Microstereolithography and AFM

2.674

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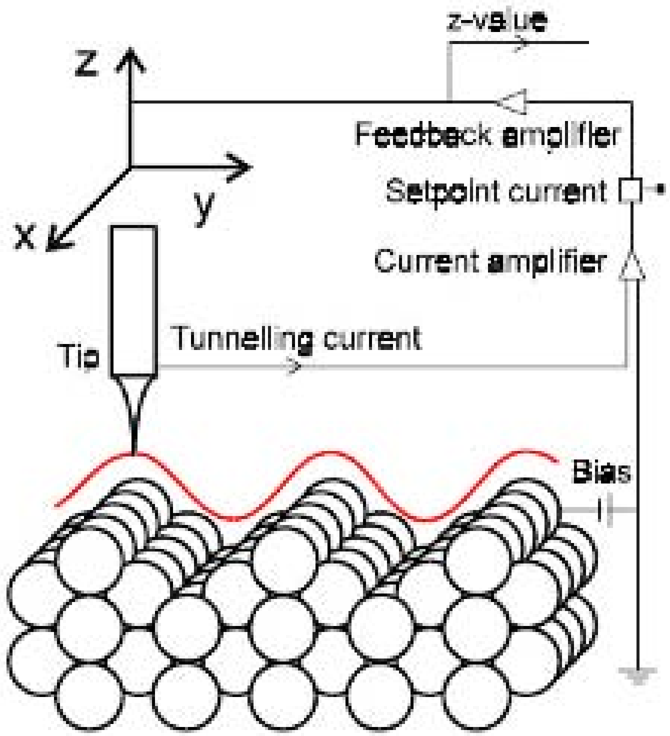
Slides courtesy Profs. Sang-Gook Kim, Rohit Karnik & Mathias Kolle

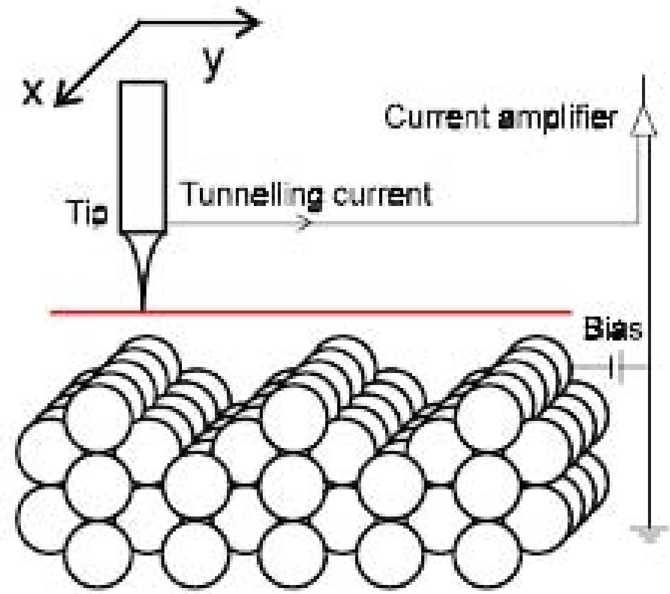
Atomic force microscope

For having high resolution image: TEM, AFM, STM

	Scanning Electron Microscope	Transmission Electron Microscope	Scanning Tunneling Microscope	Atomic Force Microscope
	SEM	TEM	STM	AFM
Lateral Resolution	5 nm	0.2 nm	0.1 nm	30 nm
Vertical Resolution	None	None	0.01 nm	0.1 nm
Magnification	2D	2D	3D	3D
Sample preparation	No	Difficult (FIB, Milling)	Extremely clean surface	Clean surface
Environment	Vacuum	Vacuum	Vacuum	Vac/Air/Liquid
Cross-section image	Yes	Yes	No	No

Scanning tunneling Microscope





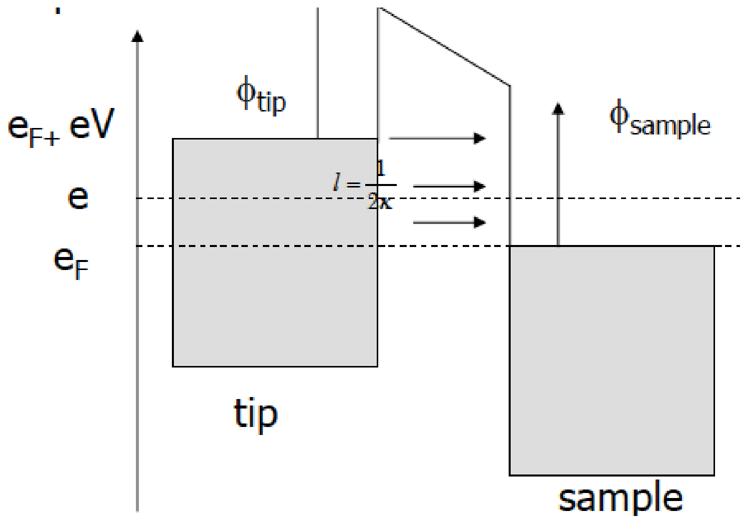
<u>Constant Current Mode</u>

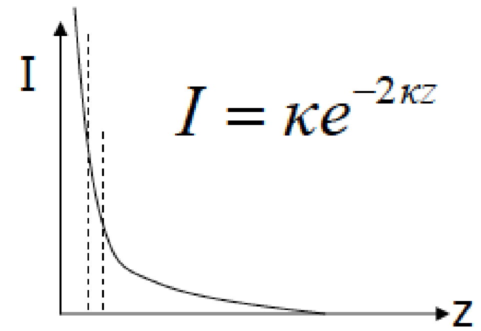
- Typical mode of operation
- Slow: z-stage must respond!
- Can tolerate rougher surface

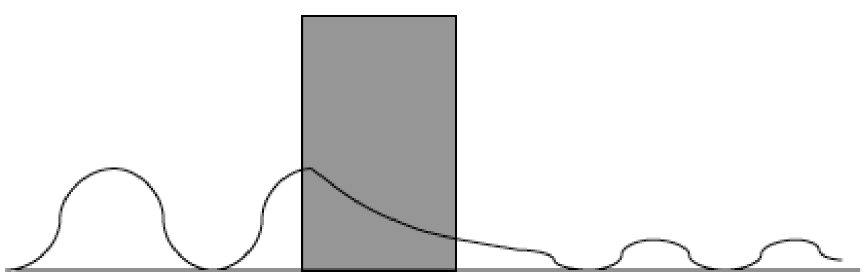
<u>Constant Height Mode</u>

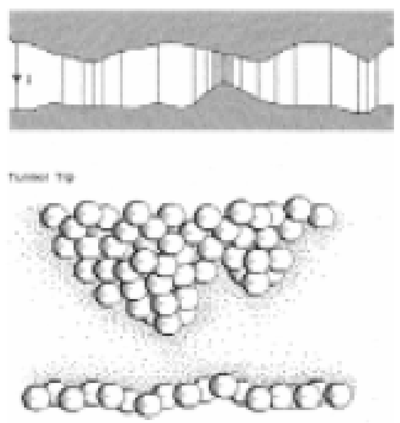
- Fast: z-stage need not respond
- Tilt sensitive
- Minimal drift
- Cannot tolerate rough surface

Quantum Tunneling



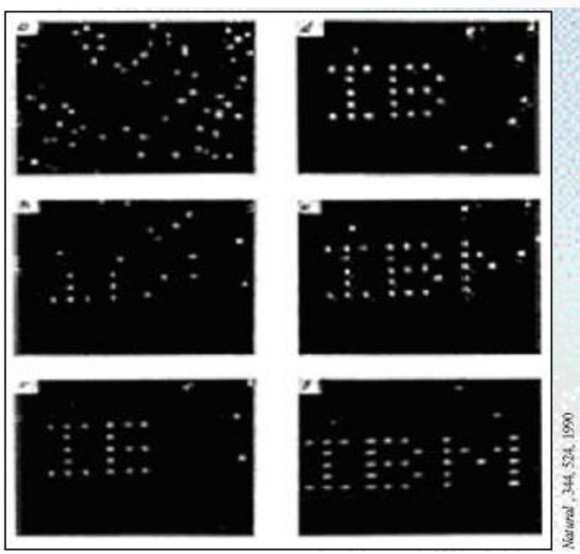


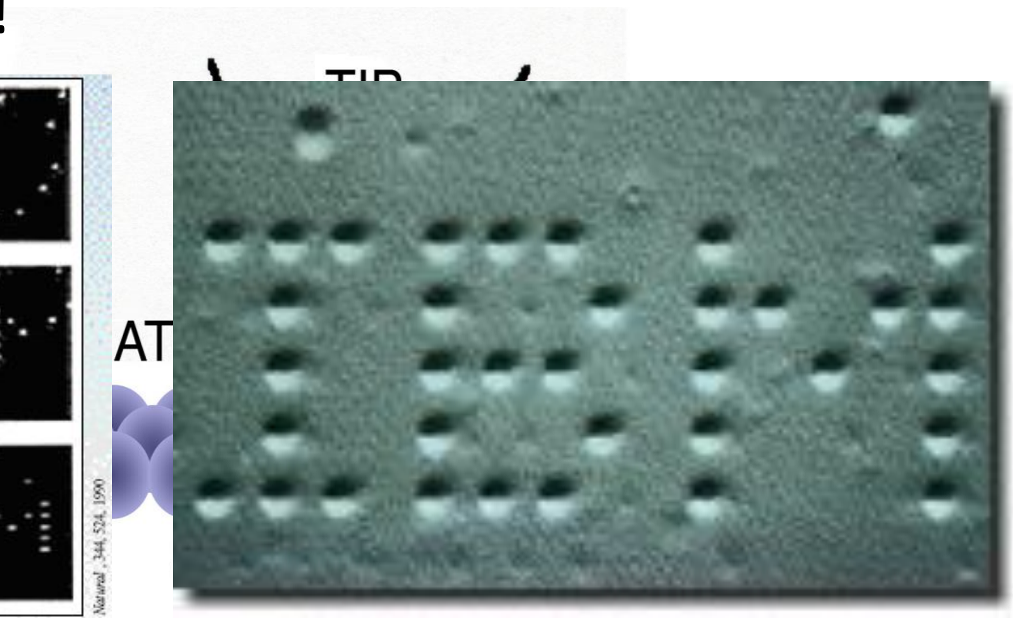




STM as a fabrication tool

- Can be used to move individual atoms!
  - Higher current creates a temporary “bond” between the tip and atom
  - “Bond” atom, move tip to new position, “release” atom!





Writing “IBM” with 35 xenon atoms on nickel (IBM Almaden, 1989)

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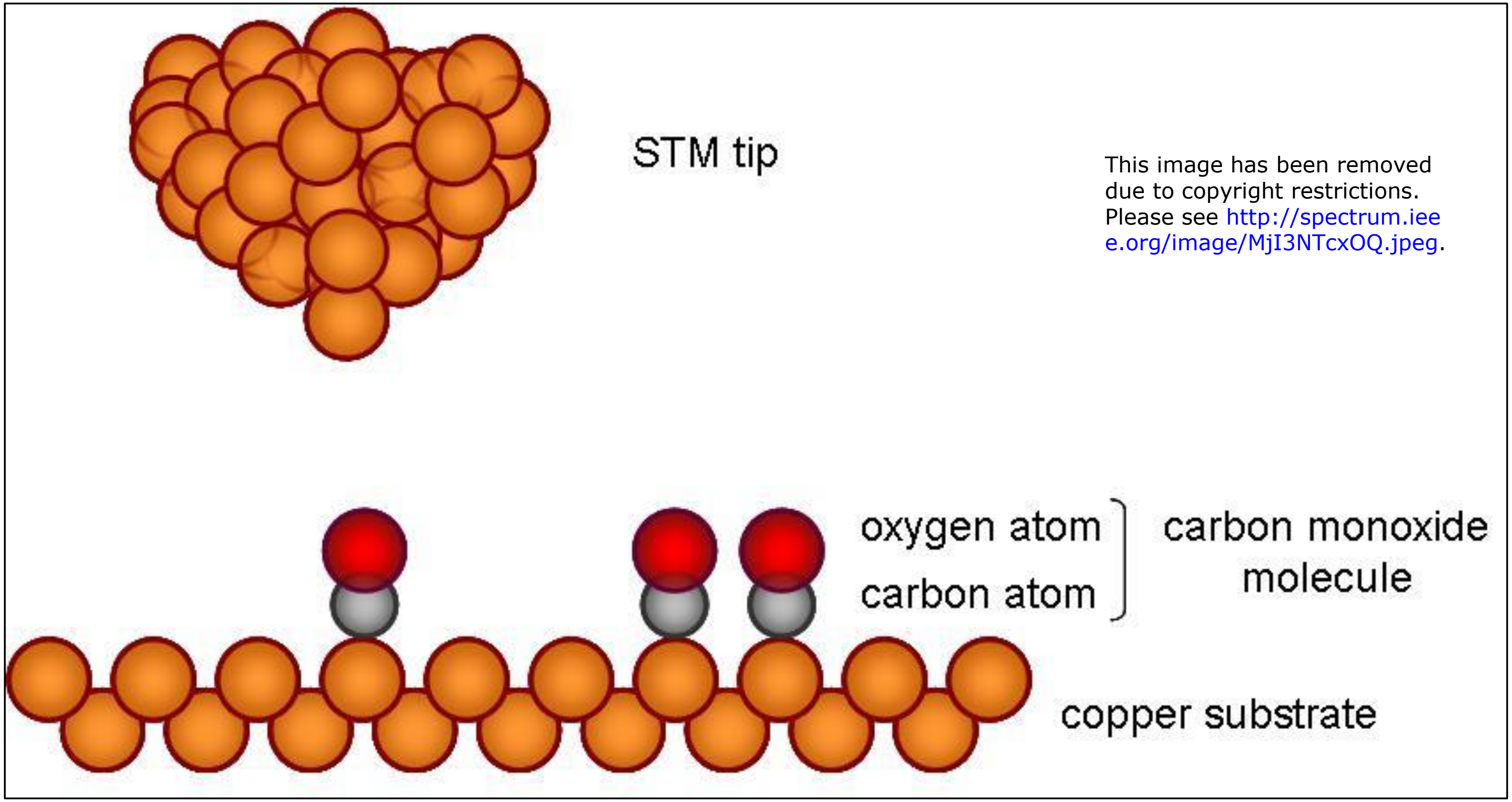
Please watch the video at https://www.youtube.com/watch?v=oSCX78-8-q0.

The atoms of (and in) Adam

To be precise – it's really molecules

Carbon monoxide on a copper (111) surface

T around 5 K (-268ºC)



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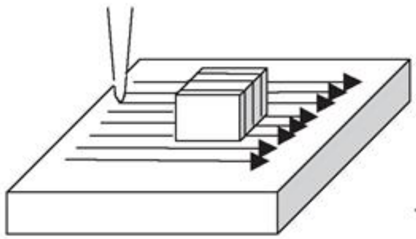
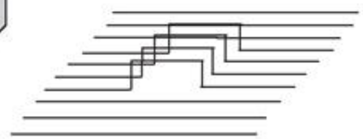
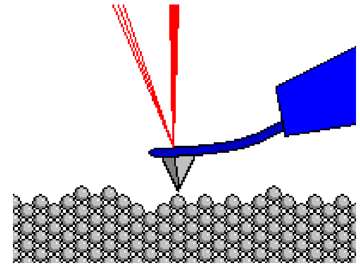
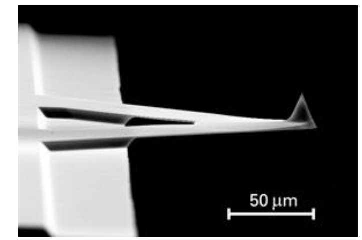
http://ibmresearchnews.blogspot.com/2013/05/atom-atom-molecule.html?cm_mc_uid=18927854944214476364271&cm_mc_sid_50200000=1447636427

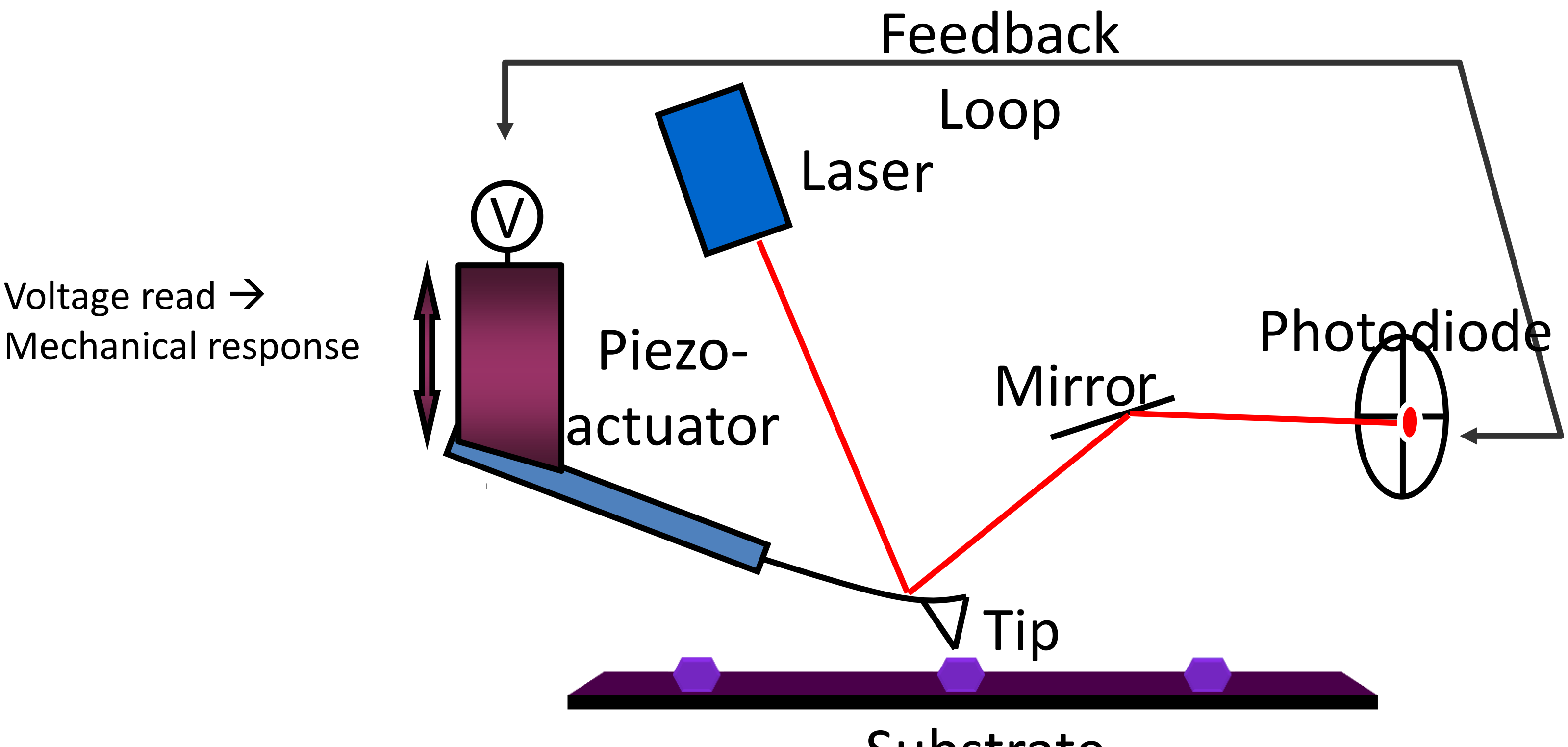
Atomic Force Microscope (AFM)











Piezoelectric materials (Perovskite)

Electric fields ←→ Elastic deformation or strain

1. Mechanical stress generates electric charge in the Sensor Mode

Jacques & Pierre Curie (1880)

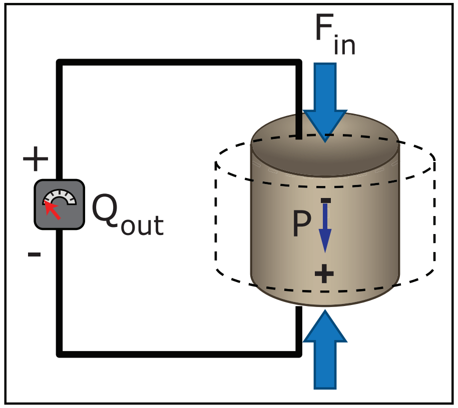
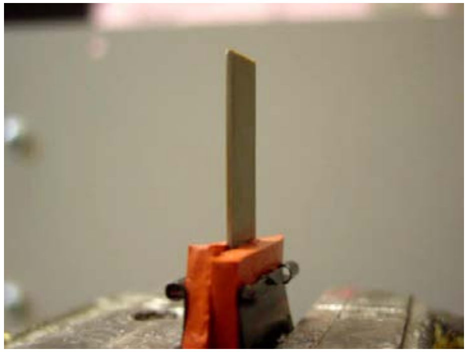
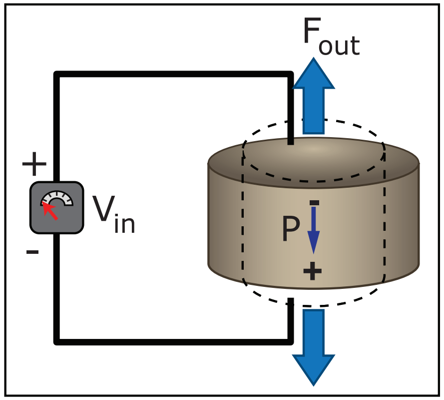


Figure by MIT OpenCourseWare.



2. Electric Field induces mechanical strain in the Actuation Mode

Lippmann (1881)



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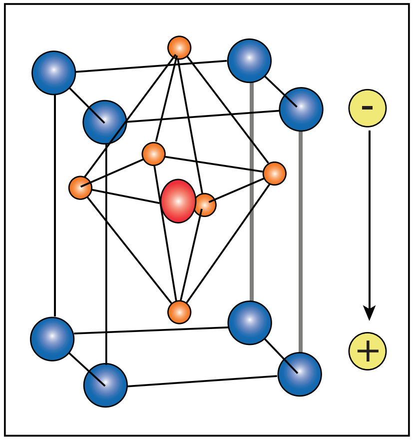

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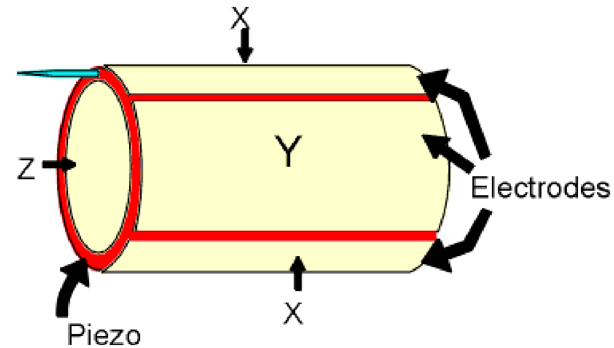
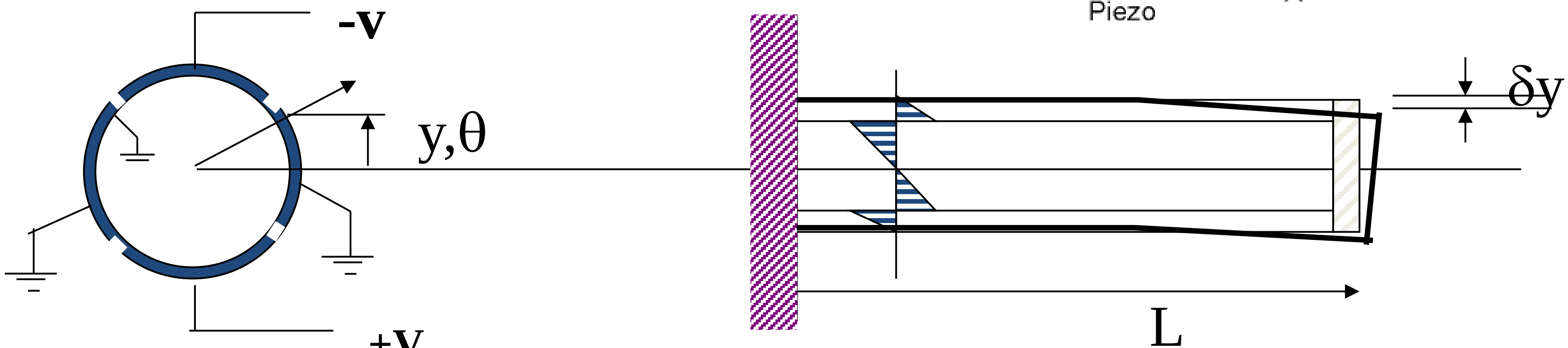
How to make x-y-z motion using piezo-actuator?

Tube scanner

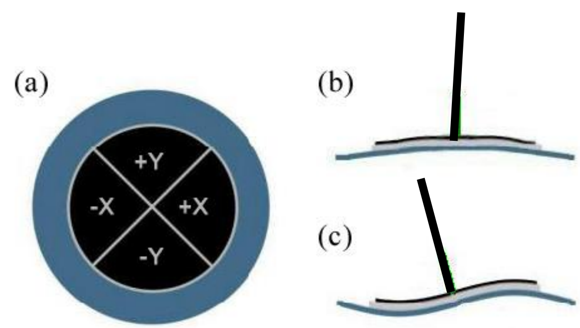


- Piezo Tube with ¼ electrodes

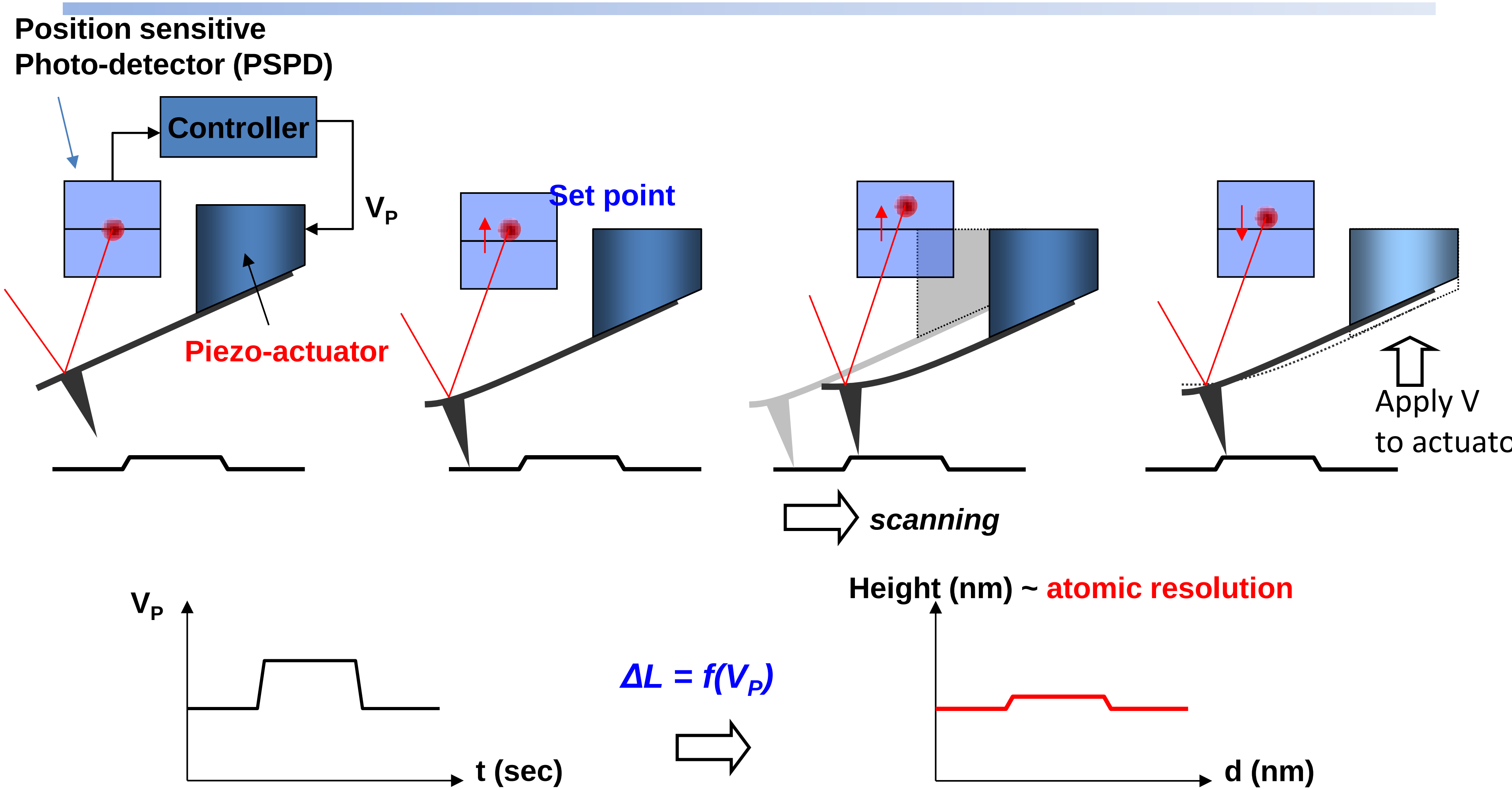


See C.J. Chen,Introduction to Scanning Tunneling Microscope, Oxford, 1993, P224-229

Piezo disc, a cheap solution



Scanning principle: Contact mode

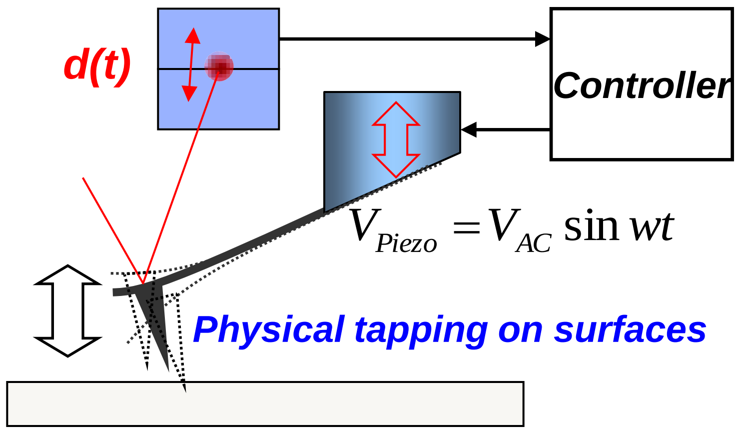


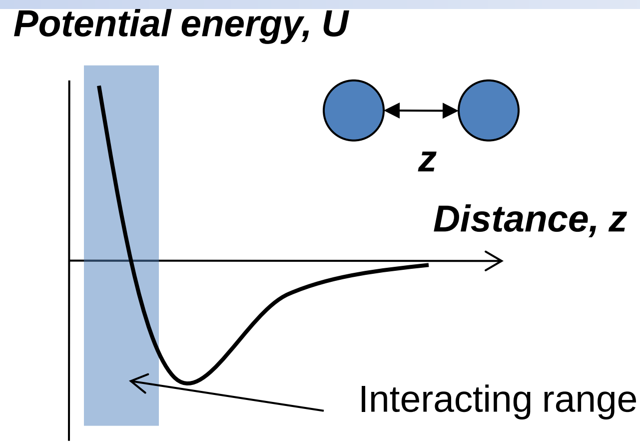
Applied voltage to the piezo-actuator

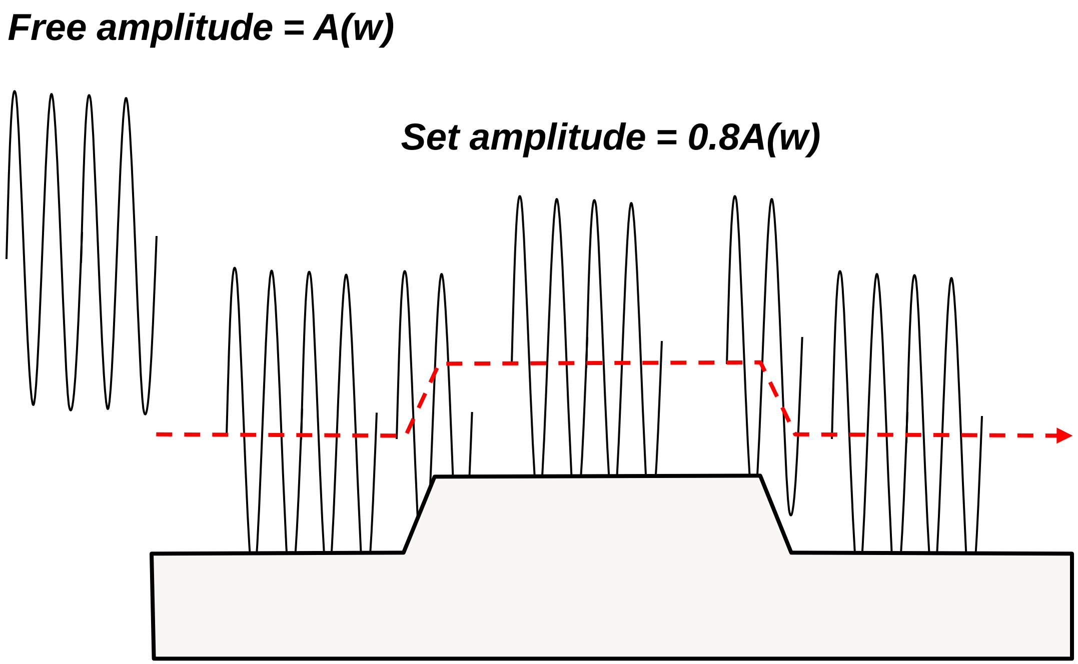
Translation of the voltage to height and position

This mode 1) damages sample surface, 2) cannot image liquid

Scanning Principle: Tapping mode (AC)



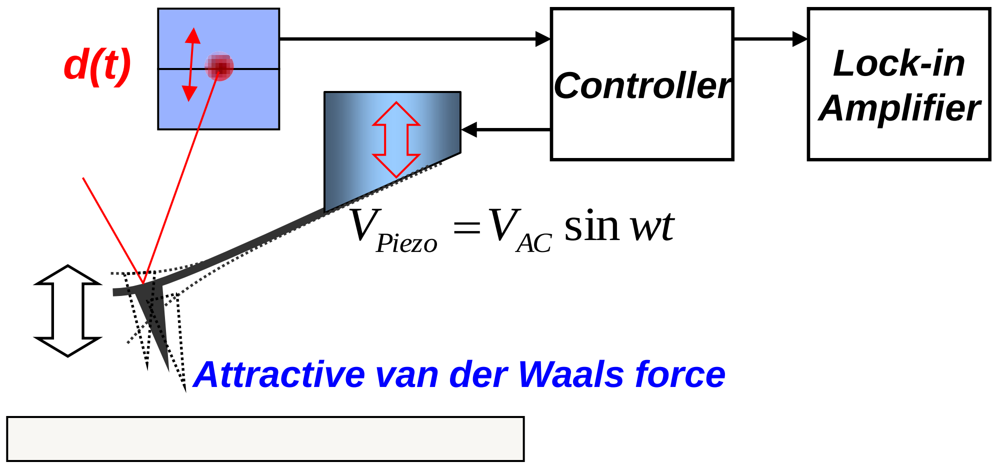


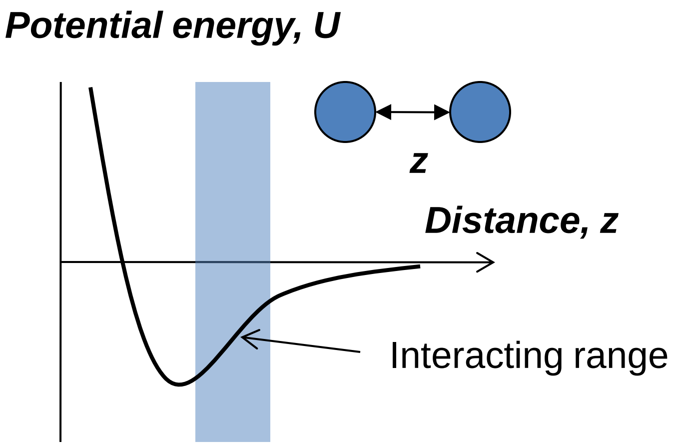


- Tapping mode is used for most surface topology
- Less damaging surface

Z-piezo actuator is controlled to maintain the set amplitude

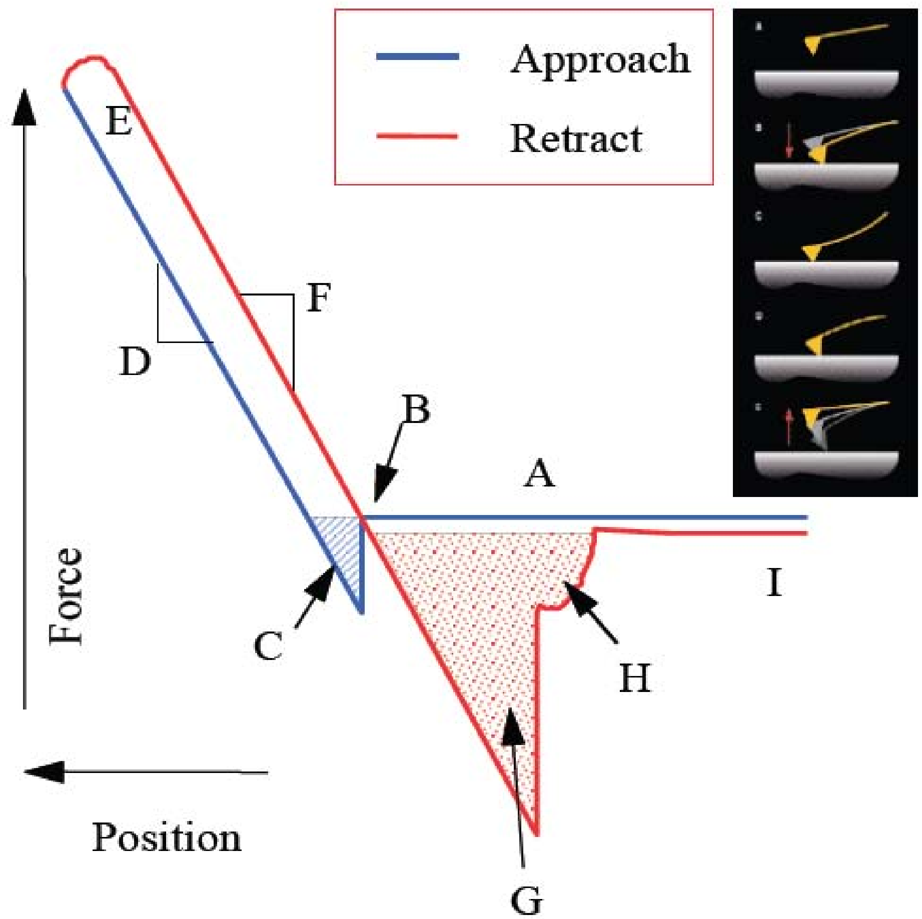
Scanning Principle: Non-contact mode (AC)





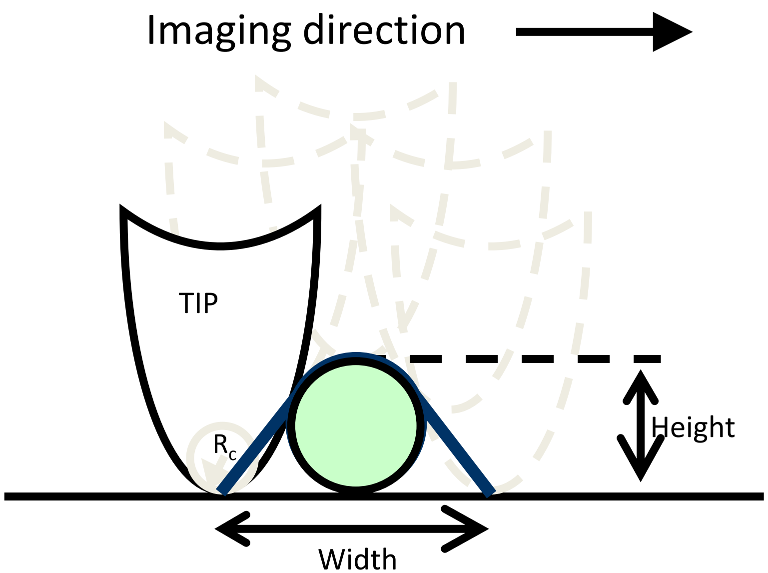
- Non-contact mode does not damage sample surface
- Non-contact mode can image liquid
- Difficult to find stable operation range

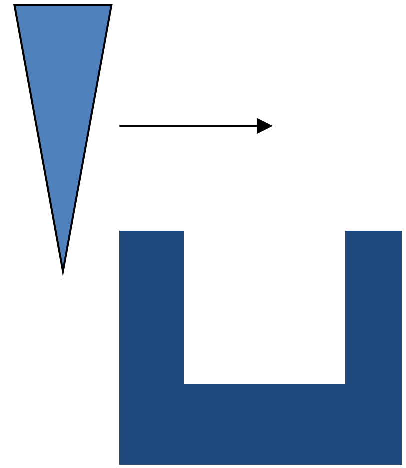
Force vs. Gap

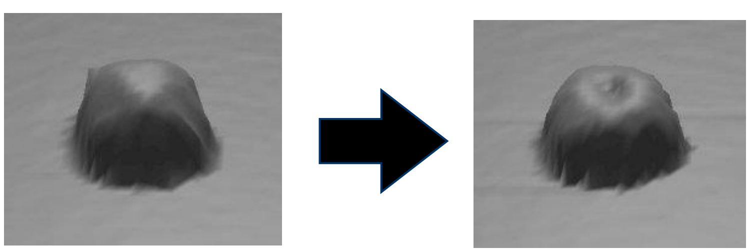


A	Cantilever approaches surface (thermal noise)
B	Snap to contact, tip is on surface (Hamaker constant)
C	"Attractive" work
D	Constant compliance region (Surface stiffness)
E	Hysteresis (viscous damping)
F	Retracting slope (surface stiffness)
G	"Adhesion" work (energy to separate surfaces)
H	Last bond(s) to break ("single bond forces")
I	Cantilever is off surface

Topological Limitation by Scanned Imaging







Tip Calibration

A home made AFM

- Interferometric AFM developed by Manalis et al. (APL, 69 (25), 1996)
- It detects the difference in motion between two neighboring cantilevers. → less sensitive to ground vibration

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Please see Figure 6 in https://www.media.mit.edu/nanoscale/courses/AFMsite/cantilevers.html.

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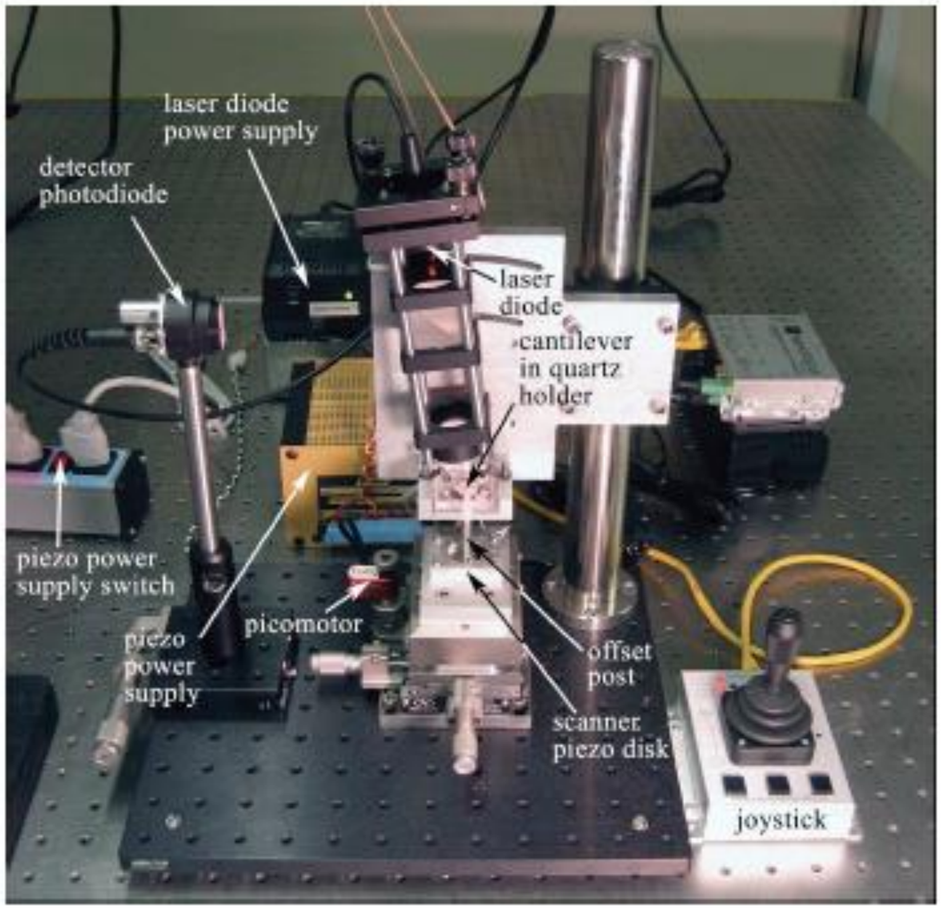
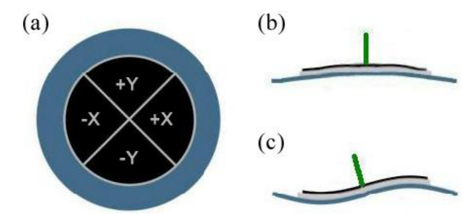
Please see Figure 1-5 in http://public.wsu.edu/~hipps/pdf_files/spmguide.pdf.

Diffraction–based AFM

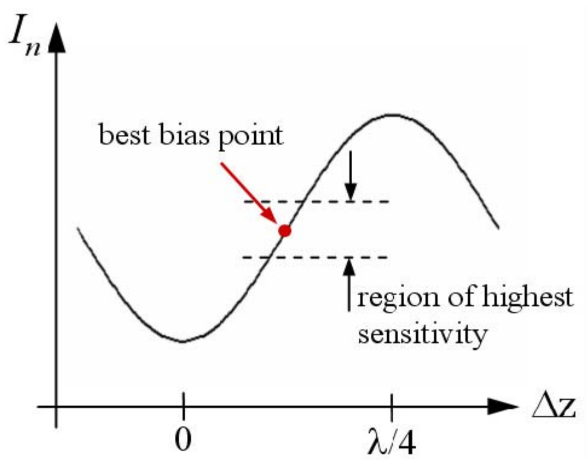
Classroom AFM System





Tunable grating

- No cantilever displacement → Fingers aligned
  - Even-numbered modes: brightest
  - Odd modes: darkest
- With cantilever displacement → Fingers displaced
  - Even-numbered modes: brightes
  - Odd modes: darkest
- This repeats every λ/4



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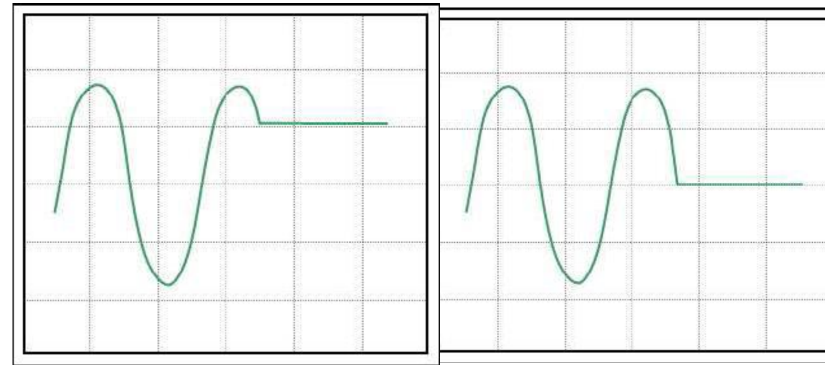
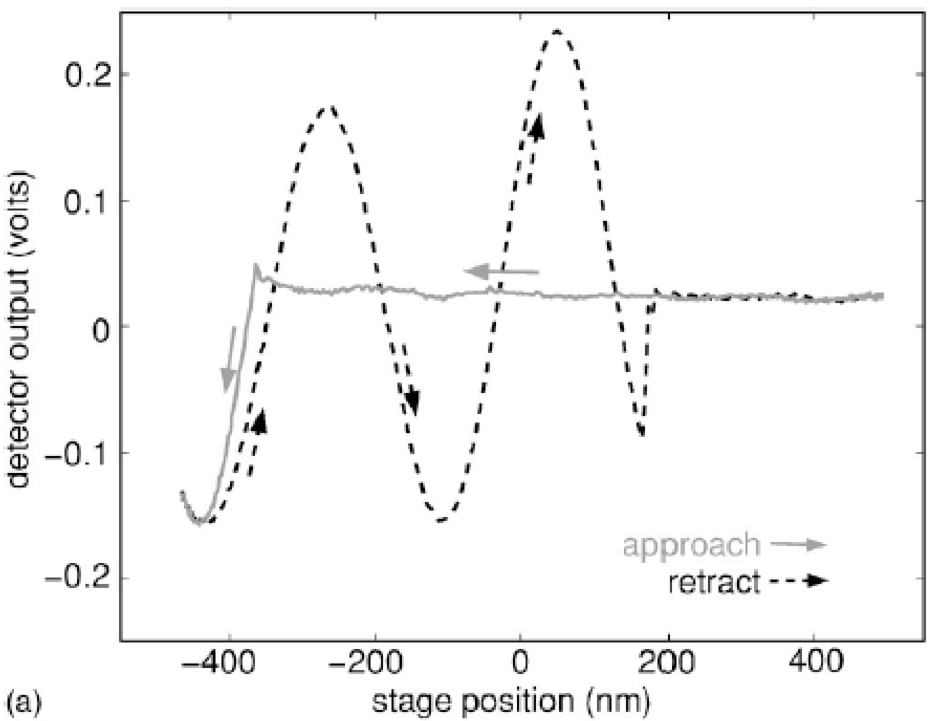
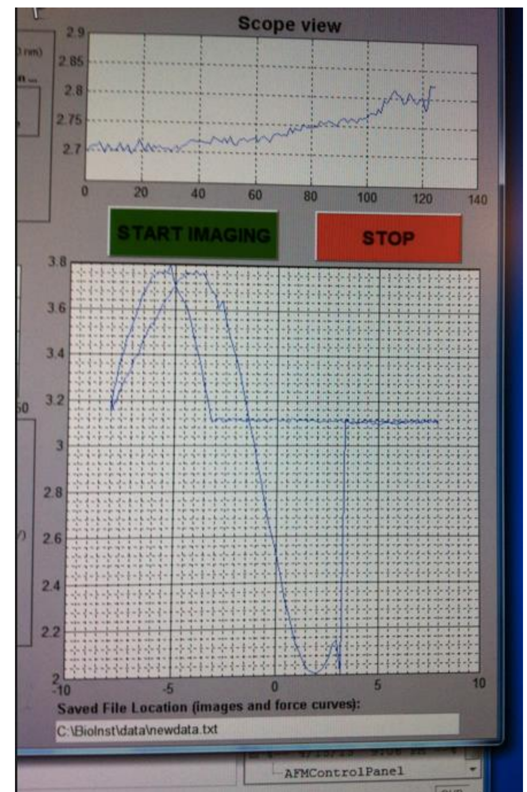
Barbastathis and Kim, 2003

Calibration

- Z-mode operation, 2Hz, 8 V
- Calibration (v/nm)

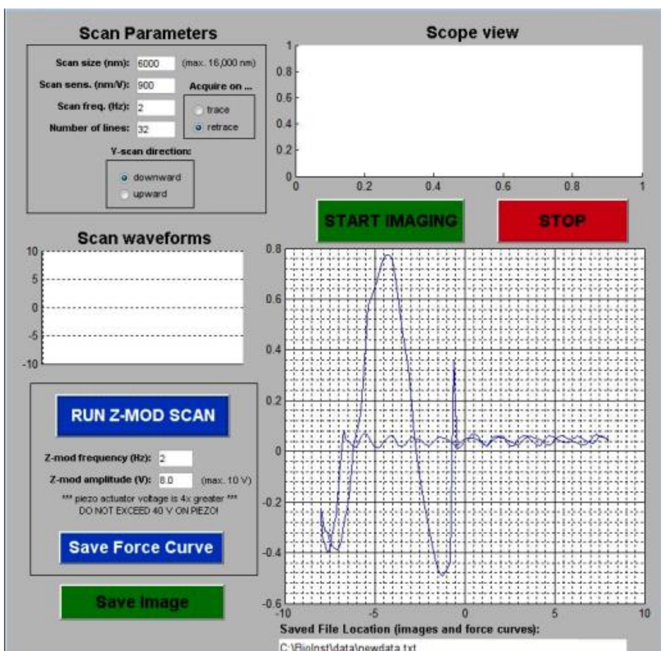


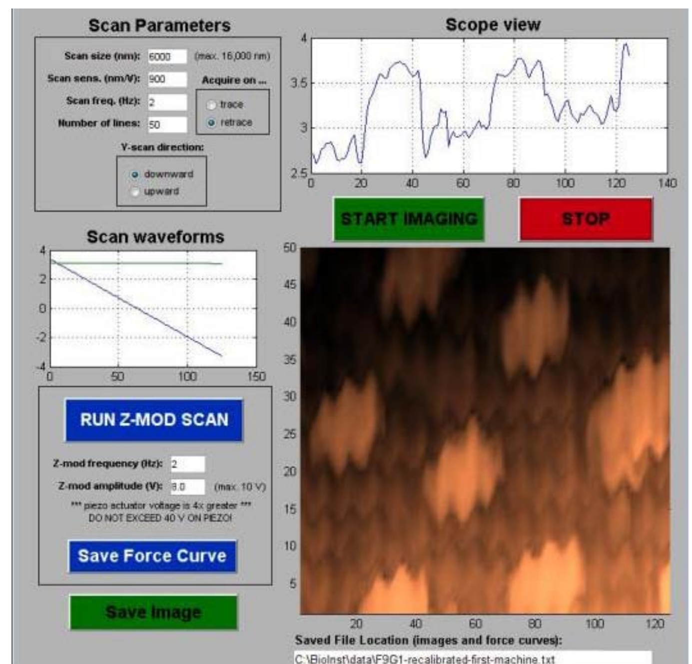




Lab #10. Part 1

- Get the laser pointing in the middle of ID fingers to get the diffraction modes on the photo detector.
- Get the tip in contact with the sample (Z-mode).
- Calibrate the system to figure out how much signal you get when you move the sample a given distance.
- Scan the sample to get image.



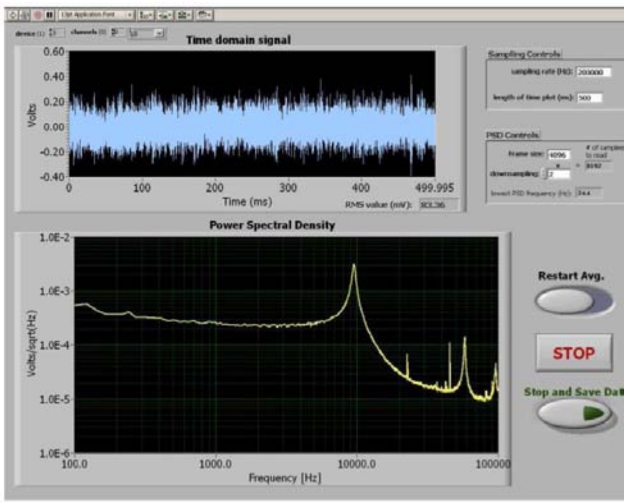


Lab #10. Part 2

- Calibrate the system.
- Measure the thermal noise spectral density.
- Relate the thermal fluctuation to the characteristics of the second order cantilever system.
- Estimate the spring constant and compare it with the theoretically calculated one.

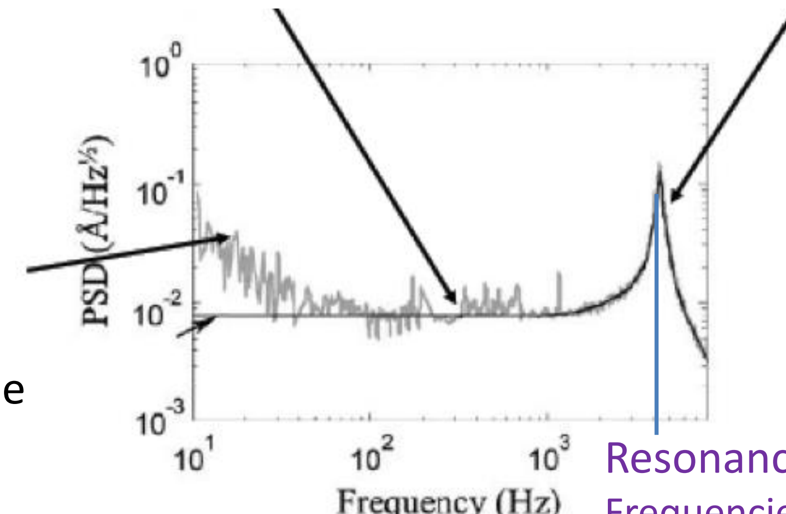
Measuring noise spectra

- Tool: Spectrum Analyzer
- Takes a series of measurements of a quantity of interest at a high sampling rate



Thermomechanical noise $\left\langle f_n^2 \right\rangle = 4k_B Tb = k^2 \left\langle x^2 \right\rangle$

Resonance peak



1/f noise

Resonance frequency:
Frequencies at which the response amplitude becomes maximum

How to relate thermal-noise to k

Noise Force $\left\langle f_n^{\,2} \right\rangle = 4k_B T b = k^2 \left\langle x^2 \right\rangle$

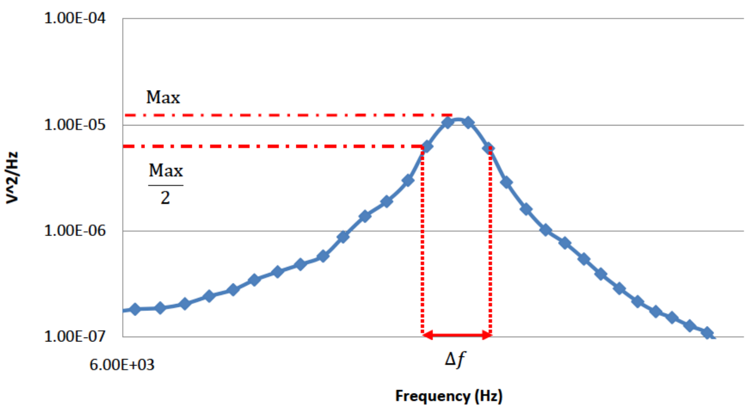
$$b = \frac{k}{Qw_o} \qquad \frac{4k_b T k}{Qw_o} = k^2 \left\langle x^2 \right\rangle$$

Quality factor $Q = \dfrac{f_0}{\Delta f} = \dfrac{k}{bw_o}$

$$\boxed{k = \frac{4k_B T}{w_0 Q \left\langle x^2 \right\rangle}}$$

k_B :Boltzmann's constant
b: Damping
k: Spring constant
$\langle x^2 \rangle$: Thermal noise x calibration^2
w_0: Resonant frequency

Q factor



f_0 : Resonant frequency of the cantilever
Δf: width of the peak at the half maximum

Cantilever, K

- For a tip loaded cantilever with constant cross-section

$$k = \frac{3EI}{L^3}$$

- The fingers can be ignored in analytical calculation.

$$k = \frac{EWh^3}{4L^3}$$

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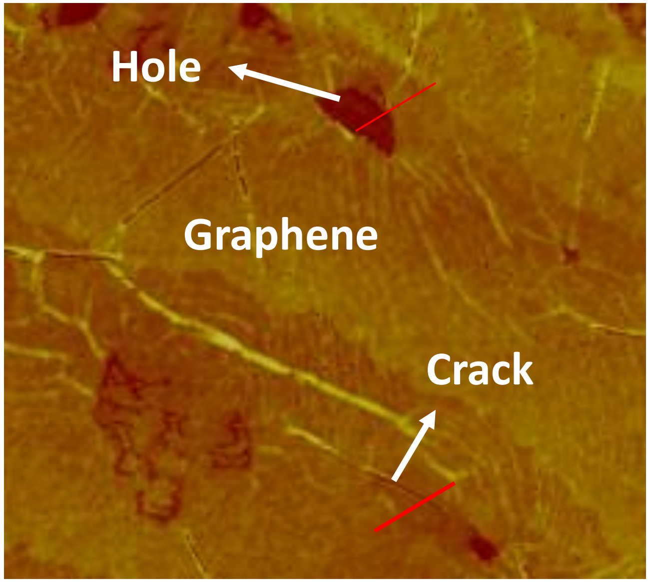
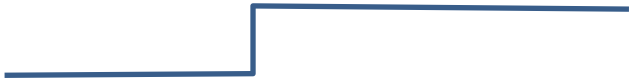
$$m\ddot{x} + b\dot{x} + kx = 0$$

$$m_{eff} = \frac{33}{140}\rho LWh$$

Lab #11 Measure graphene thickness using commercial AFM



Height?? → Monolayer??



Microstereolithography

3D printing