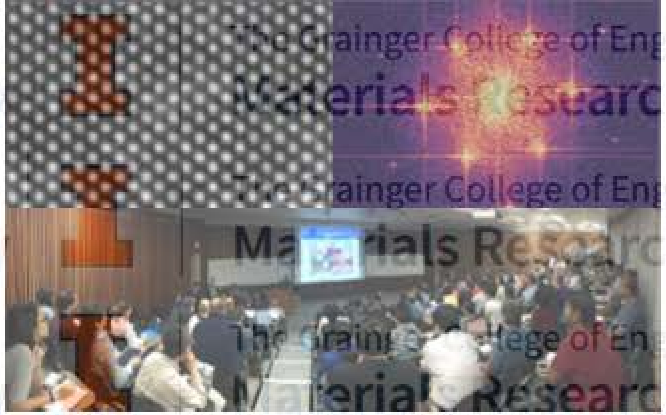


Advanced Materials Characterization *workshop*

Atomic Force Microscopy

Kathy Walsh, Ph.D.

Materials Research Laboratory
University of Illinois at Urbana-Champaign

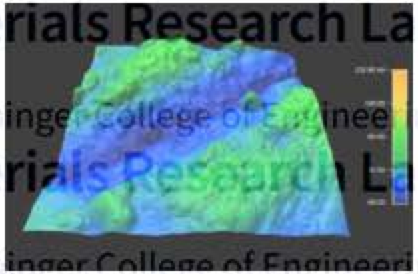
The Grainger College of Engineering
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

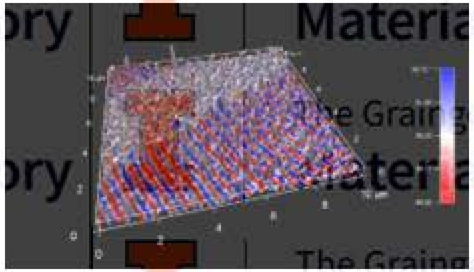
go.illinois.edu/AMC2023

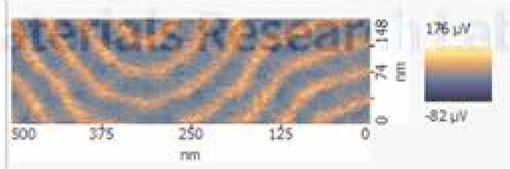
Itinerary

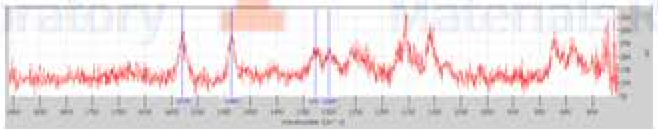
- How AFM works

- (A few) featured applications

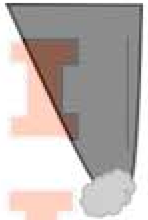






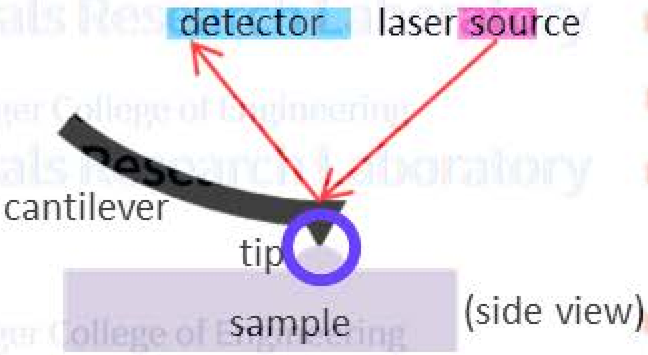


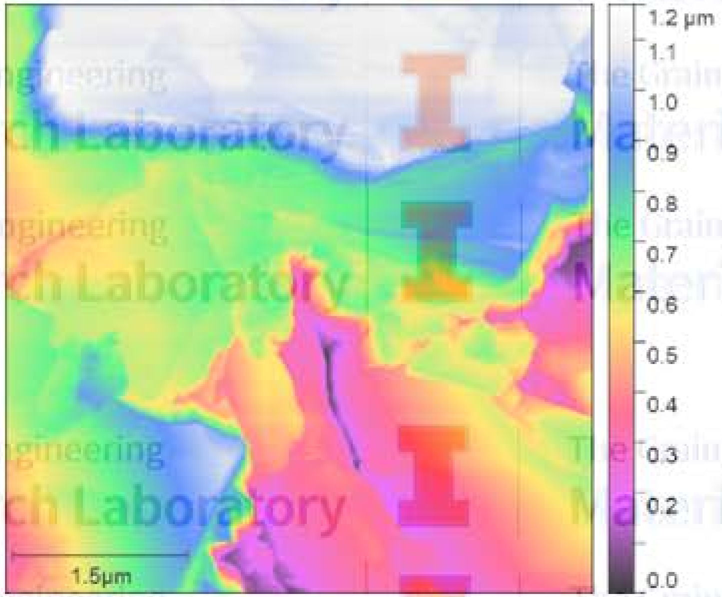
- What can go wrong?



What's an Atomic Force Microscope?

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

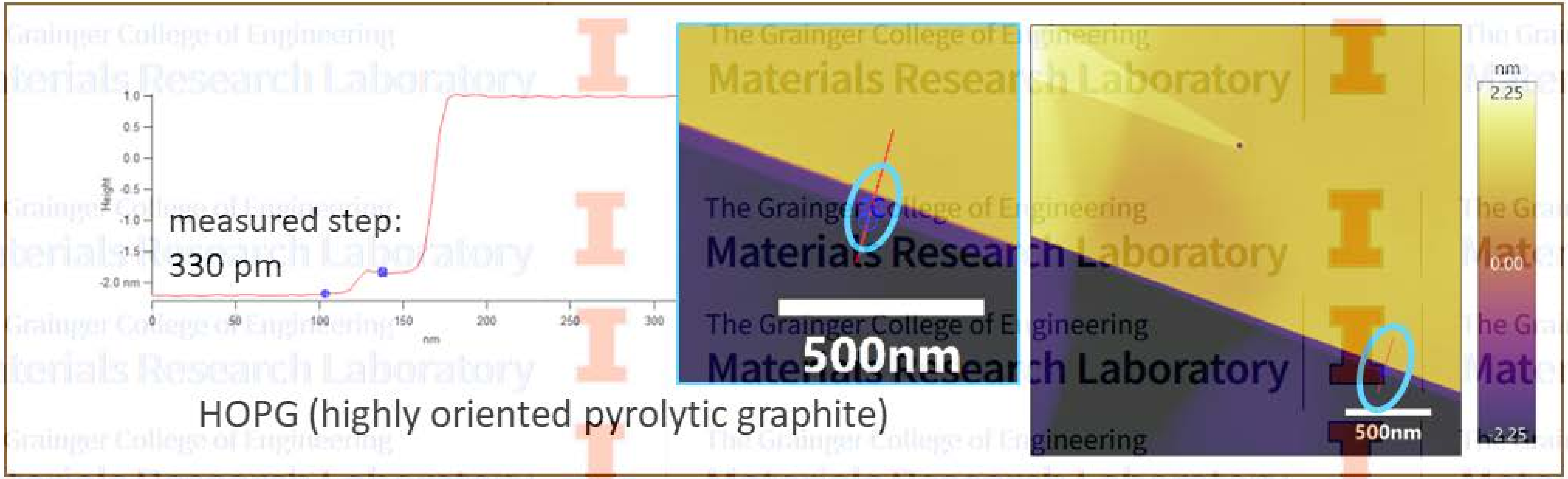




false-color surface topographs

What's an Atomic Force Microscope?

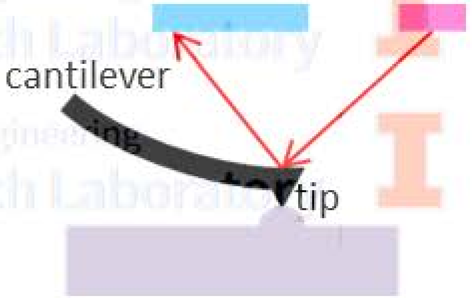
- "Atomic Force"—interactions between tip and sample
  - Sub-angstrom vertical resolution
  - Laterally, not quite atomic resolution (usually)
  - Nanoscale lateral resolution (depends on tip and sample)
- "Microscope"—surface topograph



HOPG (highly oriented pyrolytic graphite)

What's an Atomic Force Microscope?

- "Atomic Force"—interactions between tip and sample
  - Sub-angstrom vertical resolution
  - Laterally, not quite atomic resolution (usually)
  - Nanoscale lateral resolution (depends on tip and sample)
- "Microscope"—surface topograph
- Tip at the end of a cantilever
- Raster tip over surface to build up an image

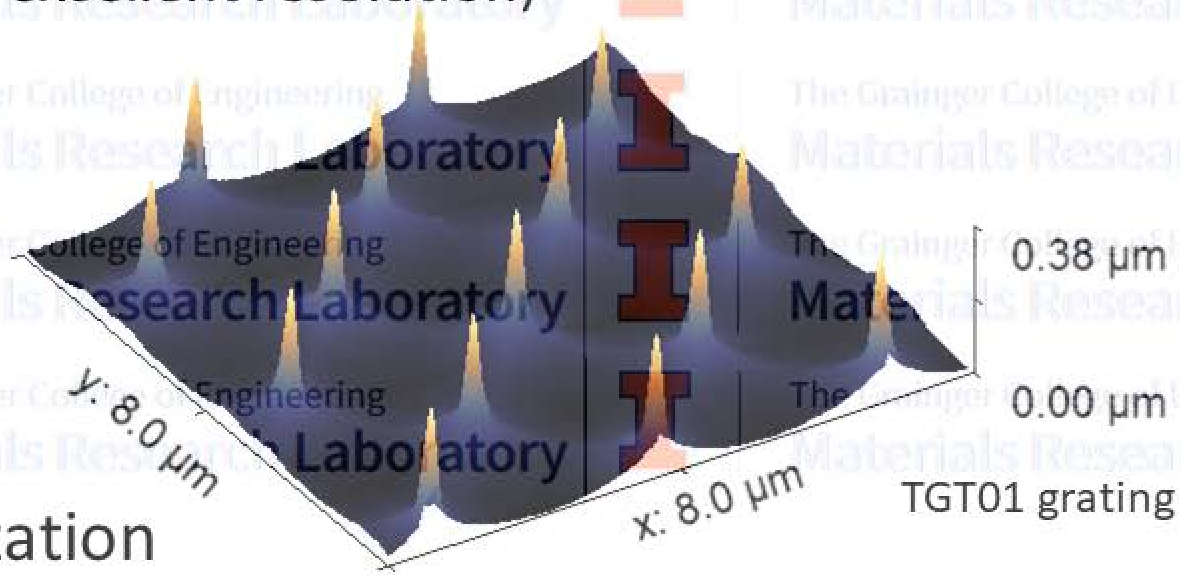


- Also sensitive to sample stiffness, adhesion, other properties depending on tip choice and instrument mode

Turquoise, 1μm x 1μm
color overlay: mechanical phase

What is Atomic Force Microscopy Used For?

- 3D surface imaging
  - XYZ coordinates of sample surfaces (with excellent resolution)
  - Quantitative height maps of surfaces
  - Step height/thickness measurements
  - Roughness measurements
- Nanomechanical characterization
- Nanoscale electromagnetic characterization
- Nanoscale optical spectroscopy
- Nanomanipulation

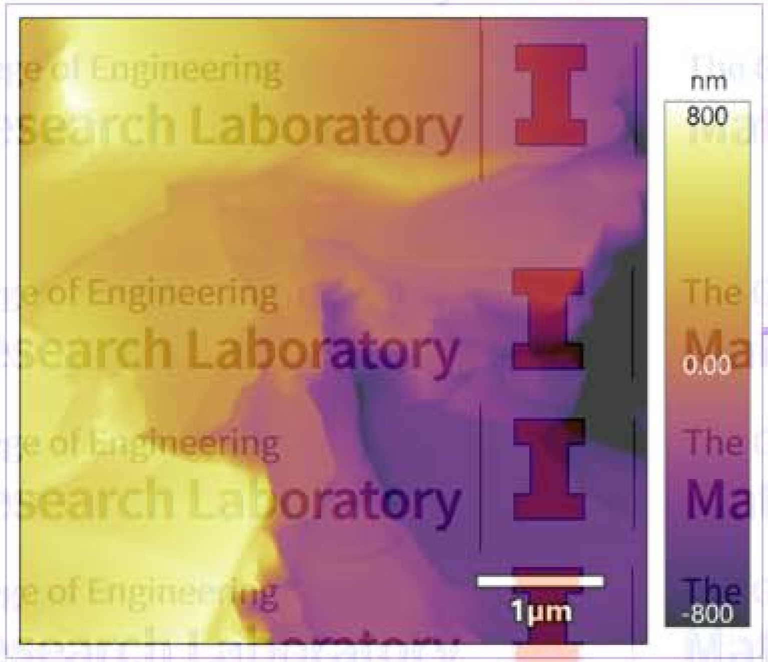


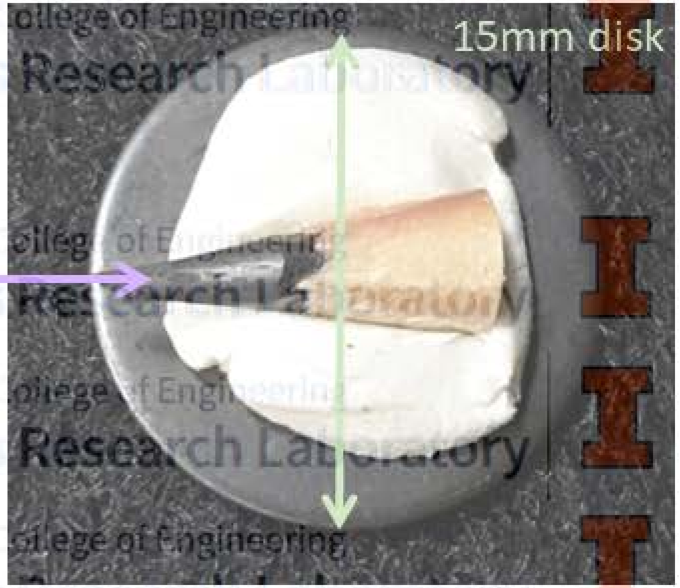
TGT01 grating

Typical AFM Scales

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

- Sample sizes — mm to cm
- Image sizes — few to few tens of µm^2
- Feature peak-to-valley — Å to µm (within scan area/field of view)

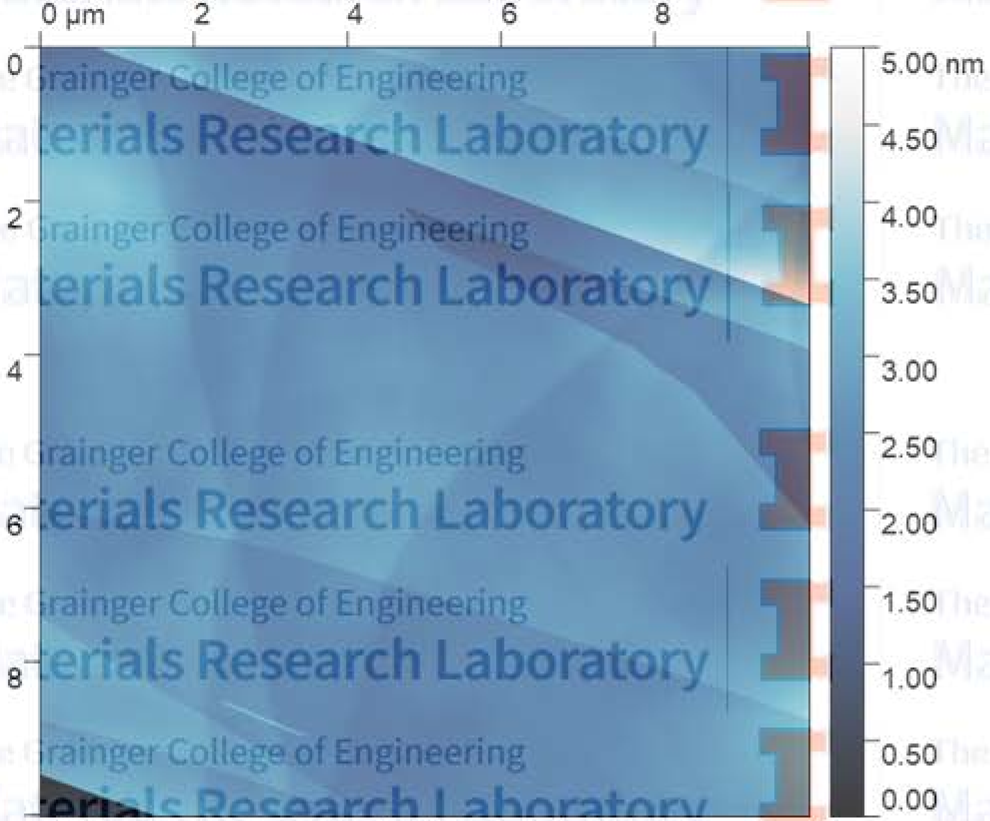


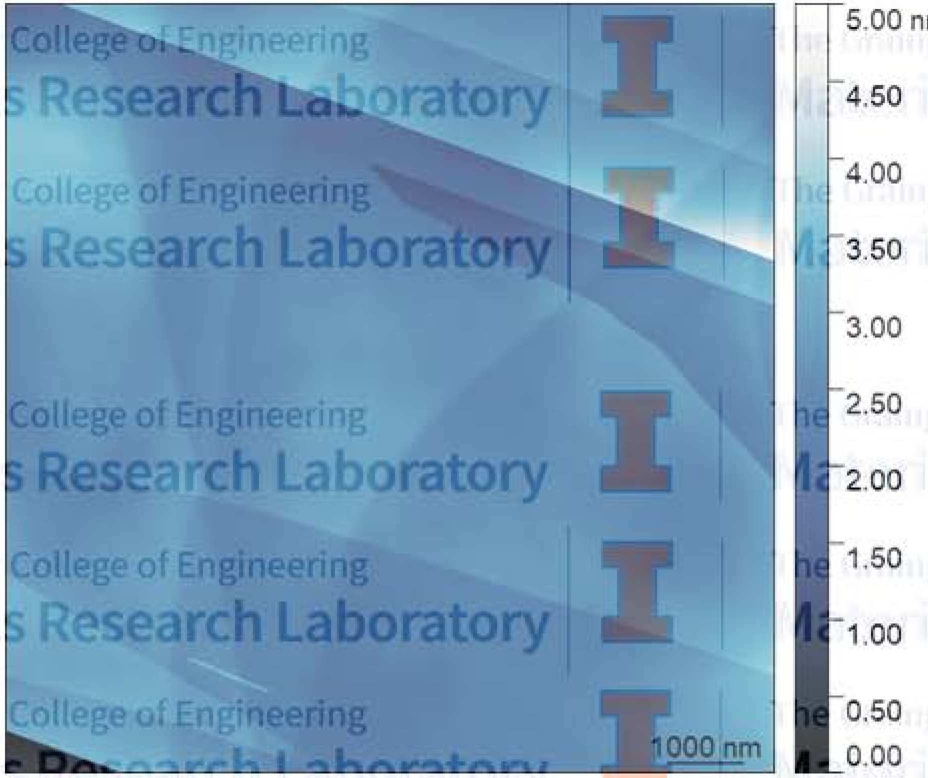


Typical AFM Scales

(only what’s most common, not all of what’s possible)

- Sample sizes — mm to cm
- Image sizes — few to few tens of µm^2 verbal shorthand 10µm, 10x10 (usually square)



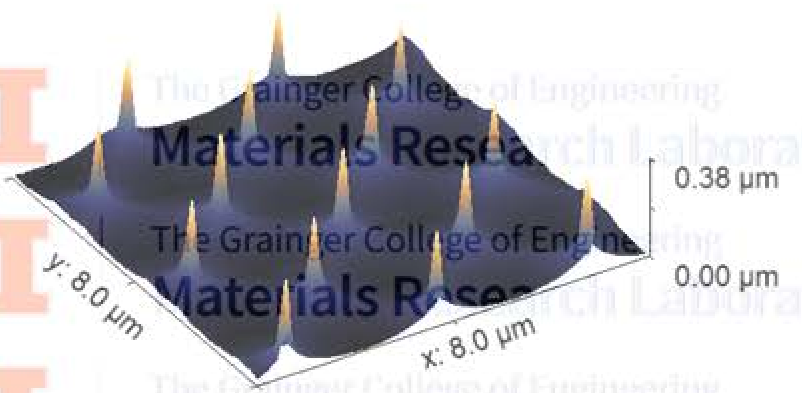


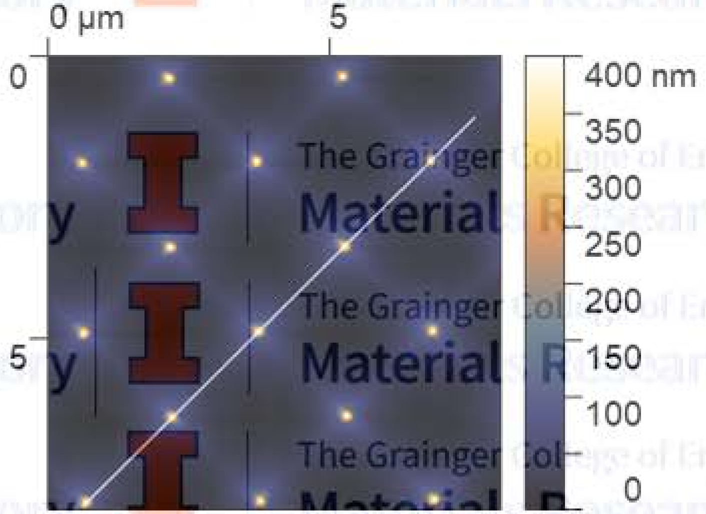
HOPG, Asylum Cypher S AFM, processed using Gwyddion

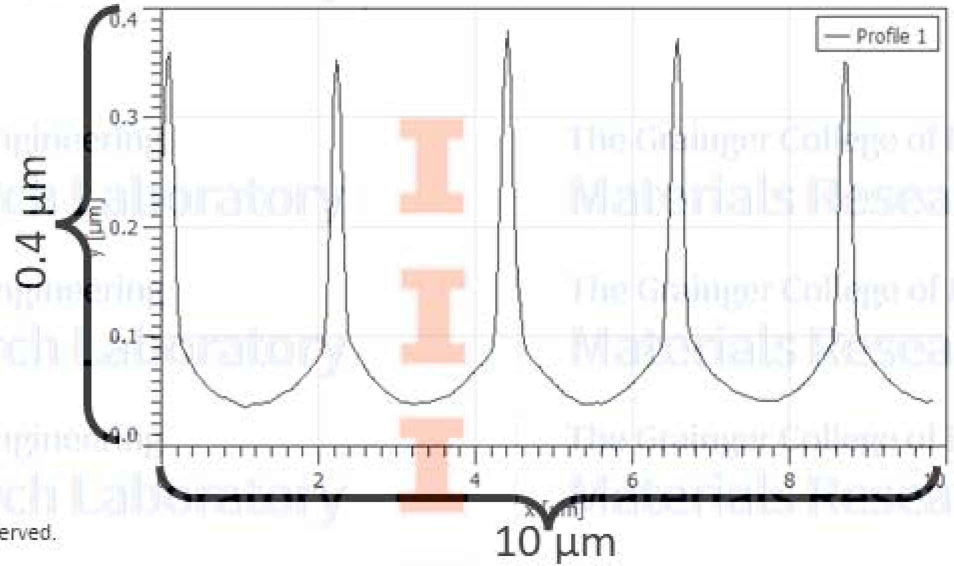
Typical AFM Scales

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

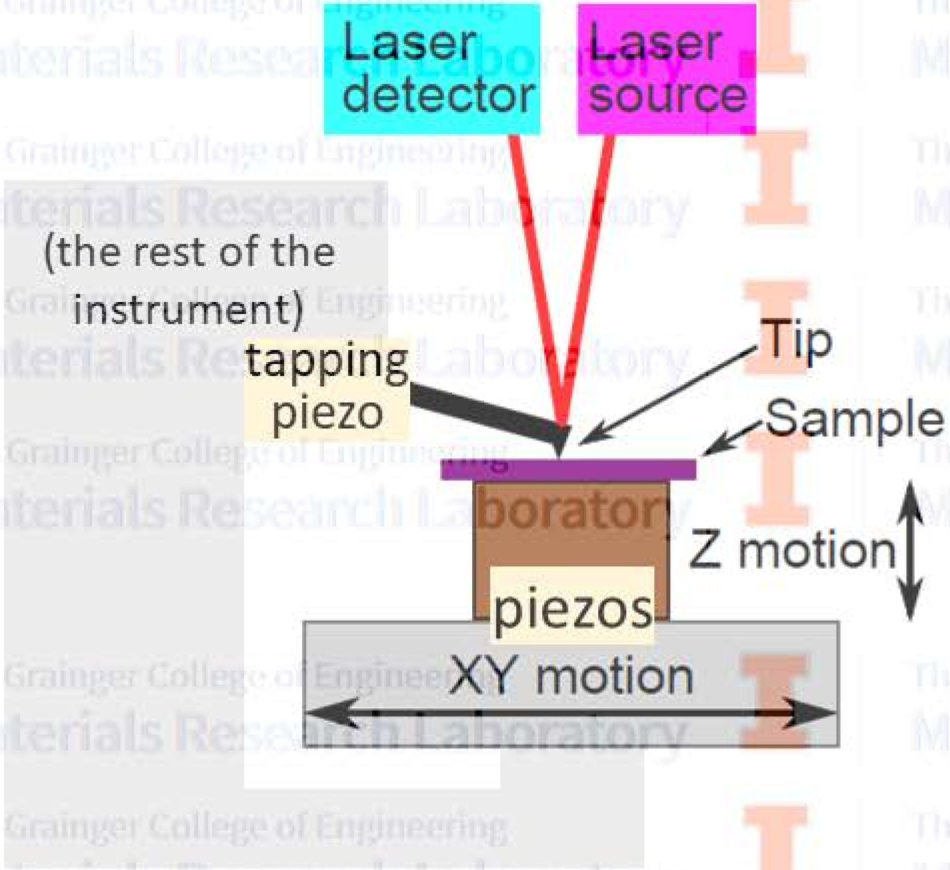
- Sample sizes — mm to cm
- Image sizes — few to few tens of μm^2
- Feature peak-to-valley — Å to µm (within scan area/field of view)
  - Overall sample thickness — sub-mm to many cm
  - Z range — ~2 µm to ~40 µm (max feature height + sample tilt)

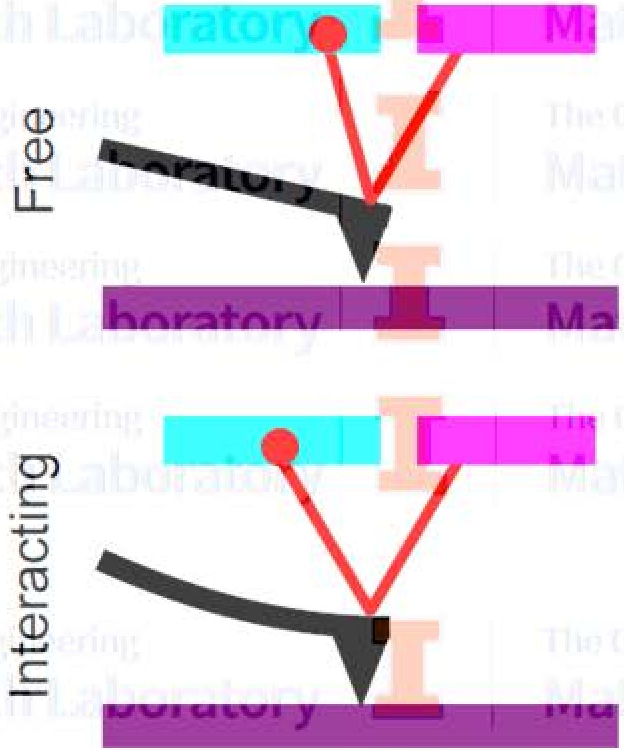




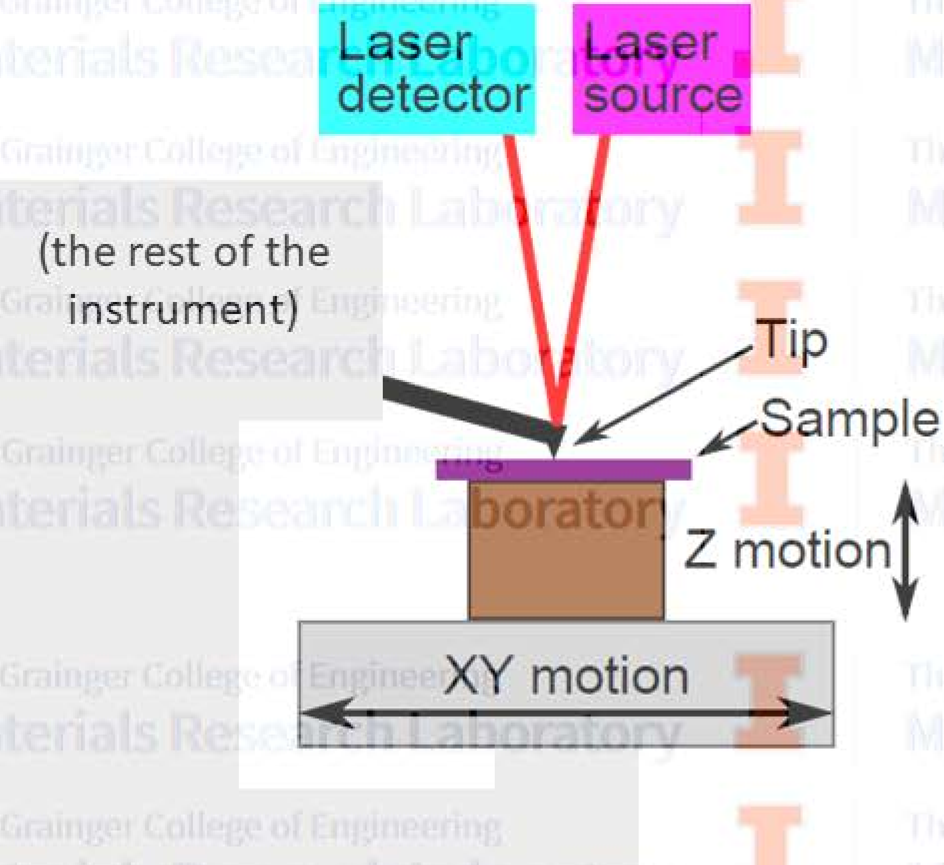


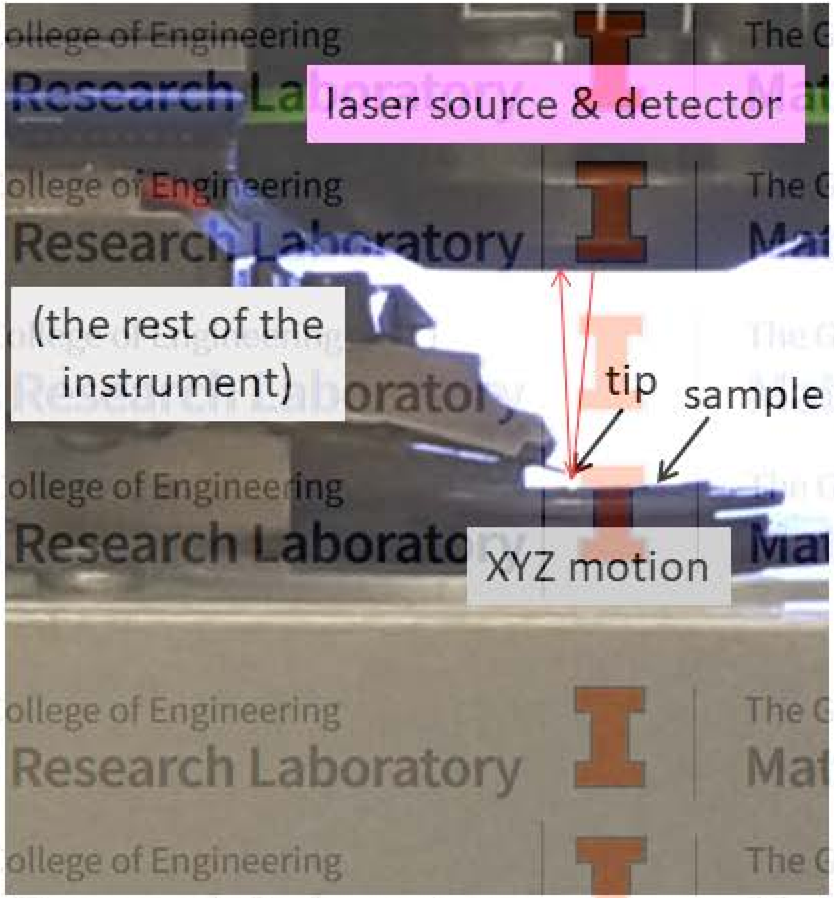
AFM Schematic





AFM in the Lab

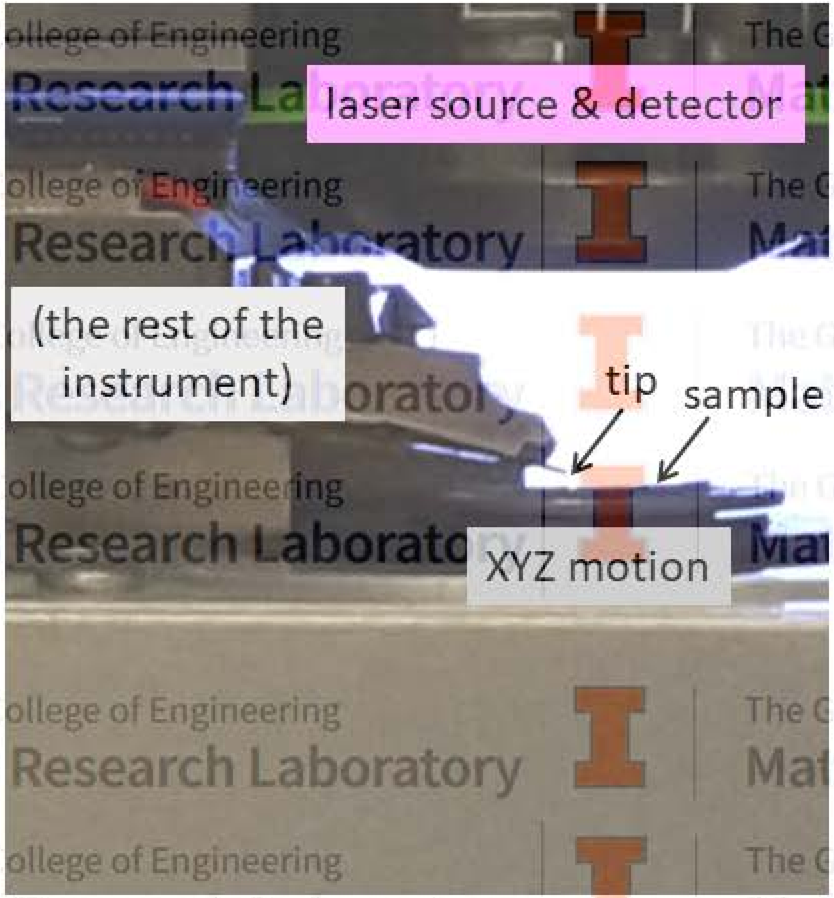




side view
Asylum Research Cypher S AFM

AFM in the Lab

top view



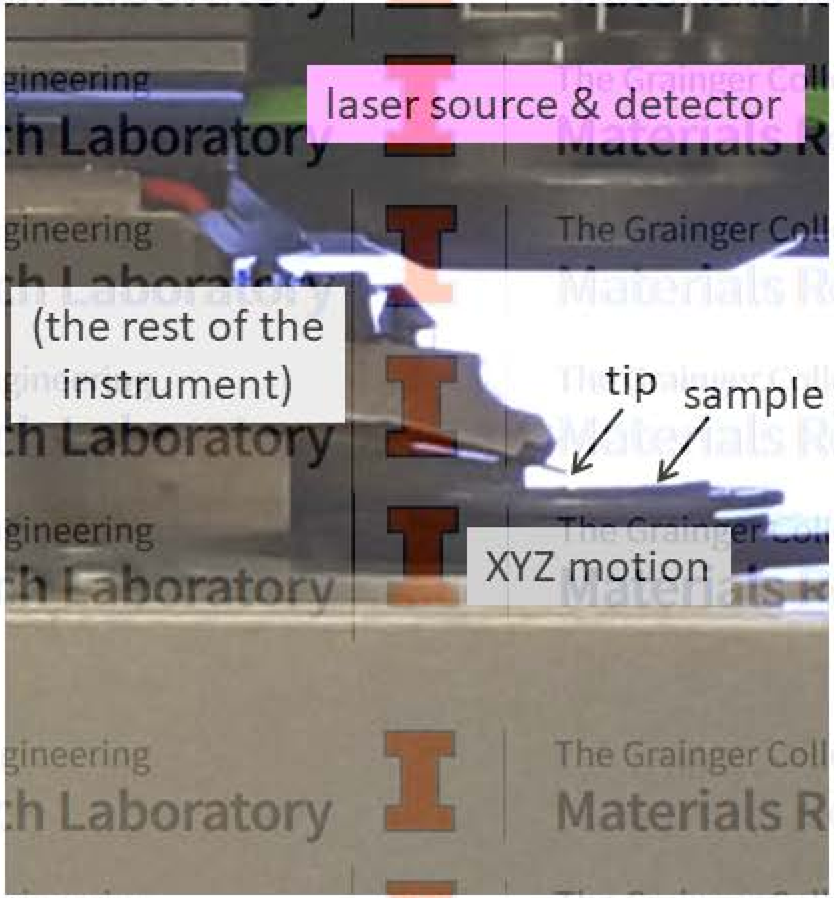
side view

Asylum Research Cypher S AFM

samples are mounted flat on steel disks, glass slides, etc. depending on the AFM model

AFM Measurement Process

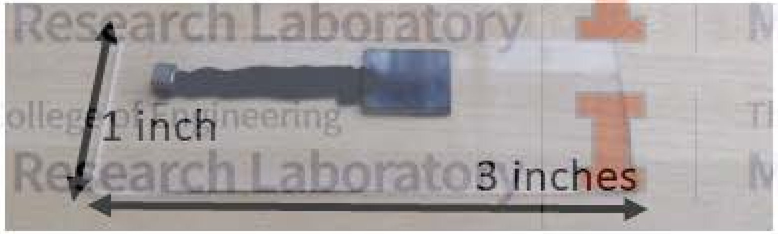
- Load sample and tip
- Scan
- Process image
- Extract numerical results (application-dependent)



Sample Mounting

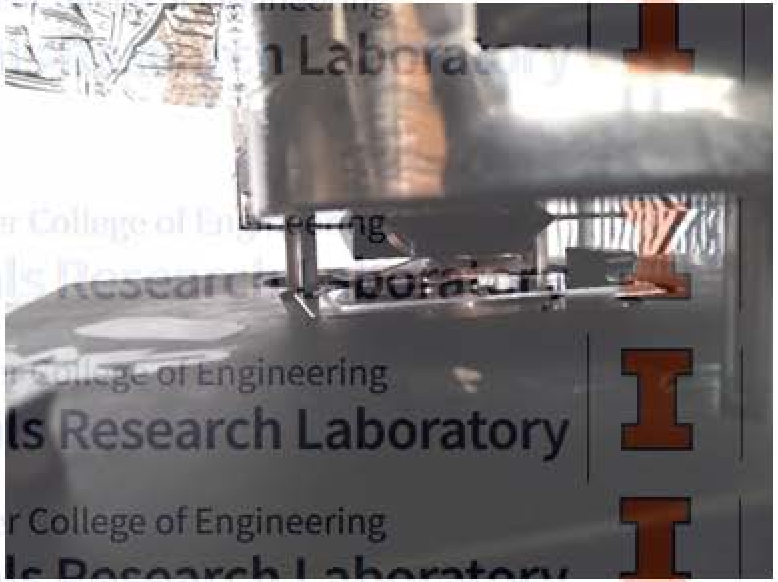
steel disk

sample mounted
for conductive AFM



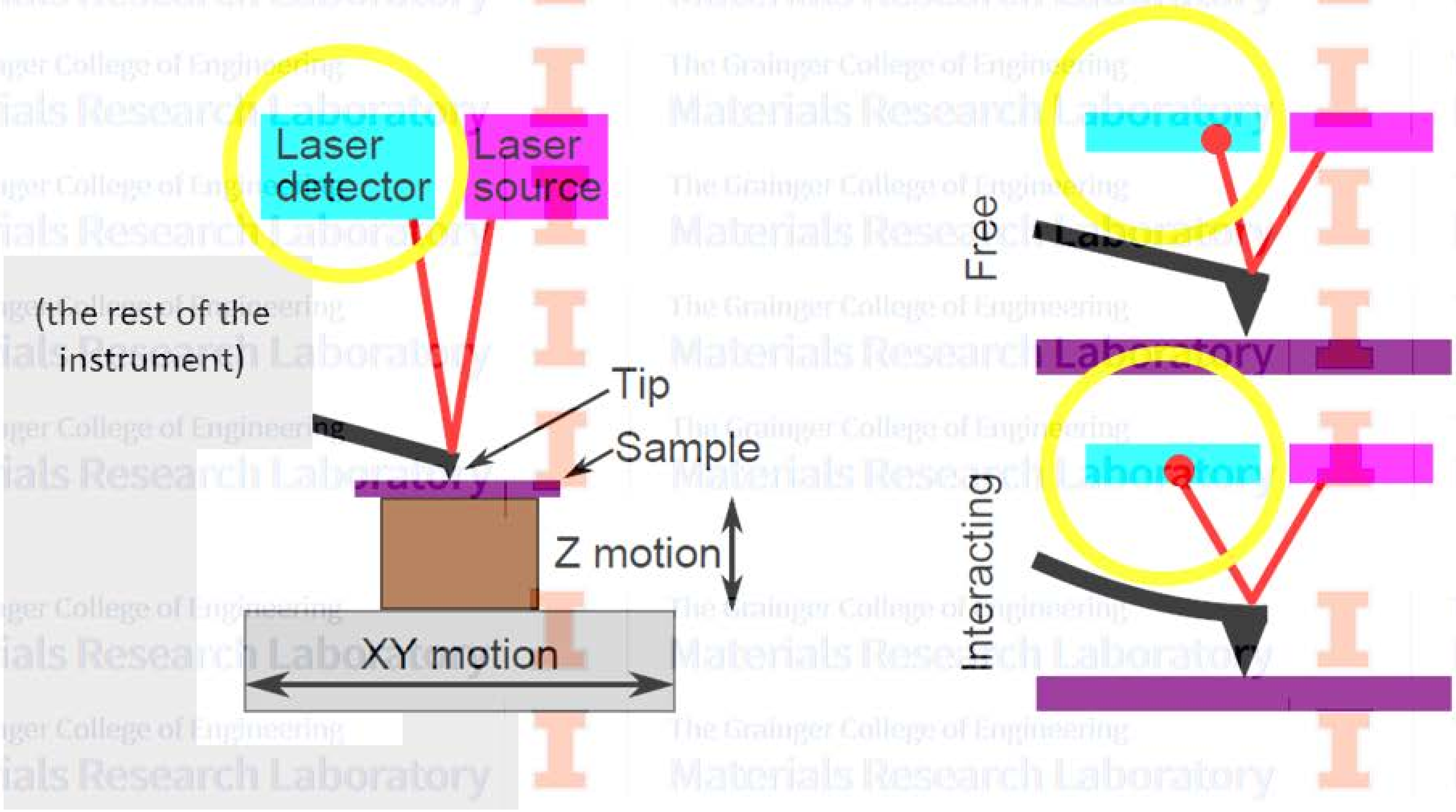
in a petri dish lid
for fluid

in the AFM



in a fluid heater
(sample is a
pink gel)

AFM Schematic

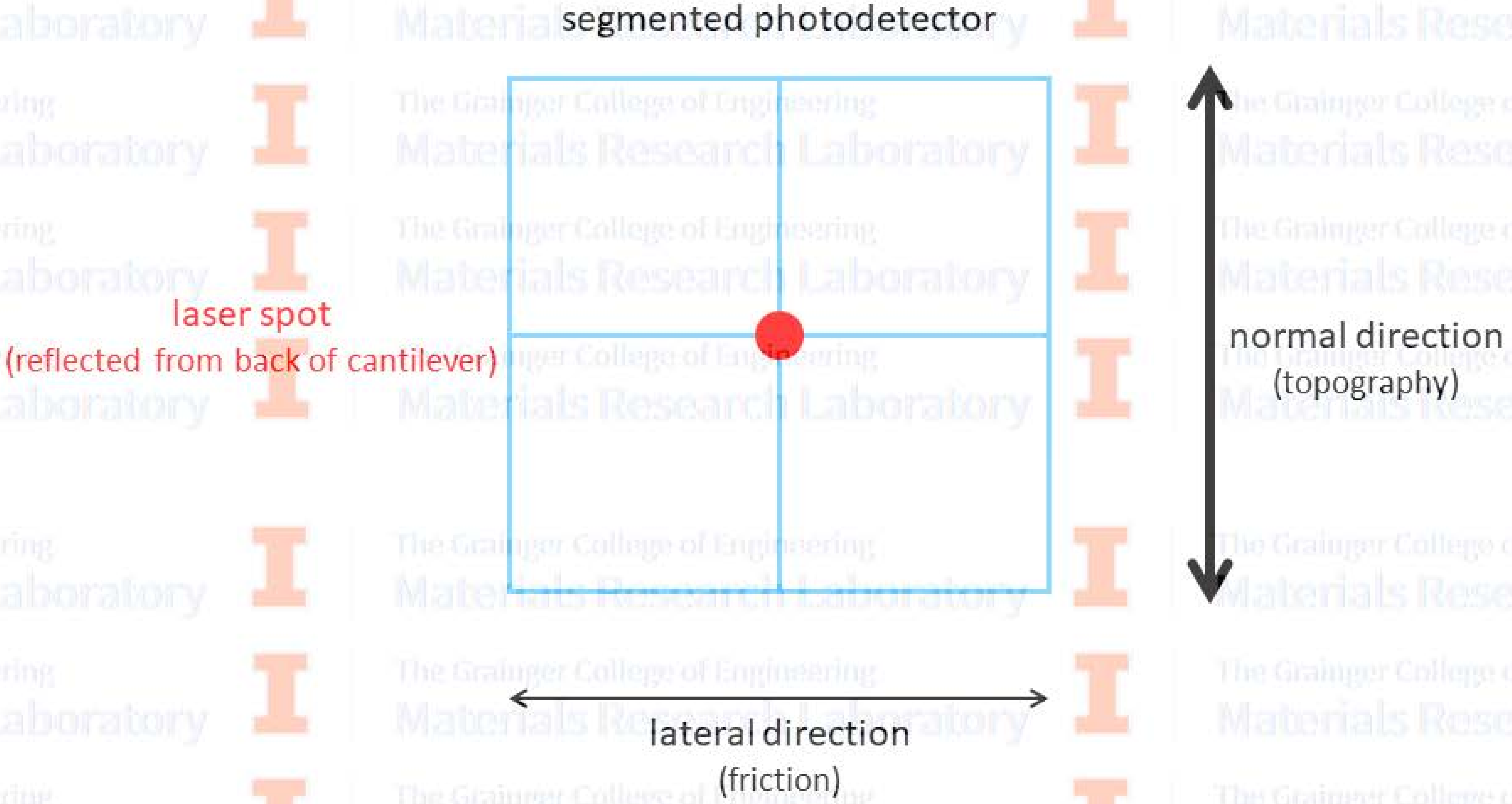


Deflection Detection

(exaggerated schematic)

non-interacting

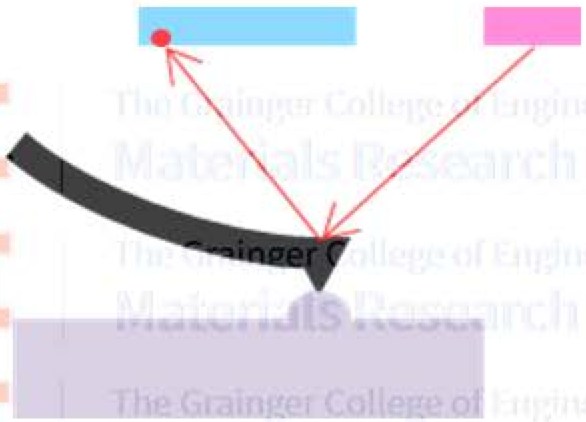
(side view)



Deflection Detection

(exaggerated schematic)

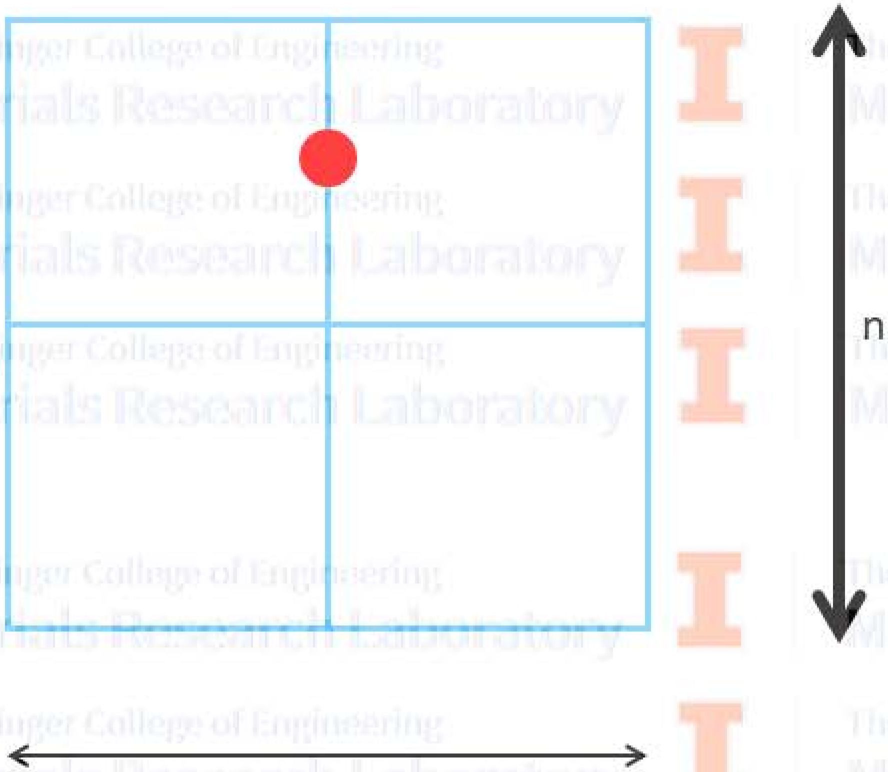
sample pushing up



(side view)

laser spot
(reflected from back of cantilever)

segmented photodetector



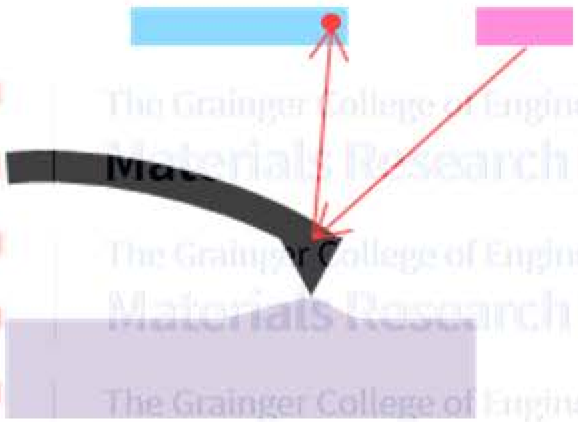
normal direction
(topography)

lateral direction
(friction)

Deflection Detection

(exaggerated schematic)

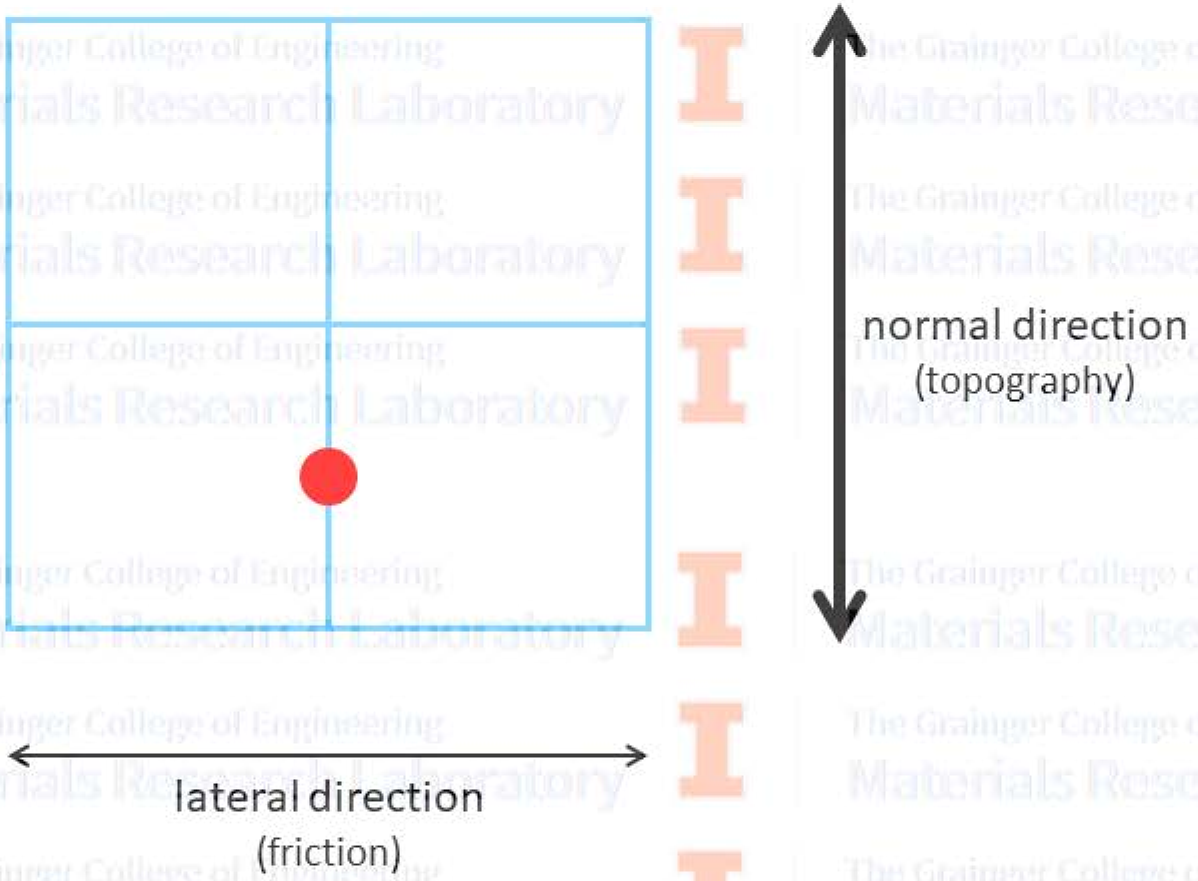
sample pulling down



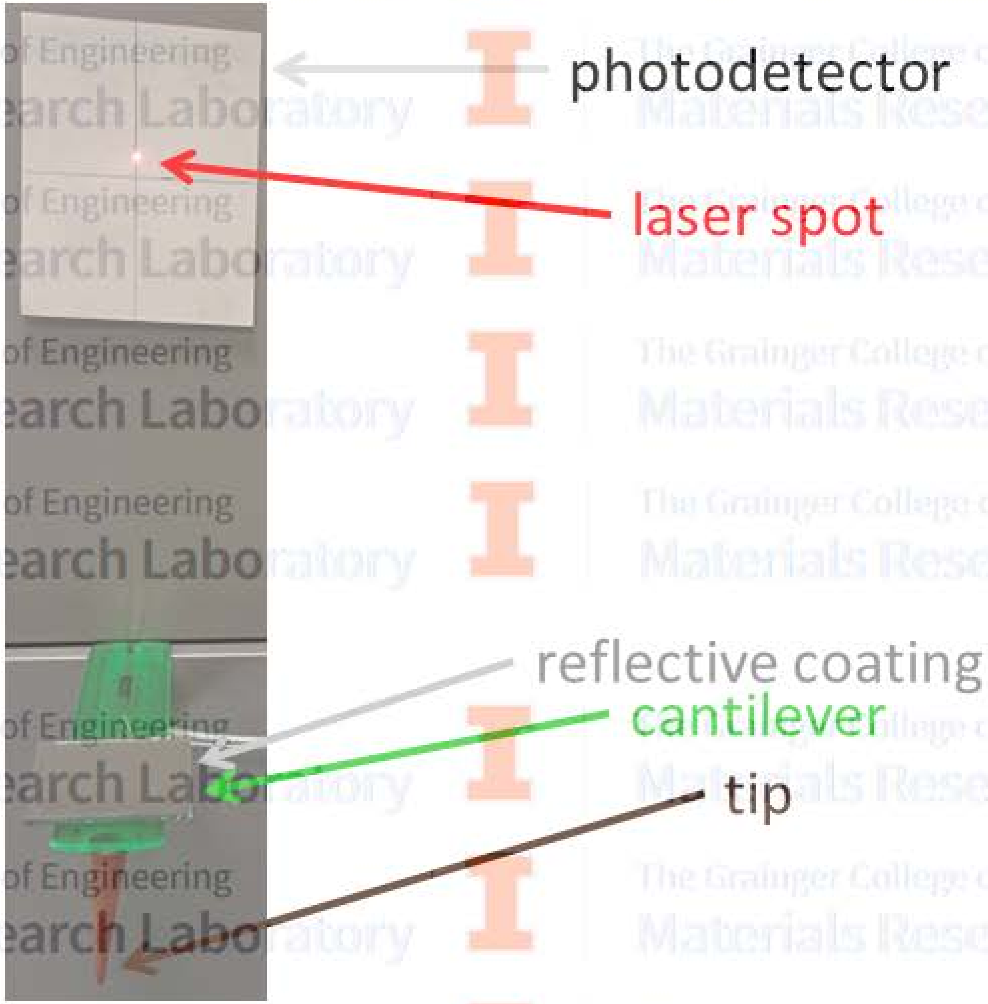
(side view)

laser spot
(reflected from back of cantilever)

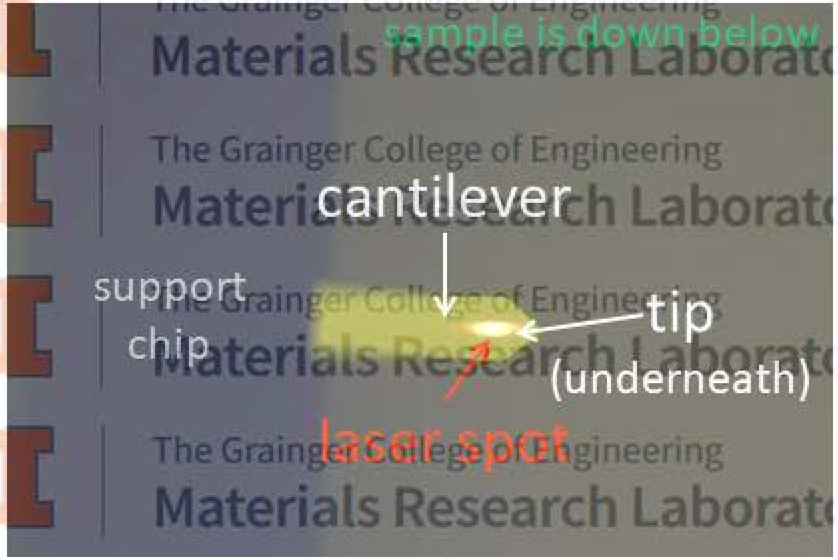
segmented photodetector



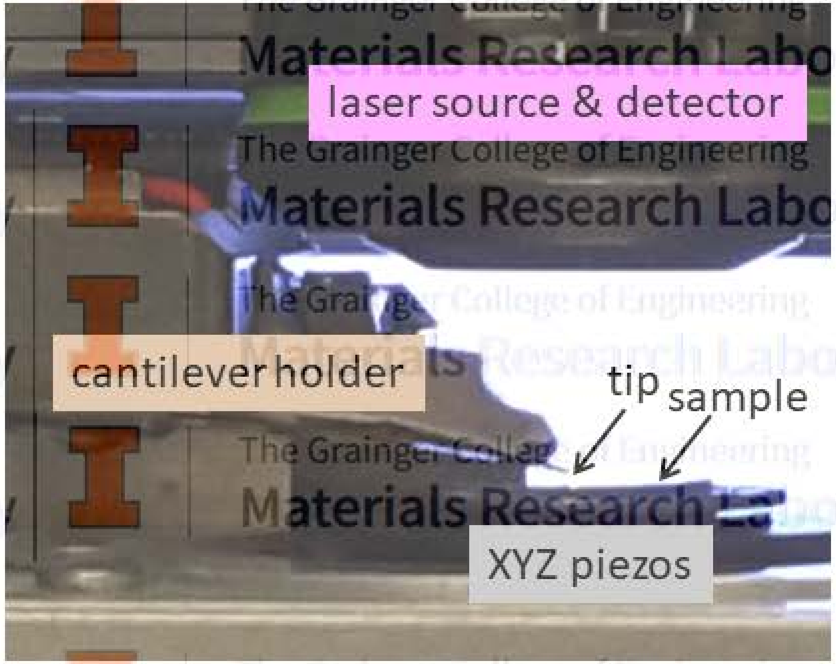
Deflection Detection: A Metaphor



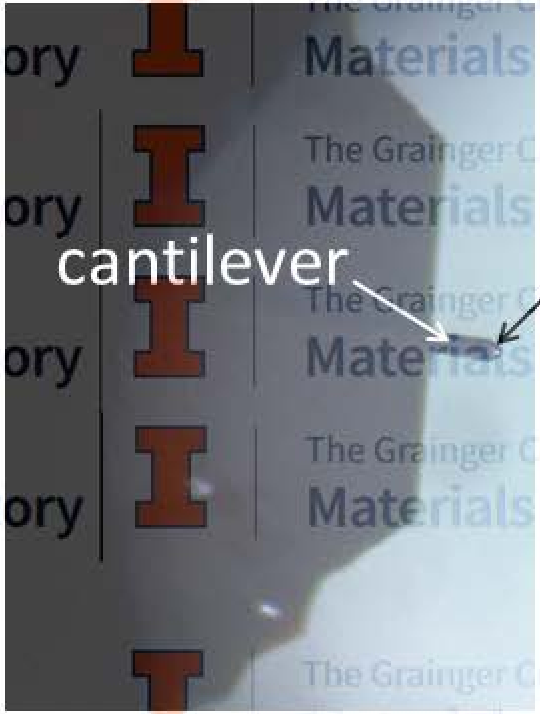
AFM Tips



top view



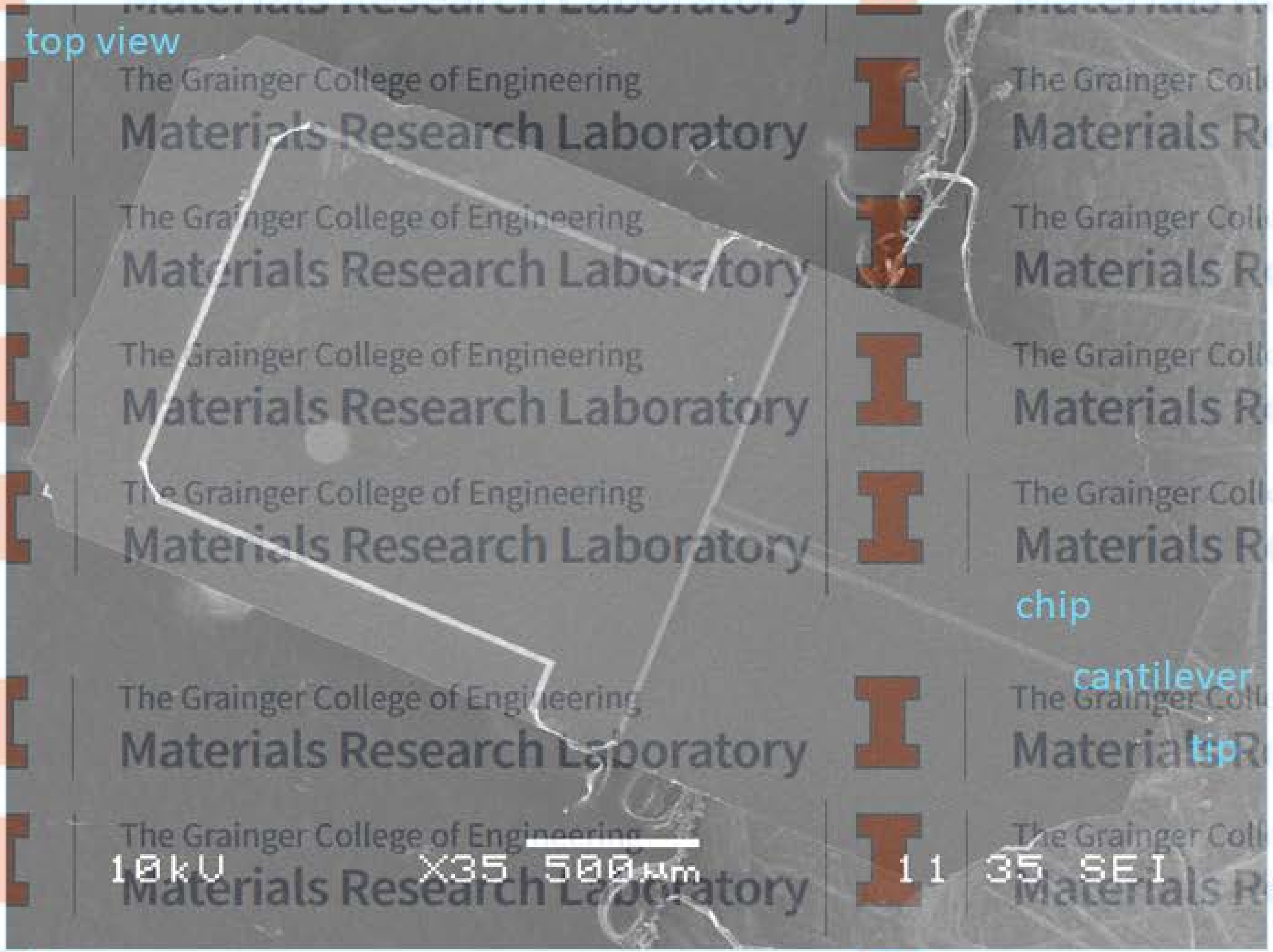
side view

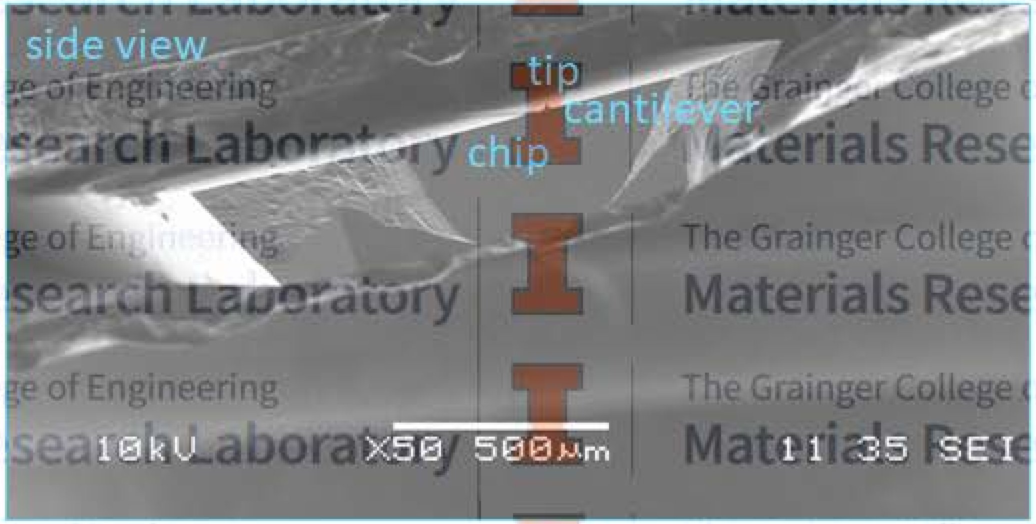


tip view

AFM tips are consumables, not instrument components

Tip Terminology

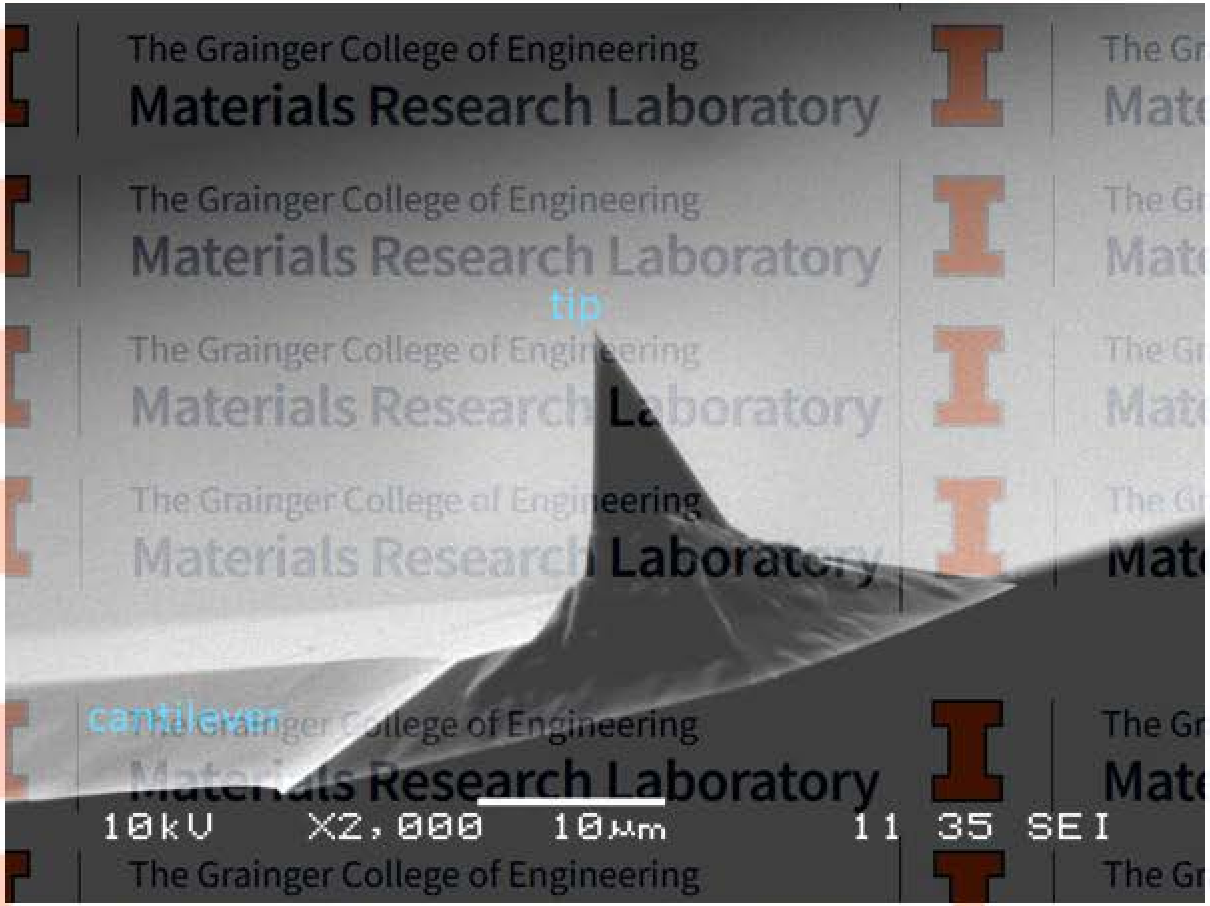




scanning *probe* microscopy

SEM images taken using
MRL's JEOL 6060LV

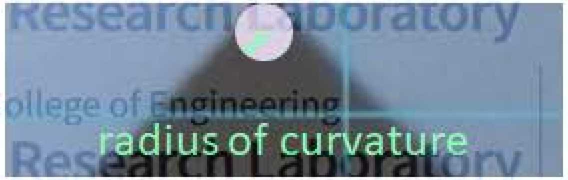
A Closer Look at the Tip



SEM images taken using MRL's JEOL 6060LV

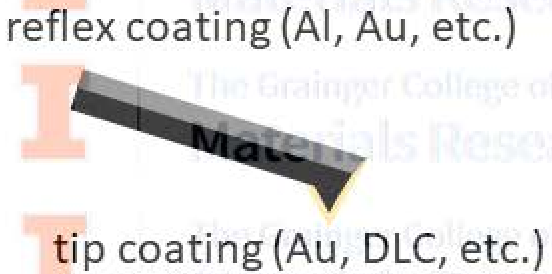
one (of many) common tip for imaging

- silicon tip, radius of curvature < 10 nm
- cantilever stiffness ~25-40 N/m

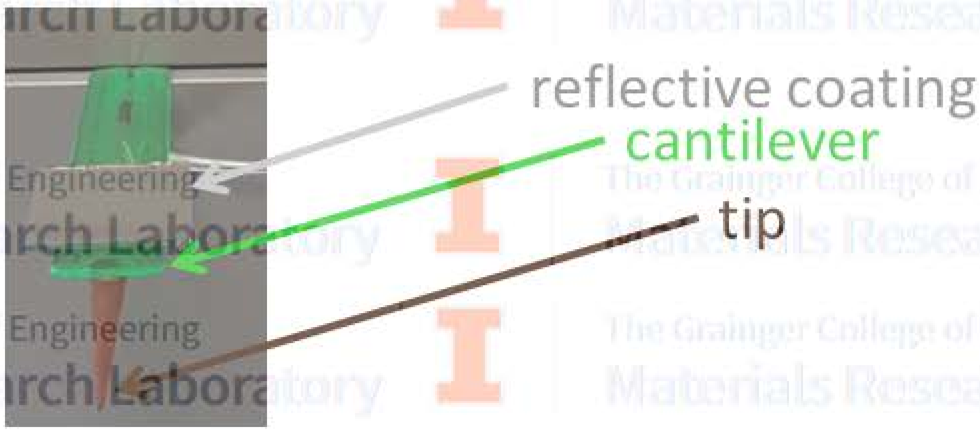


Types of Tips

- Different cantilever back side ("reflex") coatings (*e.g.,* Al, gold)
- Different tip coatings (wear-resistant, conductive, magnetic)



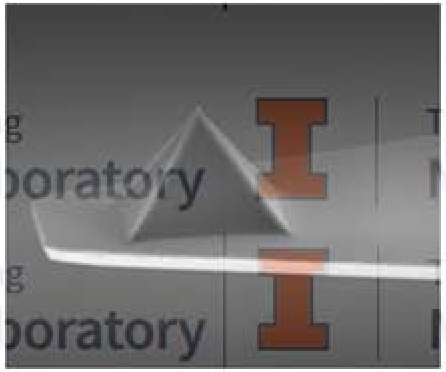
- Ultrasharp or high aspect ratio tips — preserve with careful handling
- Colloidal probes, specialty coated tips, made-to-order probes
- Functionalized tips
  - Make your own coatings



Types of Tips

- Different cantilever back side ("reflex") coatings (*e.g.,* Al, gold)
- Different tip coatings (wear-resistant, conductive, magnetic)

- Ultrasharp or high aspect ratio tips — preserve with careful handling
- Colloidal probes, specialty coated tips, made-to-order probes
  - Basically anything (tiny) you want to stick on the end of the cantilever
  - Make your own using "tipless cantilevers"
- Functionalized tips
  - Adhesion, coefficient of friction between materials
  - Make your own coatings



http://www.nanoandmore.com/ AFM-Probe-PNP-TR

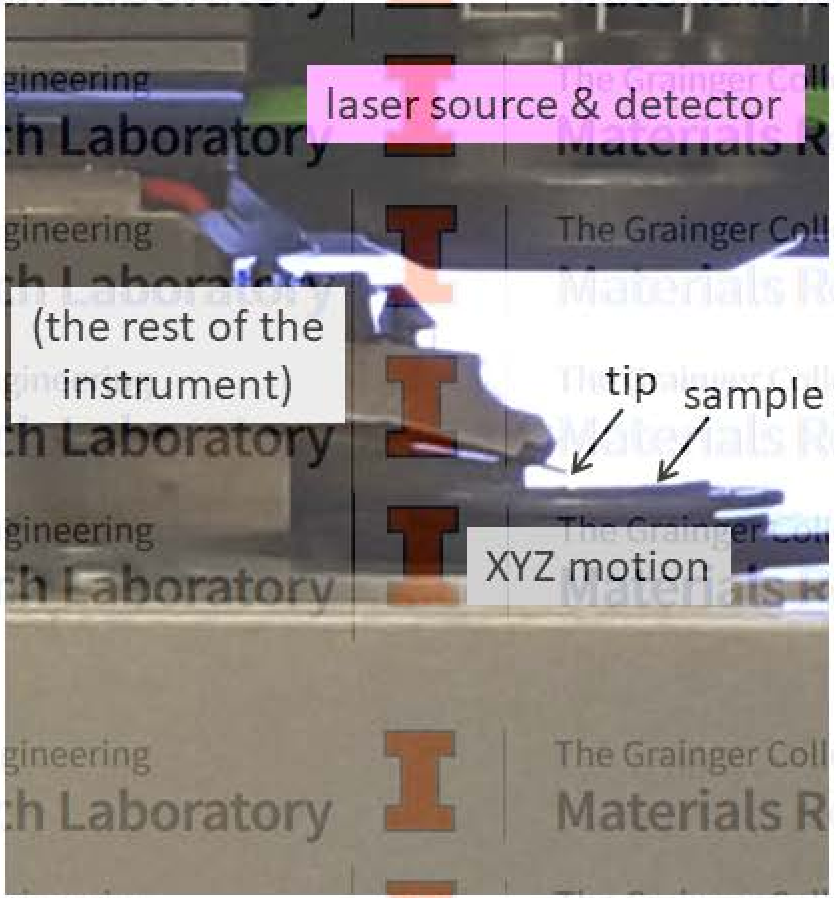
http://www.nanoandmore.com/ AFM-Probe-CP-PNP-SiO

"How long does a tip last?"

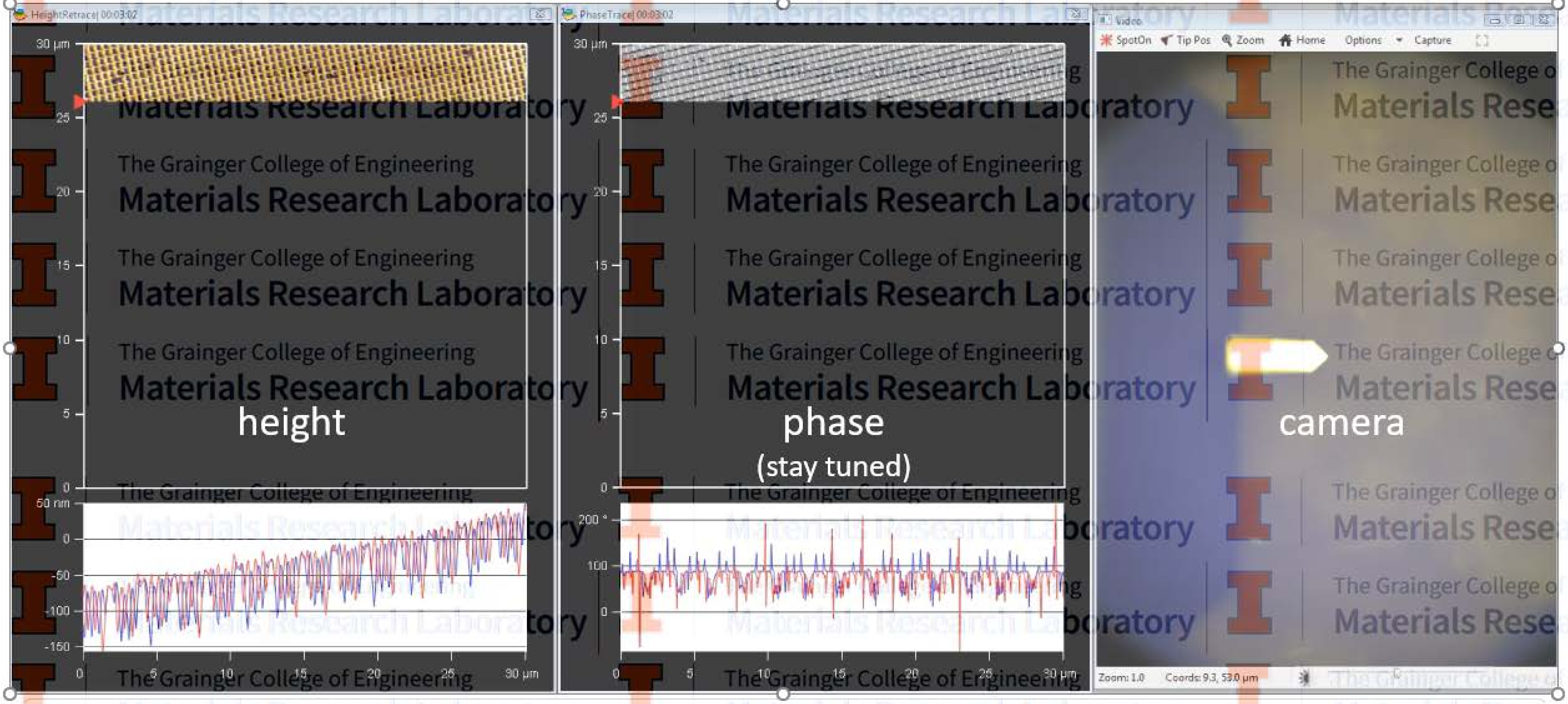
- Tips are consumables
  - Contamination from samples
  - Wear from samples
  - Dropping them
- Typical tapping mode tip ~$21
  - When your tip goes bad, just throw it out!
- Generally purchased in 10-packs
  - 50-packs to stock up
  - 5-packs for pricey tips

AFM Measurement Process

- Load sample and tip
- Scan
- Process image
- Extract numerical results (application-dependent)



Raster Scanning on the AFM



Feedback

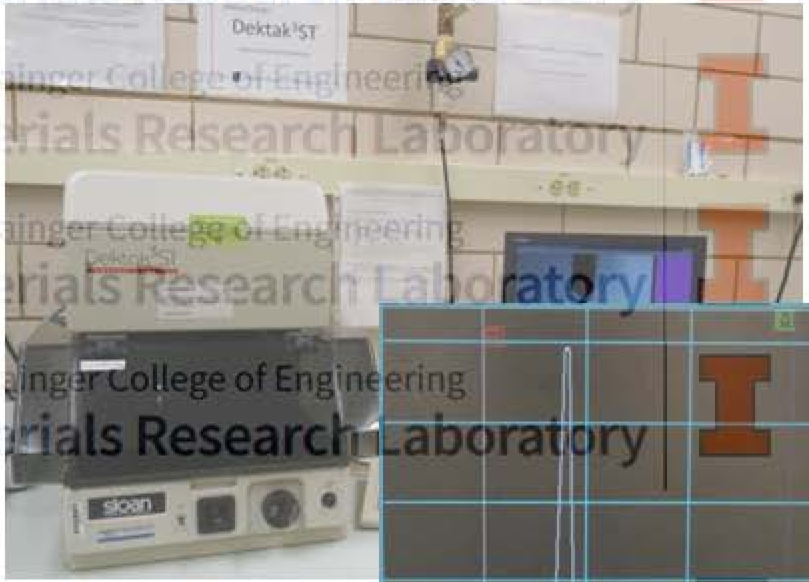
Feedback on the AFM

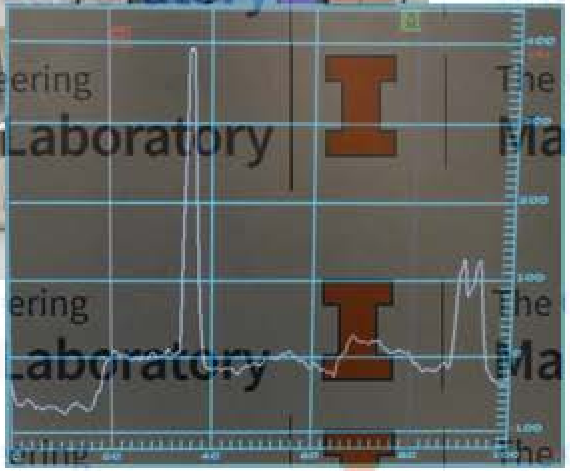
- Cantilever position adjusted to keep feedback signal equal to setpoint
  - too much force—move away
  - too little force—move closer

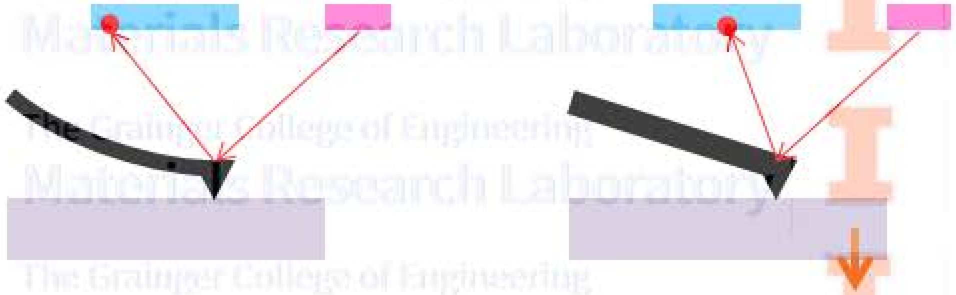
  atomic *force* microscopy
  - deflection for contact mode, usually amplitude for tapping mode
- Distance extended or retracted describes the height of the feature

Contact Mode Imaging

- Drag tip along surface like a stylus profilometer
- Feed back on the deflection (proportional to force)
- Adjust tip-sample separation to keep cantilever deflection constant





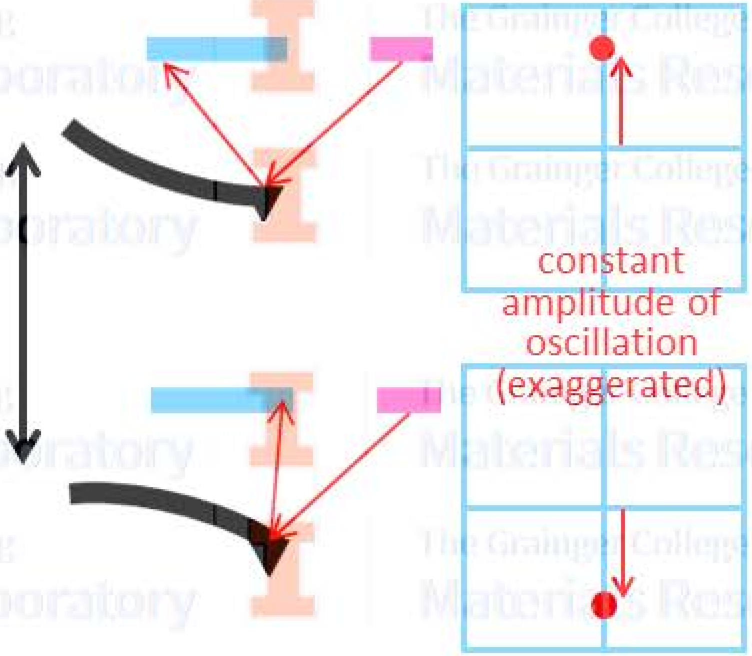


Tapping Mode Imaging

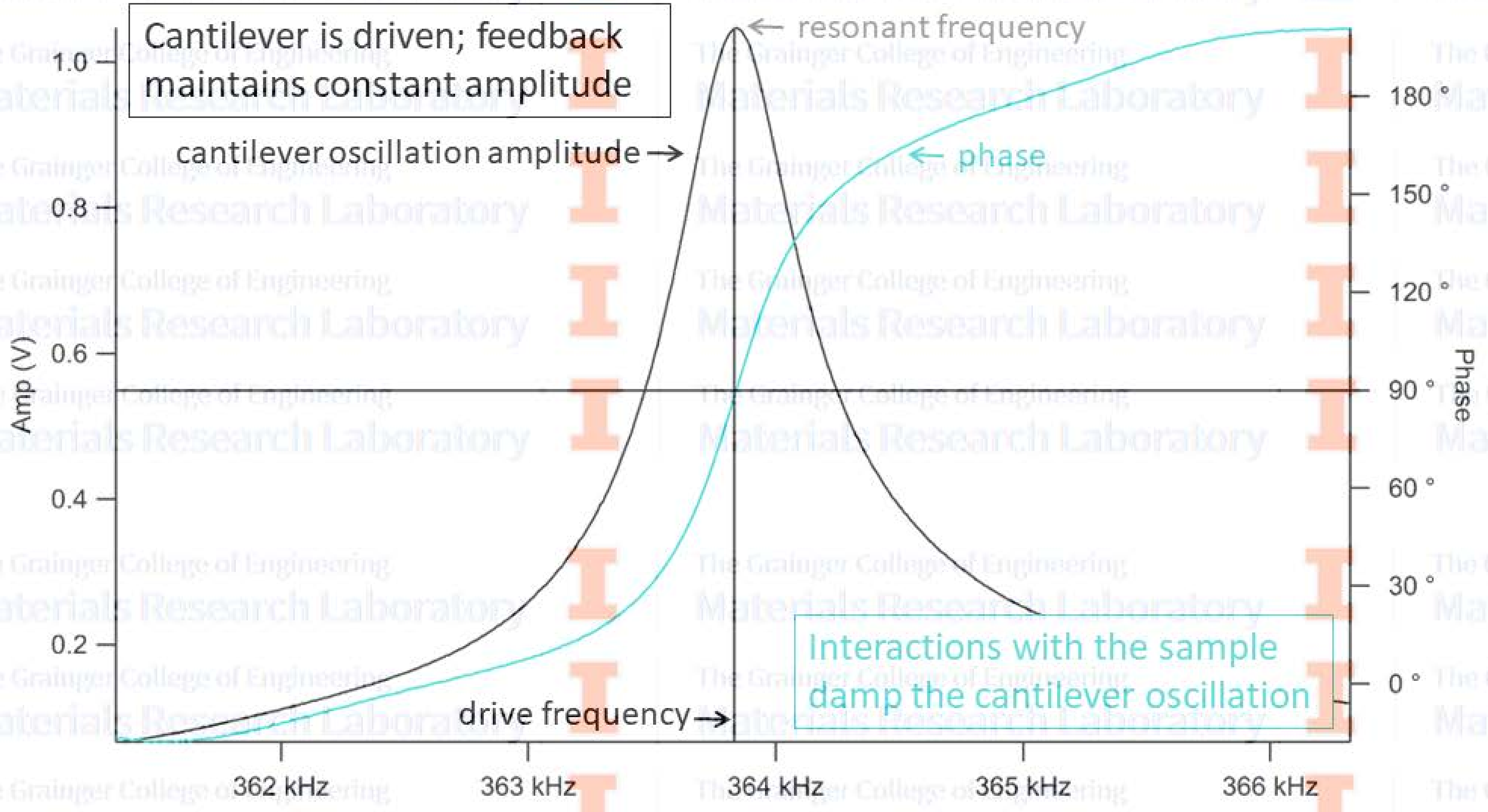
- Standard mode for AFM topography
- Tip is not constantly in contact with the surface
- Driven, oscillating cantilever
- Tip—sample interaction forces affect cantilever oscillation
- Tapping, AC, TappingMode™, amplitude modulation*, intermittent contact*, non-contact*

* specific meaning

tip oscillates at tens of kHz to MHz

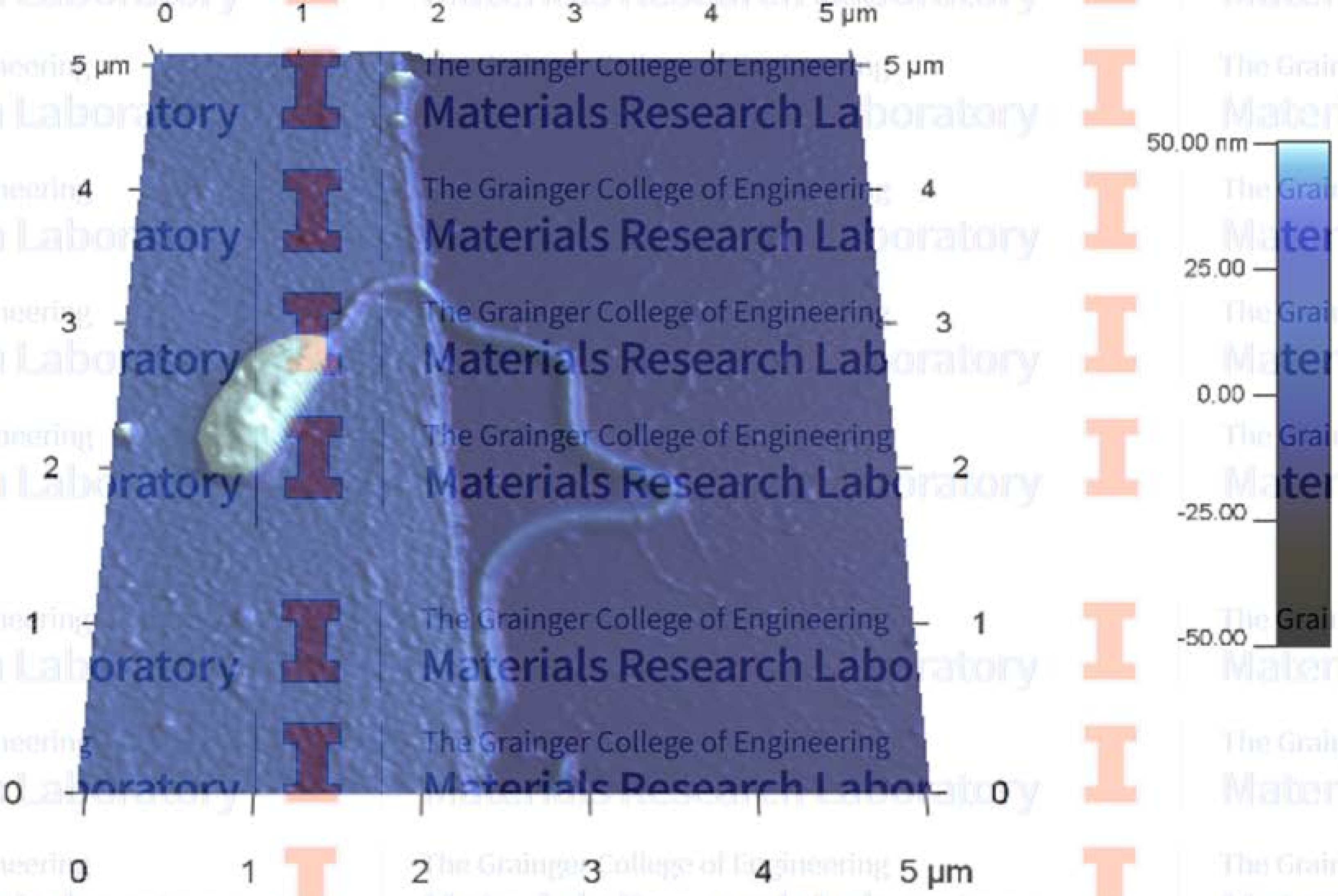


Driven, Damped Harmonic Oscillator



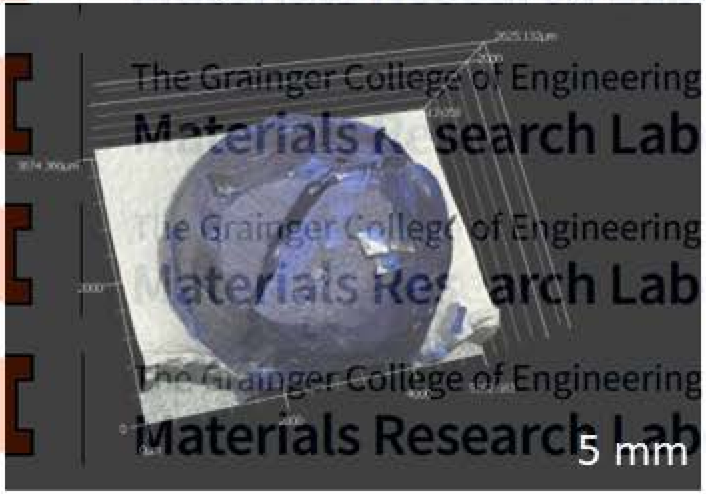
Application: Imaging

Cell on
gold electrode
on SiO2



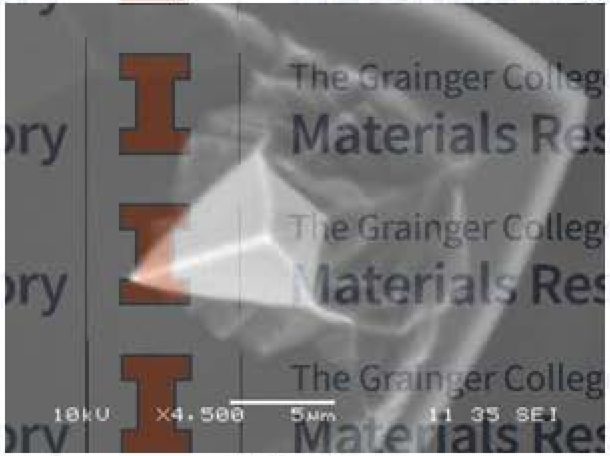
Complementary Techniques: Imaging

3D Optical Profilometry



blue glitter crayon tip

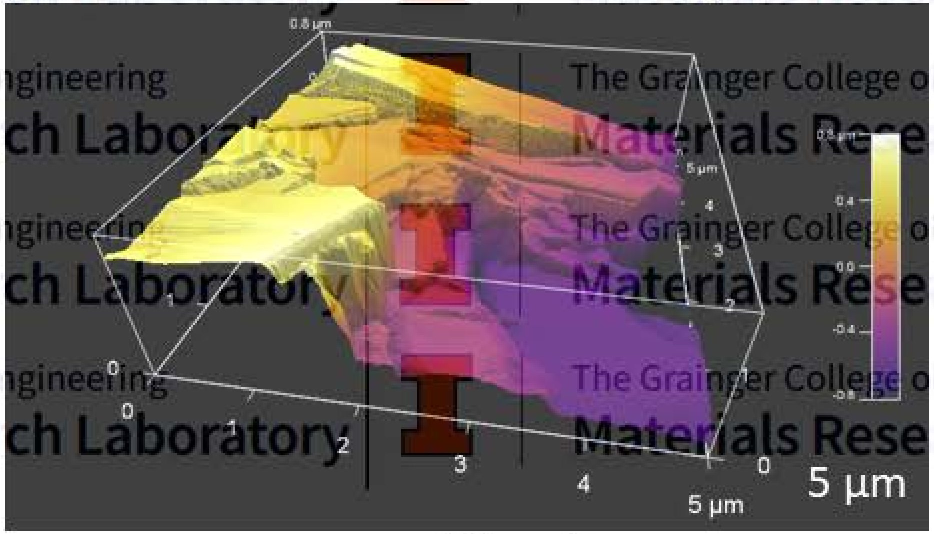
Scanning Electron Microscopy



AFM tip

(quantitative height measurements are trickier)

Atomic Force Microscopy



pencil “lead”

Optical characterization tutorial earlier this morning

Roughness measurements by 3D optical profilometry **today, 1pm**

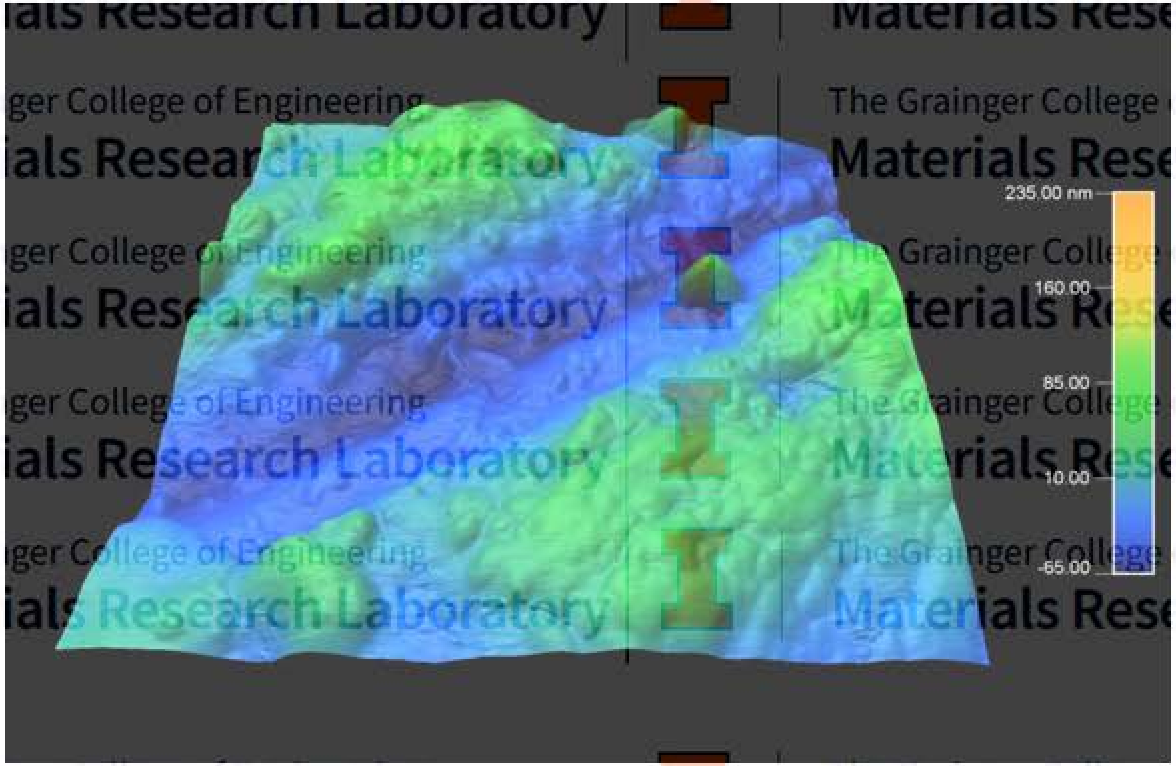
SEM tutorial **tomorrow, 9am**

Advanced AFM applications **today, 3pm**

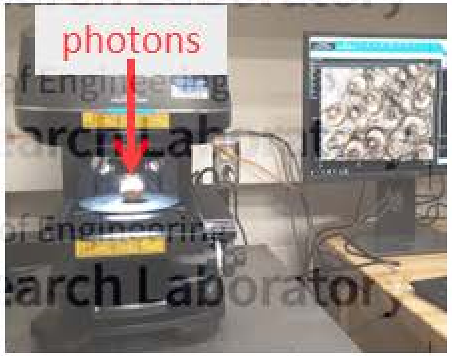
AFM and 3D Optical Profilometry

Similar applications to 3D optical profilometry, but...

- Far better resolution
- Samples can be truly transparent
- No index of refraction effects
- Can't "zoom out" to get low-magnification images



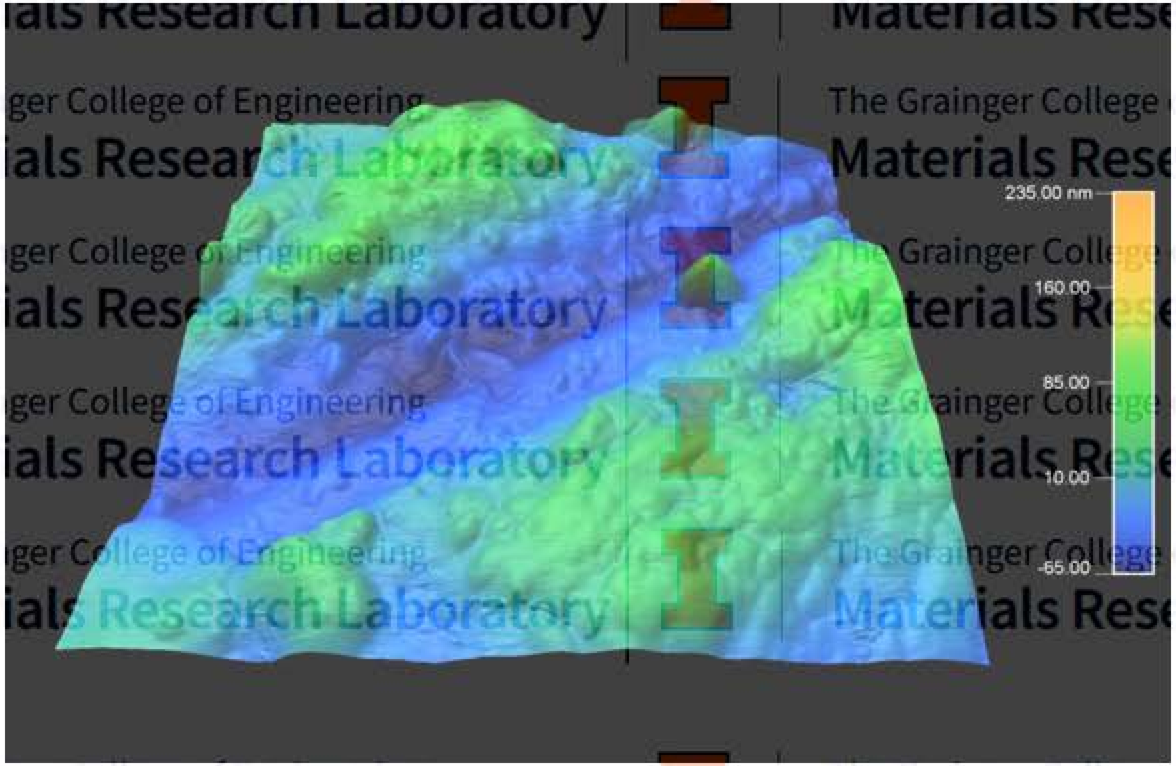
Turquoise, 1µm x 1µm AFM topograph
(false color, true Z:XY ratio in 3D)



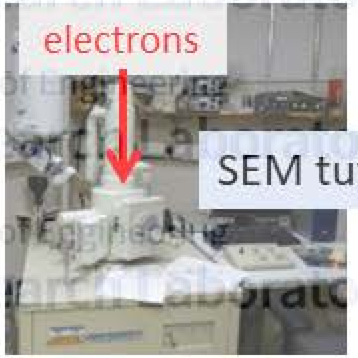
AFM and SEM

Similar applications to SEM, but...

- Easily measure true depths/heights
- Samples do not need to be electrically conductive
- Can be done in air, in liquids, in vacuum/inert gas
- Can't "zoom out" to get low-magnification images

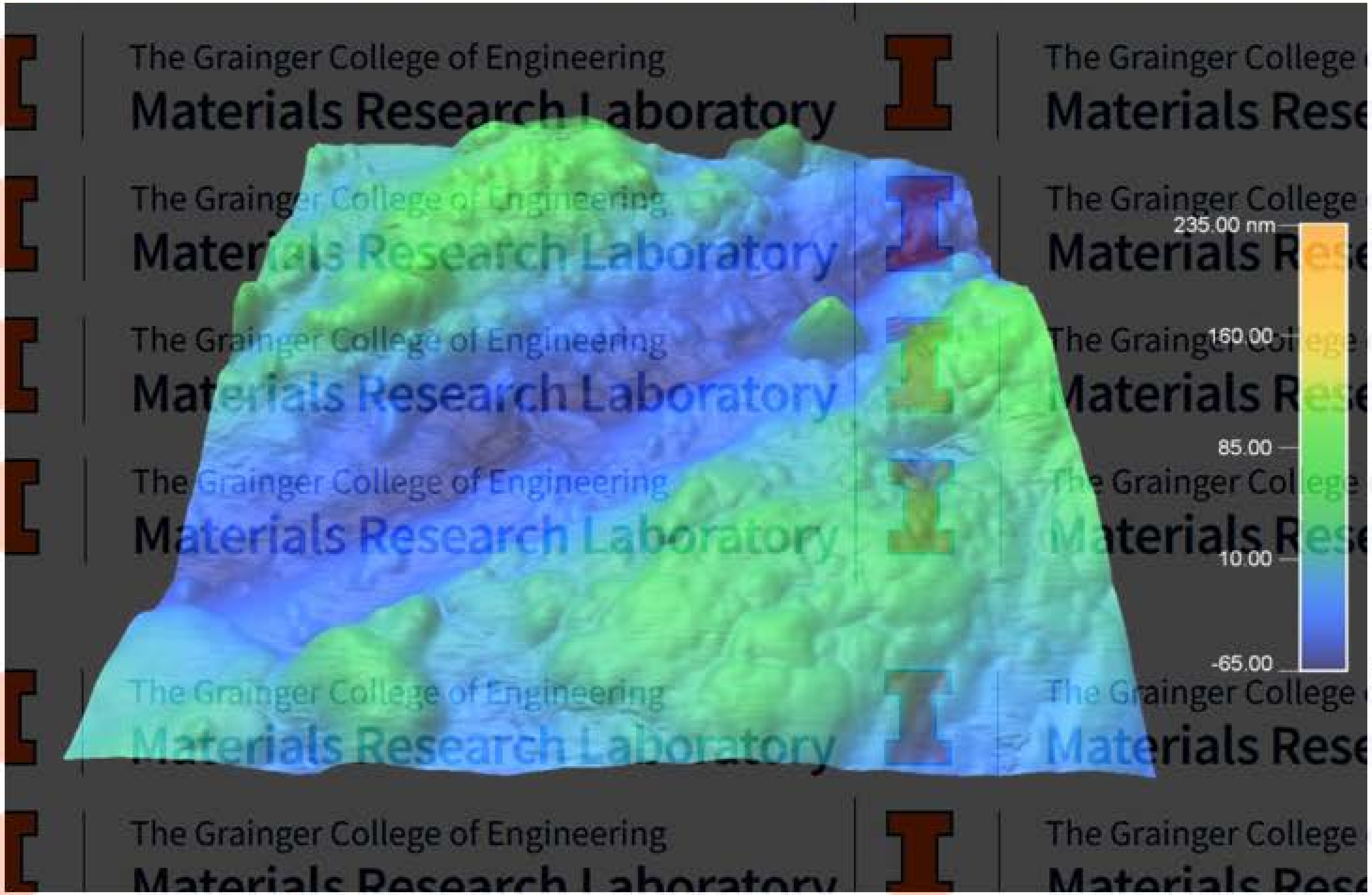


Turquoise, 1µm x 1µm AFM topograph
(false color, true Z:XY ratio in 3D)



SEM tutorial **tomorrow, 9am**

Interpreting Height Colorscales

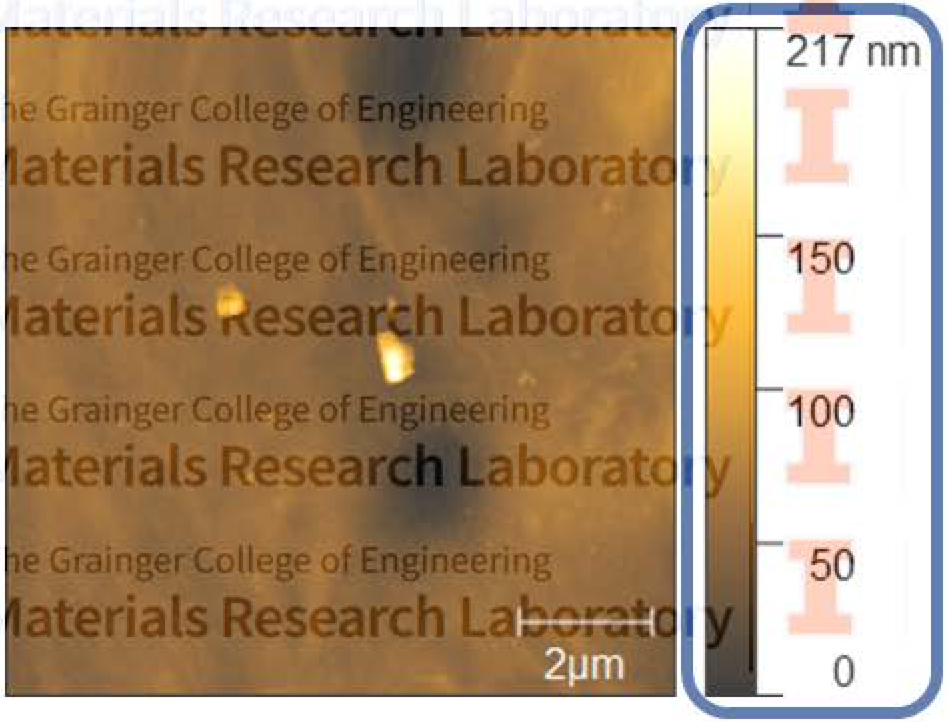


Turquoise, 1μm x 1μm AFM topography (false color, correct apparent height)

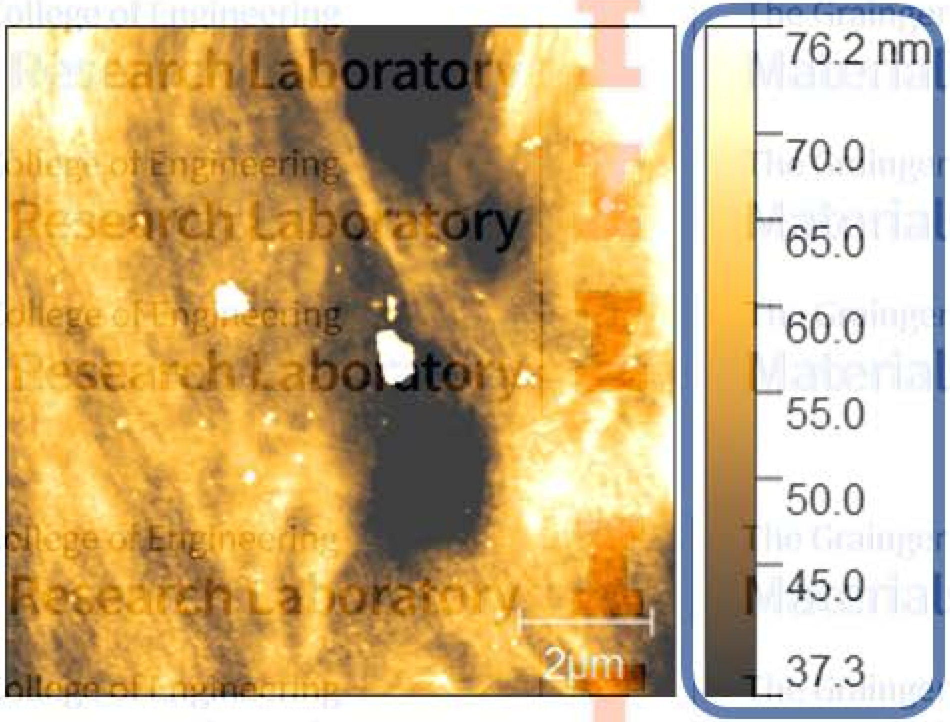
range of colors in the scale,
not necessarily heights in the image

- Some colors may not have corresponding heights
- Some heights may not have corresponding colors

Interpreting Height Colorscales



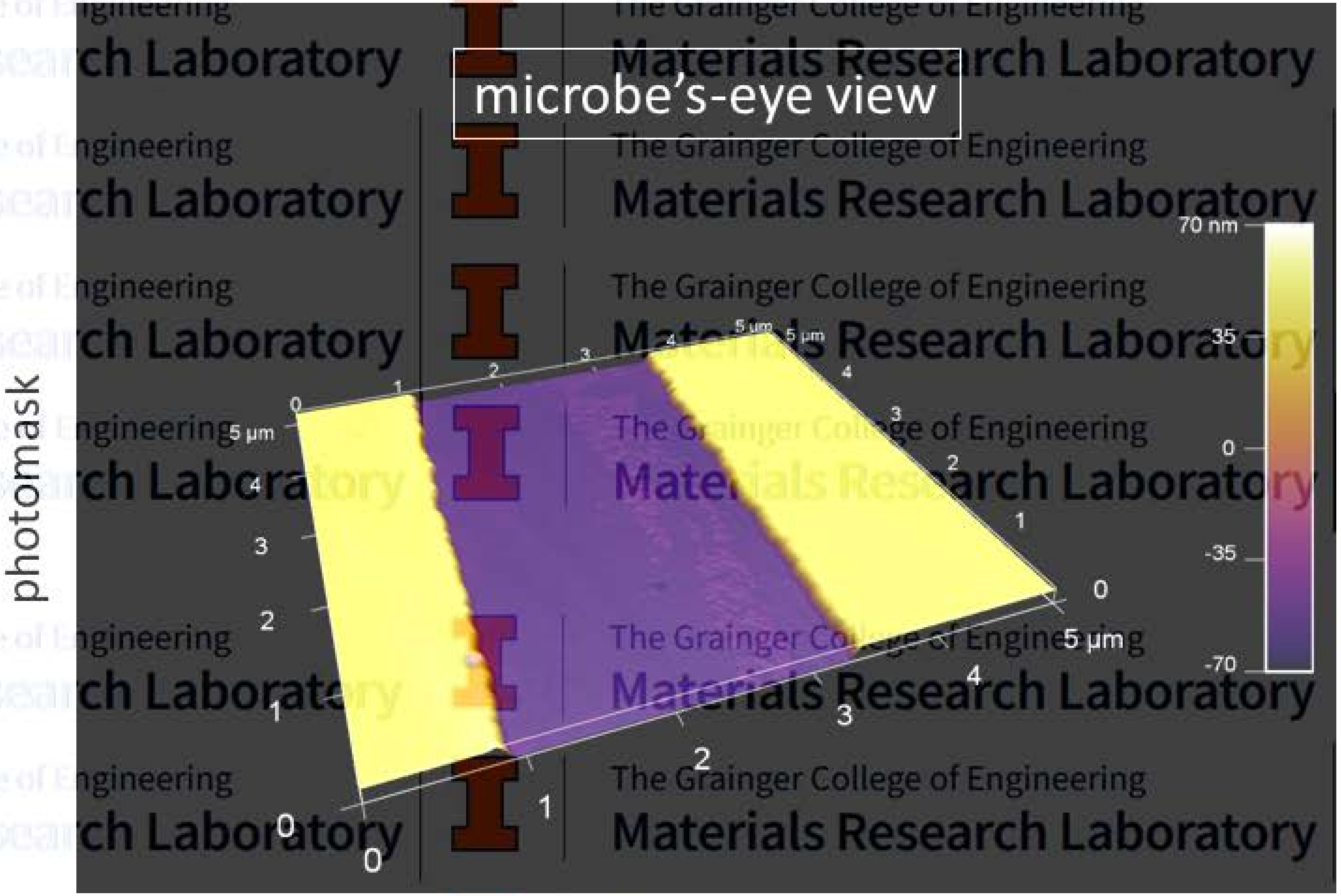
same image, different color ranges



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

polymer blend, 10μm x 10μm AFM topograph (false color)
processed using Gwyddion data analysis software

Interpreting 3D Images

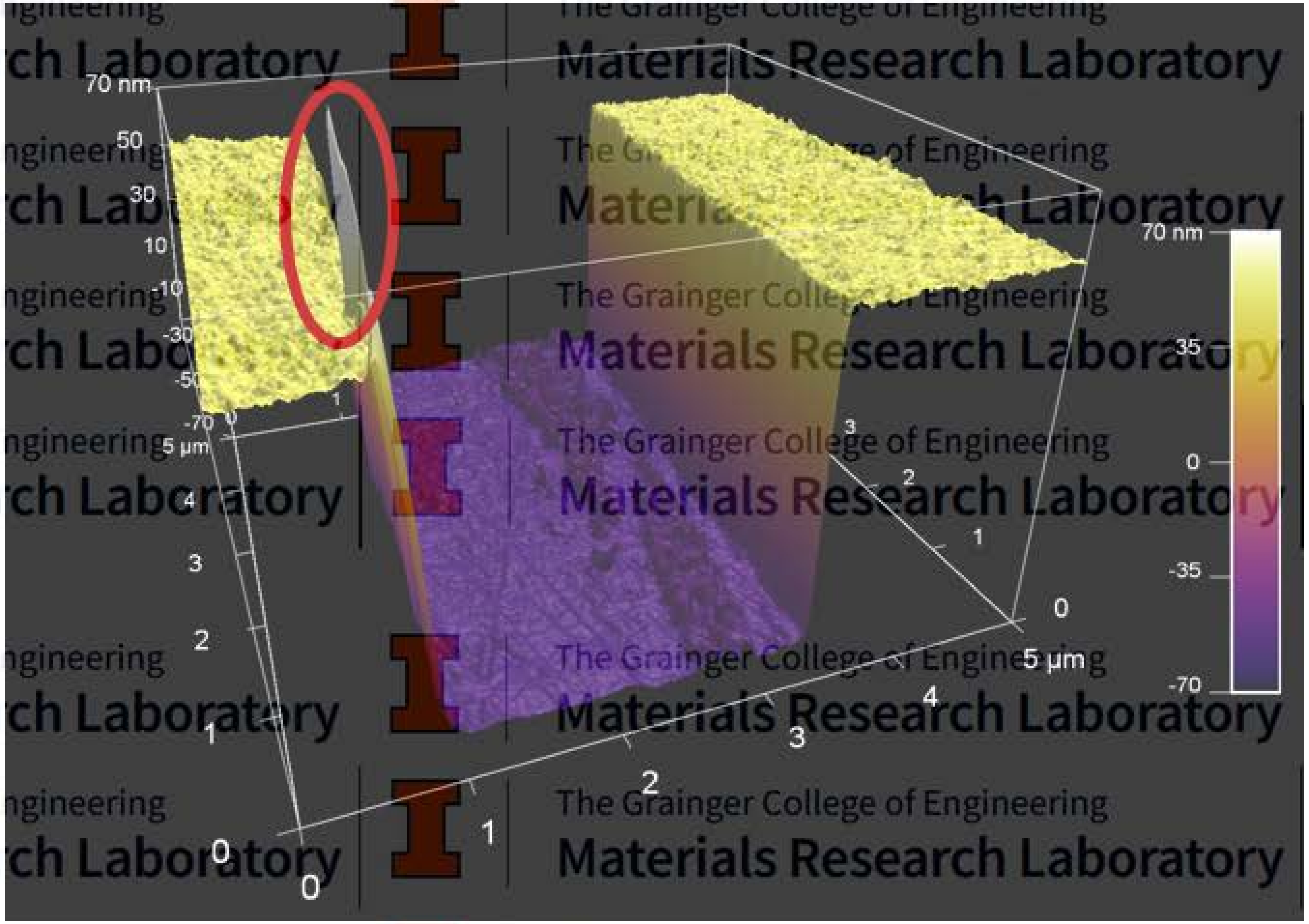


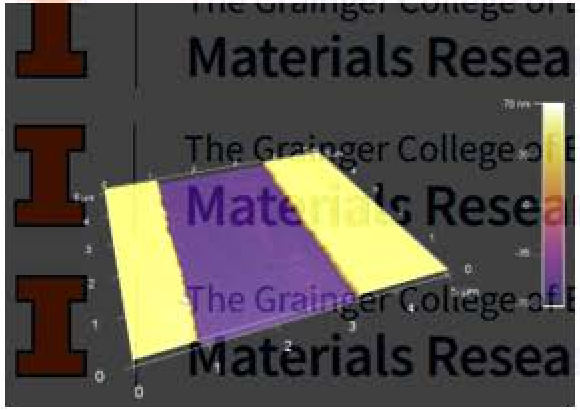
Interpreting 3D Images

not necessarily 1:1:1 Z:X:Y

Z often exaggerated compared to XY to **convey texture information**

photomask



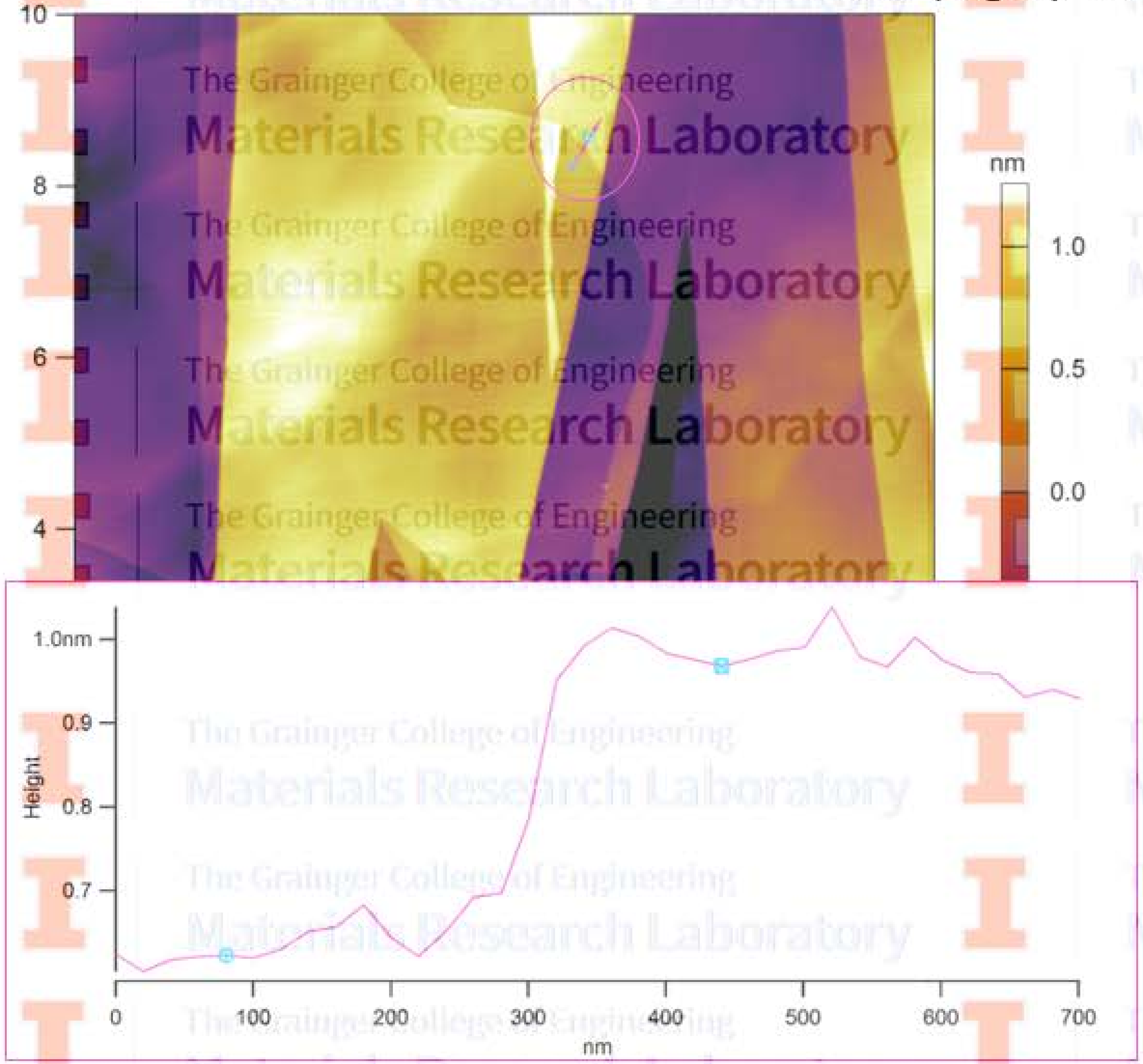


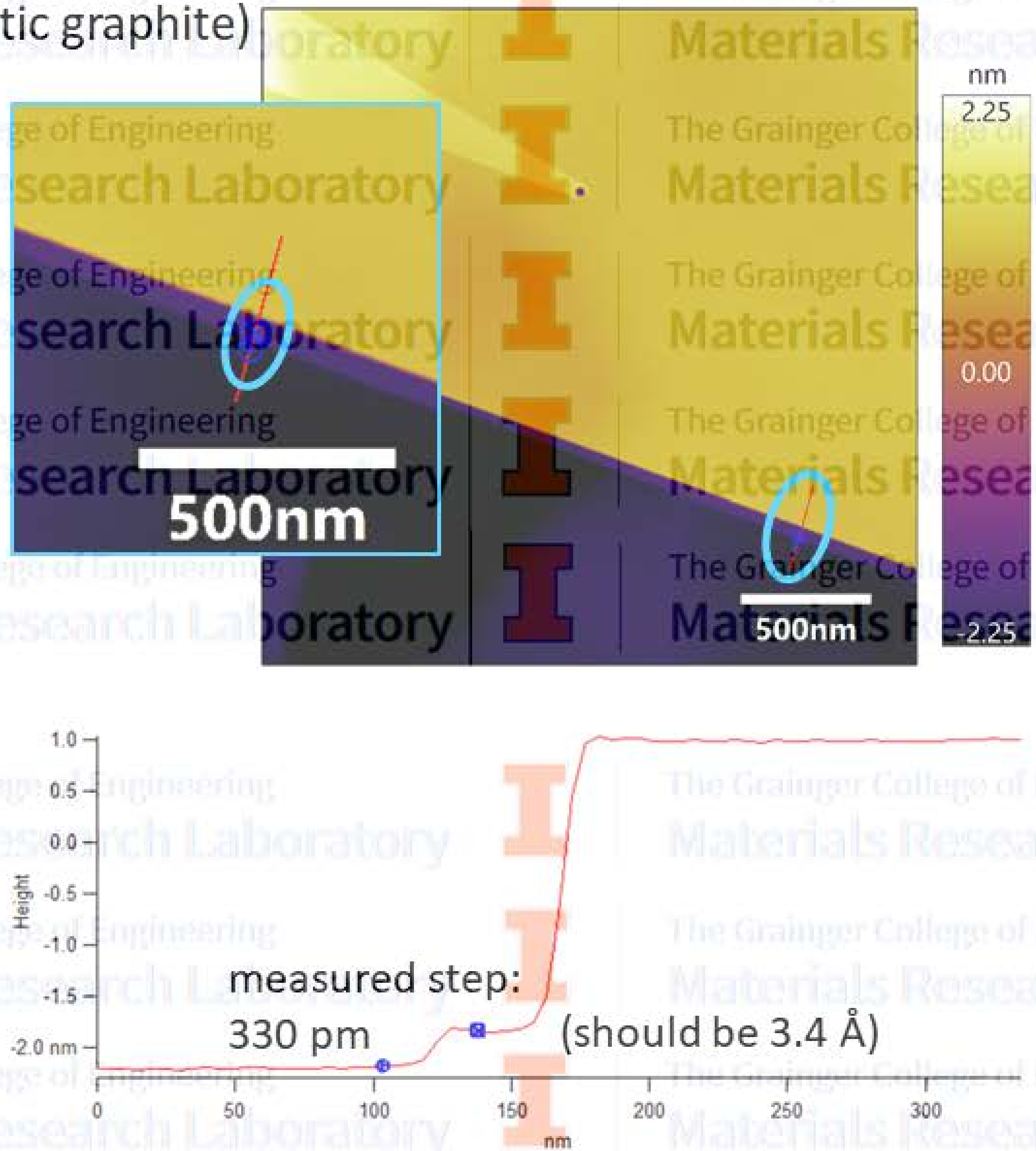
Measuring Surface Topography: Step Heights

- AFM measures relative heights
  - Need a height difference
  - There is no “sea level” equivalent
  - Can only see the tops of surfaces
- 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

Application: Step Heights

HOPG (highly oriented pyrolytic graphite)





Complementary Techniques: Step Height/Film Thickness

If your step's too broad for the AFM (continuous film or with a step edge width >~80um), try…

- Stylus profilometry
- 3D optical profilometry

Need a height difference (step) like AFM

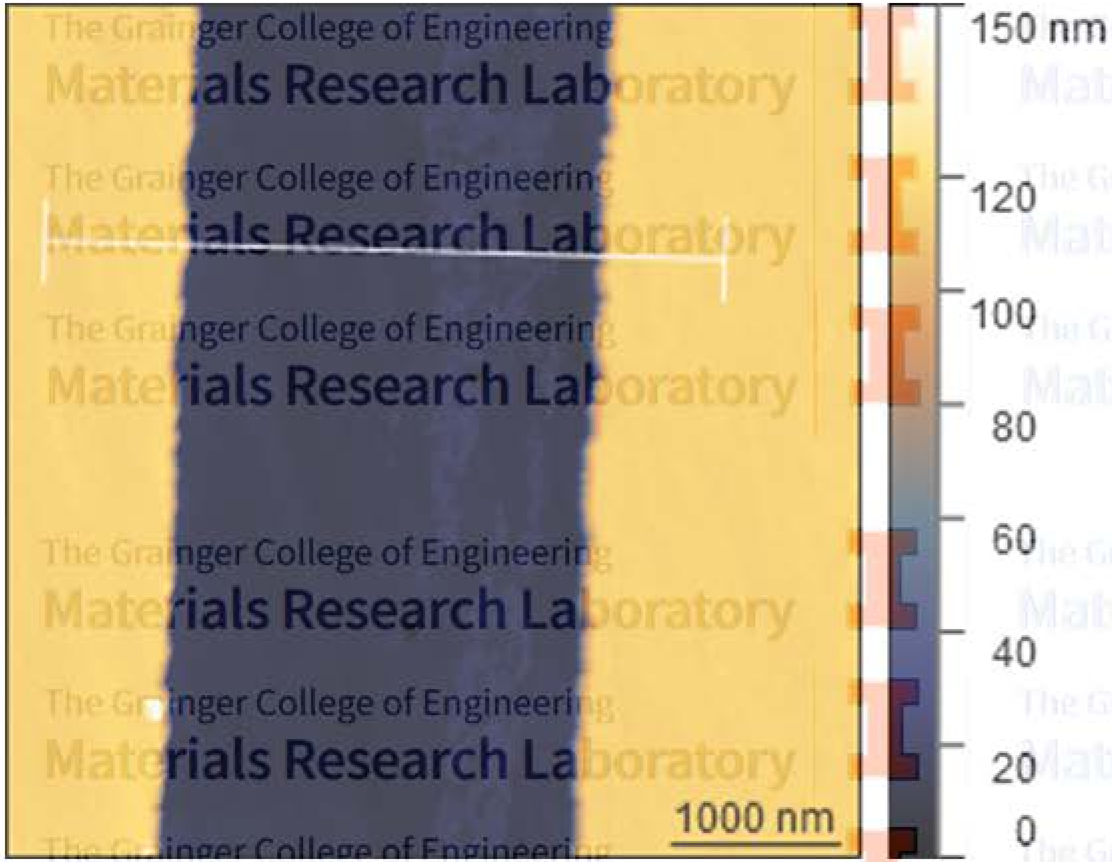
- X-ray Reflectivity (XRR)
- Rutherford Backscattering Spectrometry (RBS)

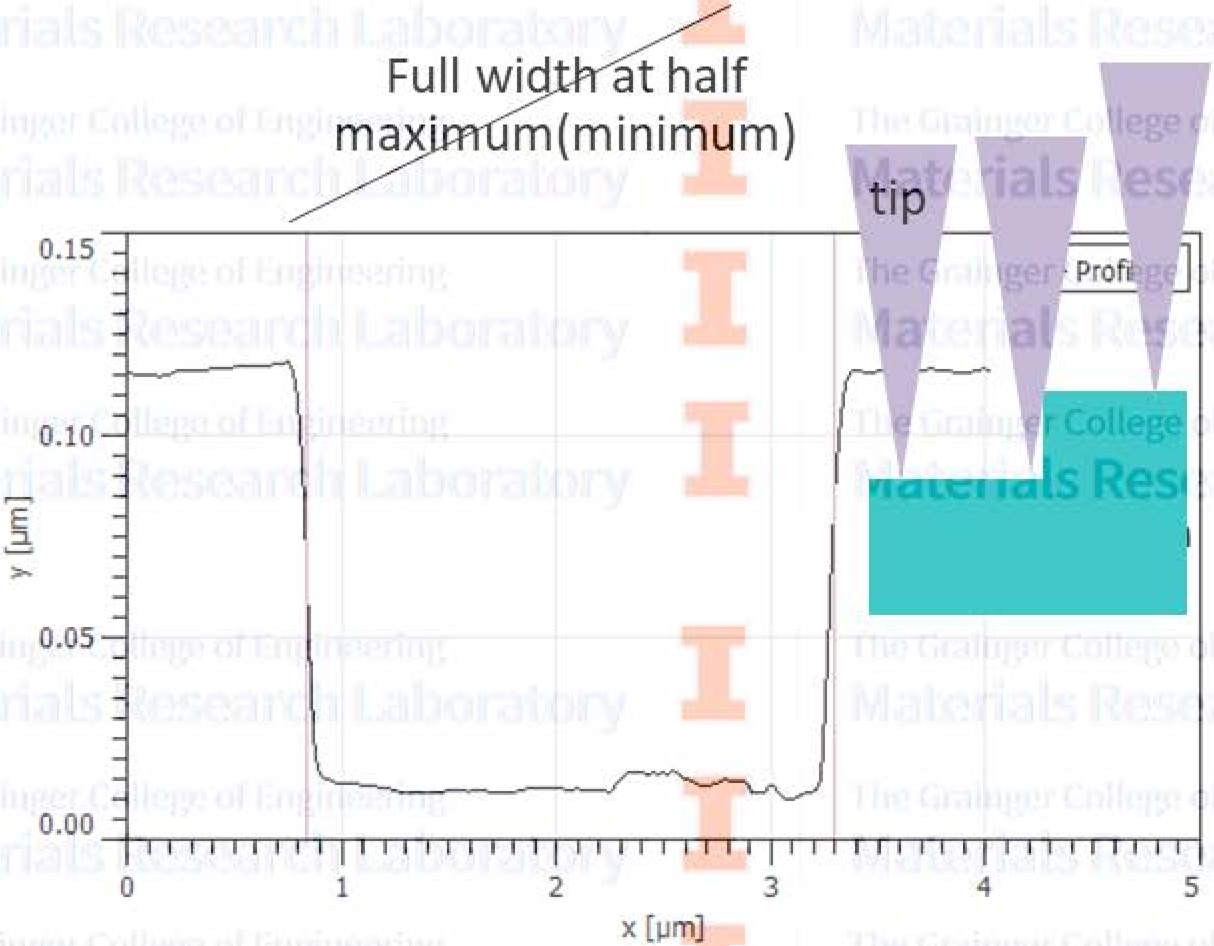
Continuous film (no steps)
May need to know other parameters

X-ray analysis tutorial **today, 4pm**

RBS tutorial **tomorrow, 8:30am**

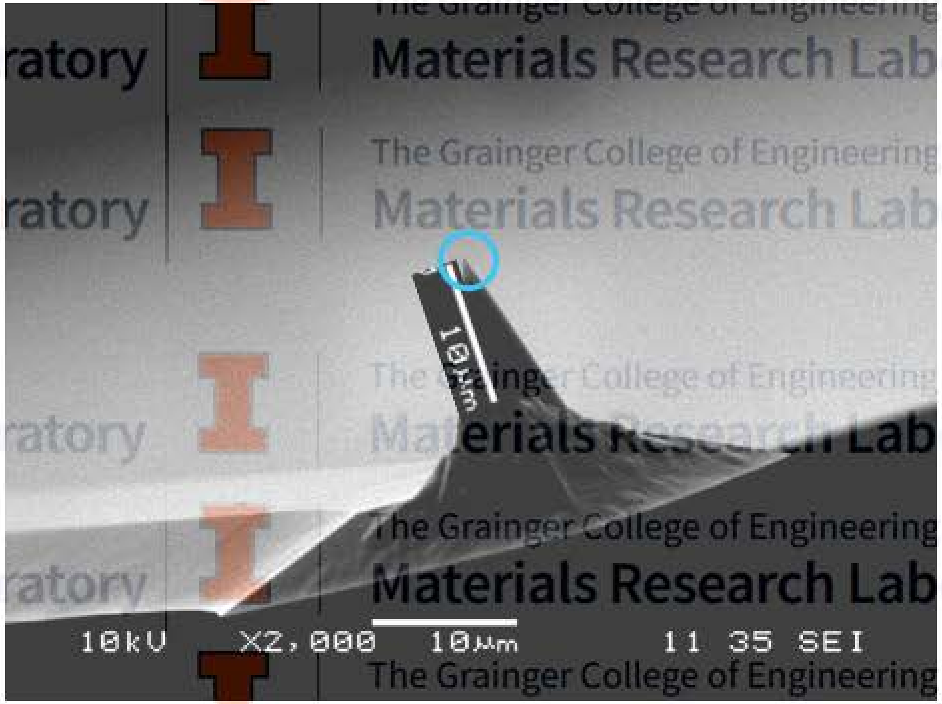
Step Heights and Widths





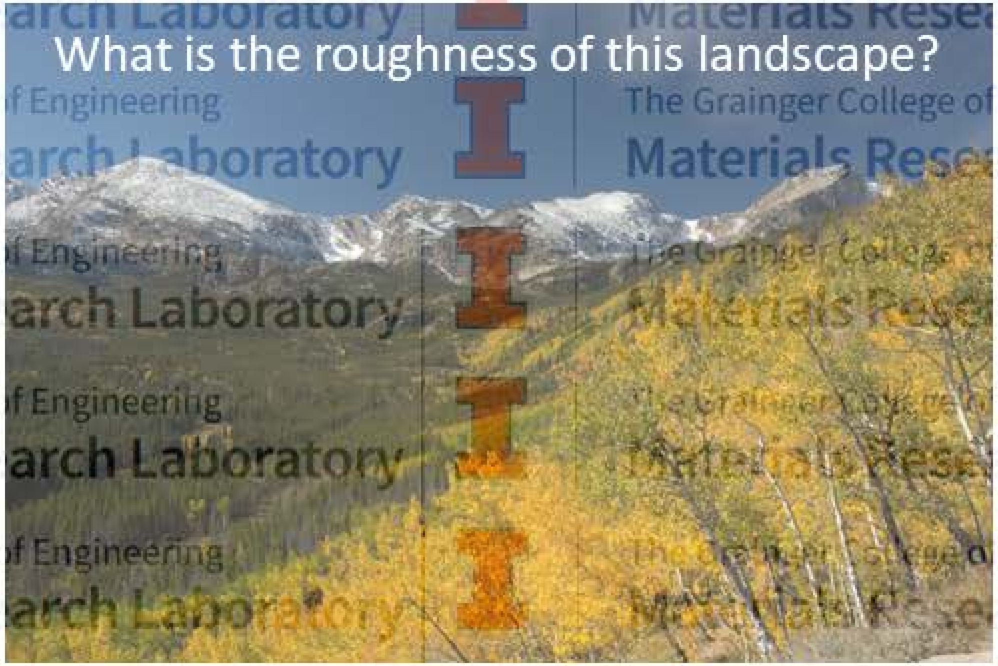
Step Heights and Widths

- 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
  - Stylus profilometry
  - 3D optical profilometry
- AFM probes nanoscale roughness
  - Not always a predictor of macroscale roughness
  - Peak-to-valley height must be within the instrument range (typically < a few µm)



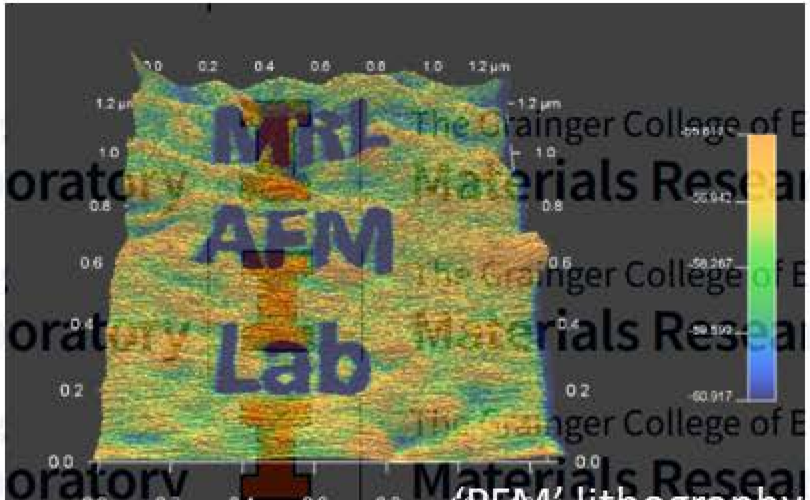
Michael Jeffords and Susan Post
University of Illinois Prairie Research Institute
https://photojournalingm-s.smugmug.com/Colorado-and-Kansas/i-3tJ3DZk/A

Beyond Surface XYZ Coordinates

- Tip-sample interaction forces come from various sources, not just contact
  - Electrostatic
  - Magnetic
  - Chemical
  - Optical
- AFM-level resolution of sample properties besides topography
  - Often in the couple 10s of nm lateral resolution
- Correlative measurements: in the same location, AFM topography + …

Application: Electromagnetic Characterization

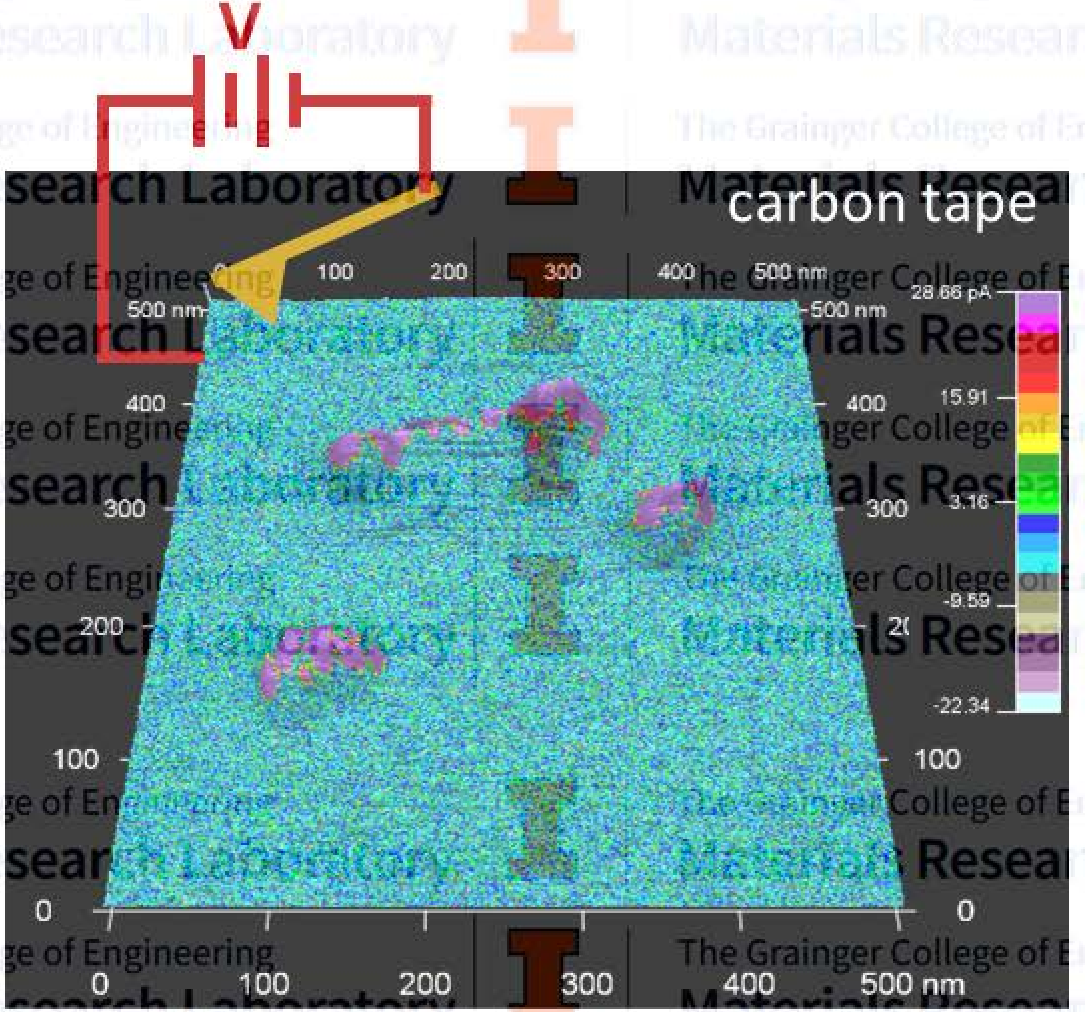
- *Conductive AFM*
  - Scan at fixed or varying bias, measure current
    - I—V curves
- *Magnetic Force Microscopy*
- Piezoresponse Force Microscopy
- Electrostatic Force Microscopy
- Kelvin Probe Force Microscopy
- Scanning Microwave Impedance Microscopy
- and more, many more…



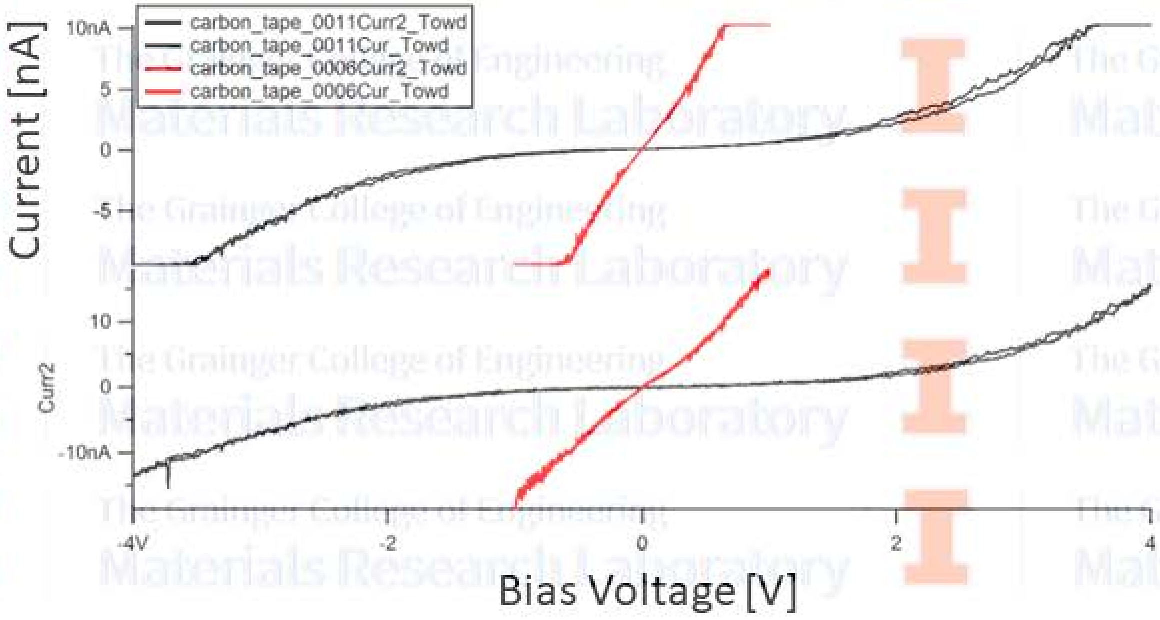
'PFM' lithography

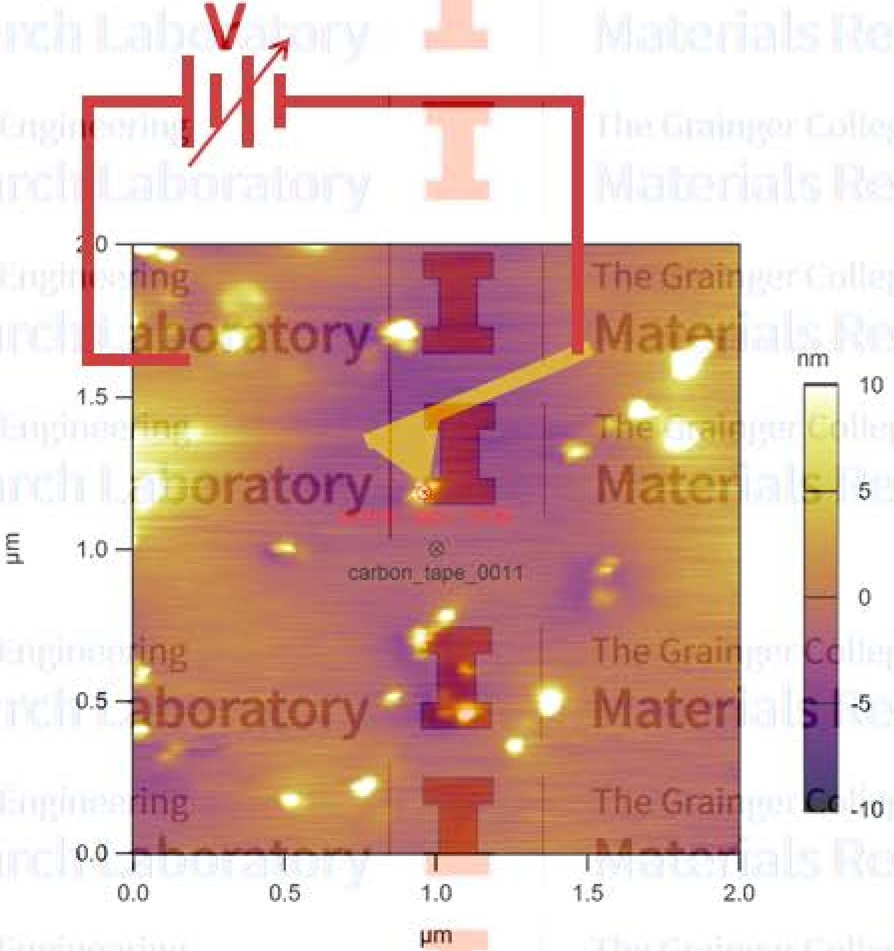
Application: Conductive AFM

- Measure electrical conductivity of sample
  - Use conductively coated tip as an electrical probe
  - Caveat: contact resistance
- Transverse conductivity through a sample
  - Bias sample substrate
  - Scan in contact mode
  - Conductive/insulating areas
- Need a conductive pathway
  - OK – insulators in conductors
  - Won't work – conductors in insulators (conductors *on* insulators may work)



I—V Curves





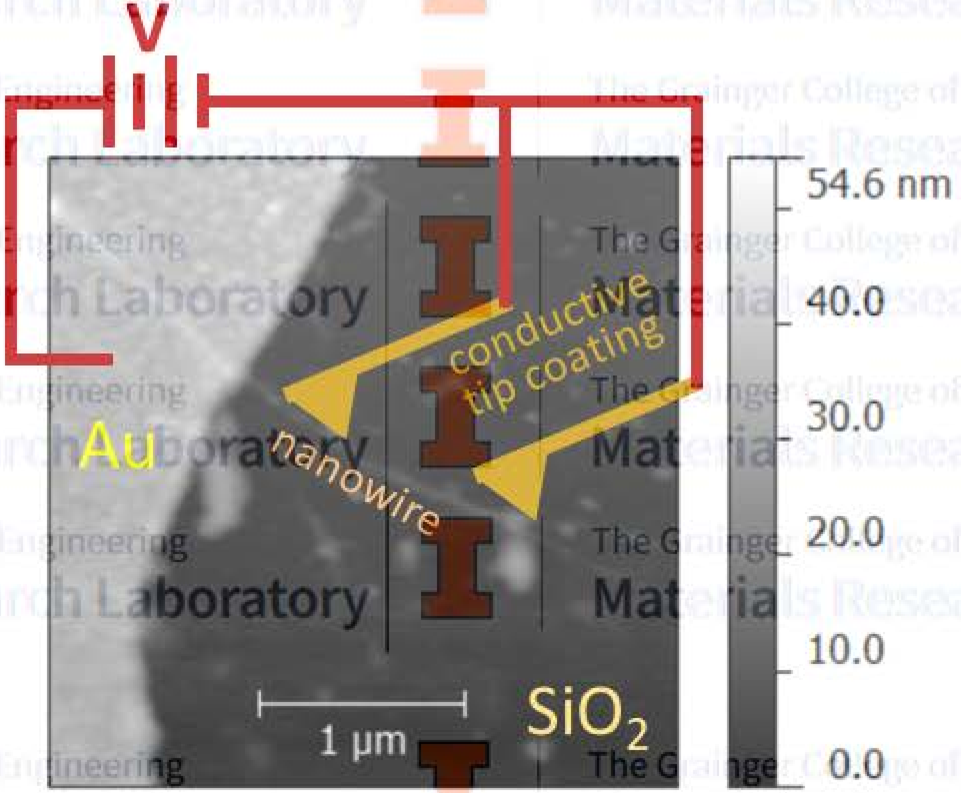
I—V curves on carbon tape

Asylum Cypher AFM

(carbon tape's pretty conductive)

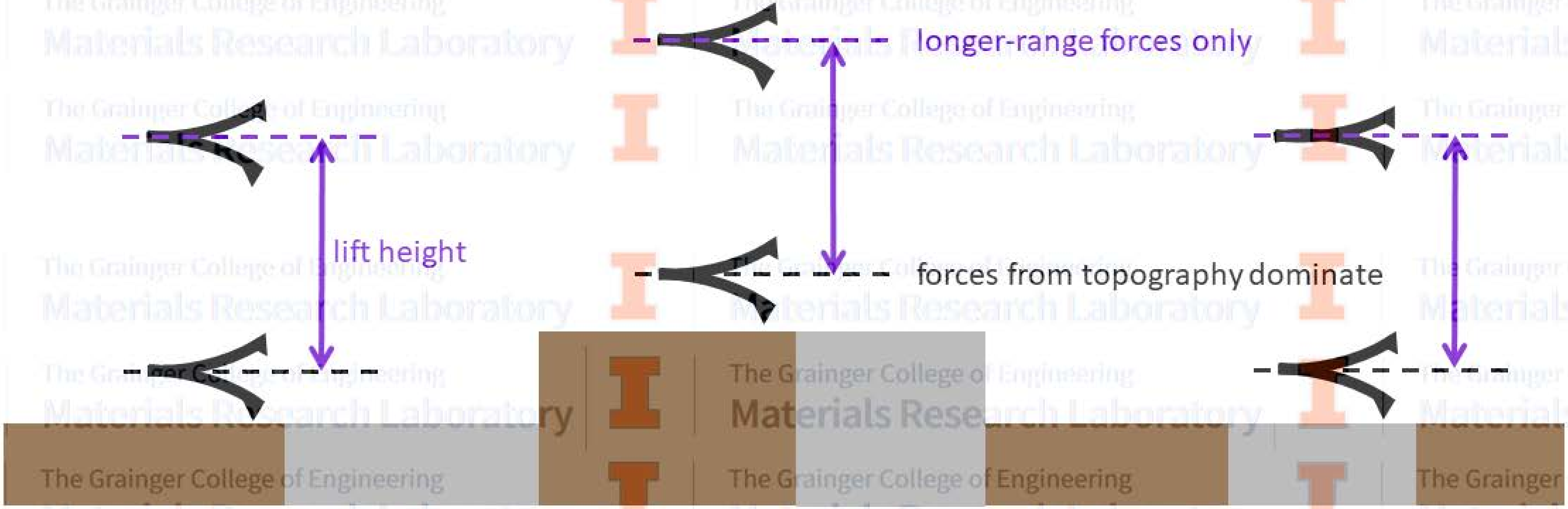
Conductive AFM

- Longitudinal (two-point) conductivity along sample
  - I—V curves
  - Sample (*e.g.*, nanowire) on insulating surface
  - One end of sample on a biased electrode
  - Conductive AFM tip as movable other electrode
- Caveat: contact resistance



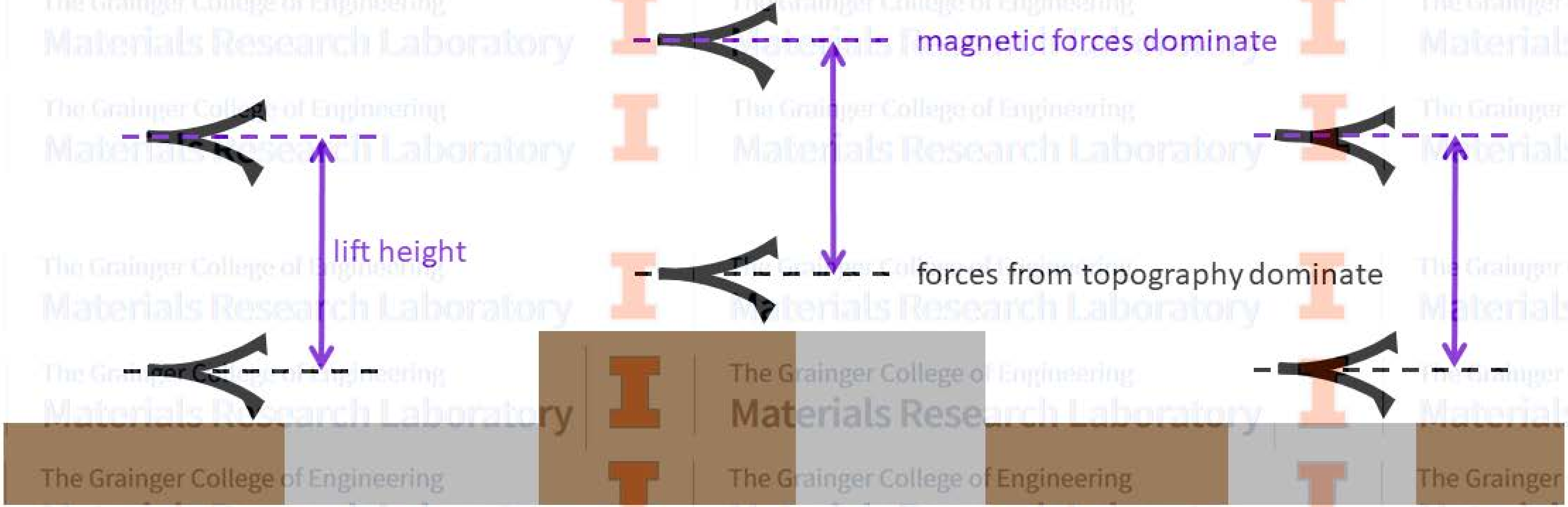
Two-Pass Techniques

- Interleaved—topography, other signal
- Image a line, then repeat that line raised by a few tens/hundreds of nm
- Long-range (non-topographic) forces between the tip and sample affect the cantilever

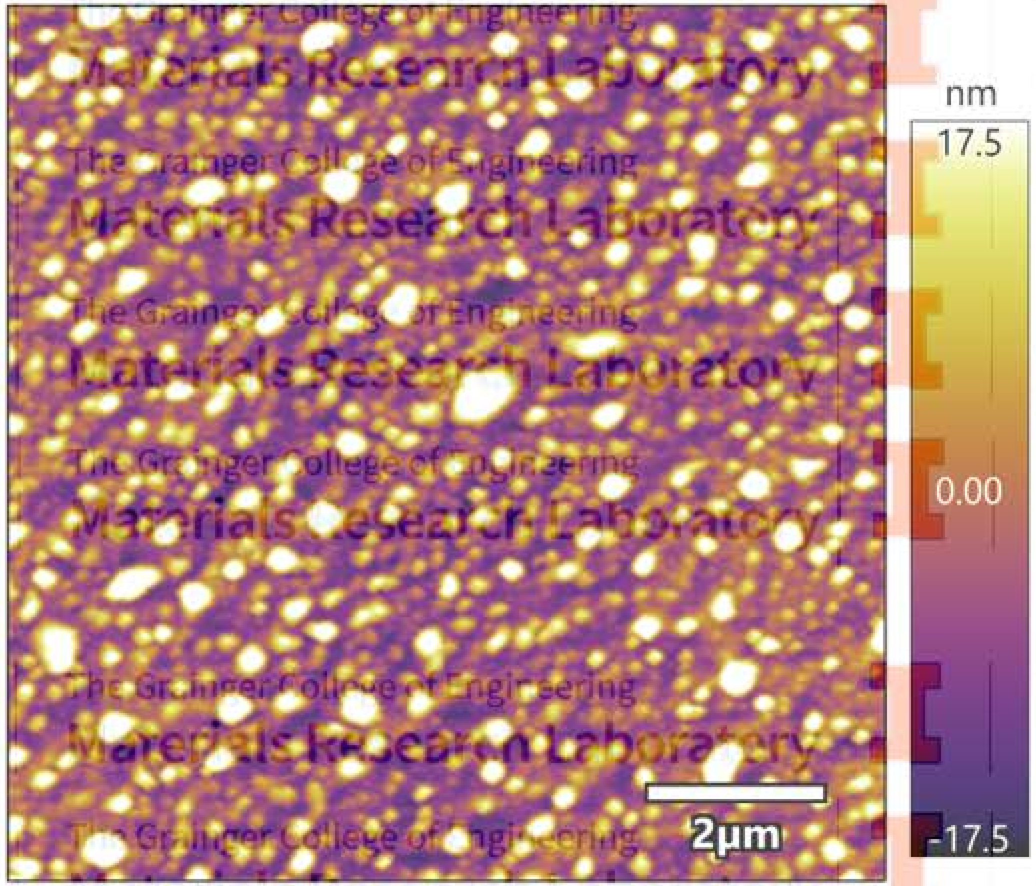


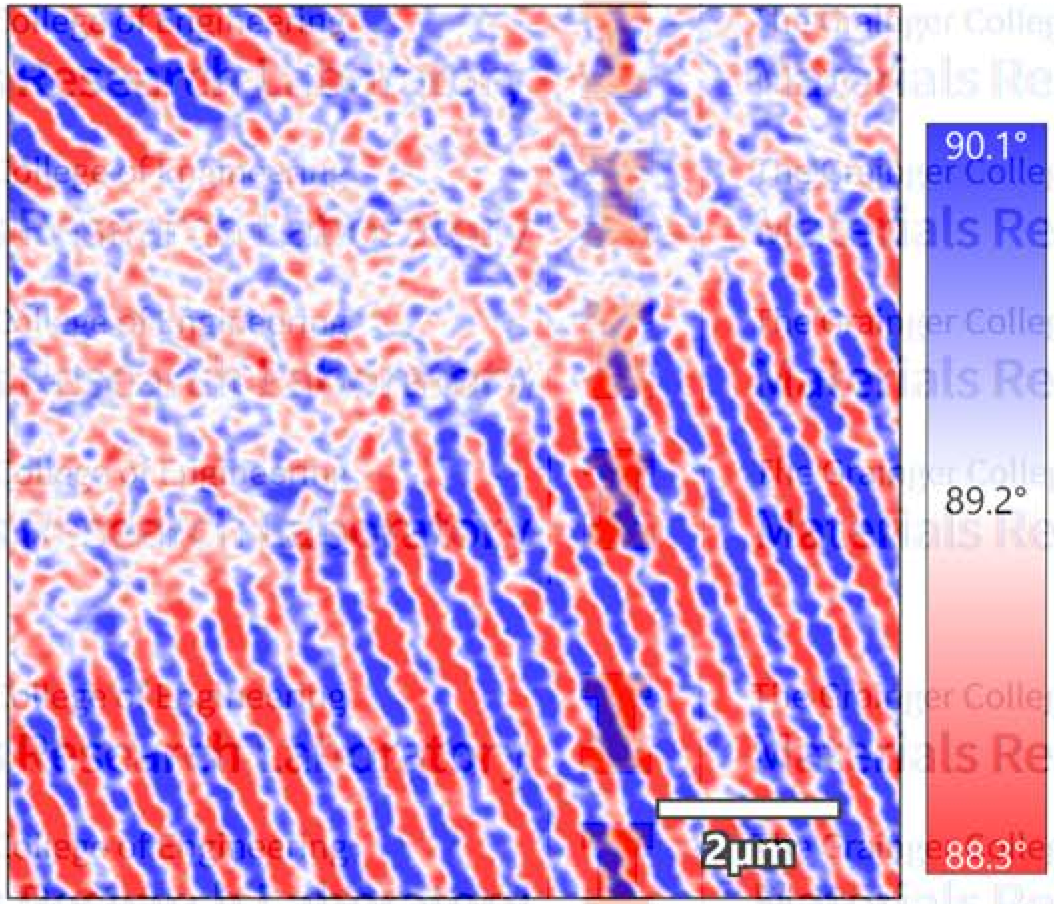
Magnetic Force Microscopy

- Tip coated with a magnetic material, then magnetized
- Magnetic forces from the sample attract or repel the tip

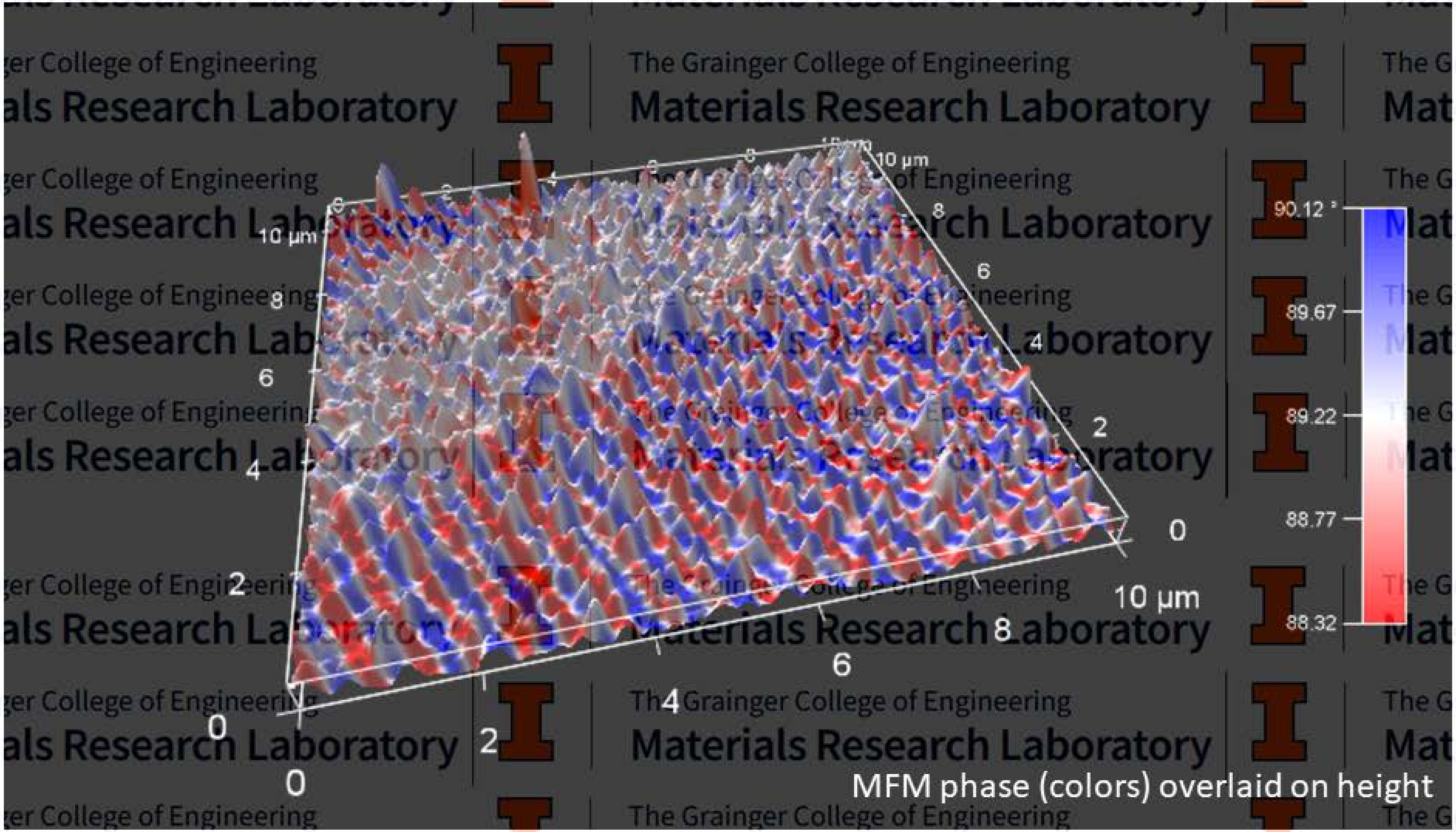


Magnetic Force Microscopy

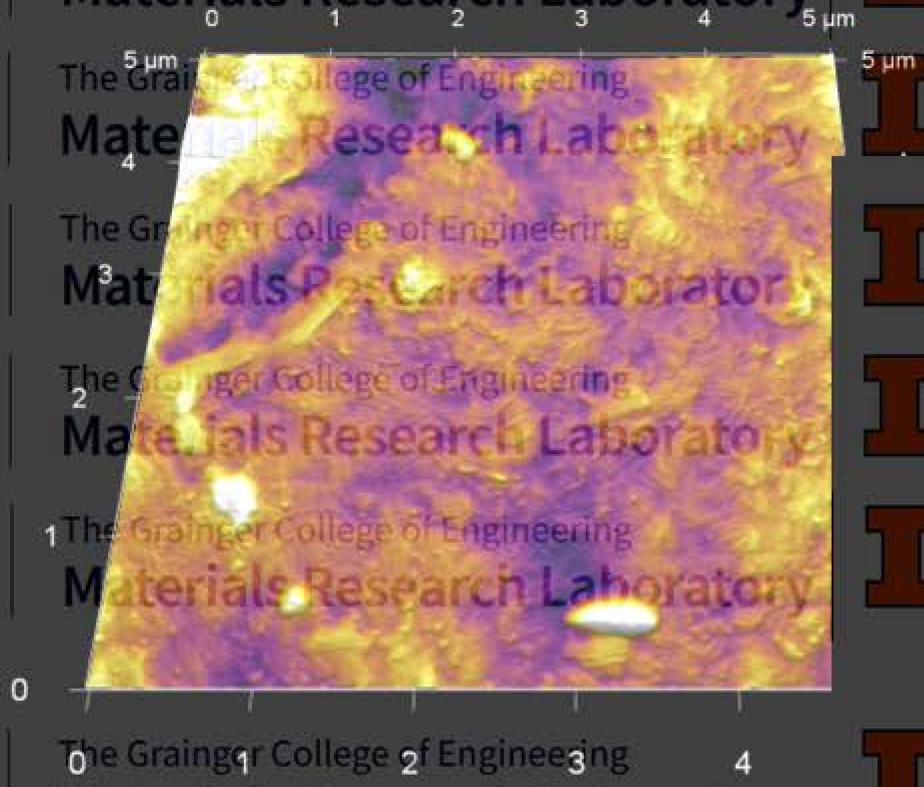




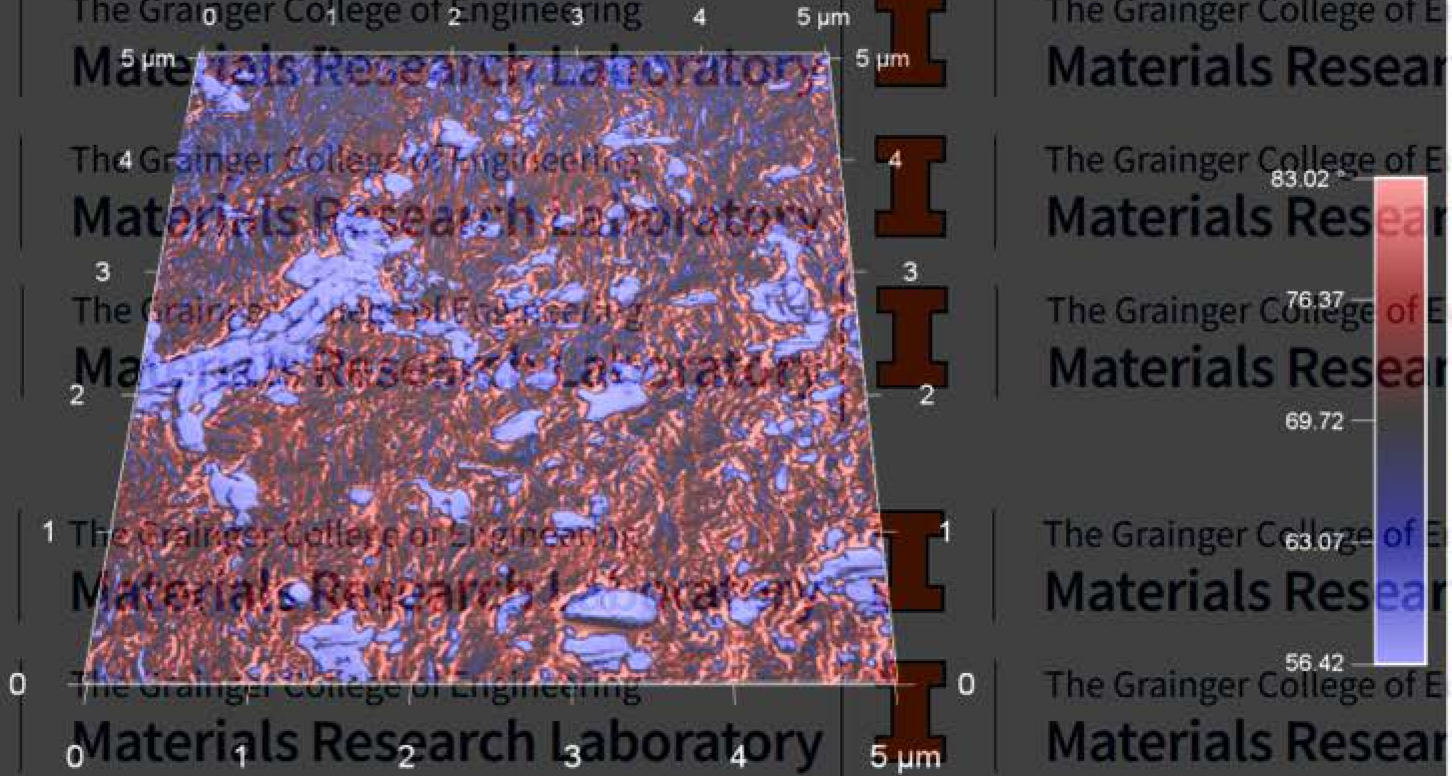
Magnetic Force Microscopy



Tapping Mode Imaging: Phase



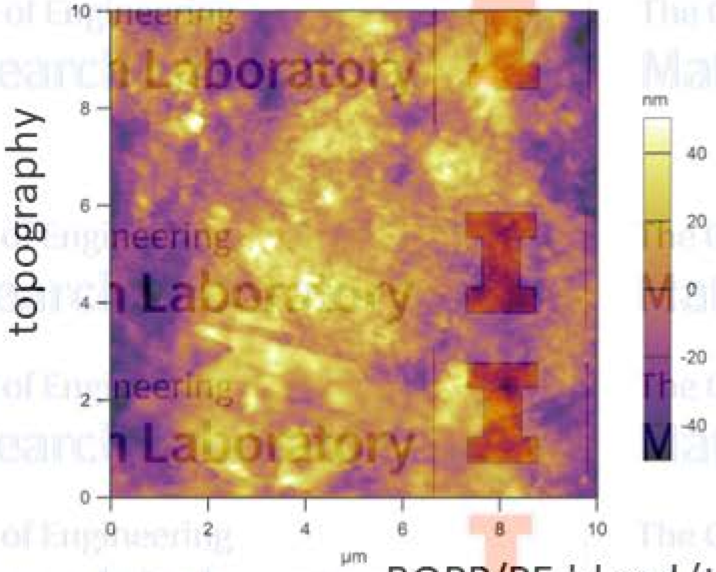
BOPP/PE toothbrush package

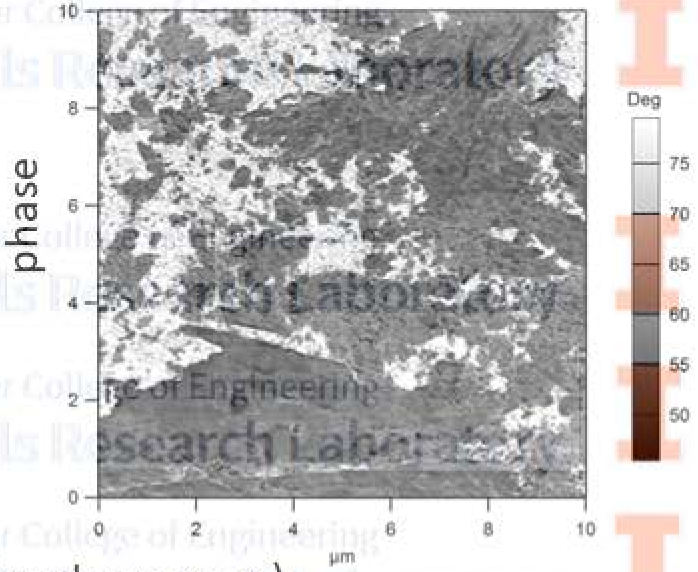


phase colorscale overlaid on 3D topography
redder areas are more dissipative

Application: Mechanical Characterization

- Tapping mode phase: easy qualitative characterization of mechanical differences within a sample
- Image of mechanical differences
  - Phase (tapping mode)
  - Maps of quantitative measurement results
  - Force modulation, AM-FM, contact resonance, etc.

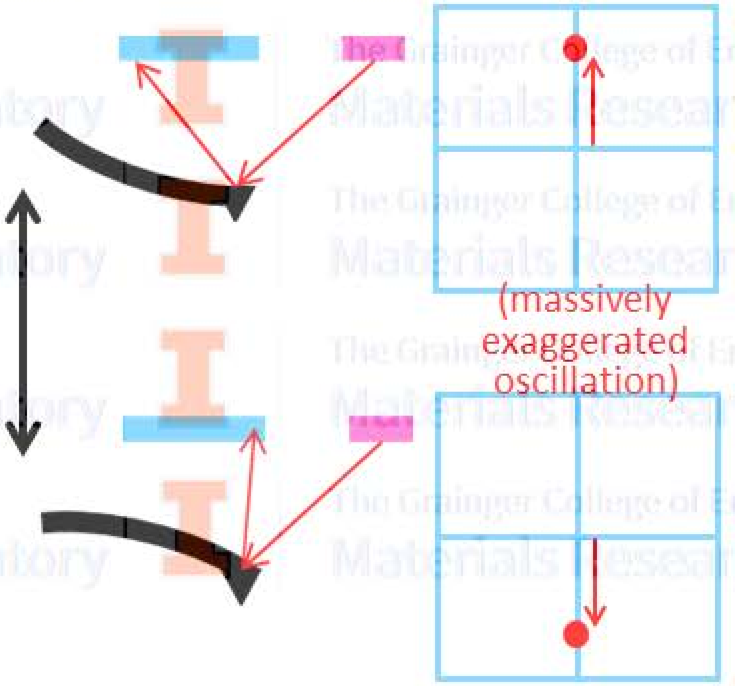




BOPP/PE blend (toothbrush wrapper)

Phase

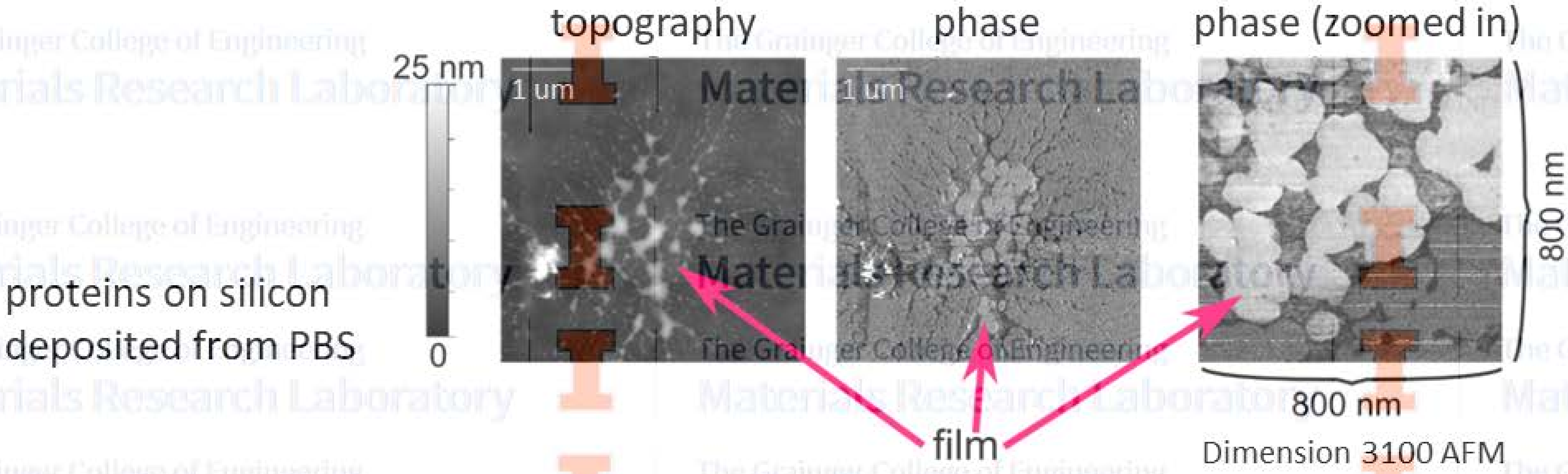
- Tip—surface interactions affect cantilever oscillation
  - Cantilever driven at a specific frequency
  - Dissipative interactions cause a phase lag
    - Compliant areas
    - Sticky areas



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

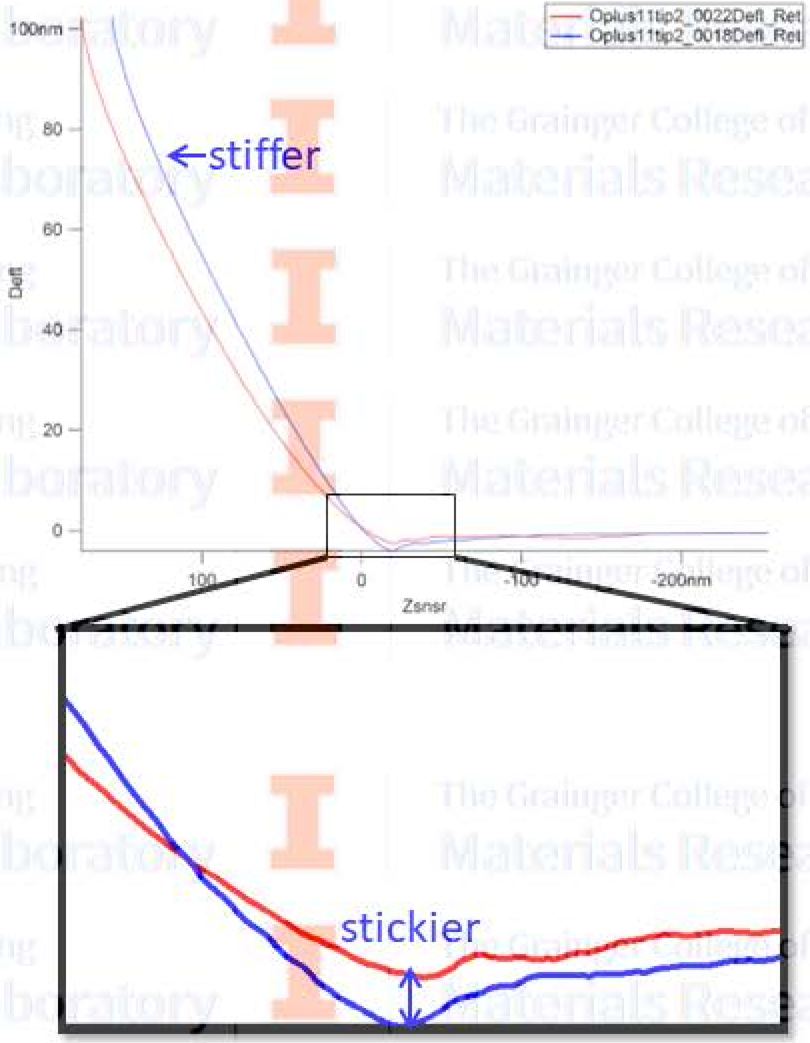
Phase (Qualitative)

- Can help locate and identify small sample components
- Can point out contaminants in sample
  - If phase isn't homogeneous, neither is the material
  - Can't do explicit chemical identification (stay tuned)

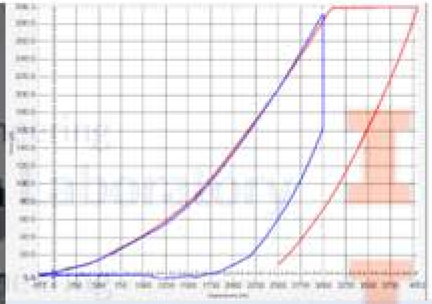


Quantitative Nanomechanical Measurements

- Force curves (pointwise or mapping)
  - Force curves are good for ~few kPa to 10s of GPa
  - For higher-modulus materials, consider nanoindentation



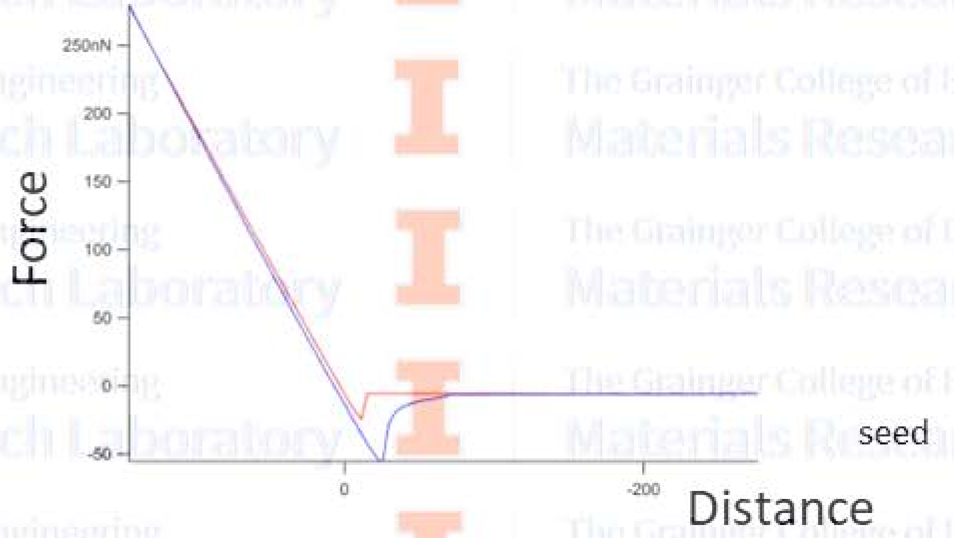
- Contact resonance, force modulation, AM-FM, other mapping modes



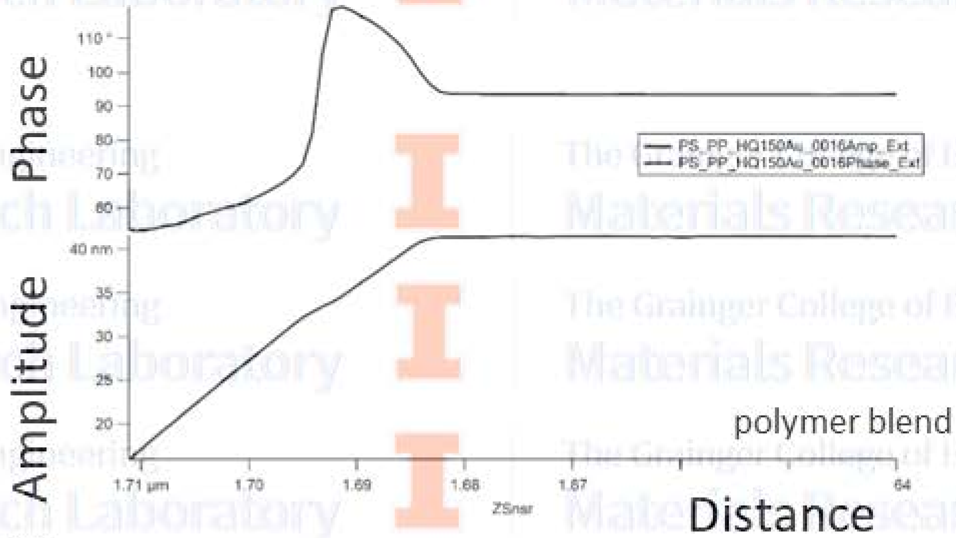
Nanoindentation tutorial tomorrow, **10:50am**

Force Curves

- Force—distance curves at one point

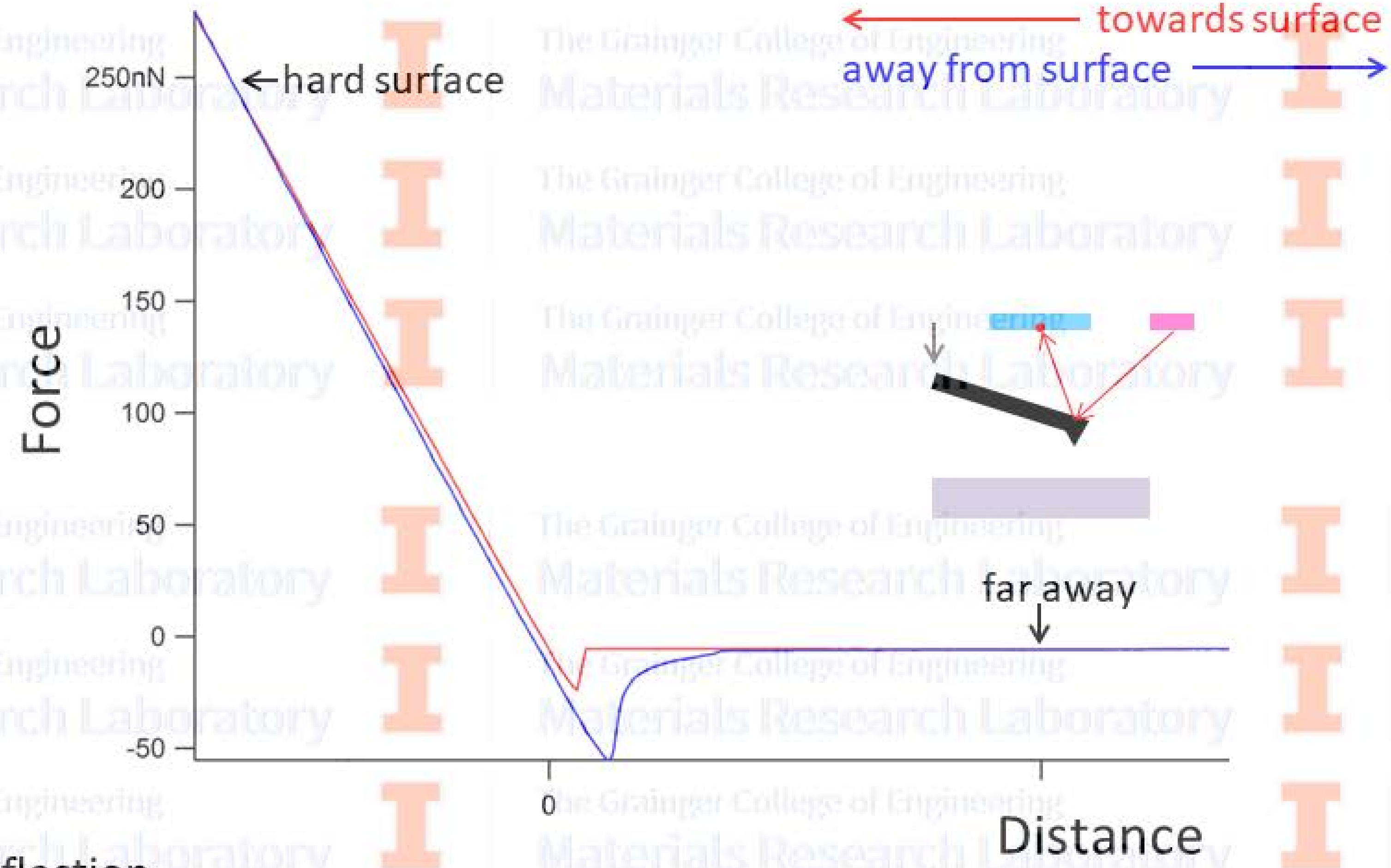


- Quasistatic (most common)
  - Cantilever is not oscillating
  - Force is proportional to deflection
- Dynamic
  - Cantilever is oscillating
  - Damping force decreases oscillation amplitude



Force Curves

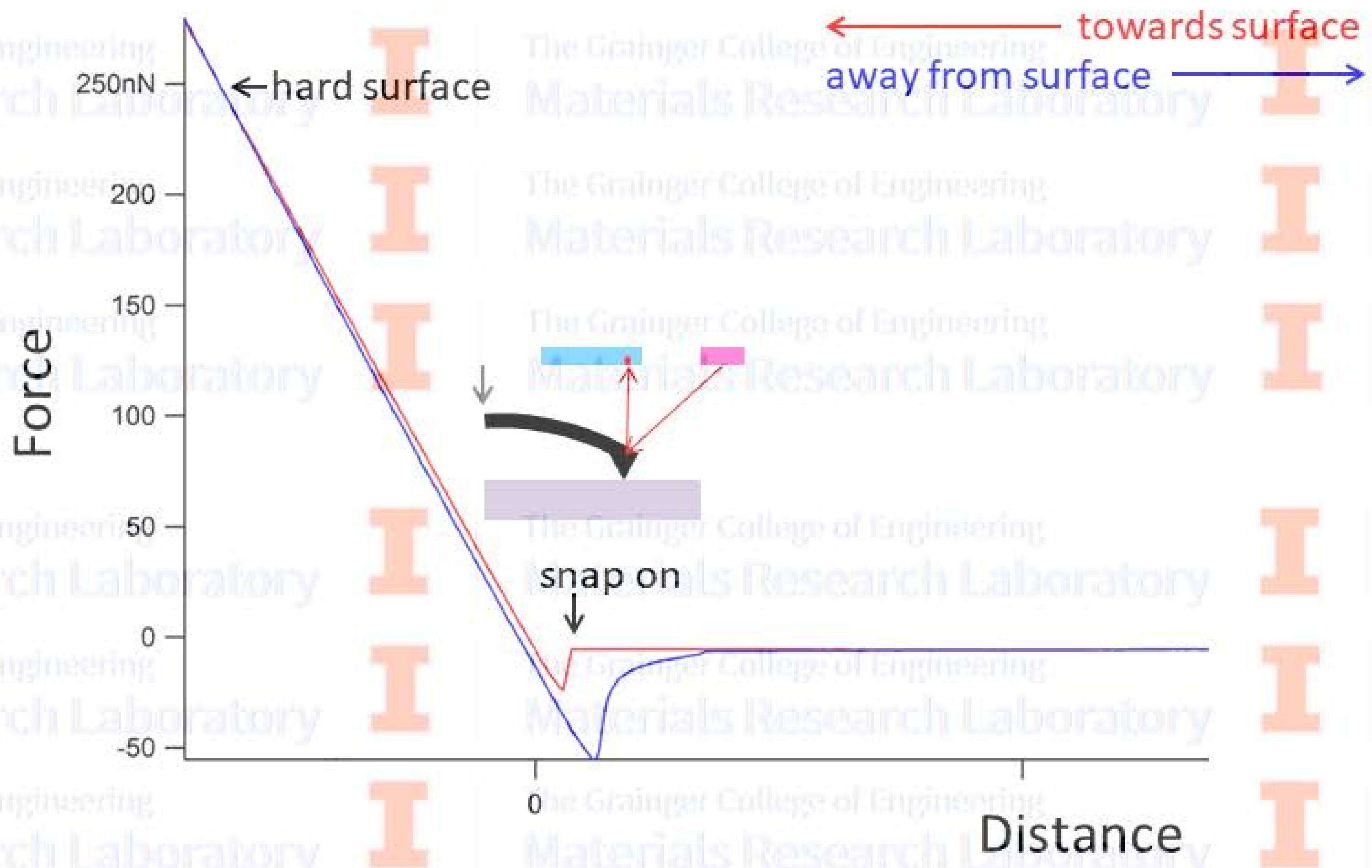
Tip pushes into surface, deflecting cantilever



Force is proportional to Deflection

Force Curves

Tip pushes into surface, deflecting cantilever



Force Curves

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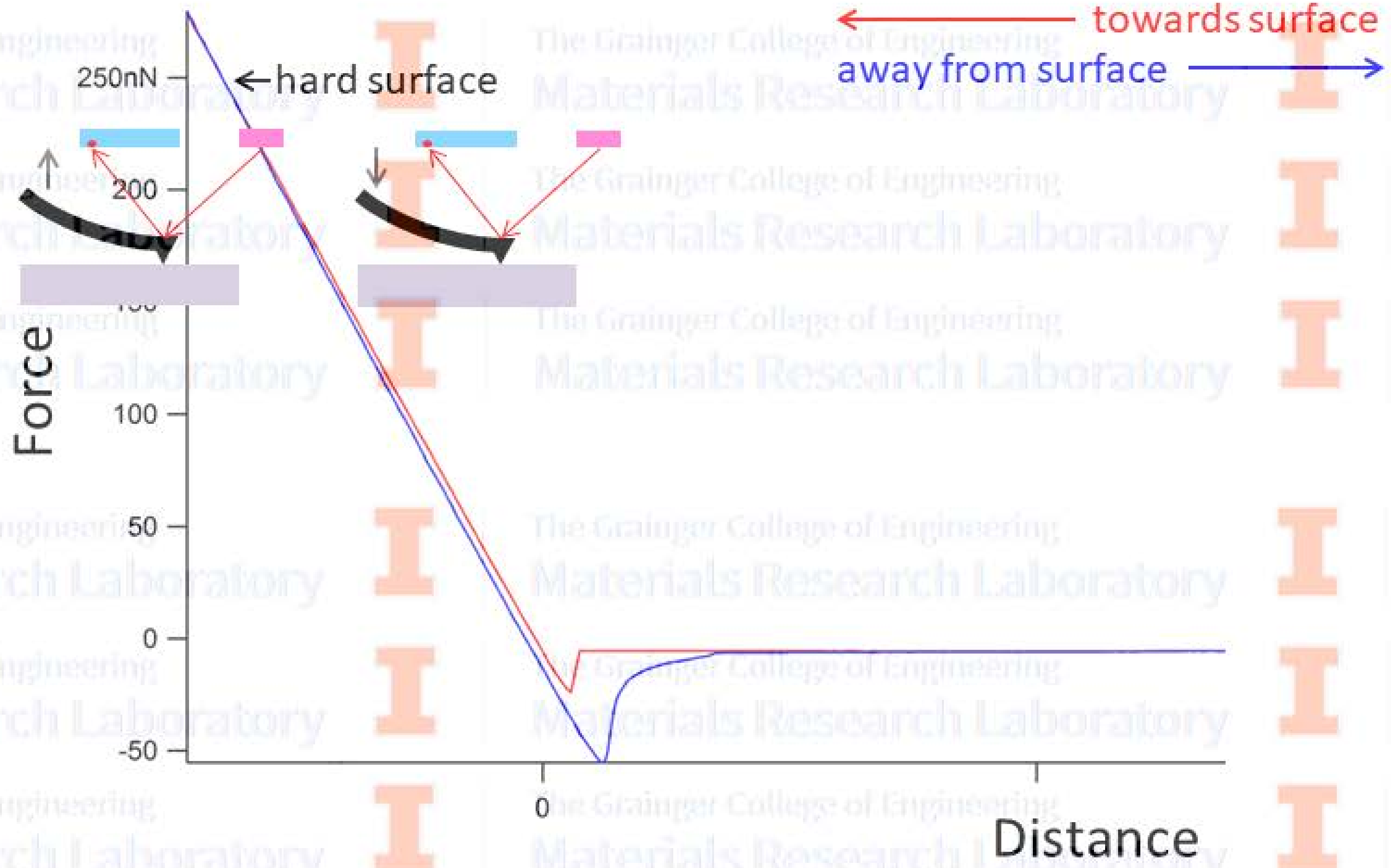

Force Curves

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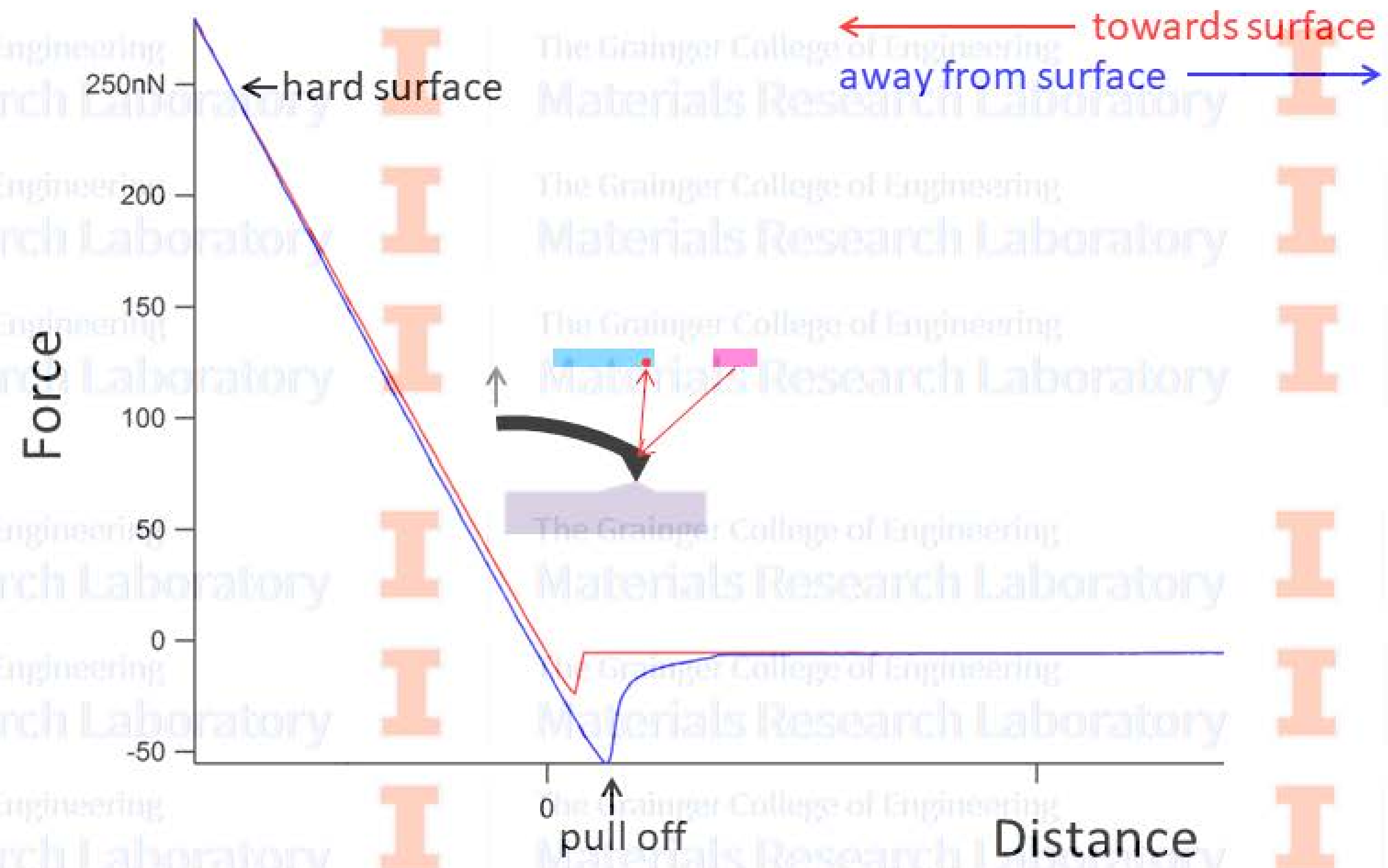
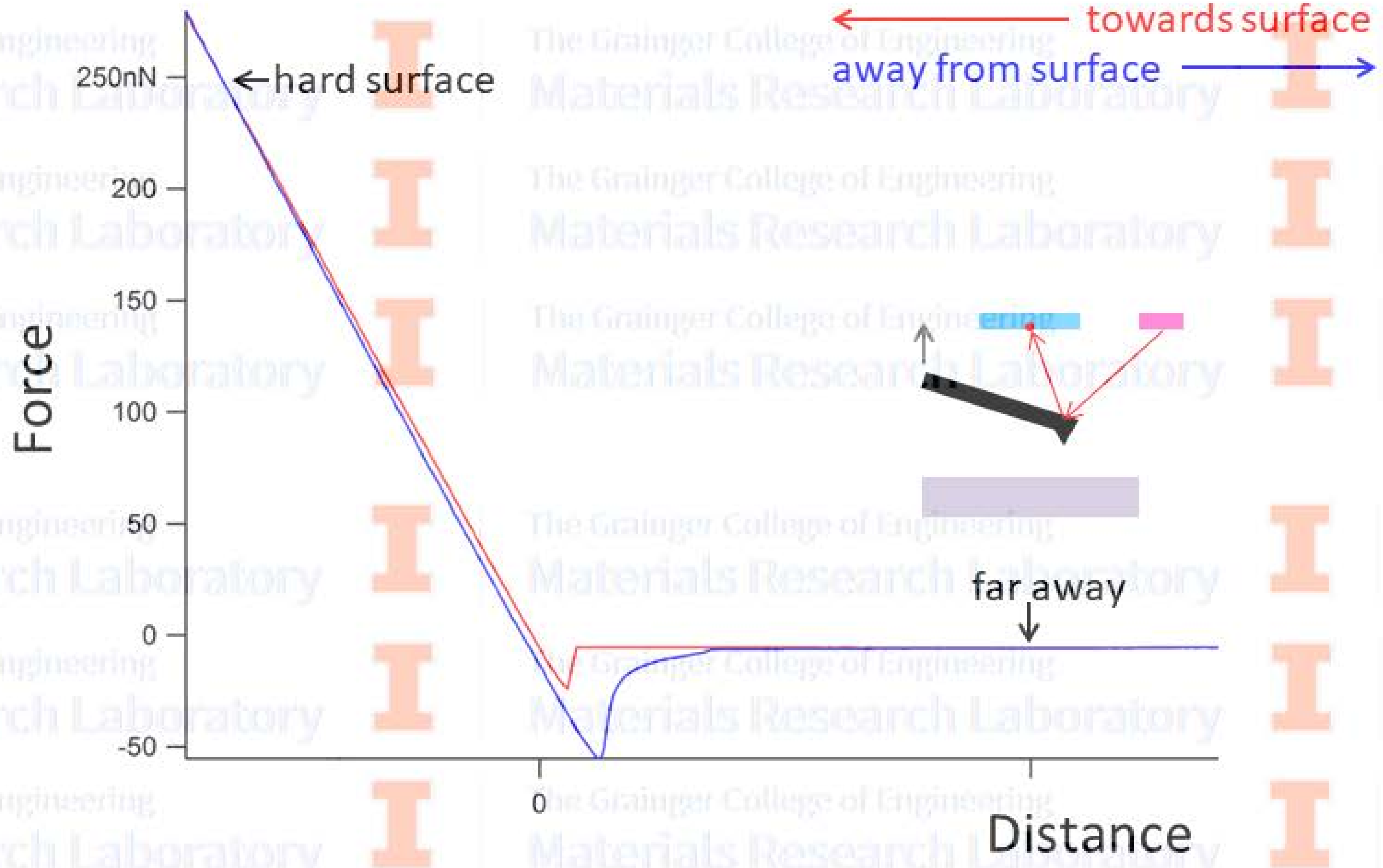


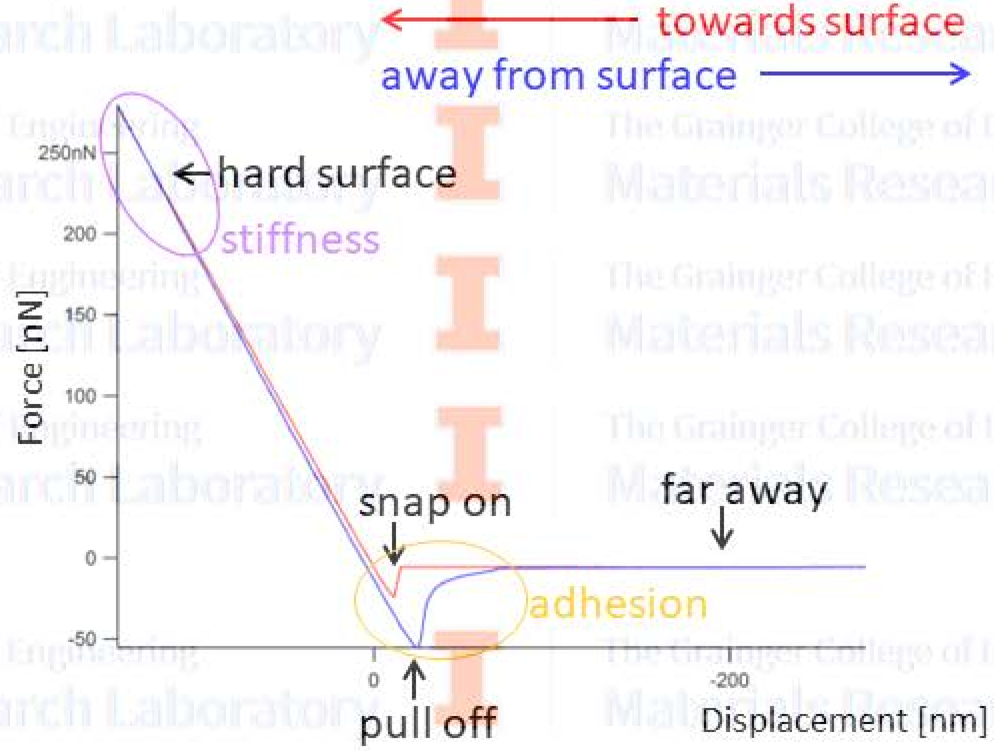
Force Curves

Tip pushes into surface, deflecting cantilever



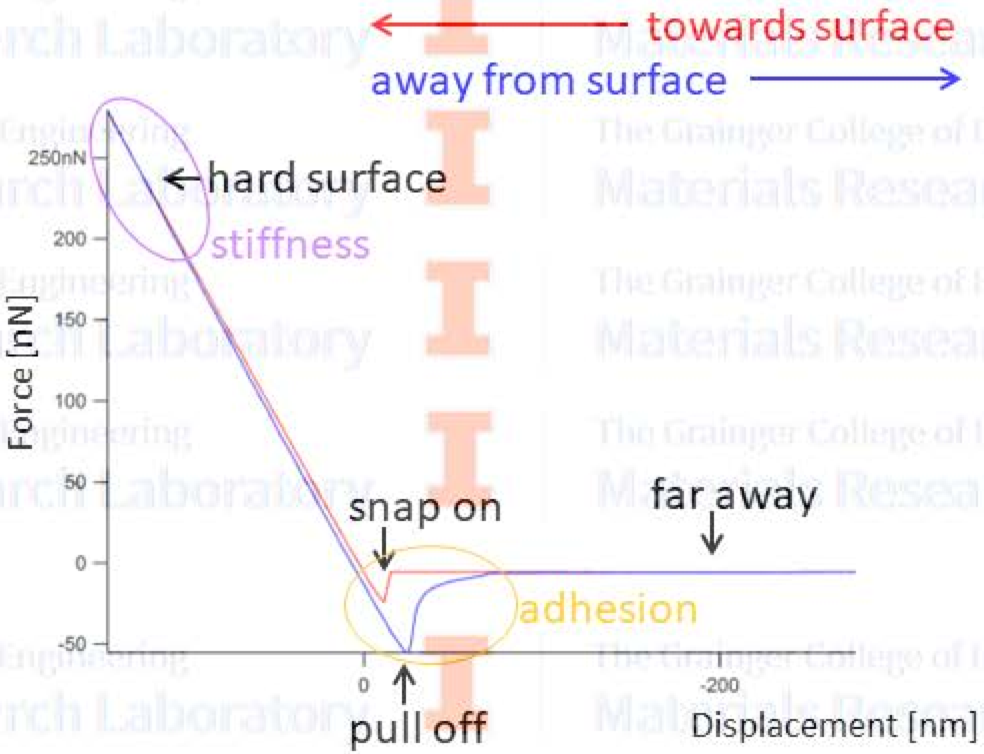
Force Curves

- Slope: sample stiffness
  - Can be converted to modulus with some care
- Easier to compare stiffnesses
  - Determining moduli requires careful fitting, modeling, assumptions
  - Overlaying force curves is easy



Force Curves

- Depth of well in retraction curve: adhesion
  - Depends on tip material
    - Silicon tip, metal-coated tip
    - Functionalized tip
  - Depends on the weather
    - Humidity and capillary forces
  - Depends on contact area between tip and sample
    - Colloidal (bead) probes
    - Varies with surface roughness



Force Curves: Extracting Numbers

- Models for AFM
  - Sneddon > Hertz
  - JKR—strong adhesion
  - DMT—sharp tips

- Unless high spatial resolution is needed, consider colloidal probes

- Tricky to know the exact contact area with ordinary tips
  - Only a few nm displacement into the sample (indentation depth)
  - Quoted radius of curvature is an assumption
    - Tip-to-tip variation
    - Tip damage
    - Not actually a sphere

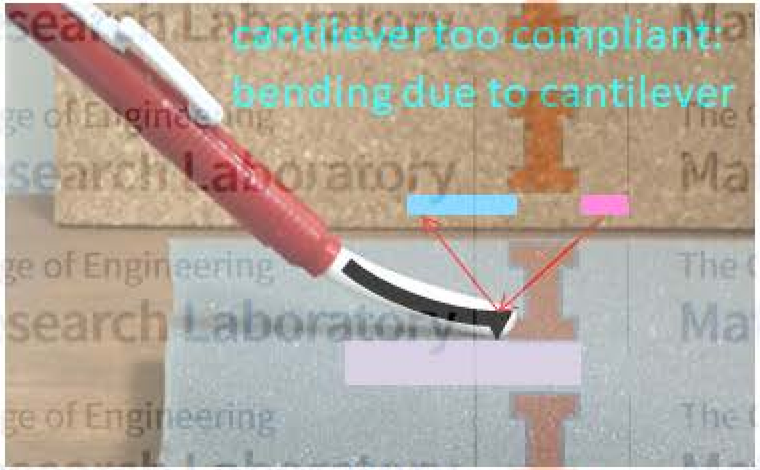
How to Choose a Cantilever

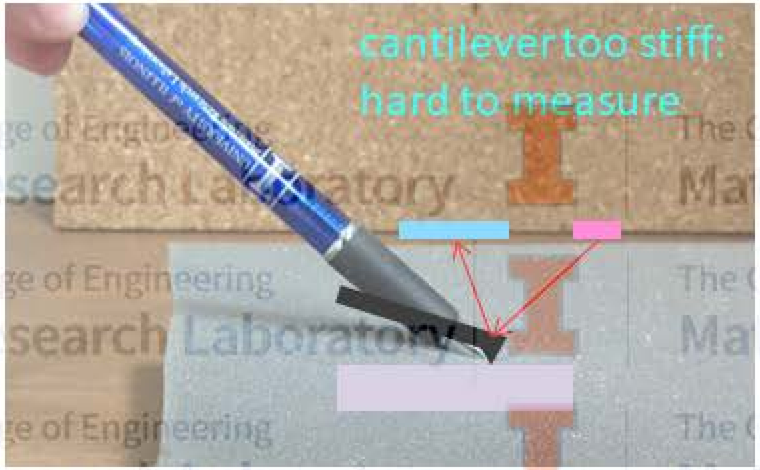
Cantilever stiffness should be similar to sample stiffness for force curves

- Cantilever too *compliant*: most observed bending is due to cantilever itself, not to sample

- Cantilever too **stiff**: cantilever isn't deflected much by interaction with the sample

- Calibrate to account for cantilever compliance





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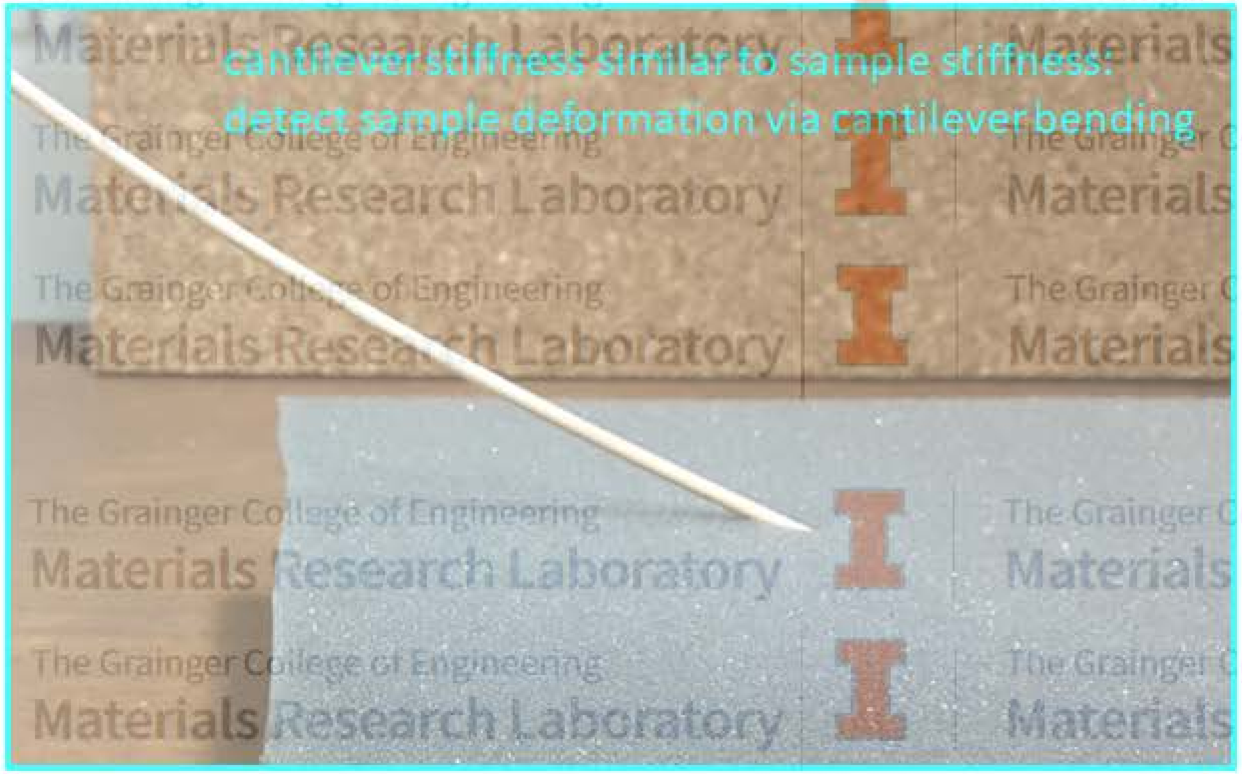
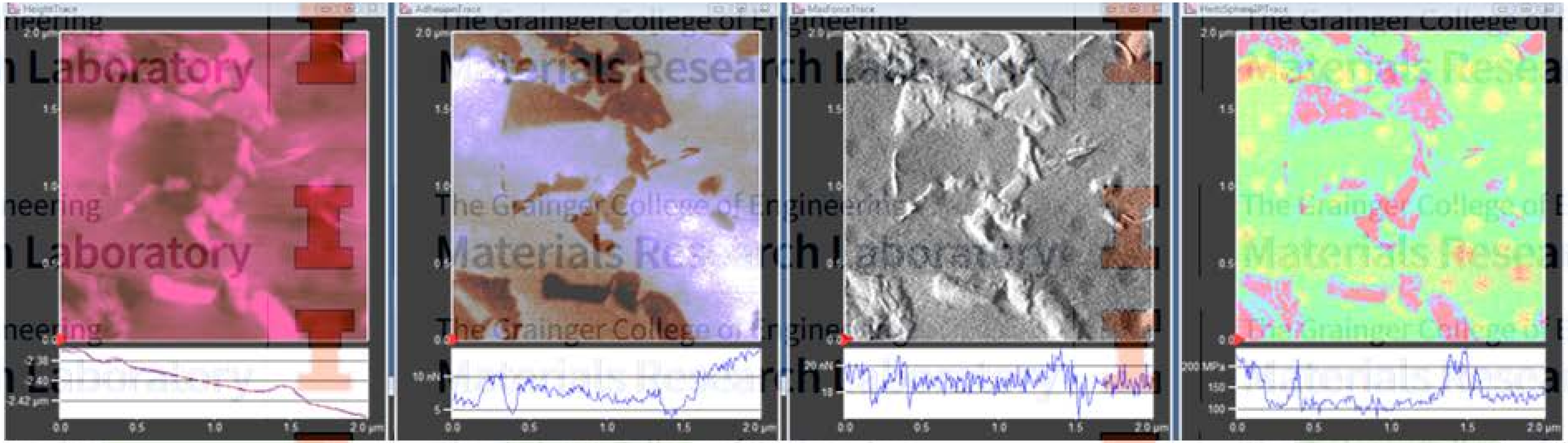
Cantilever stiffness should be similar to sample stiffness for force curves



Easiest: try a couple different cantilevers

Beyond a Single Force Curve

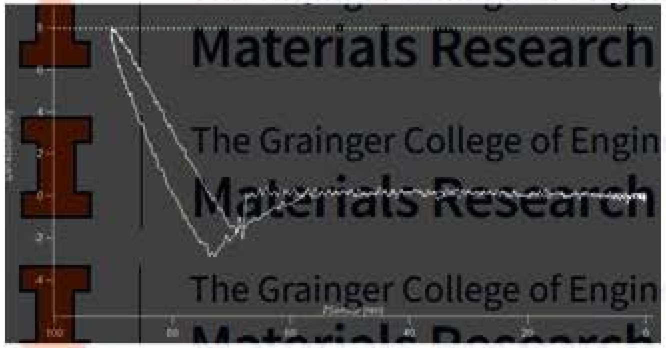
- Force volume maps
  - Grid of force curves
  - Build an "image" out of the results (height, stiffness, adhesion)
  - ~1 second/force curve
- Fast force mapping

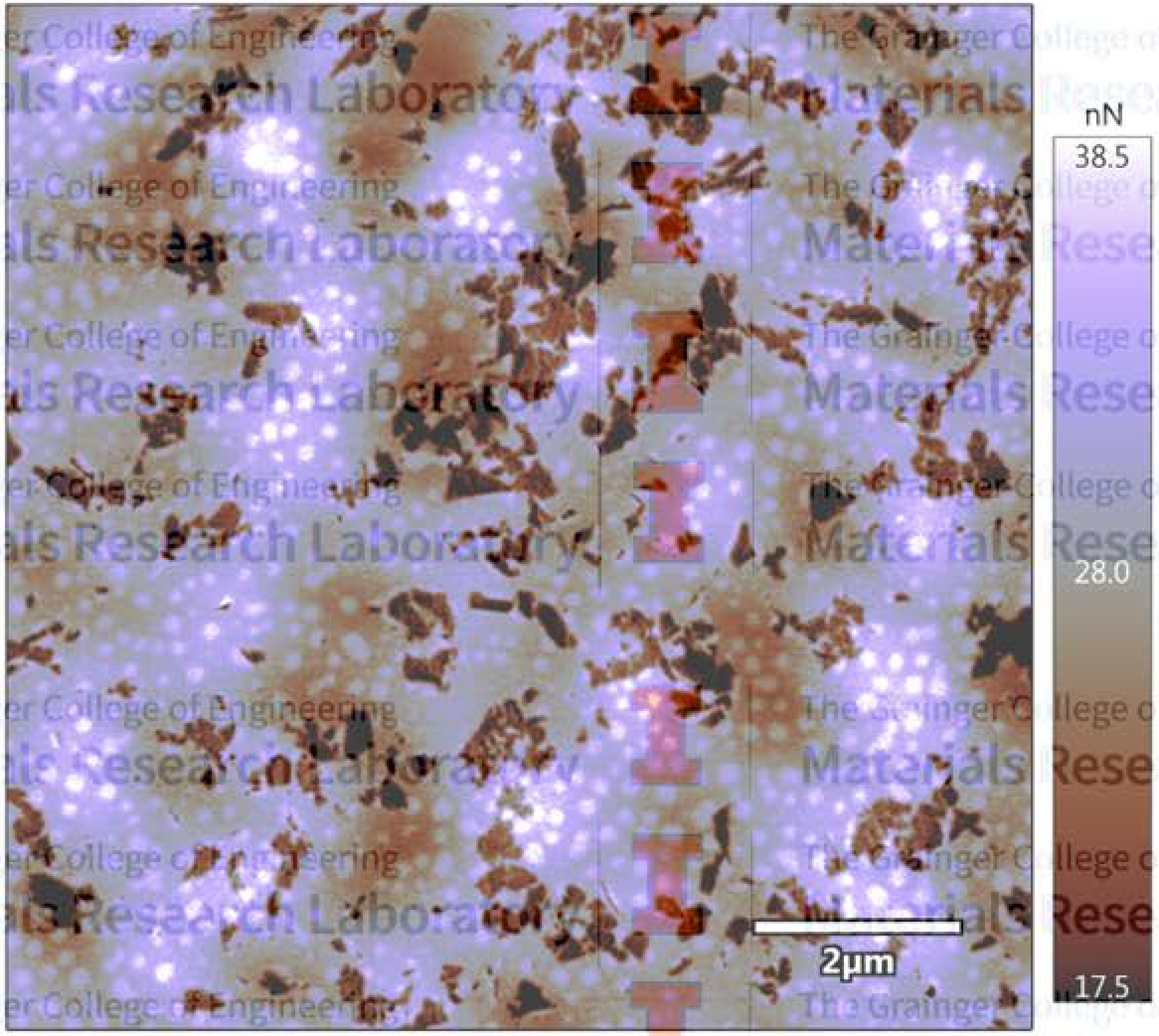


Topography Adhesion Modulus (quick fit)

Beyond a Single Force Curve

- Force volume maps
  - Grid of force curves
  - Build an "image" out of the results (height, stiffness, adhesion)
  - ~1 second/force curve
- Fast force mapping
  - Speed depends on cantilever and on desired loading rate

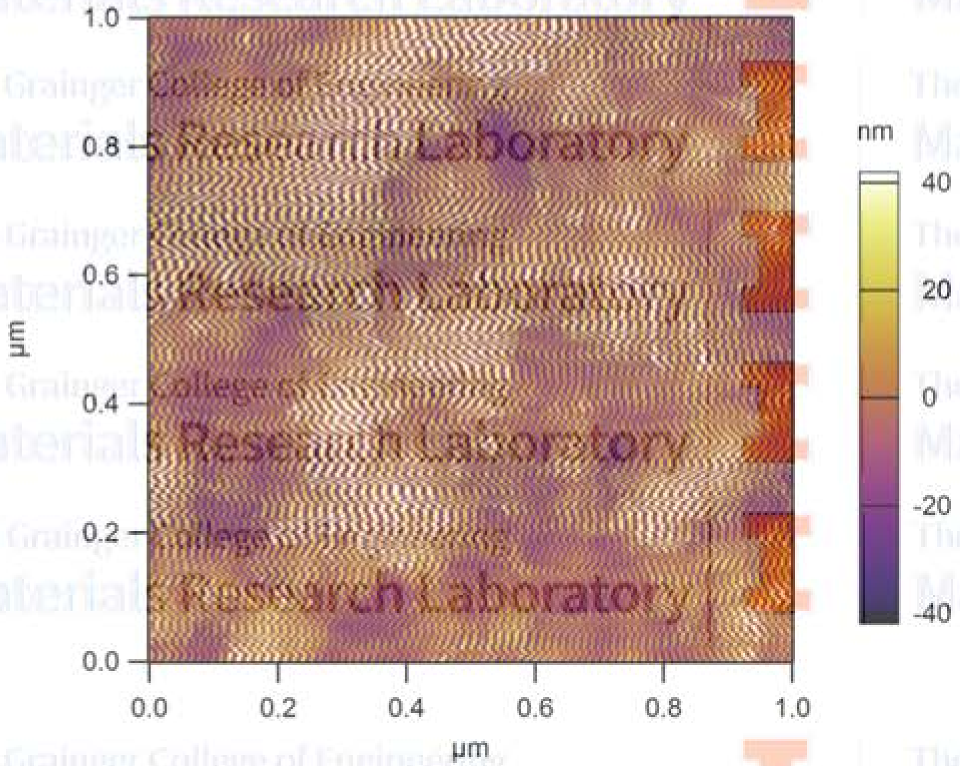




nail polish adhesion map
10 μm x 10 μm
512 x 512 force curves
Asylum Research Cypher VRS
in Fast Force Mapping mode

Application: Sticky Samples

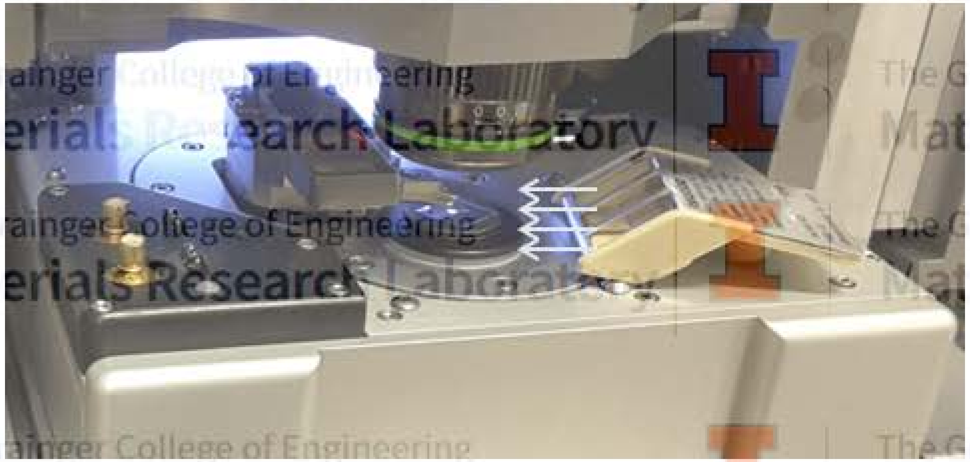
- Tip can stick to sample
  - Can't scan, or can't scan nicely
  - Can damage the tip
  - Can contaminate the tip



Application: Sticky Samples

- Tip can stick to sample
  - One strategy: image with a higher tapping amplitude
  - One strategy: different tip material

- Static discharger

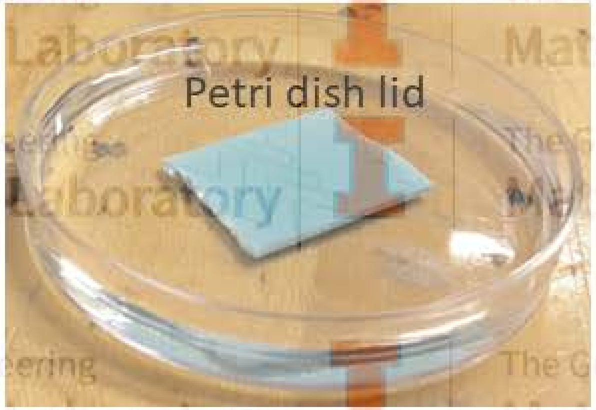


- Work in fluid

Application: Fluid

- Can image and do some mechanical measurements in fluid

- Different setups
  - Droplet of fluid on sample
  - Submerged sample in open dish
  - Closed fluid cell



- Fluid is trickier
  - Setup (need to be more careful)
  - Hydrodynamics (partial solution: photothermal cantilever excitation)

Droplet on Sample

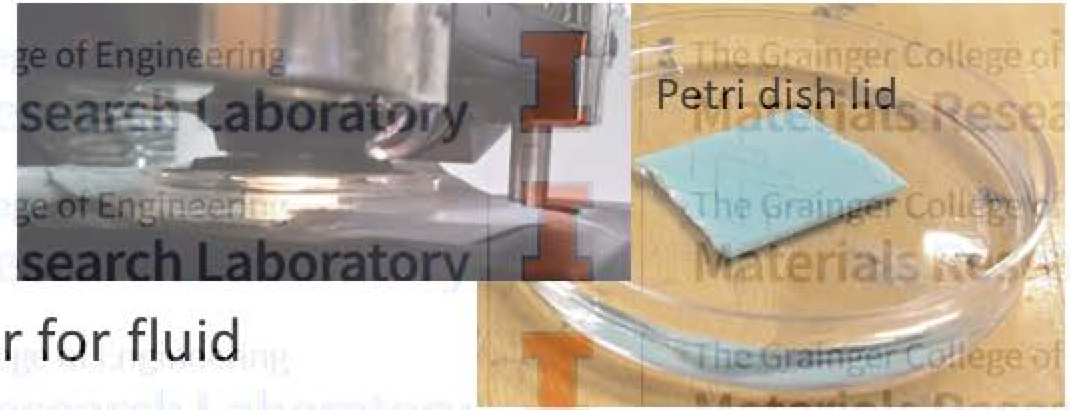
- Easiest to set up
- Good for samples which
  - Don’t swell much when wet
  - Aren’t porous
  - Use fluid which doesn’t evaporate quickly
- Cantilever is also completely immersed in fluid

droplet on sample
easiest way if your sample allows

hydrophobic barrier
(ring drawn with hydrophobic pen)
allows small sample to be inside droplet

AFM in Fluid

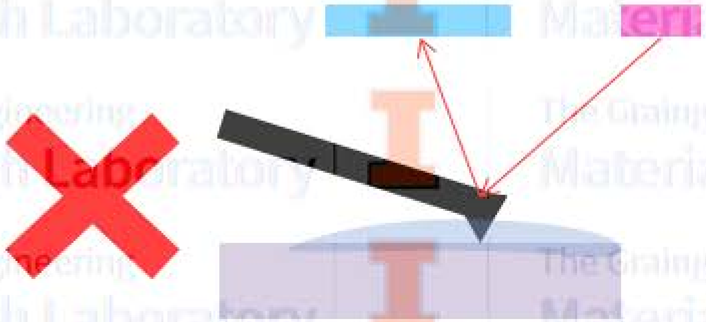
- Instrument setups for fluid
  - droplet of fluid on sample
  - submerged sample in open or covered dish
  - closed fluid cell
  - some AFMs need a different cantilever holder for fluid
  - some AFMs can’t do fluid at all
- Fluid is trickier
  - setup (be more cautious)
  - hydrodynamics (partial solution: photothermal cantilever excitation)



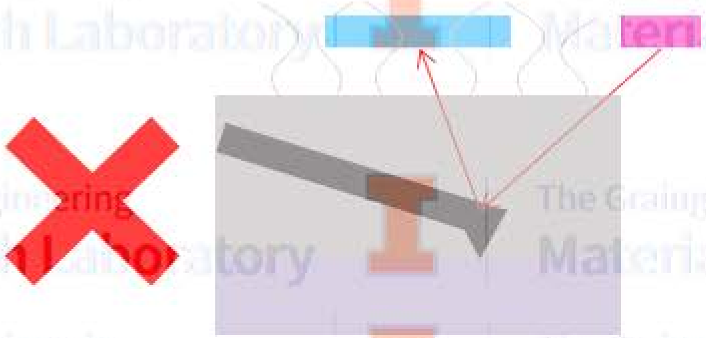
What Fluids are OK?

Unless using a closed fluid cell…

- Must not evaporate too quickly

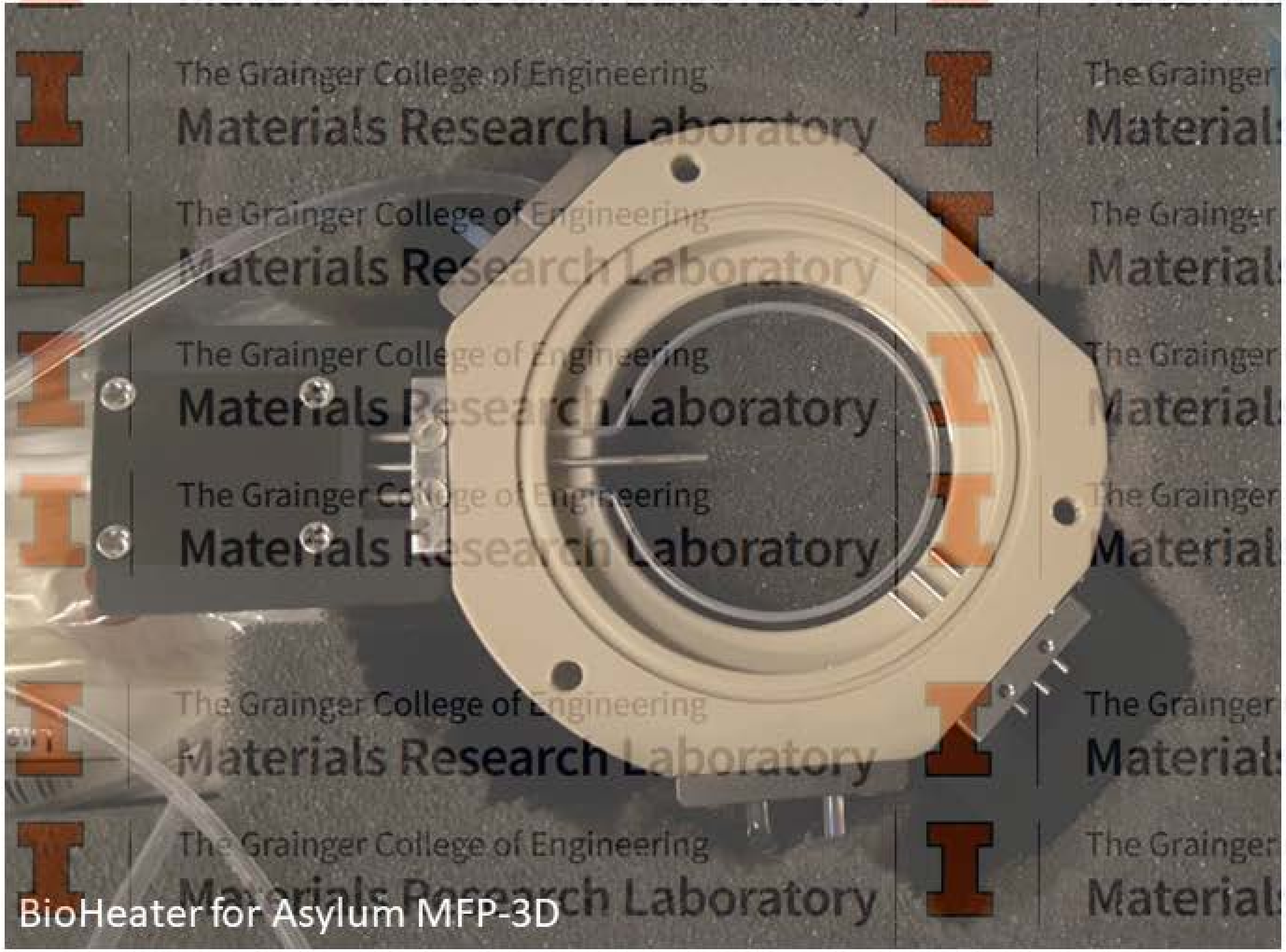


- Must not produce toxic vapors or vapors which can get into the electronics

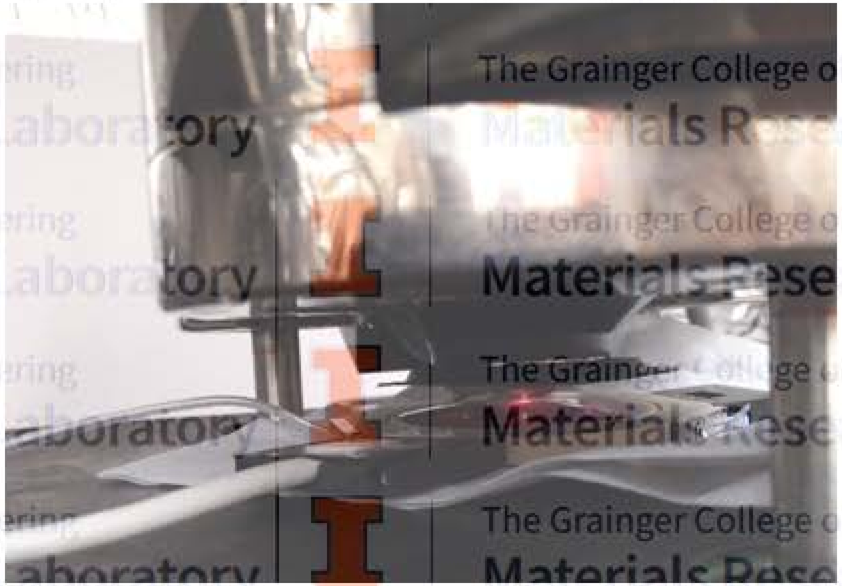


Side note: some closed cells are gas-tight and can be used for air-sensitive samples

Environmental Control



heated, sealable fluid cell



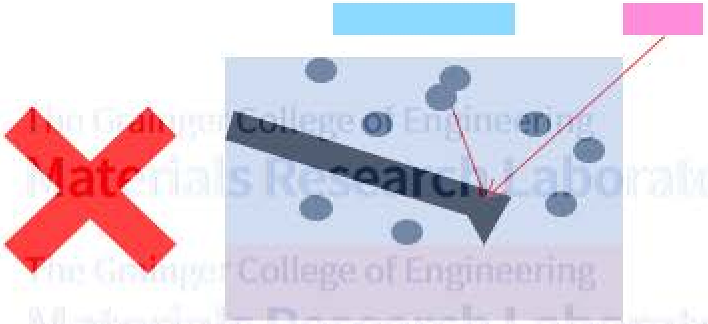
(sample is a pink gel)

Some closed cells are gas-tight and can be used for air-sensitive samples

What Fluids are OK?

Must allow the laser to pass through and be detected

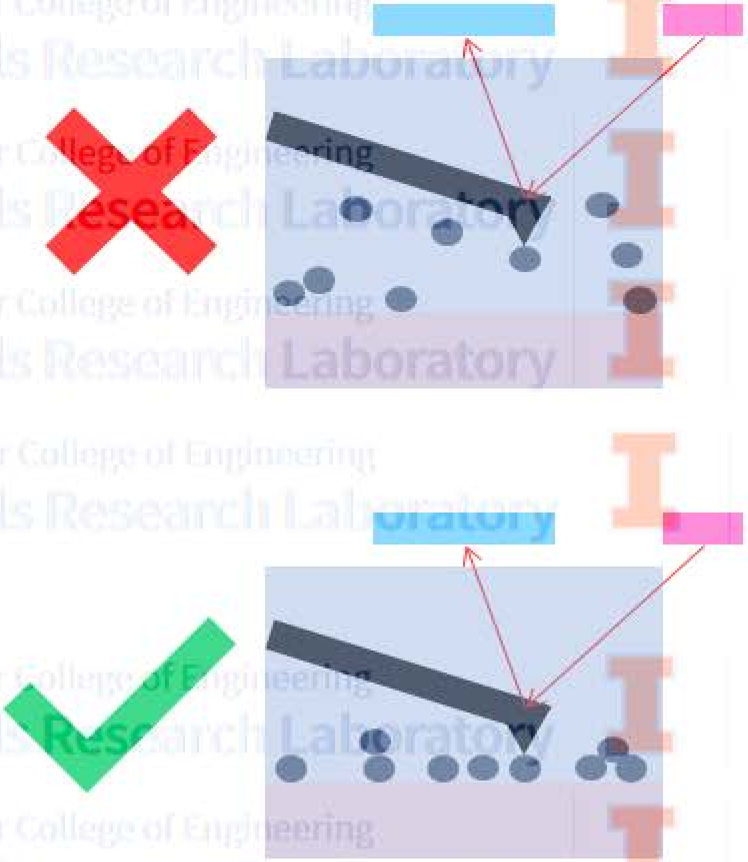
- Transparent to the laser wavelength (usually infrared or red)



- No particulates floating in fluid which could block the laser

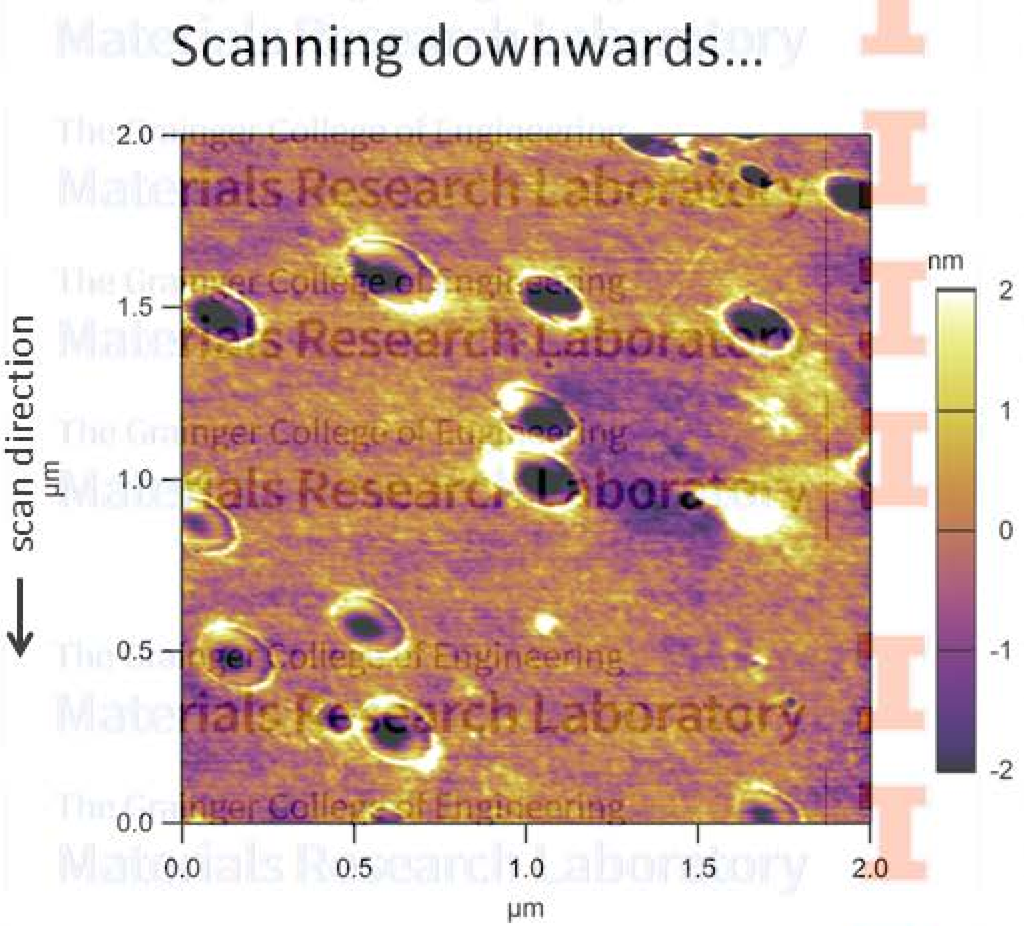
If your samples are suspended …

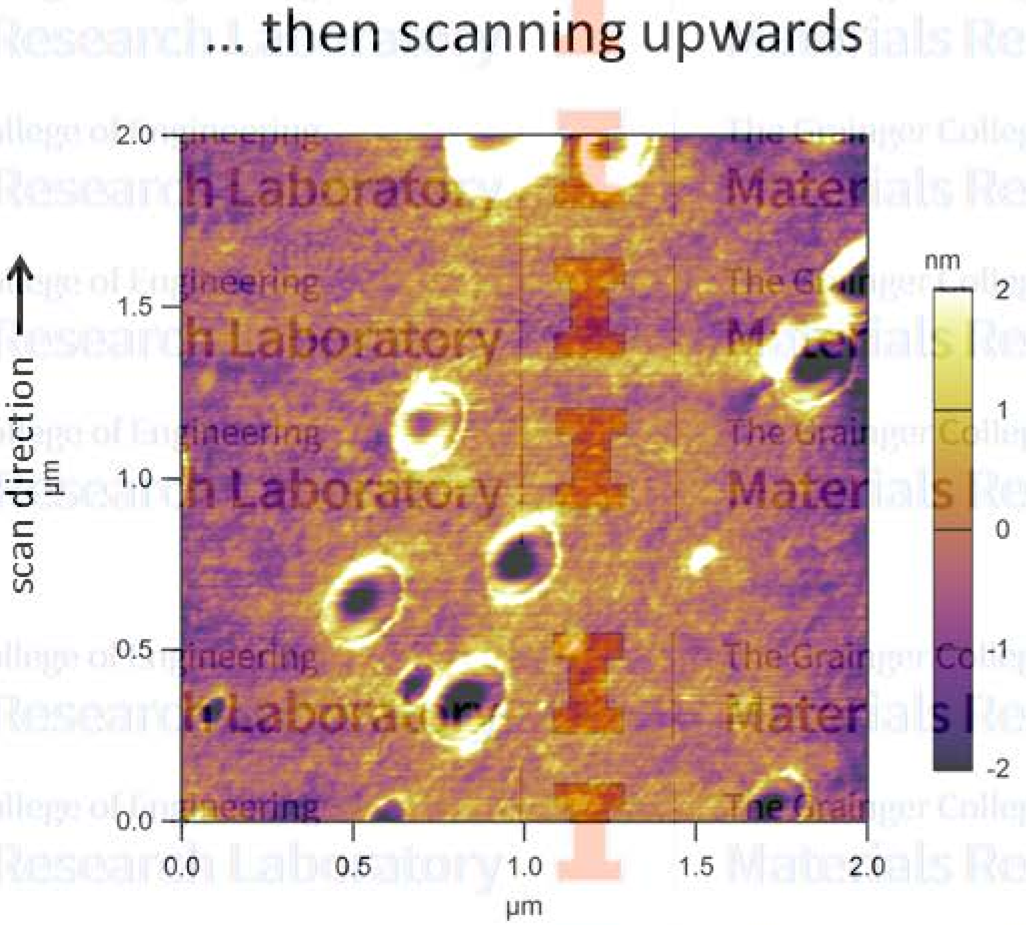
Samples Shouldn't Float or Flex



Samples Shouldn't Move

(unless you're trying to move them)



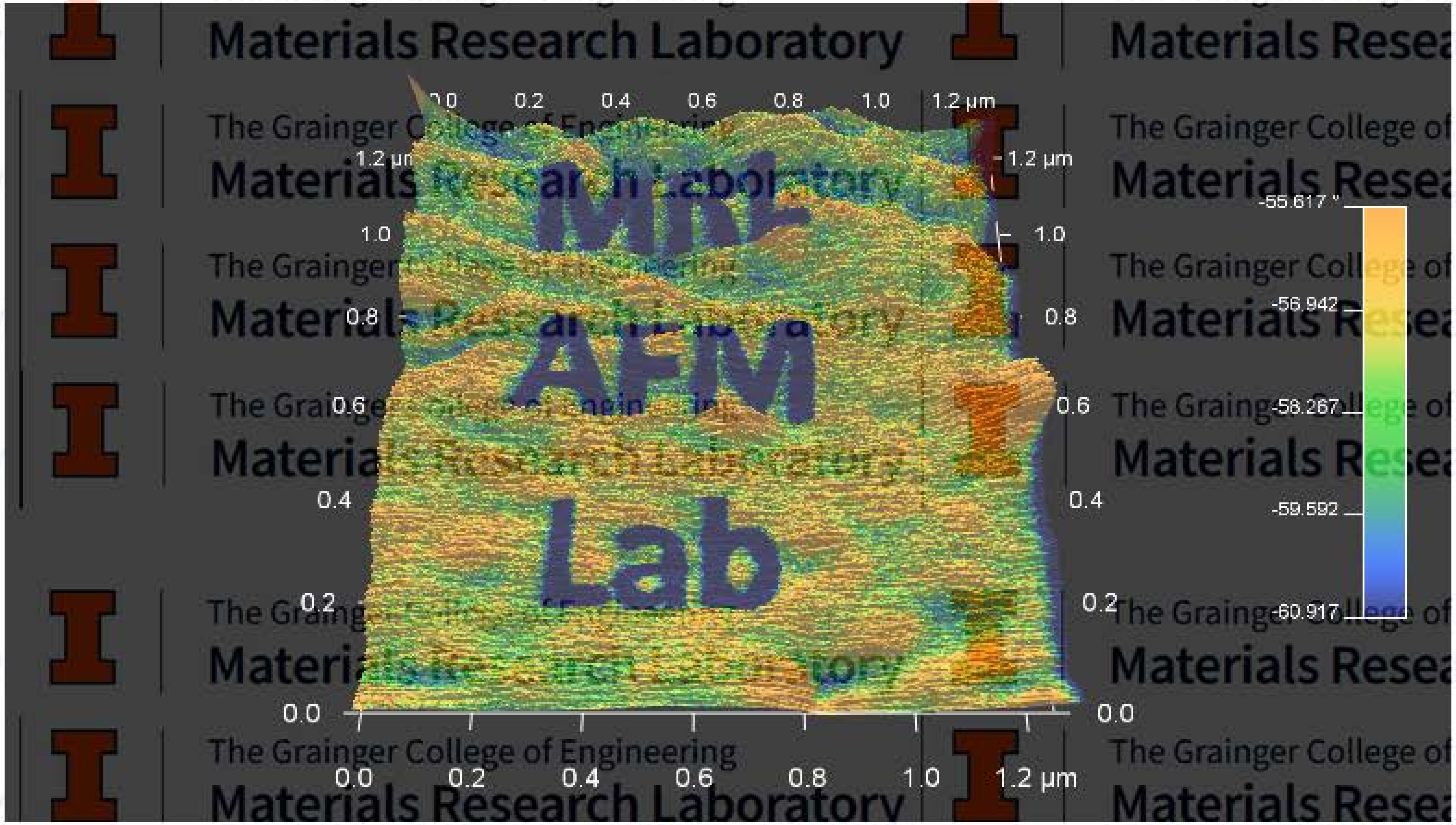


dehydrating chewing gum in air

Application: Nanolithography

Use the tip to alter the sample

- Force
- Magnetization
- Local surface charge
- Piezoelectric domains

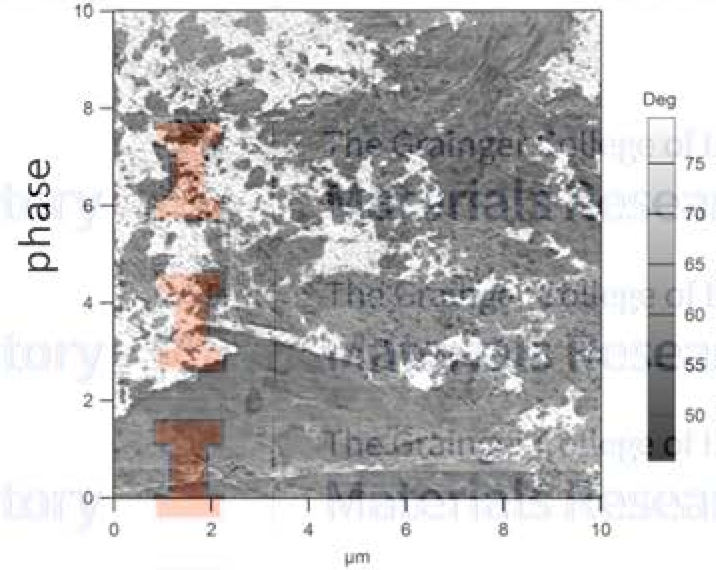


charge lithography on quartz, imaged with DART PFM on the Asylum Cypher AFM
colorscale: 2nd phase, topography slightly exaggerated in z

Application: Chemistry

- Phase shows material contrast… but which material is which?
  - Force curves can differentiate mechanically (A is stiffer than B, etc.)
  - Mechanical mapping techniques (contact resonance, etc.) can differentiate based on modulus
  - Functionalized tips can differentiate based on strength of interactions with the tip coating
- If you know what is in your sample, AFM can tell you where that is…

… but what if you don't know what is in your sample?

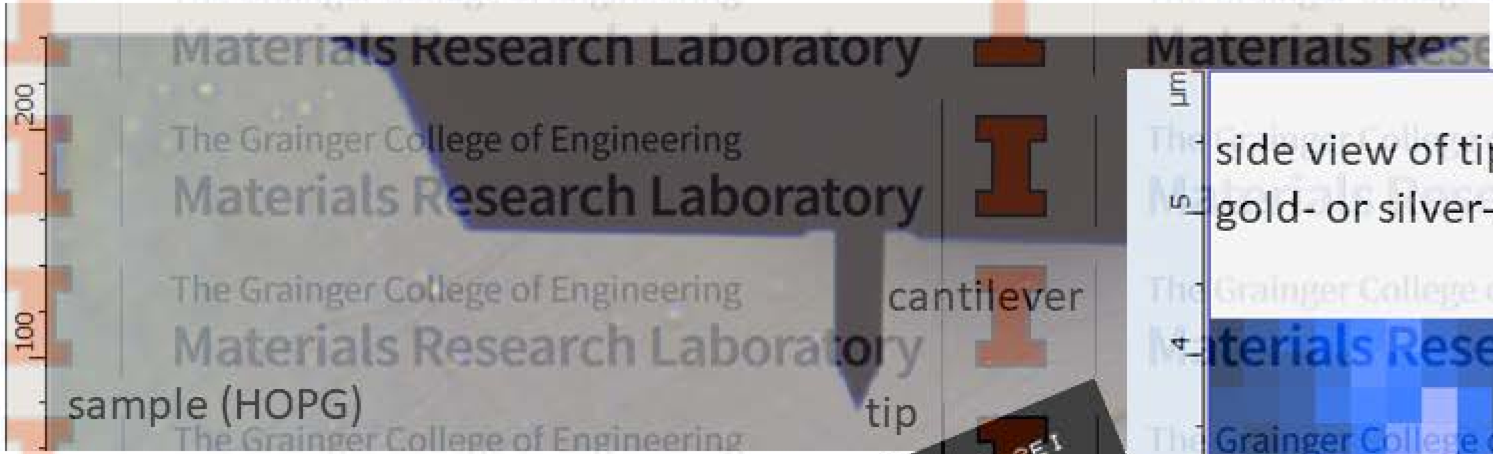


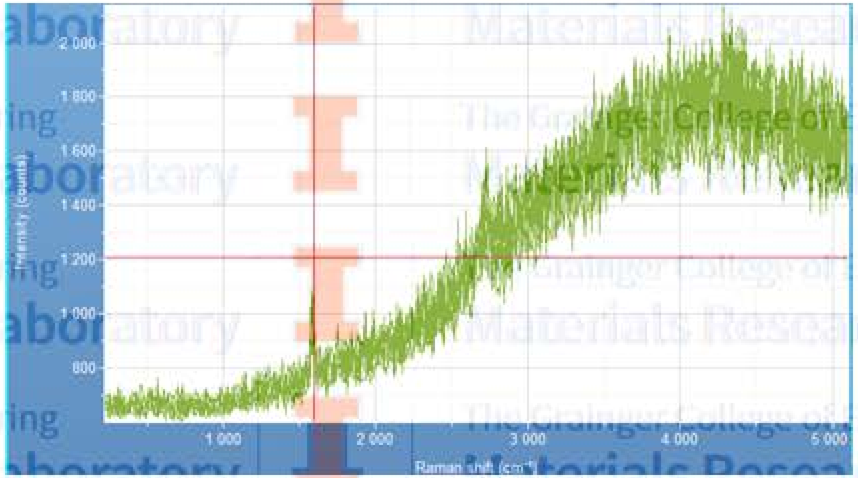
Scanning Probe Optical Spectroscopy

- Optical techniques (IR, Raman) combined with AFM
- Chemical information with tens of nm lateral and nanoscale vertical resolution (better than confocal)
- AFM-scale lateral resolution (~ few or ~10s of nm)
- AFM + optical spectroscopy
- Tip-enhanced optical spectroscopy
- AFM + infrared (various types)
- Generally separate instruments rather than instrument accessories

Scanning Probe Optical Spectroscopy

Tip-enhanced Raman spectroscopy (TERS)





Raman shift [cm^{-1}]

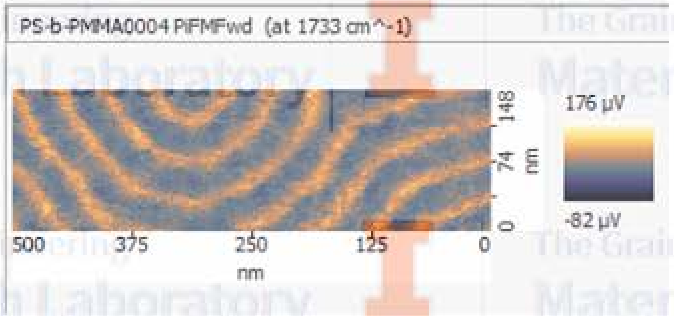
Scanning Probe Optical Spectroscopy

AFM + infrared microscopy/spectroscopy

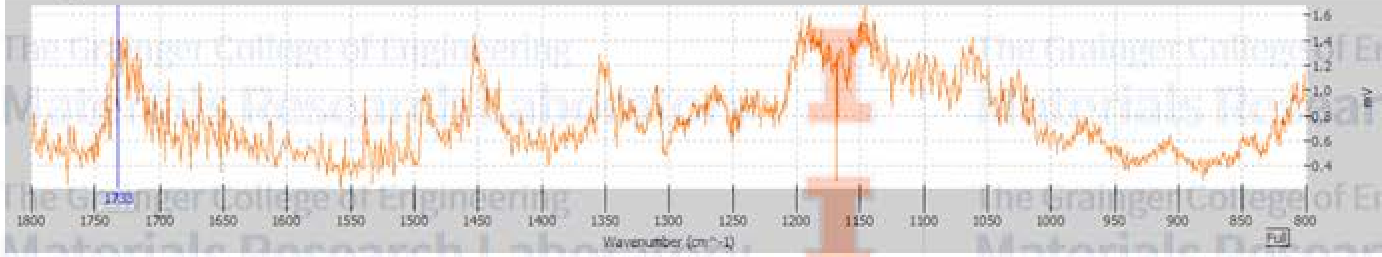
- Shine an IR laser at the tip-sample interface
- Detect
  - scattered light
  - thermomechanical changes to the sample
  - tip-sample force changes

  as a function of IR wavenumber
- Map an area at a specific wavenumber
- Sweep the laser frequency to get spectra

Photo-induced force microscopy and spectroscopy



illuminated at 1733 cm^{-1}



Vista One (Molecular Vista)

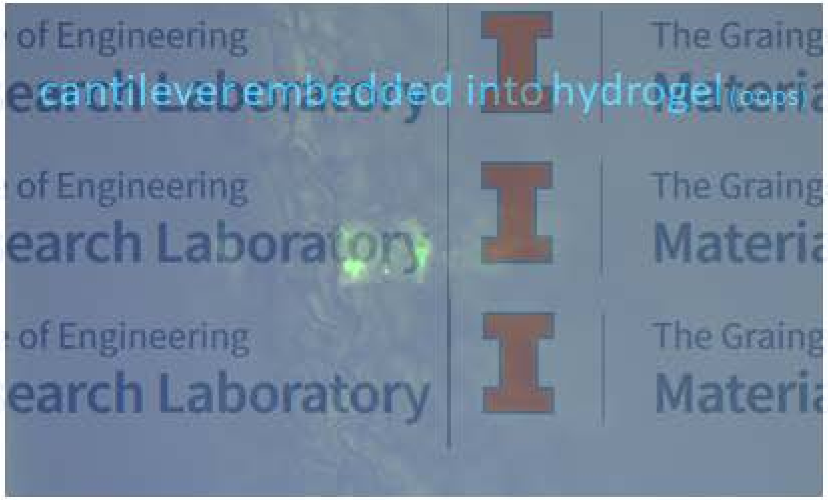
Artifacts

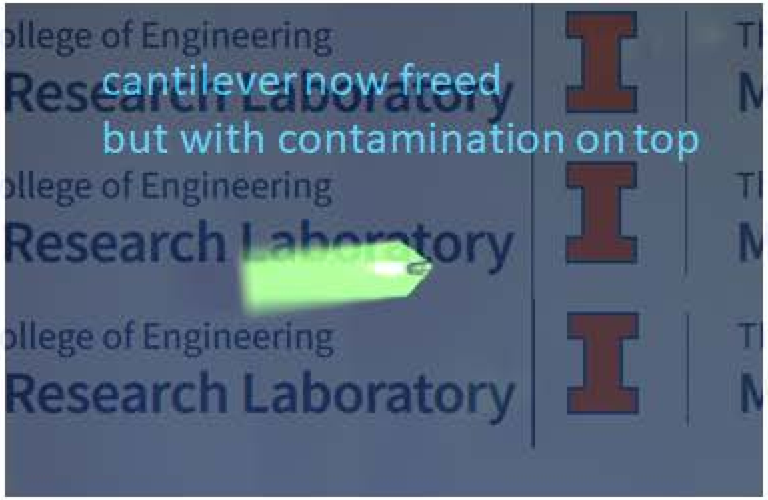
What Can Go Wrong in AFM?

- Sample
  - Moving too quickly (setup and scanning)
  - Drift (sample mounting, thermal)
- Tip
  - Multiple tip
  - Tip contamination/breaking/wear
- Image processing
  - Flattening artifacts

Navigating the Sample Too Quickly

- Sample
  - Moving too quickly (setup and scanning)

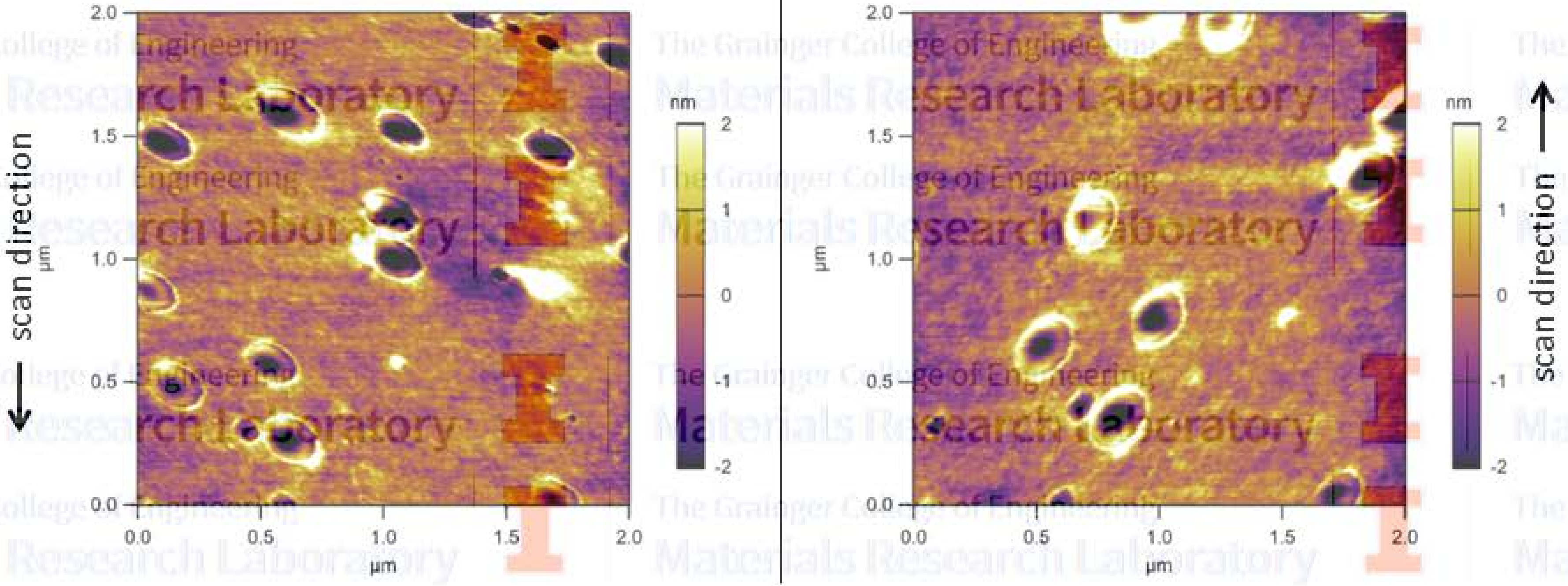




Be cautious when moving around on rough or tilted or transparent samples

Sample Drift

- Sample
  - Moving too quickly (setup and scanning)
  - Drift (sample mounting, thermal)

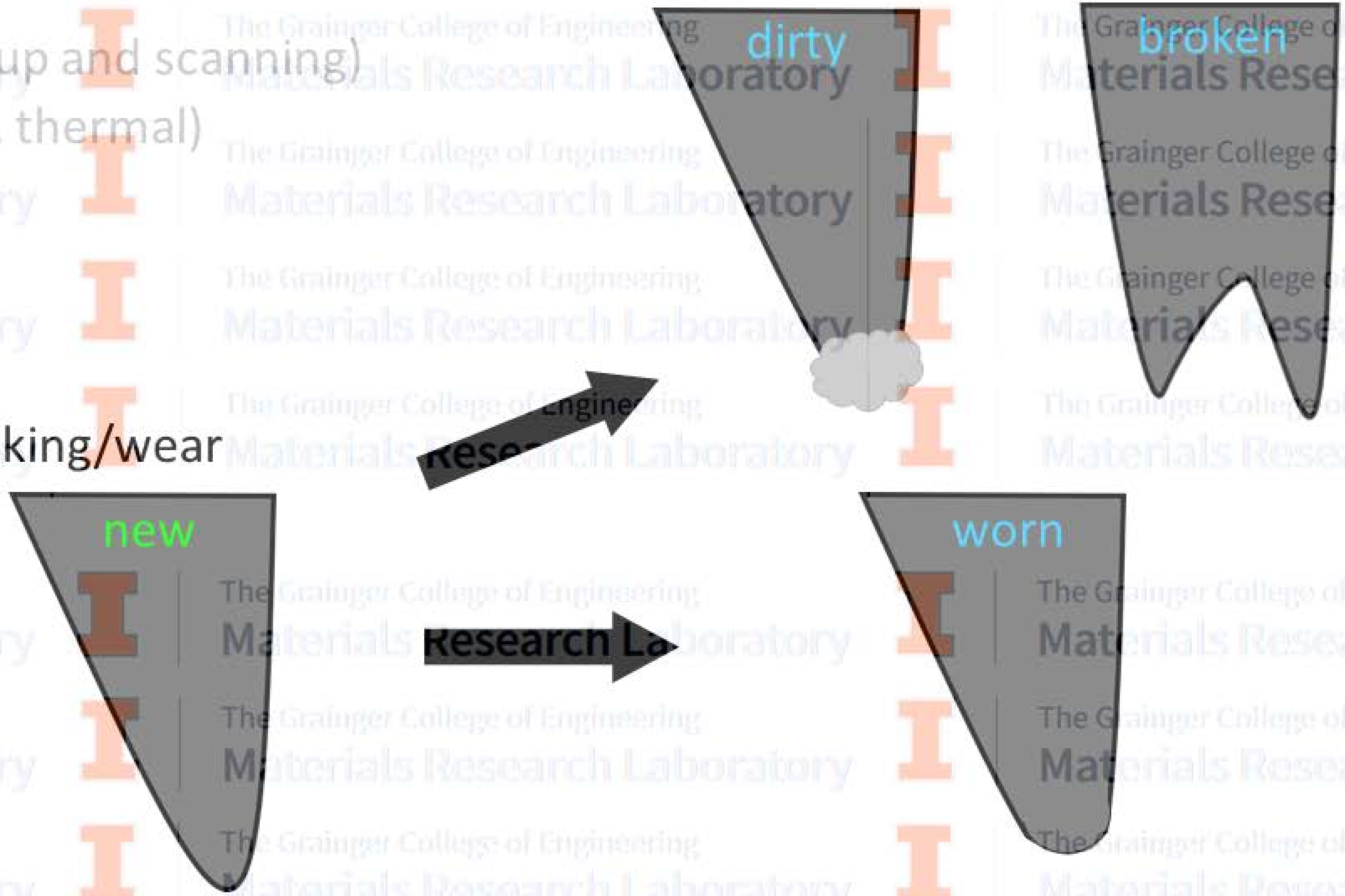


gradually dehydrating chewing gum

Tip Artifacts

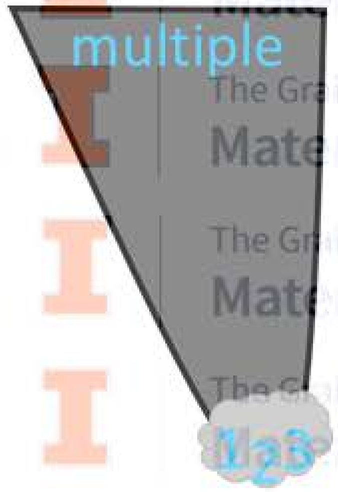
- Sample
  - Moving too quickly (setup and scanning)
  - Drift (sample mounting, thermal)

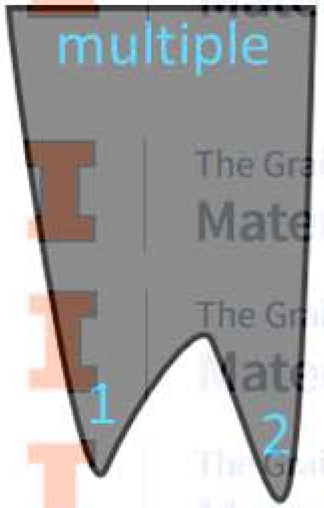
- Tip
  - Multiple tip
  - Tip contamination/breaking/wear



Multiple Tip Artifact

- Tip contamination
- Tip breaking
- Tip-sample forces occur between the sample and tip 1, tip 2, tip…



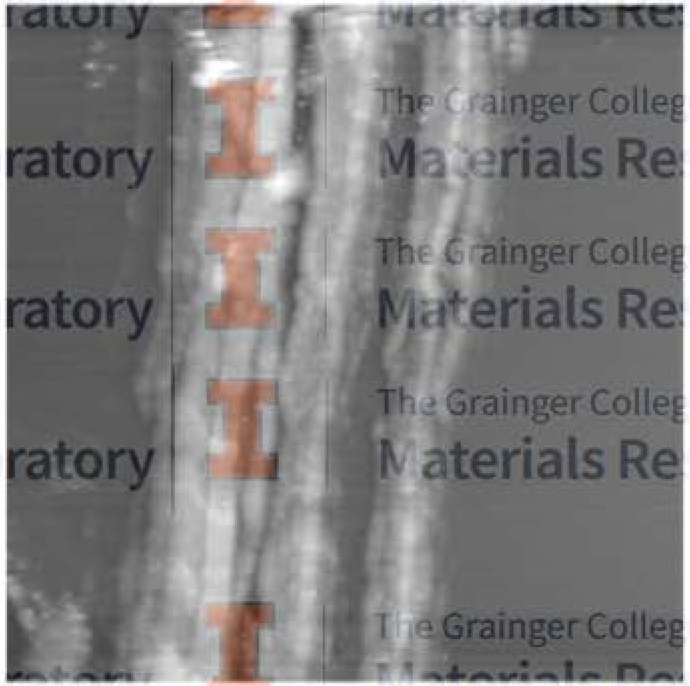


Multiple Tip Artifact

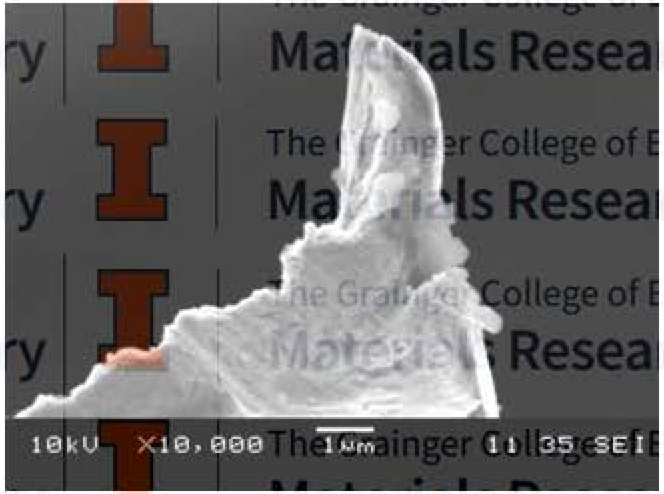
Really, really multiple tip

Cypher STM (+ 0.5 V, 0.08 nA)

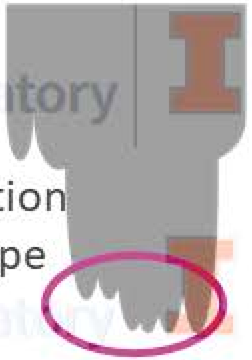
500 nm x 500 nm



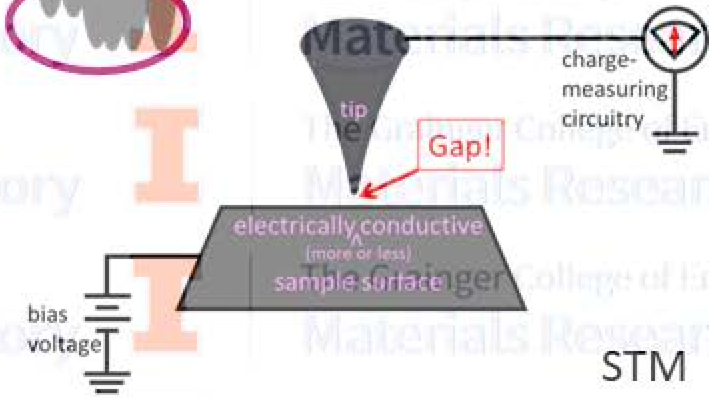
125 nm x 125 nm



SEM of an STM tip (not this tip)

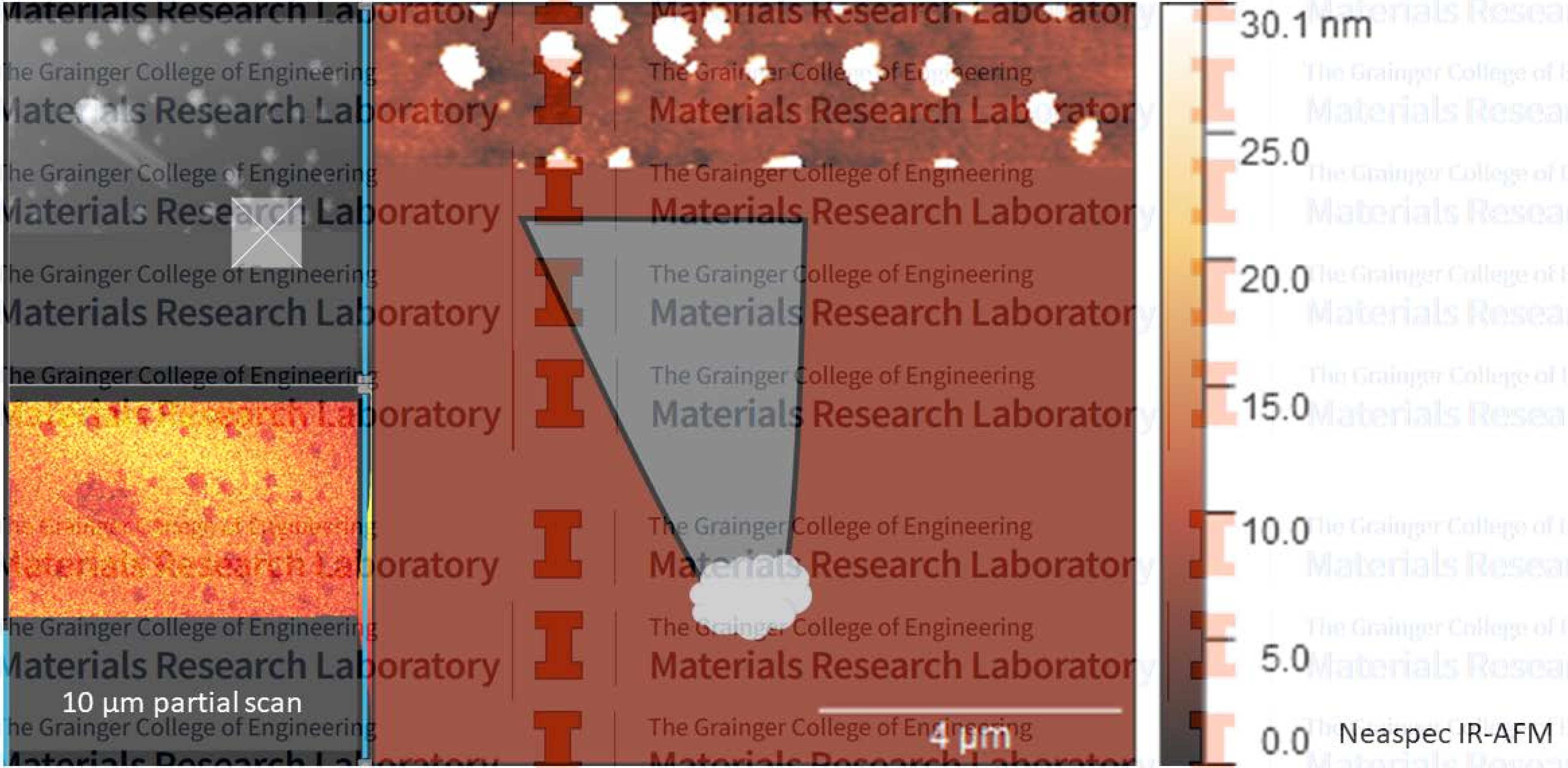


artist's conception of this tip's shape

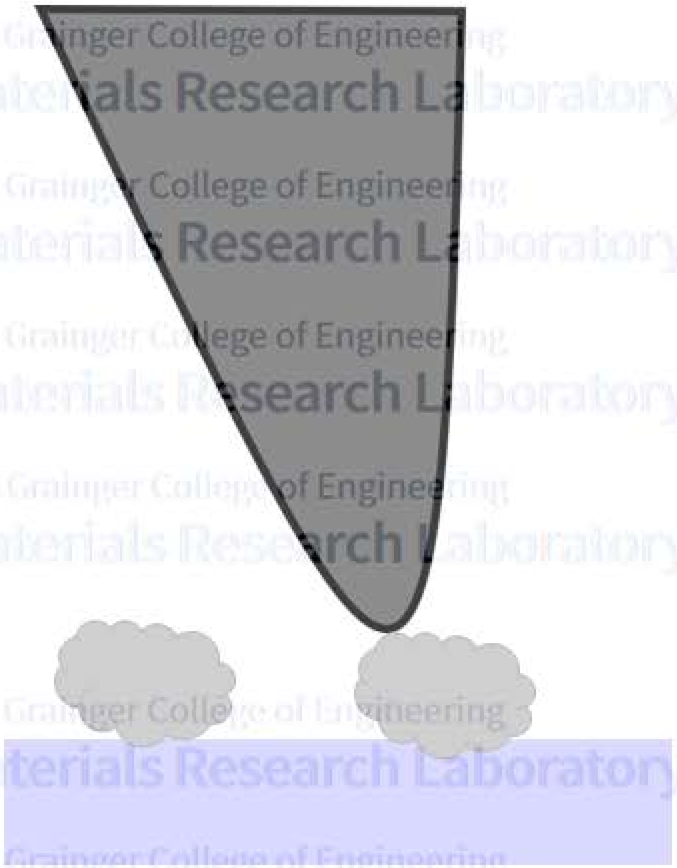


STM

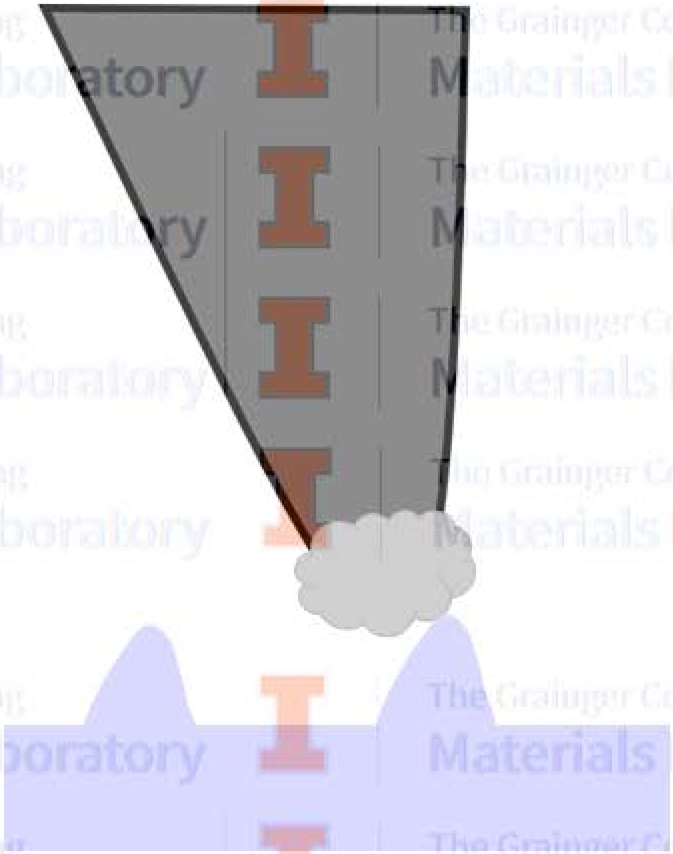
Contaminated Tip



Contaminated Tip

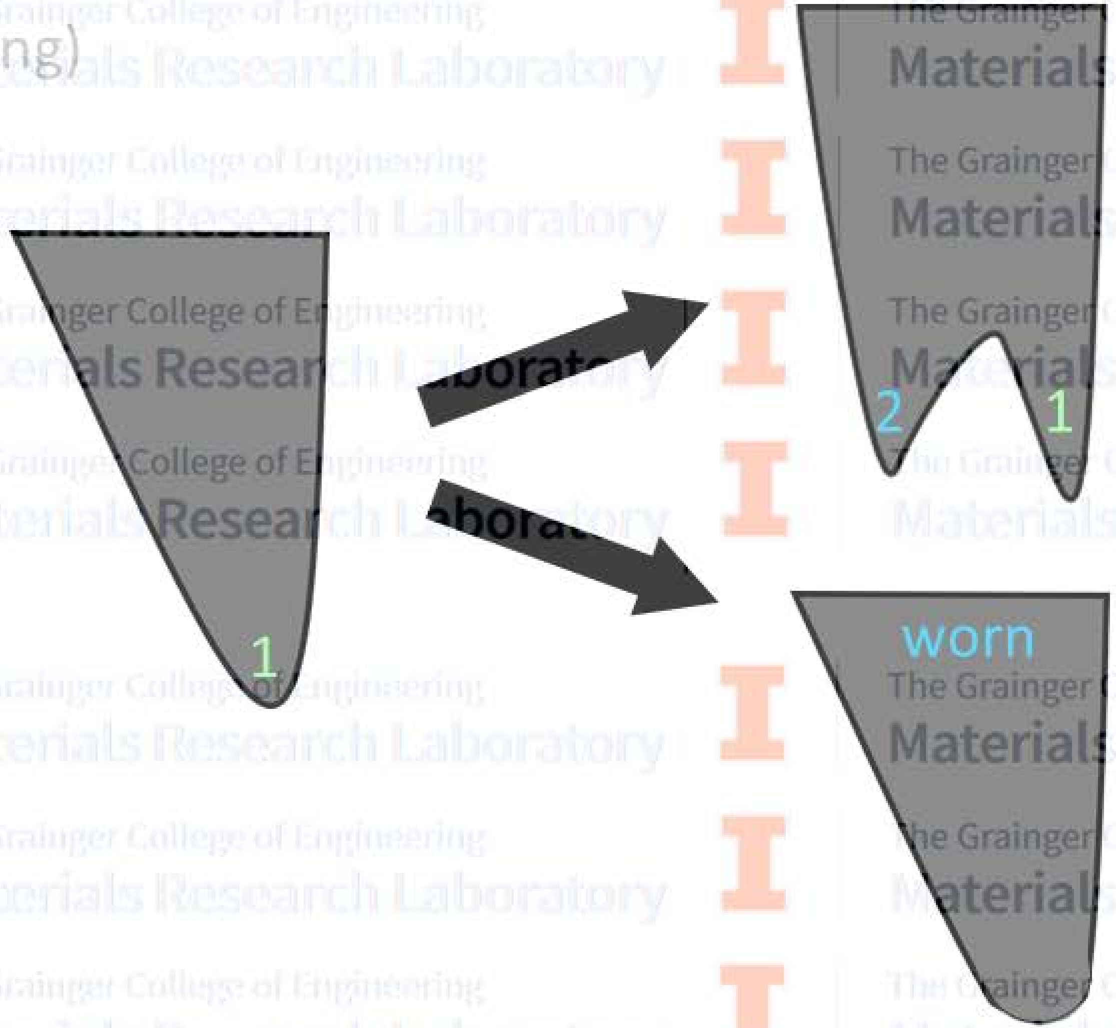


looks like



Tip Artifacts

- Sample
  - Moving too quickly (setup and scanning)
  - Drift (sample mounting, thermal)
- Tip
  - Multiple tip
  - Tip contamination/breaking/wear



What Can Go Wrong in AFM?

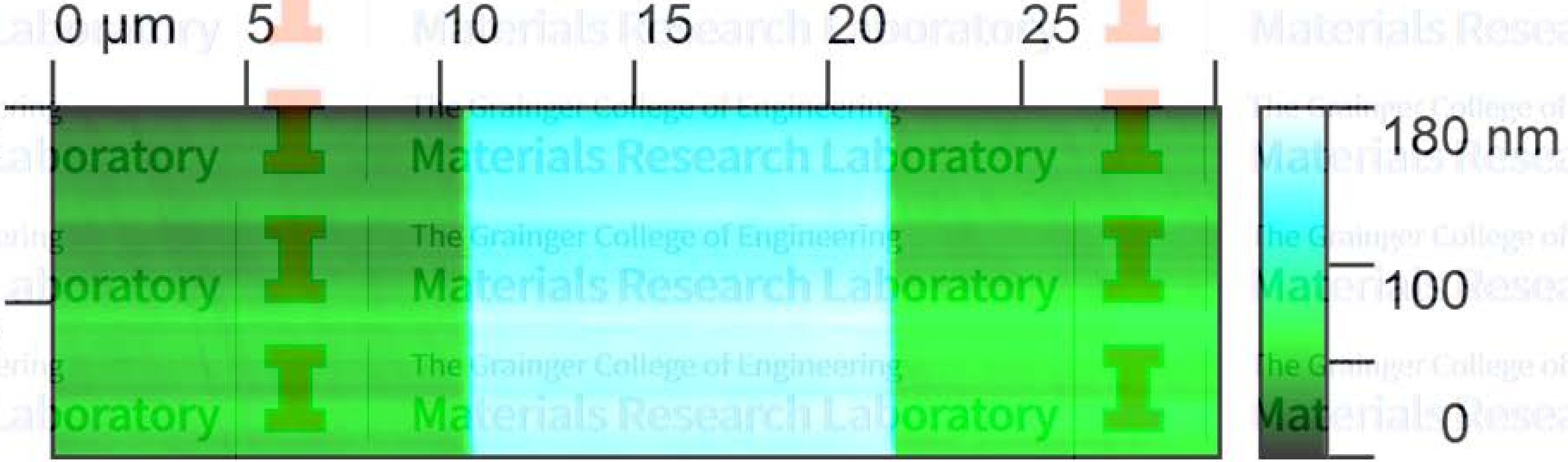
- Sample
  - Moving too quickly (setup and scanning)
  - Drift (sample mounting, thermal)
- Tip
  - Multiple tip
  - Tip contamination/breaking/wear
- Image processing
  - Flattening artifacts

Image Processing

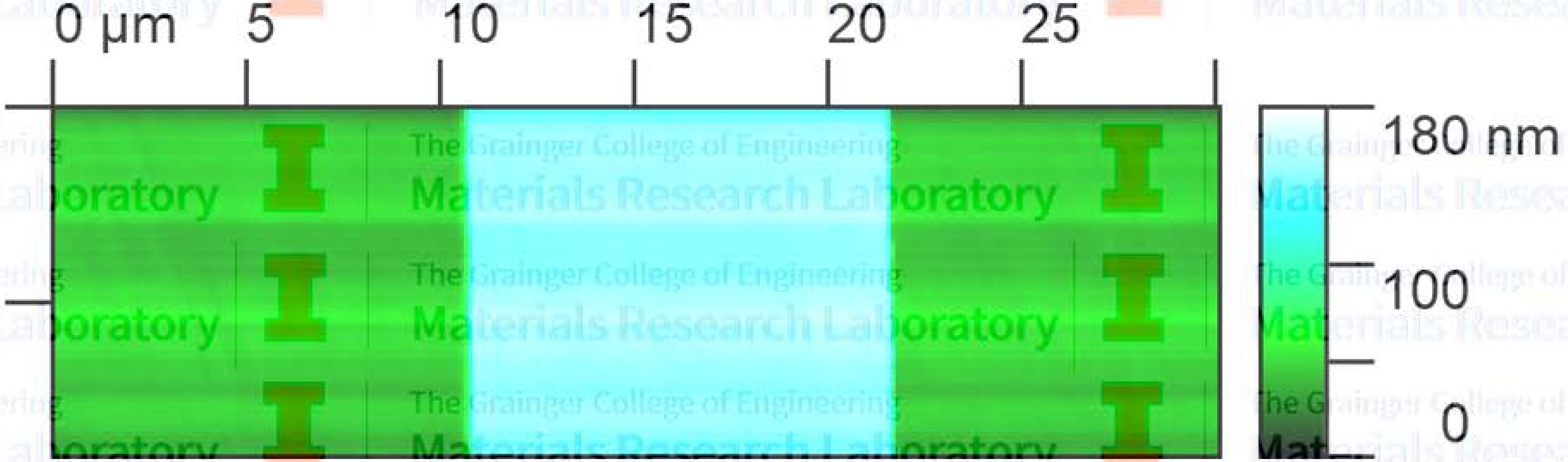
- Image processing generally needs to be done
- Practically every sample is tilted on the nanoscale with respect to the tip
- Either a plane or line-by-line subtraction is generally needed
- Image processing can introduce artifacts or misleading appearances
  - Flattening artifacts
  - Confusing colorscale choices
  - Watch out for these in papers

Tilt Correction

Original



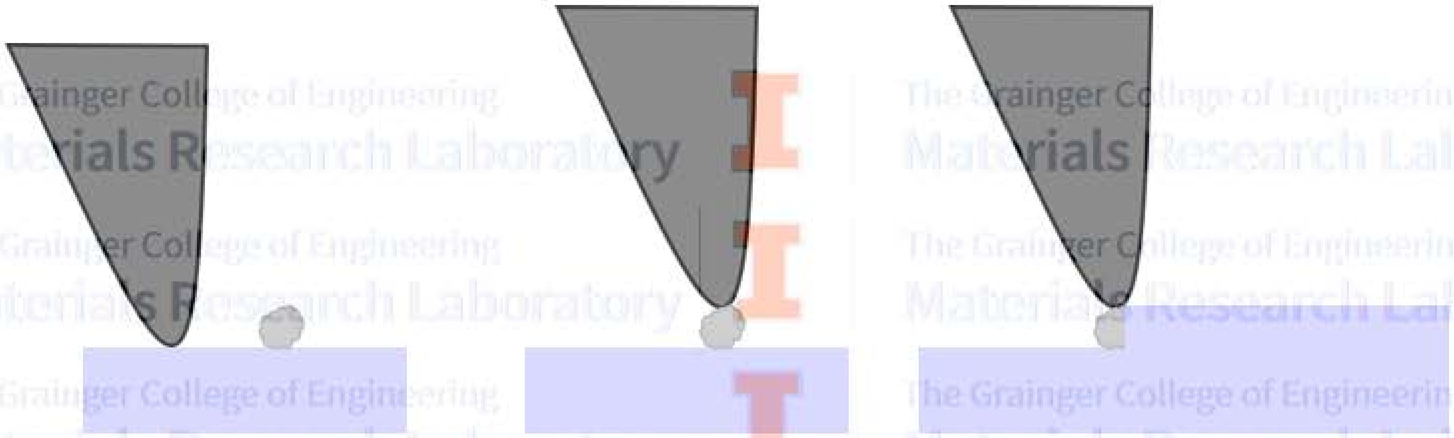
After subtracting substrate tilt

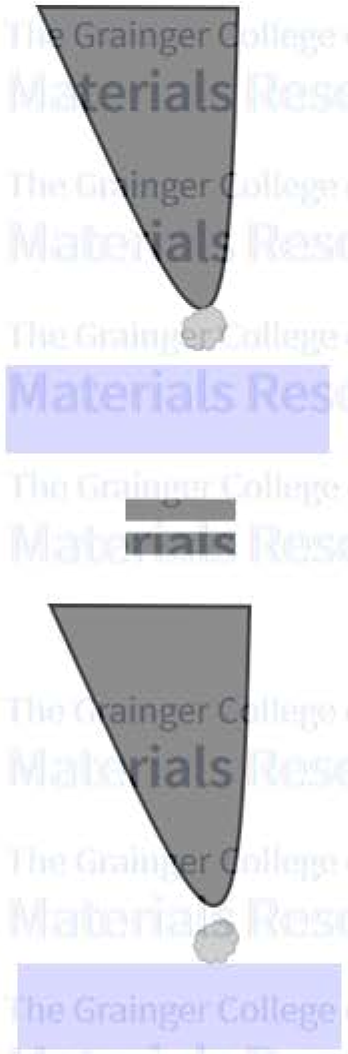


photomask sample courtesy of Jeff Grau

Line-by-Line Correction

- Difference from line to line, abrupt or gradual
- Rastering has a fast scan and slow scan direction
- Changes often happen along the slow scan direction
  - Drift
  - Periodic noise
  - Tip condition changes
- Polynomial subtraction

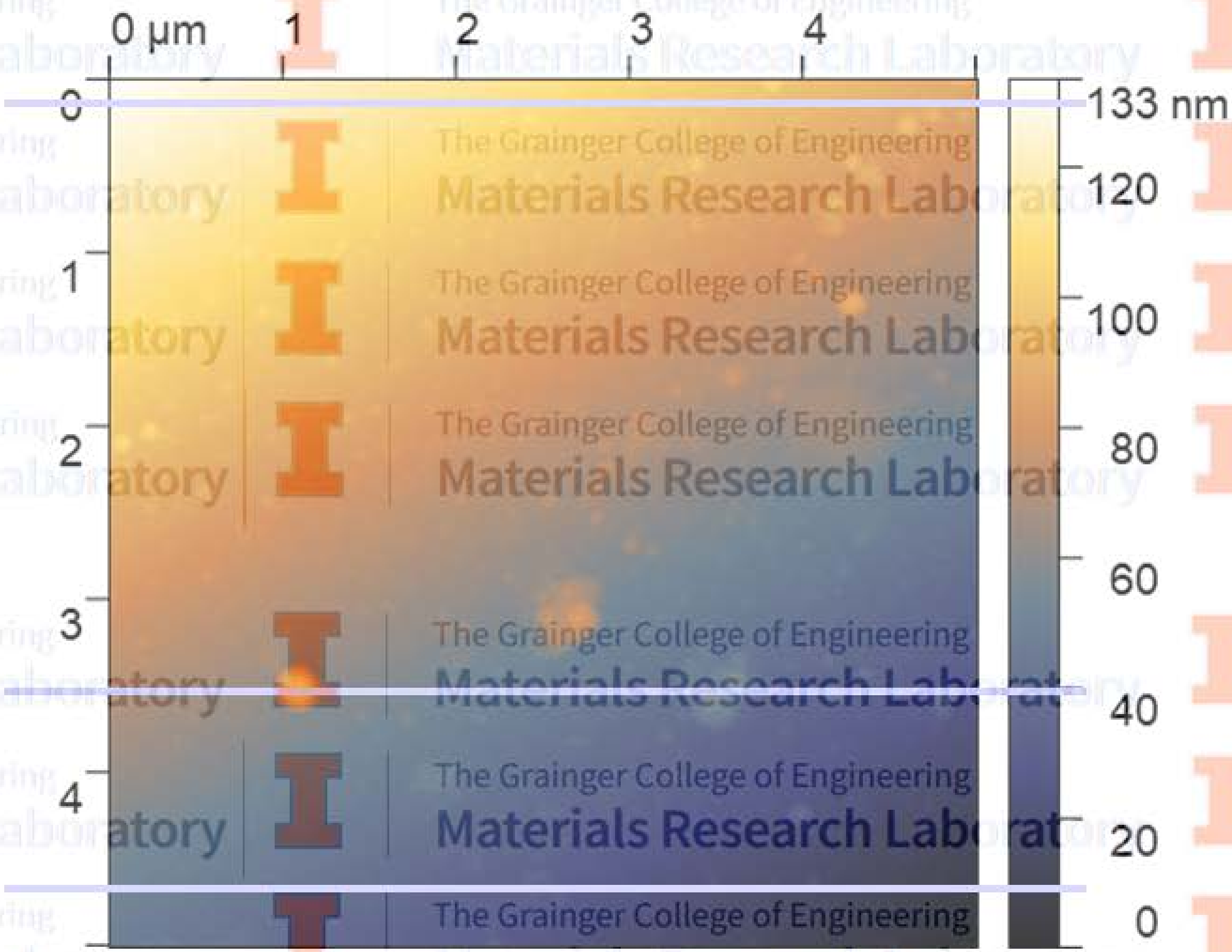




Masking

masking: ignore outliers when processing

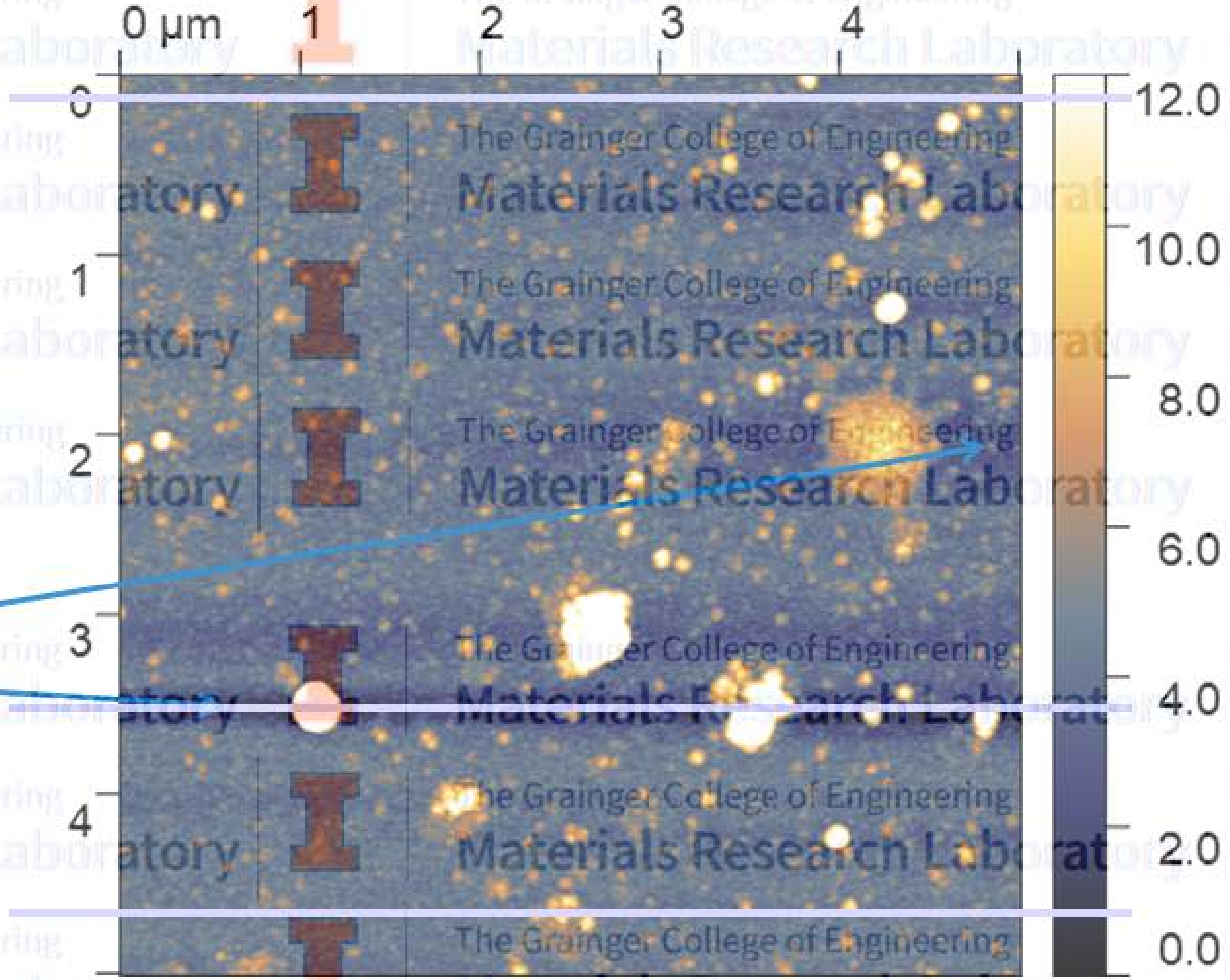
raw image



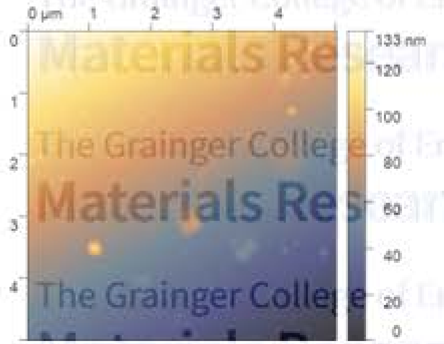
Si_3N_4 sample courtesy of Toyanath Joshi

Masking

line subtraction



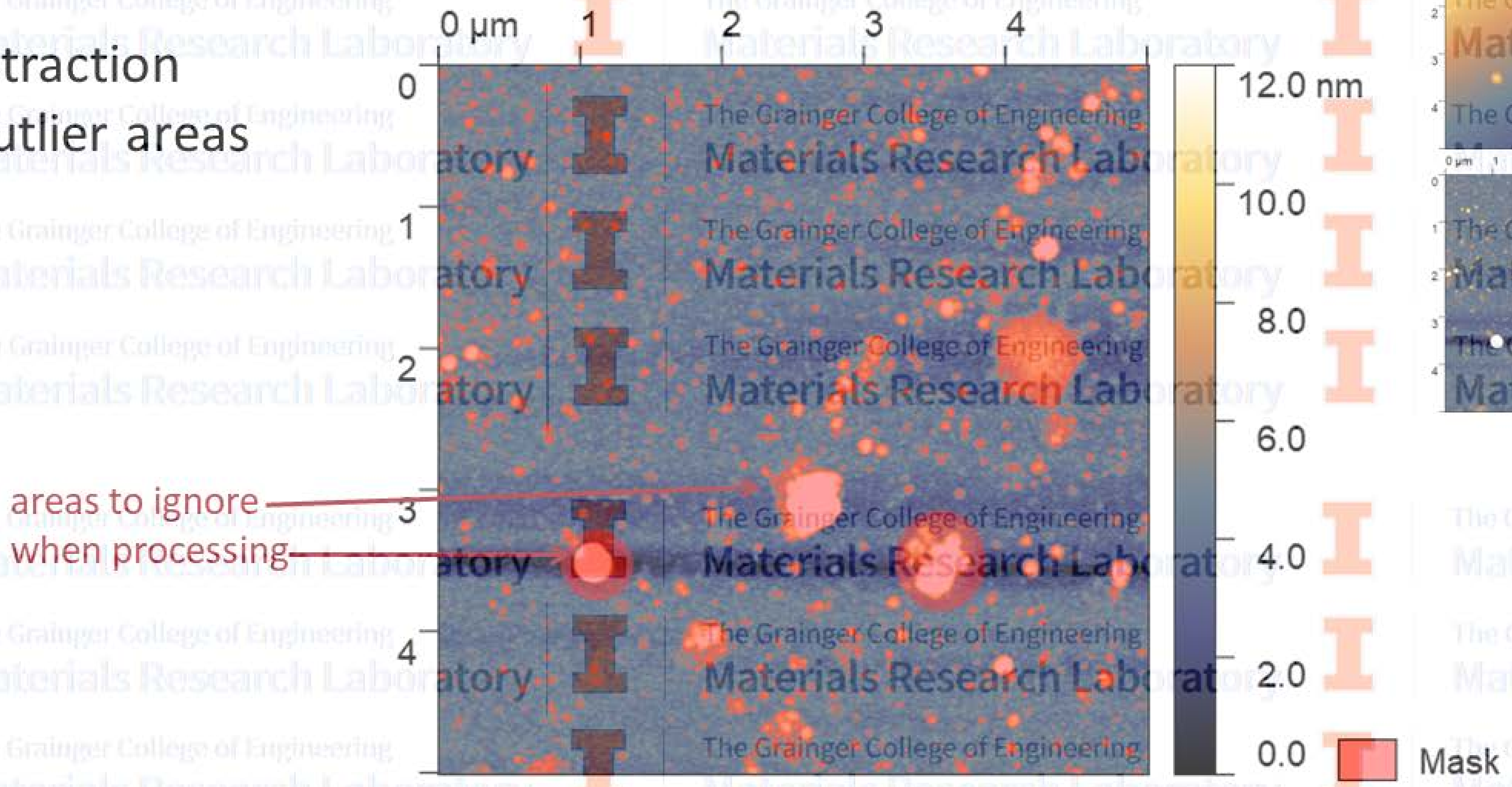
artifactually
lowered areas

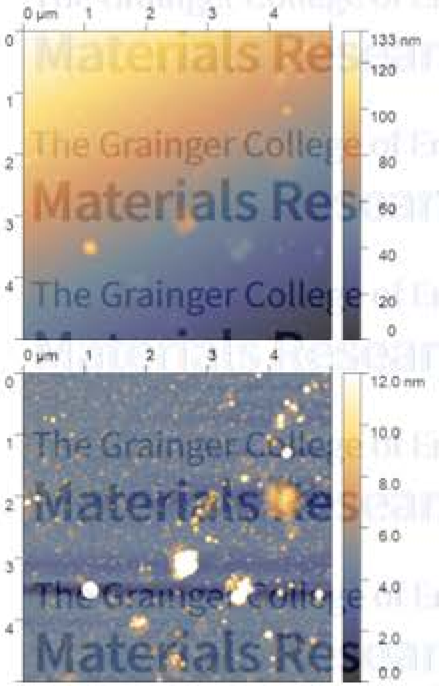


Masking

line subtraction

mask outlier areas



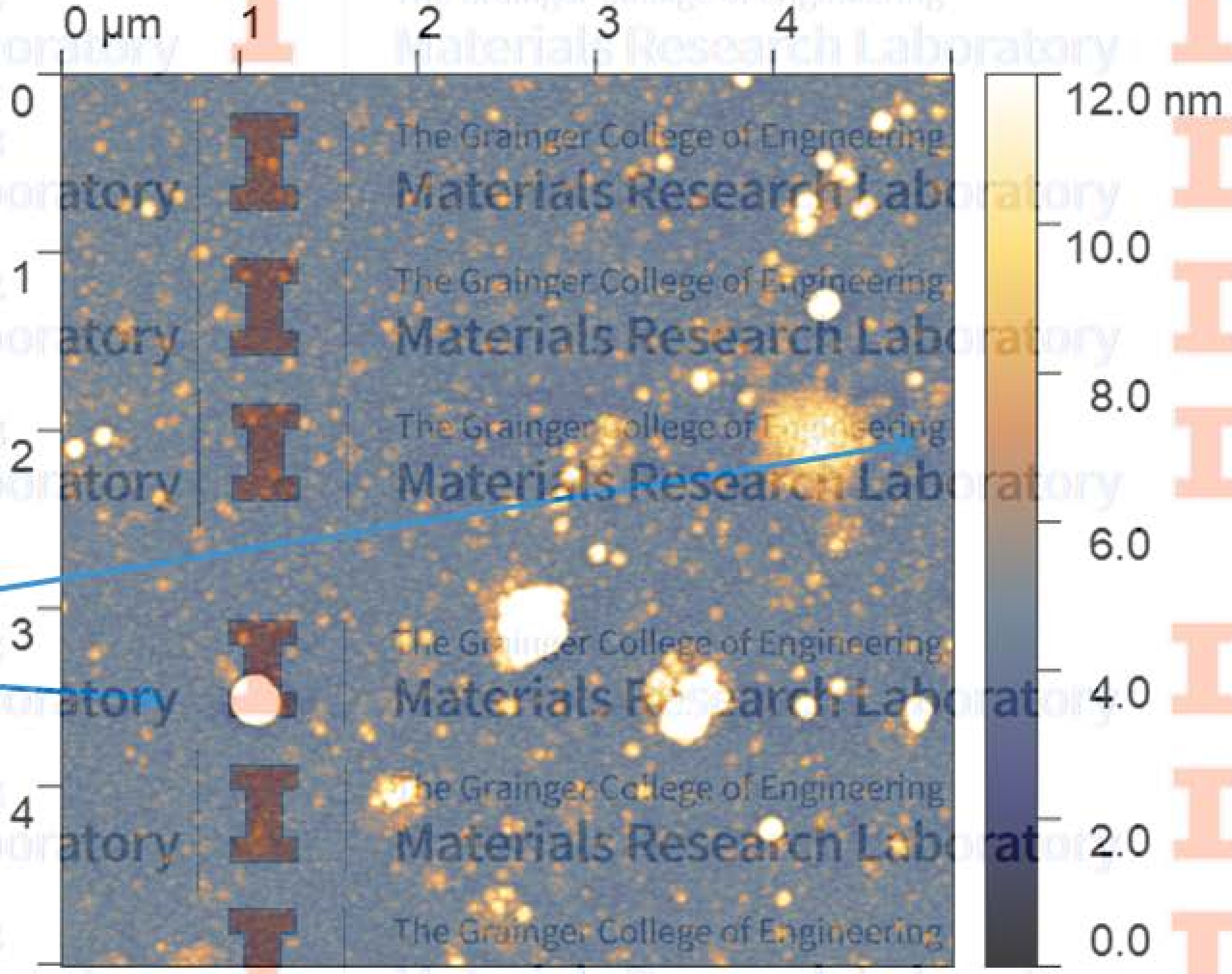


Masking

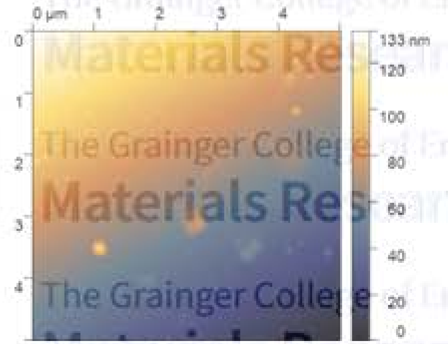
line subtraction

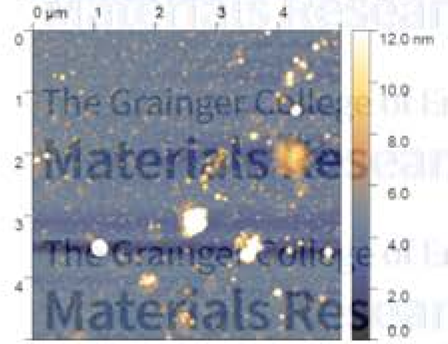
masked line subtraction

(polynomial of order 1)



no more streaks





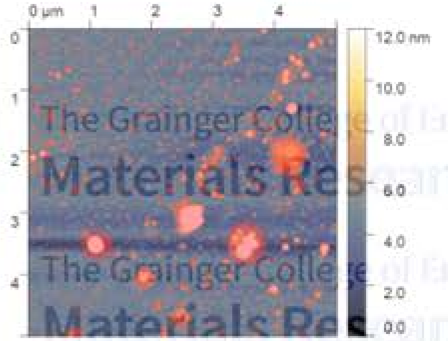
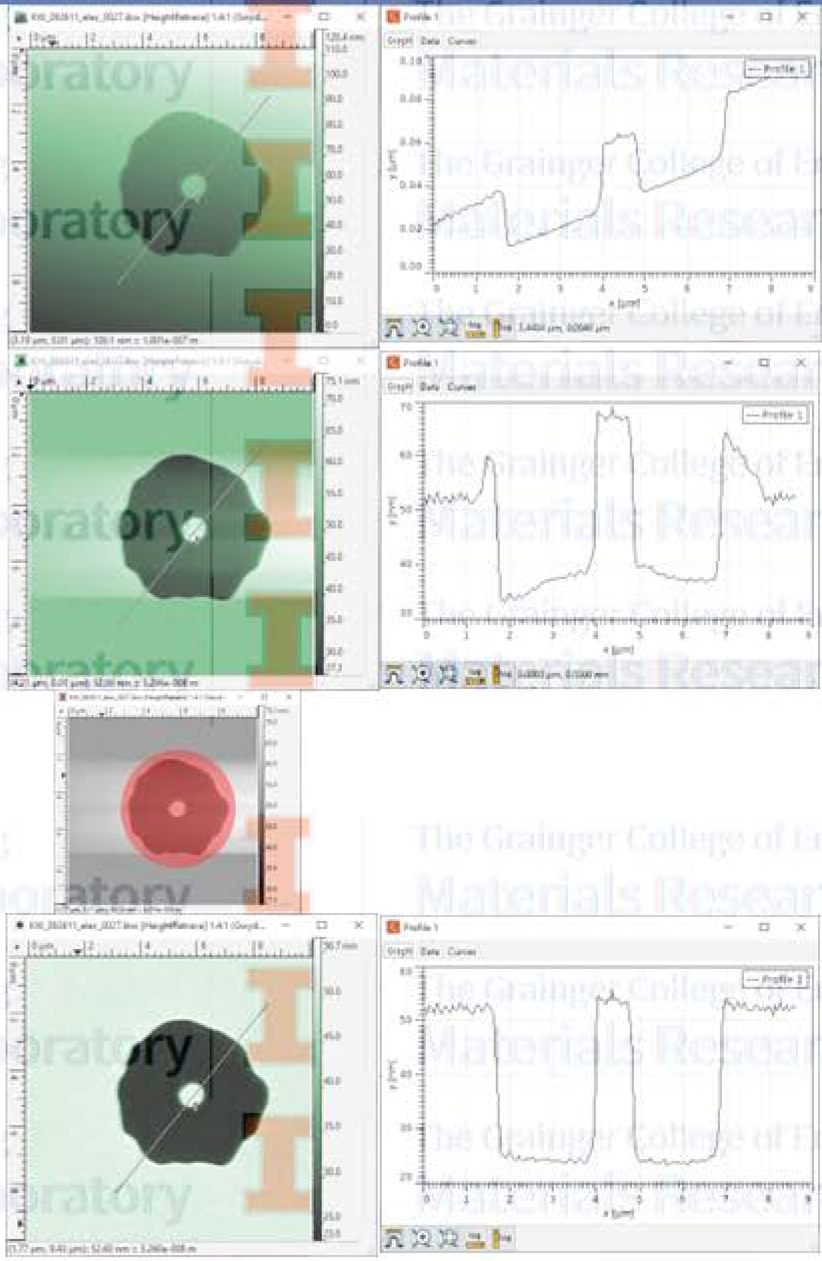


Image Processing

- Image processing will affect the image appearance
- Image processing will affect step height results
- Image processing will affect roughness results

- But XYZ coordinates are not all AFM can give…

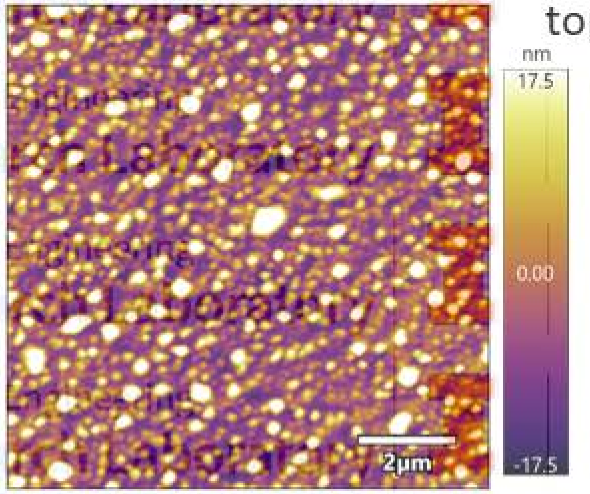


So Many Applications

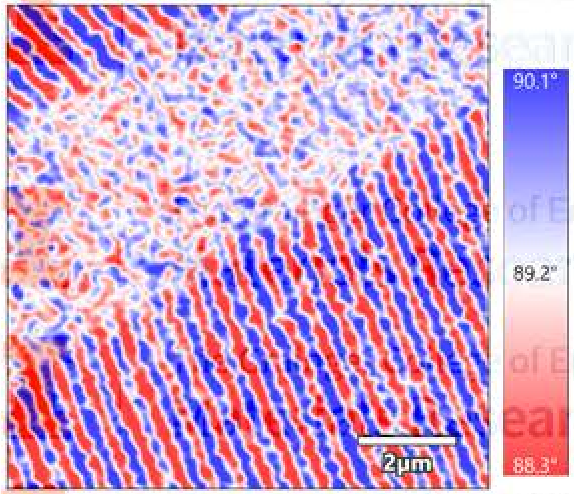
- EFM (conductors in insulators)
- KPFM (surface electrical potential)
- MFM (magnetic domain mapping)
- LFM (friction)
- PFM (piezoelectric domain mapping)
- Nanolithography/nanomanipulation

- … and these are just a few of the ones that generally don't need extra gear (except different tips)

topography



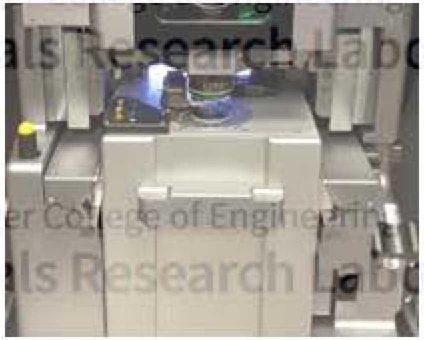
MFM phase

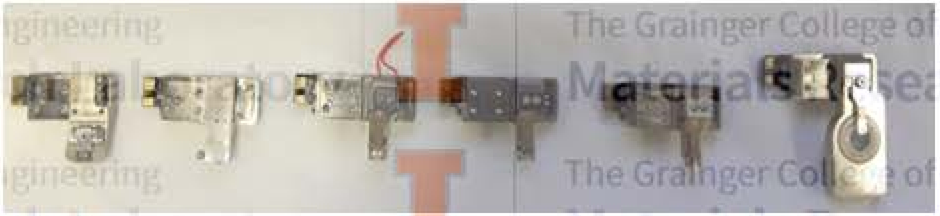


Accessories for the MRL AFMs

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

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





cantilever holder assortment

MRL AFM Labs

Lab tour **tomorrow 4-5pm** (don't miss it!)

B12: main MRL lab (Cypher, MFP-3D-SAs)

0024: scanning probe optical spectroscopy lab (PiFM/Raman, TERS/TEPL, sSNOM)

0026: bio AFM lab (MFP-3D on inverted optical fluorescence microscope)

B80: stylus and optical profilometry lab (affiliated techniques)

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