Scanning Probe Microscopy (SPM)

- **Scanning Tunneling Microscopy (STM)**

- **Near-Field Scanning Optical Microscopy (NSOM)**
  --- D. W. Pohl (1982)

- **Atomic Force Microscopy (AFM)**

- **Scanning Thermal Microscopy (SThM)**
  --- C. C. Williams, H. Wickramasinghe (1986))

- **Magnetic Force Microscopy (MFM)**

- **Friction Force Microscopy (FFM or LFM)**
  --- C. M. Mate et al (1987)

- **Electrostatic Force Microscopy (EFM)**

- **Scanning Capacitance Microscopy (SCM)**

- **Force Modulation Microscopy (FMM)**
Atomic Force Microscopy (AFM)

\[ F = k \Delta z \]

\[ F = 10^{-9} - 10^{-6} \text{ N} \]

\[ k = 0.1 - 1 \text{ N/m} \]

References:

Interaction between the probe and sample

**Lennard-Jones potential**

\[ \phi(r) = - \frac{A}{r^6} + \frac{B}{r^{12}} \]

**Short-range:**
1) Bonding
2) Repulsion

**Long-range:**
1) Van der Waal
2) Capillary
3) Magnetic
4) Electrostatic
Deflection of Cantilever vs Piezo displacement

- **Cantilever Deflection (volts)**
- **Piezo scanner Z-position (nm)**

1. Total contact force
2. Cantilever spring force (applied load)
3. Set point deflection
4. Tip-sample adhesive force
Reaction of the probe to the force
Structure of AFM

Detection mechanism

Display

Feedback mechanism

Cantilever

Local probe

Sample

X-Y-Z Piezo transducer (Fine positioning)

Coarse approach and positioning

Vibration isolation
Core components of AFM

- Laser
- Detector
- Tip and cantilever
- Sample
- Piezoelectric Tube Scanner
- Display
- Computer and Feedback Controller
Position-sensitive Photo Diode (PSPD)

D ~ 10mm  d ~ 1mm  s ~ 0.01mm
Three scanning modes of AFM

- **Contact Mode AFM**
- **Semicontact Mode AFM** (Tapping mode)
- **Non-contact Mode AFM**
Two imaging methods in contact mode

- **Constant force method**: By using a feedback loop the tip is vertically adjusted in such a way that the force always stays constant. The tip then follows a contour of a constant contact force during scanning. A kind of a topographic image of the surface is generated by recording the vertical position of the tip.

- **Constant height method**: In this mode the vertical position of the tip is not changed, equivalent to a slow or disabled feedback. The displacement of the tip is measured directly by the laser beam deflection. One of its advantages is that it can be used at high scanning frequencies.
Problems with the contact mode

Cantilever with tip
Fluid layer
Electrostatic charge

100 nN
AC imaging mode

\[ \omega_1 = \omega_0 \left(1 - \frac{F'}{2c}\right) \]
Comparison of three scanning modes
Tapping mode

Amplitude Detector
High Resolution Oscillator
System Controller

Silicon Cantilever with Tip
Sample

Laser

Photo-detector

Oscillation Piezo (10K – 1MHz)

“Free” amplitude (> 20 nm)

“Tapping”

Amplitude reduced

Fluid layer
Tapping mode
Three Types of Data Collected in Tapping Mode

1) Height Data: z-axis position monitored by input voltage to piezo tube scanner.

2) Phase Data (i): phase of feedback signal compared to phase of output signal from photo diode detector.

3) Amplitude Data: output signal measuring RMS value of laser y-axis position on detector.

Piezo driver vibrates cantilever at resonance frequency.
Images by tapping mode

AFM image of a fresh Alfalfa root section
Fabrication of AFM probes

Typical Tip Dimension: 150μm x 30μm x 0.5μm
Materials: Si$_3$N$_4$

k ~ 0.1 N/m
f$_r$ ~ 100 kHz
Materials: Si
V-shaped

Rectangular-shaped

Pyramid Tip

Diamond-coated Tip

Ultrasharp Tip

Materials: Si, SiO$_2$, Si$_3$N$_4$
Ideal Tips: hard, small radius of curvature, high aspect ratio
Criteria for AFM probe

1) Small spring constant \((k)\) \( F = k \Delta z \)
   To detect force of \(~\text{nN}\)

2) High resonant frequency \((f_r)\) \( f_r \propto (k / m)^{1/2} \)
   To enable scanning and other operations

3) Highly anisotropic stiffness
   Easy to bent and difficult to twist

4) Sharp protrusion at the apex
   To better define the tip-sample interaction
Tip of small shear force
(for Contact mode)

Typical Tip Dimension:
150μm x 30μm x 0.5μm
\( k \approx 0.1 \text{ N/m} \)
Materials: Si₃N₄
Tip of high resonant frequency
(for Tapping mode)

Typical Tip Dimension:
150\(\mu\)m x 30\(\mu\)m x 3\(\mu\)m
\(f_r \sim 100\) kHz
Materials: Si
AFM versus STM

1. STM has better resolution than AFM.
2. The force-distance dependence in AFM is much more complex when characteristics such as tip shape and contact force are considered.
3. STM is generally applicable only to conducting samples while AFM is applied to both conductors and insulators.
4. AFM offers the advantage that the writing voltage and tip-to-substrate spacing can be controlled independently, whereas with STM the two parameters are integrally linked.
AFM versus SEM

1. AFM provides extraordinary topographic contrast direct height measurements and SEM provides only 2D mapping of surface features.
2. For insulating samples, no metallic coating is necessary for AFM.
AFM versus TEM

1. Compared with Transmission Electron Microscopes, three dimensional AFM images are obtained without expensive sample preparation and yield far more complete information than the two dimensional profiles available from cross-sectioned samples.

2. No charging effect occurs in AFM.
AFM versus Optical Microscope

1. AFM has much better resolution than Optical Microscope.
2. AFM provides unambiguous measurement of step heights, independent of reflectivity differences between materials.
Ultra-sharp tip
Effects of the Tip Shape

[Diagram showing effects of different tip shapes on the trace of contact with a sample.]
The diagram illustrates the difference between true imaging and tip imaging.

- **True Imaging**: A conical tip is used, and the path of the tip is shown as a smooth curve. The sample is shown as a flat surface.

- **Tip Imaging**: A pyramidal tip is used, and the path of the tip is shown as a jagged line. The sample is shown as a flat surface.

The diagram highlights the impact of tip shape on imaging quality.
AFM Tip + Carbon Nanotube

AFM tip

Carbon Nanotube
$\phi \approx 20\text{nm}$
$L \approx 80\text{nm}$
Image of high aspect ratio
AFM images

CD pits

Integrated circuit

Chromosomes

DVD pits

Bacteria

DNA
Force-Distance Curve

1. cantilever
2. sample

Approach
3. photodiode response
4. sample position

Retract
5. jump to contact
6. break away

Response
7. photodiode response
Atomic Image of Si(111)-(7×7) Taken with AFM

Force measurement of an unfolding complex molecule.

Advanced graphical user interface shows titin muscle molecule force curve.
The load-displacement curves provide a “mechanical fingerprint” of material’s response to deformation, from which parameters such as hardness and young’s modulus of elasticity can be determined.

In measuring the mechanical properties of thin coated system, the size of contact impression should be kept small relative to the film thickness.
Nanolithography of Tapping-Mode AFM

Image of polycarbonate film on silicon surface

(1.2 \(\mu \text{m} \times 1.2 \mu \text{m}\)) (2.5 \(\mu \text{m} \times 2.5 \mu \text{m}\))