Atomic Force Microscopy (AFM)

Arvind Raman, Associate Professor
Mechanical Engineering
Birck Nanotechnology Center
NASA Institute of Nanoelectronics and Computation (INAC)
Further reading

Outline

- History of Atomic Force Microscopy (AFM)
- Instrumentation
- Static force-distance curves and force spectroscopy
- Dynamic AFM and force gradient spectroscopy
- Imaging
- Applications and emerging areas

Binnig and Rohrer awarded Nobel Prize in Physics in 1986 for STM

If $|V_t|$ is small compared to workfunction $\Phi$, and tunneling current is given by $I_t(z) = I_0 e^{-2\kappa_t z}$ where $z$ is the gap $l_0$ is a function of the applied voltage and the density of states in the tip and the sample, and $\kappa_t = \sqrt{2m\Phi / \hbar}$

For most metals, $\Phi \sim 4eV$, so that $\kappa_t = 1Å^{-1}$

Most current carried by “front atom” blunt tips, so atomic resolution possible even with relatively blunt tips

Only electrically conductive samples, restricting its principal use to metals and semi-conductors
Binnig invented the AFM in 1986, and while Binnig and Gerber were on a Sabbatical in IBM Almaden they collaborated with Cal Quate (Stanford) to produce the first working prototype in 1986.
FIG. 3. The AFM traces on a ceramic ($\text{Al}_2\text{O}_3$) sample. The vertical scale translates to a force between sample tip of $10^{-10} \text{ N/Å}$. For the lower trace the force is $3 \times 10^{-8} \text{ N}$. The stability of the regulated force is better than $10^{-10} \text{ N}$. The successive traces are displaced by a small amount along the $y$ axis.

FIG. 4. The AFM traces for another area of the ceramic sample. The curves grouped under $A$ were recorded with additional low-pass filtering. For this set the stabilizing force, $f_0$, was reduced by thermal drifts as we moved from the lowest to the highest traces of set $A$. The force $f_0$ is near $10^{-8} \text{ N}$ for the highest curve. We note that the structure vanishes on the traces when the sample-to-tip force is reduced below this level. The force $f_0$ was reset to a higher value near $5 \times 10^{-8} \text{ N}$ for the traces marked $B$. 

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The microcantilever – the force sensor

www.olympus.co.jp

www.nanosensors.com
Detecting deflection

- STM tip
- Capacitance/laser interferometry
- Beam deflection

Courtesy - J. Gomez, UAM, Spain
The beam deflection method

(a) Normal force

Up
A+B= UP
C+D=DOWN

Down

(b) Lateral Force

left
A+C= LEFT
Right
B+D=Right

Courtesy- J. Gomez- Herrero, UAM, Spain
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Tip-sample interaction forces in AFM

- Long-range electrostatic and magnetic forces (upto 100 nm)
- Capillary forces (few nm)
- Van der Waals forces (few nm) that are fundamentally quantum mechanical (electrodynamic) in nature
- Casimir forces
- Short-range chemical forces (fraction of nm)
- Contact forces
- Electrostatic double-layer forces
- Solvation forces
- Nonconservative forces (Dürig (2003))
The microcantilever – the force sensor

- From elementary beam theory, if E=Young’s modulus, I=bh$^3$/12 then
  - $\delta=w(L)=F\frac{L^3}{3EI}$, and $\theta=dw(L)/dx=FL^2/(2EI)$
  - Deflection and slope linearly proportional to force sensed at the tip
  - $k=3EI/L^3$ is called the bending stiffness of the cantilever
Force-displacement curves

\[ F(d) = k\delta \]

- Inaccessible region
- Snap-in
- Pull-off

\[ W_{\text{Adhesion}} = \text{blue shaded area above} \]
\[ W_{\text{Cantilever}} = \text{shaded area above} \]
Three distinct regions

If \( k \) is known then from the static-force distance curve, \( F(d) \) can be calculated for all \( d \) except for inaccessible range near snap-in

It can be shown that \( W_{\text{Cantilever}} \) is related to the \( W_{\text{Adhesion}} \)

Slope in III is a good measure of repulsive forces (local elasticity)

Animation courtesy J. Gomez-Herrero, UAM, Spain
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Dynamic AFM

- Cantilever driven near resonance
- Non-contact AFM, Tapping mode AFM, Amplitude Modulated AFM, Frequency Modulated AFM are all dynamic AFM
- The cantilever's resonant frequency, phase and amplitude are affected by short-scale force gradients

Attractive gradient equivalent to additional spring in tension attached to tip, reducing the cantilever resonance frequency.

Repulsive gradient equivalent to additional spring in compression attached to tip, increasing the cantilever resonance frequency.
Dynamic AFM & force gradient spectroscopy

- Variation of amplitude, resonance frequency, and phase measured as Z is decreased.
- From this it is possible to reproduce the Force gradients between the tip and the sample.
- Even non-conservative interactions can be resolved.
- Offers many advantages over static-force distance curve based force spectroscopy.
- Quantitative information is hard to come by because the forces are nonlinear.

Input parameters

- D[0] = -1.00 [nm]
- FPA tip = 0.00 [nm]
- F[0] = 2 [MHz]
- V = 3.000000000000000E-02 [nm/s]
- Q = 1000
- F[0] = 2.0 [MHz]
- k[0] = 0.0 [N/cm]
- R = 0.00 [nm]
- K = 10.0 [GPa]
- r = 1.0
- D[01] = 0.01 [nm]
- w = 7.199999999999999E-02 [J/m^2]

Computed data

- m[0] = 6.33257397599238 [plkg]
- lambda = 6.647861733899854
- b[0] = 6.285028234257542E-03 [1/Hz]
- b[1] = 6.283028234237542E-03 [1/Hz]
- Q[0] = 0.0 [nm]
- Q[1] = 0.0 [nm]
- D[00] = 1.72314408935211 [nm]
- P[0] = 4.17861969829358 [GPa]
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First tip contacts surface with some setpoint normal force which is kept constant during the scan.
In Tapping mode the tip is oscillated at the resonance frequency and the amplitude of oscillation is kept constant while the tip intermittently enters the repulsive regime.
Phase Imaging

- Regular tapping mode implemented but signal phase monitored
- Phase contrasts are related to differences in local dissipation

AFM height (left) and phase (right) images of poly(methylmethacrylate)

(Digital Instruments, Inc.)
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Carbon nanotube tips (CNT)

- Provide high resolution
- Show little evidence of wear
- Promising technology for critical dimension metrology of semiconductors, and nanobiological investigations
- Buckling, friction and stiction of CNT become important

Dynamic AFM images of a 100 nm trench on Si using conventional silicon probe (left) and a MWCNT probe (right)

- CNT attached strongly to Force modulation etched Si probe (Ni evaporation)
- Straight MWCNT, diameter 10 nm, length 7.5µm, Frequency 72.5 kHz
- Repulsive and attractive states do not appear to co-exist for long CNT tips

Static force-distance curves

- CNT buckles, slips, and slides
- High adhesion on the CNT sidewalls

Shorter CNT tips - noncontact mode

- Divot artifacts associated with switching between attractive (noncontact) and repulsive (tapping states)
- Ringing artifacts associated with CNT adhesion and stiction to sidewalls

300 nm Tungsten nanorods
Exploiting anharmonic oscillations

- NC vibration spectrum depends on local adhesion properties
- Experiments performed using 47 kHz microcantilever on wild and mutant bacteriorhodopsin membrane
- 2\textsuperscript{nd} bending mode freq $\sim 7 \times$ 1\textsuperscript{st}

Thermal vibration

Driven in air

On mica (50 % setpoint)

“Probing Van der Waals forces at the nanoscale using higher harmonic dynamic force microscopy”, Crittenden, Raman, Reifenberger (in press PRB)
Application to local adhesion estimation

- 3500 nm x 3500 nm scans

- Clear distinction between lipids and proteins
- Presence of internal resonance critical in the method
- The method shows promise for the measurement of local attractive forces of soft biomolecules
- Can be extended to electrostatic force microscopy or capacitance microscopy for dopant profiling

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Virus capsid mechanics studied using AFM

A computer model of the prohead structure of the P22 and HK97 virus capsids. (T. Ferrin, UCSF Computer Graphics Lab)
Friction Force Microscopy

- Torsional vibrations due to atomic and molecular friction
- Lateral forces are specific
- Applications to nanotribology, probe based lithography

Friction force image of a self assembled monolayer (Riefenberger Group)

www.chem.nwu.edu/~mkngrp/
Dip-pen lithography

Contact mode oxidation lithography

Conley, Raman, Krousgrill, submitted
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Questions & Answers
Application to local adhesion estimation

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