

ME597/PHYS57000

Fall Semester 2010

Lecture 02

Early Successes

How to Make an STM

Ron Reifenberger

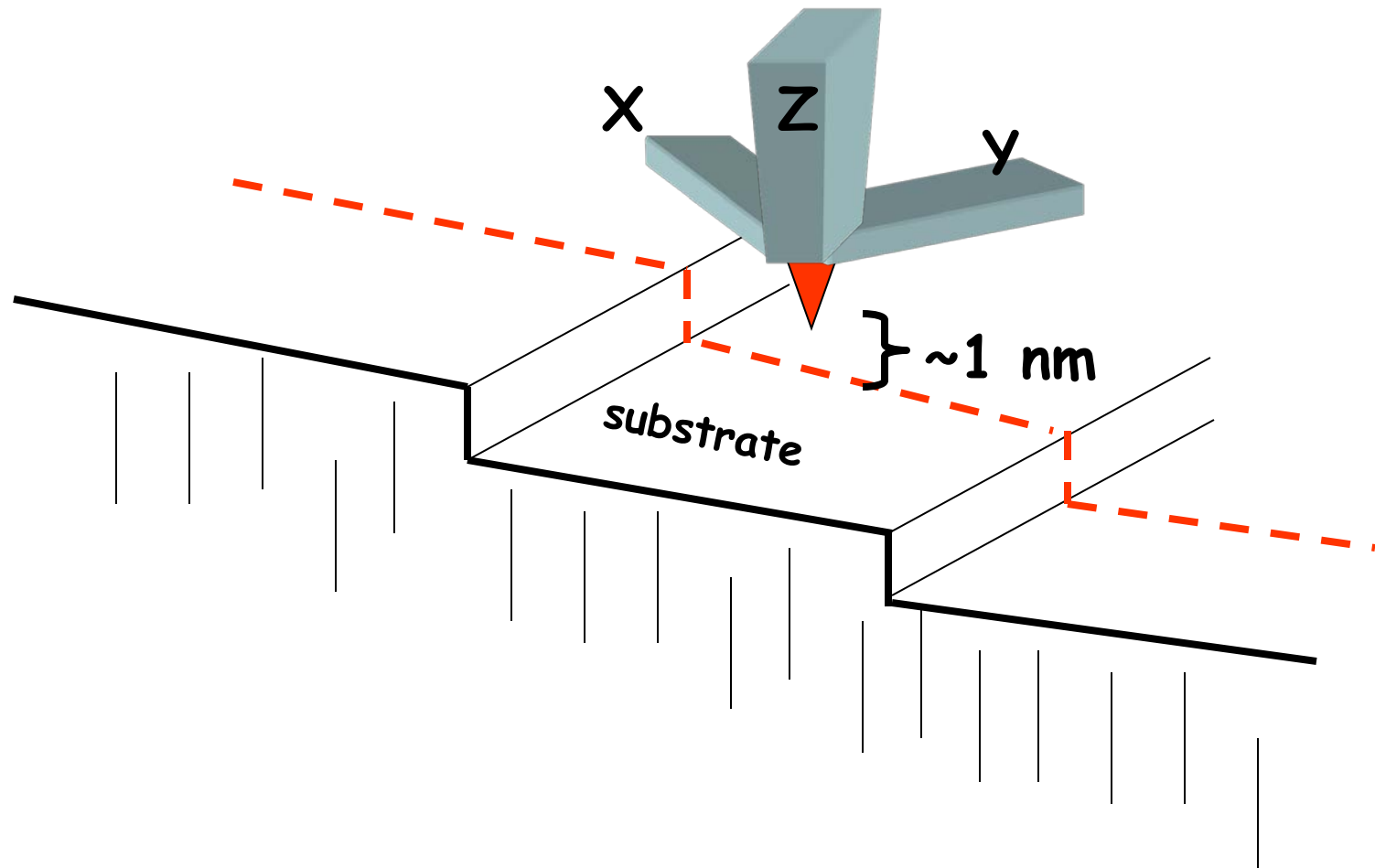
Birck Nanotechnology Center

Purdue University

Suggested Reading: G. Binnig, 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 $e^{-2\alpha d} = \text{constant}$, 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).

Si(111) reconstruction reflects the equilibrium surface structure (lowest energy arrangement) after annealing Si 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 minima corresponding to empty adatom positions and maxima corresponding to the presence of adatoms

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

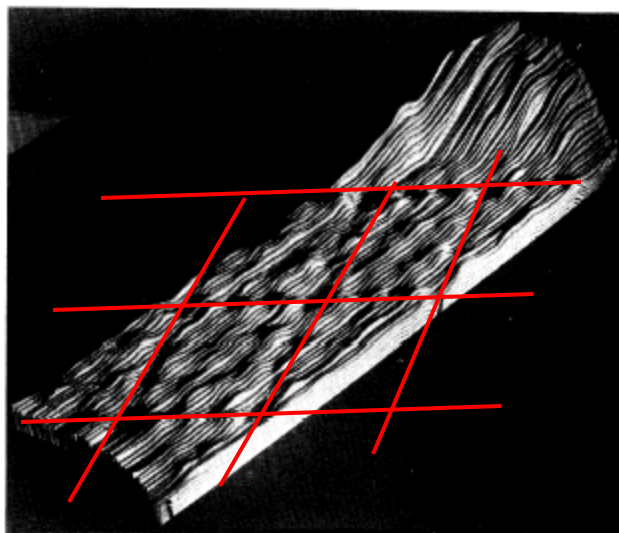


FIG. 1. Relief of two complete 7×7 unit cells, with nine minima and twelve maxima each, taken at 300 °C. Heights are enhanced by 55%; the hill at the right grows to a maximal height of 15 Å. The $[\bar{2}11]$ direction points from right to left, along the long diagonal.

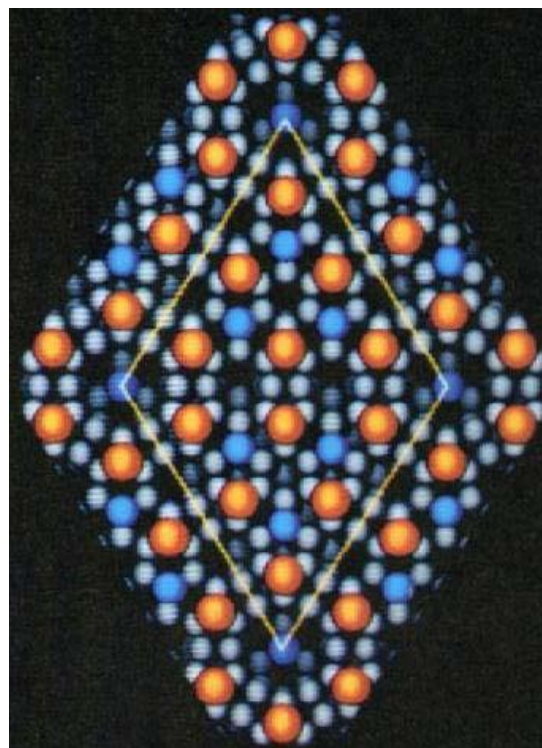
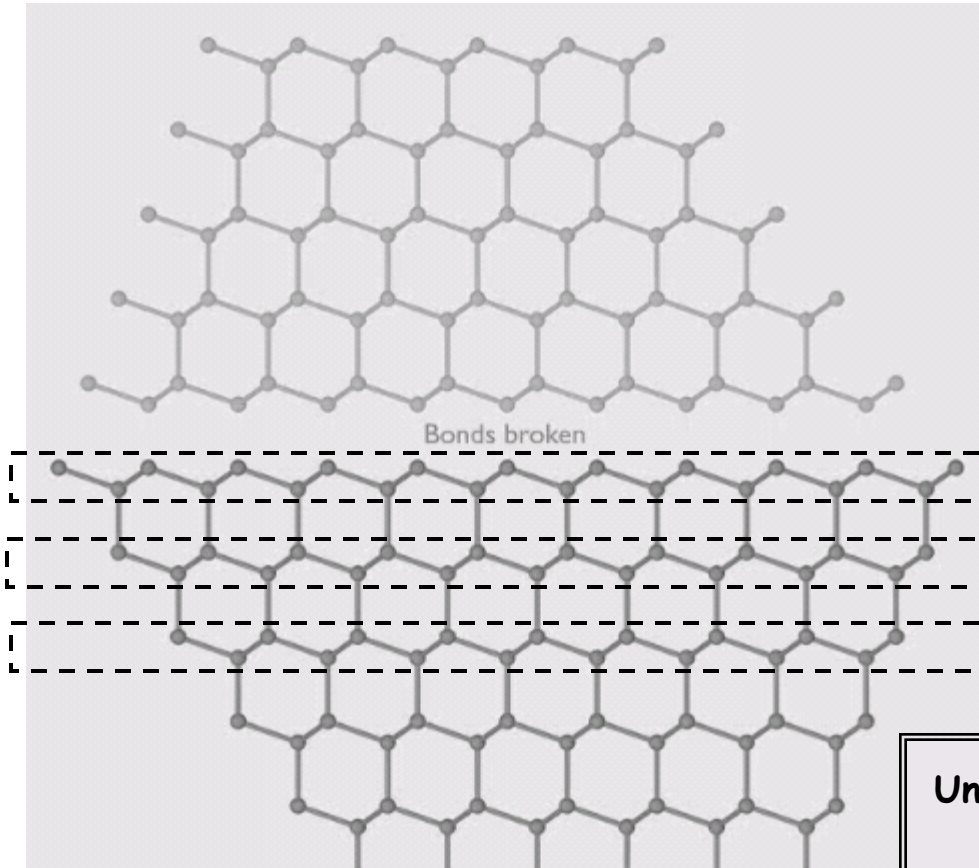


Figure from R.M. Tromp, IBM

Some Details



1st bilayer

Si(111) surface

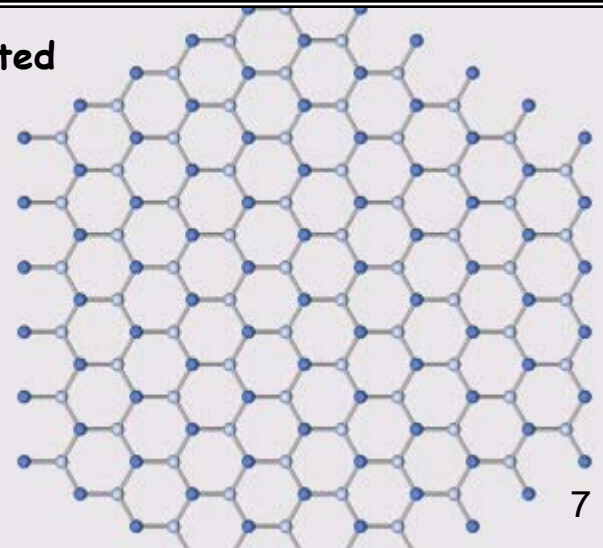
1st bilayer

2nd bilayer

3rd bilayer

Top view of 1st bilayer

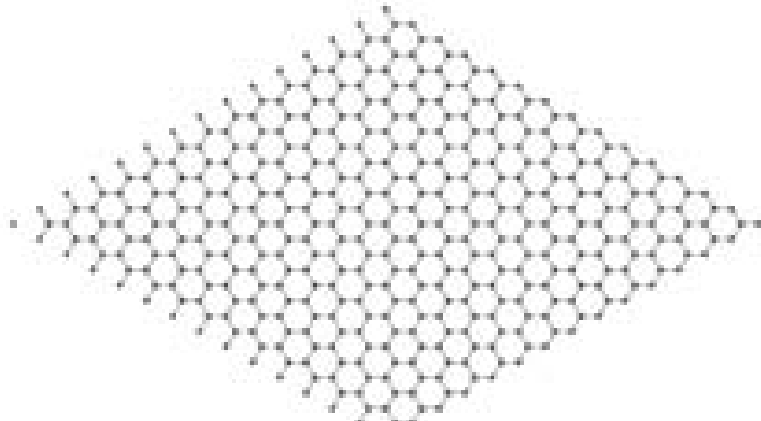
Unreconstructed
surface



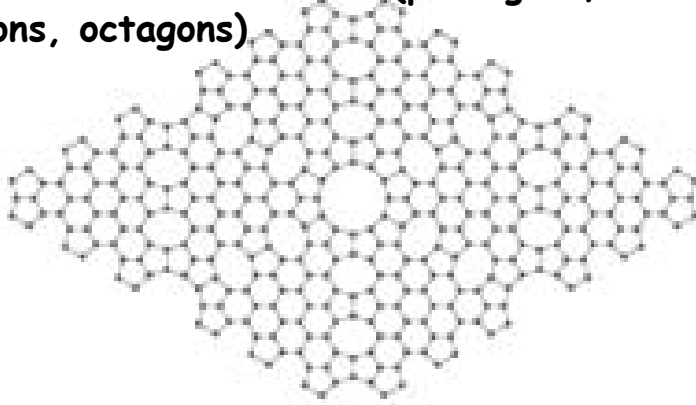
For animation by Yan Liang, see:
<http://www.vimeo.com/1086112>

Comparison

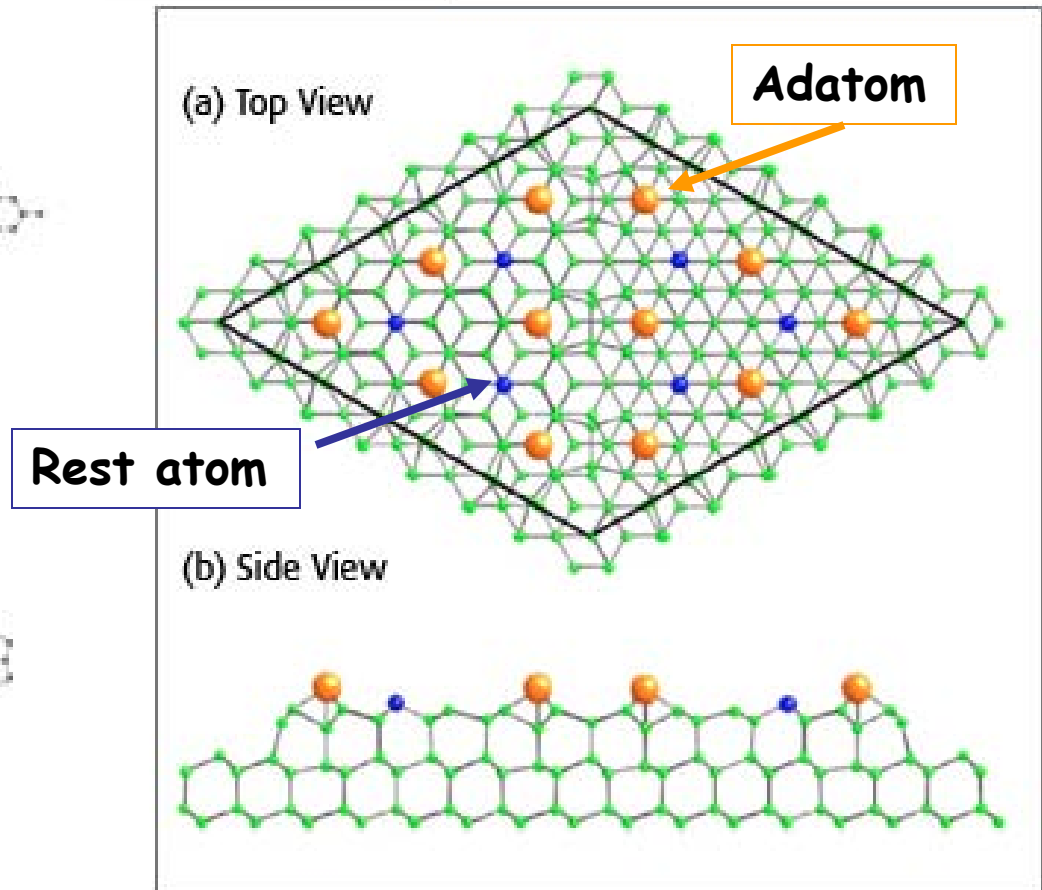
Unreconstructed 7x7 surface (all hexagons)



Reconstructed 7x7 surface (pentagons, hexagons, octagons)



From Omicron Web site:

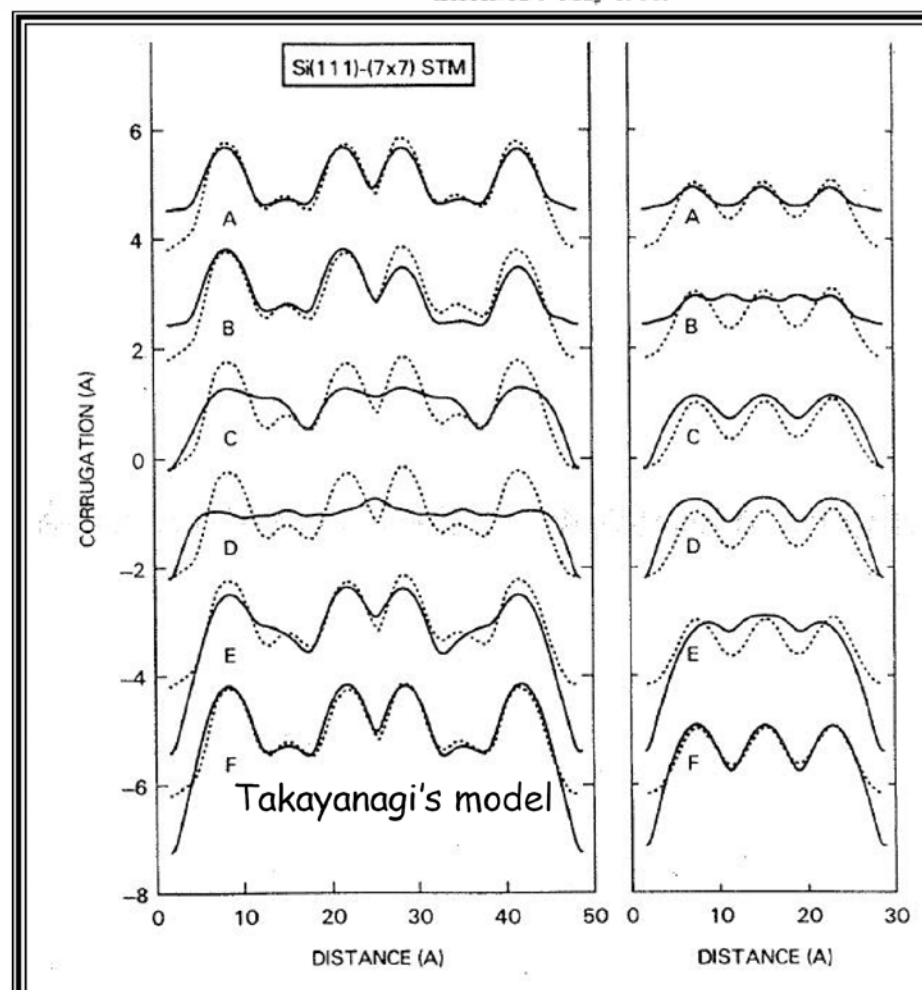


Atomic and electronic contributions to Si(111)-(7×7) scanning-tunneling-microscopy images

R. M. Tromp, R. J. Hamers, and J. E. Demuth

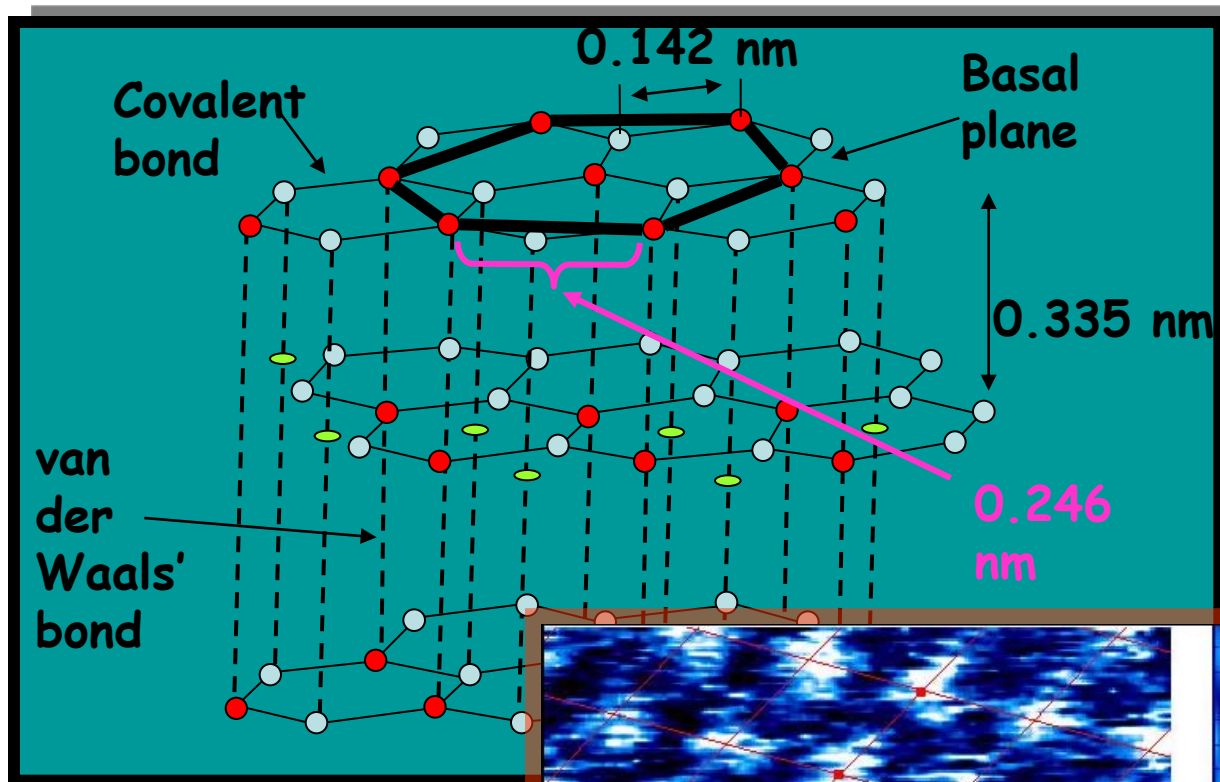
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

(Received 9 May 1986)

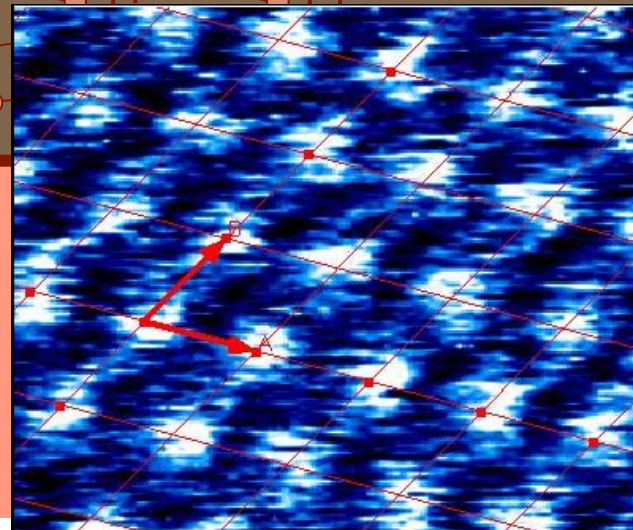


Experiment:

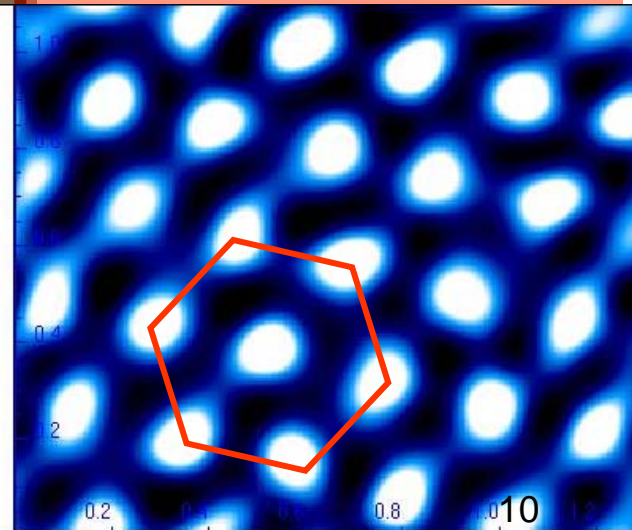
A flat substrate: Highly Oriented Pyrolytic Graphite (HOPG)



(1.3 x 1.1 nm)

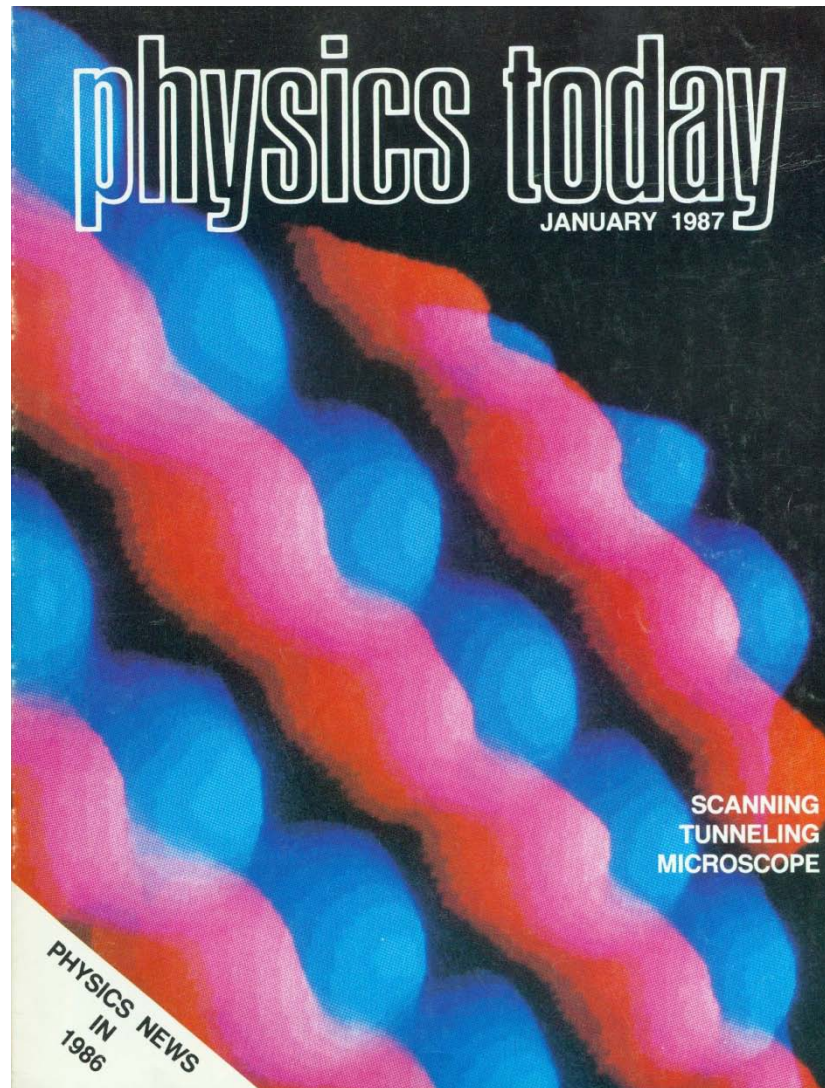


Raw data



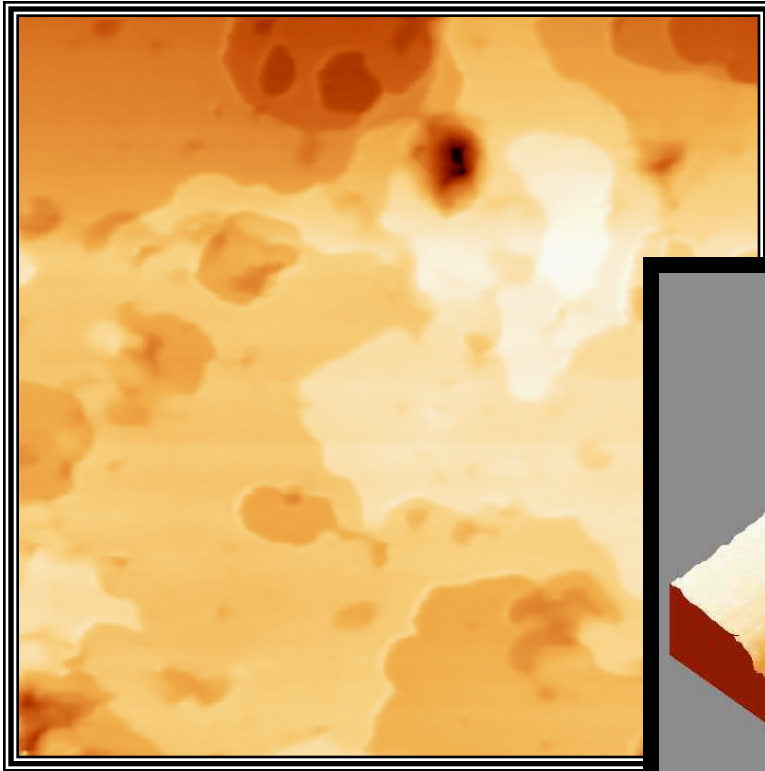
Fourier filtered image

STM of GaAs



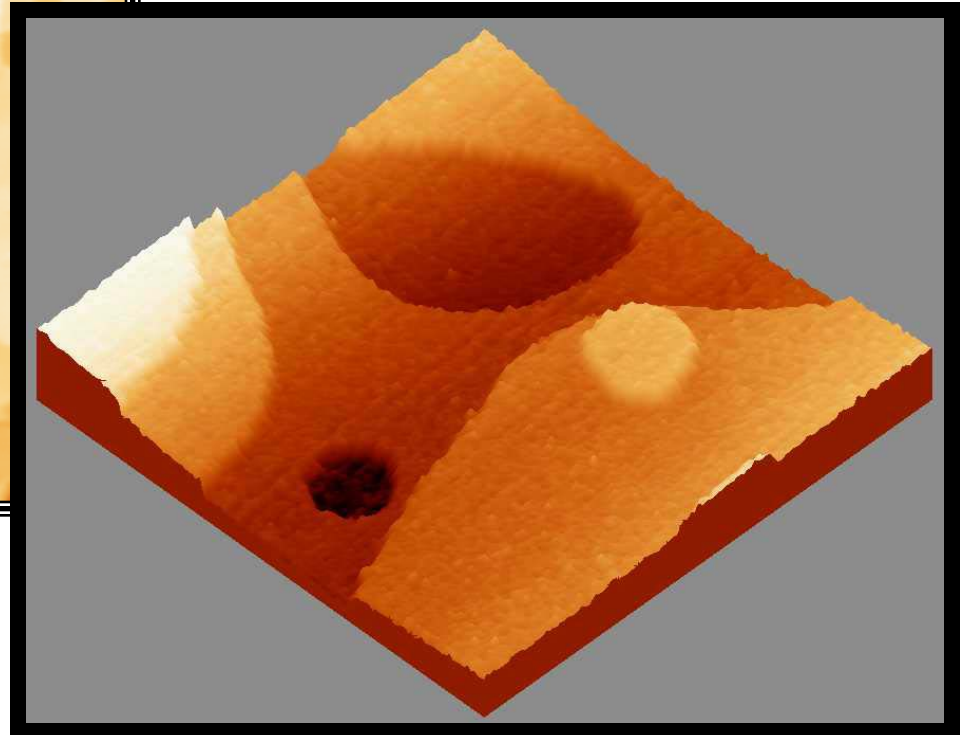
Ga: red sites; As: blue sites

Imaging the surface of Au(111)



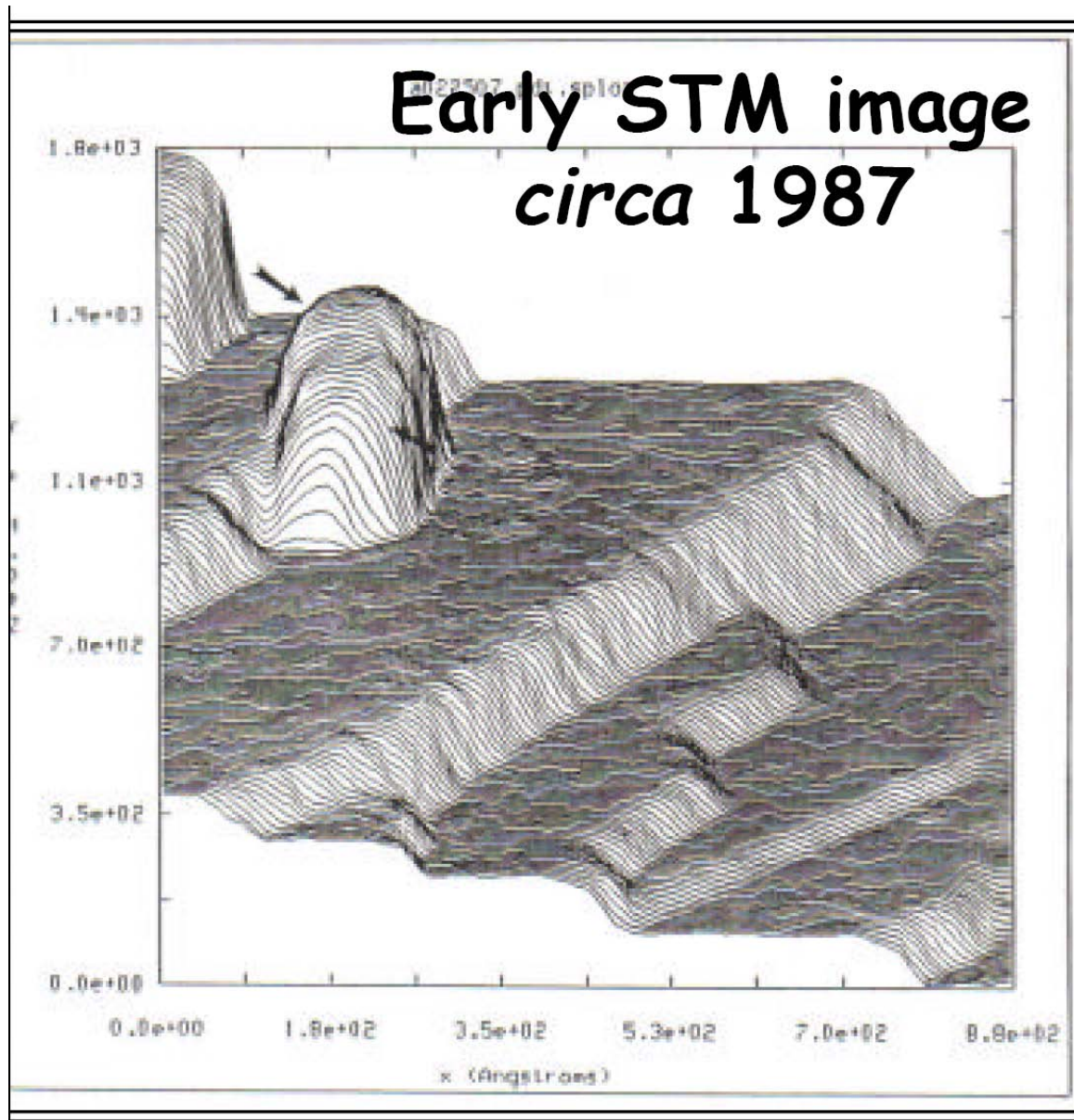
Top View

0.236 nm steps
on Au(111)

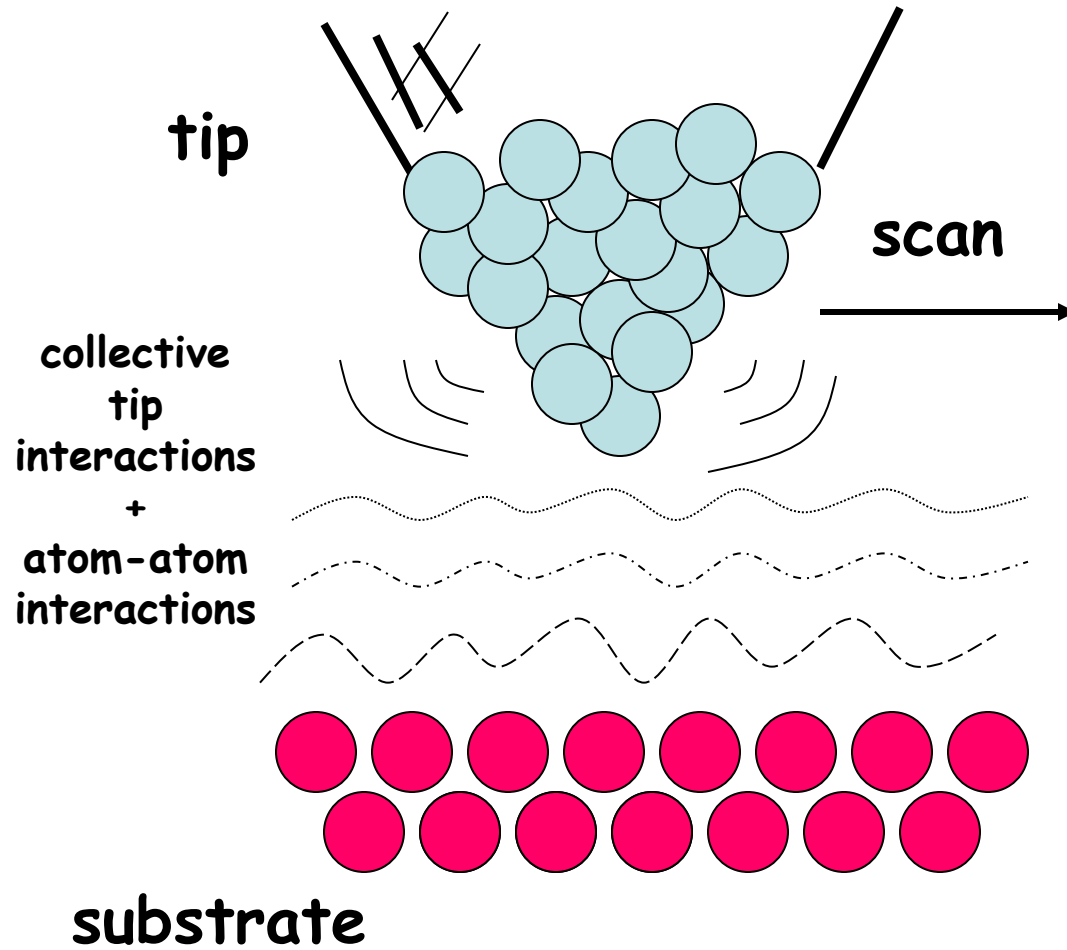


100 nm x 100 nm

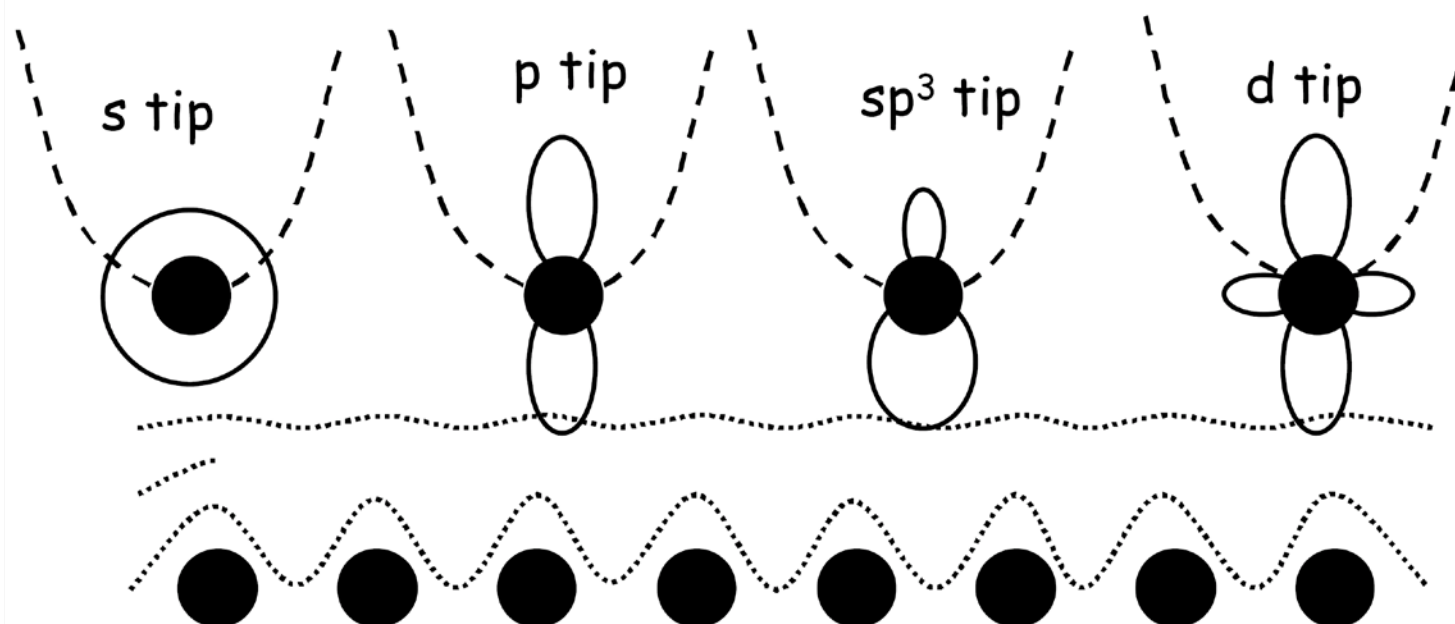
Au nanoclusters on Au substrate



Why it Works

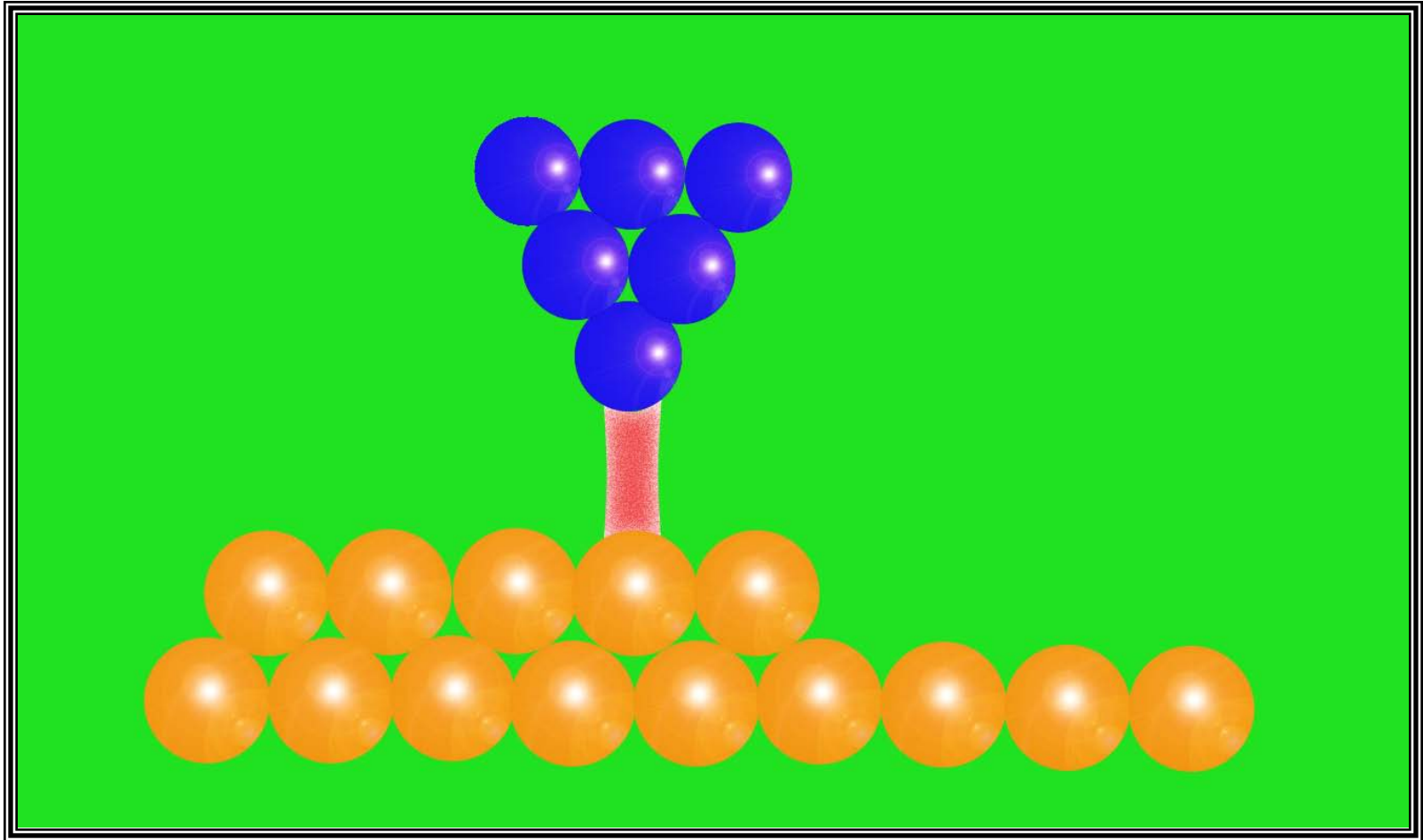


Microscopic view of STM imaging mechanism



C.J. Chen: (1993)

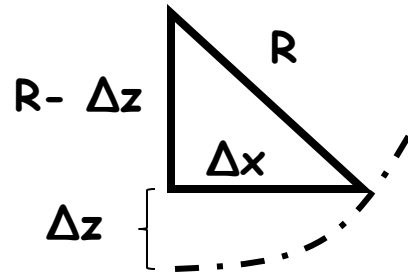
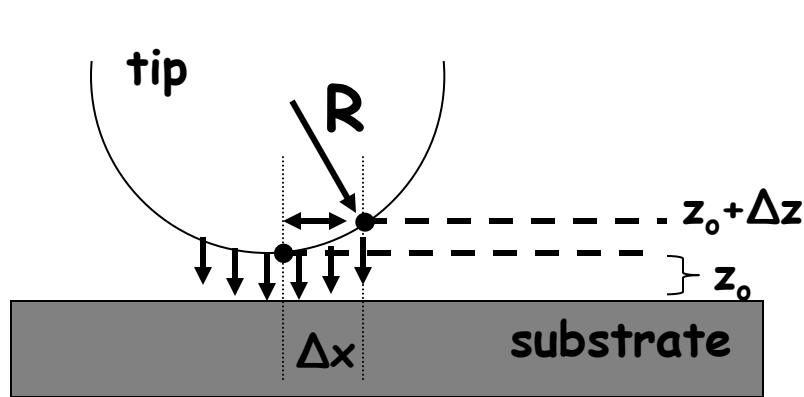
The Front Atom IS Important



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

Second Law of STM: Reliable STM data usually requires UHV

Lateral Resolution?



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

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

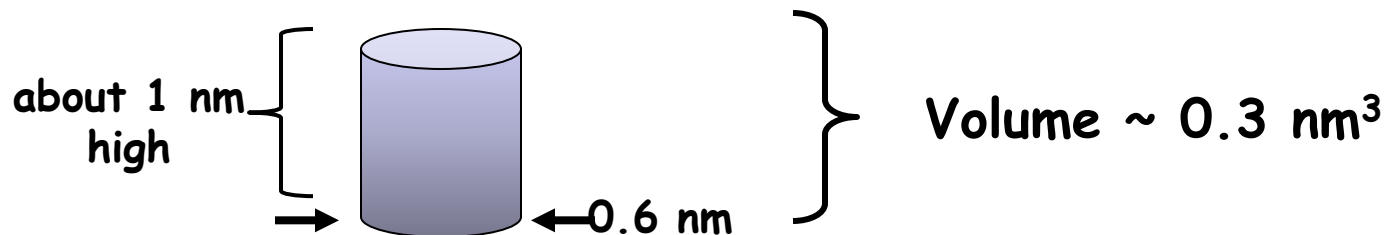
Assume: $\alpha \approx 11 \text{ nm}^{-1}$; $R \approx 0.5 \text{ nm}$

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

A: When $e^{-2\alpha(\Delta z)} \approx 0.1 \Rightarrow \Delta x = 0.3 \text{ nm}$.

"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 cm³ at atmospheric pressure?

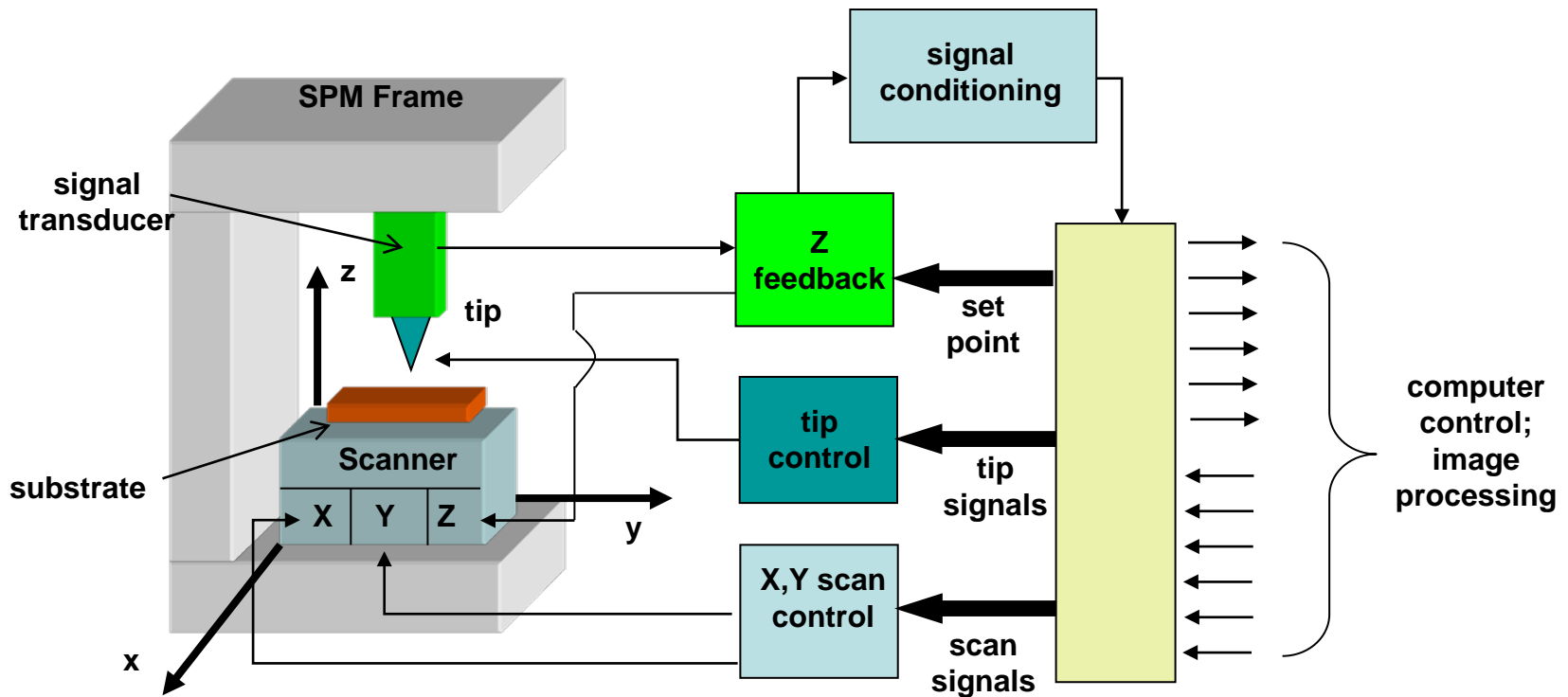
Ideal gas law: $PV=nk_B T \rightarrow$

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

$$\begin{aligned}\frac{n}{V} &= \frac{P}{k_B T} = \frac{6 \times 10^{23}}{22.4 \text{ liters}} \times \frac{1 \text{ liter}}{0.001 \text{ m}^3} \times \frac{1 \text{ m}^3}{1 \times 10^6 \text{ cm}^3} \\ &= 2.7 \times 10^{19} \text{ cm}^{-3} \quad (\text{Loschmidt's Number - 1865}) \\ &= 2.7 \times 10^{19} \text{ cm}^{-3} \times \left(\frac{1 \text{ cm}}{1 \times 10^7 \text{ nm}} \right)^3 = 0.03 \text{ molecules per nm}^3\end{aligned}$$

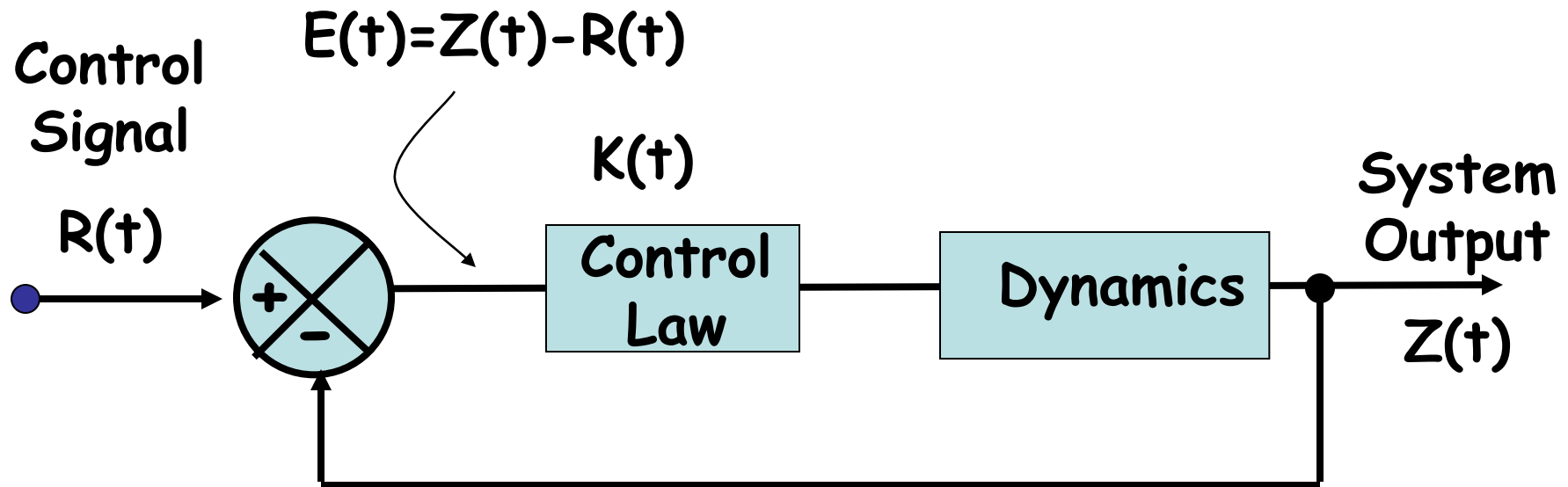
How to make it work

STM System Overview



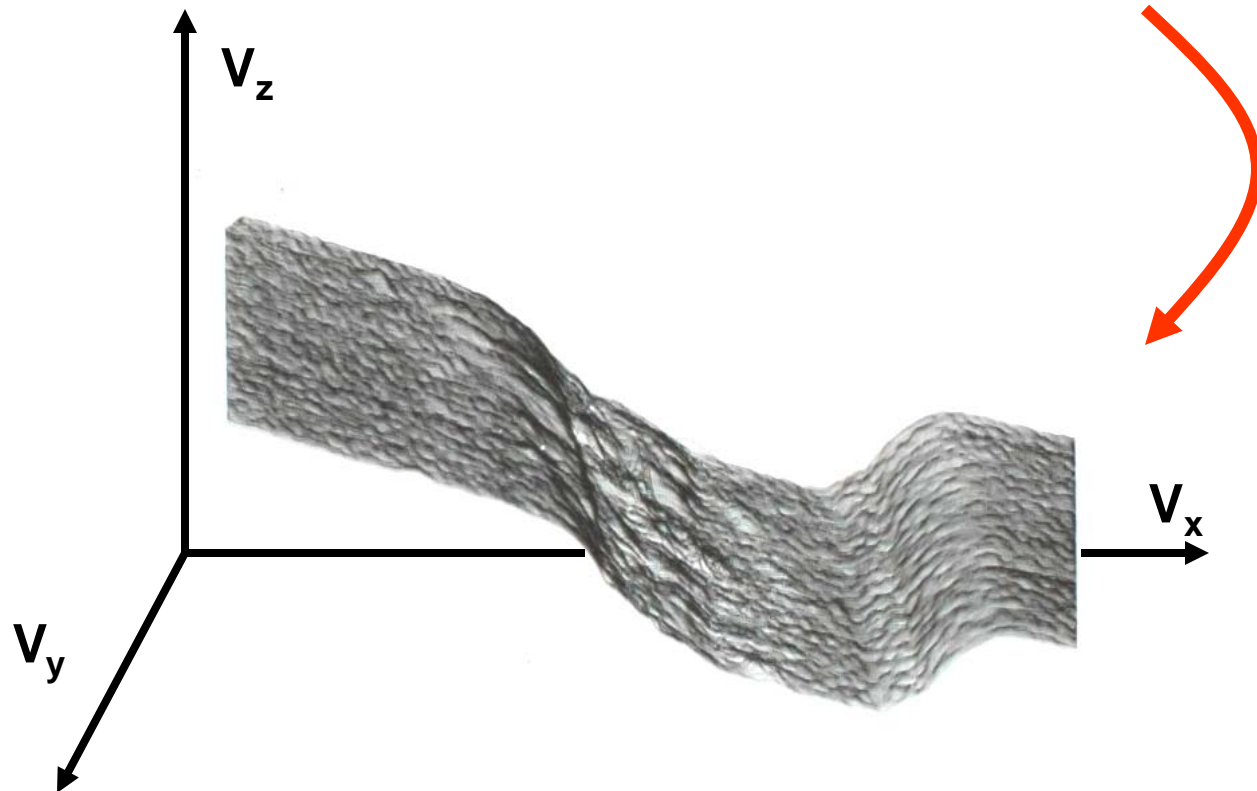
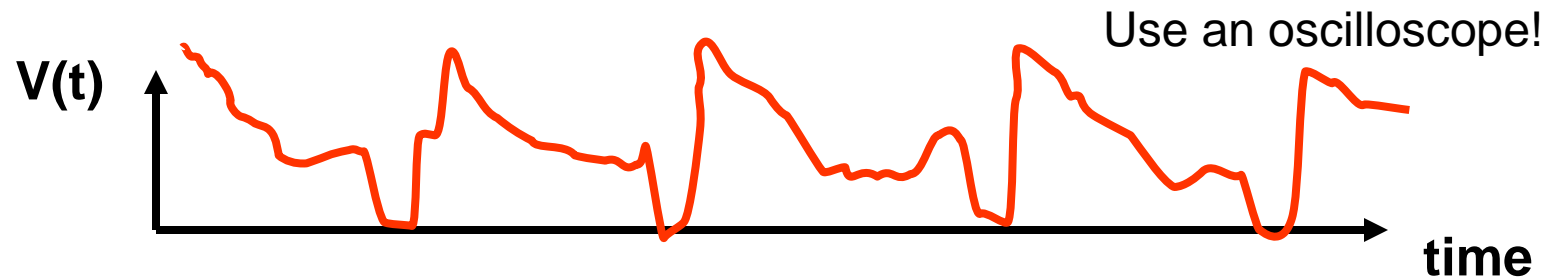
Feedback Control

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



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

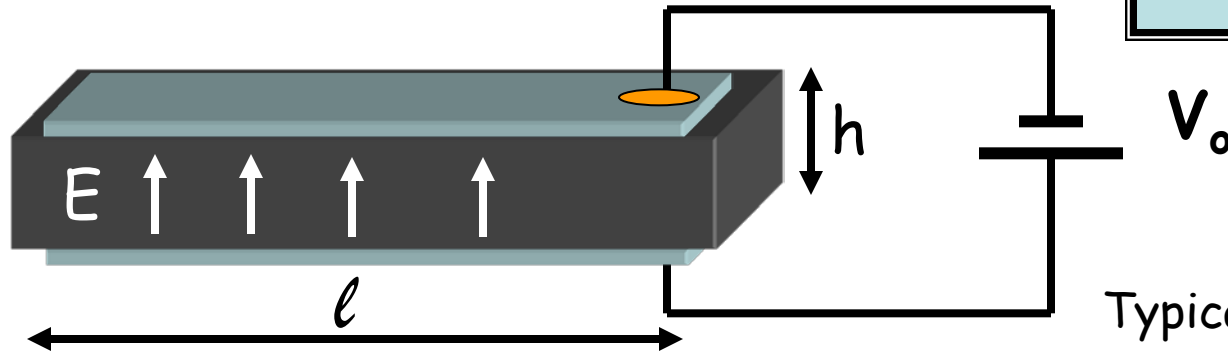
ALL STM images are derived from voltages!



Implications for Imaging Processing

Achieving Vibrationless Motion at the Nanoscale

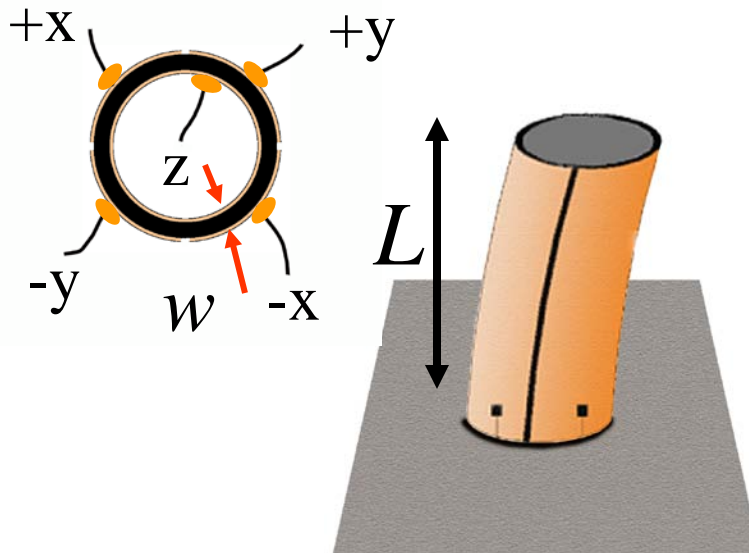
Piezoelectric Bar



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

Typically, $\Delta \ell \sim 0.5 \text{ nm/V}$

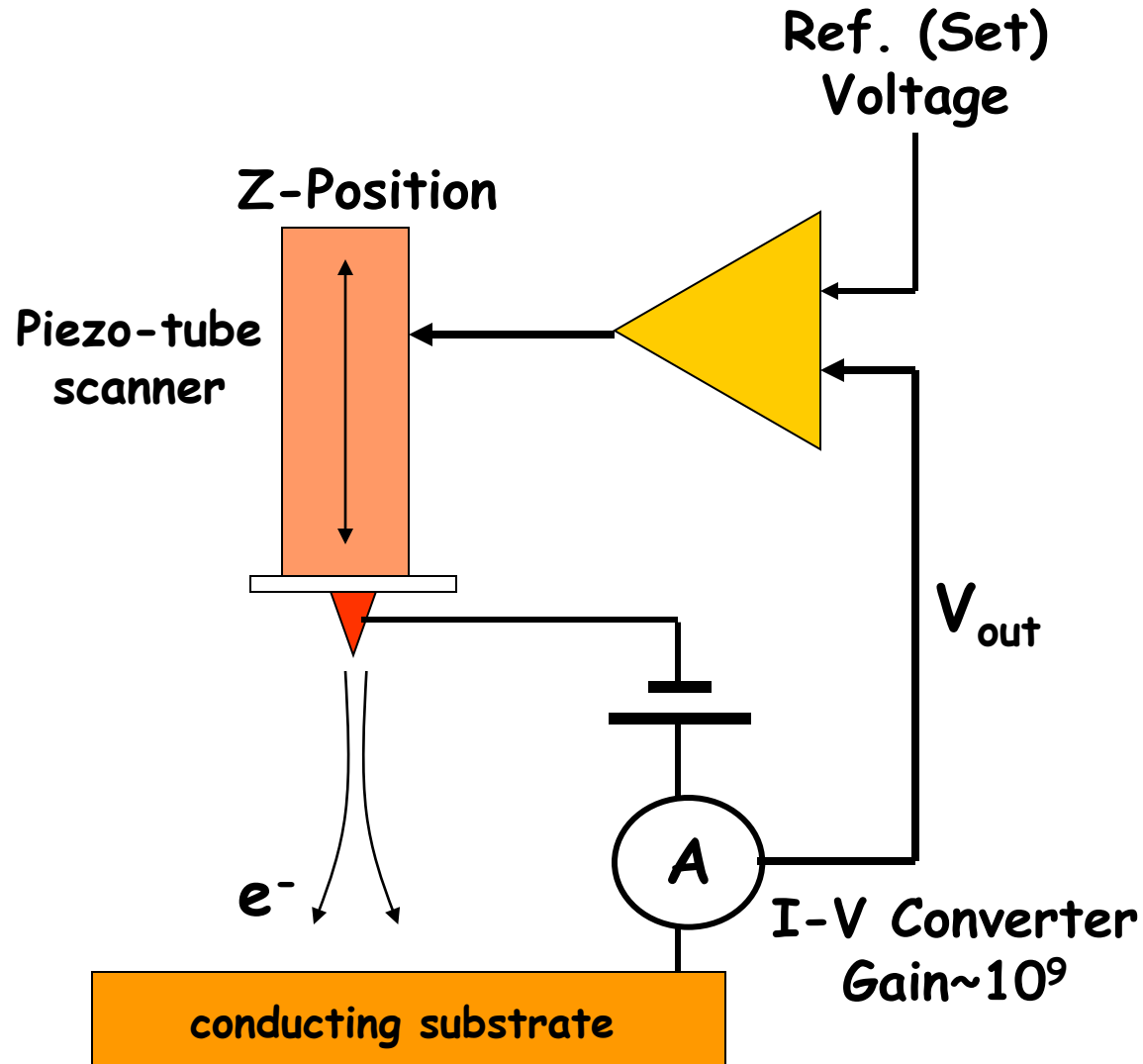
Quadranted Piezoelectric Tube



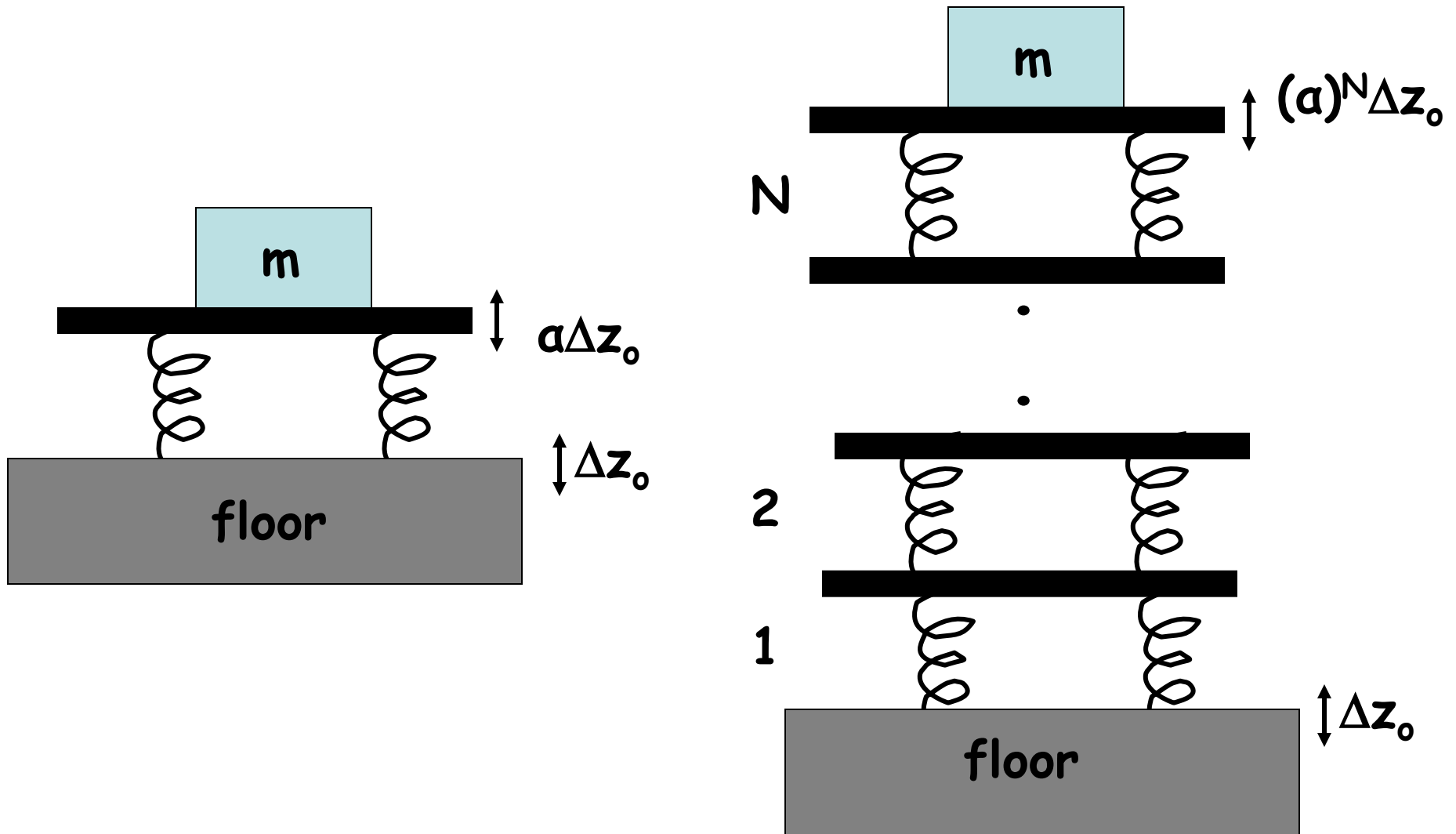
$$\Delta z = L \frac{V_o}{w} d_{31}$$

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

Controlling the Tunnel Gap

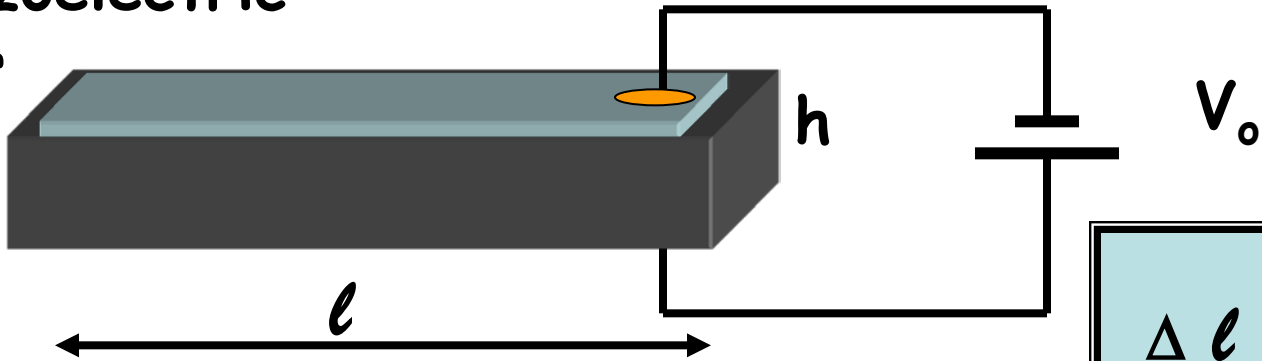


Vibration Damping

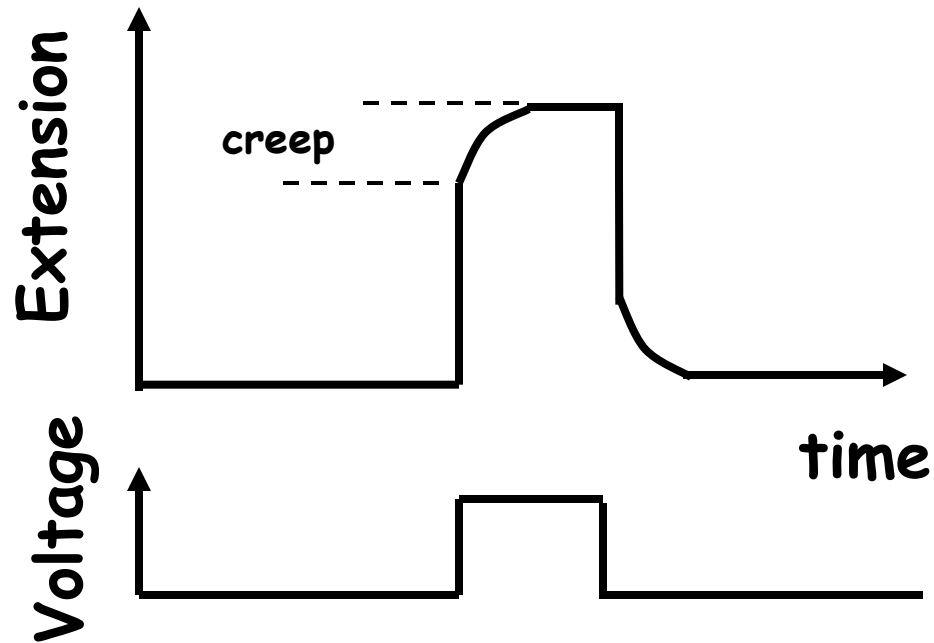


Limitations of Piezos

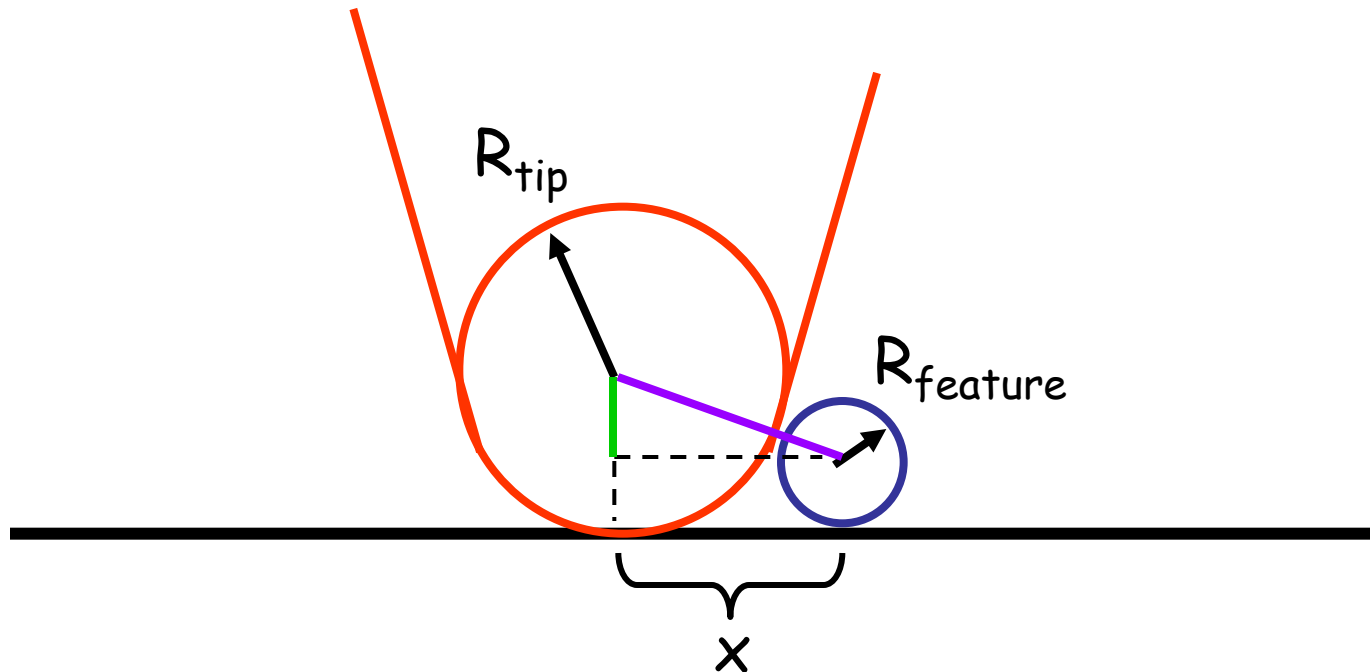
Piezoelectric
Bar



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



Apparent width of small object



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

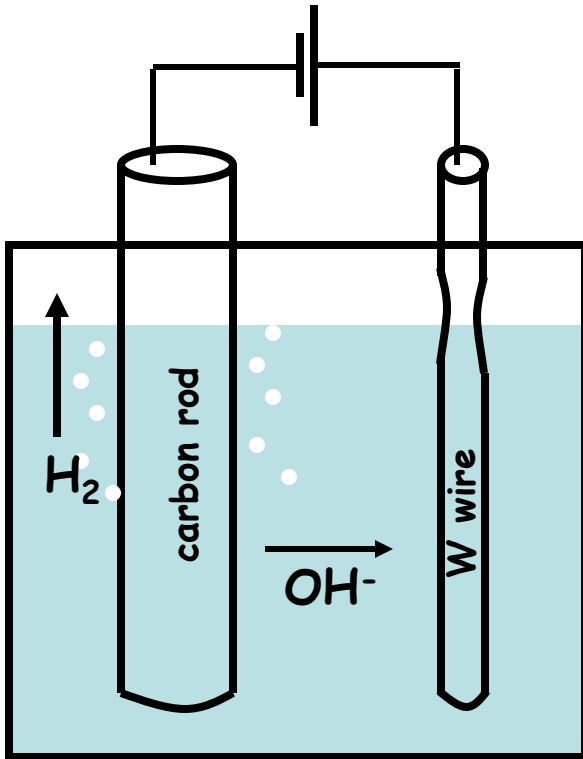
$$x^2 = \cancel{R_{tip}^2} + 2R_{tip}R_{feature} + \cancel{R_{feature}^2} - \cancel{R_{tip}^2} + 2R_{tip}R_{feature} - \cancel{R_{feature}^2}$$

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

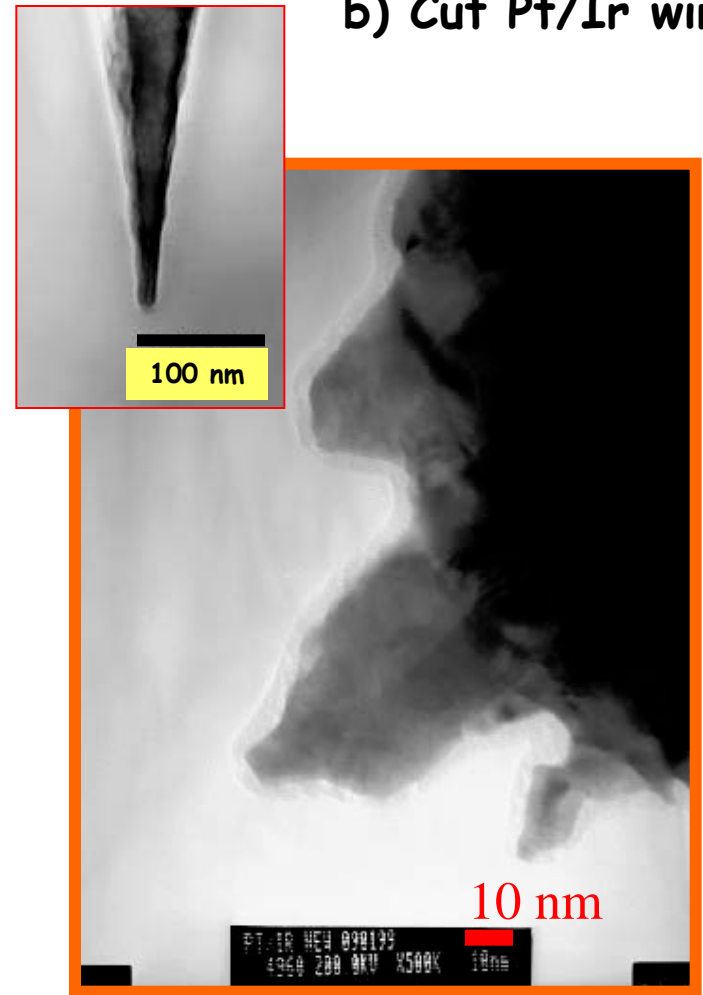
$$\text{apparent feature width} \simeq 2x = 4\sqrt{R_{tip}R_{feature}}$$

Tip Fabrication

a) Electrochemical etch of W wire



b) Cut Pt/Ir wire



STM tip
(~ 75 exterior atoms)₂₈