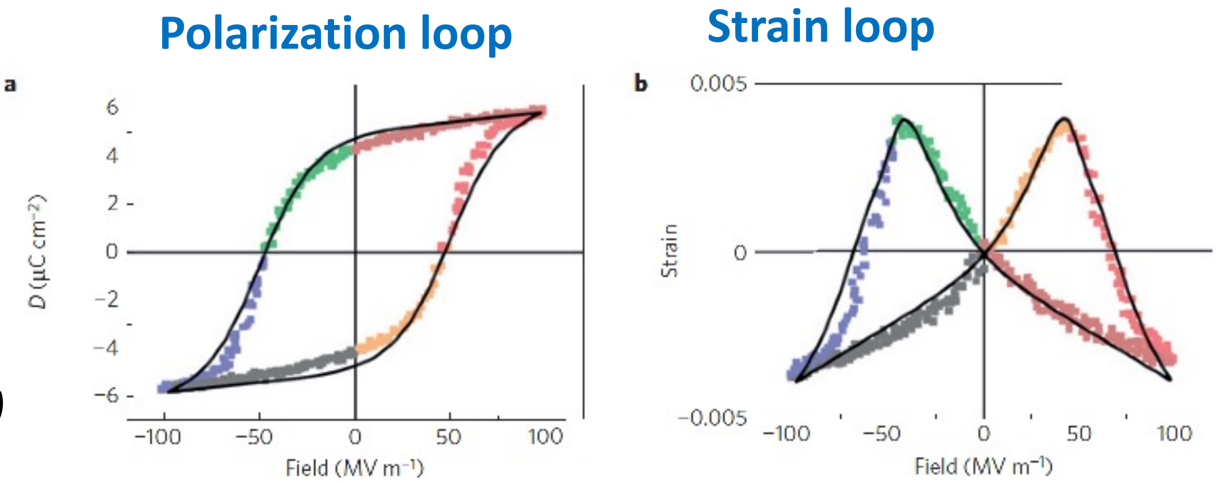
)

Probing nanoelectromechanics with dc bias:
Strain-field curves (DC), electrostriction

PVDF-TrFE ferroelectric polymer: negative electrostriction (Q_{33}=-1.5m^4/C^2), strain ***x*** is linked to the polarization ***P*** : ***x=QP²*** ($x=QP^2$)

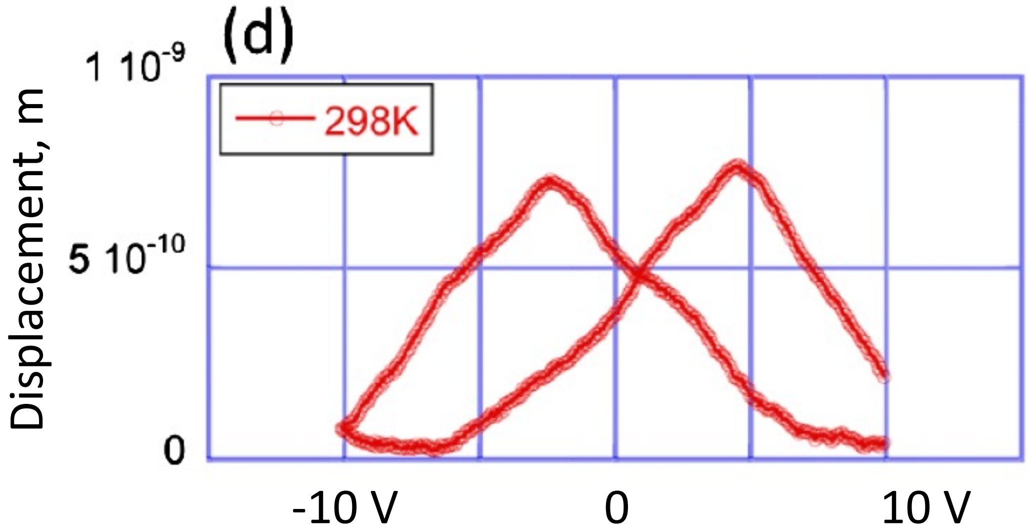
Polarization loop and strain curve: data from X-ray analysis

Nature Materials, 15, 78 (2016)



AFM data:
Direct measurement of displacement vs. DC voltage
(PVDF 20nm nano-island)

PRL, 108, 027603 (2012)

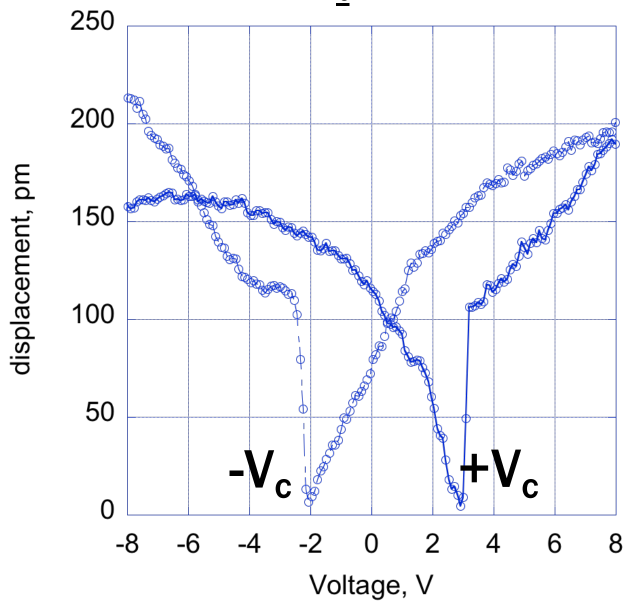


Stability problem!
Noise problem!
Low-signal ac measurements are better!

Omicron Cryo-SFM in IMX-EPFL: low noise and high stability of scanner allows for strain curve measurements with pm resolution

<u>Example: PZT 50nm, 120K, raw data (strain)</u>

<u>A direct way to track V_c</u>



Raw data, AFM tip deflection, feedback off, no filtering, no data smoothing

Full swing 2Å, 3-5pm between dots (no lock-in)

Summary PFM

- Measurements of linear electromechanical response
- Drive with low ac signal – measure mechanical response at the same frequency (amplitude, phase)
- Contact technique, conductive probe (electric contact required)
- ac signal maybe combined with dc to study switching
- Very weak response (down to pm), maybe enhanced by cantilever resonance
- Quantitative measurements of piezoelectric coefficient

- Polarization is a vector, piezoresponse – 3th rank tensor, full characterization involves vertical, lateral and angle-resolved measurements (PFM – tensorial SPM method)

Lectures on YouTube, PFM, KPFM and other related techniques

Useful lectures from ORNL team

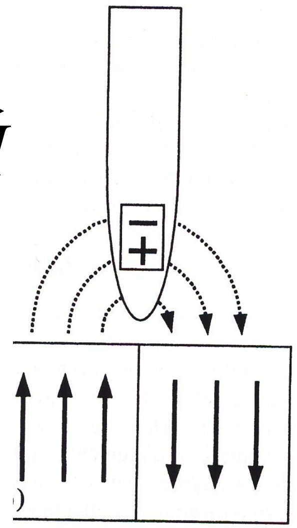
- PFM
  - https://www.youtube.com/watch?v=UsyRW2_Kp-Y
  - https://www.youtube.com/watch?v=BDmXUt4OOuY
  - And others in the series
- KPFM and other electrical methods
  - https://youtube.com/watch?v=WB0s9cwIuxM
  - https://youtube.com/watch?v=PjjjXij7930
  - And others in the series

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

Magnetic force microscopy: an overview

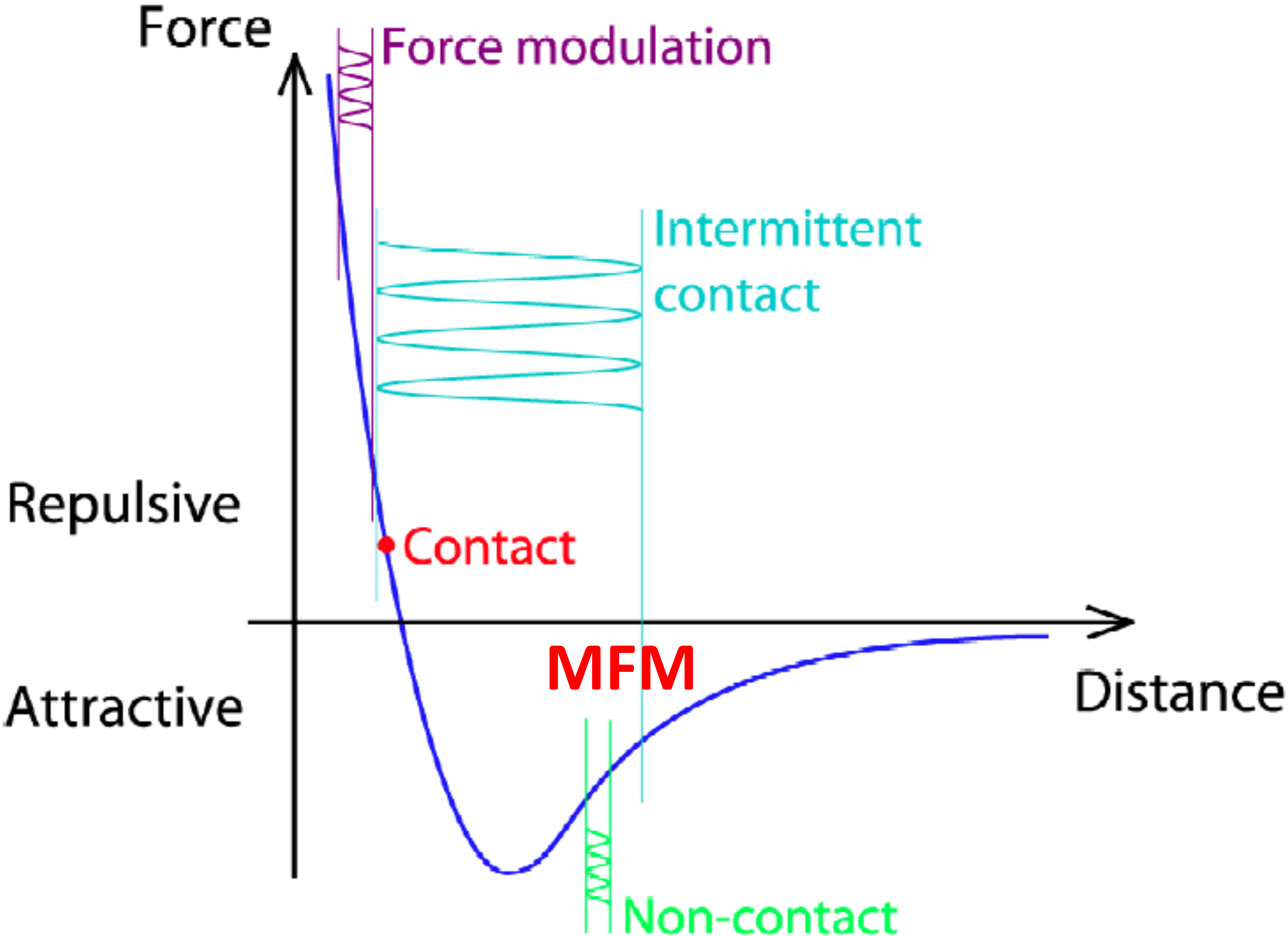
In MFM measurements, the magnetic force between the sample and tip can be expressed (in point dipole approximation) as:

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



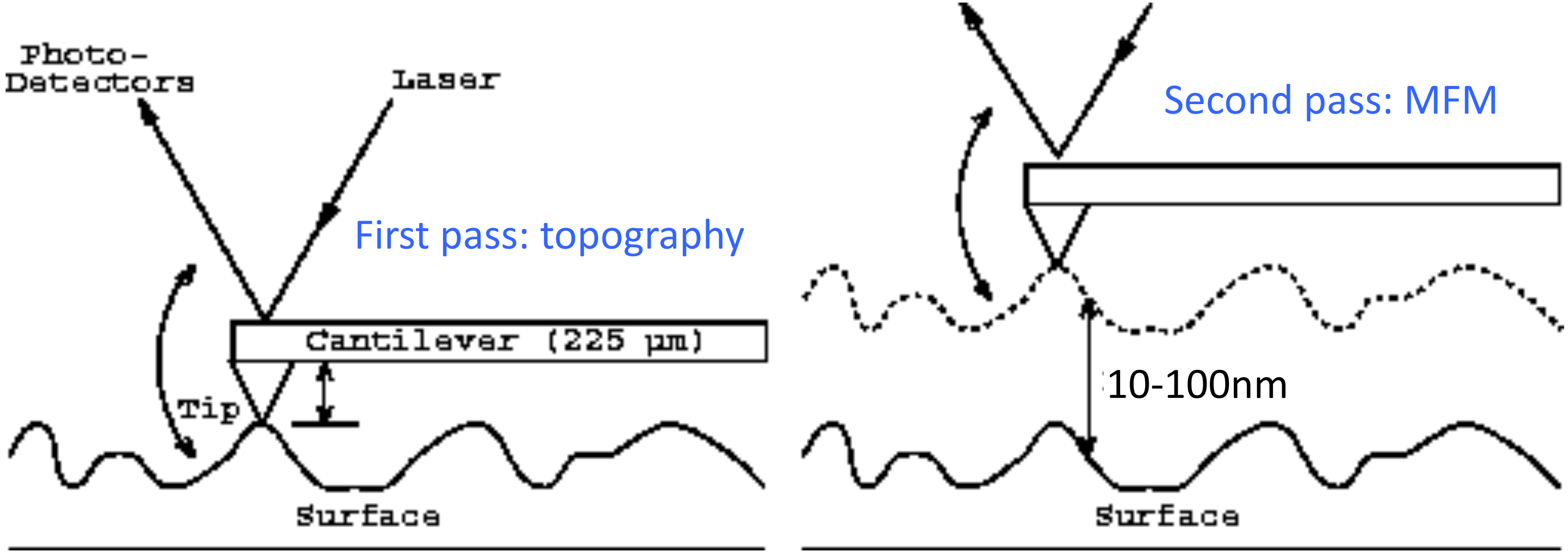
Here $\vec{m}$ is the magnetic moment of the tip approximated as a point dipole, ***H*** is the magnetic stray field from the sample surface.
For calculating the total force the integration has to be performed over the volume and the magnetic domain configuration needs to be known.
MFM relies on long-range 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
Distance
Attractive
Non-contact

Magnetic force microscopy

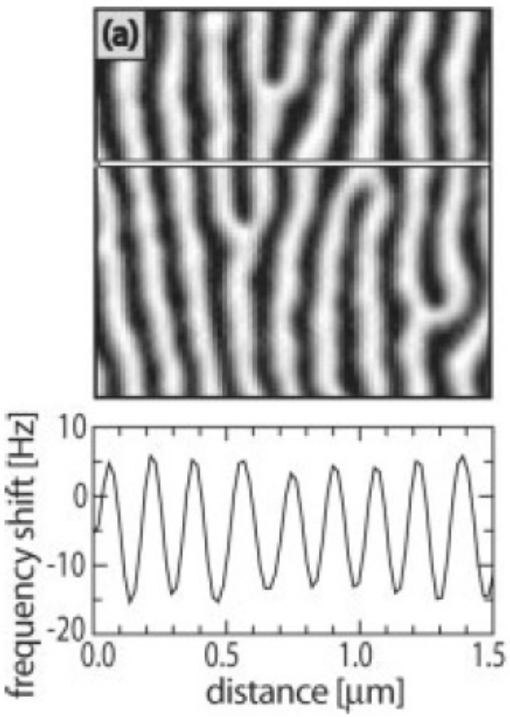
MFM is generally performed in combination with topography imaging. Two-pass scan is a useful technique to avoid crosstalk between two sets of data.
Technically it is implemented as follows:
AFM operates in non-contact or tapping mode. Initially a line is scanned in topography mode and the height profile 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



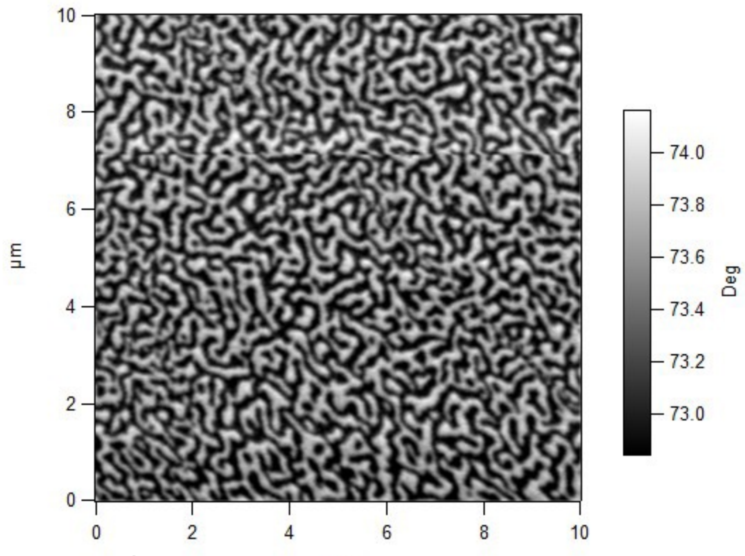
The two-pass approach is not necessary for atomically flat substrate. In this case instead of getting detailed topography the slope of the surface in X and Y direction is detected. Then the tip is retracted to required distance and MFM data are collected

Magnetic force microscopy: examples

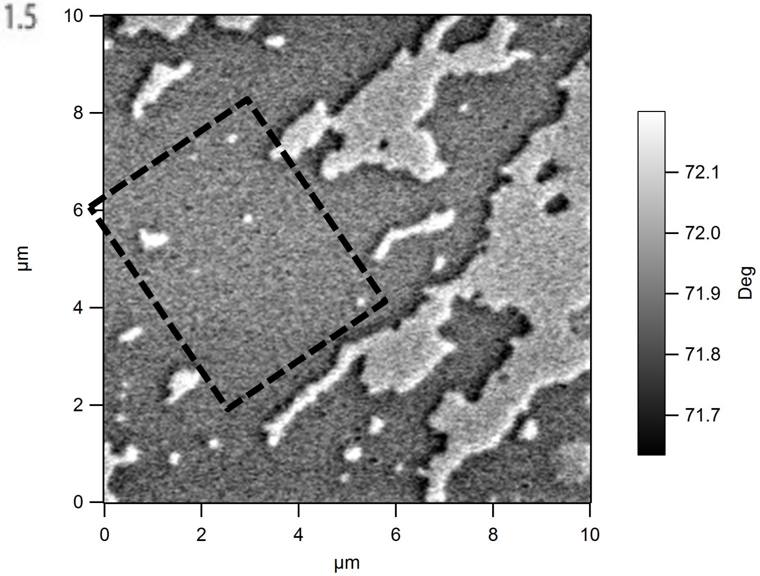
Magnetic domain structure of
Co/Pt multilayered sample
P. Kappenberger et al., Adv. Eng. Materials, 7, 332 (2005)



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

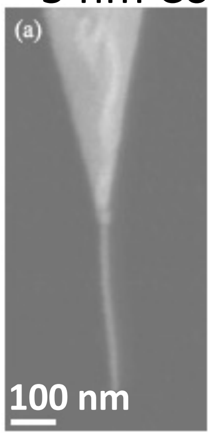
Material:	0.01 - 0.025 Ωcm Antimony (n) doped Si
Geometry:	Rectangular
Cantilevers Number:	1
Cantilever Thickness (Nom):	2.75 μm
Cantilever Thickness (RNG):	2.0 - 3.5 μm
Front Side Coating:	Magnetic CoCr
Back Side Coating:	Reflective CoCr

- 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)

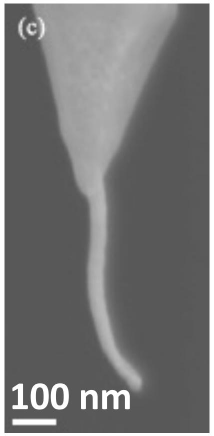
- The tips typically need to be magnetized before measurements
- In-situ magnetic coating is used for some special measurements in UHV

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

5 nm Co



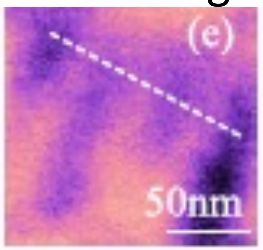
15 nm Co



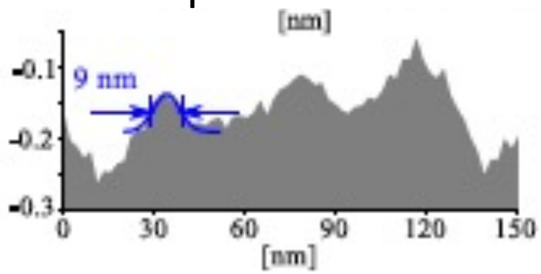
- Special solution for high-resolution MFM: Co-coated carbon nanotube

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