Early Successes
How to Make an STM

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

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 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 [211] direction points from right to left, along the long diagonal.
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:

(a) Top View

(b) Side View

Adatom

Rest atom
Atomic and electronic contributions to Si(111)-\((7 \times 7)\) 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)

Covalent bond

van der Waals' bond

Basal plane

0.142 nm

0.335 nm

0.246 nm

(1.3 x 1.1 nm)

Raw data

Fourier filtered image
HOPG in 3-dimensions
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

Early STM image
circa 1987

Li, Reifenberger, Andres
Why it Works

tip + atom-atom interactions

collective tip interactions

substrate

scan
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?**

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

\[ \Delta z \approx \frac{(\Delta x)^2}{2R} \]

\[ \alpha \approx 11 \text{ nm}^{-1}; R \approx 0.5 \text{ nm} \]

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

\[ \Rightarrow \Delta x = 0.3 \text{ nm}. \]

"Effective" diameter of current column is

\( \sim 2\Delta x \approx 0.6 \text{ nm} \) \( \rightarrow \) estimate for lateral resolution

\[ \{ \begin{align*}
\text{1 nm high} \\
\text{0.6 nm}
\end{align*} \]

\[ \text{Volume } \sim 0.3 \text{ nm}^3 \]
How many gas molecules per cm$^3$ at atmospheric pressure?

Ideal gas law: \( PV = nk_B T \rightarrow \)

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

\[
\frac{n}{V} = \frac{P}{k_B T} = \frac{6 \times 10^{23}}{22.4 \text{ liters}} \times \frac{1 \text{ liter}}{0.001 \text{ m}^3} \times \frac{1 \text{ m}^3}{1 \times 10^6 \text{ cm}^3}
\]

\[= 2.7 \times 10^{19} \text{ cm}^{-3} \quad (\text{Loschmidt's Number - 1865})\]

\[= 2.7 \times 10^{19} \text{ cm}^{-3} \times \left(\frac{1 \text{ cm}}{1 \times 10^7 \text{ nm}}\right)^3 = 0.03 \text{ molecules per nm}^3\]
How to make it work
STM System Overview
Feedback Control

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

$E(t) = Z(t) - R(t)$

- $K(t)$ 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

\[ \Delta l = d_{31} \frac{V_o}{h} \]

Typically, \( \Delta l \sim 0.5 \text{ nm/V} \)

Quadranted Piezoelectric Tube

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

\[ \Delta x \approx \Delta y = \frac{2\sqrt{2}}{\pi D} \frac{V_o}{w} L^2 d_{31} \]
Controlling the Tunnel Gap

- Conducting substrate
- Z-Position
- Piezo-tube scanner
- I-V Converter
  - Gain \( \approx 10^9 \)
- Ref. (Set) Voltage
- \( V_{out} \)
- \( e^- \)
Vibration Damping

\[ m \]

\[ \Delta z_0 \]

\[ \alpha \Delta z_0 \]

\[ \Delta z_0 \]

\[ (\alpha)^N \Delta z_0 \]

\[ \text{floor} \]

\[ \text{floor} \]
Limitations of Piezos

Piezoelectric Bar

\[ \Delta l = d_{31} \frac{l}{h} V_o \]

Extension

creep

time

Voltage

Limitations of Piezos
Apparent width of small object

\[ x^2 = (R_{\text{tip}} + R_{\text{feature}})^2 - (R_{\text{tip}} - R_{\text{feature}})^2 \]

\[ x^2 = R_{\text{tip}}^2 + 2R_{\text{tip}}R_{\text{feature}} + R_{\text{feature}}^2 - R_{\text{tip}}^2 + 2R_{\text{tip}}R_{\text{feature}} - R_{\text{feature}}^2 \]

\[ x = 2\sqrt{R_{\text{tip}}R_{\text{feature}}} \]

apparent feature width \( \approx 2x = 4\sqrt{R_{\text{tip}}R_{\text{feature}}} \)
Tip Fabrication

a) Electrochemical etch of W wire

- Carbon rod
- W wire
- H₂
- OH⁻

b) Cut Pt/Ir wire

STM tip
(~ 75 exterior atoms)
Scanning Modes

**Constant Current → Topography**

- Tip
- Path of tip
- Tunnel current
- Image
- Substrate

**Constant Height → High Speed**

- Tip
- Path of tip
- Tunnel current
- Image
- Substrate
Seeing atoms in a day

Highly oriented pyrolitic graphite (HOPG)

4.8 nm x 4.8 nm
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