Introduction to Atomic Force Microscope

Not that kind of "atomic"
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Introduction to Scanning Force Microscope

Scanning Tunneling Microscope (STM)

Heinrich Rohrer & Gerd Binnig
Nobel Prize in 1986
©IBM


Applicable only to conducting samples.

Invention of Atomic Force Microscope (AFM)


• One of the most versatile analytical tools to appear on the research scene in a century.
• No. 4 of Most Cited PRL papers as of November, 2002.

But no atomic resolution then!

Invention of Atomic Force Microscope (AFM)

Seeing by feeling the force!
Hooke’s Law at atomic scale!

The Concept

What force?
Tip-Sample Forces: Microscopic Description

- The Lennard-Jones potential:

\[ \Gamma_{\text{L-J}}(r) = 4 \epsilon [(\sigma/r_0)^{12} - (\sigma/r_0)^{6}] \]

- van der Waals, attractive
- Short range, Pauli + chemical, repulsive

Long Range Tip-Sample Forces: Magnetic Force

- If the tip were coated with magnetic material, it would be sensitive to the stray field from the surface.
- Due to the extent of the tip geometry, the force acting on the tip is the integral over all the dipole moments on the tip:

\[ F_{\text{magnet}} = \int m_{\text{tip}} (r) \cdot \nabla \psi(r) \, d^3r \]

Long Range Tip-Sample Forces: Electrostatic Force

- The strength and distance dependence of electrostatic forces obey Coulomb's law.
- Electrostatic force:

\[ F_{\text{el}} = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r^2} \]

- \( q \): Tip radius \( R \), Potential difference
- For \( R = 20 \text{ nm} \) at a tip-sample distance of \( r = 0.5 \text{ nm} \) and \( U = 1 \text{ V} \), \( F_{\text{el}} = 0.5 \text{ nN} \)
- Zero bias voltage normally does not correspond to a minimal electrostatic force. The contact potential difference has to be compensated.

Force Sensors

"You must feel the force around you."

Total force on the force sensor (cantilever) = sum of all forces.

Reference: Intermolecular and surface forces (2011) by Jacob N. Israelachvili

First determination of the constant \( G \) in 1798 by Henry Cavendish
Force Sensors for AFM: Cantilevers

- Hooke's Law
  \[ F = k \Delta \]
  
- Spring constant \( k \):
  
  \[ k = \frac{F}{\Delta} \]
  
  Typical values: 0.01 - 100 N/m
  
  Young's modulus \( E_Y \) ~ 10\(^{12}\) N/m\(^2\)
  
- Resonant frequency \( f_0 \):
  
  \[ f_0 = \frac{1}{2\pi} \sqrt{\frac{E_Y}{\rho}} \]
  
  Typical values: 7 - 500 kHz

Deflection Sensors

- Tunneling current
  
  \[ I_{\text{tunneling current}} \]

- Optical interferometer
  
  \[ I_{\text{optical interferometer}} \]

- Capacitive detection
  
  \[ I_{\text{capacitive detection}} \]

Mostly obsolete from today's AFMs.

Deflection Sensors: Optical Beam Deflection

- Most widely used in commercial AFM

Deflection Sensors: Fiber Optic Interferometer

- Fresnel Reflection
  
  Interference:
  
  \[ I_{\text{Fresnel}} \sim I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \frac{2\Delta \phi}{\lambda} \]
  
  Great for low temperature!

Deflection Sensors: Self-sensing Methods

- Piezo-resistive detection
  
  - Self-sensing
  
  - Doped Si
  
  - Low Q

  \[ V_{\text{out}} = \frac{\Delta F}{2Z_m} \frac{\Delta \phi}{\phi_0} \]

- Tuning fork detection
  
  - Used in non-contact attractive force region.
  
  - \( f_0 \sim 20 \text{ kHz} \)
  
  - Frequency-modulated operation

Mostly obsolete from today's AFMs.
Operation Modes for Topography

- Contact mode
- Tapping mode
- Non-contact mode

Contact Mode Operation

- Repulsive force region
- Slow scan rate
- Local deformations or destructions of the sample surface.
- Tip wear issue

Feedback on oscillation amplitude?

Contact Mode Operation

- Repulsive force region
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Non-contact Mode Operation

- Force constant
- z constant

Dynamic Operation of AFM

- Cantilever is driven at its resonance:
  \( m \ddot{x} + k \dot{x} + f_x \ddot{z} = F \)

- The particular solution is \( x = x_p + x_y \)

- Transient state:
  \( x_p = \left( A \exp \left( -\frac{m}{2B} \right) + B \exp \left( \frac{m}{2B} \right) \right) \exp \left( \frac{m}{2B} t \right) \)

- Steady state:
  \( x_y = A \sin \left( \omega_0 (t - \delta) \right) \)

  where \( \delta = \tan^{-1} \left( \frac{\omega}{\omega_0} \right) \)

  \( A = \frac{A_0}{k_0} \left( 1 + \frac{1}{\omega^2} - \frac{1}{(\omega_0)^2} \right) \)

Dynamic Operation of AFM

- Frequency modulation is used for high Q situation, especially in vacuum.

Dynamic Operation of AFM: Frequency Modulation

- Feedback loop 1:
  The cantilever oscillation is controlled at the resonance with the same amplitude by tracking the phase shift.

- Feedback loop 2:
  The tip-sample distance is controlled to keep the frequency shift constant and hence the same tip-surface force.

Limits of Force Sensitivity

- A cantilever in equilibrium with a bath of temperature, \( T \) has an energy expectation value for each mode equal to \( kT/2 \).

- Minimum detectable force due to thermal fluctuation:
  \( F_{\text{min}} = \frac{\hbar k}{2B(\Delta t)^2} \)

  where \( B = \) measurement bandwidth

- A spring in equilibrium has a constant force due to thermal fluctuations.

- Optimization:
  1. Higher Q
  2. Higher resonance frequency
  3. Lower temperature
  4. Amplitude?
  5. Stiffer cantilever?

- Tuning fork?
  \( f_0 \approx 32\text{kHz}, k \approx 1800 \text{N/m}, Q \approx 50000 \) in vacuum

Non-contact mode operation.
True Atomic Resolution

F. J. Giessibl and G. Binnig (1991)

KBr(001) by contact AFM


Si(111) 7x7 by noncontact AFM in May, 1994

Piezoresistive cantilever, FM detection

STM vs AFM : Si(111) 7x7


STM vs AFM : Graphite

S. Hembacher et al., PNAS 100, 12539 (2003)

Quantitative Measurement of Short-Range Chemical Bonding Forces

M.A. Lantz et al., Science 291, 2580 (2001)

Chemical Identification of Surface Atoms by AFM

Pb and Si atoms are indistinguishable from topograph

Yoshida, Kagoshima et al., Nature 446, 64 (2007)

Magnetic Force Microscopy (MFM)

- Magnetic force on a magnetic tip

\[ f_{\text{magnetic}} = \int |\vec{r}_{\text{tip}}(r)| \cdot |\vec{r}_{\text{sample}}(r)| \, dy \]

- The shift in resonance frequency

\[ \Delta f = \frac{2 \pi f_0}{2 \pi} \]

- The phase shift

\[ \Delta \phi = -\frac{2 \pi \Delta f}{2 \pi} \]

Magnetic bits on hard disk

8.3 μm

Sample

AFM

MFM

\[ \vec{B}_{\text{sample}} \]
Magnetic Force Microscopy (MFM)

La_{2-x}Sr_xMn_{2+2x}O_{7+y}, x=0.32

Sample: Dr. J. Goodenough @ UT Austin

Out-of-plane magnetization

E-M. Chng, et al., JAP 70, 2577 (1991)
S. Huang, et al., JAP 77, 4284 (2000)

Electrostatic Force Microscopy (EFM)

PZT film

The shift in resonance frequency:

\[ \Delta \omega = \frac{2E}{m} \frac{\varepsilon_s}{\varepsilon_0} \]

The phase shift:

\[ \Delta \phi = \frac{2\pi}{\lambda} \frac{\varepsilon_s}{\varepsilon_0} \]

Atomic Manipulation by AFM

Sn on Si(111)

Review article: Nature Nanotechnology 4, 803 - 810 (2009)

MIDAS (Micro Imaging Dust Analysis System)

Rosetta orbiter for Comet 67 P/Churyumov-Gerasimenko

MIDAS is designed to capture and image dust particles in situ with AFM.

See also AFM on Mars:
http://phoenix.lpl.arizona.edu/index.php

AFM image of a cosmic spherule


The Need for High Speed AFM

- Mostly in tapping mode, scan size up to 500nm, >7 frames/sec.
- The scan rate is limited by the slowest component:
  1. Smaller cantilever for higher resonance
  2. Faster scanner
  3. Faster feedback and control

Review article: Toshio Ando, Nanotechnology 23, 062001 (2012). Mostly bio-imaging

AFM manufacturers:
http://www.bruker.com/fastscan

Imaging of Molecular Dynamics by High-speed AFM

Directly visualized walking Myosin V molecules

Images taken at 146.7 ms / frame

Improving AFM Cantilevers

AFM Cantilever with AgGa nanoneedle

Review:
Carbon nanotube tips for AFM
Nature Nanotechnology 4, 483 (2009)

Improving MFM Cantilevers

Fe-filled Carbon nanotube for MFM

F. Wolny et al., Nanotechnology 21, 435501 (2010)

Other Magnetic Force Imaging Techniques

- Scanning Hall Probe Microscopy
  Direct B measurement
  Limited spatial resolution due to sensor size
  Other means for feedback for topography is required.

AFM Universe