ME597/PHYS57000

Fall Semester 2009

Lecture 04

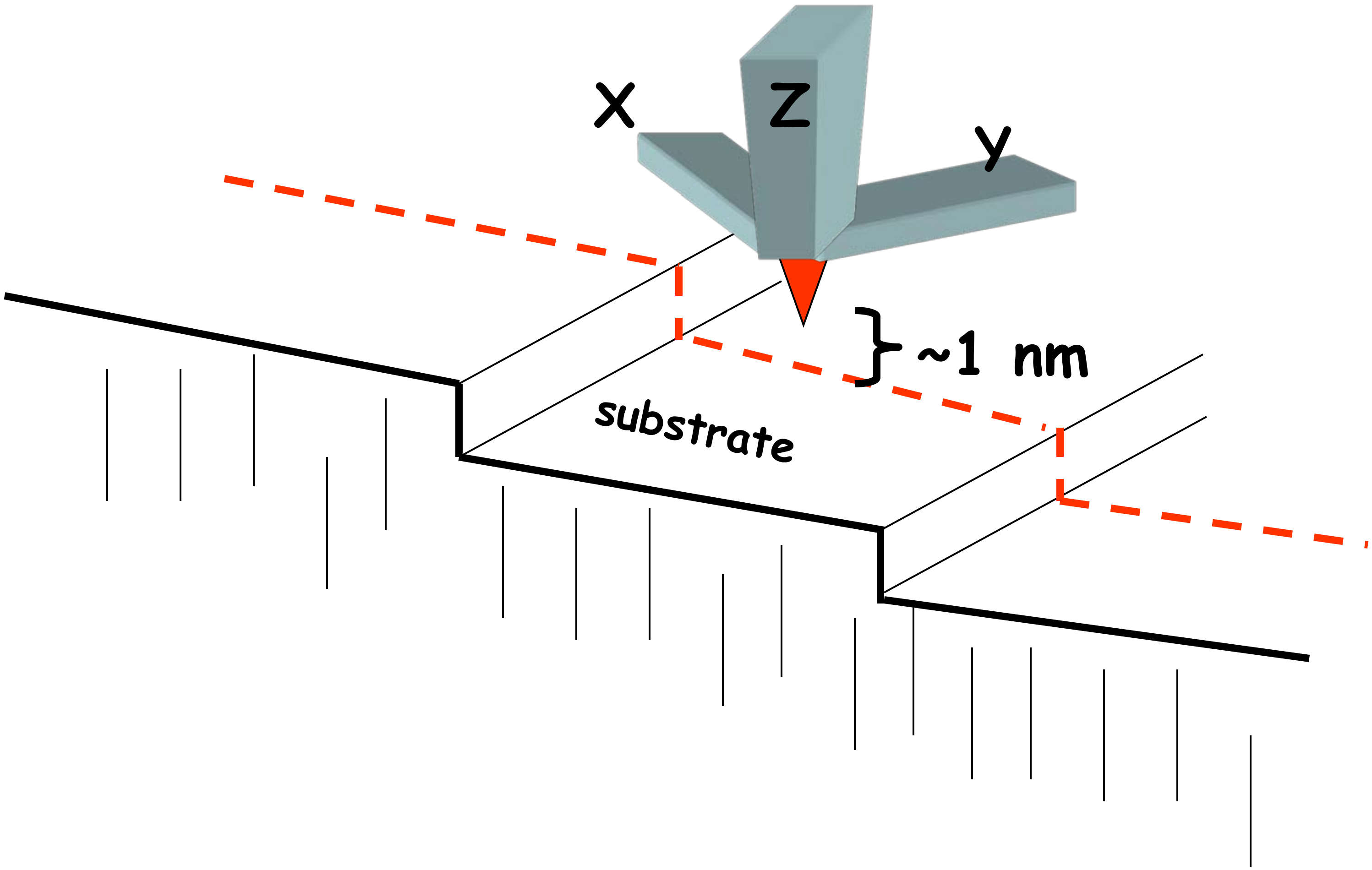
Early Successes

How to Make an STM

Suggested Reading: G. Binning, H. Rohrer, Ch. Gerber, E. Weibel, "7x7 Reconstruction of Si(111) Resolved in Real Space", Phys. Rev. Lett. **50**, 120 (1983)

If gap is controllable, then hold gap at a fixed d so that e^{-2ad} = constant, then

$I(x,y) \propto e\Delta V\ \rho(z=0,x,y;E_F)$



What might effect LDOS?

- Surface
  - atom positions
  - step edges, terraces
  - reconstruction – position of atoms
- Grain Boundaries
- Adsorbates
- Impurities
- Anti-site Defects
- Dislocations
- Vacancies
- Interstitials
- etc. etc.

A Few Early Successes

- Si(111) 7x7
- HOPG
- GaAS

The Si(111) story

The Si(111) reconstruction was first reported in 1959 by R. Schlier and H. Farnsworth, J. Chem. Phys. **30**, 917 (1959).

Equilibrium surface structure (lowest energy arrangement) after annealing under UHV.

After the Si(111) reconstruction was discovered, there were ~20 papers written per year for 25 years, i.e. ~500 publications, attempting to conclusively identify the nature of the reconstruction.

The exact reconstruction was finally solved in a few days in 1982 using the STM. The STM data clearly showed a (7x7) unit cell bounded by <u>minima</u> corresponding to empty adatom positions and <u>maxima</u> corresponding to the presence of adatoms

VOLUME 50, NUMBER 2 PHYSICAL REVIEW LETTERS 10 JANUARY 1983

7 × 7 Reconstruction on Si(111) Resolved in Real Space

G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel
IBM Zurich Research Laboratory, 8803 Rüschlikon-ZH, Switzerland
(Received 17 November 1982)

The 7×7 reconstruction on Si(111) was observed in real space by scanning tunneling microscopy. The experiment strongly favors a modified adatom model with 12 adatoms per unit cell and an inhomogeneously relaxed underlying top layer.

PACS numbers: 68.20.+t, 73.40.Gk

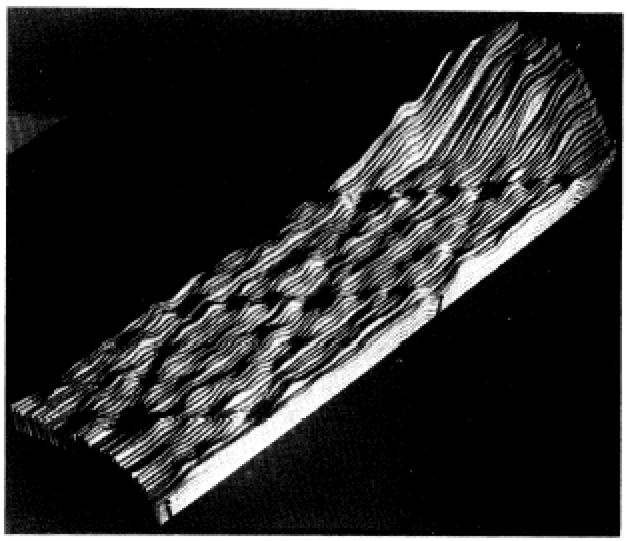


FIG. 1. Relief of two complete 7×7 unit cells, with nine minima and twelve maxima each, taken at 300 °C. Heights are enhanced by 55%; the hill at the right grows to a maximal height of 15 Å. The [$\bar{2}$11] direction points from right to left, along the long diagonal.

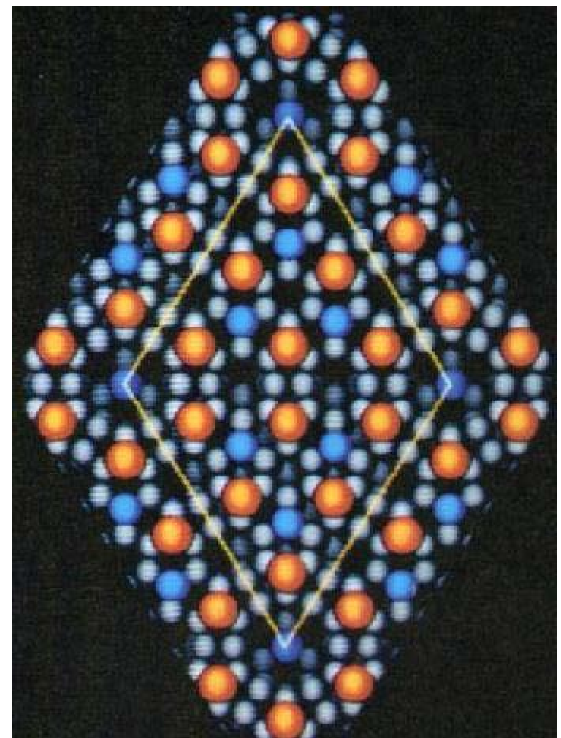
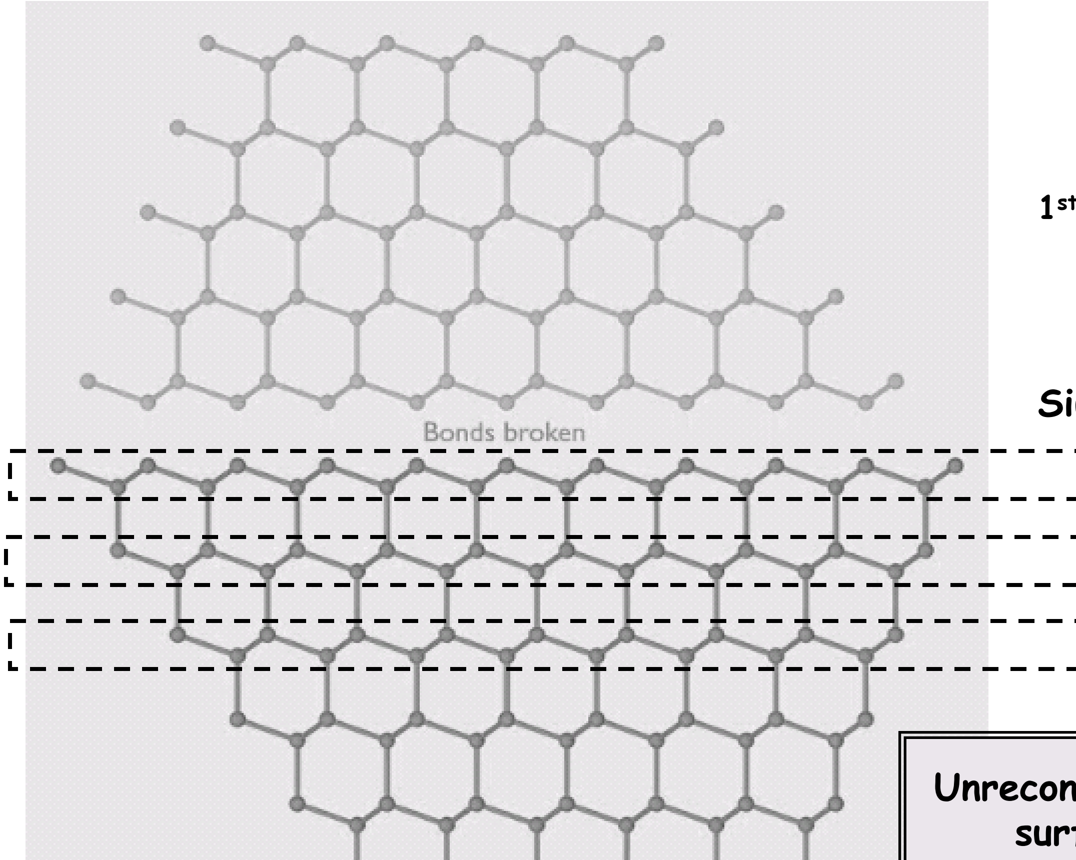
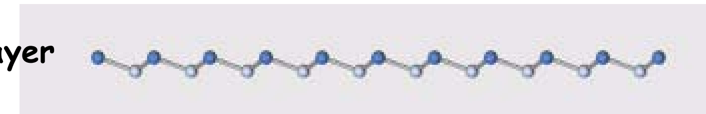


Figure from R.M. Tromp, IBM

Some Details



1st bilayer



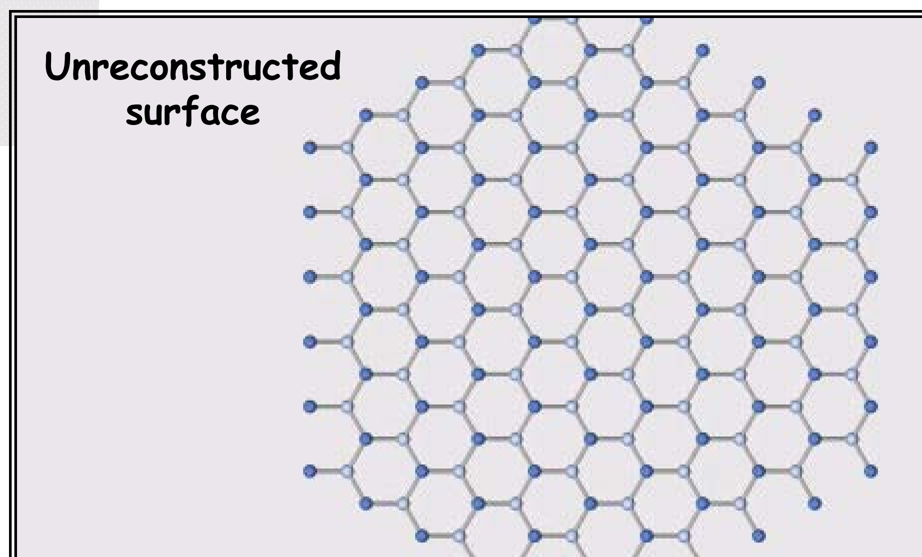
Si(111) surface

1st bilayer

2nd bilayer

3rd bilayer

Top view of 1st bilayer

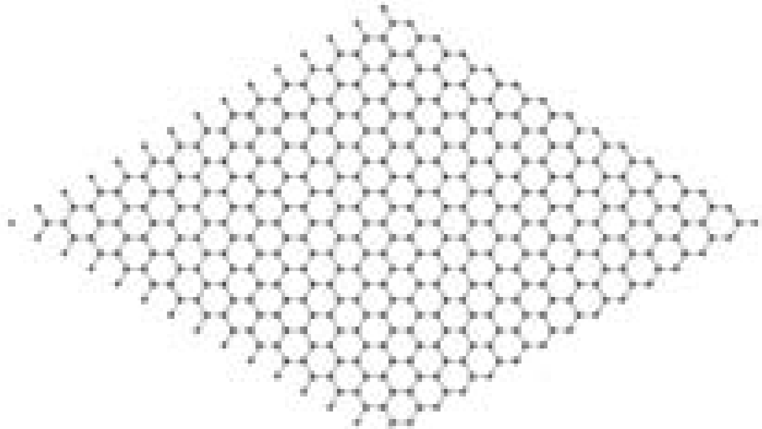


For animation by Yan Liang, see:

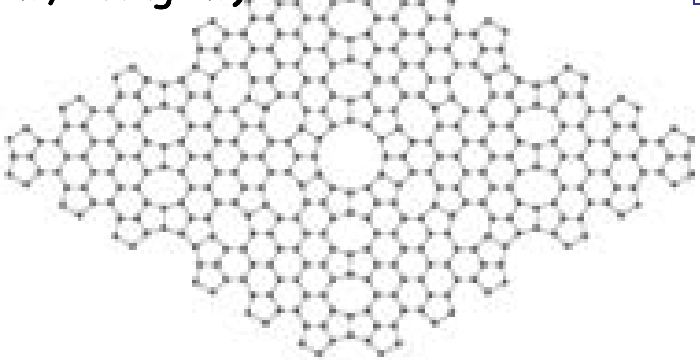
http://www.vimeo.com/1086112

Comparison

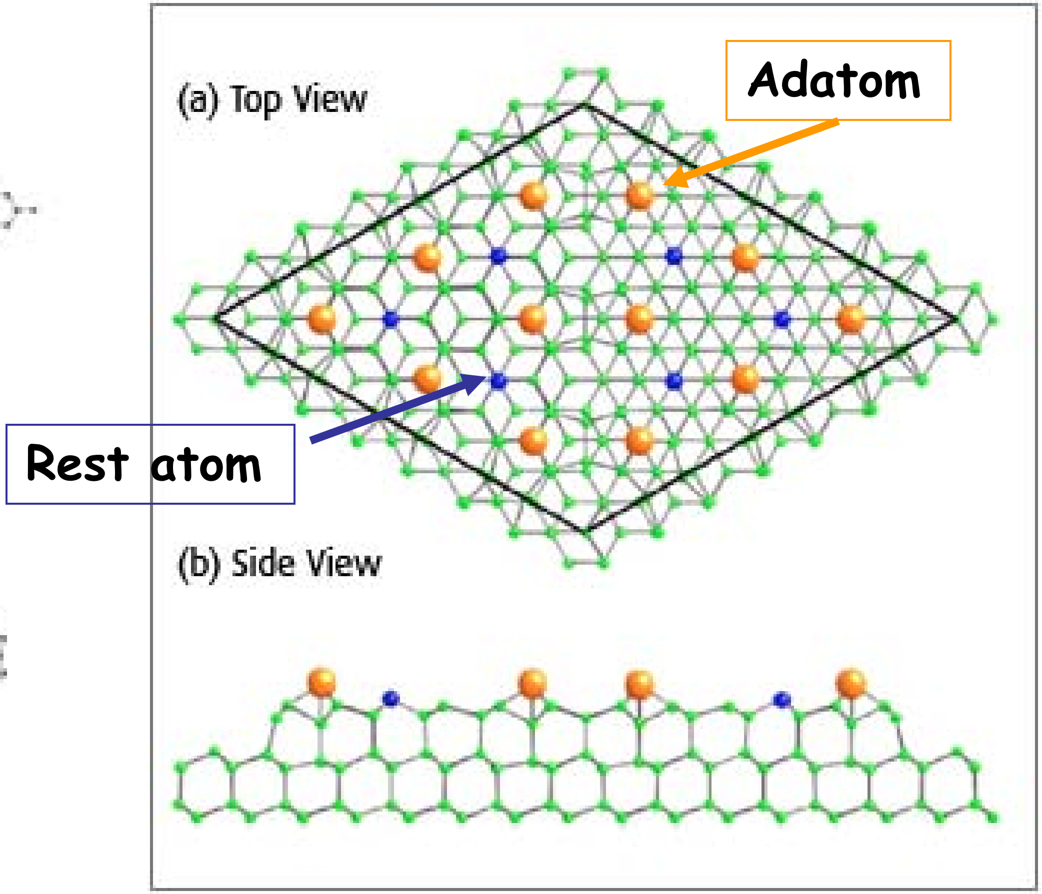
Unreconstructed 7x7 surface (all hexagons)



Reconstructed 7x7 surface (pentagons, hexagons, octagons)



From Omicron Web site:



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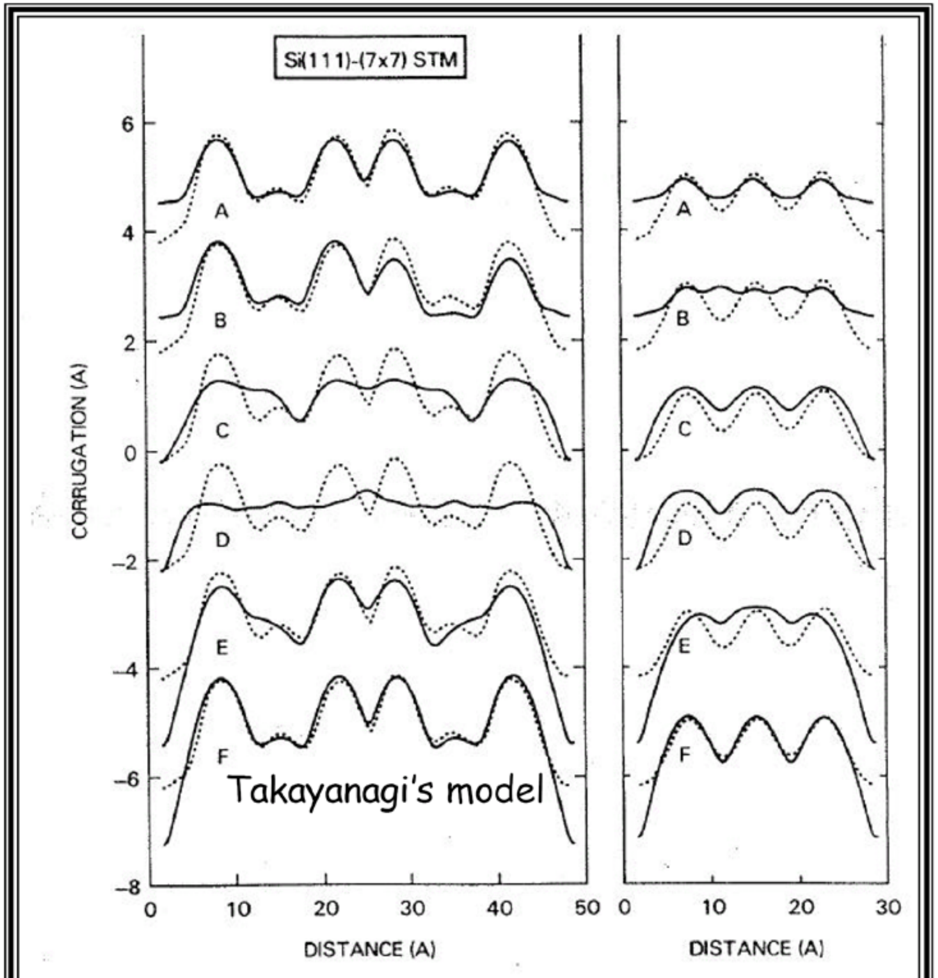
Atomic and electronic contributions to Si(111)-(7×7) scanning-tunneling-microscopy images

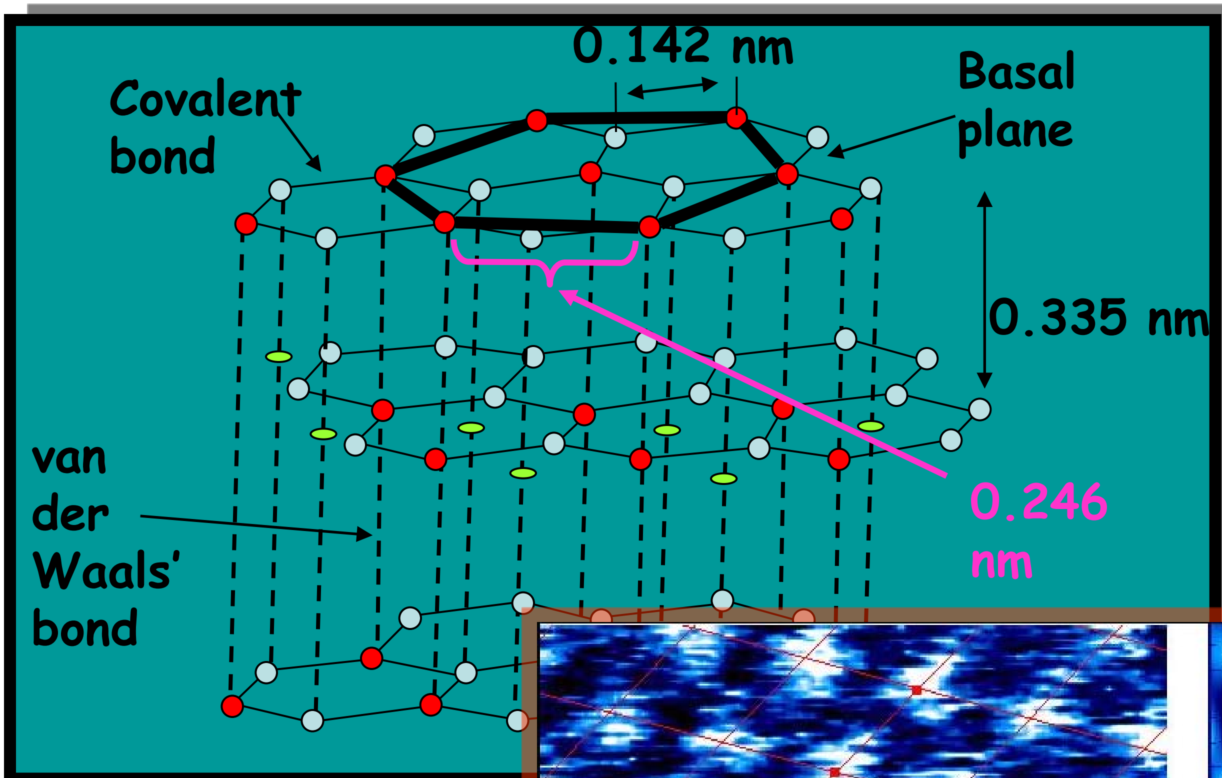
R. M. Tromp, R. J. Hamers, and J. E. Demuth
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

(Received 9 May 1986)

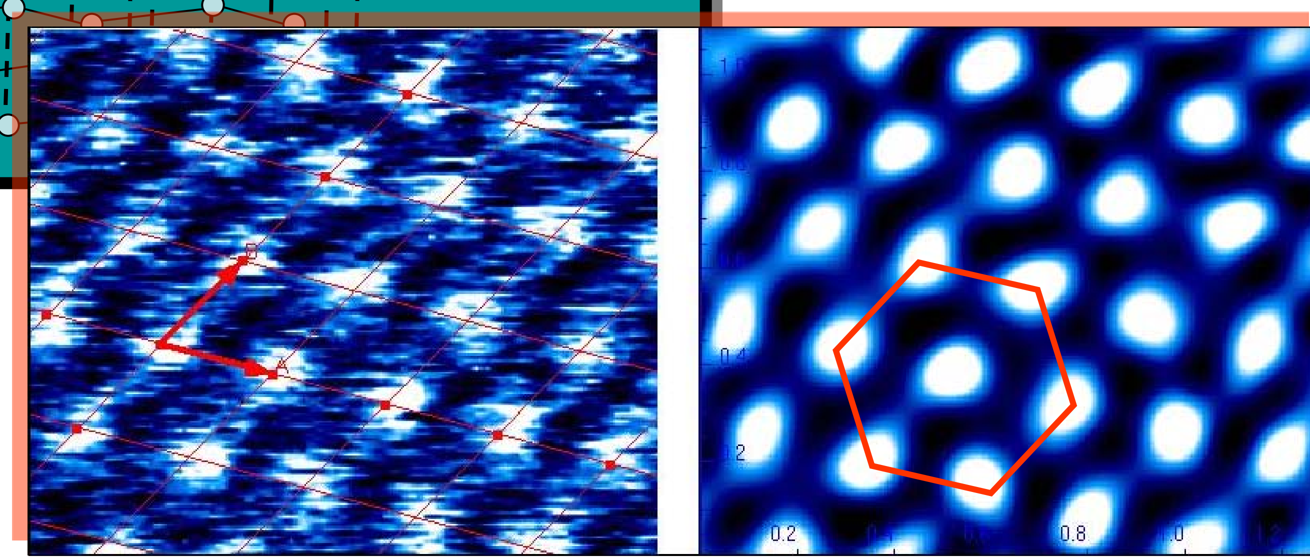


Experiment: ·······

A flat substrate: Highly Oriented Pyrolitic Graphite (HOPG)



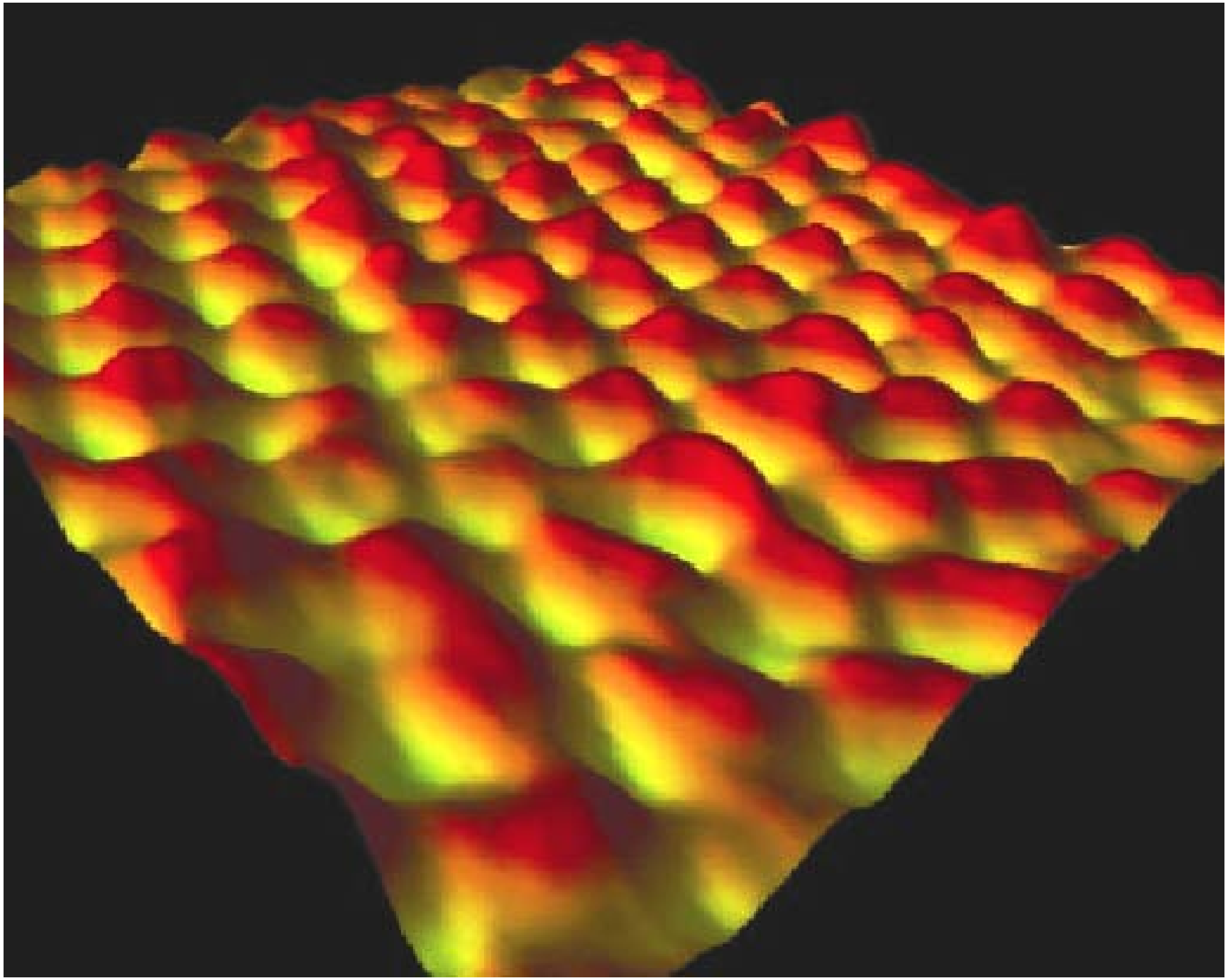
(1.3 x 1.1 nm)



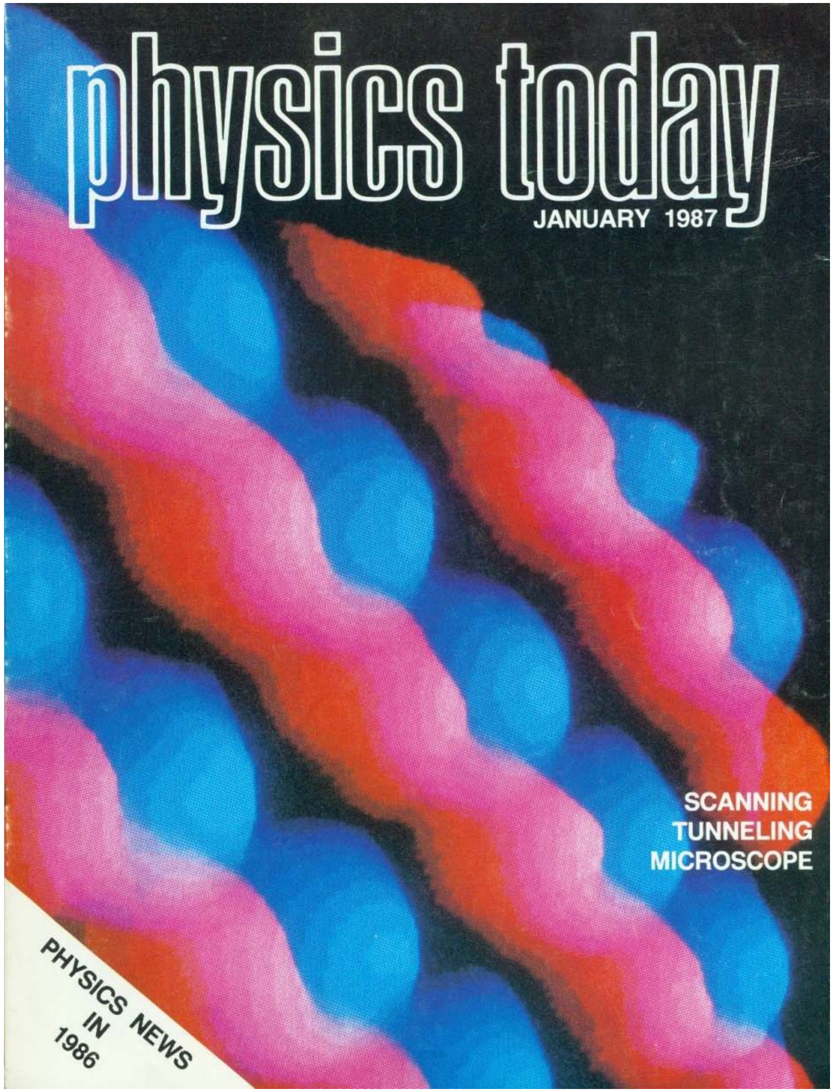
Raw data

Fourier filtered image

HOPG in 3-diemnsions

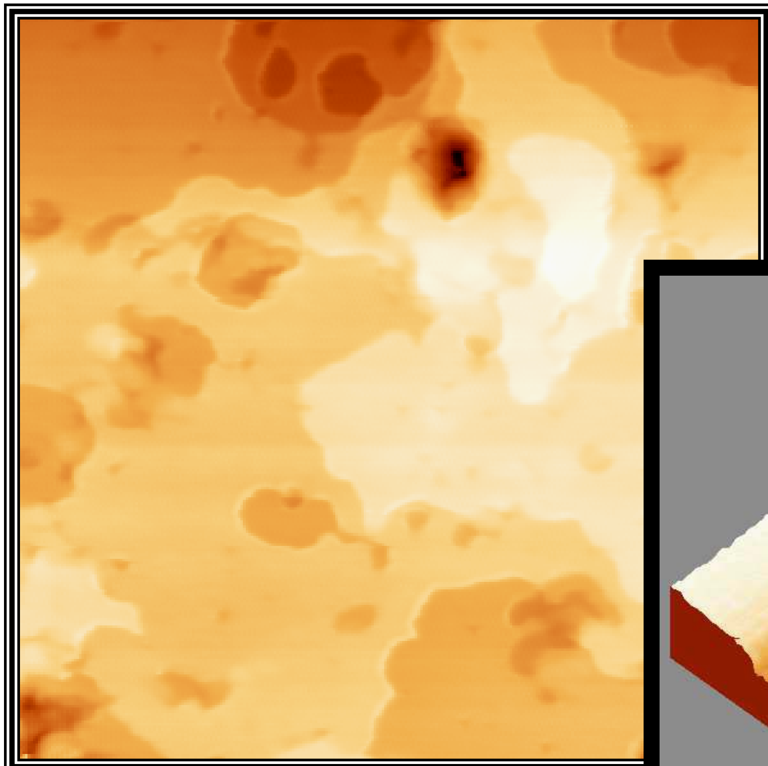


STM of GaAs

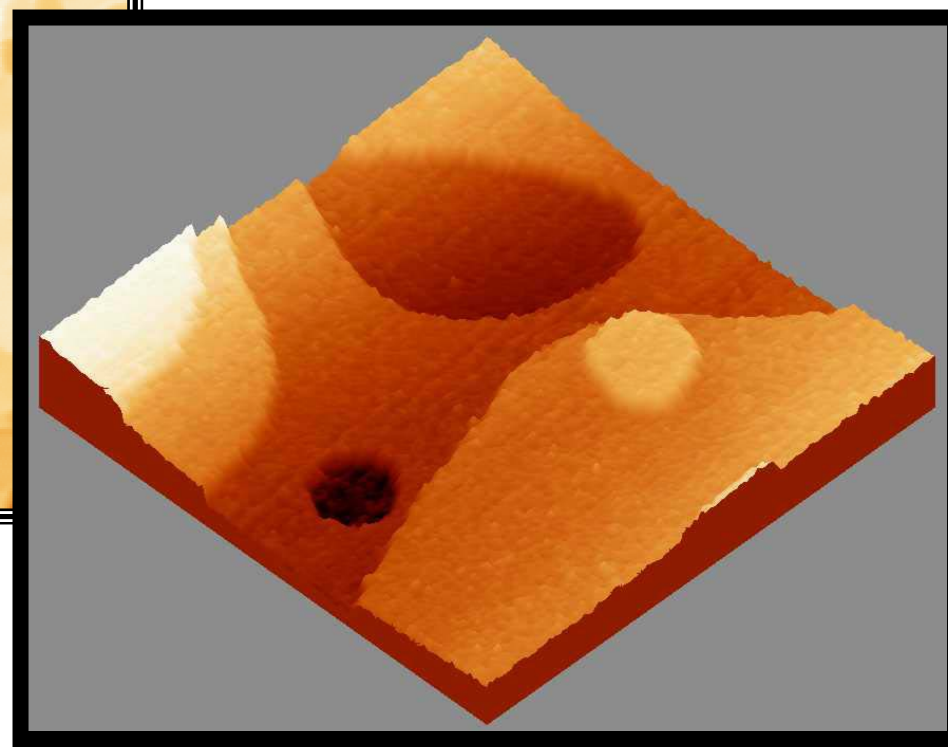


Ga: red sites; As: blue sites

Imaging the surface of Au(111)



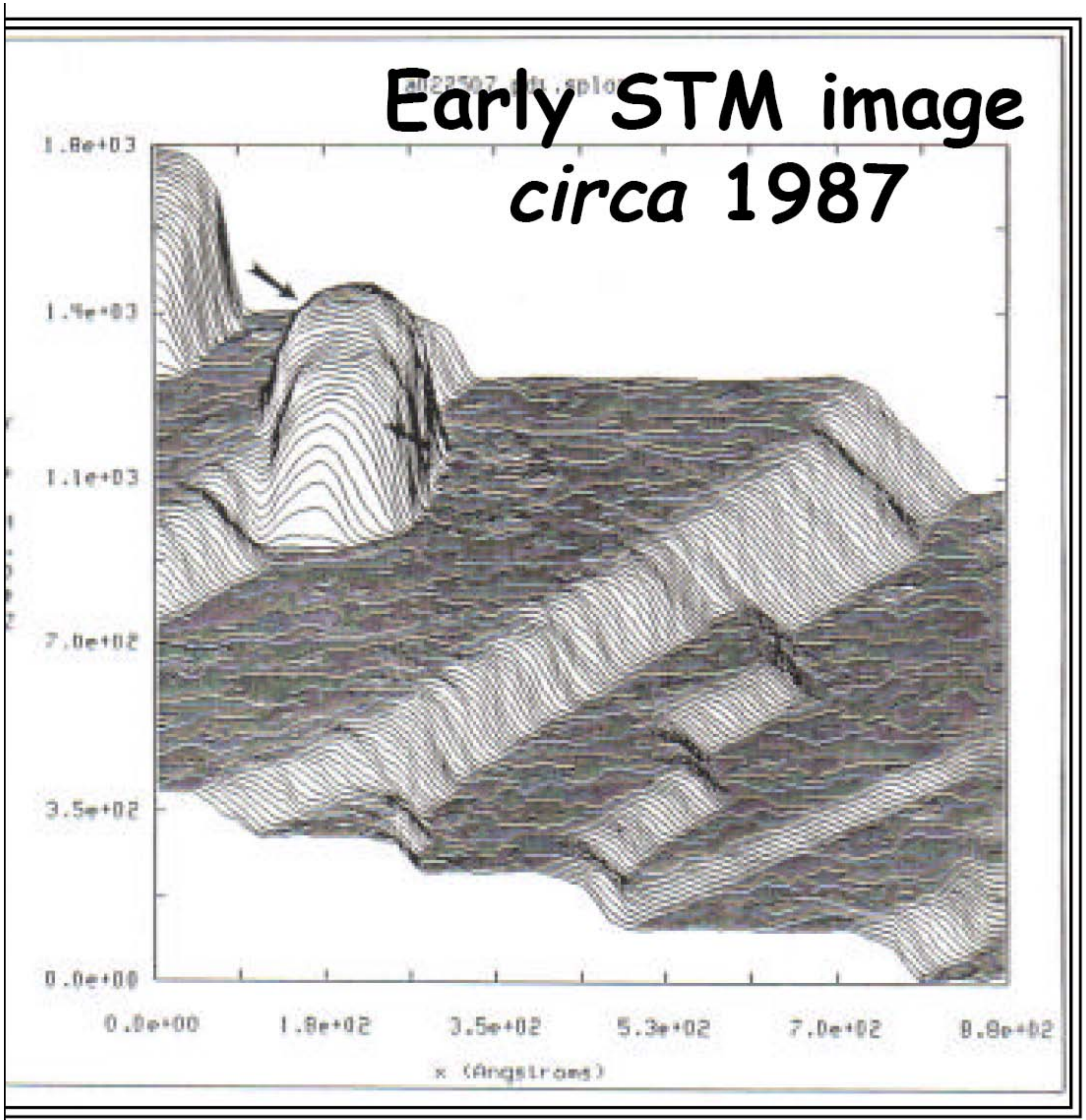
0.236 nm steps on Au(111)



Top View

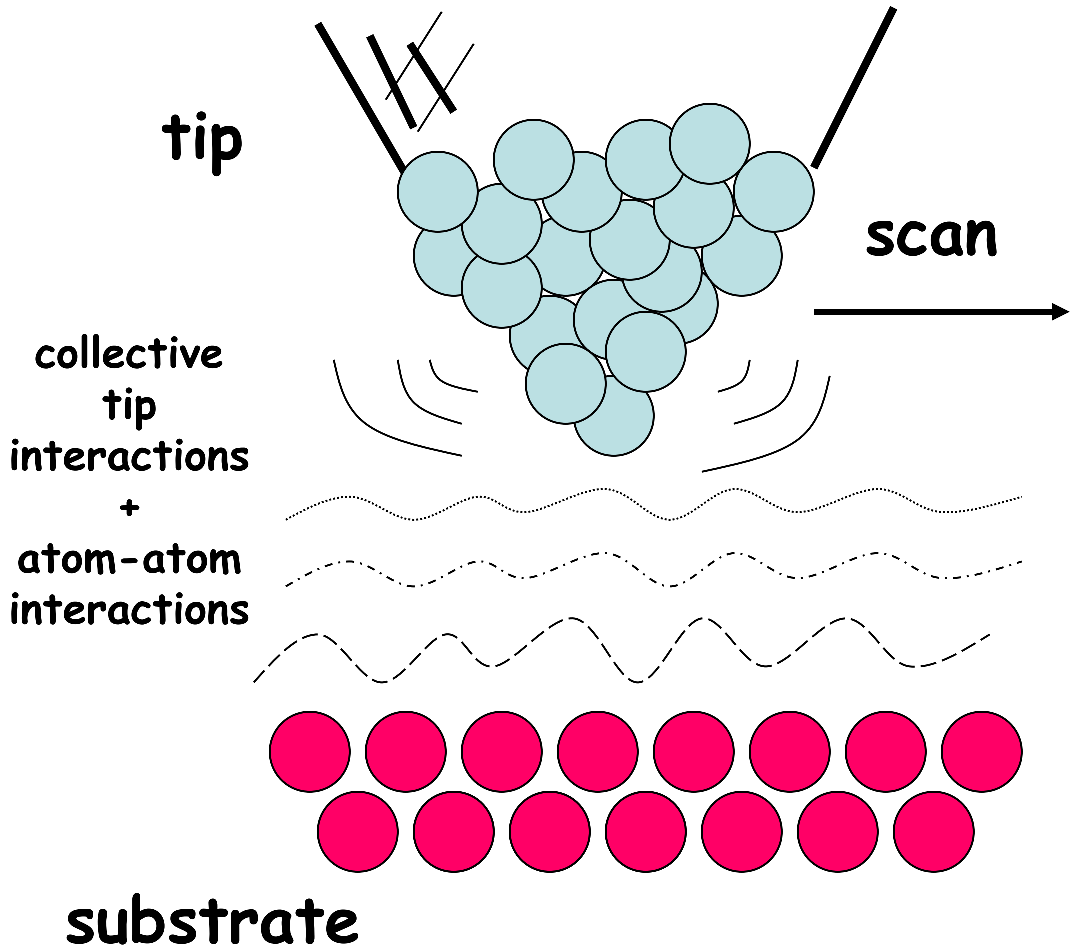
100 nm x 100 nm

Au nanoclusters on Au substrate



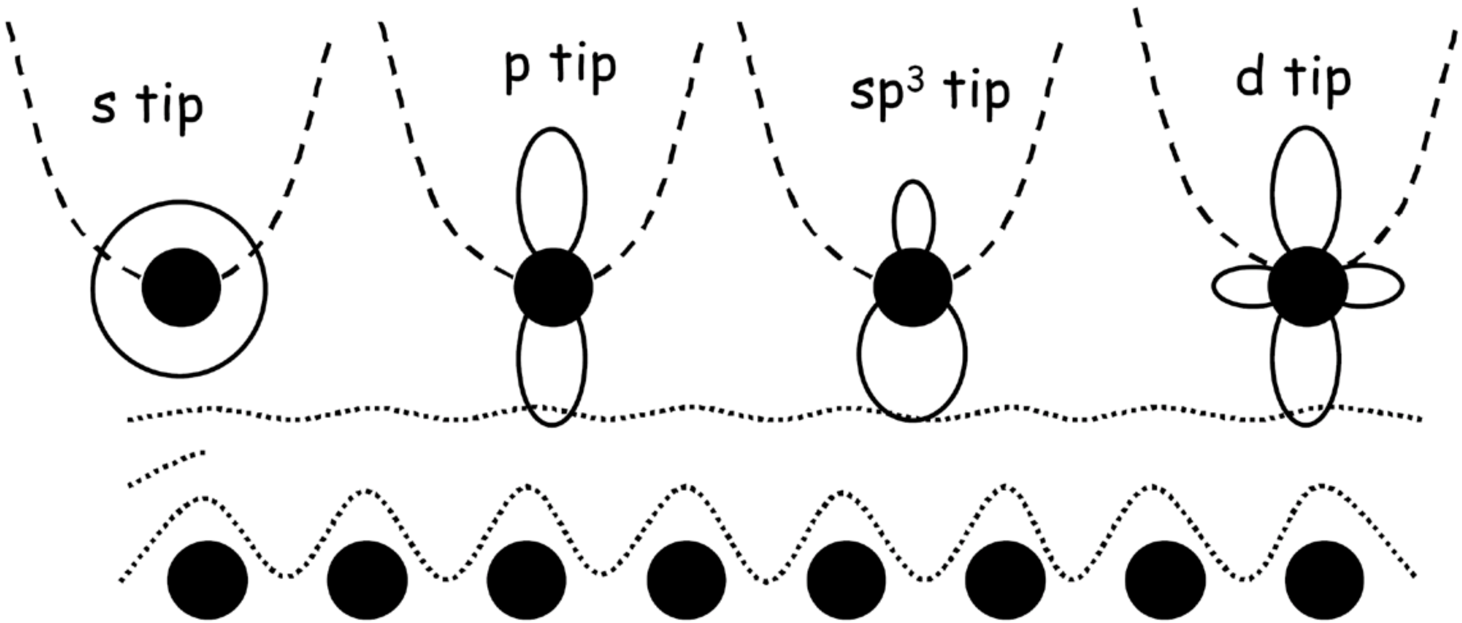
Li, Reifenberger, Andres

Why it Works



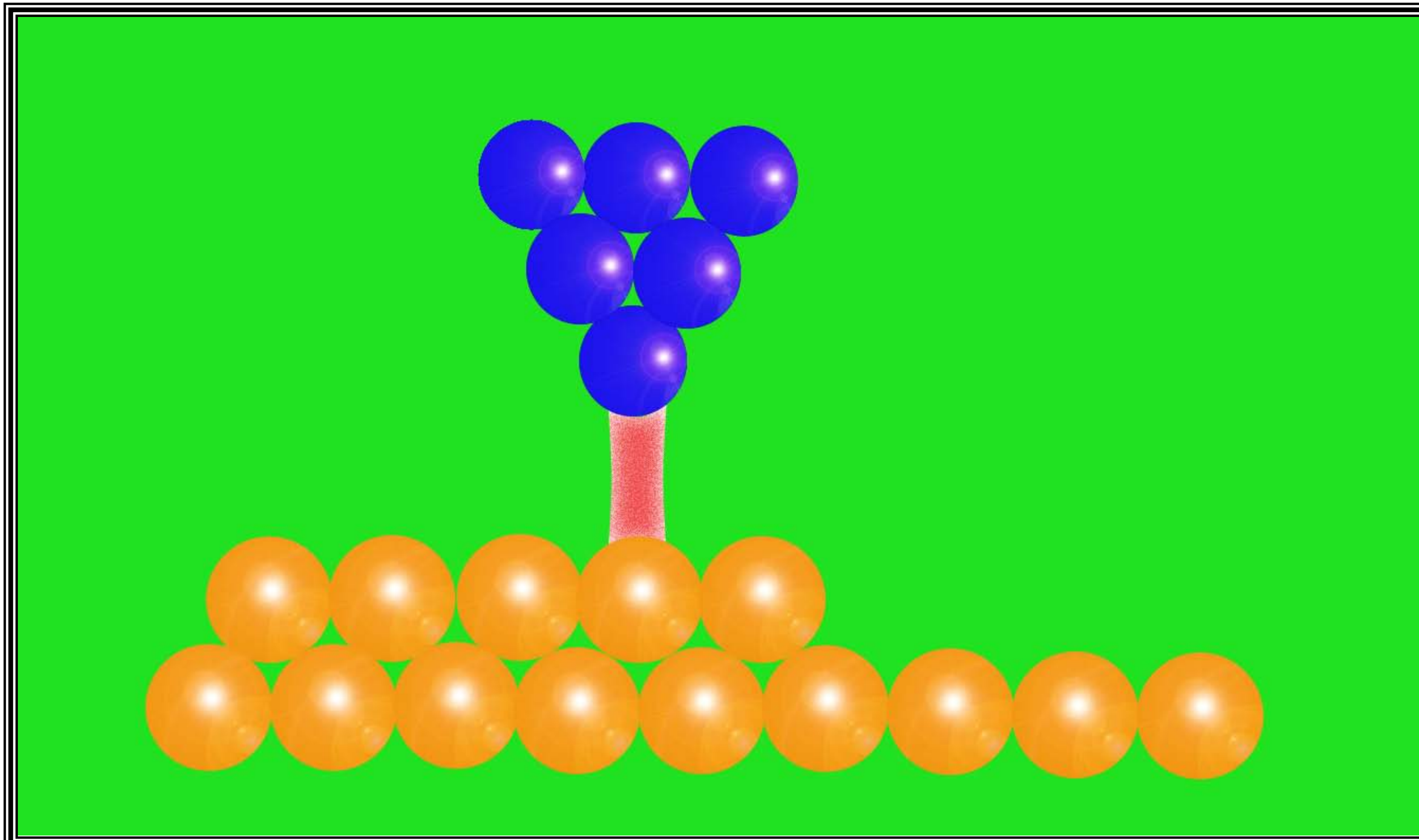
tip
scan
collective
tip
interactions
+
atom-atom
interactions
substrate

Microscopic view of STM imaging mechanism



C.J. Chen: (1993)

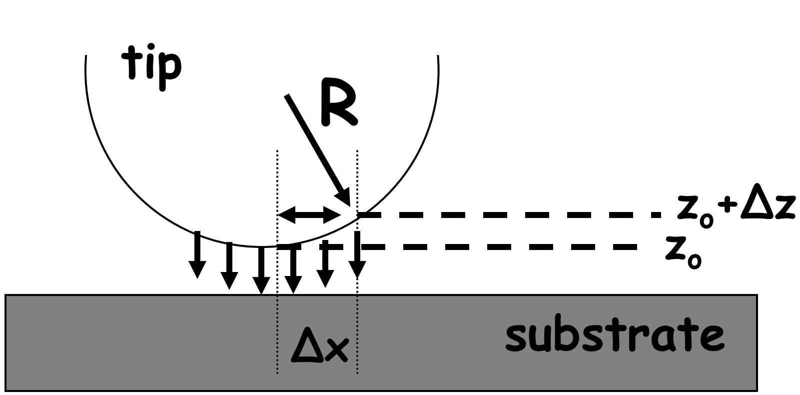
The Front Atom IS Important

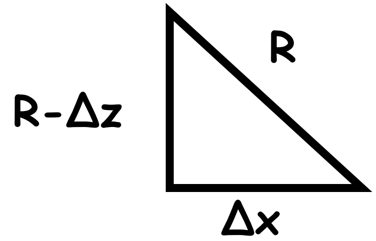


First Law of STM: Every good tip ends in one atom

Second Law of STM: Reliable STM data usually requires UHV

Lateral Resolution?





$$R^2 = (\Delta x)^2 + (R - \Delta z)^2$$

$$\Delta z \simeq \frac{(\Delta x)^2}{2R}$$

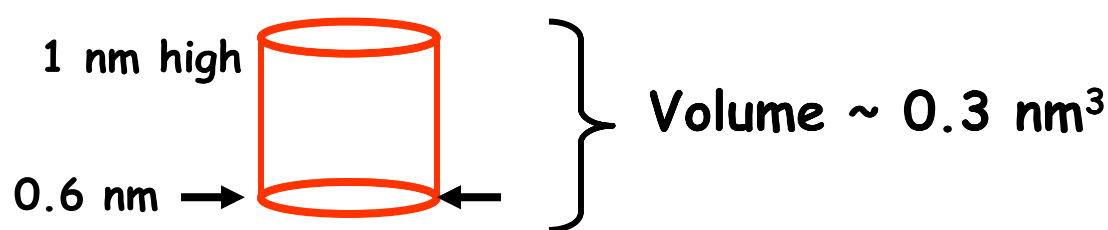
$$\alpha \approx 11\, nm^{-1};\ R \approx 0.5\, nm$$

$$When\ e^{-2\alpha(\Delta z)} \approx 0.1\ then\ I \simeq I_o e^{-2\alpha(z_o + \Delta z)} \simeq 0.1 I_o e^{-2\alpha(z_o)}$$

$$\Rightarrow \Delta x = 0.3\, nm.$$

"Effective" diameter of current column is

$\sim 2\Delta x \simeq 0.6\,\text{nm} \rightarrow$ estimate for lateral resolution



How many gas molecules per cm^3 at atmospheric pressure?

Ideal gas law: $PV=nk_BT$ →

1 mole of gas (6×10^{23} molecules) occupies 22.4 liters at STP

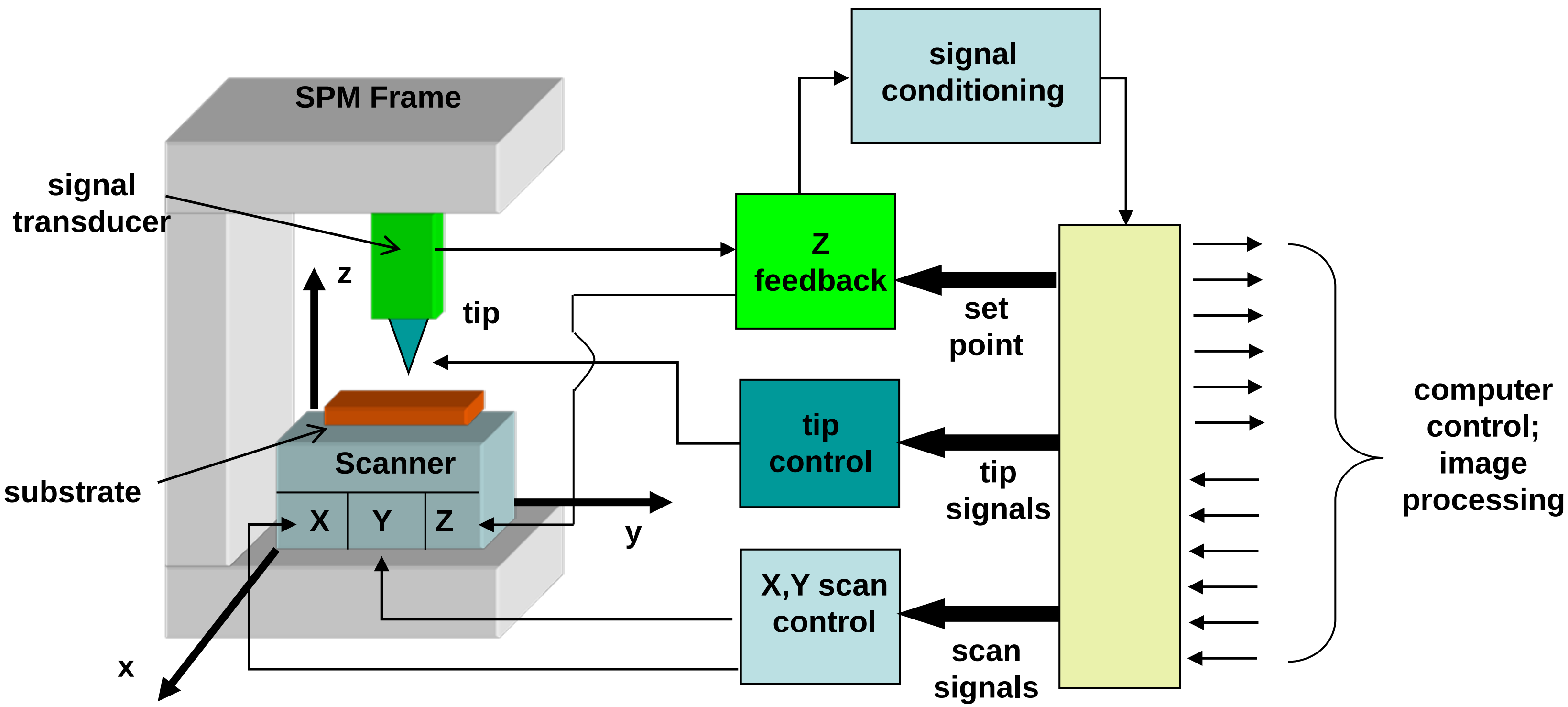
$$\frac{n}{V}=\frac{P}{k_BT}=\frac{6\times10^{23}}{22.4\ \text{liters}}\times\frac{1\ \text{liter}}{0.001\text{m}^3}\times\frac{1\text{m}^3}{1\times10^{6}\,\text{cm}^3}$$

$$=2.7\times10^{19}\,\text{cm}^{-3}\quad\text{(Loschmidt's Number - 1865)}$$

$$=2.7\times10^{19}\,\text{cm}^{-3}\times\left(\frac{1\text{cm}}{1\times10^{7}nm}\right)^3=0.03\,\text{molecules per nm}^3$$

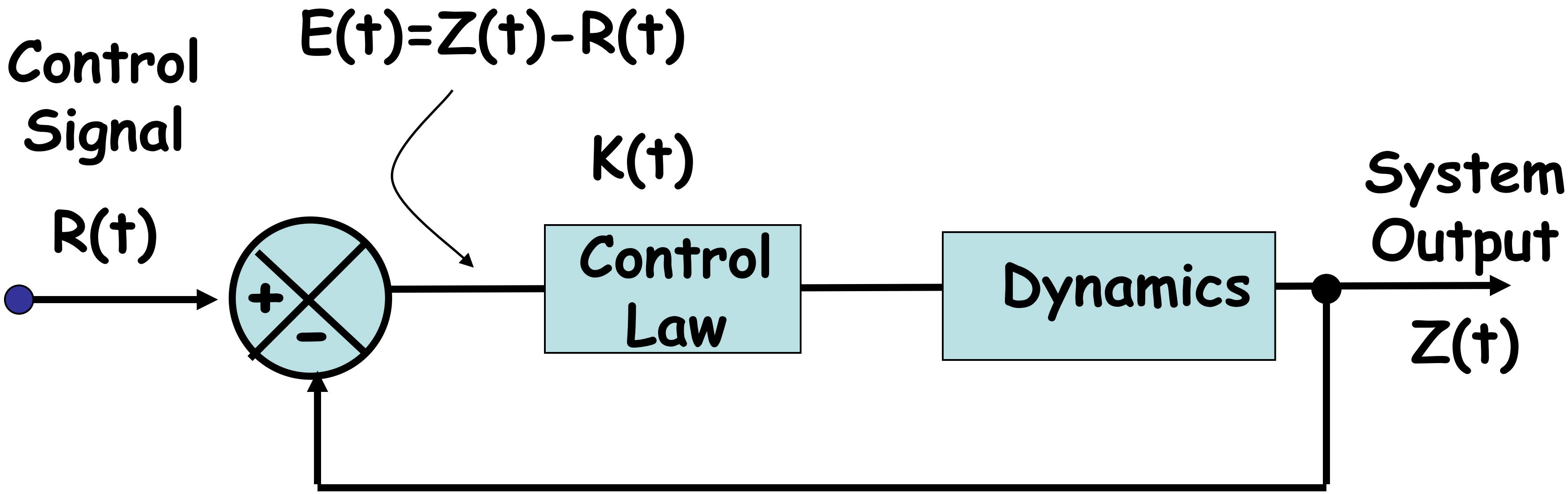
How to make it work

STM System Overview



Feedback Control

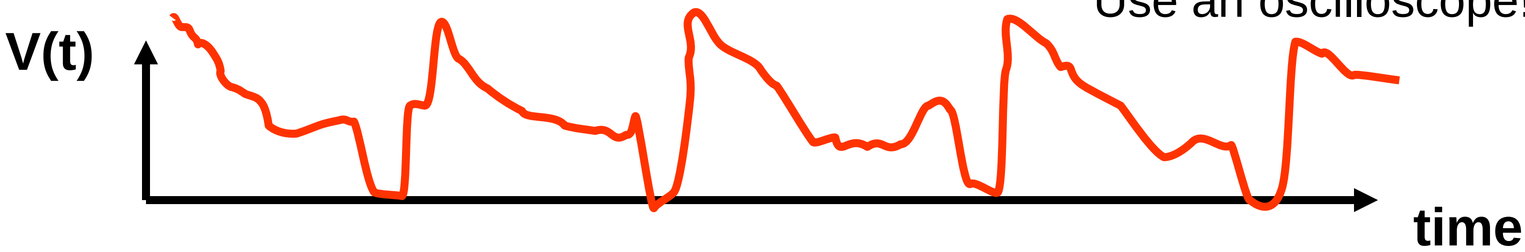
Goal: Make Z(t) follow R(t) as closely as possible

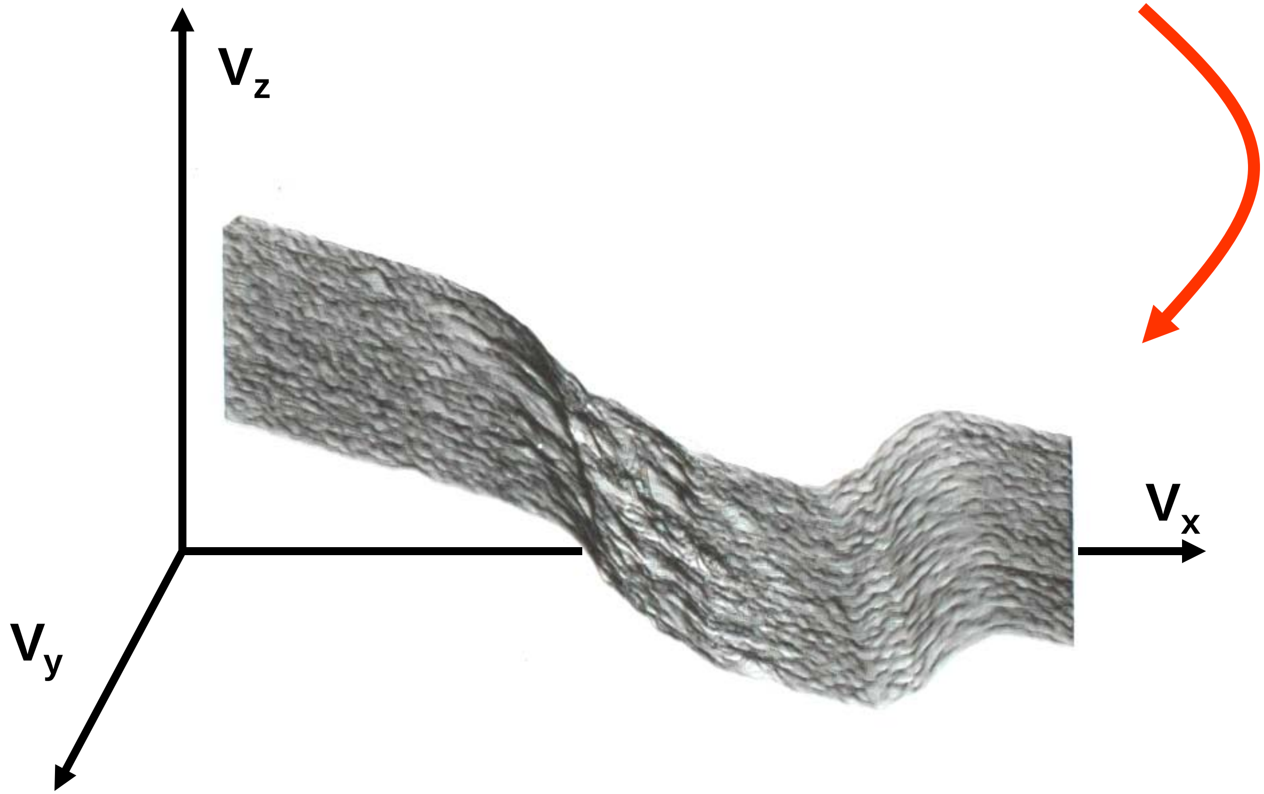


- K(t) tries to minimize E(t)
- Self-correcting system → negative feedback!
- A simple proportional feedback is $Z(t)=K \cdot E(t)$

ALL STM images are derived from voltages!

Use an oscilloscope!

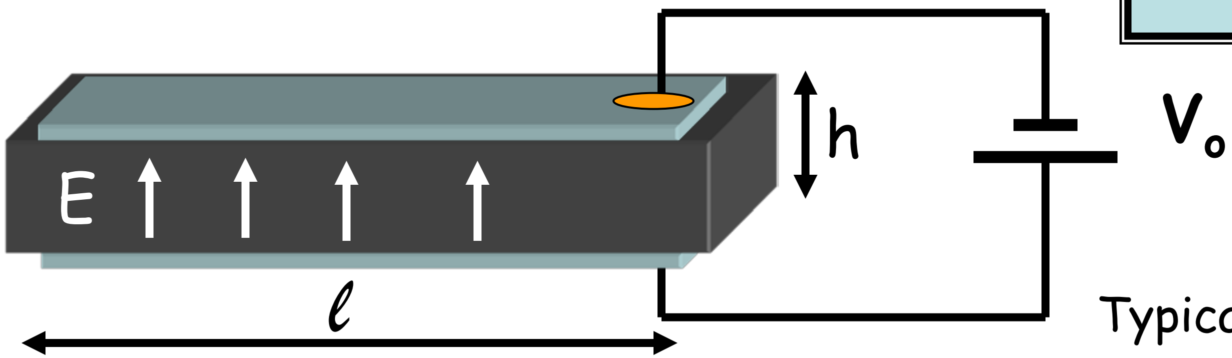




Implications for Imaging Processing

Achieving Vibrationless Motion at the Nanoscale

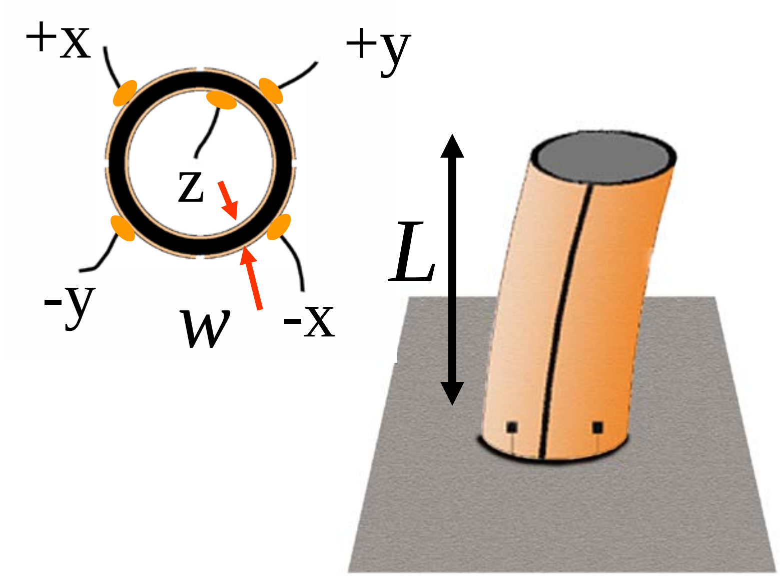
Piezoelectric Bar



$$\Delta \ell = d_{31} \frac{\ell}{h} V_o$$

Typically, $\Delta \ell \sim 0.5$ nm/V

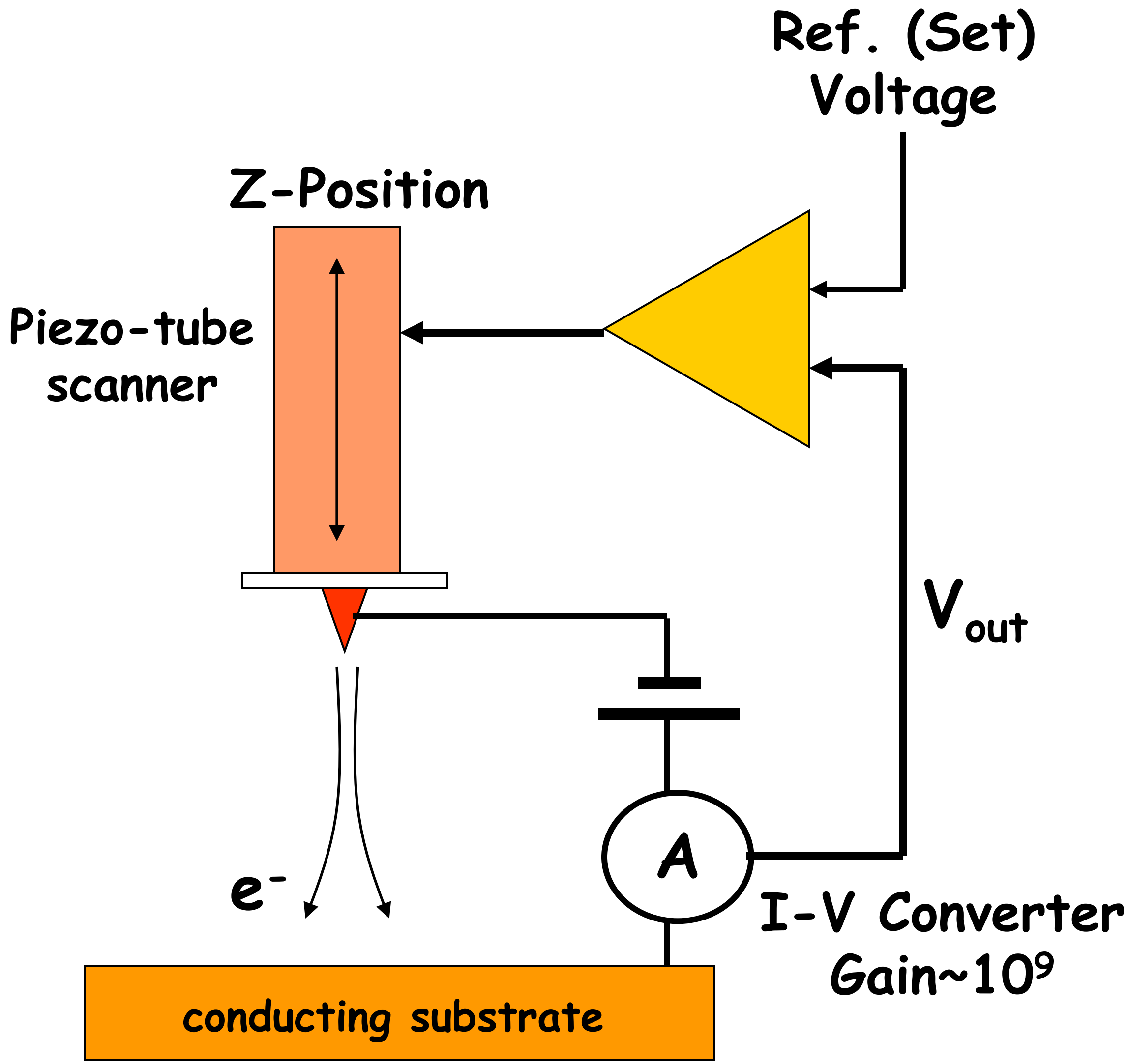
Quadranted Piezoelectric Tube



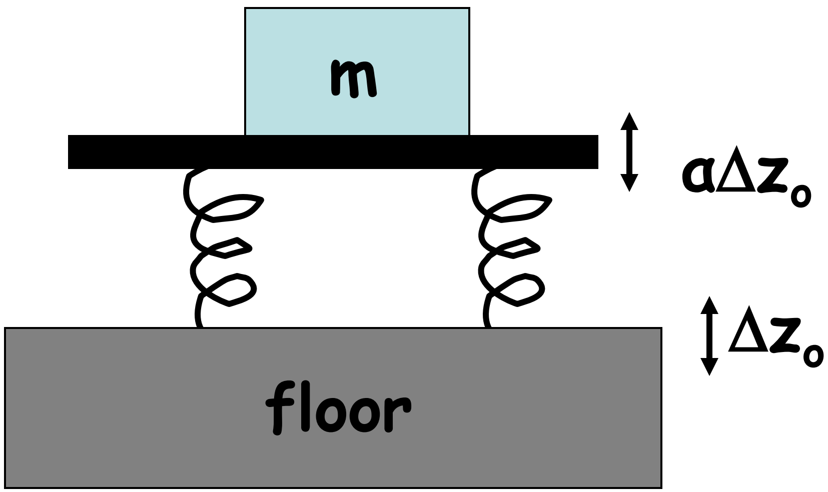
$$\Delta z = L \frac{V_o}{w} d_{31}$$

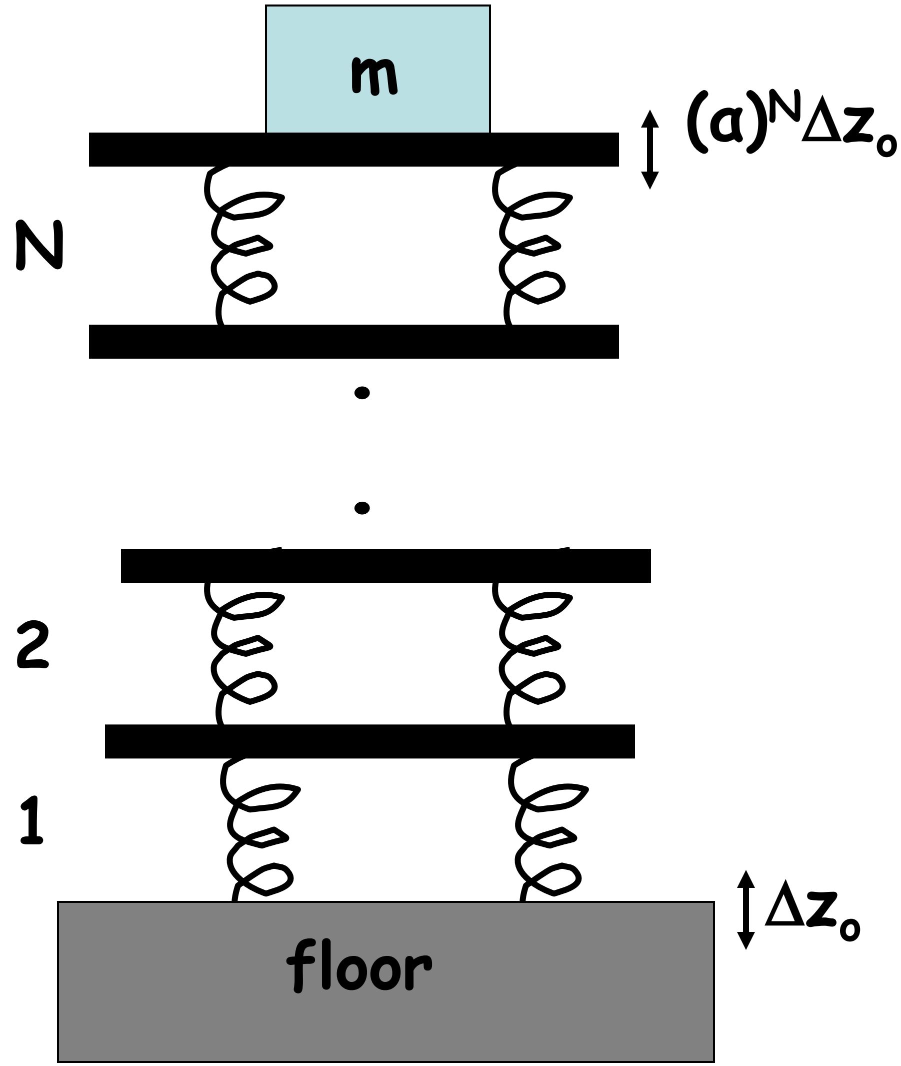
$$\Delta x \simeq \Delta y = \frac{2\sqrt{2}}{\pi D} \frac{V_o}{w} L^2 d_{31}$$

Controlling the Tunnel Gap

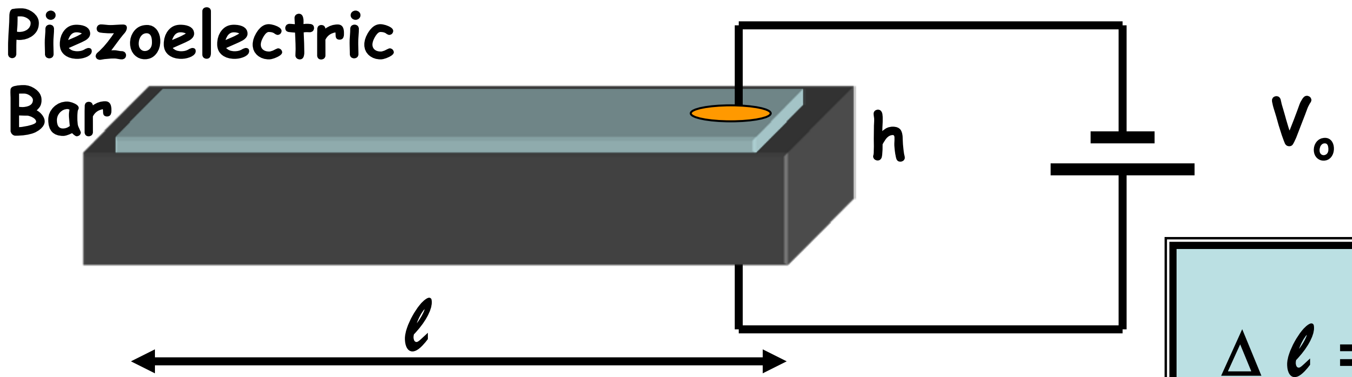


Vibration Damping

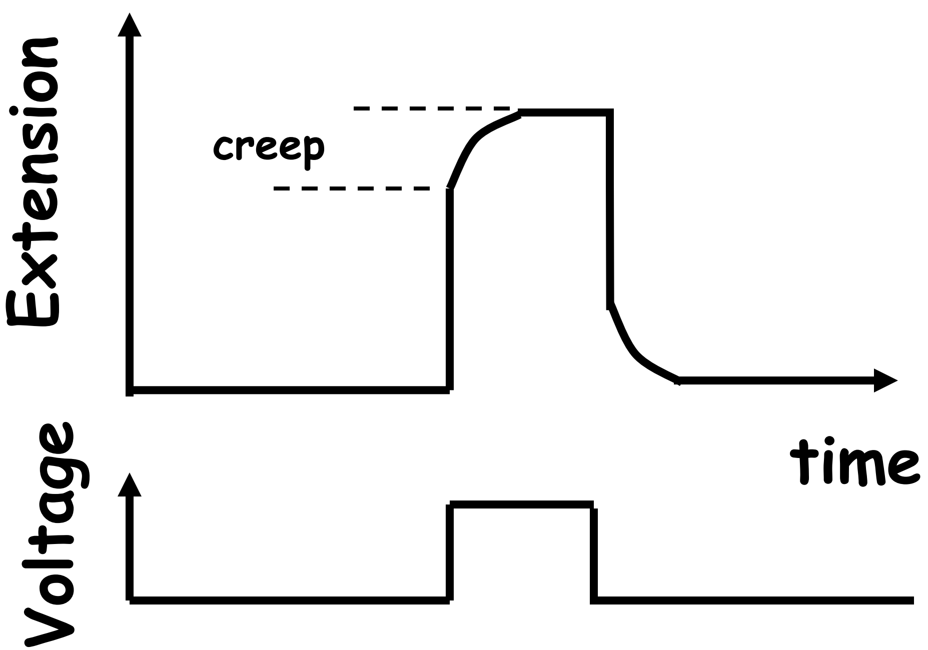




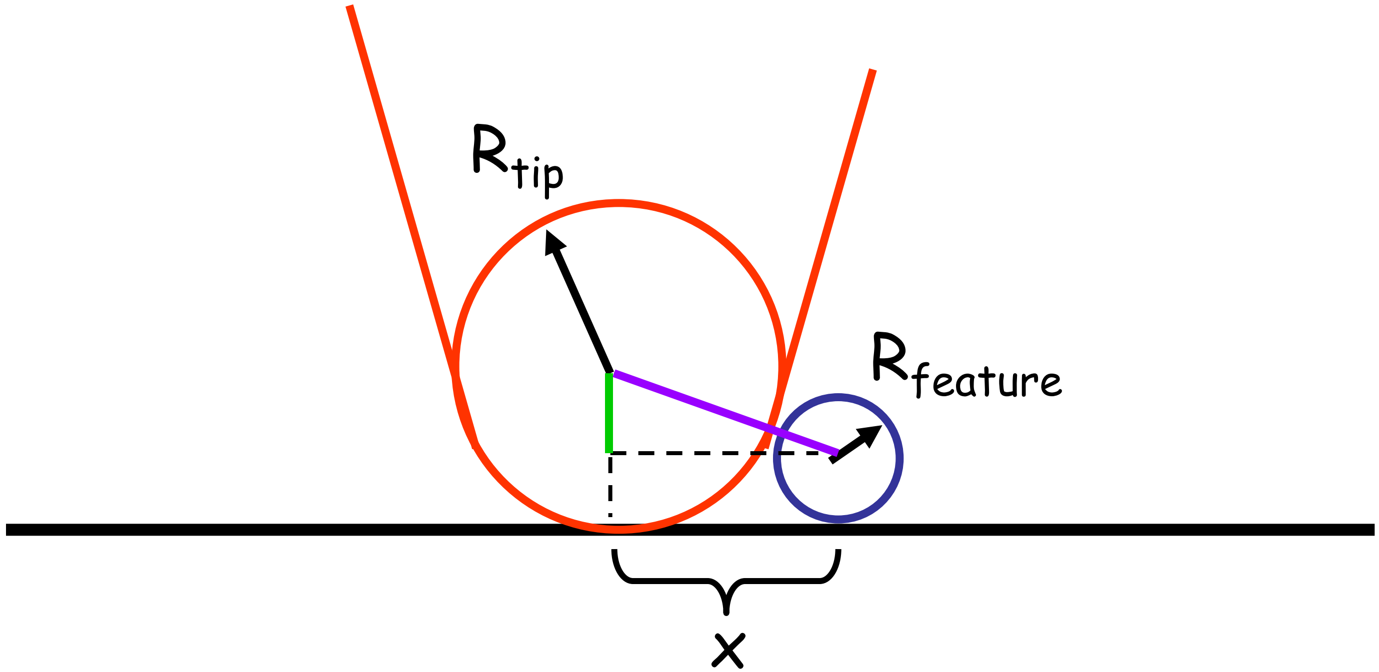
Limitations of Piezos



$$\Delta \ell = d_{31} \frac{\ell}{h} V_o$$



Apparent width of small object



$$x^2 = (R_{tip} + R_{feature})^2 - (R_{tip} - R_{feature})^2$$

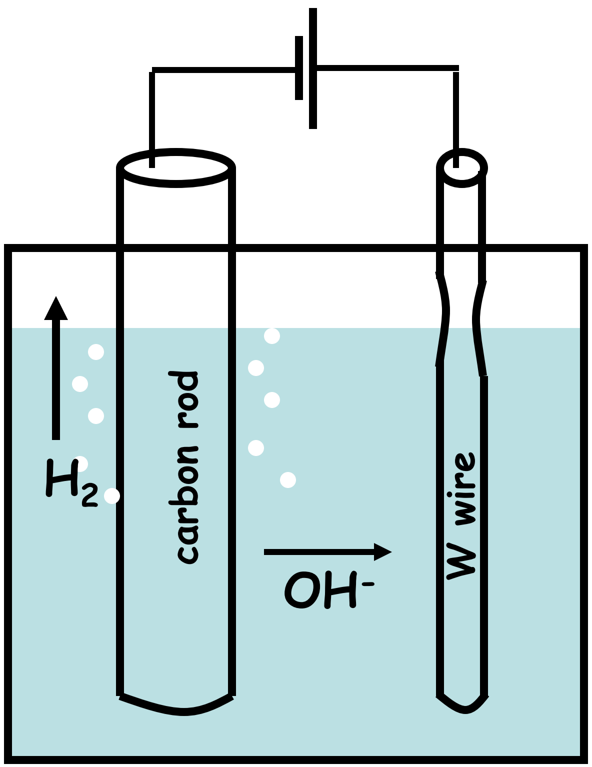
$$x^2 = \cancel{R_{tip}^2} + 2R_{tip}R_{feature} + \cancel{R_{feature}^2} - \cancel{R_{tip}^2} + 2R_{tip}R_{feature} - \cancel{R_{feature}^2}$$

$$x = 2\sqrt{R_{tip}R_{feature}}$$

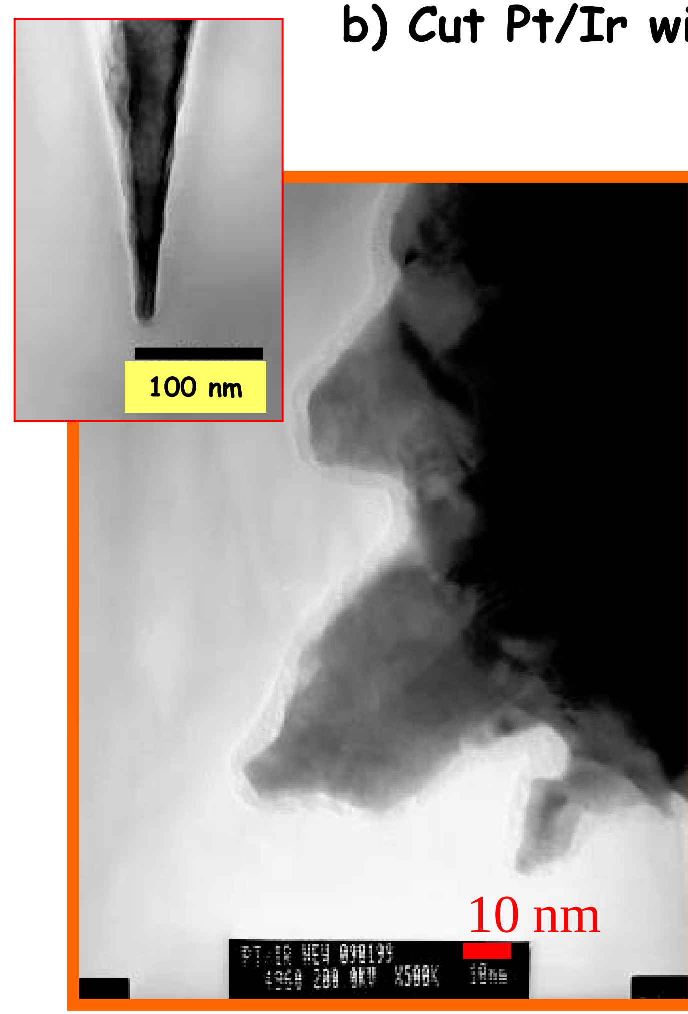
$$apparent\ \ feature\ width \simeq 2x = 4\sqrt{R_{tip}R_{feature}}$$

Tip Fabrication

a) Electrochemical etch of W wire



b) Cut Pt/Ir wire

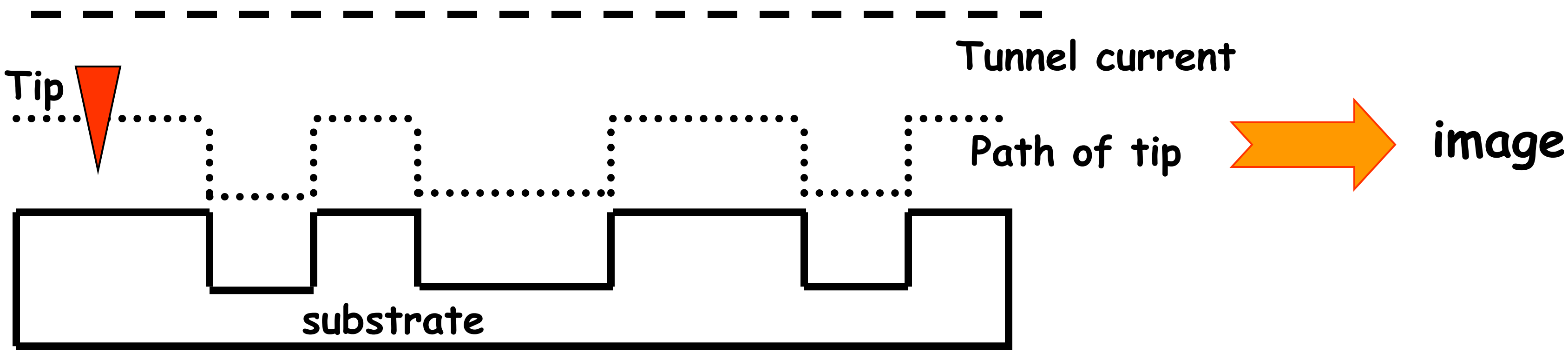


STM tip

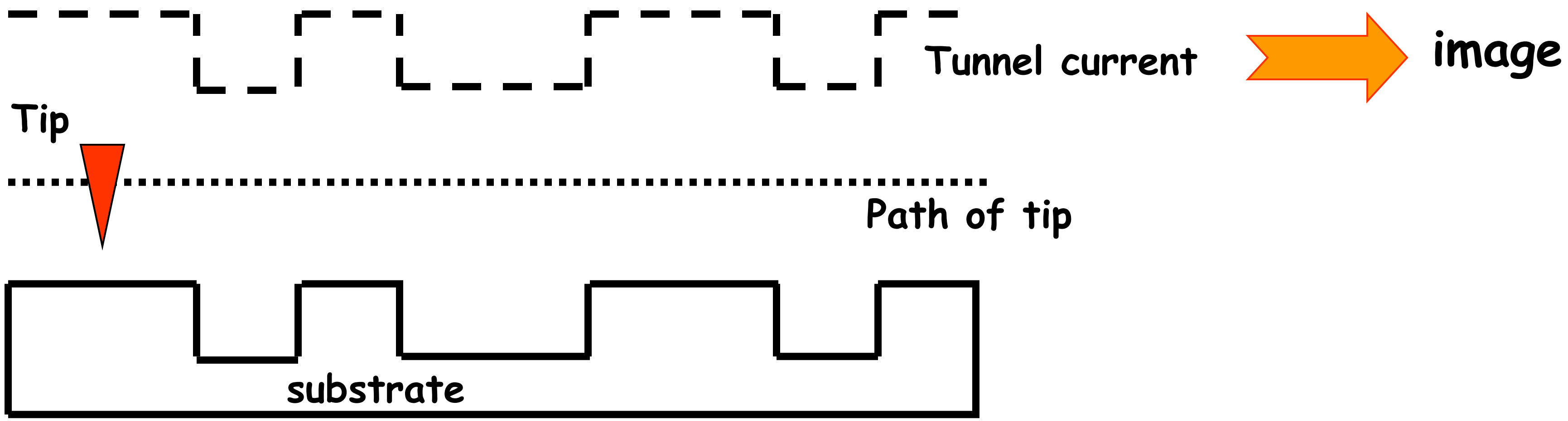
(~ 75 exterior atoms)

Scanning Modes

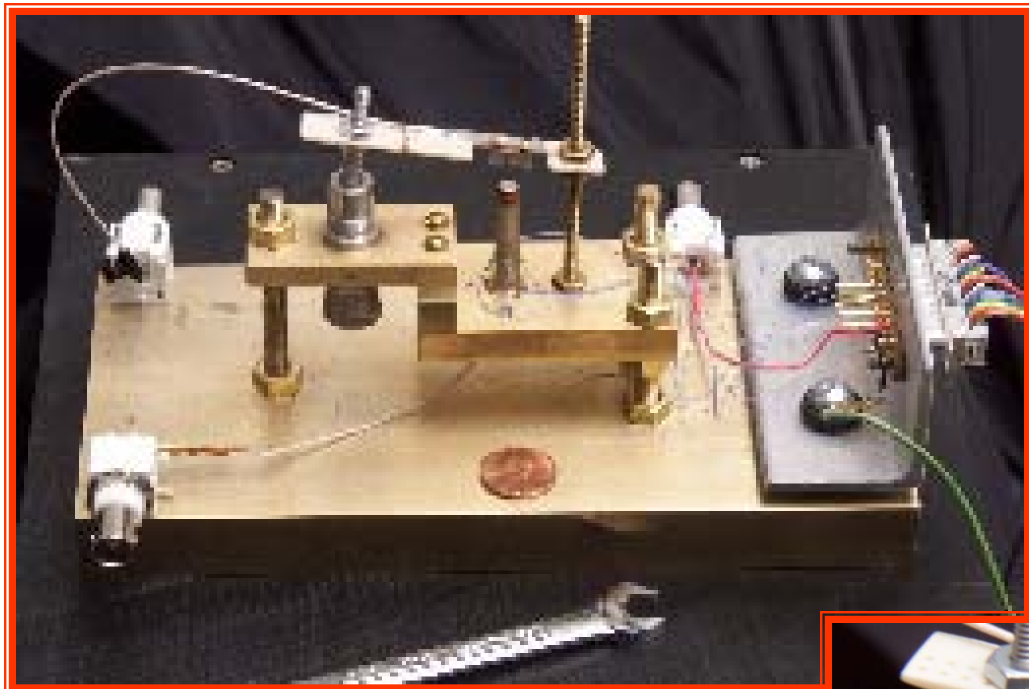
Constant Current → Topography



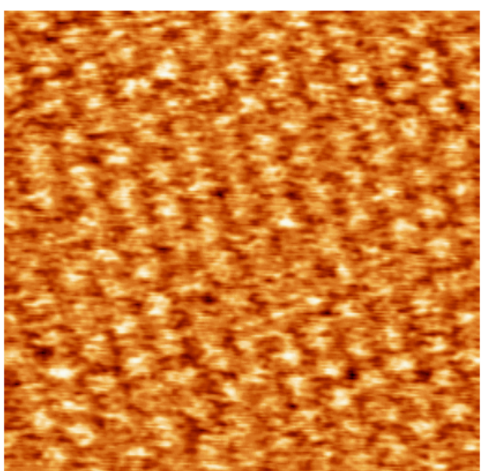
Constant Height → High Speed



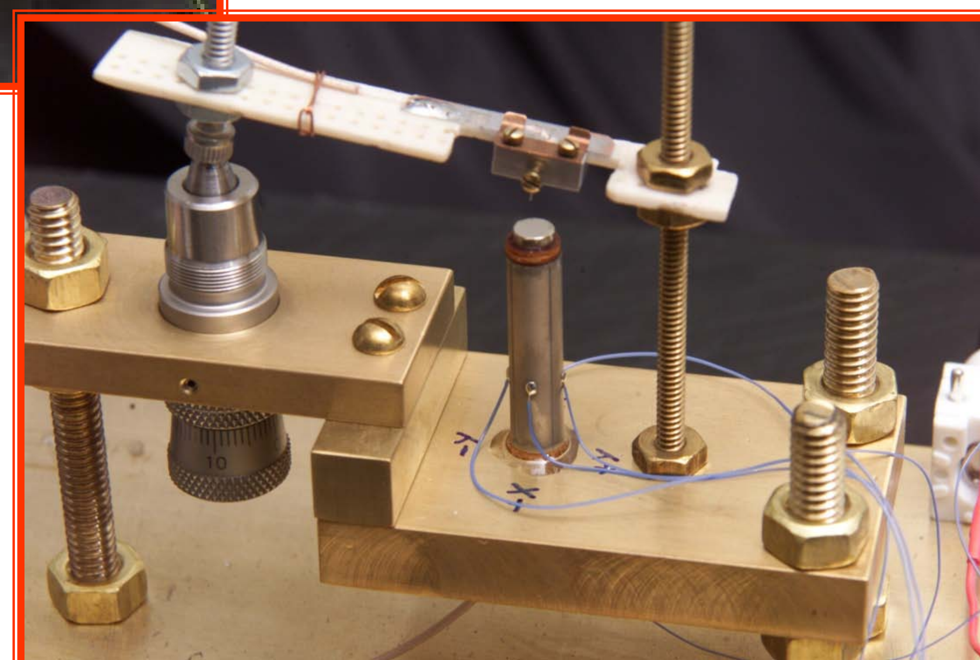
Seeing atoms in a day



Highly oriented pyrolitic graphite (HOPG)



4.8 nm x 4.8 nm



A Forerunner of STM - The Topographiner

In 1971 Russell Young and co-workers demonstrated a **noncontact** stylus profiler called a Topographiner.

Relies on the **field emission current** between a sharp metal tip and a conducting surface as a sensitive measure of the tip-sample distance.

Probe tip mounted directly on a piezoelectric ceramic

Electronic feedback circuit

Probe scans the surface in the horizontal (X-Y) dimensions using piezoelectric ceramics