Atomic Force Microscopy

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Microscopy

Optical microscopy
- no topography
- minimal sample prep
- large features

Electron microscopy
- some topography
- some sample prep
- small features

Scanning probe
- topographical
- flat sample
- atomic features

Interaction of a probe with a material • gives spatial information • allows ‘visualization’
Outline

• **Tip-sample interactions**
  • Interatomic forces
  • Cantilever dynamics

• **Build the system**
  • How to collect the information?
  • How is the system constructed?
  • How is the system controlled?

• **What can we ‘see’?**
  • Different modes of SPM
Interatomic Forces

Dipole interactions between molecules/atomic systems → Van der Waals forces

Keesom
~5-25 kJ/mol

Debye
~2-10 kJ/mol

London
~0.1-40 kJ/mol

\[ U_{VdW} = U_{\text{Keesom}} + U_{\text{Debye}} + U_{\text{London}} \]
Assume a sphere interacting with a plane:

\[ U_{vdw} = -\frac{HR}{6d} \]
\[ H = \pi^2 \rho_{sph} \rho_{surf} C_{vdw} \]

\[ F_{vdw} = \frac{\partial U_{vdw}}{\partial d} = -\frac{HR}{6d^2} \]

at 8 nm tip radius & 1 nm distance
\[ H \sim 1E-20 J \]
\[ F_{vdw} = 13.3 \text{ pN} \]
using cantilever with \( k = 0.2 \text{ N/m} \)
\[ q = 65 \text{ pm} \]

Assume a surface that has gold and copper:

\[ \rho_{Au} = 5.90 \times 10^28 \text{ m}^{-3} \]
\[ \rho_{Cu} = 8.45 \times 10^28 \text{ m}^{-3} \]

\[ F_{Au} = 15.7 \text{ pN} \]
\[ F_{Cu} = 22.5 \text{ pN} \]

\[ q_{Au} = 78.5 \text{ pm} \]
\[ q_{Cu} = 112.5 \text{ pm} \]

All of this is non-contact: bonding info gives magnetic, chemical, electrical info
Quick Example:

with 38 mm distance from cantilever to detector and 27.5° reflection angle from normal, a 1 nm deflection will move laser ~115 nm on PSD

If we raster this probe over the surface, we can map changes in height as a function of space

unaffected by temperature, chemistry, EM, etc.
Build the System

need to measure $\Delta z(x,y)$

constant height
constant force

$F = \frac{dwt^3E}{4L^3}$

measure change in deflection on detector
change stage height

Challenges:

large features
low sensitivity
blunt the tip

good feedback
fine stage control

Control Theory
Piezotube Scanners

segemened photodiode

Set a desired voltage
Keep deflection on detector to match

$V_A - V_B \propto \text{defl.}$

as $Z \uparrow$, $V_A \uparrow, V_B \downarrow$

Intensity = $\sum V$

$I(t) = V_A - V_B \propto \frac{dI}{dt}$. 
Control Theory

constant force means setting a voltage on detector and maintaining

set voltage \( S(t) \)

amplitude \( S(t) \)

meas. voltage \( z(t) \)

\[ S(t) - z(t) \]

\( err(t) \)

\[ P: -K_p \text{err}(t_n) \]

\[ l: -K_i \int_0^t \text{err}(\tau)d\tau \]

\[ d: -K_d \frac{d\text{err}(t)}{dt} \]

\[ u(t) \]

controller [z-controller]

D is unused in SPM because it's susceptible to noise

P corrects for current error, immediate response

I corrects for error in past, tracks larger features

Three variable need to be set for SPM:

\( S(t), K_p, K_i \)
Piezotube Scanners

must be able to change z more quickly than feedback loop (limits scan rates)

\[ \Delta l = d_{31} \frac{l}{h} V_0 \]
\[ \Delta l \sim 0.5 \text{ nm/V} \]

piezoelectrics:

\[ \Delta z = d_{31} \frac{l}{w} V_0 \]
\[ \Delta x \approx \Delta y = d_{31} \frac{2l^2\sqrt{2}}{\pi D_w V_0} \]

\[ \Delta z \propto l \]
\[ \Delta x \approx \Delta y \propto l^2 \]

can move z & x,y in one device allows rastering of x,y also

Need to be careful of resonant frequency:

100s-10,000s Hz
AFM as a System

tip-sample interaction → cantilever deflections → laser reflections in PSD → control measurement → components for control

secondary bonding VdW forces

non-contact: 10s-100s pm
contact: 0.01s-100s nm

small deflection can be seen on PSD

measured as function of x,y

const. height | const. force

PID control to minimize error

gives control over x,y,z

Set V → Feedback → Meas. V

Topography

Computer

error

interatomic forces

deflection $\propto F$

deflection $\propto F$

piezotube

quadrated piezo scanner tube

Georgia Tech
AFM Modes

- **Contact**: Constant force topography
- **Tapping**: Constant amplitude vibration of cantilever near resonant frequency, combo of contact and non-contact topography
- **Phase**: Constant amplitude vibration of cantilever near resonant frequency, change in phase and amplitude through lock-in amplifier
- **Lateral Force**: Constant force, 90° scan angle measures coefficient of friction, torsional deflection, topography, material properties
- **Force Modulation**: Sample is oscillated, phase, amplitude change through lock-in amplifier (stage reference signal), viscosity, elasticity
AFM Modes

**Kelvin force**
- Map surface potential
- When DC bias matches surface, amplitude is zero
- Map changes in amplitude

**Current**
- Constant force measure bias between cantilever and sample

**STM**
- Constant height measures tunneling current
- Very sensitive to height change

**Piezoforce**
- Map electrical domain structure pole with AC current in contact
- Map changes in amplitude and phase

**Magnetic force**
- Constant height detect magnetic stray fields
- Map changes in phase with lock-in amplifier
STM (quick overview)

**STM**

Tip interacts ‘electrically’ with surface

Interaction creates a tunneling current

Changes in current correspond to changes in distance

\[ I_t \propto V \rho_s(E_F)e^{-\frac{1.025}{\sqrt{\varphi z}}} \]

Typically done in vacuum (MFP of electrons)

Frequency modulated signal
Lock-in Amplifier Overview

For phase, force modulated, Kelvin force, piezoforce, and magnetic force

Need to pull out changes in amplitude and phase

\[ X = V_s(t)V_r(t) \]
\[ Y = V_s(t)V_r(t + 90\degree) \]
\[ R = \sqrt{X^2 + Y^2} \]
\[ \theta = \arctan\left(\frac{Y}{X}\right) \]