Basic 15 Nanometer Scale Measurement And Manipulation by Scanning Probe Microscope

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I. Basics of scanning probe microscope
Scanning Probe Microscope (SPM)

Scanning Probe Microscope:

- Seeing individual atoms
- Manipulation individual atoms

It opens up atomic-scale observation and manipulation.
- Gerd Bennig and Heinrich Rohrer were awarded the Nobel Prize (1987), for their invention of the scanning tunneling microscope, only six years after the invention. They demonstrated observation of individual atoms at atomic scale resolution.

- Donald M. Eigler demonstrated manipulation of individual atoms with atomic scale precision by scanning tunneling microscope, 1989.
Principle of scanning probe microscope

Trace the sample surface with a finger

Finger

Desk (sample)

Tactile sensation

Object
(sample feature)
Trace the sample surface with a finger

How should we do?
1. Touch the surface
2. Move the finger up or down so that the tactile sensation is equal
3. Memorize the position of the finger
4. Move the finger laterally
5. Go back to 1
Reconstructing the trajectories of finger

By feeding back the tactile sensation to the movement of the finger (probe) and reconstructing the trajectory, sample surface can be imaged.

Sample image by reconstructing the trajectories
Block diagram of tracing surface with a finger

Memorizing vertical movement (recording feedback signal)

Tactile feeling (sensing)

Vertical movement of finger (feedback)

Lateral movement of finger (scanning)
What happens if you have an extremely sharp finger?

Probe that you use:

- Blunt probe (finger)
  - Apex radius: 10 mm

- Sharp probe
  - Apex radius: 0.1 nm

What you can resolve:

- Eraser
  - Resolution ~ 10 mm

- Atom (radius ~0.1nm)
  - Resolution ~ around 0.1 nm
Basic configuration of scanning probe microscope

Controller

Sensor signal

z movement signal (feed back signal)

Computer

z movement signal (feed back signal)

xy movement signals (probe scan signals)

z-piezo actuator

xy-piezo actuator

Interaction between probe and sample

Sample

Probe (Sensor)
Examples of piezo actuators

Tripod type

- z-actuator
- y-actuator
- x-actuator

Tube type

- +y electrode
- +x electrode
- -x electrode
- z electrode

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How should you design a probe?

Displacement gauge

ΔZ

Spring

Probe

Tip

Sample

Force

Scan direction

0 nm

5 nm

10 nm
**Probe design: requirements for a probe**

- **High force sensitivity**
  \[ \Delta Z \] => soft spring

- **Robustness against environmental noises**
  \[ \Delta Z = \frac{F}{k} \] => high resonance frequency

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Probe design: an aluminum foil cantilever

Cantilever probe made of an aluminum foil
Thickness $h = 15\mu m$, width $b = 100\mu m$

(a) resonance frequency

(b) spring constant

When $L = 1.5\ mm \ f = 5\ (kHz), \ k = 1.7\ (N/m)$
Measurement of probe displacement

Optical lever method

\[ \Delta S = L \times 2 \Delta \theta = 2 \frac{L}{l} \Delta Z \]

\[ \Delta Z = l \times \Delta \theta \]

When \( l = 1 \text{ (mm)}, L = 1 \text{ (m)}, \Delta S_{\text{min}} = 0.1 \text{ (\mu m)}, \Delta Z_{\text{min}} = 0.1 \text{ (nm)} \)
Measurement of probe displacement 2

Optical interference method

Laser light

Detector

Optical fiber

AFM probe

Light intensity

\[ \frac{\lambda}{4}, \frac{\lambda}{2}, \frac{3\lambda}{4} \]

\[ \frac{\lambda}{4} \sim 150\text{nm} \]
Probe fabrication in the early stages

Do you want to try that?

Drop micro particles onto a cantilever.
If you have “a little” luck, you can make a probe.

Micro particle
\( (\sim 10 \mu m\Phi) \)

Adhesive

Cantilever made of a metal foil
Probe fabrication by micromachining techniques

Spring constant 0.1(N/m) → Force sensitivity 0.01 (nN)
Resonance frequency 50 (kHz)
Tip radius several nm
**Probe fabrication process 1**

a) Silicon wafer

b) Formation of tip mold and back protection layer
   - Pit for tip
   - SiO2-protection layer

c) Formation of cantilever layer
   - SiN-cantilever layer
**Probe fabrication process 2**

**d) Formation of cantilever shape**

**e) Substrate removal**

**f) Device cutout**
II. Various types of scanning probe microscope
Various types of scanning probe microscope

If you choose new interaction, you can make a new SPM.
What determines resolution of SPM?

1) distance dependence of interaction

2) tip size
Scanning tunneling microscope (STM)

Scan direction

Probe

Tunneling current

Sample

Tunneling current \( I = \exp\left(-\frac{Z}{D}\right) \)

\( D = 1 \text{ Å} \rightarrow \text{high resolution} \)
Scanning near-field optical microscope (SNOM)

Aperture type

- Aperture
- Metal film
- Near-field light
- Transmitting light
- Sample
- Detector

Aperture radius ~ several tens nm

Tip type

- Tip
- Near-field light
- Scattering light
- Sample
- Detector

Tip radius ~ several nm

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SNOM/AFM using a photocantilever

Diagram showing the setup:
- Laser
- Sample
- Prism
- Photocantilever
- Tube scanner
- PSD
- AFM signal
- Scattering light
- Near-field light
- SNOM signal

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Structure of photocantilever

- Photodiode
- Substrate
- Lead wire
- Tip

500 μm
Manipulation of individual atoms

1) Scatter atoms

Target atoms

Substrate

2) Adsorb the target atom to the probe

3) Transfer the atom

4) Adsorb the atom to the substrate
Manipulation of individual atoms 2

1) Prepare a flat substrate

2) Remove the target atom by electric field

3) Scan the probe for pattern formation

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Information storage by using SPM

1) Magnetic recording by MFM

2) Optical recording by SNOM

Magnetic probe

Magnetic field

Recoding media

Light

Aperture probe

Near-field light

Recording media
Scanning probe microscope:

- Microscope that scan a micro probe mechanically
- Integration of mechatronics and micromachining technologies
- Device that can see and manipulate indicial atoms
- Technology that opens up nanotechnology
Advanced reading

1) R. Wisendanger, Scanning Probe Microscopy and Spectroscopy, Cambridge

2) R. Wisendanger, H. -J. Guntherodt edited, Scanning Tunneling Microscopy I - III, Springer-Verlag