

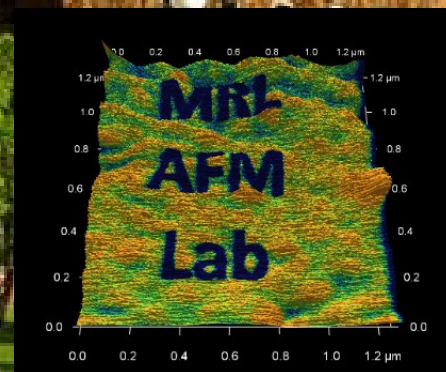
Atomic Force Microscopy

Kathy Walsh

Senior Research Scientist
Scanning Probe Microscopy

Materials Research Laboratory
Central Research Facilities

Physics 403
10/28/25





Illinois Materials Research Lab

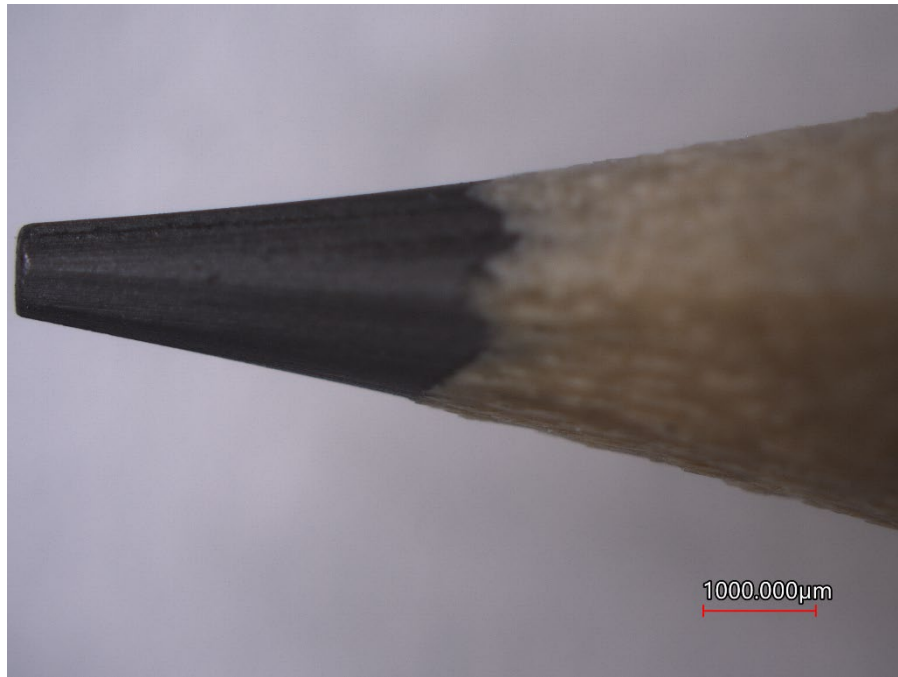
Central Research Facilities

- User facility—anyone can be trained
 - UIUC and non-UIUC researchers welcome
 - Undergraduate researchers welcome
 - Staff collaboration or analysis available
- mrl.illinois.edu/facilities
- mrl-facilities@illinois.edu

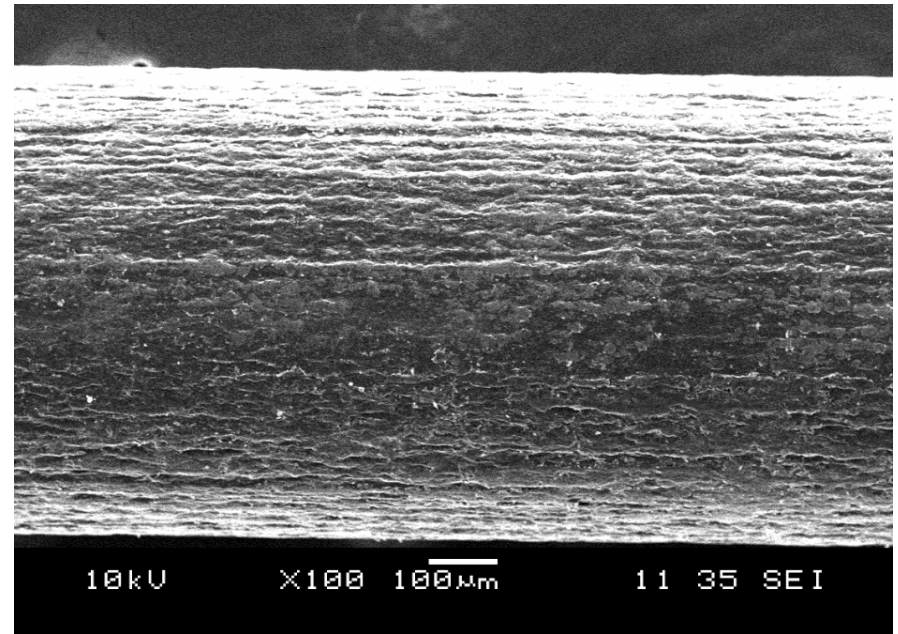


Looking at Surfaces

Optical Microscopy



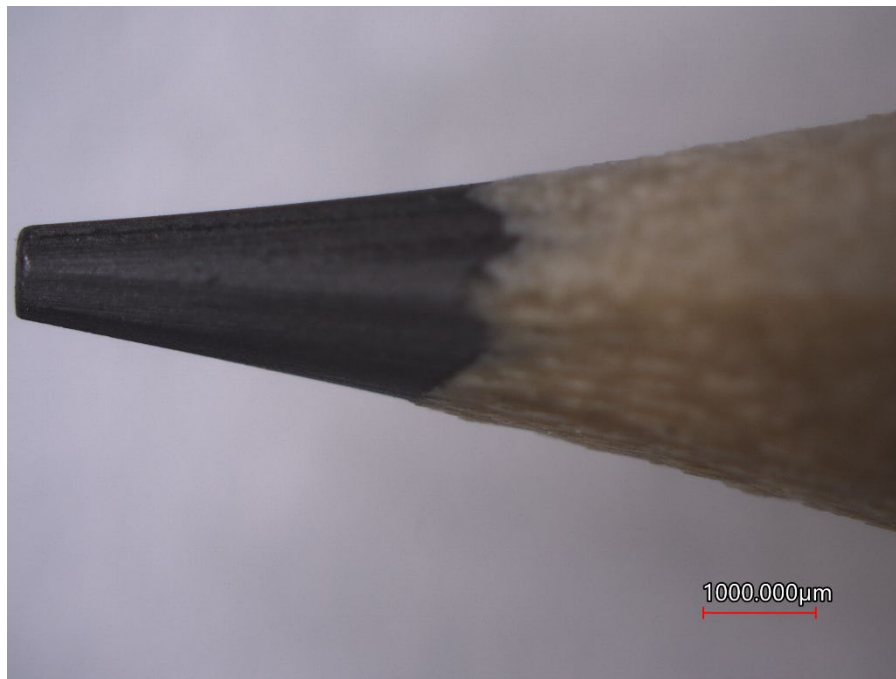
Scanning Electron Microscopy



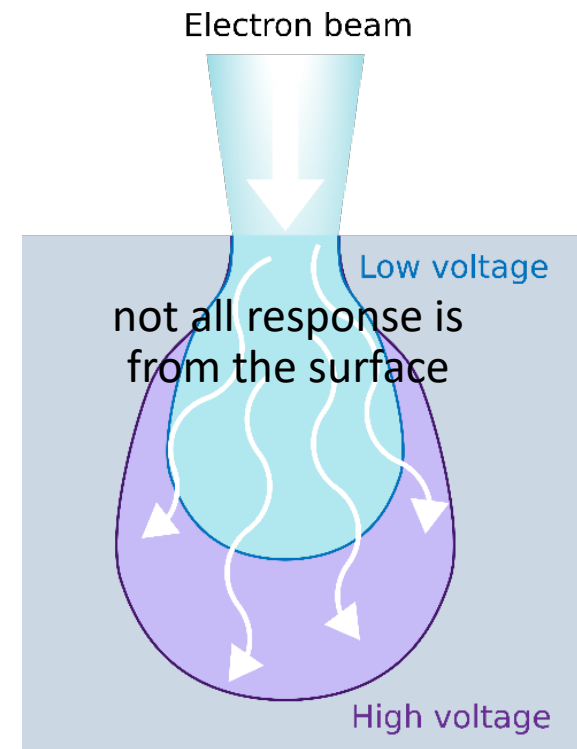
mechanical pencil “lead”

Looking at Surfaces

Optical Microscopy



Scanning Electron Microscopy

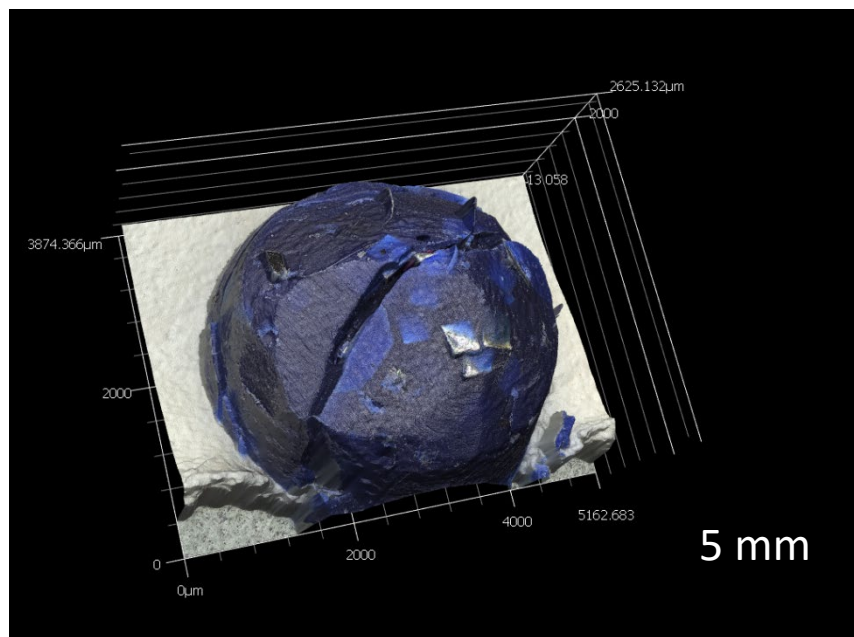


Adapted from
https://myscope.training/#/SEMlevel_2_13
(CC BY-SA 4.0)



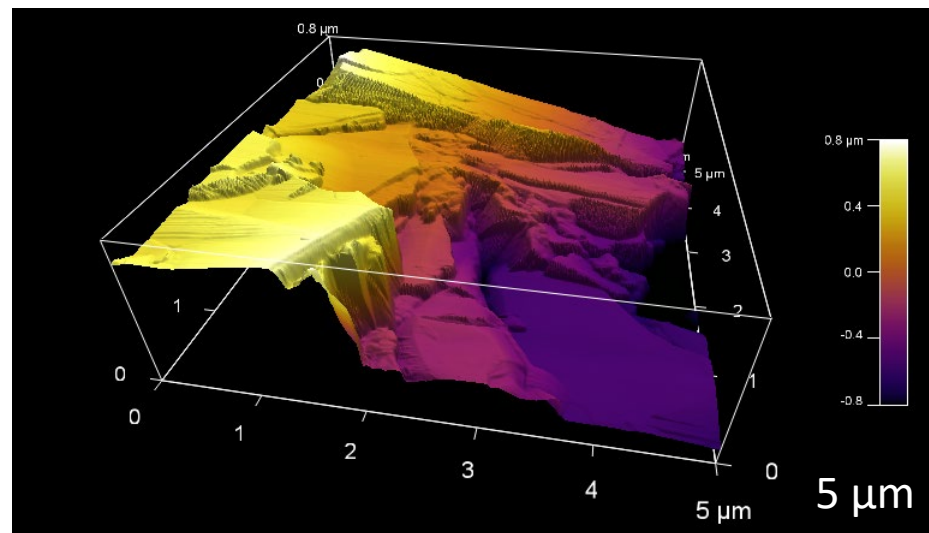
Surface XYZ Coordinates Needed

3D Optical Profilometry



blue glitter crayon tip

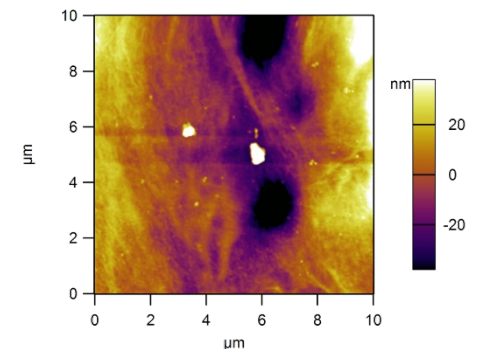
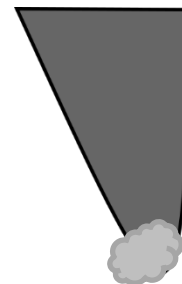
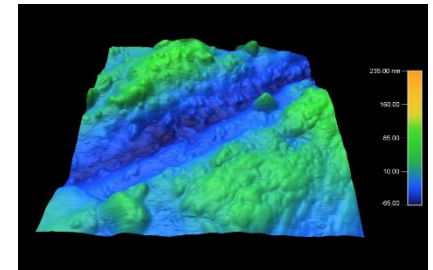
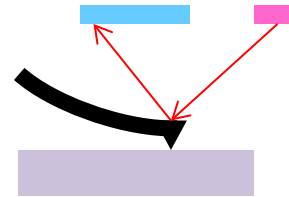
Atomic Force Microscopy



pencil "lead"

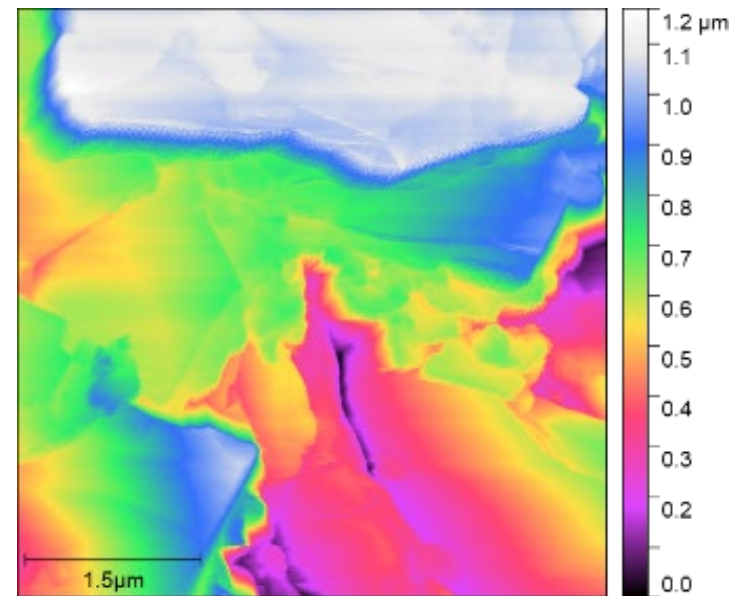
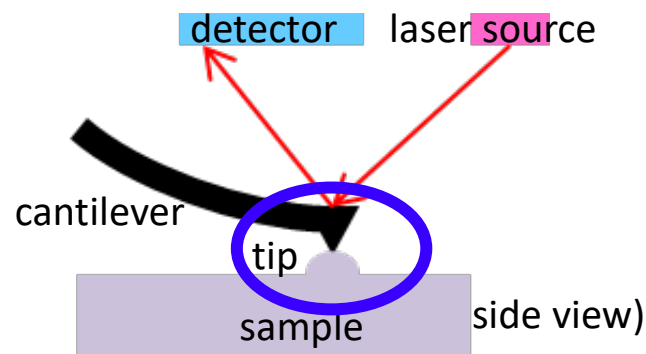
Topics for Today

- How AFM works
- Featured applications
 - Topography
 - Profiles, step height
 - Roughness
 - Phase
 - Conductive AFM
- Issues and artifacts
- Image processing



What's an Atomic Force Microscope?

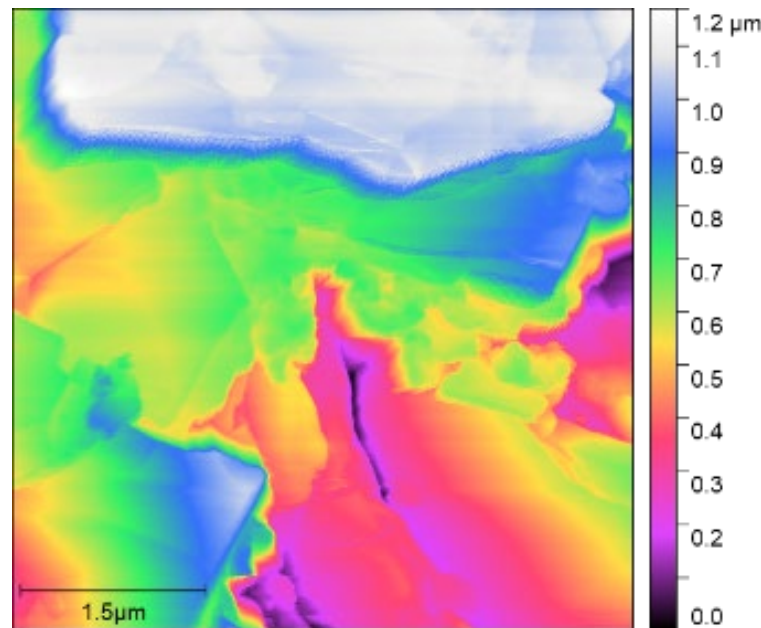
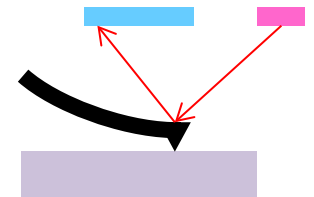
“Atomic Force” Microscopy—forces between atoms in the tip and atoms in the sample



false-color surface topographs

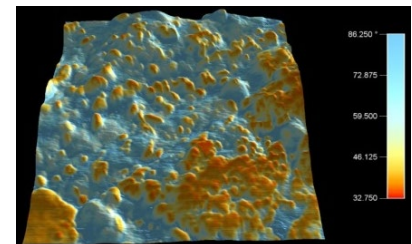
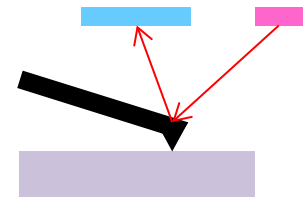
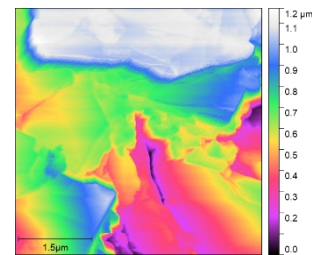
What's an Atomic Force Microscope?

- “Atomic Force”—interactions between tip and sample
 - Not actual atomic resolution (usually)
 - Nanoscale lateral resolution (depends on tip)
 - Sub-angstrom vertical resolution
- “Microscope”—surface topograph (false color)



What's an Atomic Force Microscope?

- “Atomic Force” —interactions between tip and sample
 - Not actual atomic resolution (usually)
 - Nanoscale lateral resolution (depends on tip)
 - Sub-angstrom vertical resolution
- “Microscope” —surface topograph (false color)
- Tip at the end of a cantilever
- Raster tip over surface to build up an image
- Also sensitive to sample stiffness, adhesion, other properties depending on tip choices

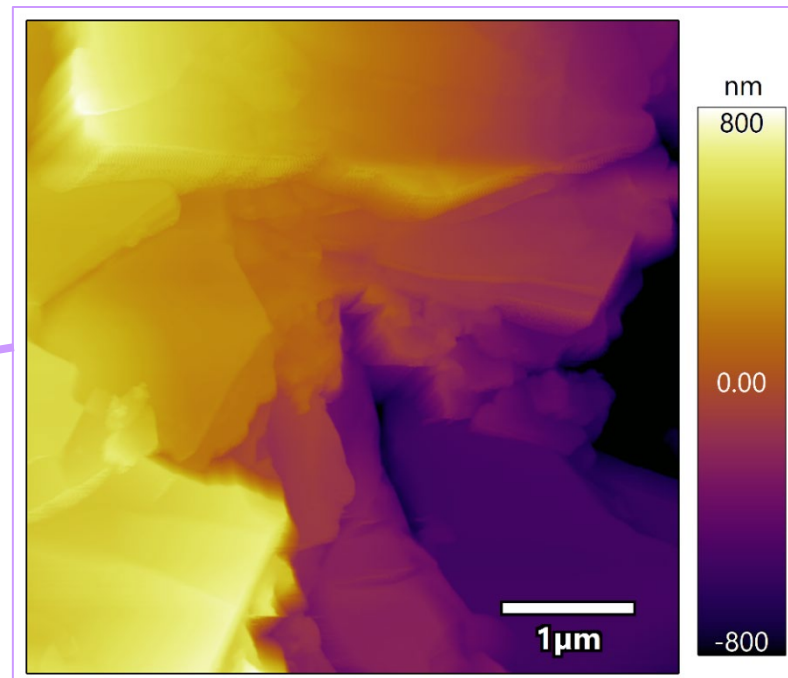
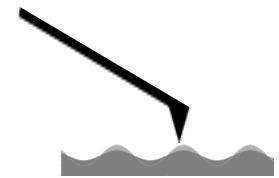


Turquoise, 1 μm x 1 μm
color overlay: phase

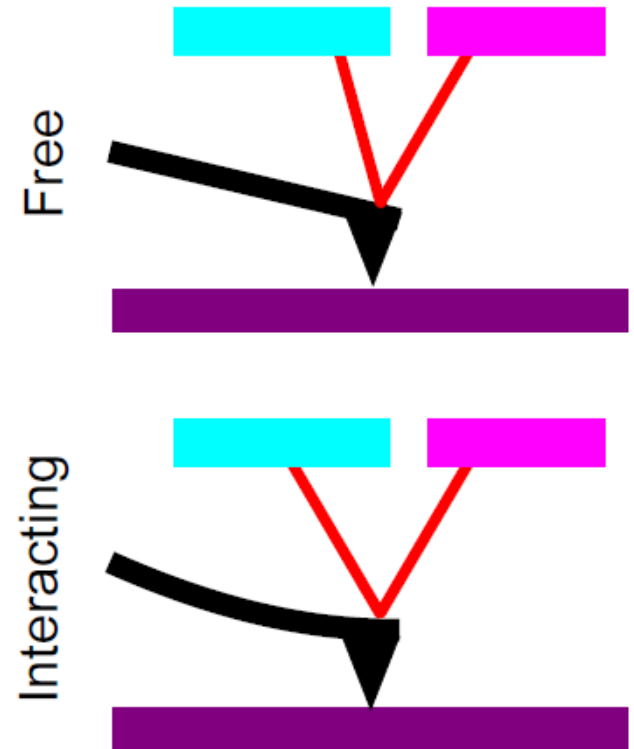
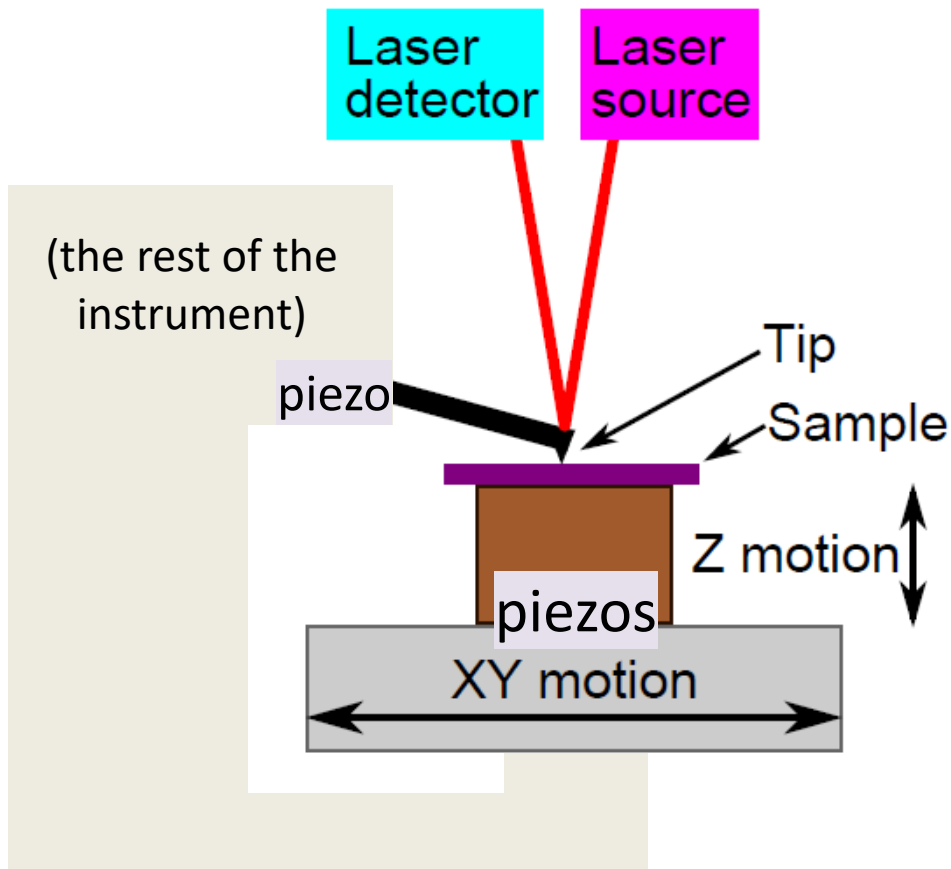
Typical AFM Scales

(only what's pretty common, not all of what's possible)

- Image sizes -- few to tens of μm^2
- Feature peak-to-valley -- $\text{\AA}$ to μm
- Sample sizes -- mm to cm
- AFM measures surfaces



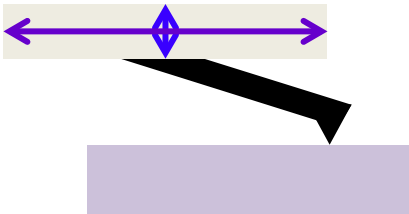
AFM Schematic



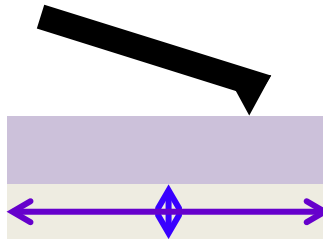
Scanners

scanning probe microscopy

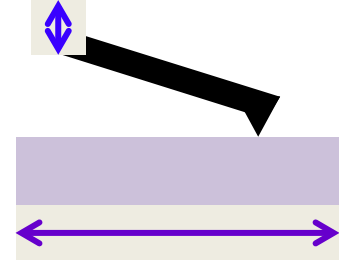
tip scanning



sample scanning



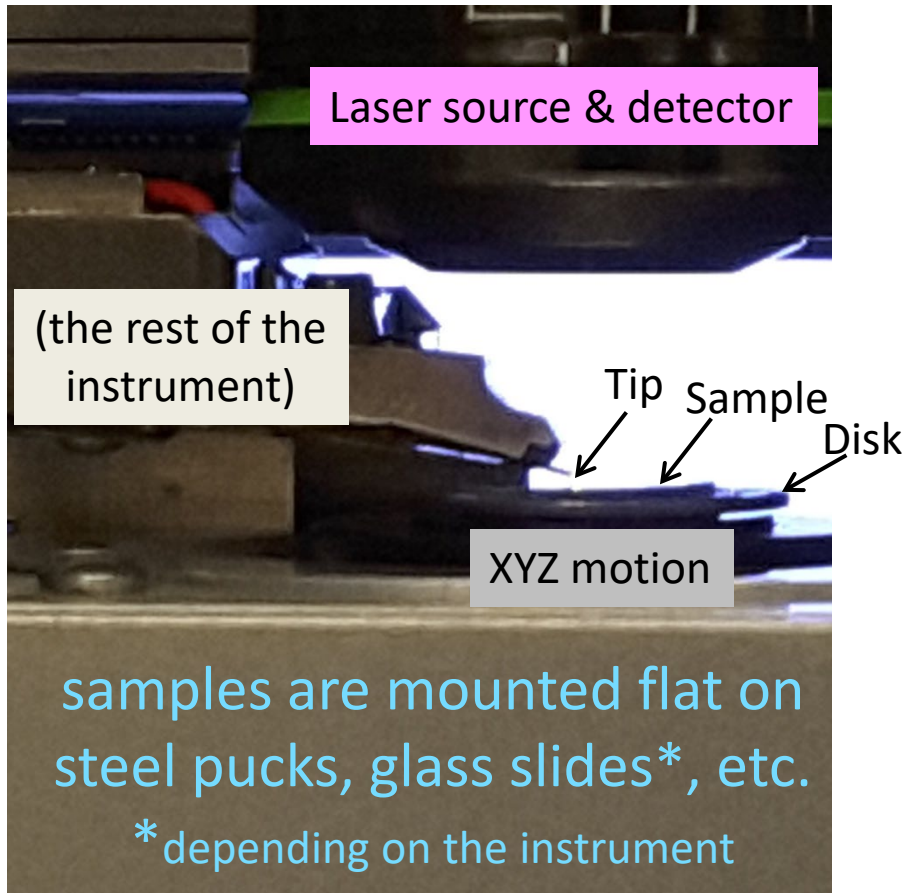
decoupled scanning



tapping is done close to or at the cantilever
(tapping mode will be described later)

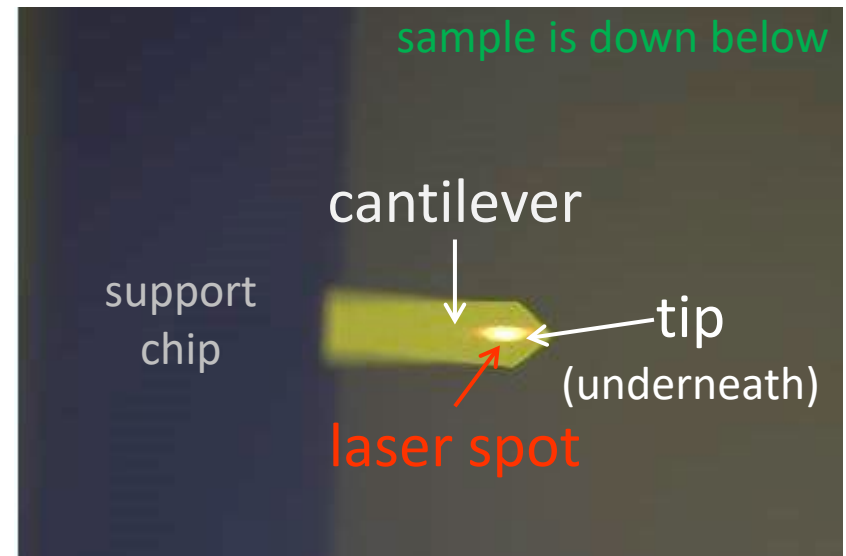


AFM Instrument

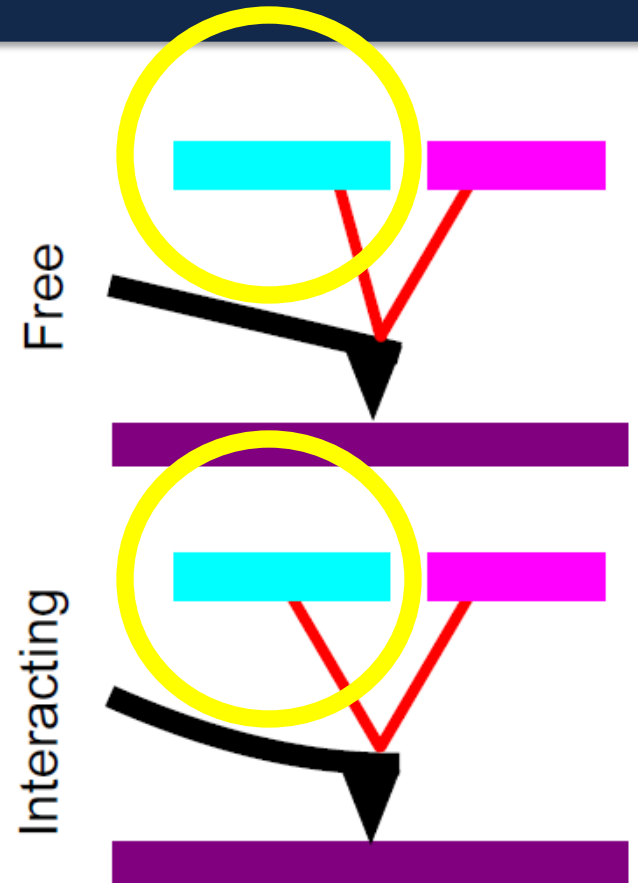
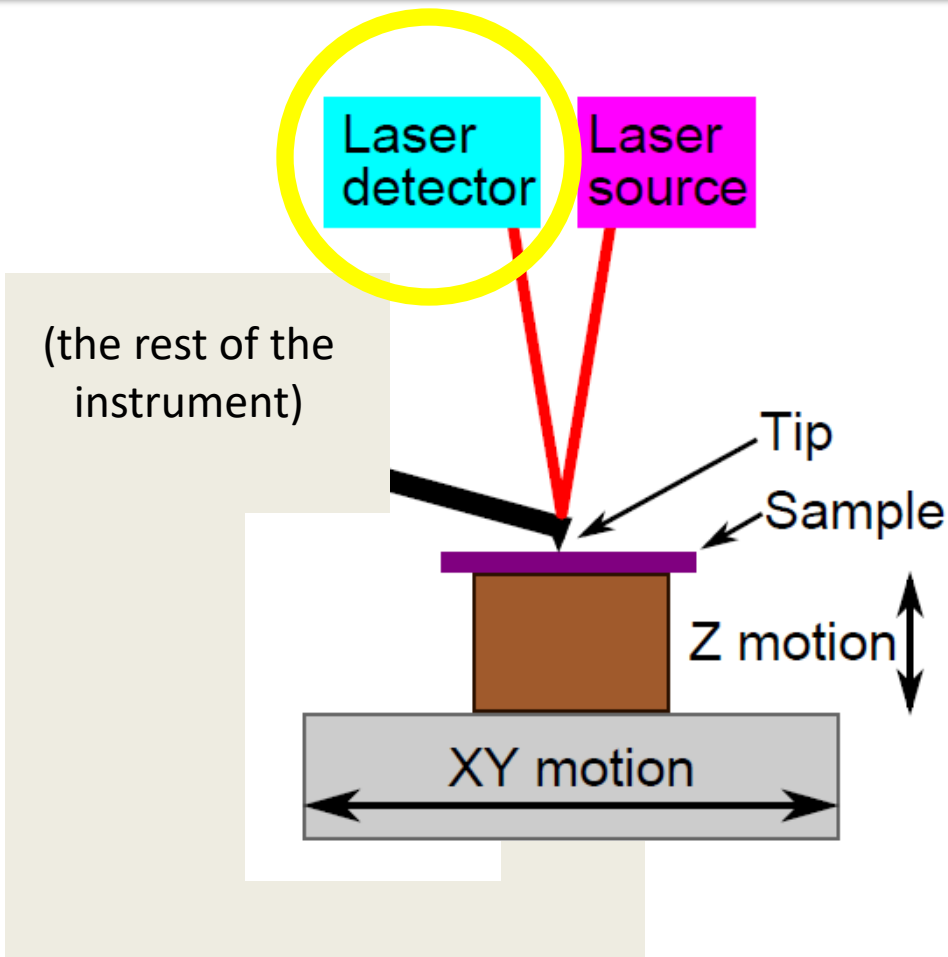


side view

top view

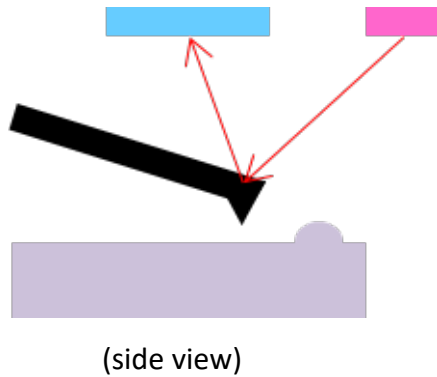


AFM Schematic

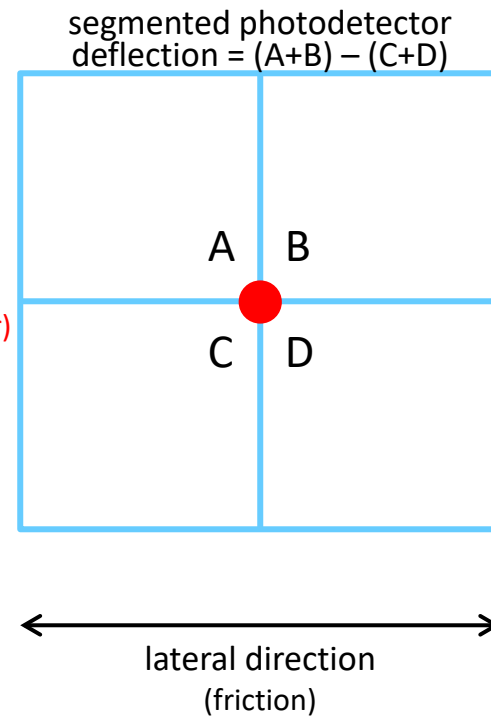


Laser Detection

non-interacting



laser spot
(reflected from back of cantilever)

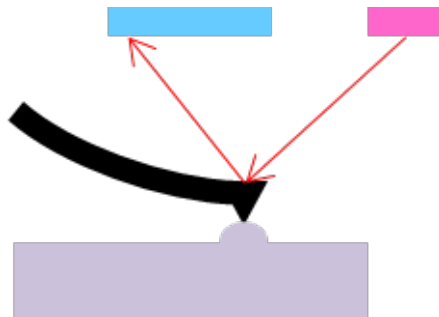


normal direction
(topography)

(exaggerated schematic)

Laser Detection

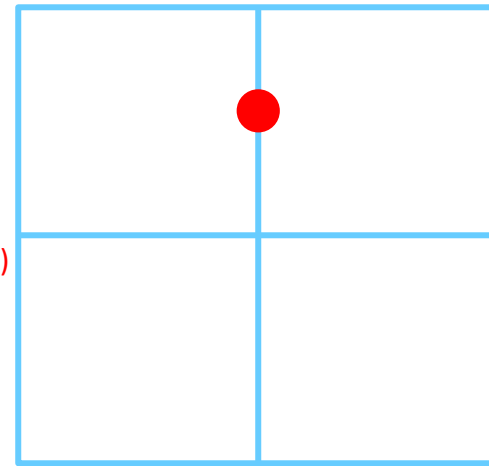
sample pushing up



(side view)

laser spot
(reflected from back of cantilever)

segmented photodetector



lateral direction
(friction)

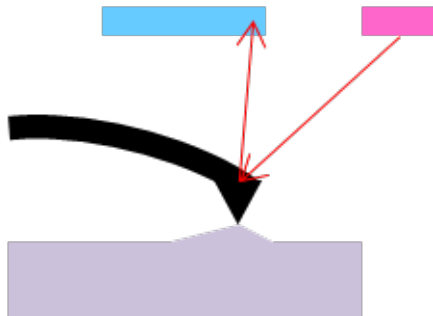


normal direction
(topography)

(exaggerated schematic)

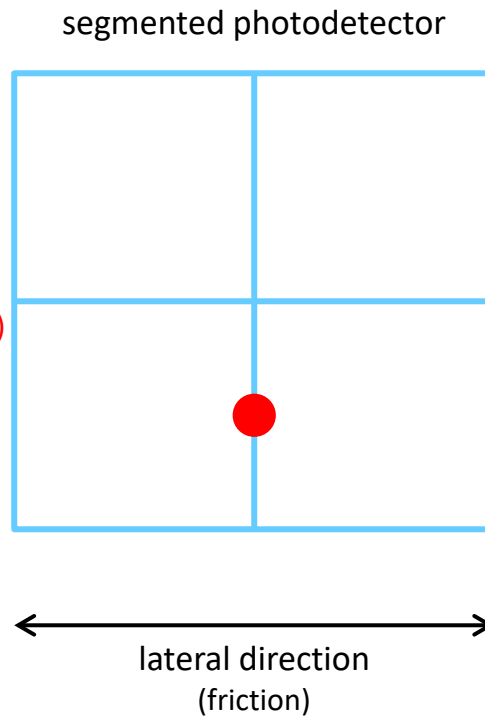
Laser Detection

sample pulling down



(side view)

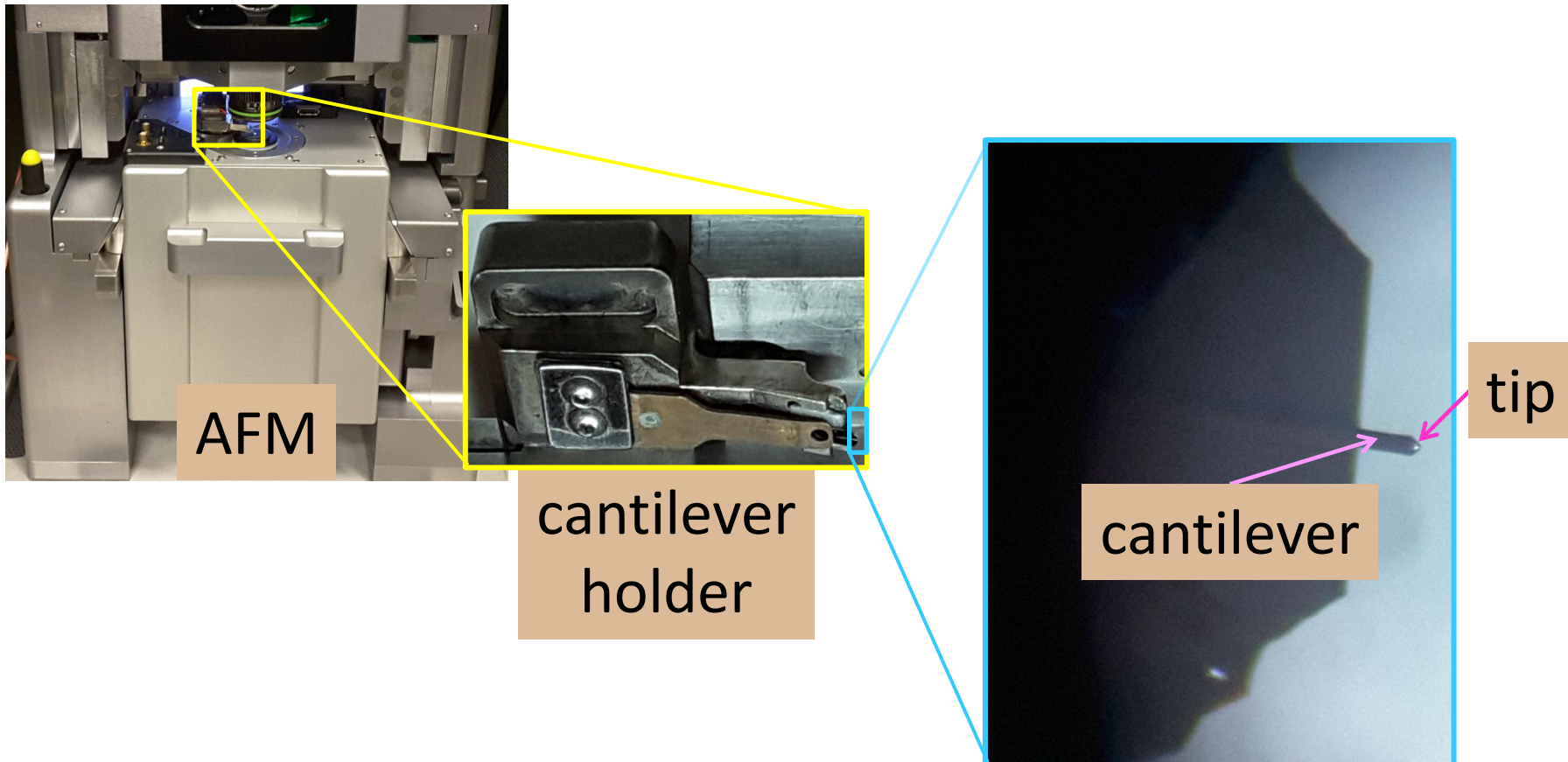
laser spot
(reflected from back of cantilever)



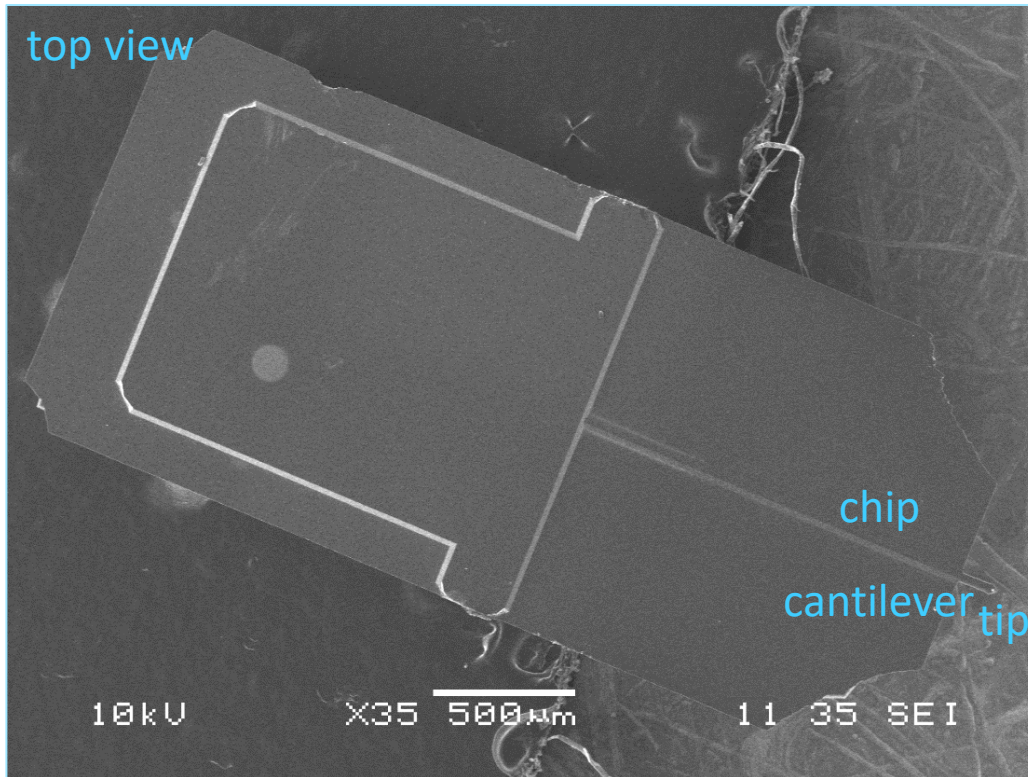
(exaggerated schematic)

AFM Tips

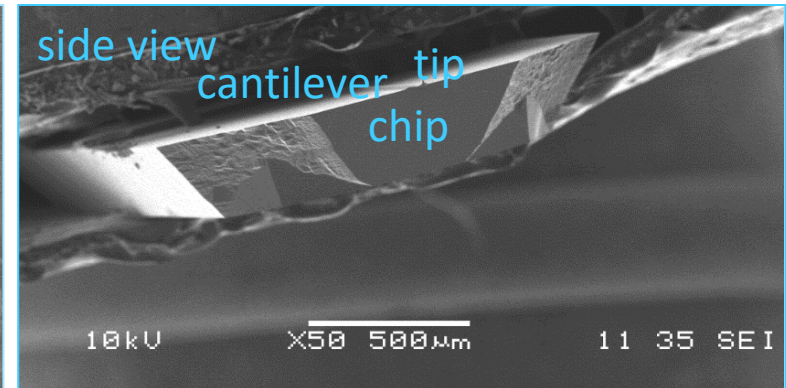
scanning *probe* microscopy



Tip Terminology

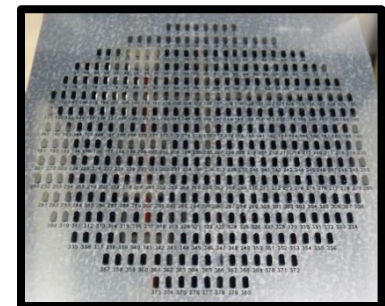


SEM images taken using MRL's JEOL 6060LV

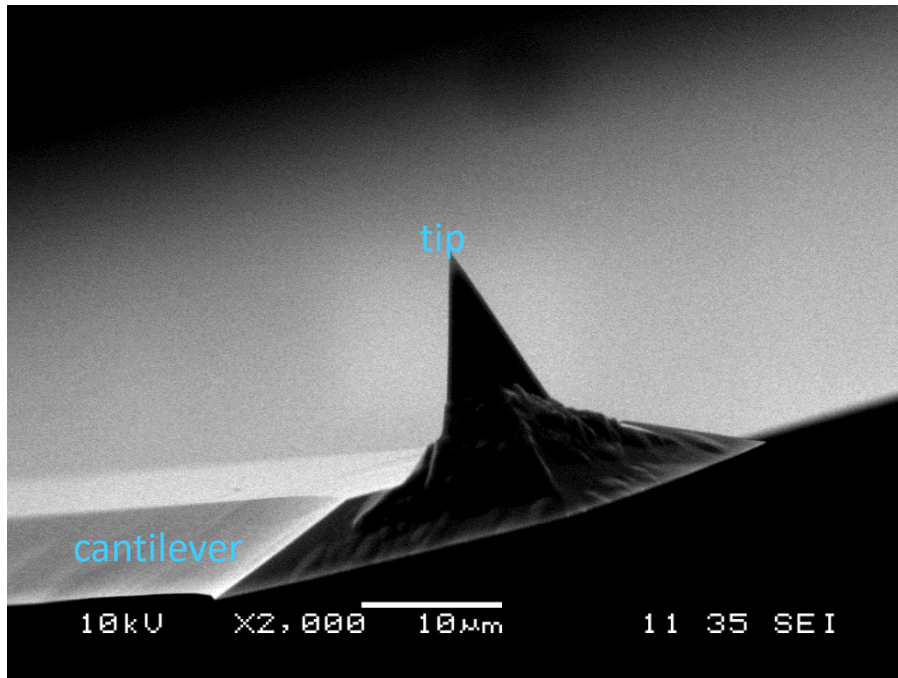


“probe”

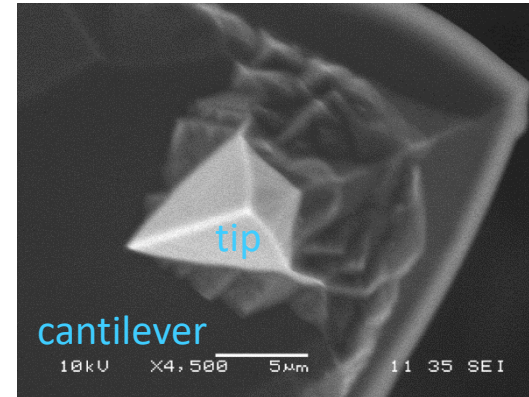
tips point upwards
in the box



Typical Tip

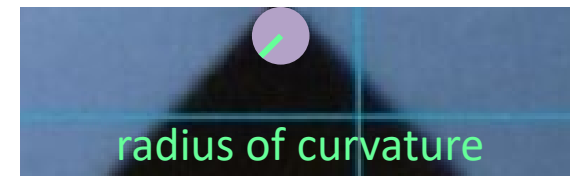


SEM images taken using MRL's JEOL 6060LV



common tip for imaging:

- tip radius of curvature < 10 nm
- silicon tip
- cantilever width $30\text{ }\mu\text{m}$
- cantilever length $125\text{ }\mu\text{m}$
- cantilever thickness $4\text{ }\mu\text{m}$



Tip Types

- Typical tapping tip cost ~\$21 (cheaper in bulk)
- Specialized tips cost more
 - Coatings (electrical, magnetic) usually a couple more dollars per tip
 - Ultrasharp tips ~\$80-200
 - Coaxial microwave waveguide tips ~\$150
 - Colloidal probes, coated tips, made-to-order probes available

 Non-Contact / Tapping Mode AFM Probes General dynamic mode measurements ★ bestsellers » new	 Force Modulation (FM) AFM Probes Multi-functional probes ★ bestsellers	 Contact Mode AFM Probes General static mode measurements ★ bestsellers	 Life Science AFM Probes Biological applications ★ bestsellers » new	 Ultra High Frequency AFM Probes High speed measurements ★ bestsellers	 Conductive AFM Probes Electrical characterization (EFM, KPFM, SSRM, TUNA, etc.) ★ bestsellers » new
 Magnetic AFM Probes Magnetic force microscopy (MFM) ★ bestsellers	 Supersharp AFM Probes Enhanced / atomic resolution measurements ★ bestsellers » new	 Diamond AFM Probes The ultimate in hardness ★ bestsellers	 Hardened / Enhanced Wear Resistance AFM Probes Long scanning, hard samples ★ bestsellers	 Nanoindentation and Lithography AFM Probes Nanomechanics and Sample Modification ★ bestsellers » new	 High Aspect Ratio (HAR) AFM Probes Deep trench measurements ★ bestsellers » new
 ScanAsyst*** AFM Probes ScanAsyst* compatible probes ★ bestsellers	 Silicon Nitride AFM Probes Soft samples in air and liquid ★ bestsellers	 Lateral Force Microscopy (LFM) AFM Probes Frictional force measurements ★ bestsellers	 Tipless AFM Cantilevers and Cantilever Arrays For functionalization and gluing spheres ★ bestsellers	 Colloidal AFM Probes Various colloidal sphere-tips for nanomechanics	 Self-Sensing & Self-Actuating AFM Probes The AFM technology of tomorrow ★ bestsellers
 Sphere AFM Tips Well defined sphere geometry for nanomechanics » new	 Platinum Silicide AFM Probes The ultimate probes for electrical characterization ★ bestsellers	 Scanning Thermal Microscopy AFM Probes Temperature and thermal conductivity measurements	 Premounted AFM Probes For Quesant / Ambios AFM systems ★ bestsellers	 NANOANDMORE USA The Nanotech Facilitator	

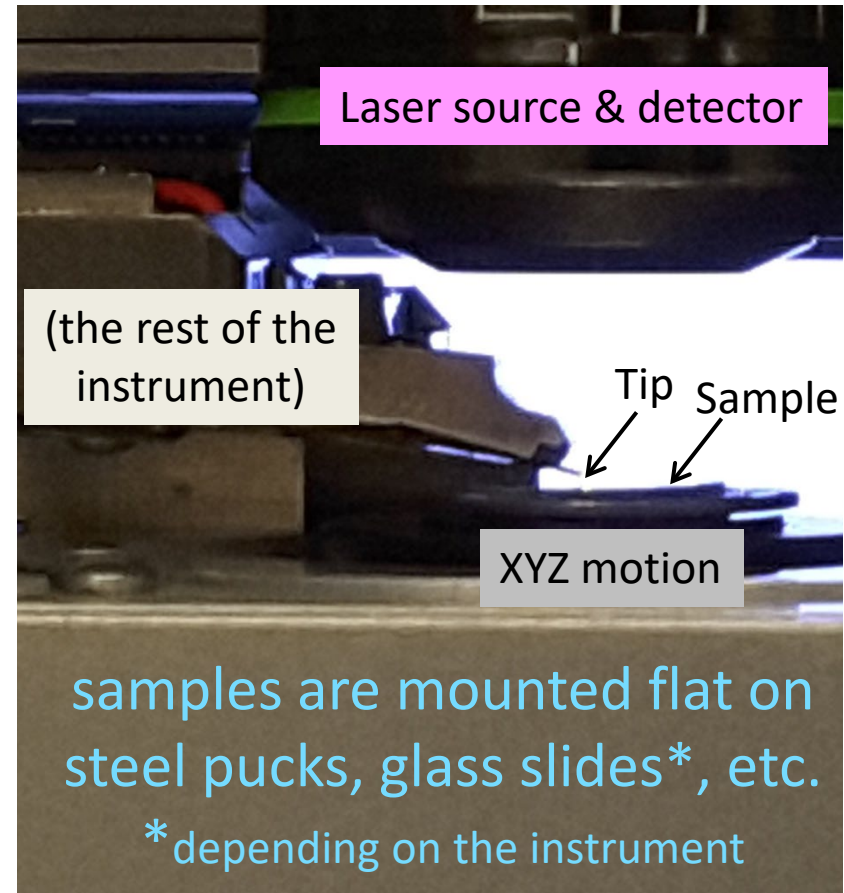
“How long does a tip last?”

- Tips are consumables
 - Contamination from samples
 - Wear from samples
 - Dropping them
- When your tip goes bad, just throw it out!
- Generally come in 10-packs
 - 50-packs if you scan a whole lot

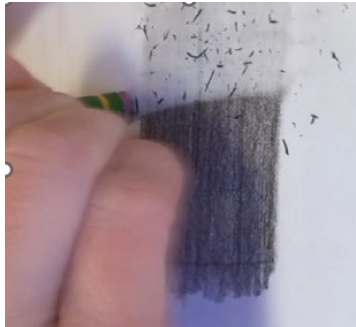


The Process

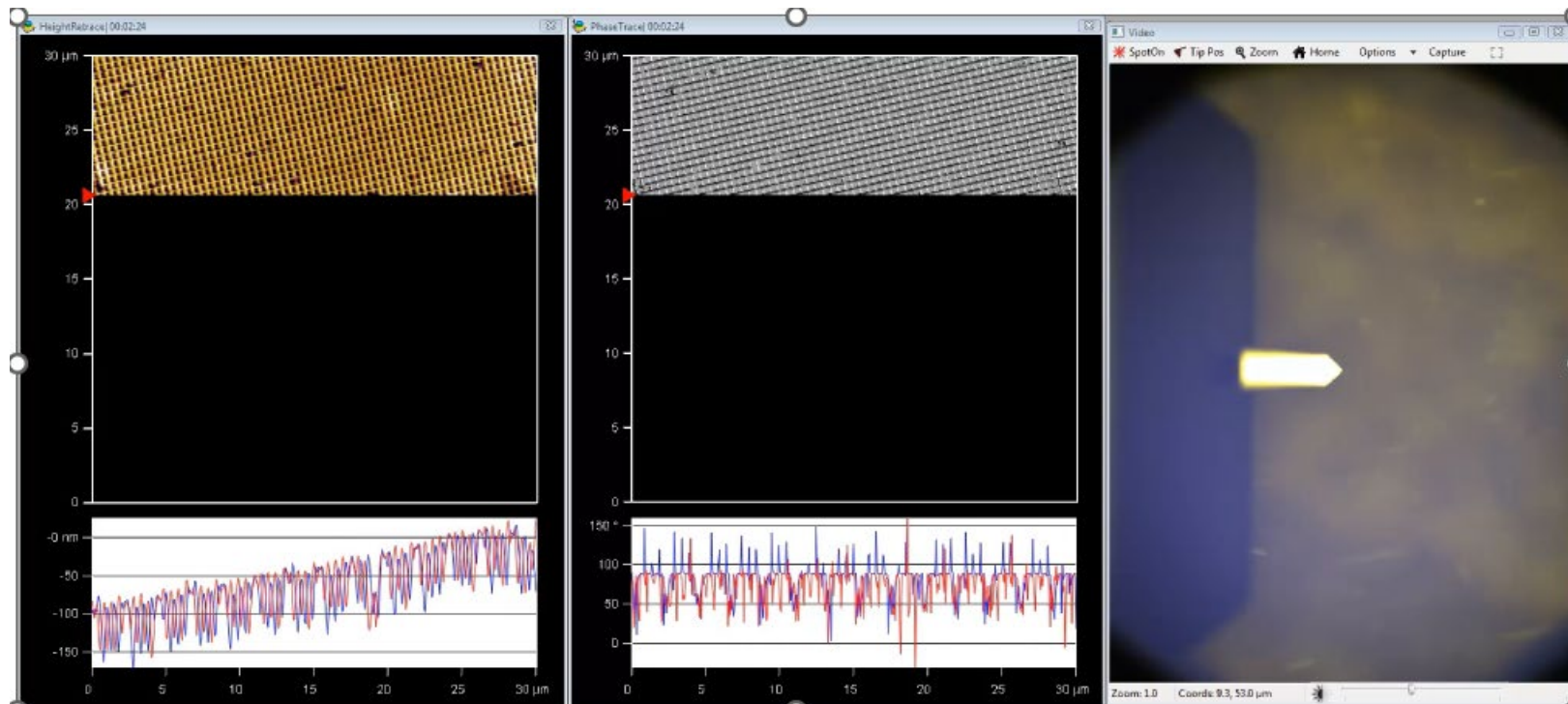
- Mount tip
- Mount sample
- Scan
- Process image
- Extract numbers
(application-dependent)



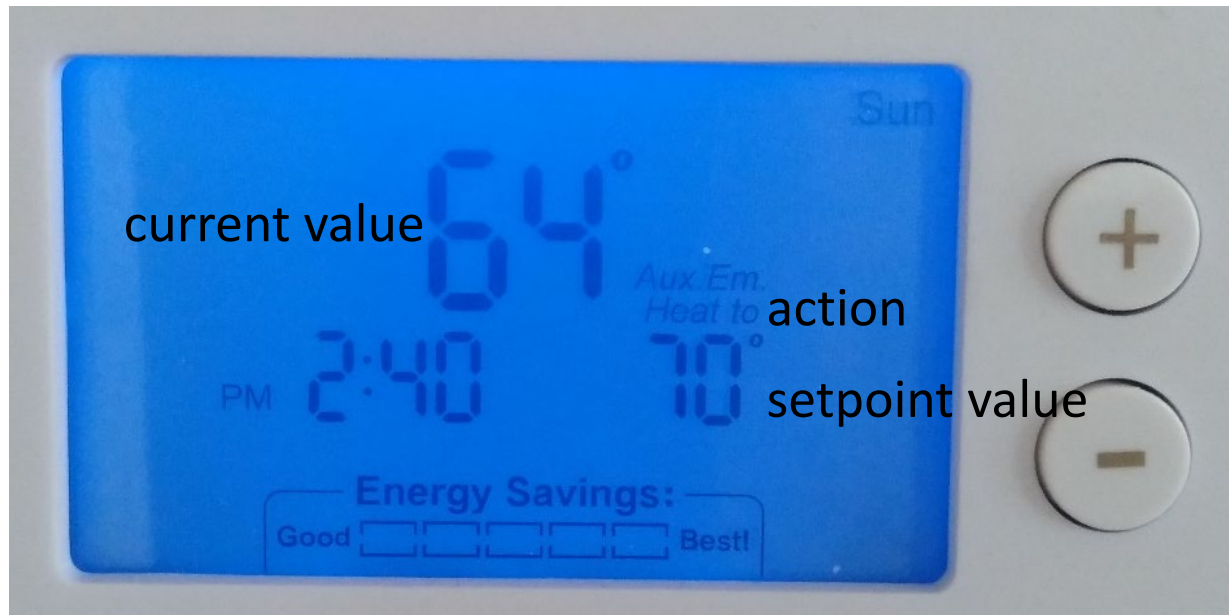
Raster Scanning



Move probe and sample with respect to one another to build up an image

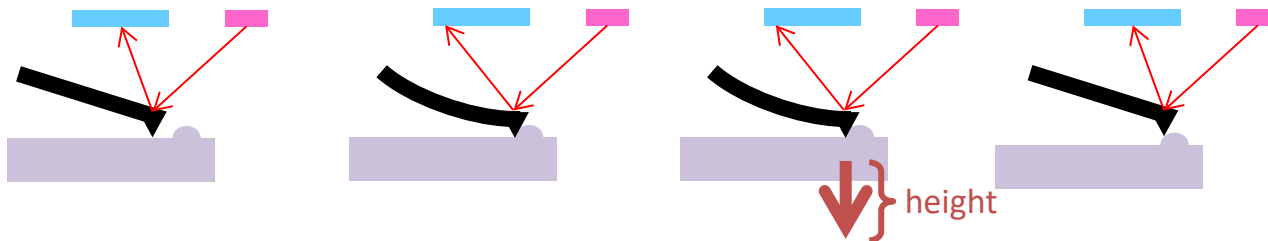


Feedback



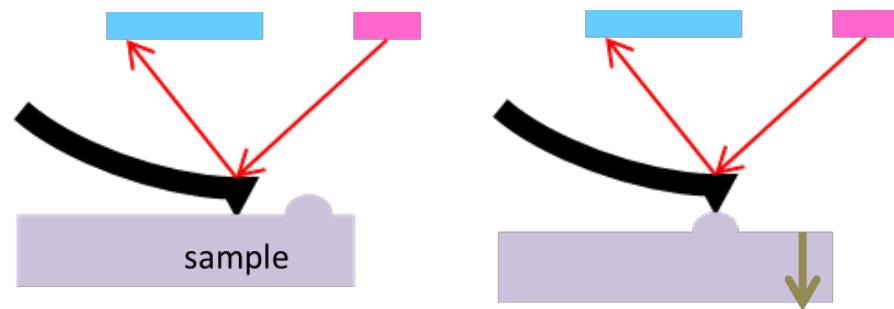
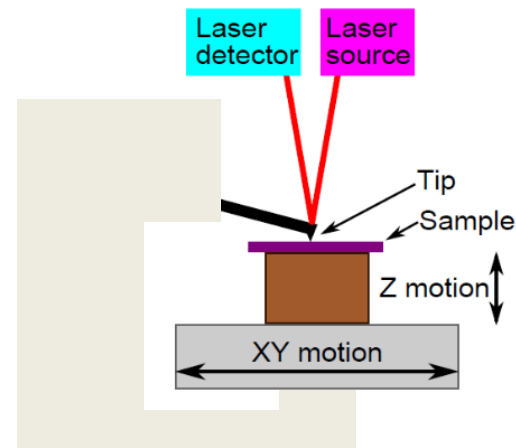
Feedback

- z piezo extension adjusted to keep **feedback signal** equal to setpoint
 - too much force—move away
 - too little force—move closer
 - **deflection for contact mode, usually amplitude for tapping mode**
- distance extended or retracted describes the height of the feature



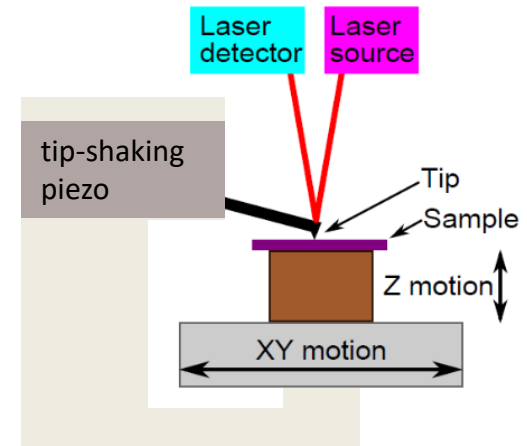
Contact Mode Imaging

- Drag tip along surface like a stylus profilometer (or like a record player)
- Adjust tip—sample separation to keep cantilever deflection constant
 - Traces sample topography
 - Some AFMs move tip; some move sample

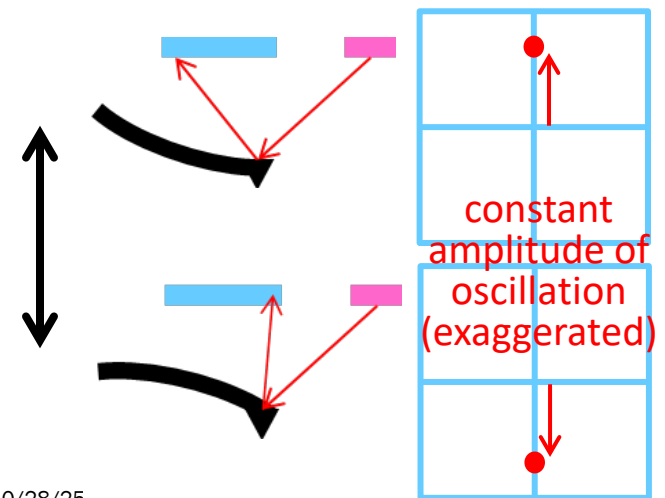


Tapping Mode Imaging

- Standard mode for AFM topography
- Names: intermittent contact, tapping, AC, amplitude modulation mode
- Not constantly in contact with the surface
- Driven, oscillating cantilever
- Tip—sample interactions affect oscillation

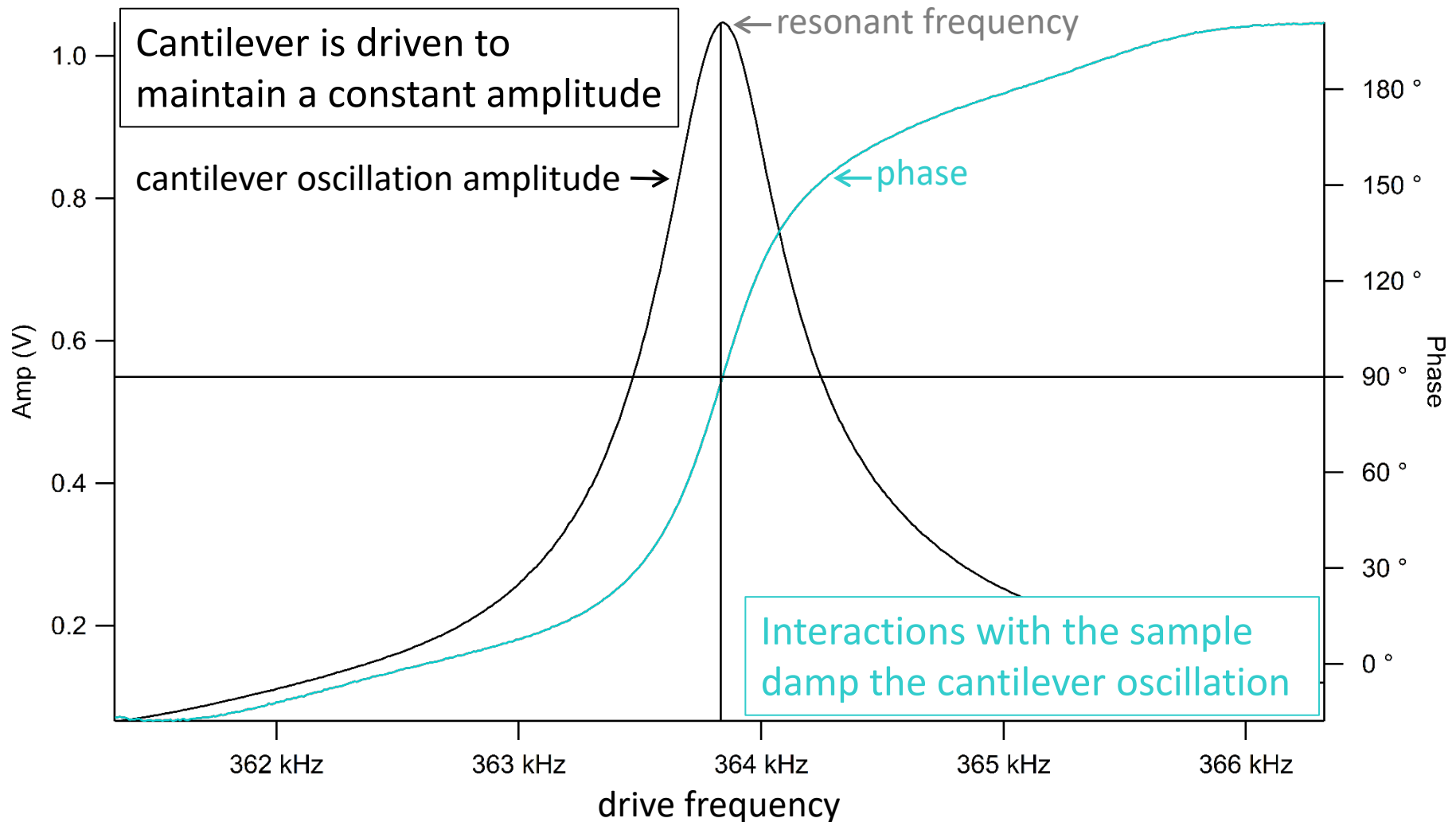


tip oscillates at tens of kHz to MHz



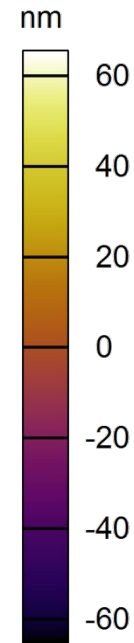
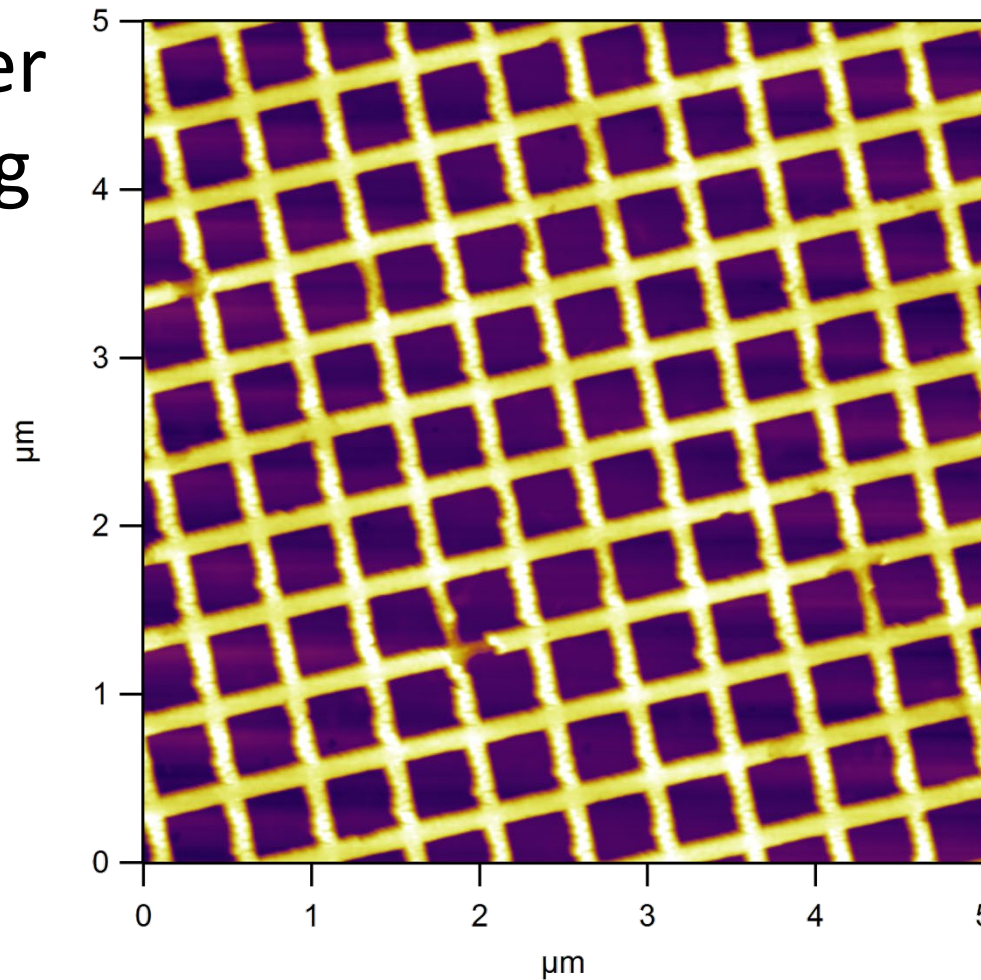


Tuning the Cantilever



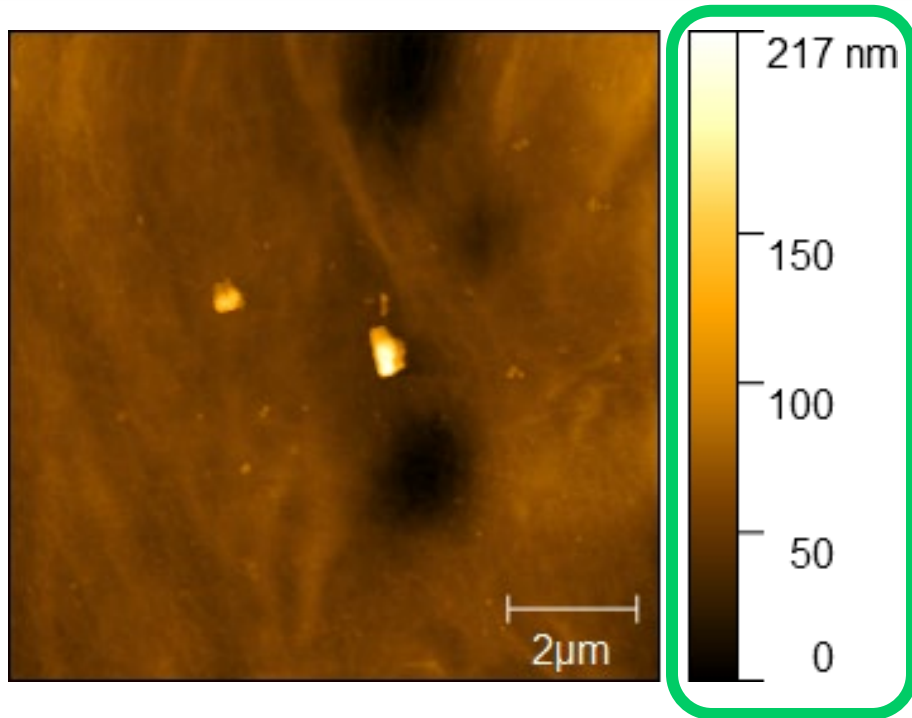
Application: Imaging

Polymer Grating

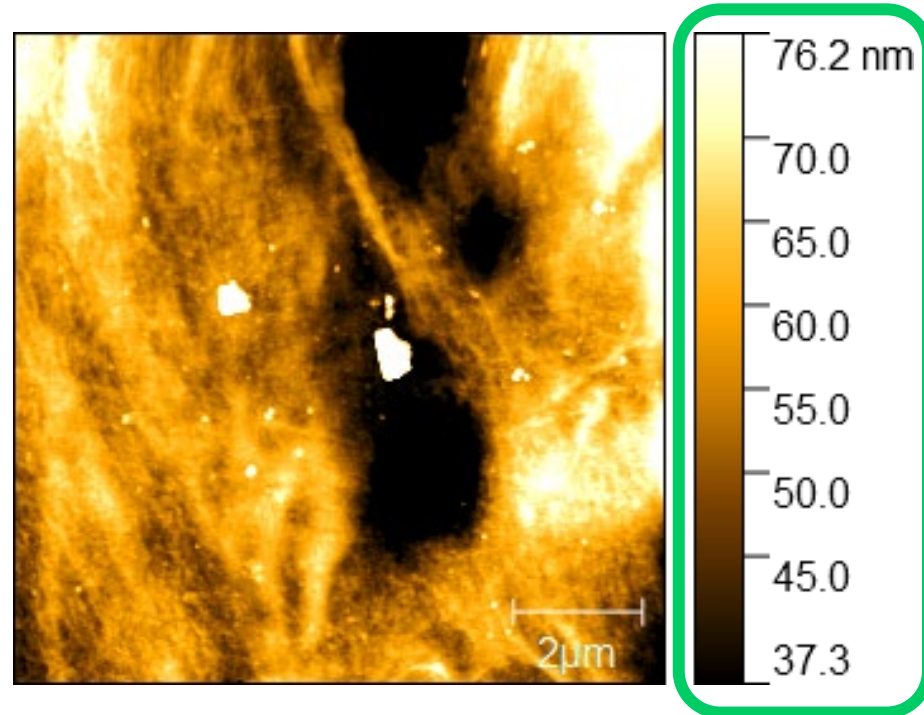


range of colors,
not heights in
the image

Reading the Colorscale

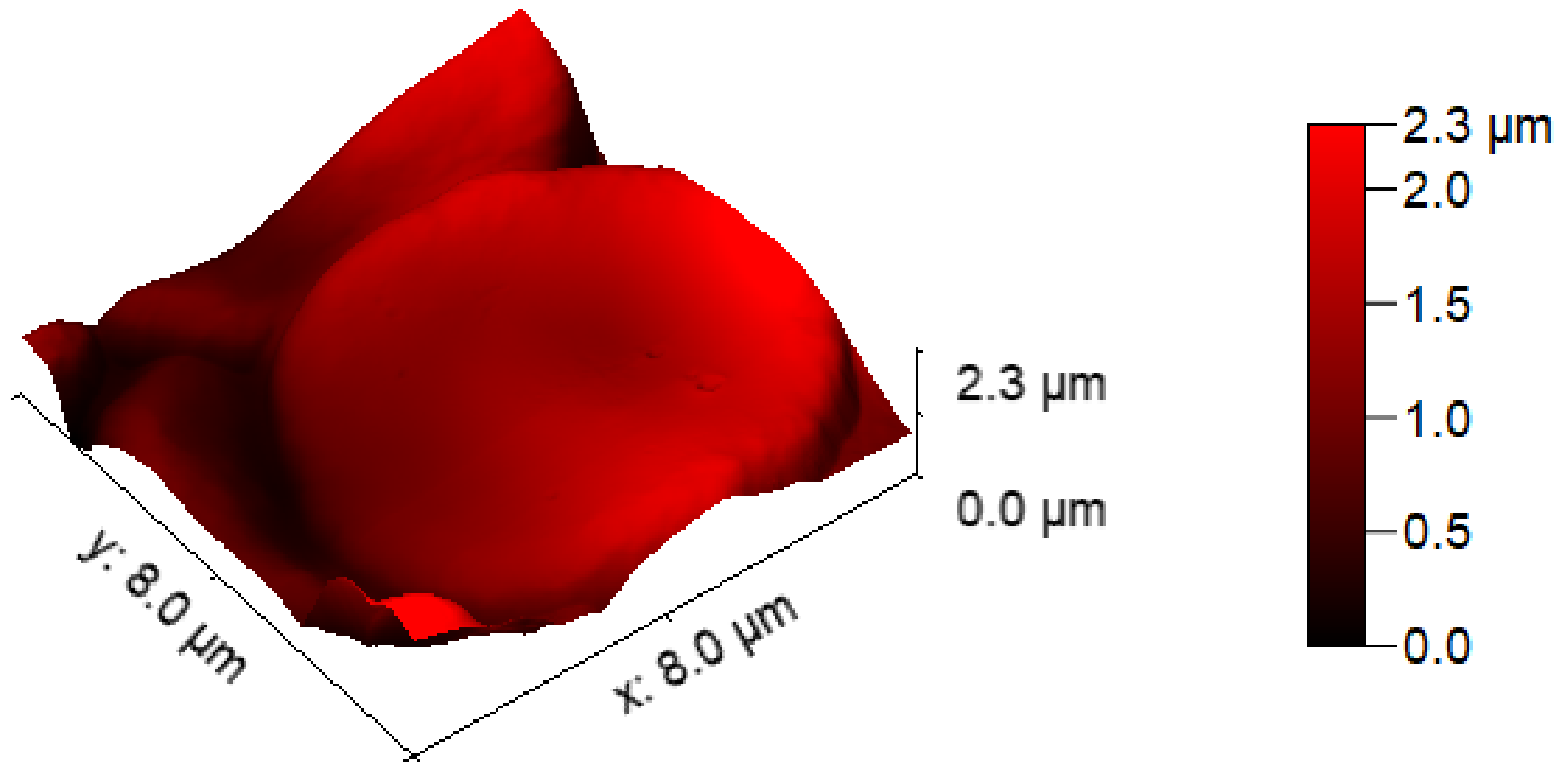


same image, different color ranges
color range of the displayed image,
not necessarily all heights on the surface



BOPP/PE polymer blend (toothbrush packaging), 10 μm x 10 μm AFM topograph

Interpreting 3D Images

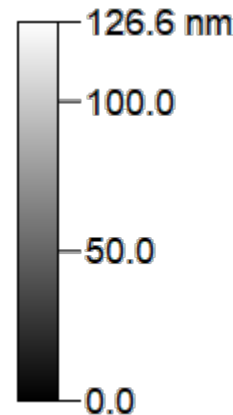
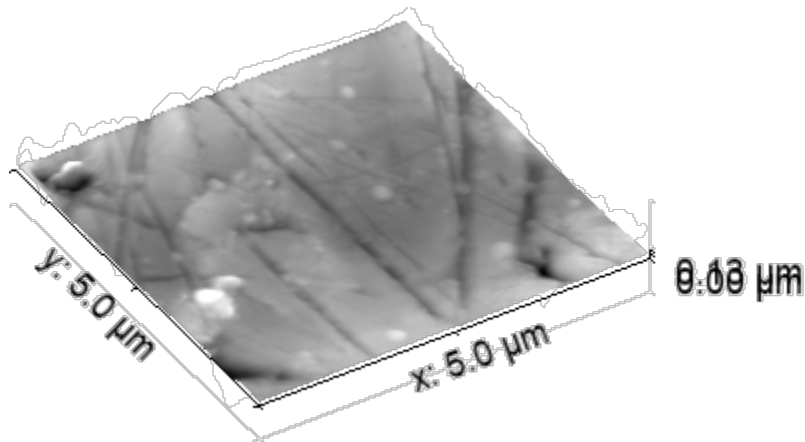
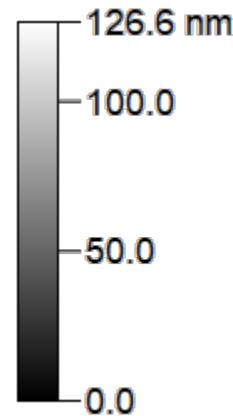
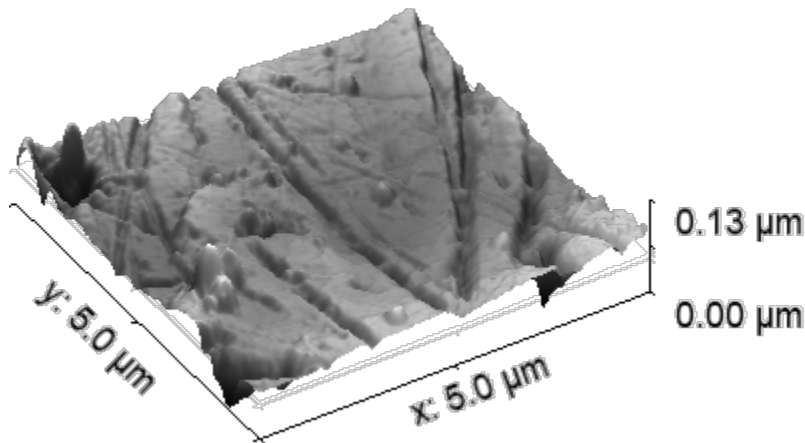


blood cells, 8 μm x 8 μm AFM topograph

Interpreting 3D Images

not necessarily 1:1:1 z:x:y

z often exaggerated compared to xy to convey texture information

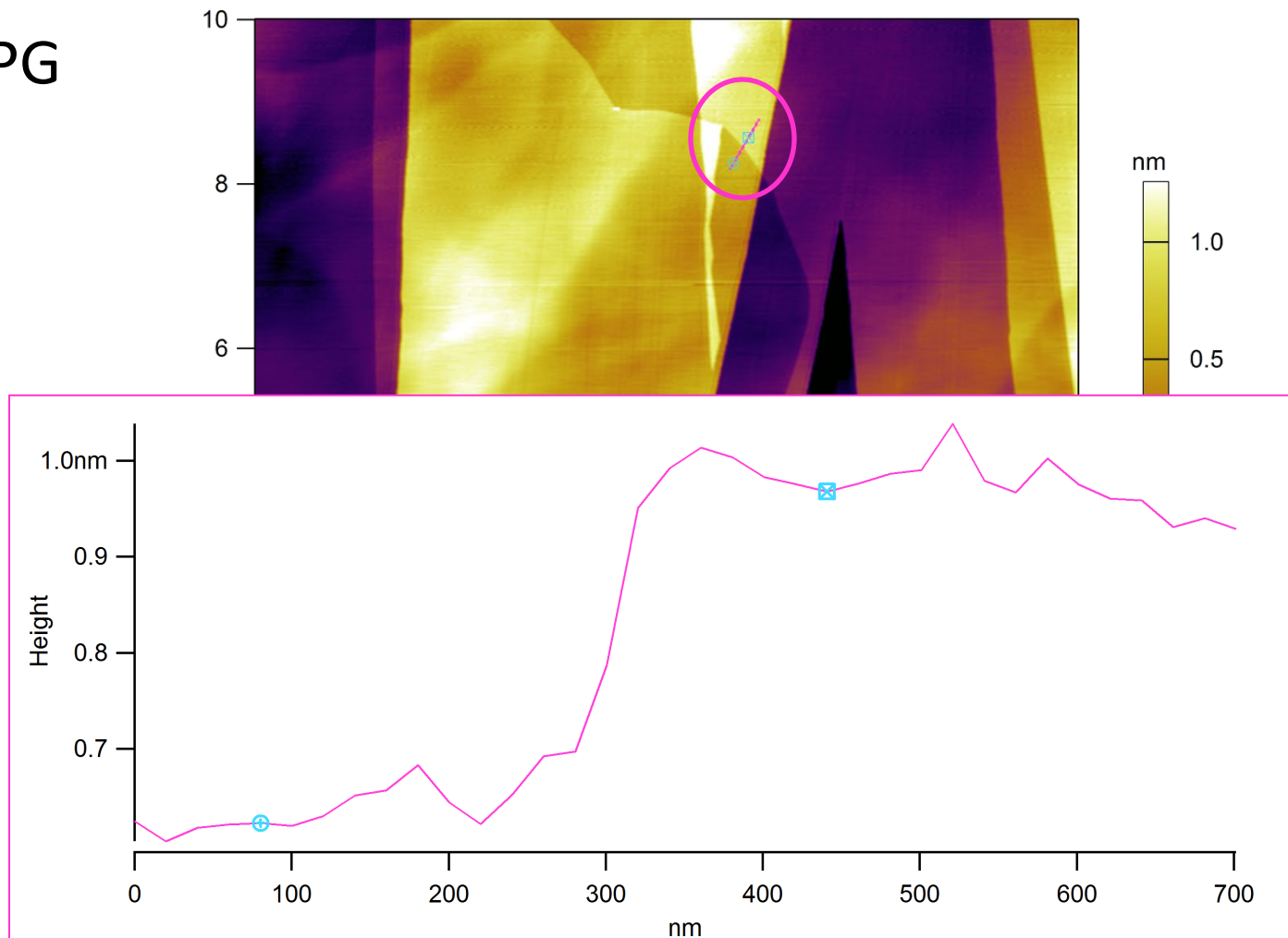


steel sample disk
5μm AFM topograph

(blood and steel samples
courtesy Physics 403 Lab 2022)

Application: Step Heights

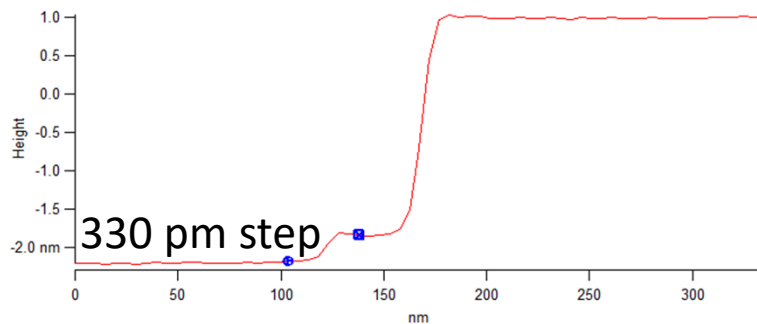
HOPG



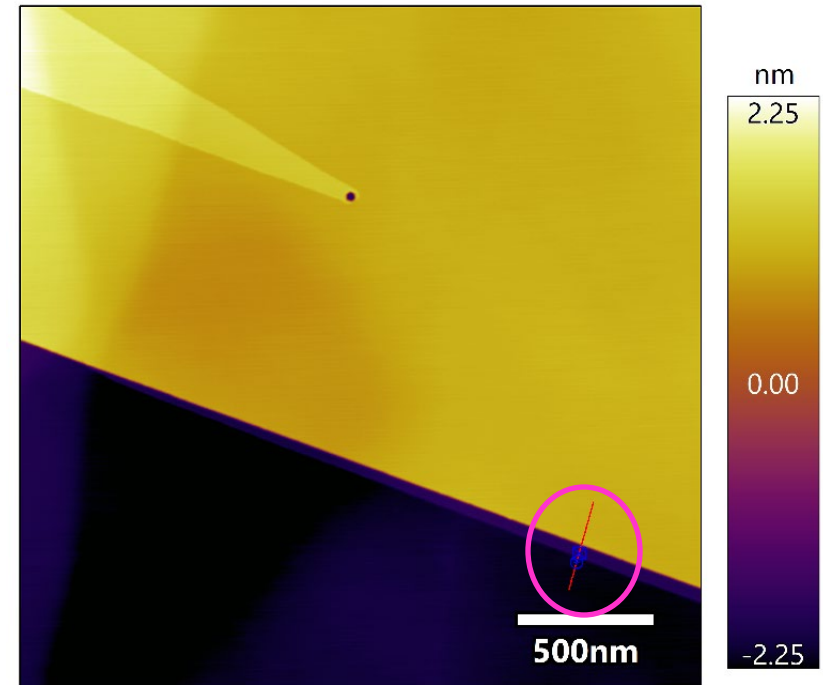
Application: Step Heights

HOPG

(highly oriented pyrolytic graphite)



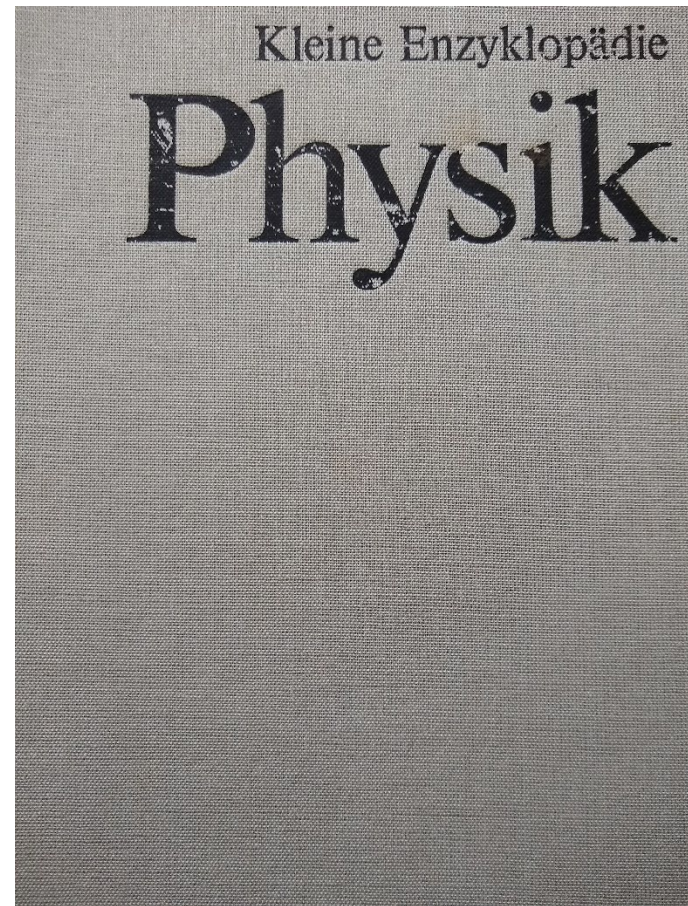
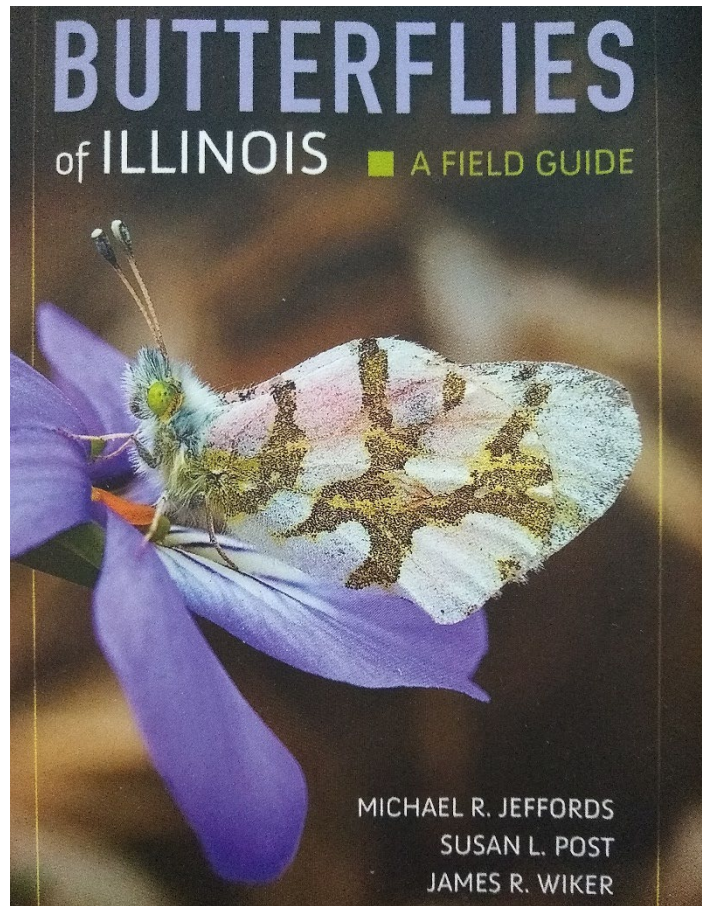
Xa	2.04 μm
Ya	458.97 nm
Za	-2.18 nm
Xb	2.05 μm
Yb	492.15 nm
Zb	-1.85 nm
dx	9.31 nm
dy	33.18 nm
dz	332.26 pm



HOPG_0006HeightTraceMod0

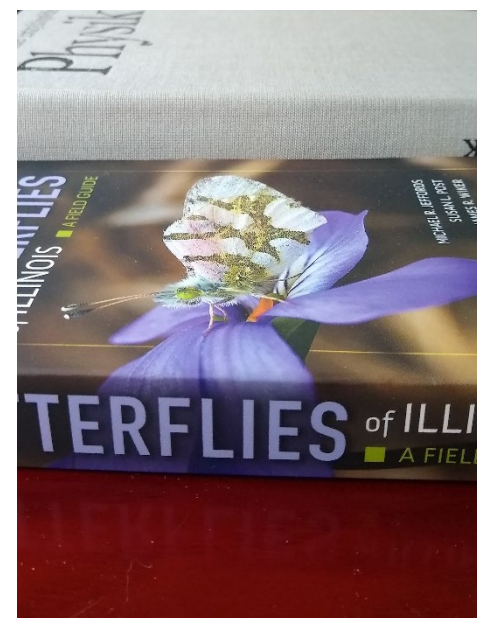
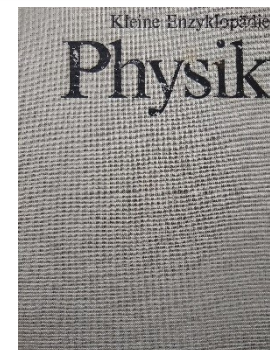
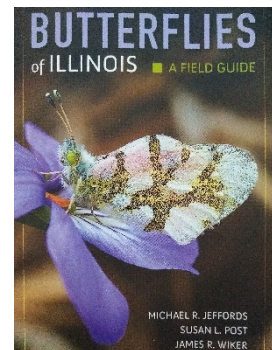
Step Heights and Thicknesses

Which book is thicker?



Step Height: Relative Height

- Film thickness is measured by step height
- Measure a height difference
 - Leave some bare substrate (patches are OK)
 - Scratch down to the substrate
 - Multilayer material—exposed underlayer



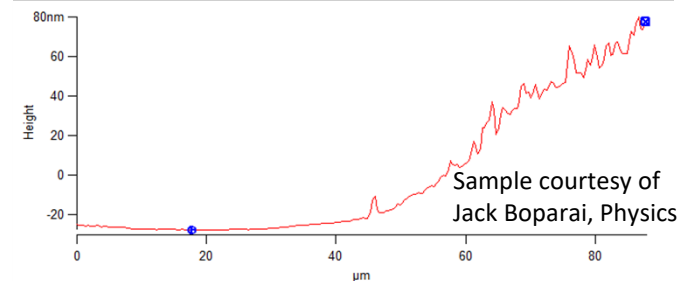
Step Height/Film Thickness: Complementary Techniques

If your step's too broad for the AFM (edge width $> \sim 80\mu\text{m}$), try...

- Stylus profilometry
- 3D optical profilometry
- X-ray Reflectivity (XRR)
- Rutherford Backscattering Spectrometry (RBS)

} Need a height difference (step) like AFM

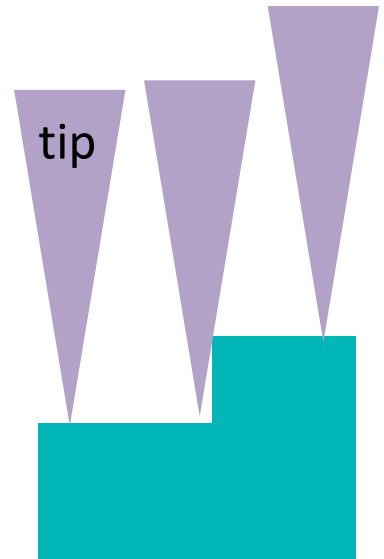
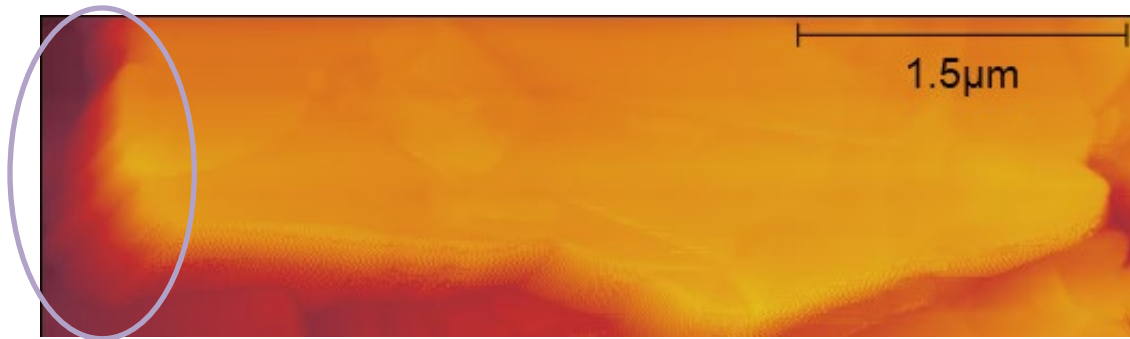
} Continuous film (no steps)
May need to know density



Width Measurements

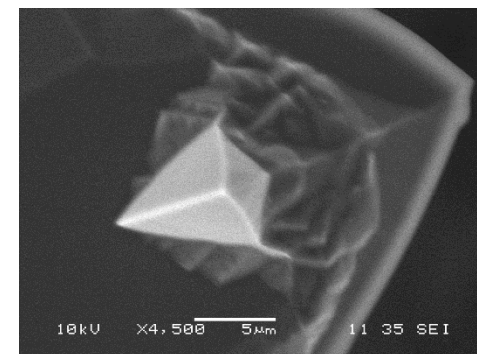
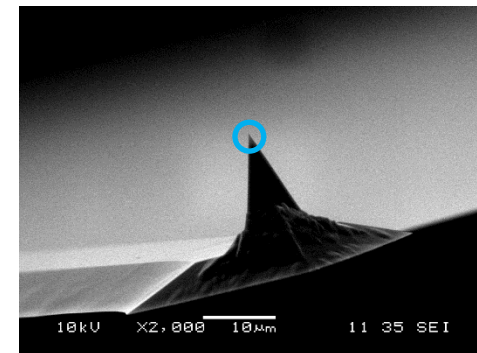
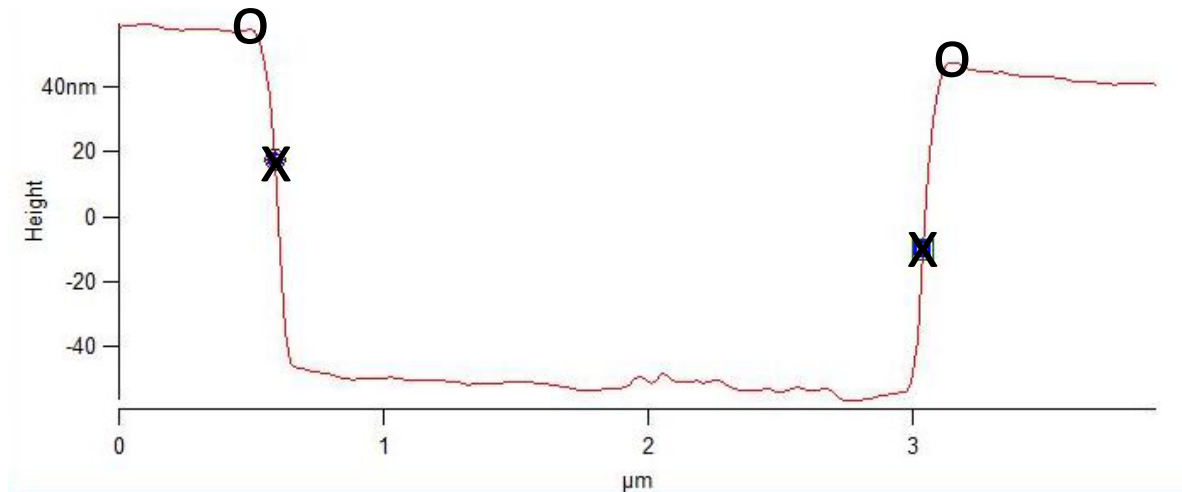
Beware of tip shape convolution

- As depth increases, tips get broader
- Steep drop-offs look less sharp
- High aspect ratio tips are available



Width Measurements

- As depth increases, tips get broader
- Steep drop-offs look less sharp
- High aspect ratio tips are available



Application: Roughness

- “The roughness” depends on the scale
- Choose measurement technique to match the feature scale of interest
 - AFM (nanoscale)
 - Stylus profilometry
 - 3D optical profilometry

What is the roughness of this landscape?

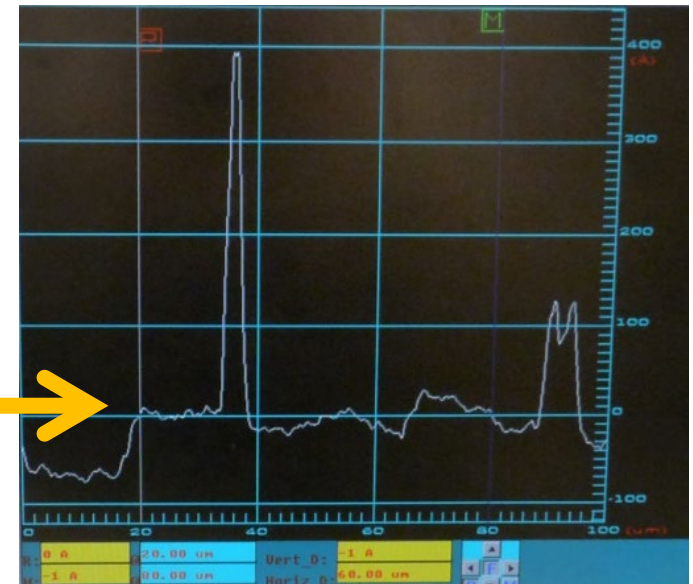
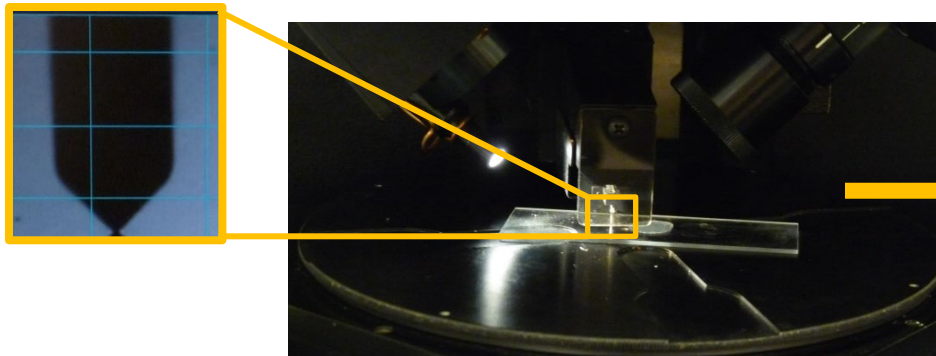


Michael Jeffords and Susan Post, University of Illinois Prairie Research Institute
<https://photojournalingm-s.smugmug.com/Colorado-and-Kansas/i-3tJ3DZk/A>

Complementary: Stylus Profilometry



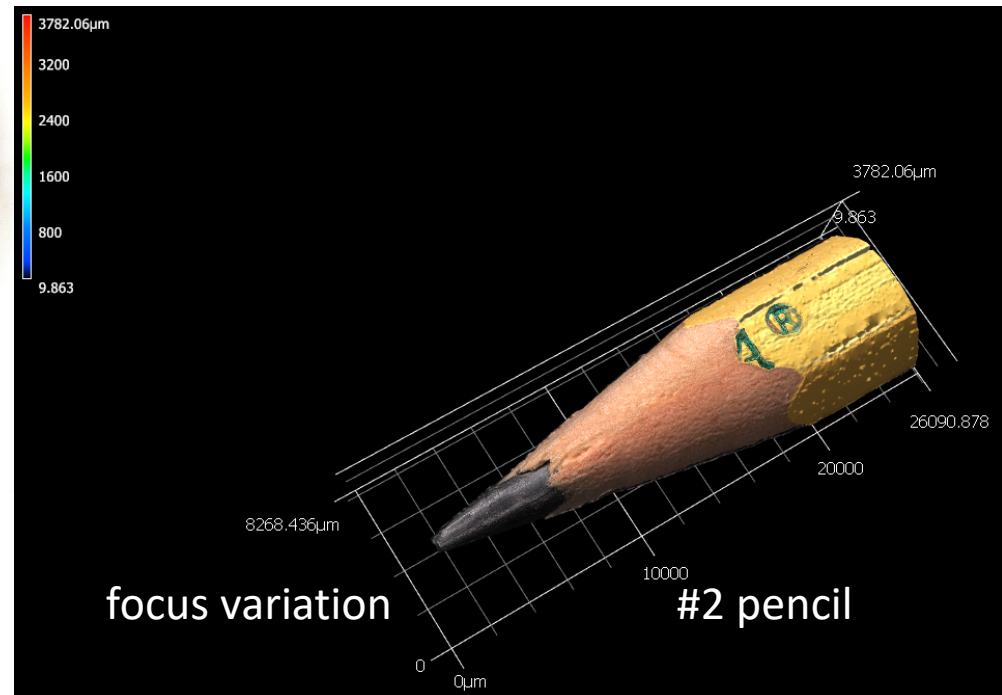
2D stylus profilometry
(line profiles) (diamond tip)



Complementary: Optical Profilometry

go.illinois.edu/MRL3DOpticalProfilometry

ladybug imaged during Cena y Ciencias using the Keyence VK-X1000
image by Kathy Walsh, MRL Facilities
sample courtesy of Julio Soares, MRL Facilities





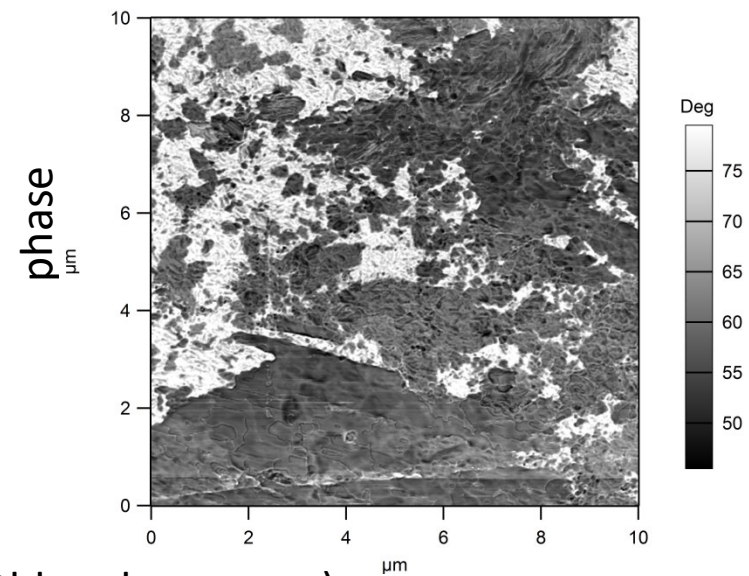
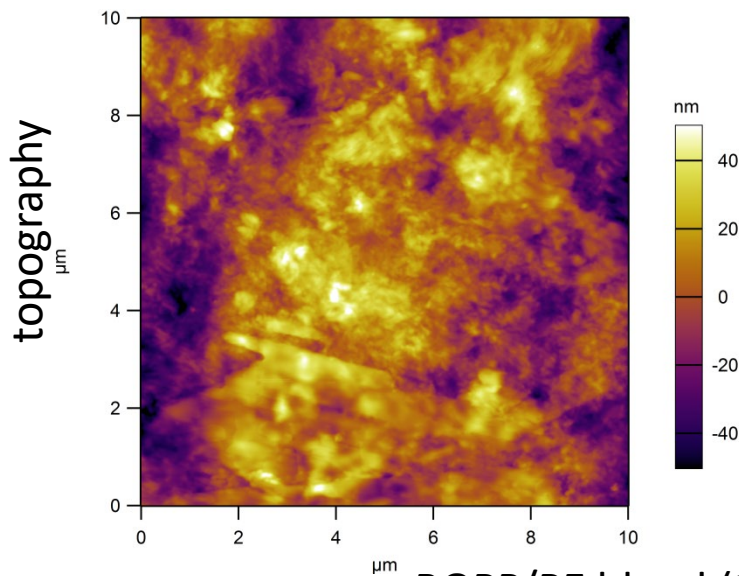
Qualitative Comparison

	AFM	2D Stylus Profilometry	3D Optical Profilometry
Vertical resolution	outstanding	OK	OK
Field of view	small	large	large
Data type	image	line	image
Max sample size	depends on instrument (~cm to large)	large	large
Max feature height	few μm	mm	mm
Force on sample	light	moderate	none
Speed	moderate	really fast	fast

Mechanical Characterization

Visualizing mechanical differences

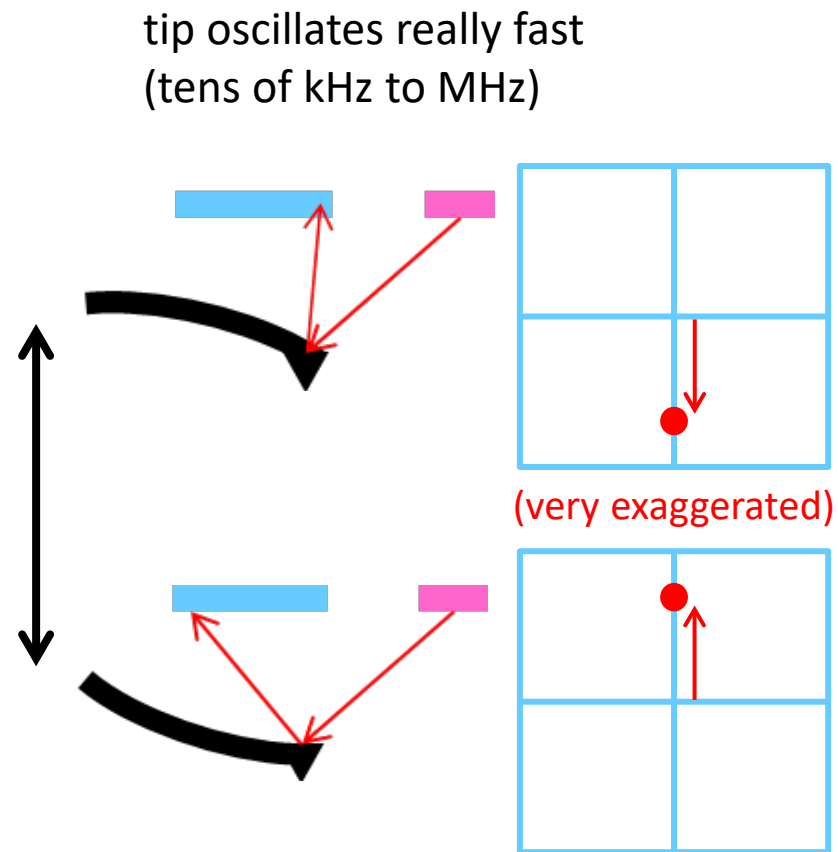
- Phase (tapping mode)
- Force modulation, AM-FM, contact resonance, etc.
- Maps of quantitative measurement results (force mapping)



BOPP/PE blend (toothbrush wrapper)

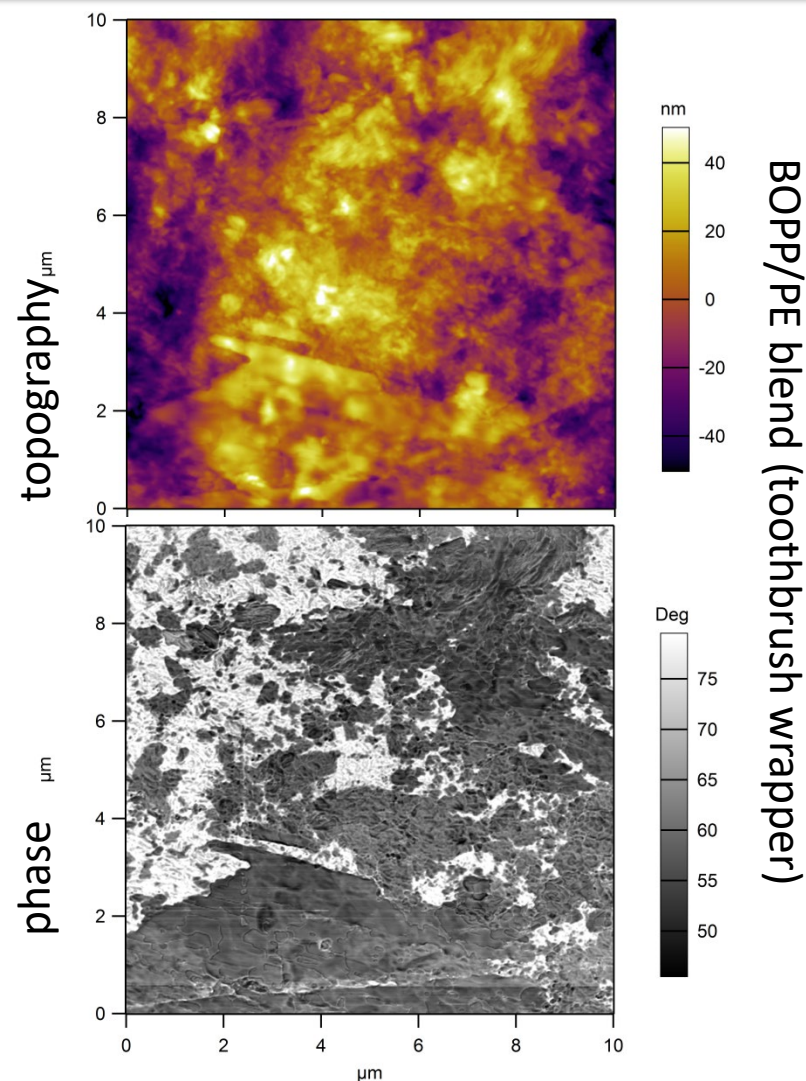
Tapping Mode Imaging: Phase

- Oscillating cantilever
- Tip—surface interactions affect oscillation
 - Cantilever driven sinusoidally to keep a constant amplitude
 - Dissipative interactions cause a phase lag (delay)
 - Viscous areas
 - Sticky areas

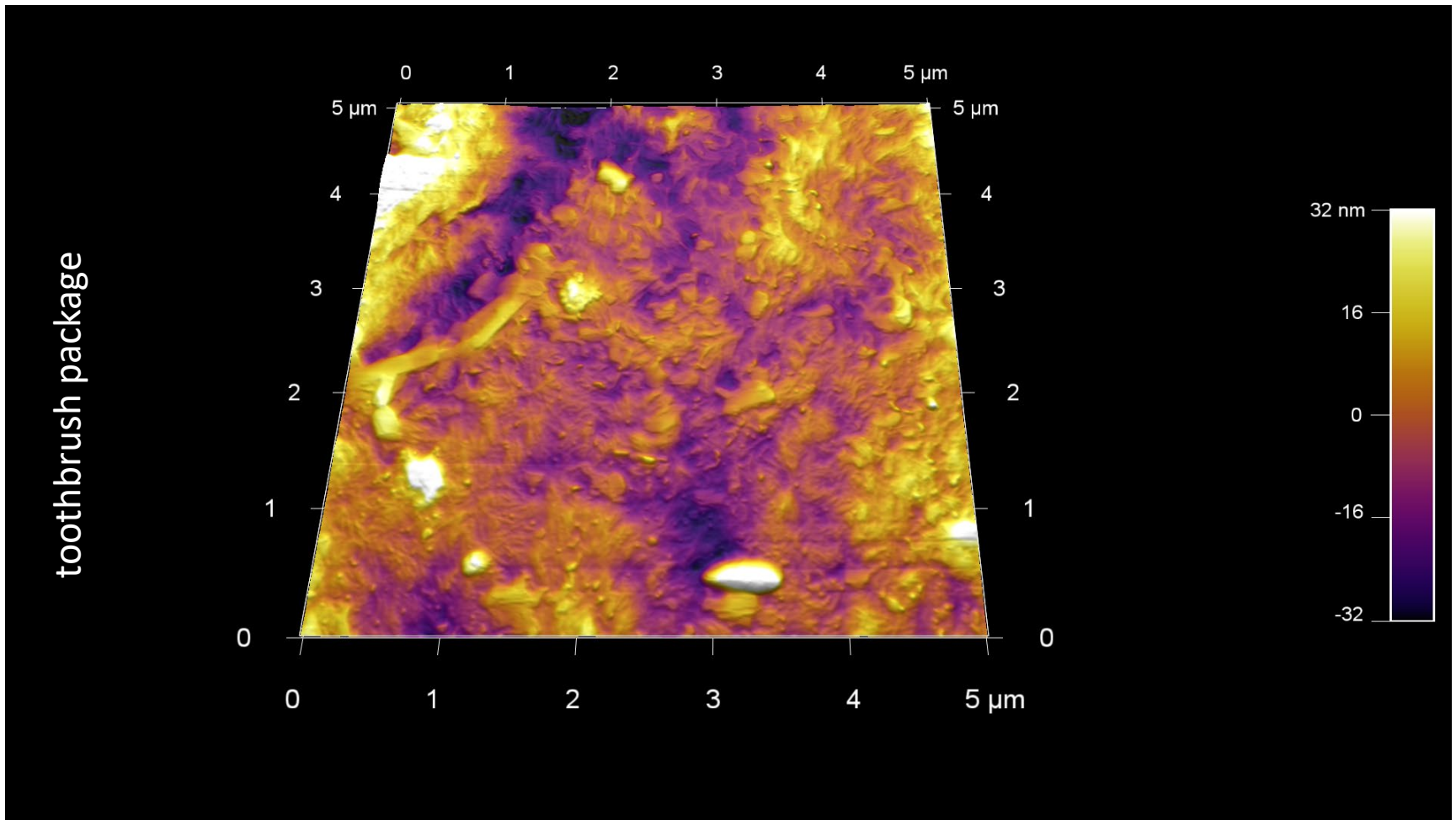


Phase (Qualitative)

- Tapping mode imaging
- Contrast in phase image shows differences in mechanical properties
 - Qualitative, not quantitative
 - Great for mixtures
 - Great for soft materials deposited on hard surfaces

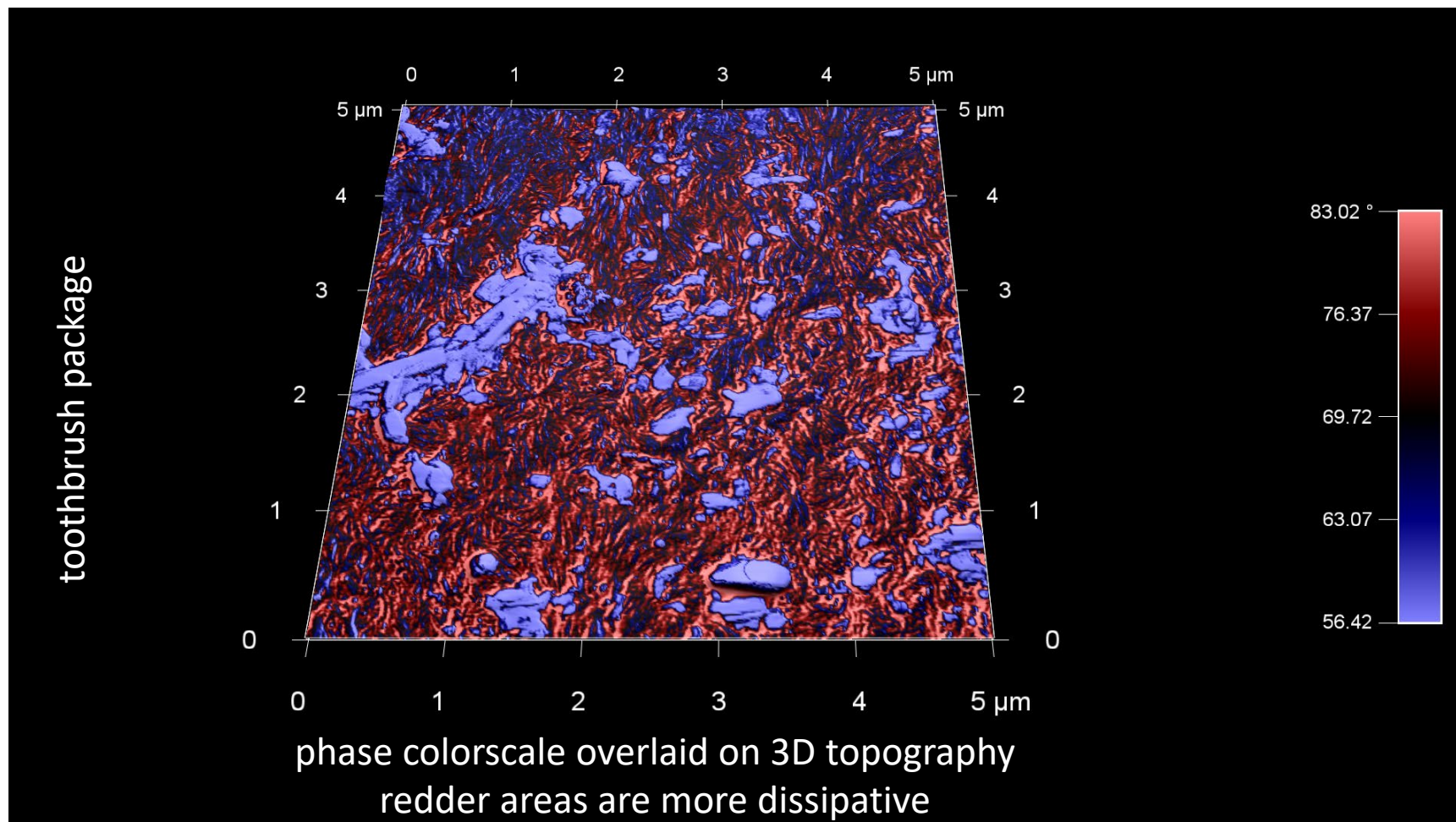


Topography



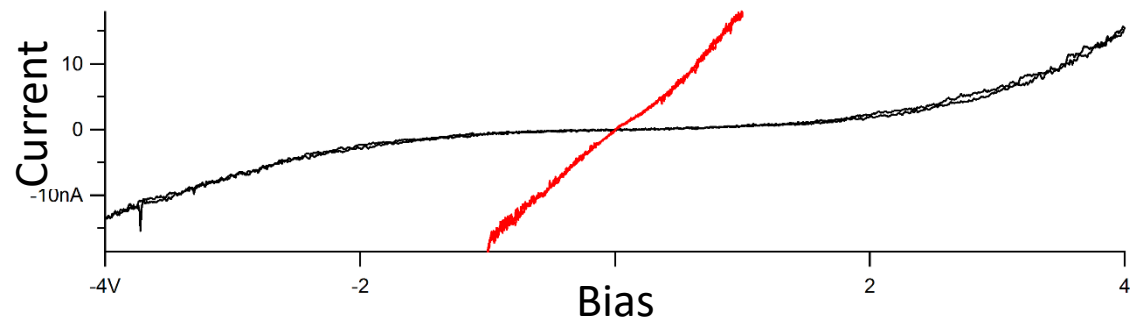
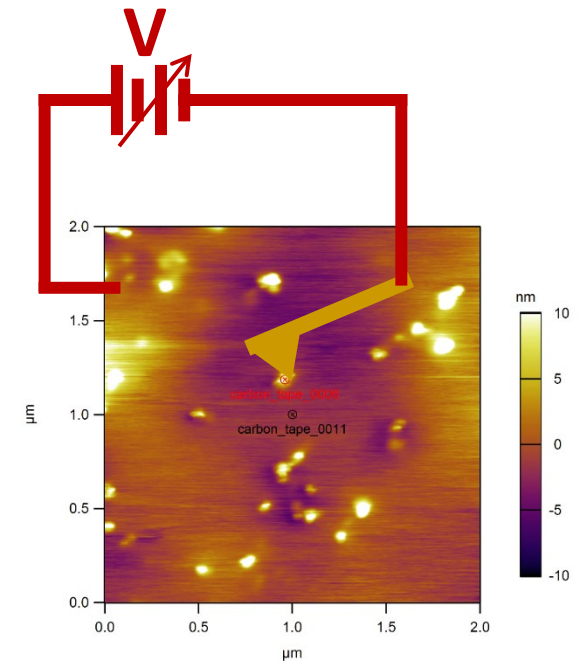
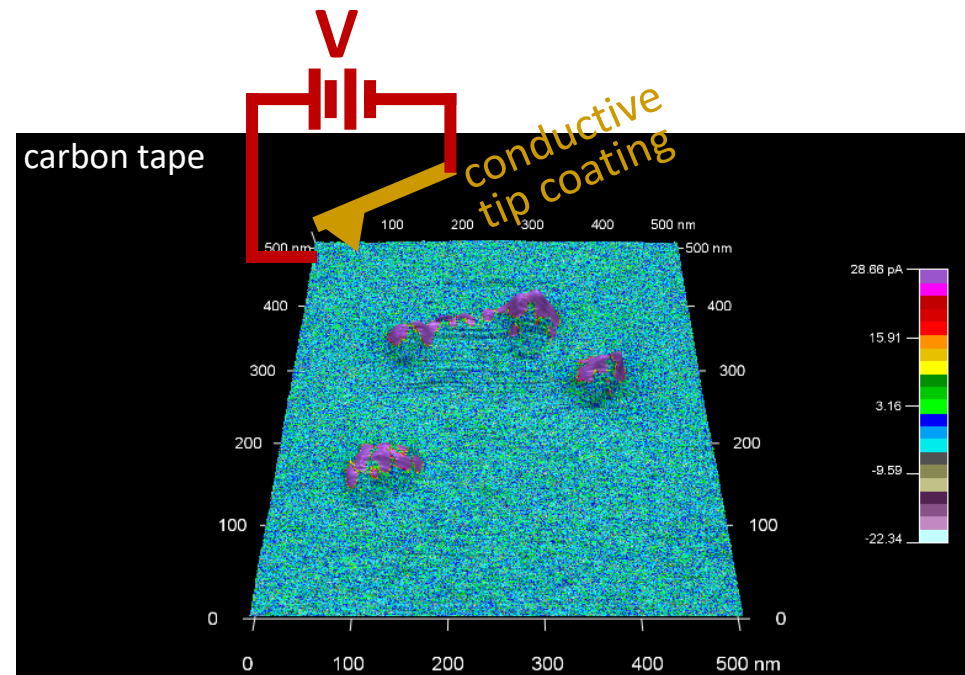


Topography with Colors from Phase





Common Application: Conductive AFM





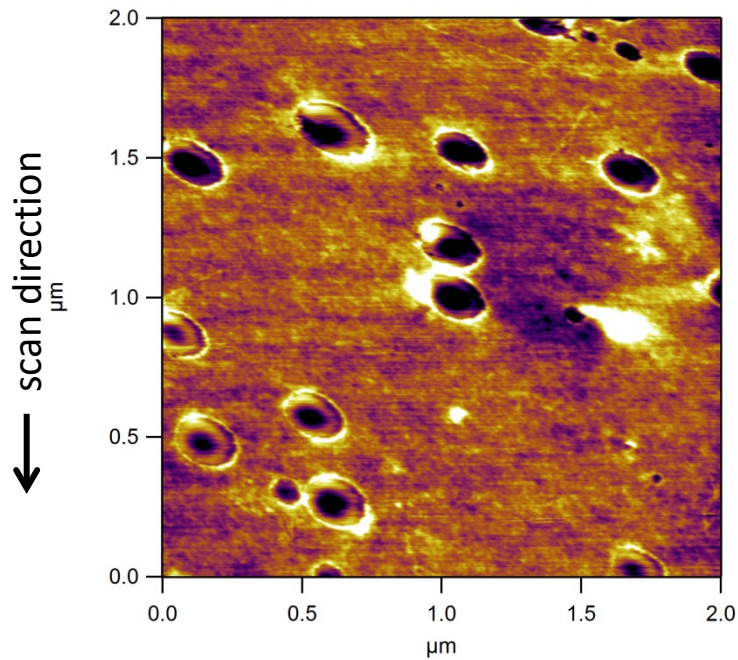
Artifacts and Image Processing

- Recognize what is (or is not) informative about the sample
- Images may not always exactly represent the sample: sample drift, tip condition/geometry
- Display data in an informative way
 - Correct for sample tilt, etc.

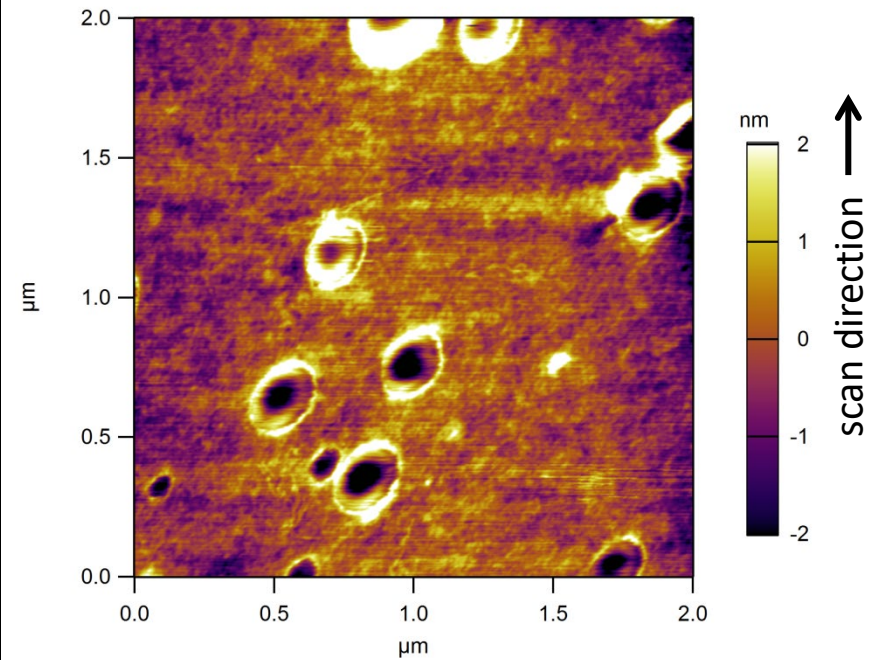


Sample Drift

Scanning downwards...



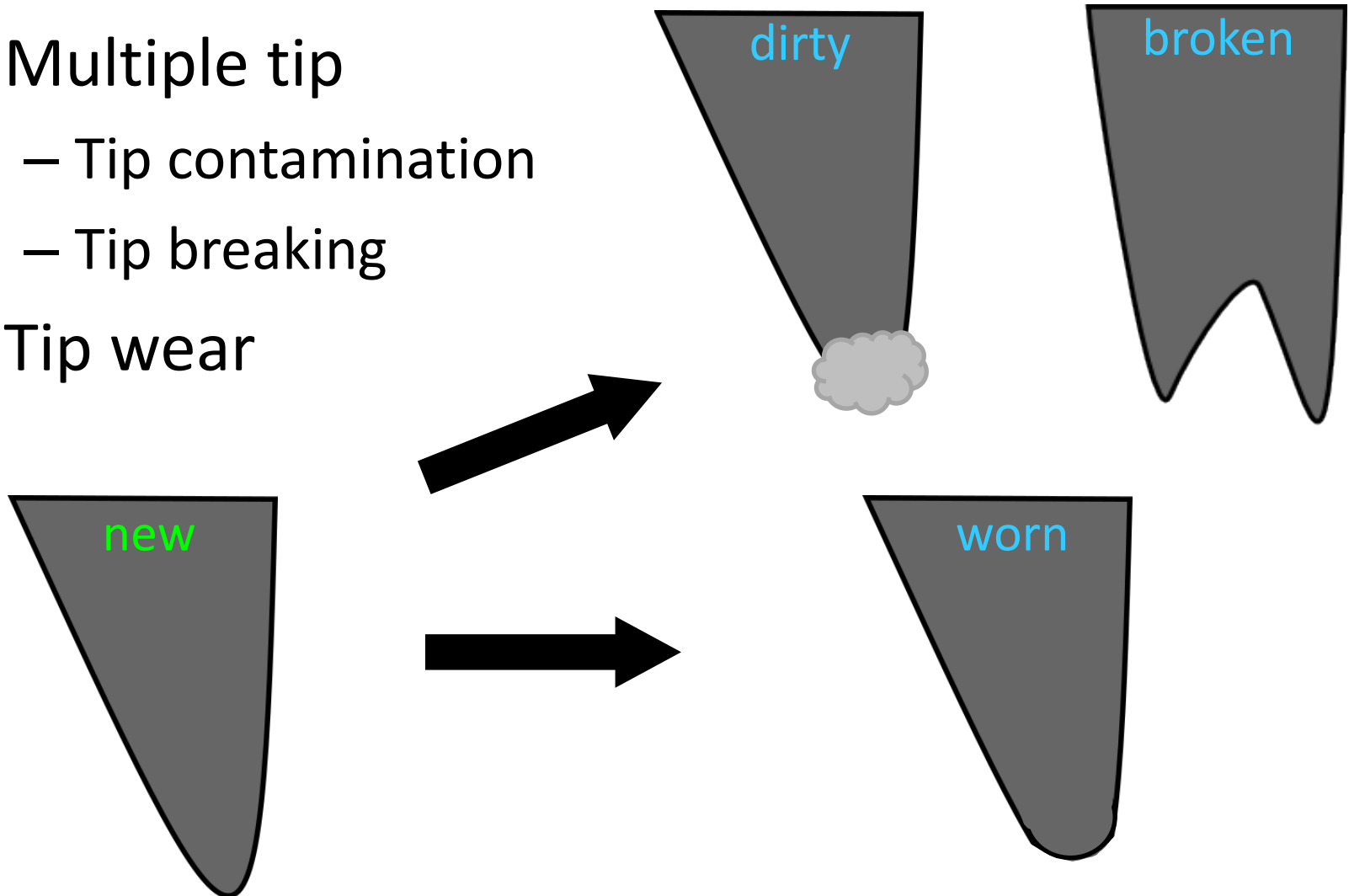
... then scanning upwards



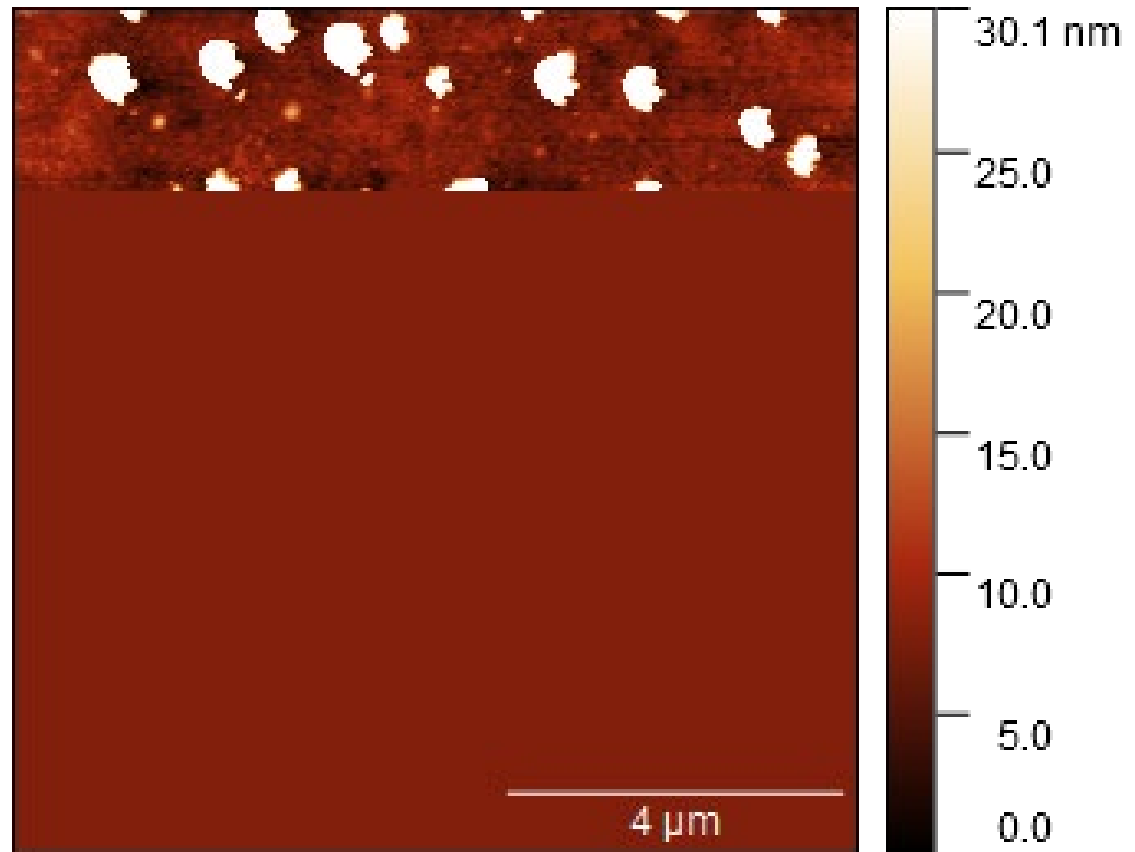
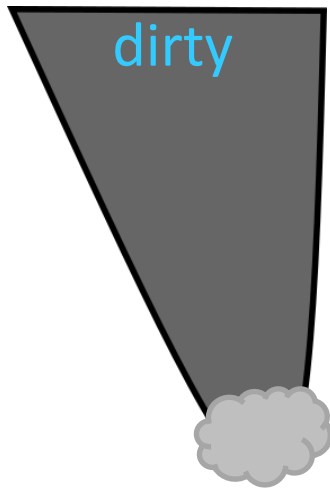
chewing gum

Tip Artifacts

- Multiple tip
 - Tip contamination
 - Tip breaking
- Tip wear



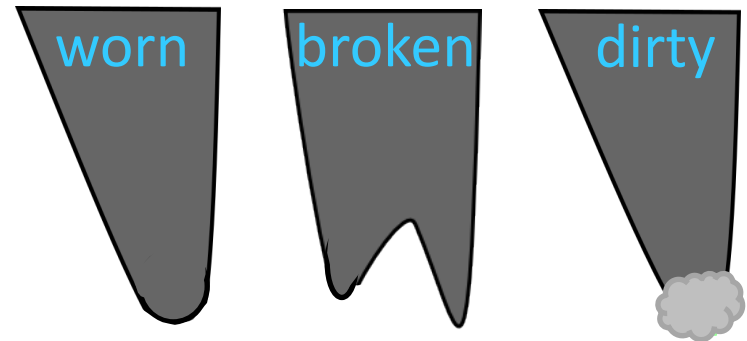
Contaminated Tip



10 μm partial scan

Tip Artifacts

- Tip shape change
 - Multiple tip
 - Tip contamination
 - Tip breaking
 - Tip wear
- Tip height change
 - Tip contamination
 - Tip wear



Line-by-Line Subtraction

- Difference from line to line
- Tip condition changes, curvature
- Polynomial subtraction

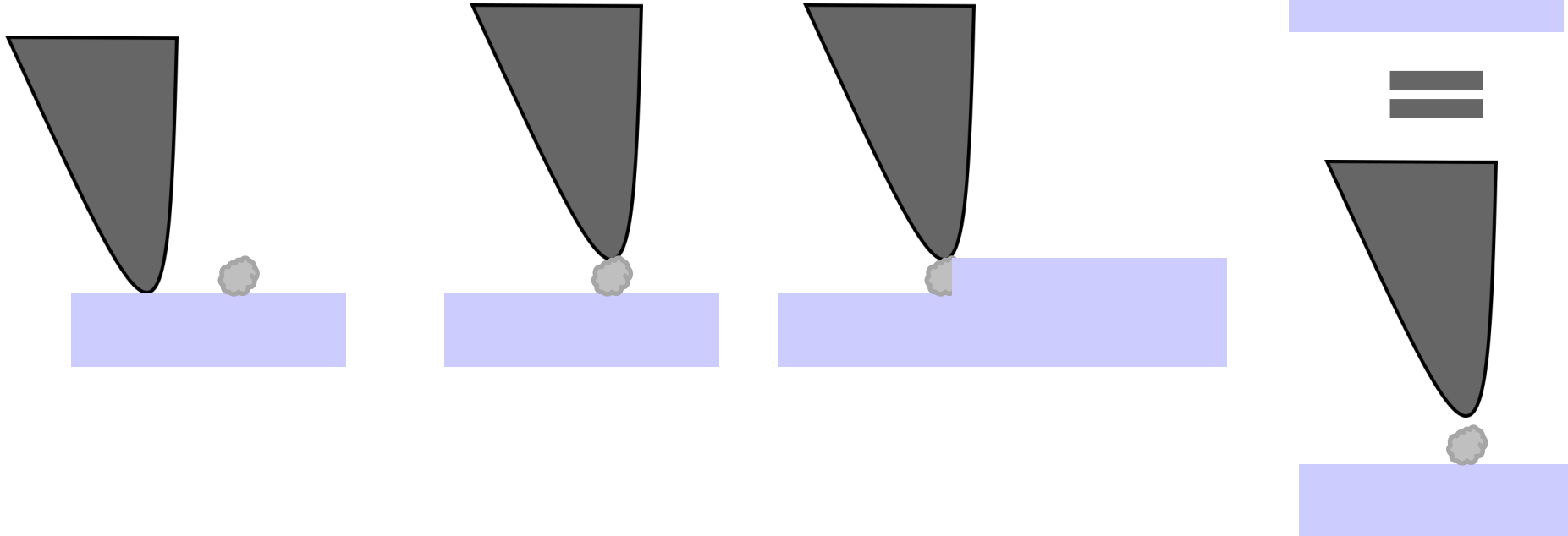




Image Processing

raw image

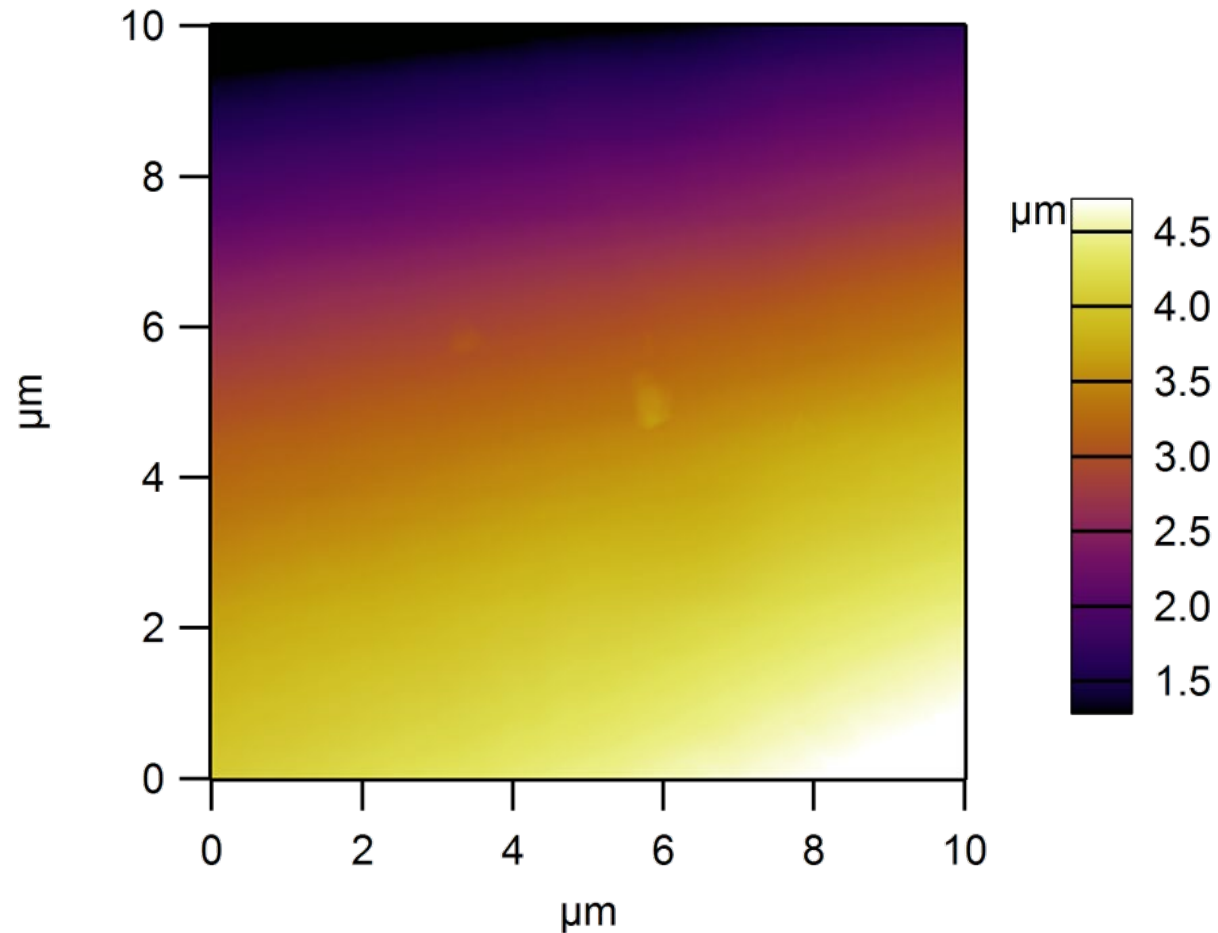




Image Processing

line subtraction

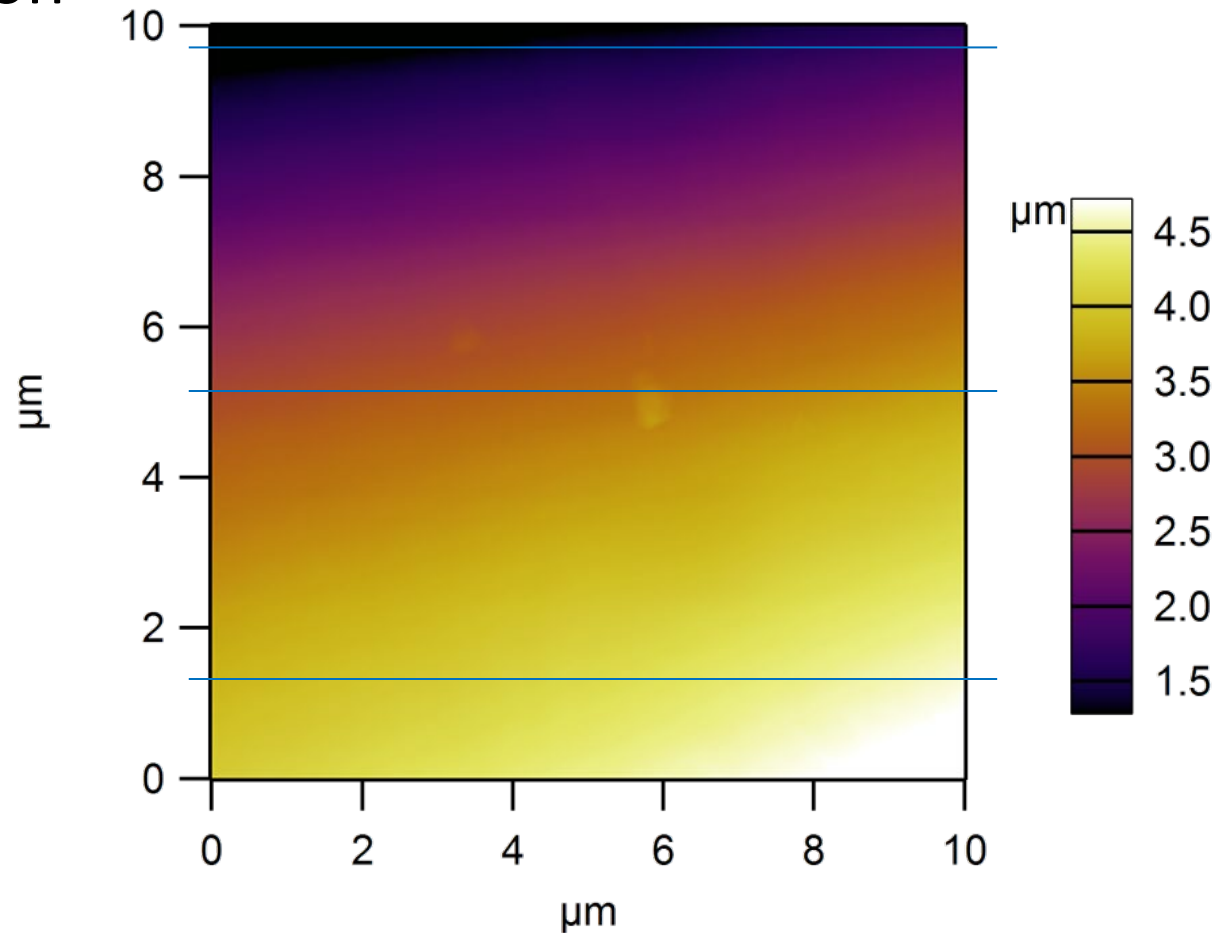


Image Processing

line subtraction

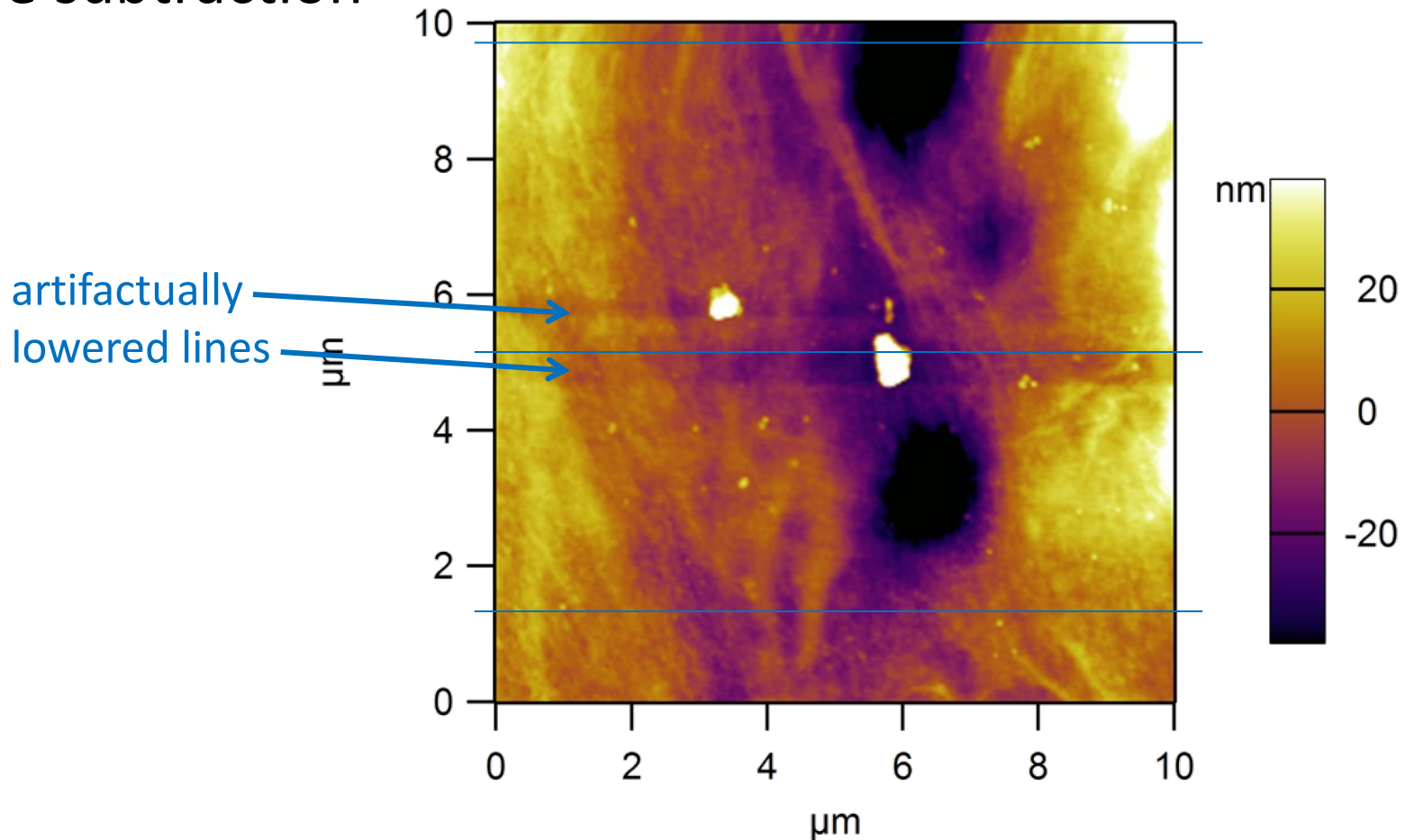


Image Processing

line subtraction:
mask outlier areas

areas to ignore
when processing

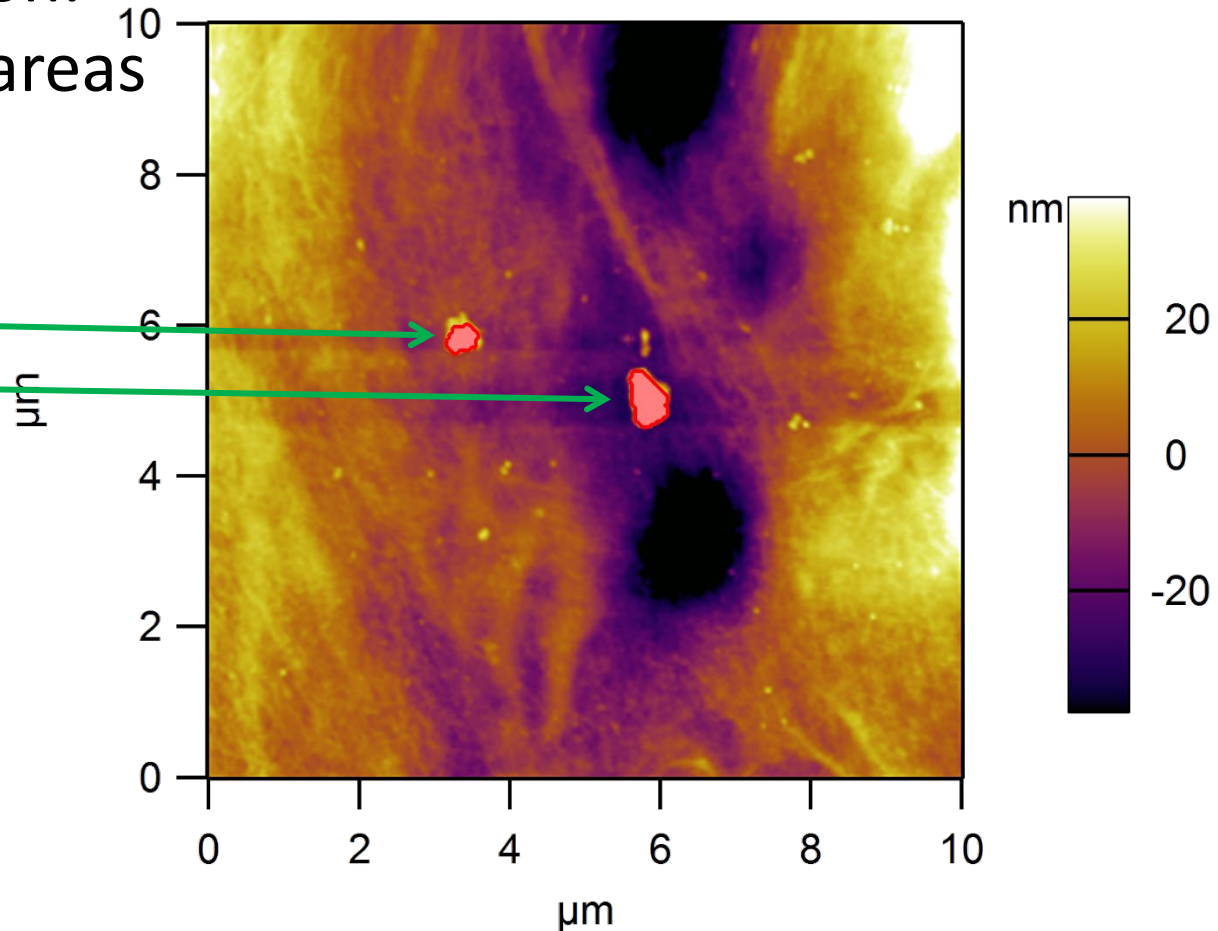
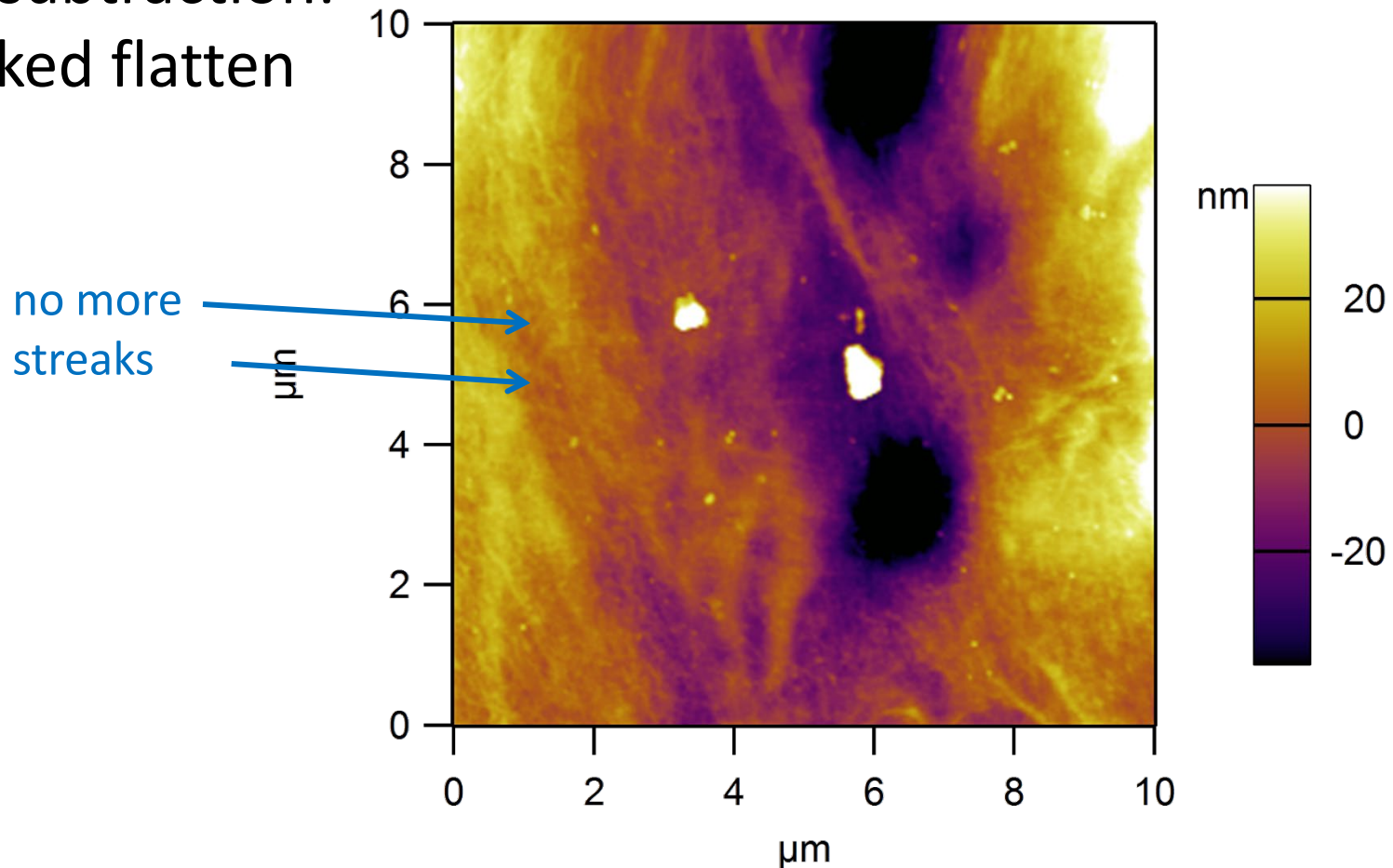
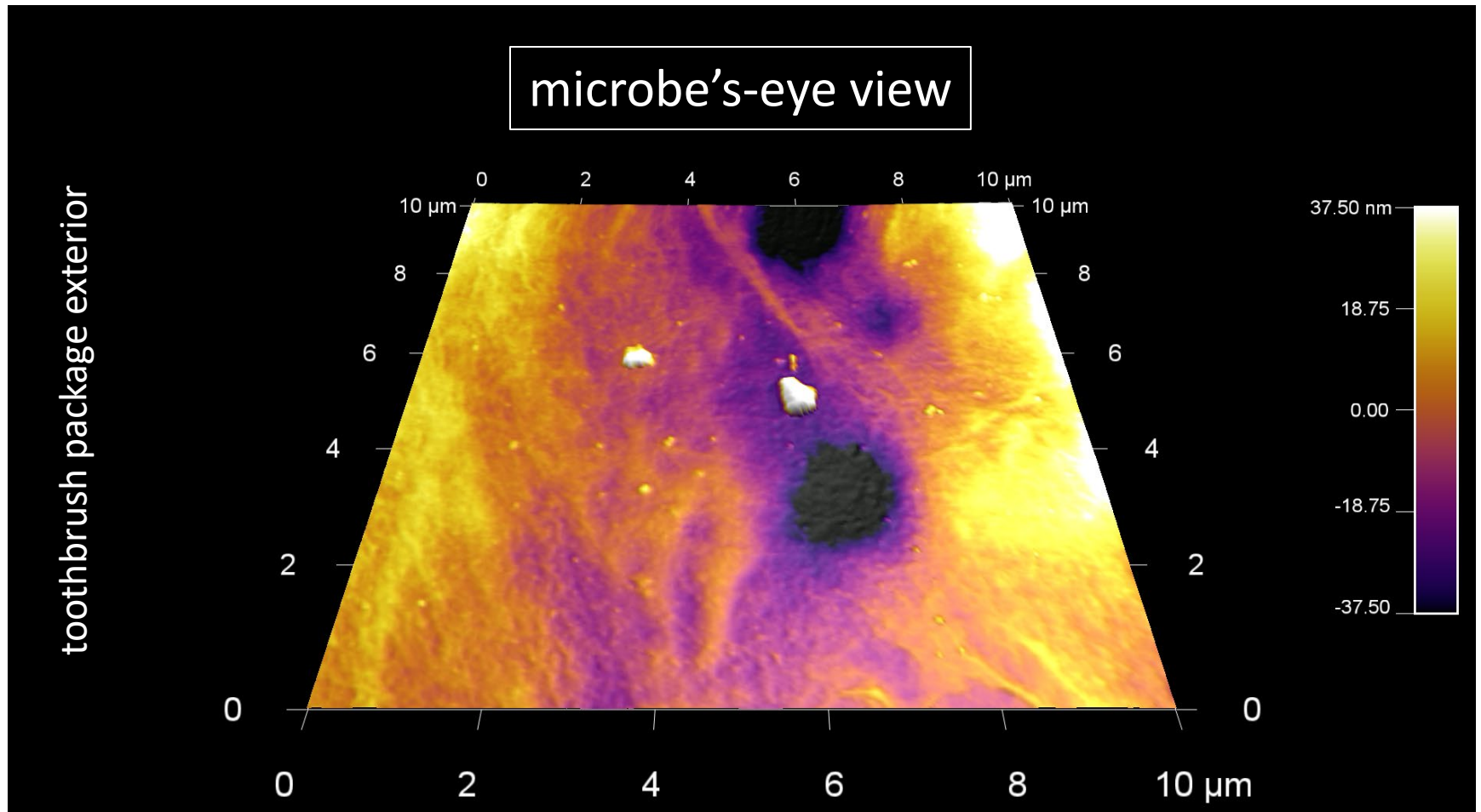


Image Processing

line subtraction:
masked flatten

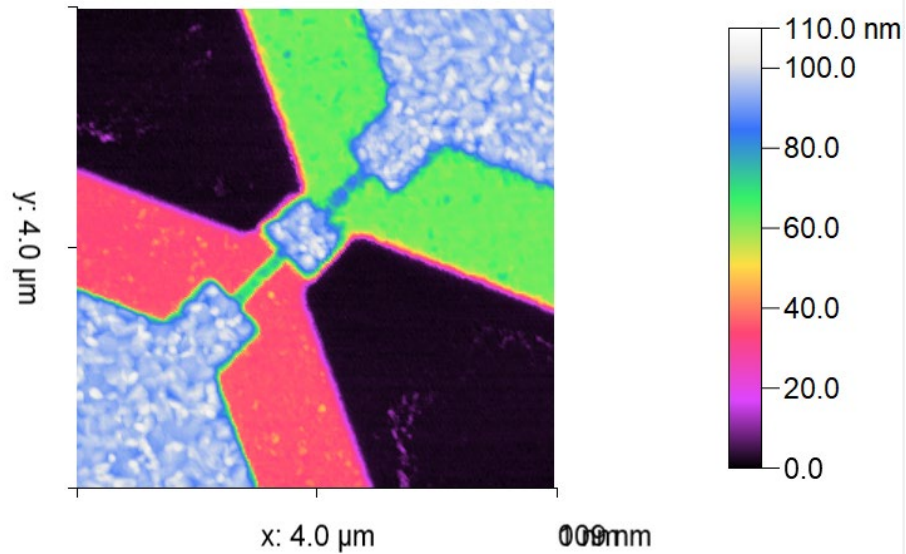


3D Display

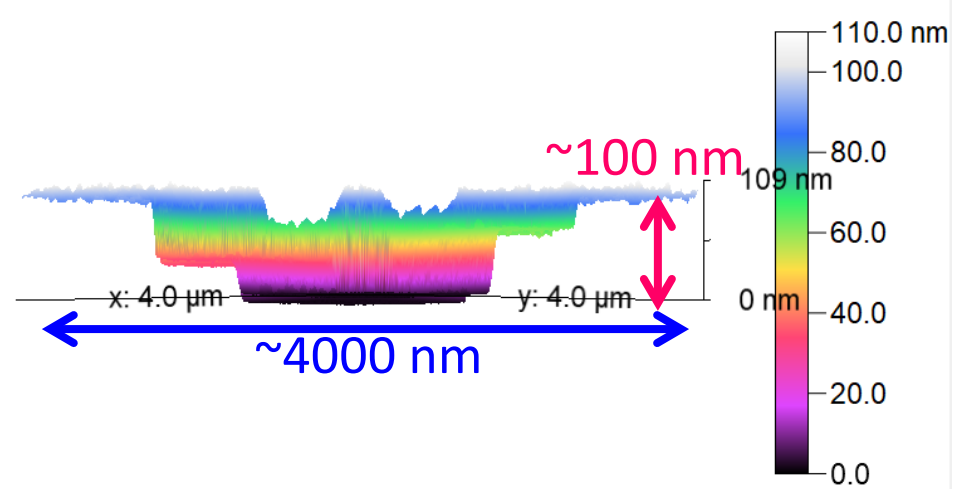


3D Display

face on



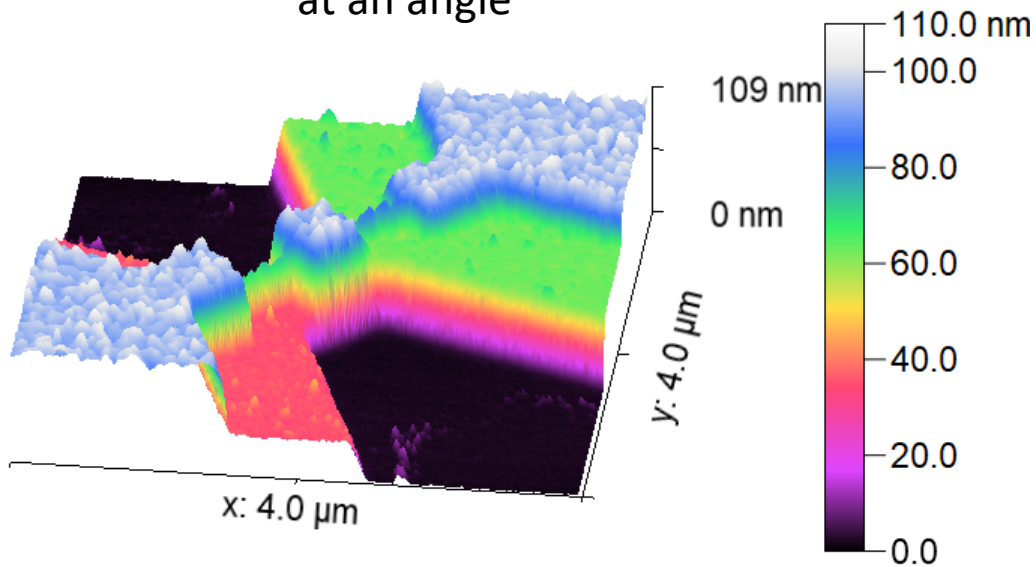
side view



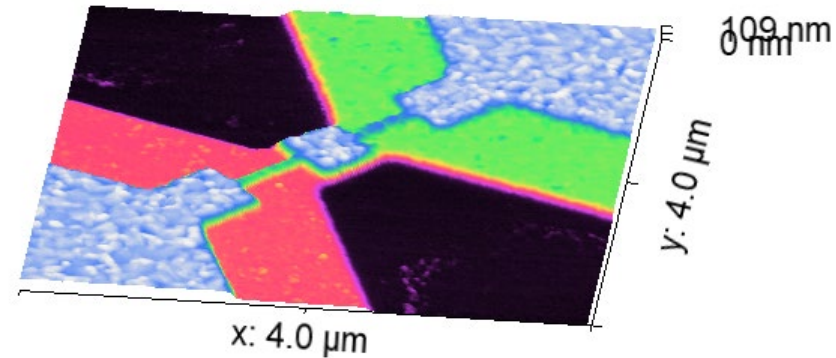
raw data courtesy of Ale Baptista,
Anton Paar Tosca 400 AFM

3D Display—z:xy

at an angle

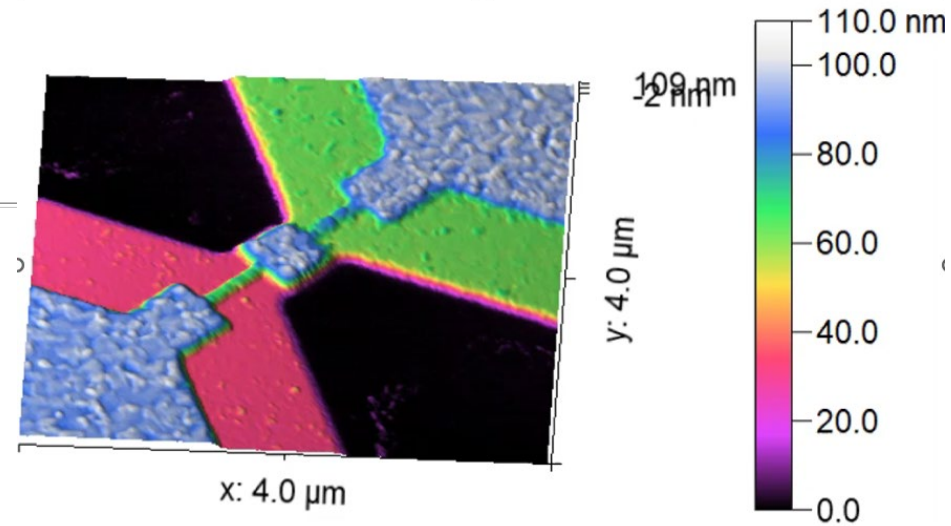
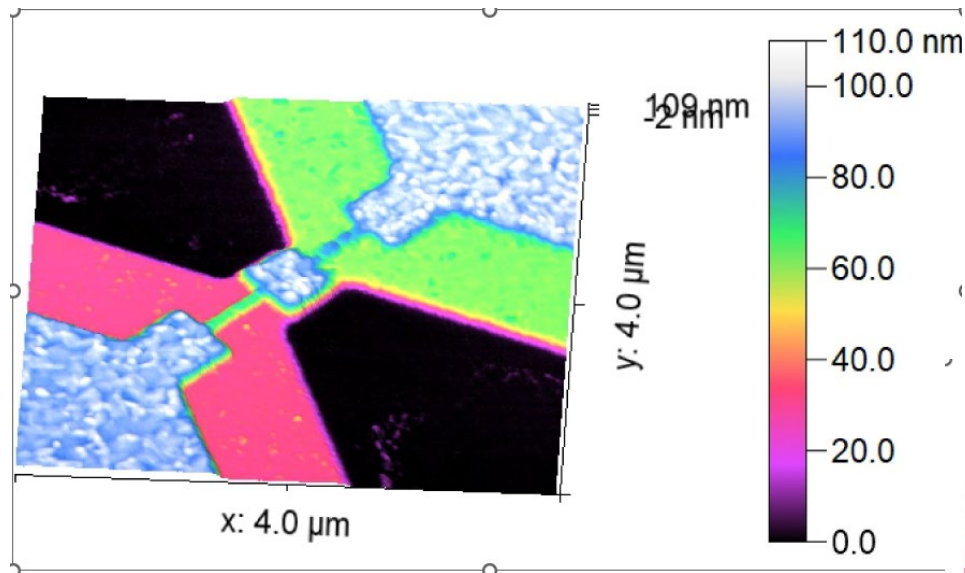


true z:xy



raw data courtesy of Ale Baptista,
Anton Paar Tosca 400 AFM

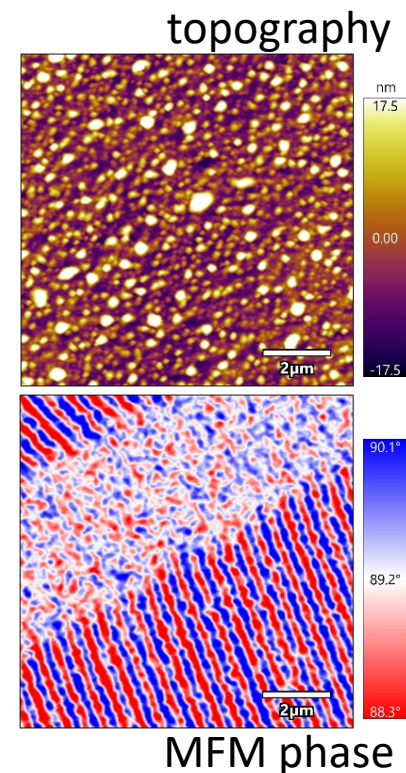
3D Display—Lighting Angle



raw data courtesy of Ale Baptista,
Anton Paar Tosca 400 AFM

Many Other Applications

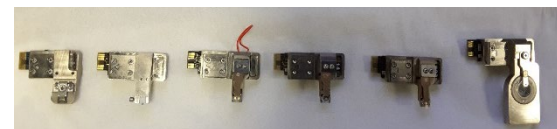
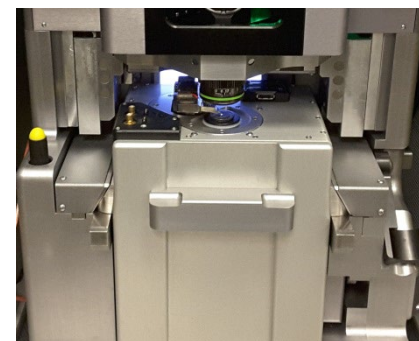
- Nanolithography/nanomanipulation
- LFM (friction, lateral force microscopy)
- EFM (electrostatic force microscopy)
- KPFM (SKPM, Kelvin probe)
- MFM (magnetic force microscopy)
- PFM (piezoresponse force microscopy)
- ... and these generally don't need extra gear (except different tips)



Accessories on the MRL AFMs

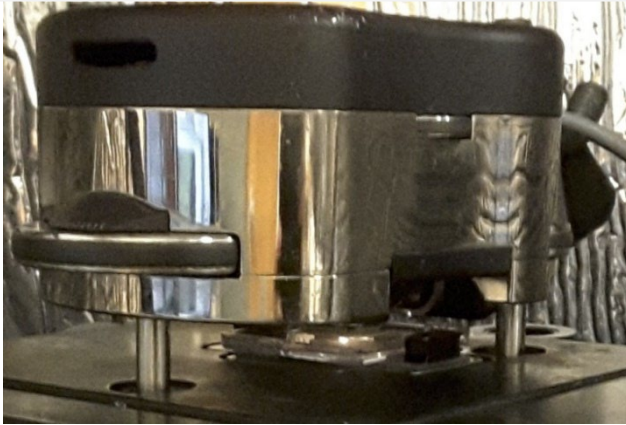
-  ORCA Conductive AFM
-  Scanning Microwave Impedance Microscopy (sMIM)
-  Environmental Controller
-  BioHeater
-  PolyHeater (up to 300°C)
-  Petri Dish Heater
-  MFP-3D Leg Extenders

-  blueDrive Photothermal Excitation
-  Fast Force Mapping
-  Dual-Gain ORCA Conductive AFM
-  Piezoresponse Force Microscopy (HV-PFM)
-  Contact Resonance Viscoelastic Mapping Mode
-  AM-FM Viscoelastic Mapping Mode
-  Scanning Tunneling Microscopy (STM)
-  Air Temperature Controller (ATC)
-  Droplet Cantilever Holder Kit

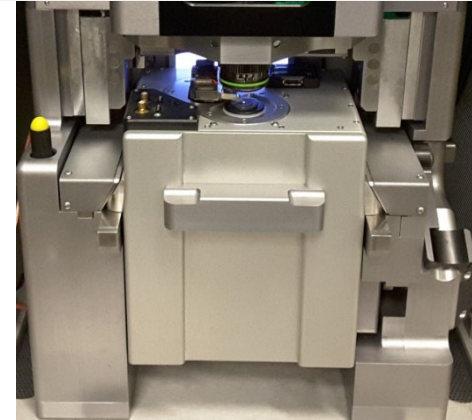


MRL AFMs—B12 MRL

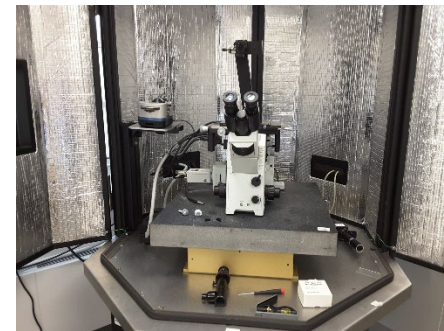
Asylum Research MFP-3D-SA (2 of these)
15 μm z range, 90 μm x 90 μm scan size



Asylum Research Cypher
5 μm z range, 30 μm x 30 μm scan size



0026 Supercon: Asylum Research MFP-3D-Bio
on an inverted optical fluorescence microscope



Related Instruments at MRL

Highly localized chemical information

- Molecular Vista PiFM

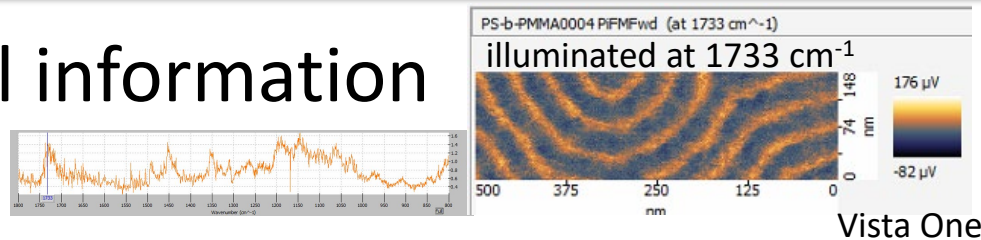
- Photo-induced force microscopy and spectroscopy

- Horiba TERS/TEPL

- Tip-enhanced Raman spectroscopy

- Neaspec Nano-IR

- AFM + infrared



Profilometry

- Dektak stylus profilometer

- Keyence 3D optical profiler



Keep Learning

- MRL Webinar Series
 - go.illinois.edu/MRLYouTubeChannel
 - Basics of Atomic Force Microscopy (Kathy Walsh)
 - The Versatility of Nanomechanics with AFM (Jessica Spear)
 - 3D Optical Profilometry (Julio Soares and Kathy Walsh)
- Kathy Walsh, kawalsh@illinois.edu

