Nanomaterials

Lecture 9: Scanning Probe Lithography

Scanning Probe Lithography

C. Julian Chen, *Introduction to Scanning Tunneling Microscopy*

The Scanning Tunneling Microscope (STM)

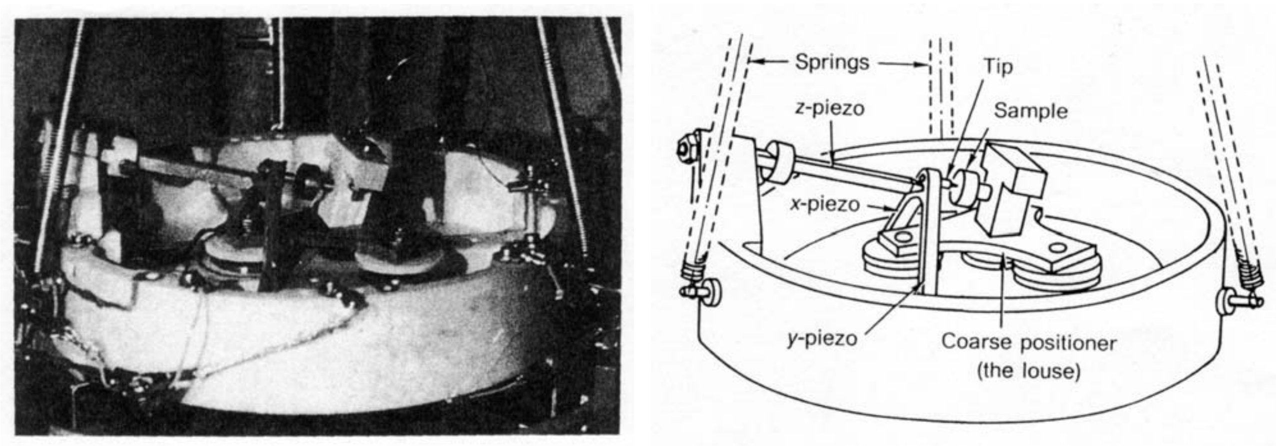

Plate 2. A humble gadget that shocked the science community. Upper, a photograph of an earlier version of the scanning tunneling microscope that enabled real-space imaging of the Si(111)-7×7 structure. Lower, a schematic of it. See Binnig and Rohrer (1982). Original photograph courtesy of Ch. Gerber.

- STM invented by Gerd Binnig and Heinrich Rohrer in 1982
- Led to Nobel Prize in Physics, 1986

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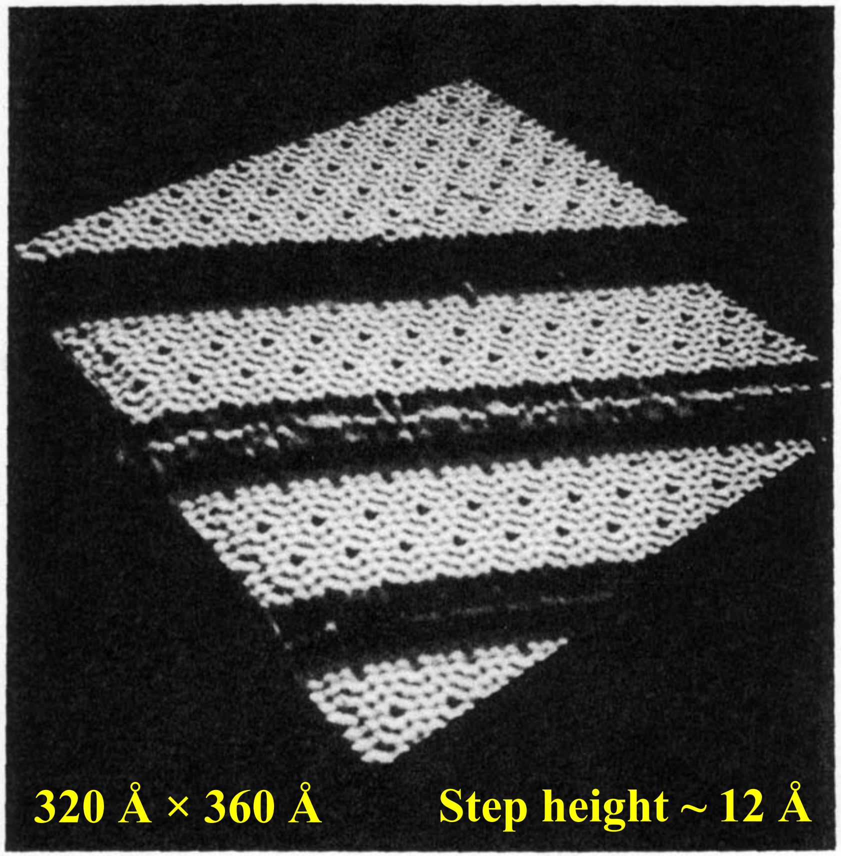
Si(111)-7×7: "Stairway to Heaven"



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Scanning Tunneling Microscope Schematic

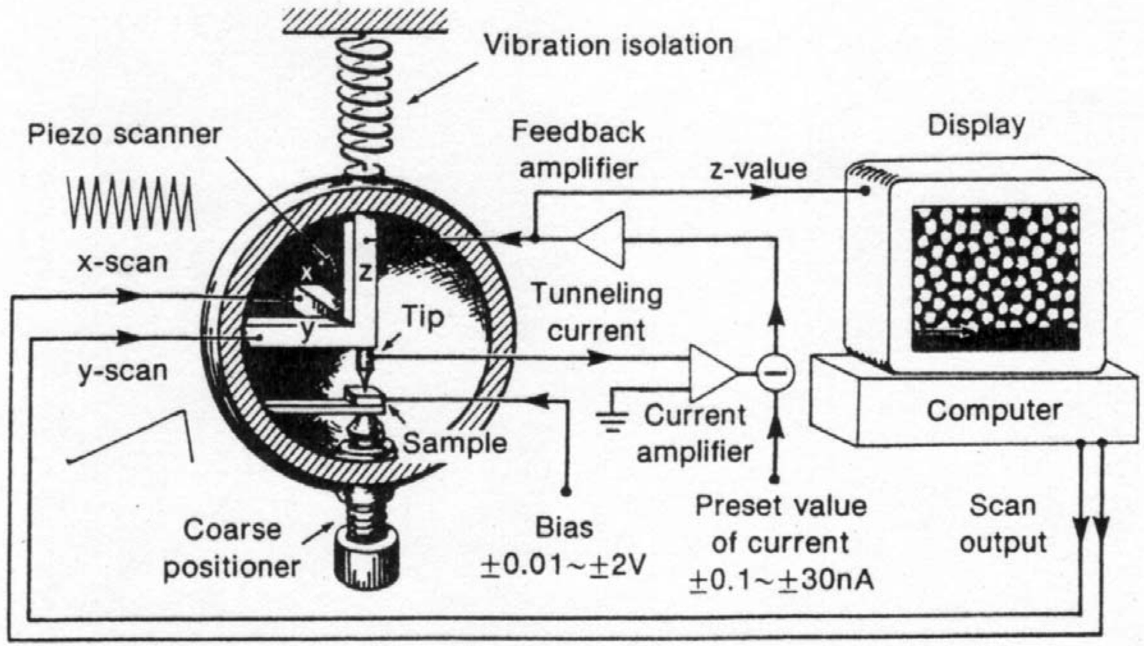

Fig. 1.1. Schematic diagram of the scanning tunneling microscope.

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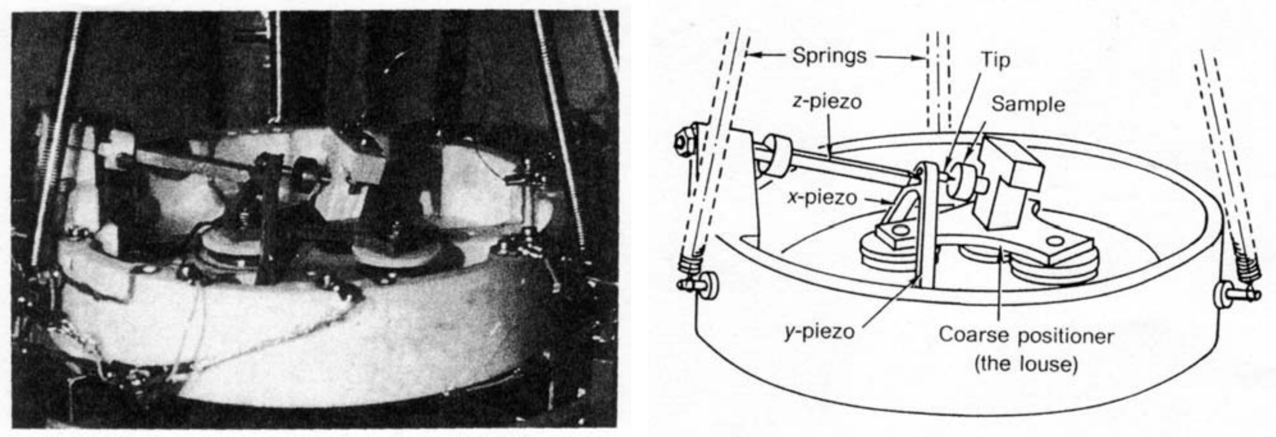
The Scanning Tunneling Microscope (STM)



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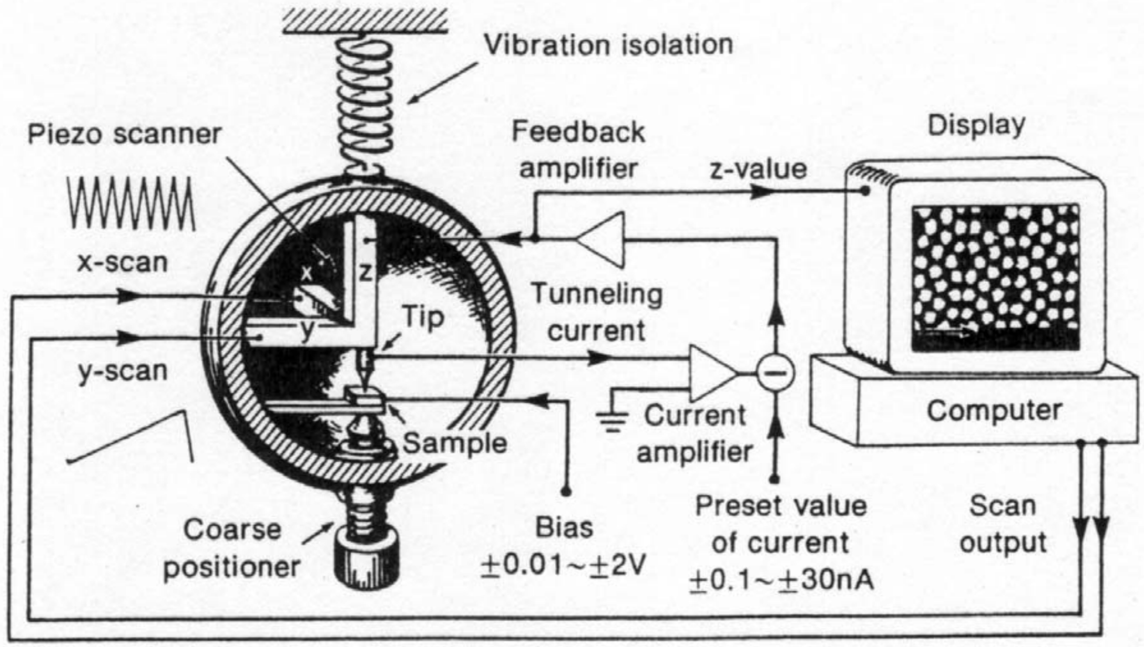

Fig. 1.1. Schematic diagram of the scanning tunneling microscope.

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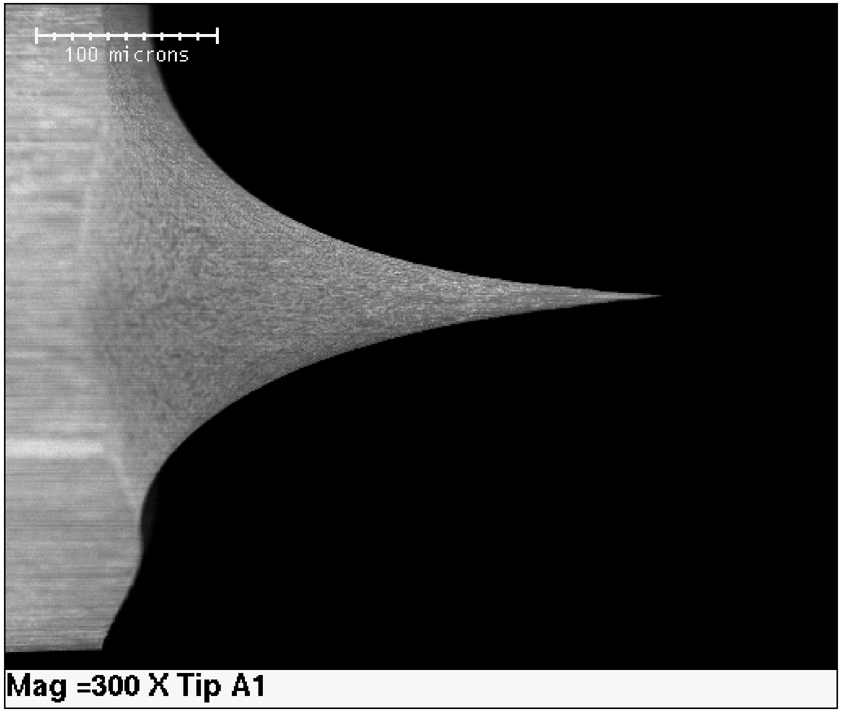
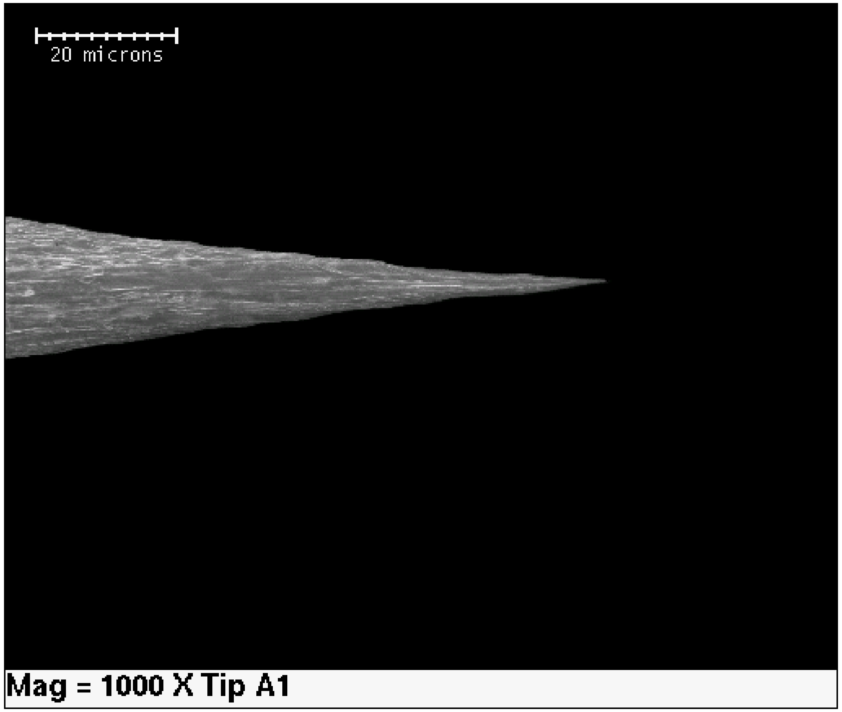
Tungsten STM Tip





- Electrochemically etched using NaOH
- Ideally, the tip is atomically sharp

One-Dimensional Tunnel Junction

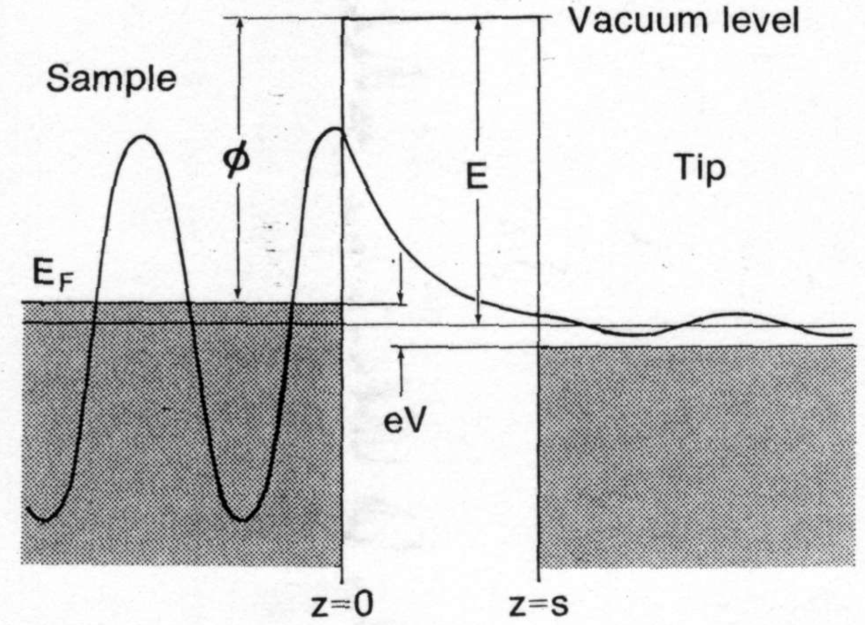


Fig. 1.4. A one-dimensional metal–vacuum–metal tunneling junction. The sample, left, and the tip, right, are modeled as semi-infinite pieces of free-electron metal.

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Tunneling Current – Approach #1

Assume metal-vacuum-metal junction, solve Schrödinger Equation:

$$I \propto V\rho_s e^{-2kW}, \text{ where } k = \frac{\sqrt{2m\phi}}{\hbar} = 0.51\sqrt{\varphi(eV)}\ \text{Å}^{-1}$$

I = tunneling current

V = tip-sample voltage

ρ_s = local density of states of sample

W = width of barrier

Typically, $\varphi \sim 4$ eV → $k \sim 1$ Å^{-1}

→ Current decays by $e^2 \sim 7.4$ times per Å

One-Dimensional Tunnel Junction

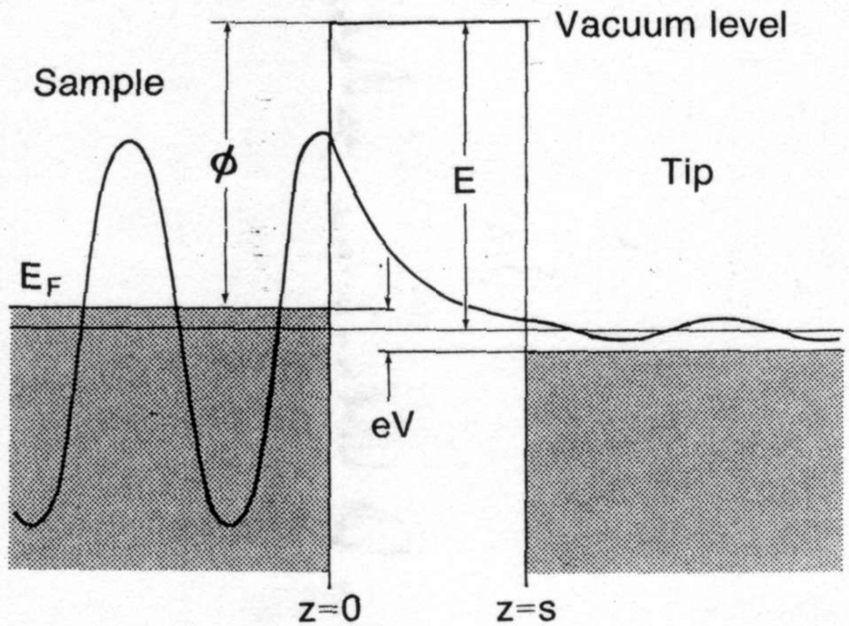

Fig. 1.4. A one-dimensional metal–vacuum–metal tunneling junction. The sample, left, and the tip, right, are modeled as semi-infinite pieces of free-electron metal.

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Bardeen Tunneling Theory

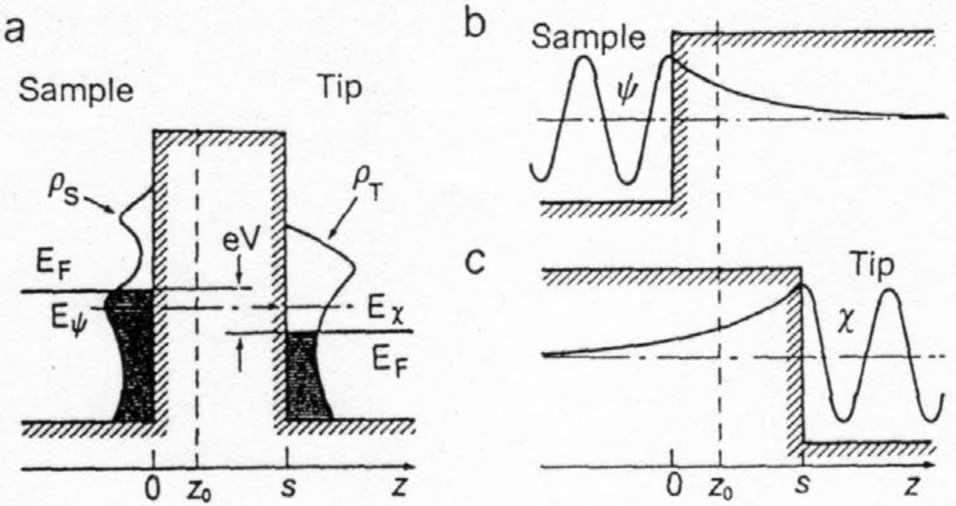

Fig. 1.20. The Bardeen approach to tunneling theory. Instead of solving the Schrödinger equation for the coupled system, a, Bardeen (1960) makes clever use of perturbation theory. Starting with two free subsystems, b and c, the tunneling current is calculated through the overlap of the wavefunctions of free systems using the *Fermi golden rule*.

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Tunneling Current – Approach #2

Consider overlap of wavefunctions from either side of barrier:

Using Fermi's Golden Rule (assuming kT << energy resolution of the measurement),

sample → ρ_s, tip → ρ_t

$$I \propto \int_0^{eV} \rho_s(E_F - eV + \varepsilon)\rho_t(E_F + \varepsilon)d\varepsilon$$

For a free electron metal tip, ρ_t is constant:

$$\frac{dI}{dV} \propto \rho_s(E_F - eV)$$ → STM Spectroscopy

Atomic Force Microscopy (AFM)

- Invented at Stanford by Binnig and Quate in 1986
- Bring tip-mounted micromachined cantilever into contact or close proximity of the surface
- “Atomic forces” deflect cantilever and is detected with laser deflection into a position sensitive photodiode
- Cantilever deflection is control signal for the feedback loop
- AFM can be done on “any surface” (i.e., conductive, insulating, semiconducting, biological, etc.) in “any environment” (i.e., air, vacuum, liquid, etc.)

Fluid Cell for Atomic Force Microscopy

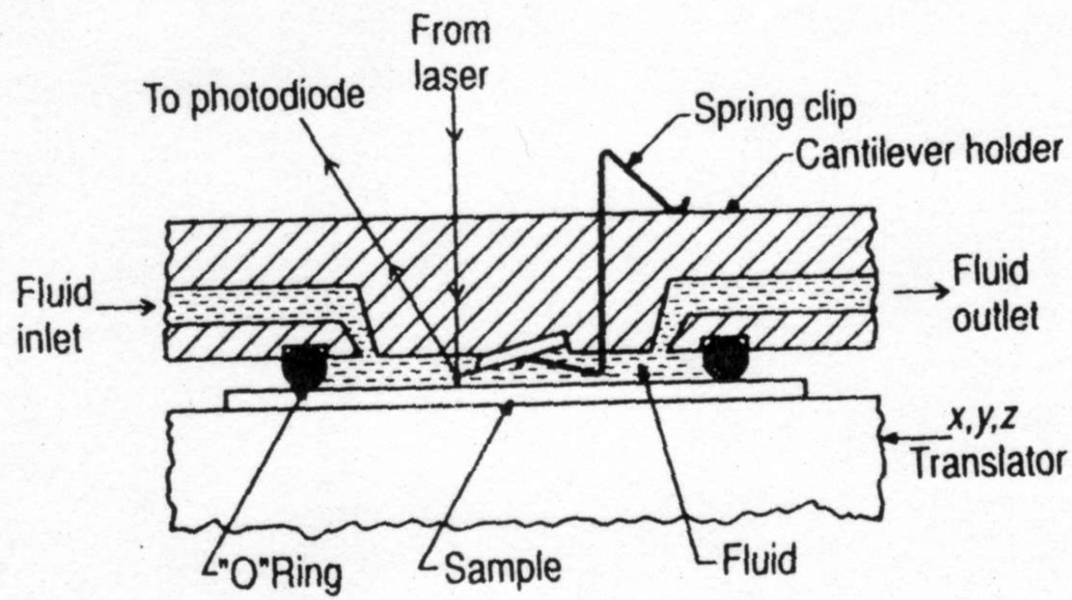

Fig. 15.10. Fluid cell for AFM study of electrochemistry. (Reproduced from Manne et al., 1991, with permission.)

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Force Detection with Optical Beam Deflection

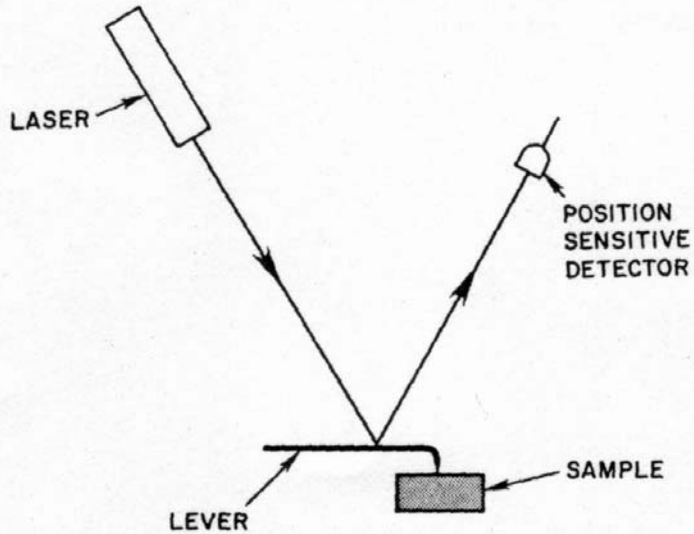

Fig. 15.7. Detection of cantilever deflection by optical beam deflection. A light beam, typically from a solid-state laser, is reflected by the top surface of the cantilever. The cantilever is vacuum deposited with gold, which reflects red light almost perfectly. The deflection of the mechanical cantilever deflects the optical beam, thus changing the proportion of light falling on the two halves of the split photodiode. The difference of the signals from the two halves of the photodiode is detected. (Reproduced from Meyer and Amer, 1988, with permission.)

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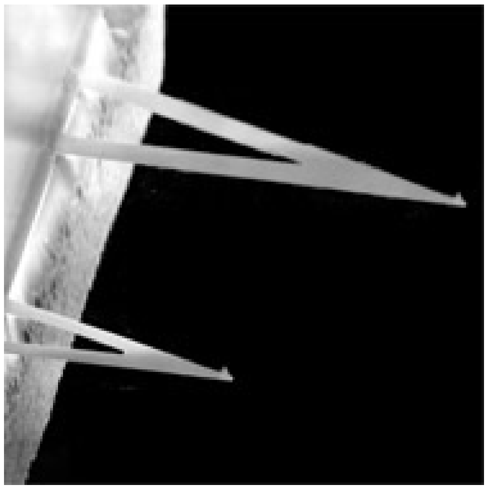
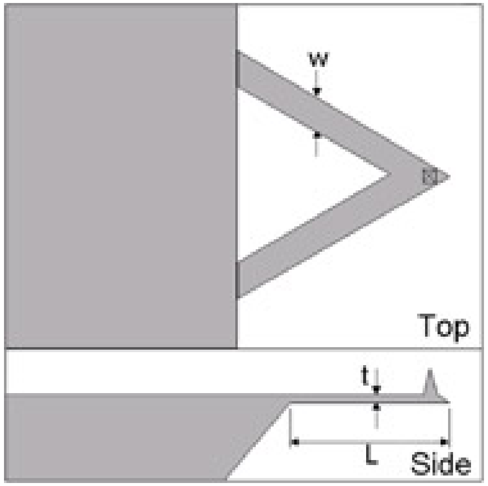
Atomic Force Microscope Cantilevers



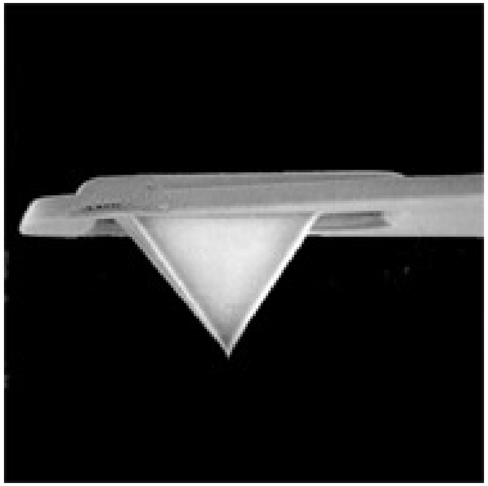


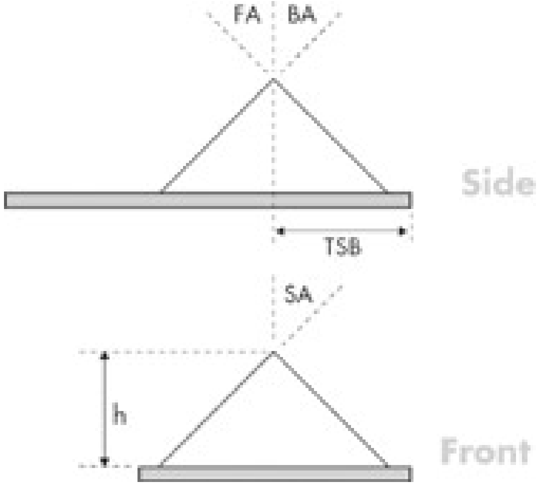
L = 100 µm
w = 20 µm
t = 0.5 µm

- Fabricated using conventional microfabrication procedures
- Backside coated with an optically reflective material (e.g., Au)

https://www.veecoprobes.com/

Atomic Force Microscope Tips





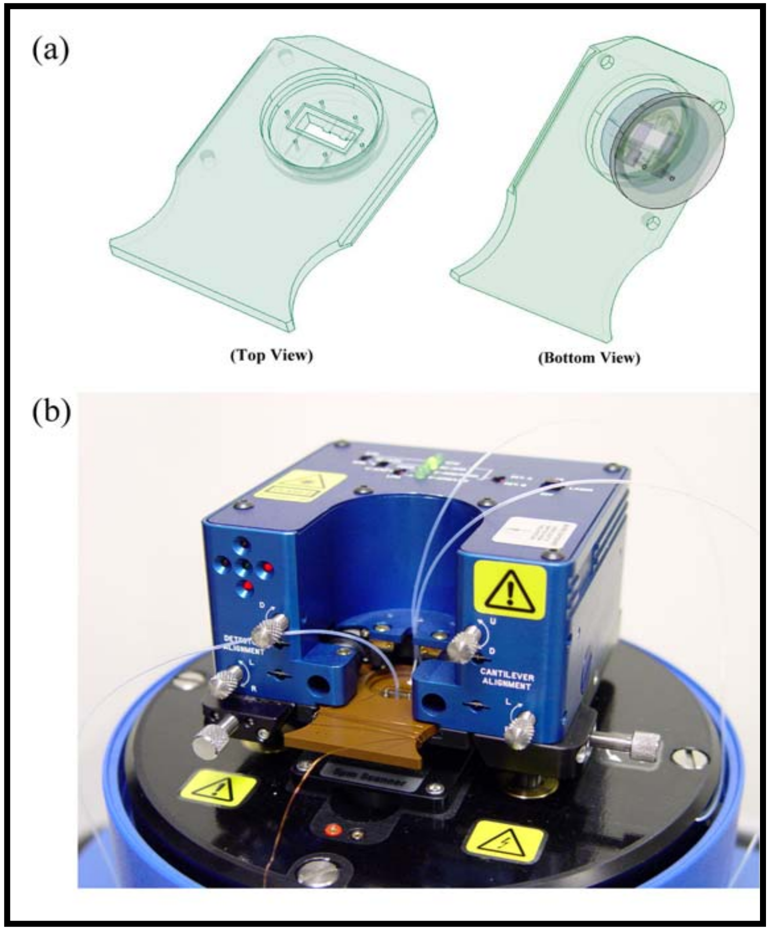
h = 3 μm
Angles = 35º

- Typical radius of curvature is ~ 10 nm
- Tips are often coated with conductive materials, magnetic materials, low wear materials, or organic/biological molecules.

https://www.veecoprobes.com/

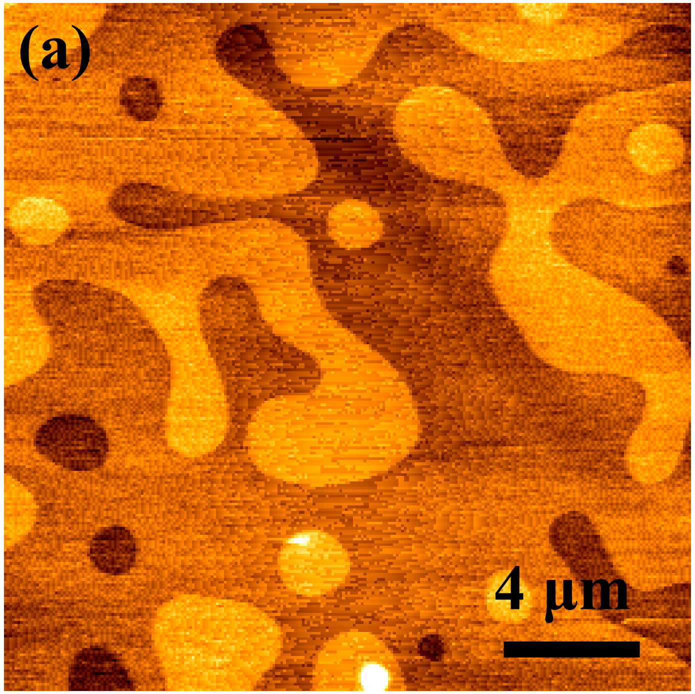
AFM Photographs

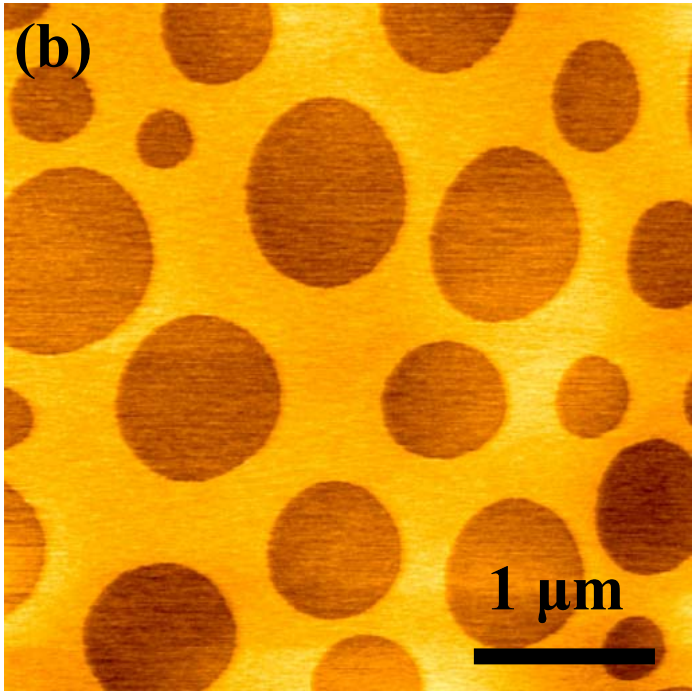
Thermomicroscopes
CP Research AFM



Custom Liquid Cell

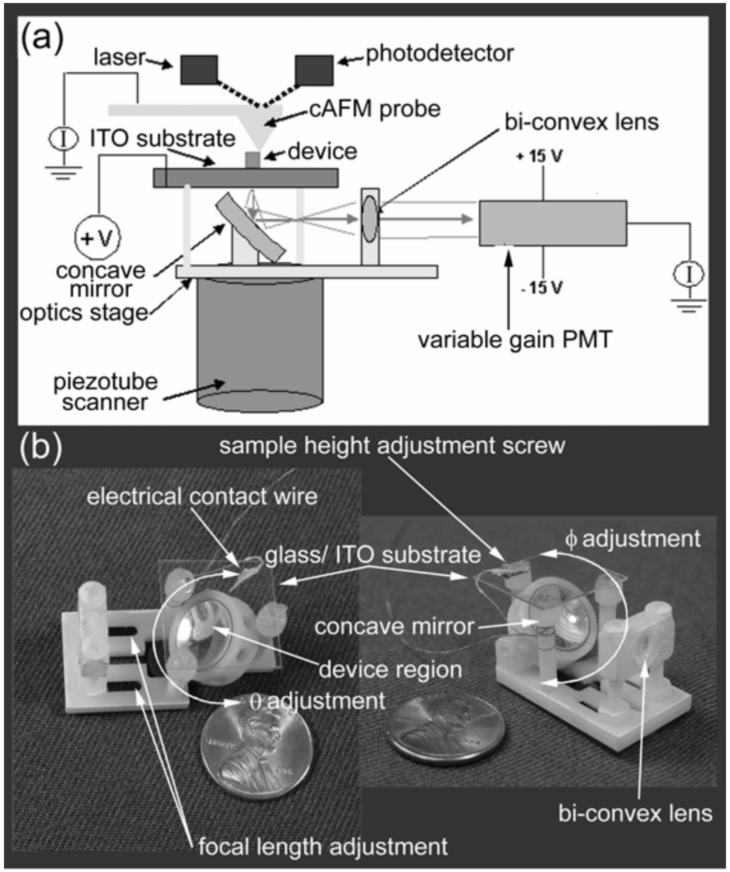
AFM Images of Hematite

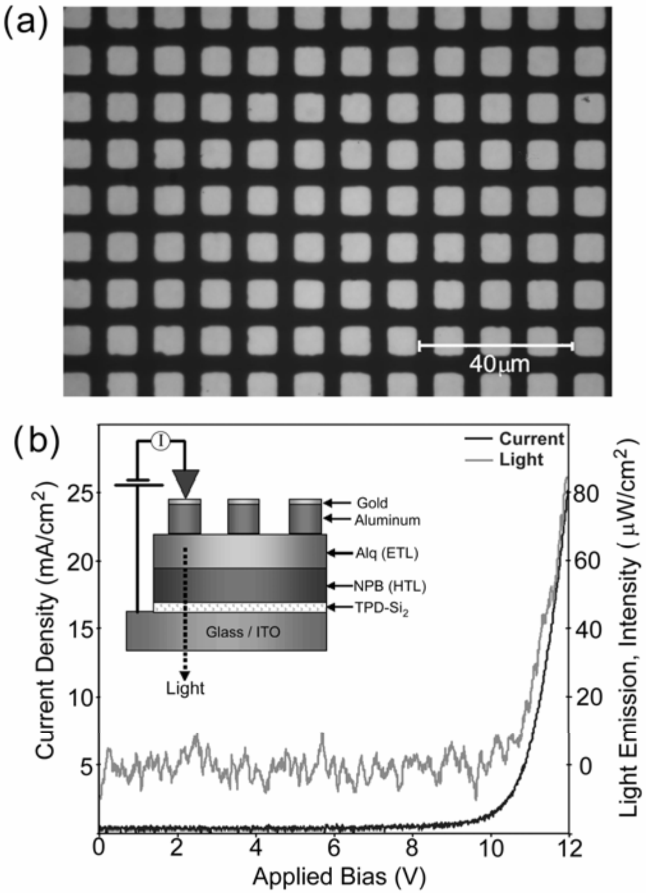




- Measured atomic step height of 2.2 Å
- Vertical spatial resolution of ~0.1 Å in air.

Atomic Force Electroluminescence Microscopy (AFEM)





L. S. C. Pingree, M. C. Hersam, M. M. Kern, B. J. Scott & T. J. Marks, *Appl. Phys. Lett.*, 85, 344 (2004).

AFEM on Organic LED Arrays