Nanoscale measurements

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http://www.phys.sinica.edu.tw/TIGP-NANO/Course/2007_Spring.htm

Outline

A. Introduction

B. Operational Principles:

a.Electron b.X-ray c.Scanning Probe

C. From measuring to sensing

D. From measuring to manipulating

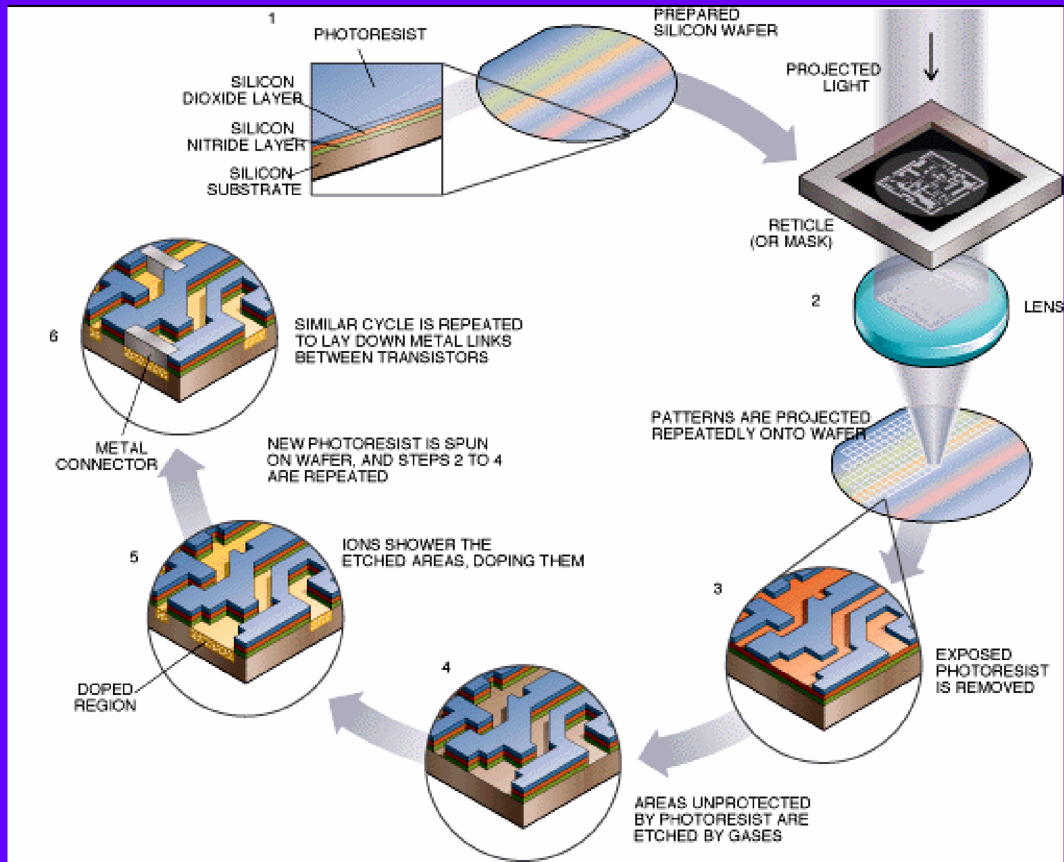
E. From measuring to fabricating

F. Considerations for making nanoscale tools

G. Future development of nanoscale measurements

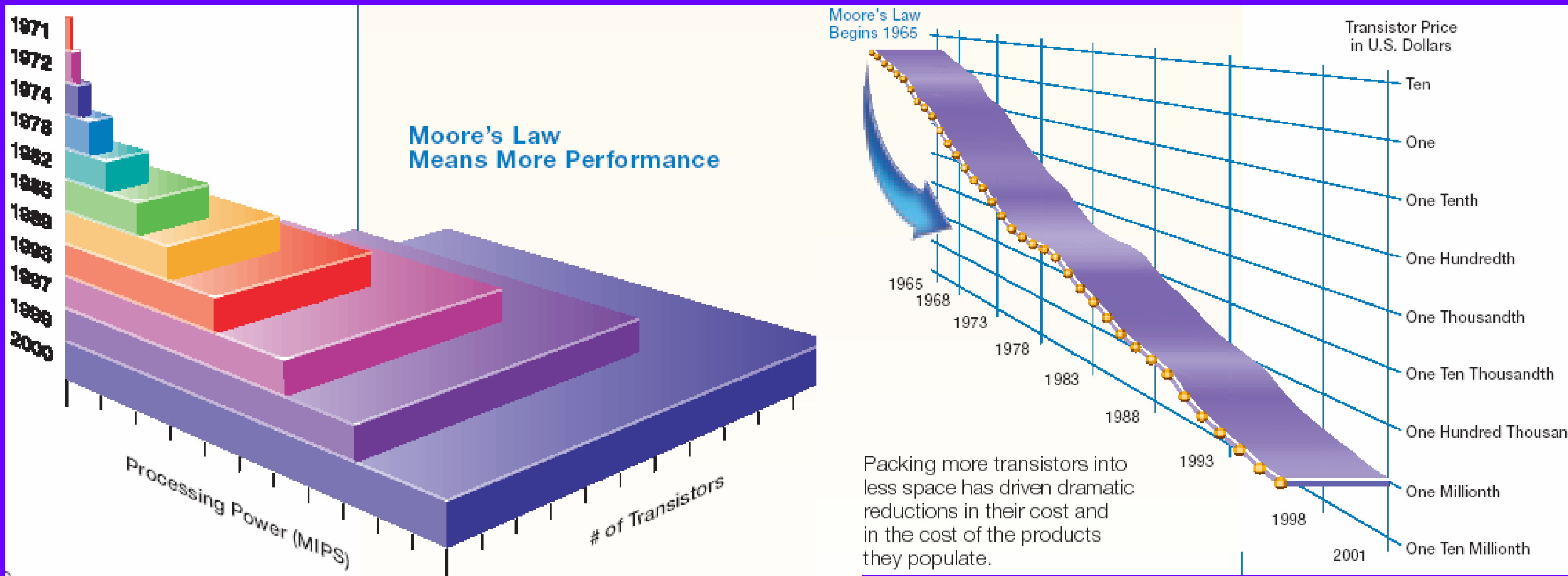
H. Conclusions

Optical lithography and planar fabrication of VLIC



Intel Corp.

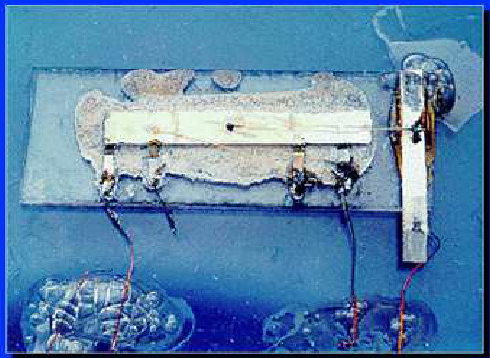
Numbers of transistors in an IC



Intel Corp.

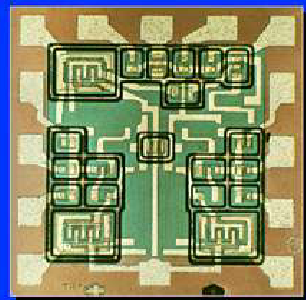
Evolution of IC industry

Kilby's First IC, 1958

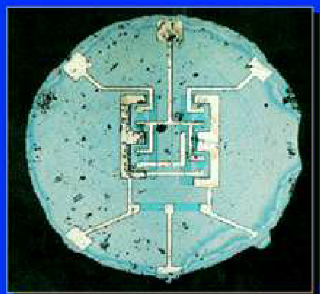


1965

- This DTL triple-gate device was the first radiation hardened product made with dielectric isolation and thin-film resistors.



The First Planar Integrated Circuit, 1961

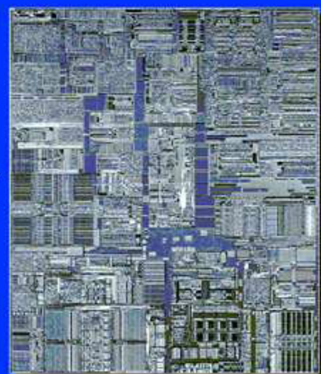


Jean Hoerni

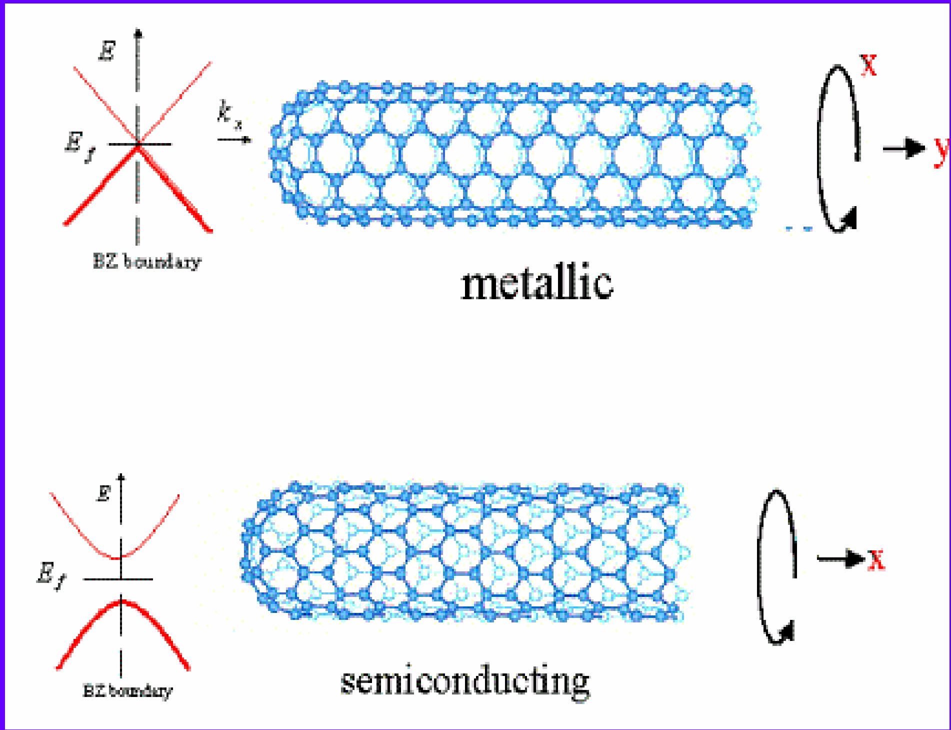
Modern IC

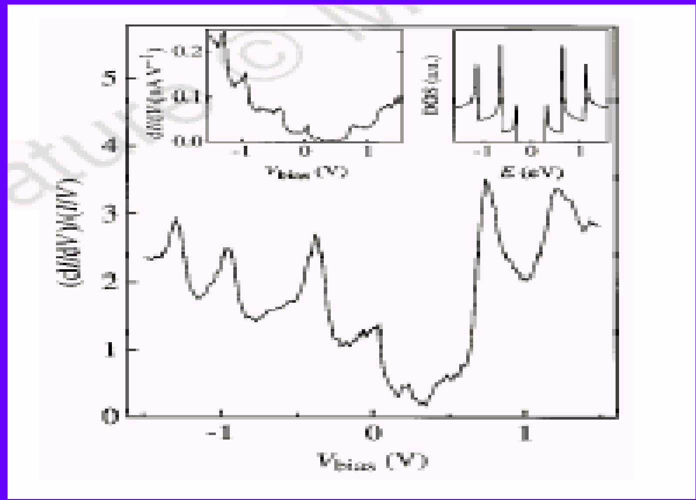
Pentium® III Processor

Transistors:	9,503,153
Die Size:	408.9 mils x 484.8 mils
Area:	127.9 mm^2

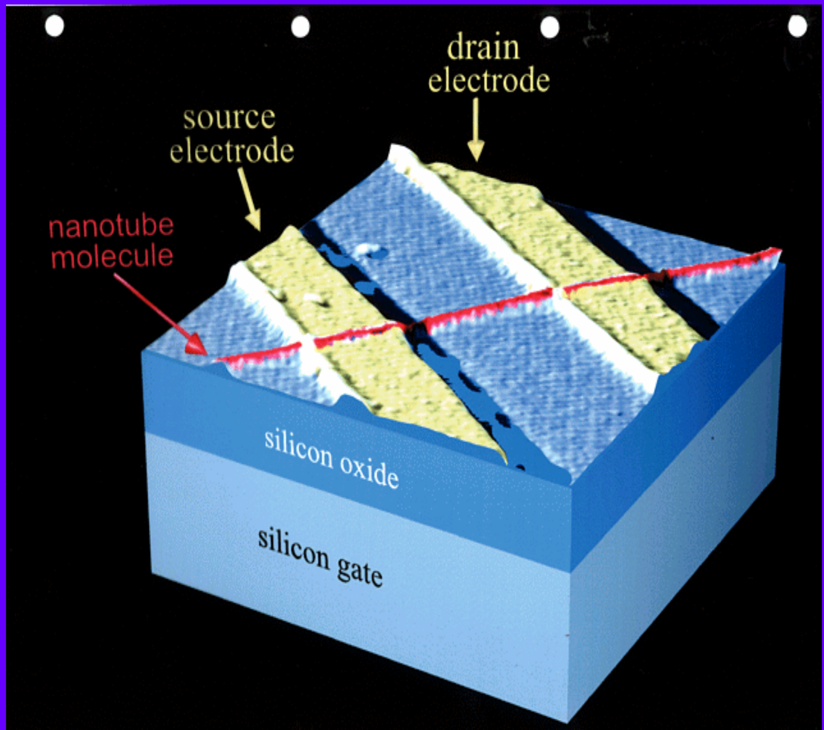


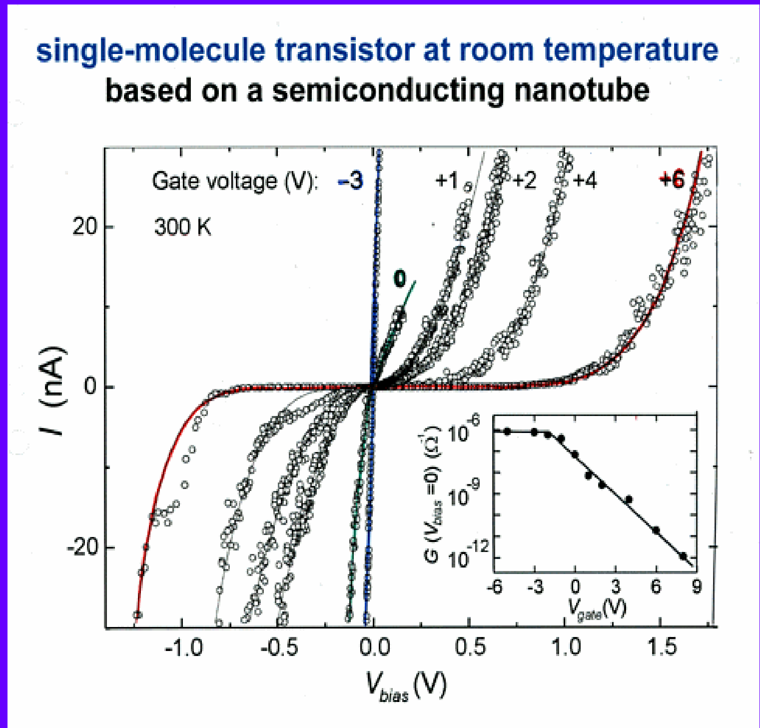
Electronic properties of a carbon nanotube





Single-walled CNT transistor





S.J. Tans *et al.*, *Nature* 393, 49 (1998).

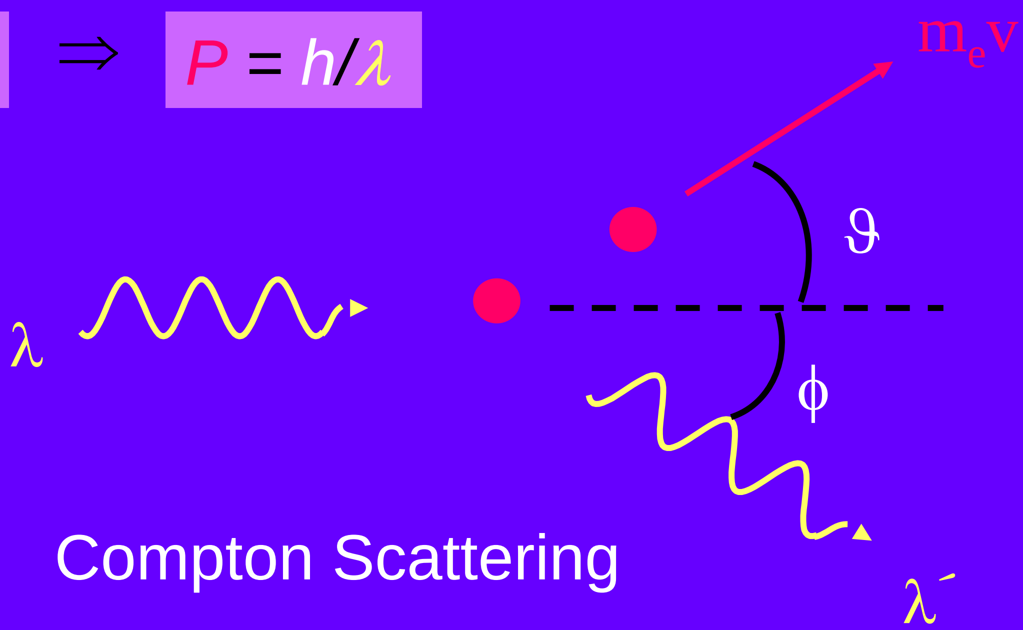
奈米科技的基礎

奈米結構的大小約爲 **1** 到 **100**奈米，也就是在分子和次微米結構之間。在此尺寸下，許多量子效應與現象特別顯著，因此，奈米結構能產生完全不同於大尺寸物質的新性質。除了尺寸小以外，奈米結構的特徵還包括高表面/體積比、高密度堆積的潛力、以及在結構組合上的彈性。

Photon as a particle

Einstein's proposal:

$E = h\nu \Rightarrow P = h/\lambda$



Compton Scattering

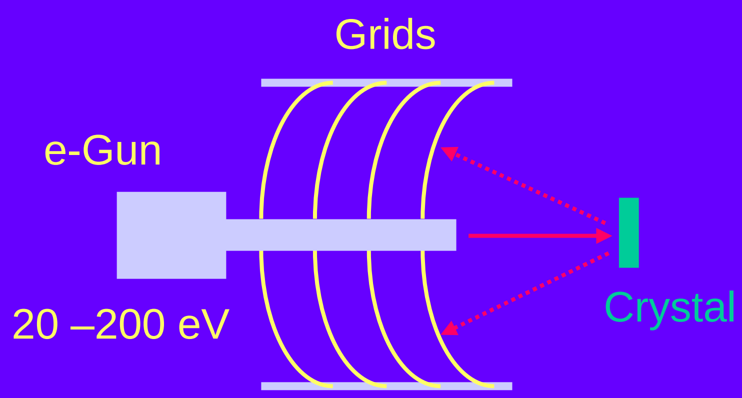
Electron as a wave

de Broglie's proposal:

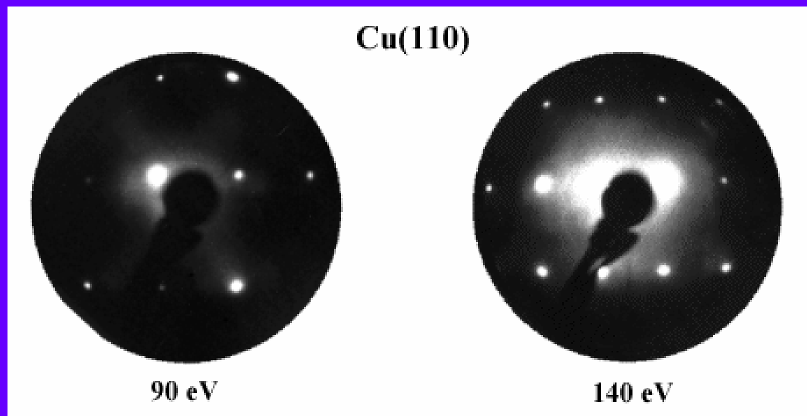
$\lambda = h/P \Rightarrow \nu = h/E$

For electrons:

$\lambda\,(nm) = 1.22/E^{1/2}(eV)$

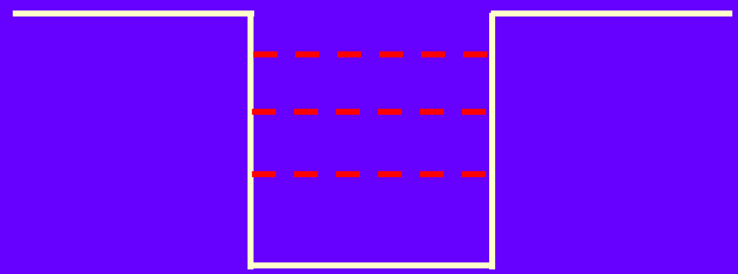


LEED

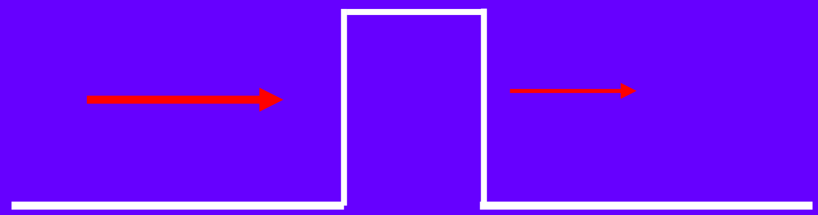


Fundamentals of Quantum Mechanics

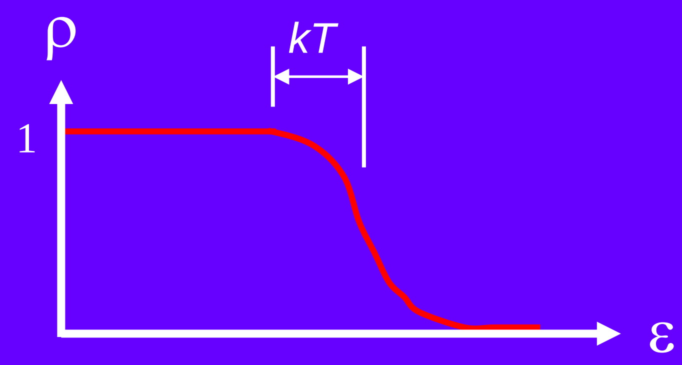
1. Quantization



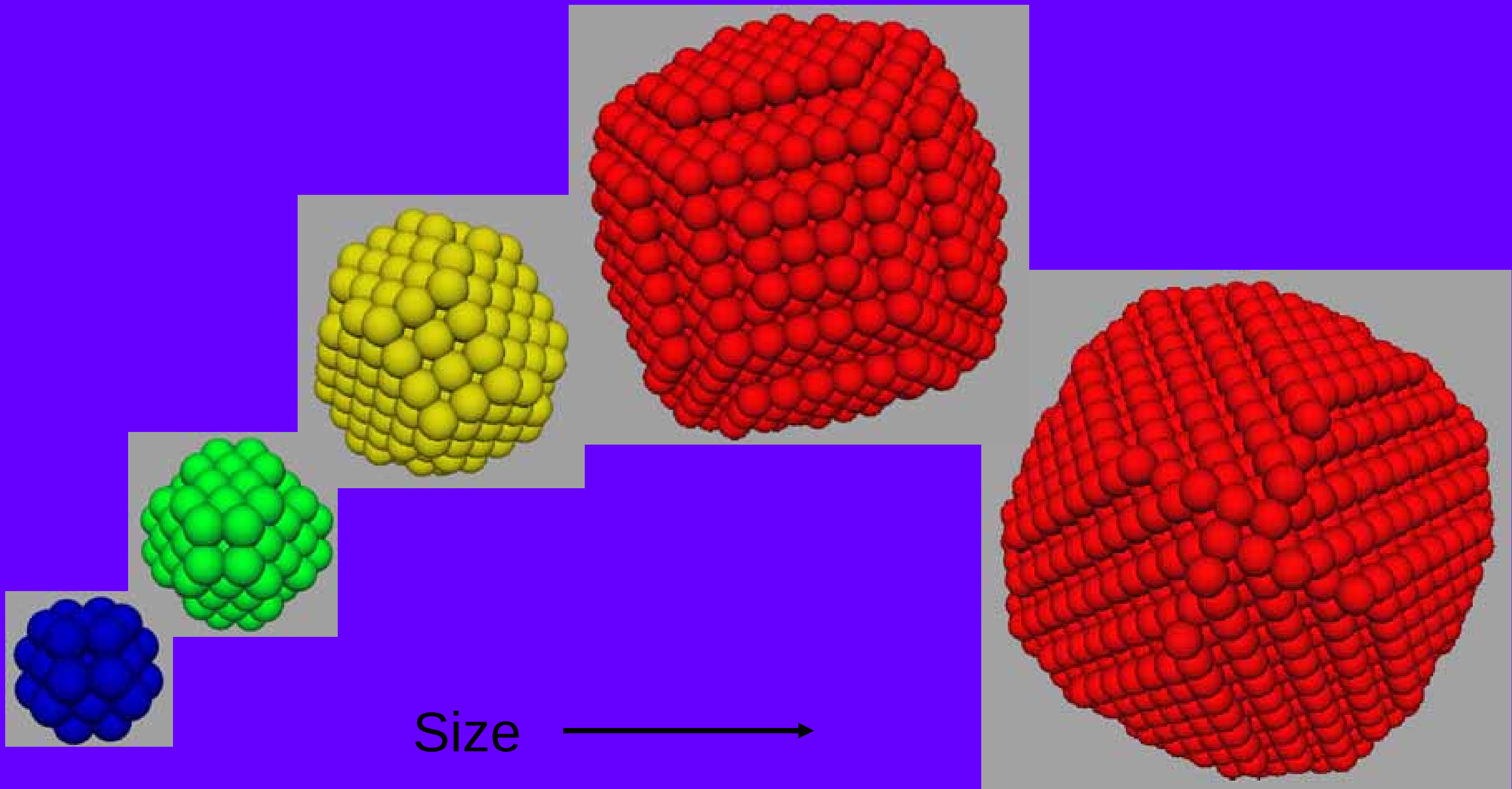
2. Tunneling



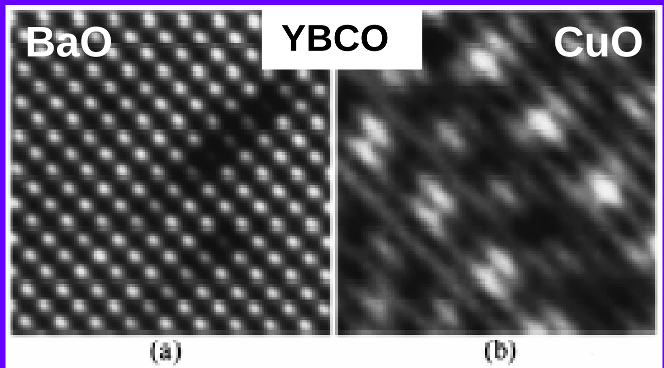
3. Statistics

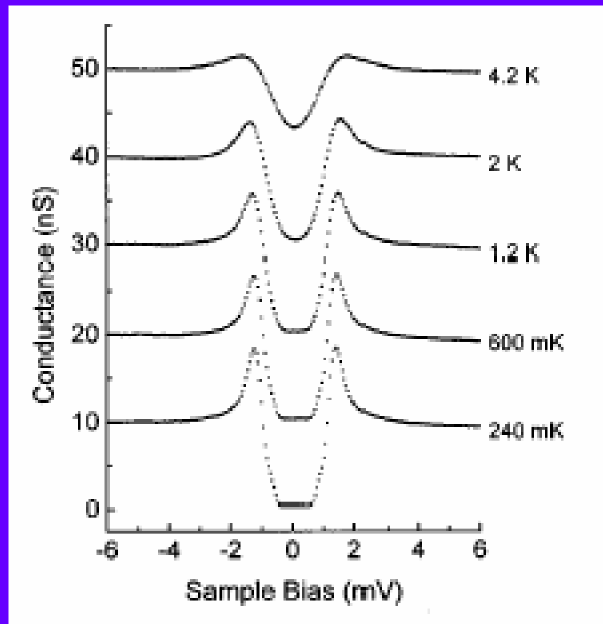


Size effect



Measurement of electronic states



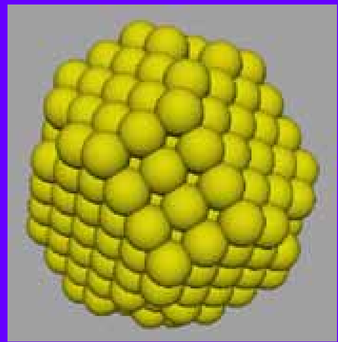


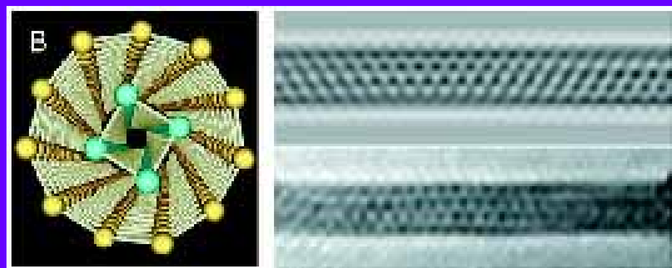
S. H. Pan *et al., Rev. Sci. Instru.* 40, 1459 (1999).

Properties of a nanostructure

<u>Microscopic</u>

Size
Structure
Shape
Symmetry
Domains
Defects
.
.
.



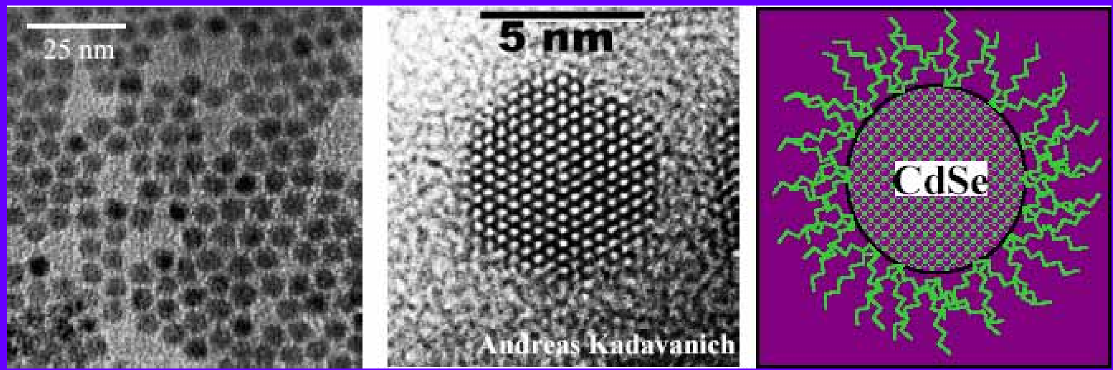


<u>Analytical</u>

Composition
Stoichiometry
Electronic
Magnetic
Thermal
Mechanical
.
.
.

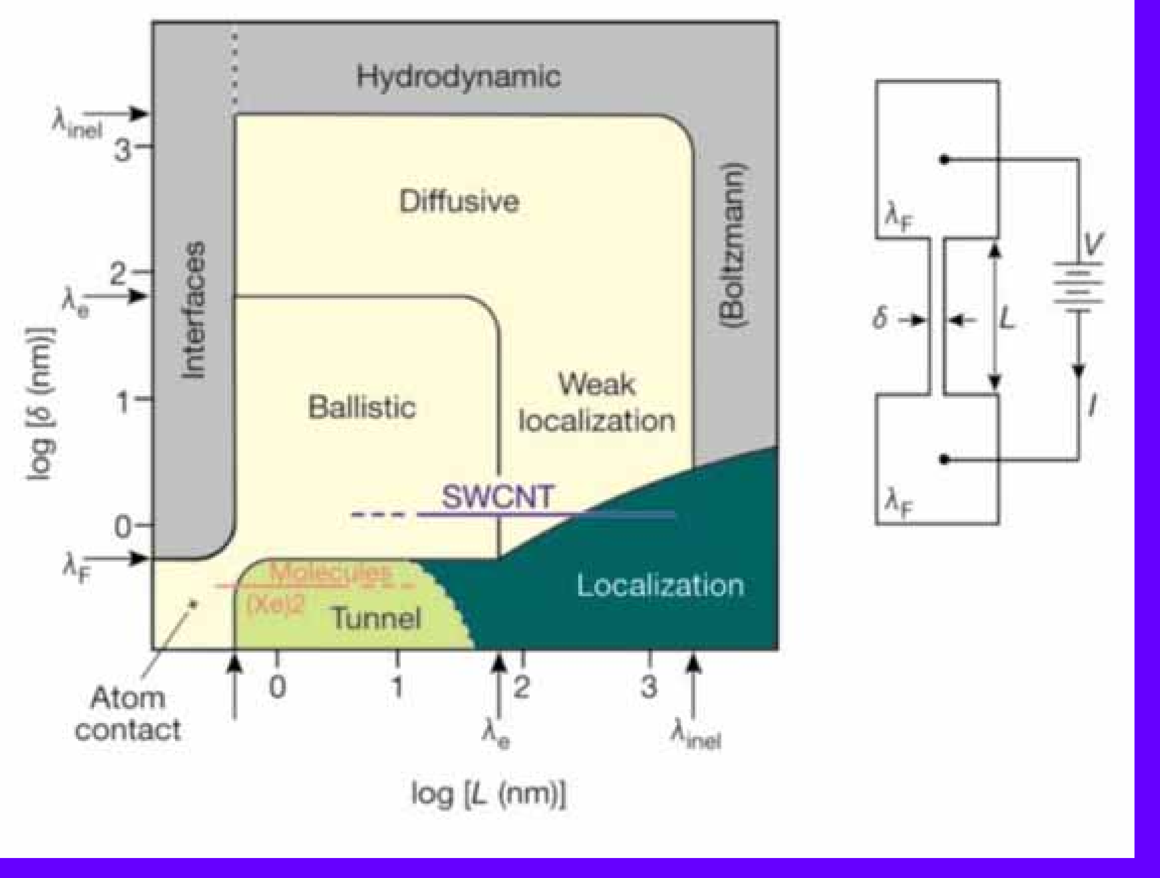
photons, electron, ion, neutron, proximal nanoobjects …

Semiconducting quantum dots



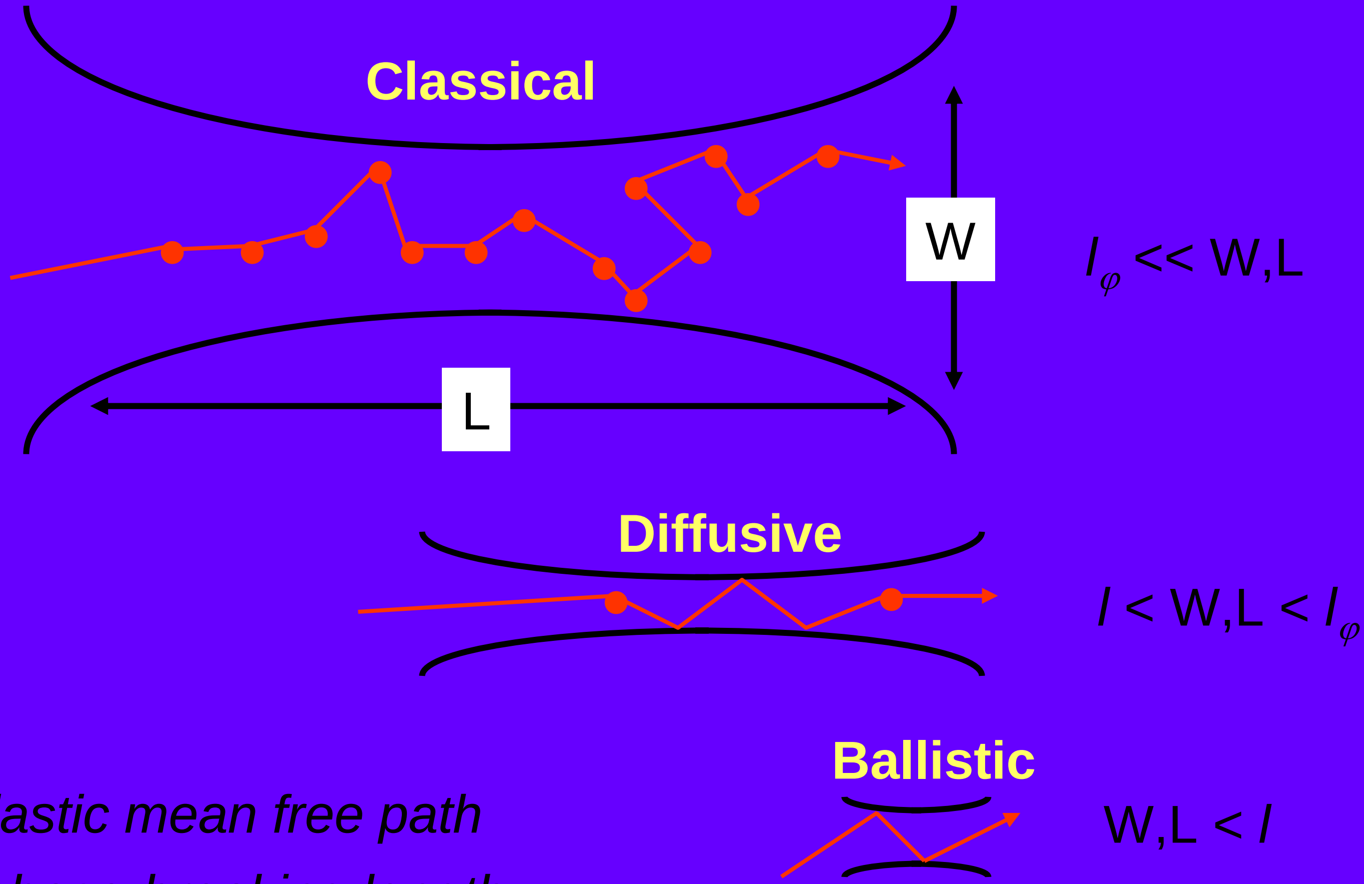
(Reproduced from Quantum Dot Co.)

Critical lengths



C. Joachim *et al.*, *Nature* 408, 541 (2000).

Characteristics of electron transport



l : elastic mean free path

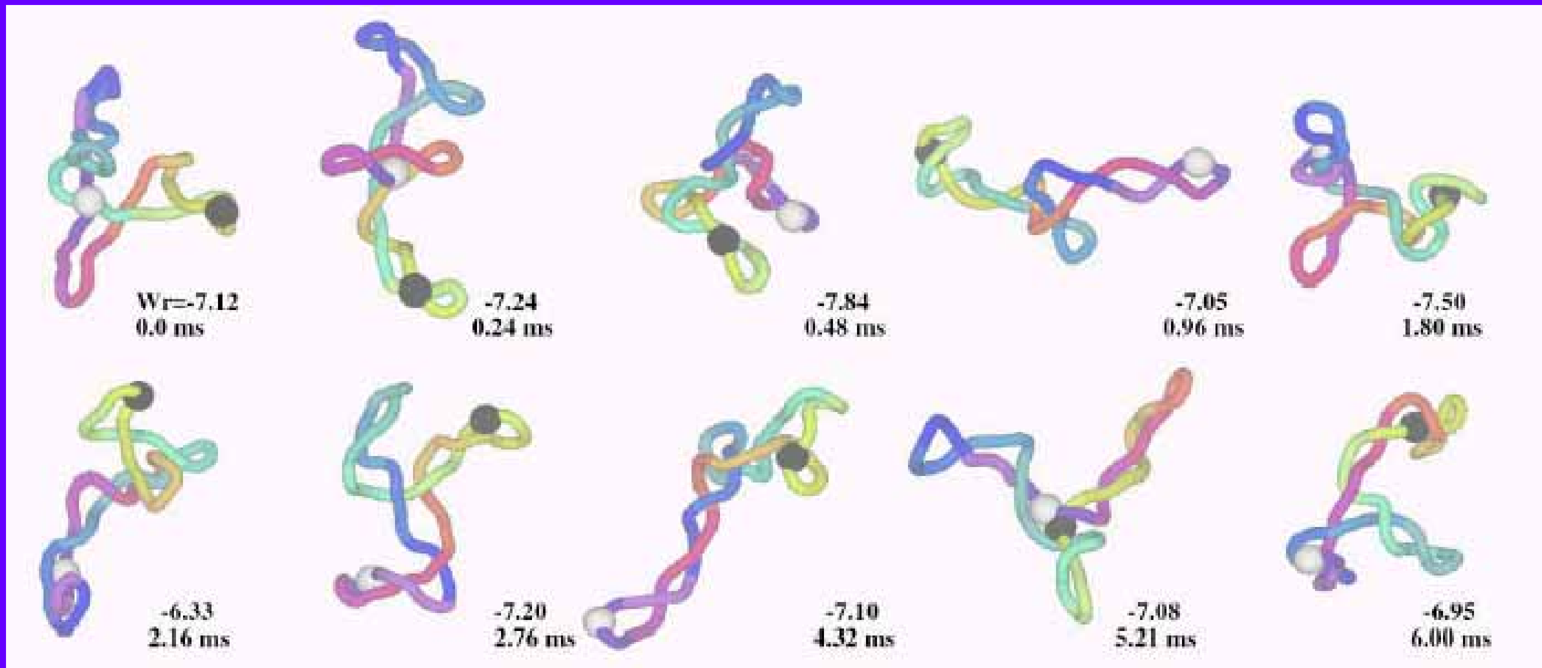
l_φ : phase-breaking length

Minituralization of length scale

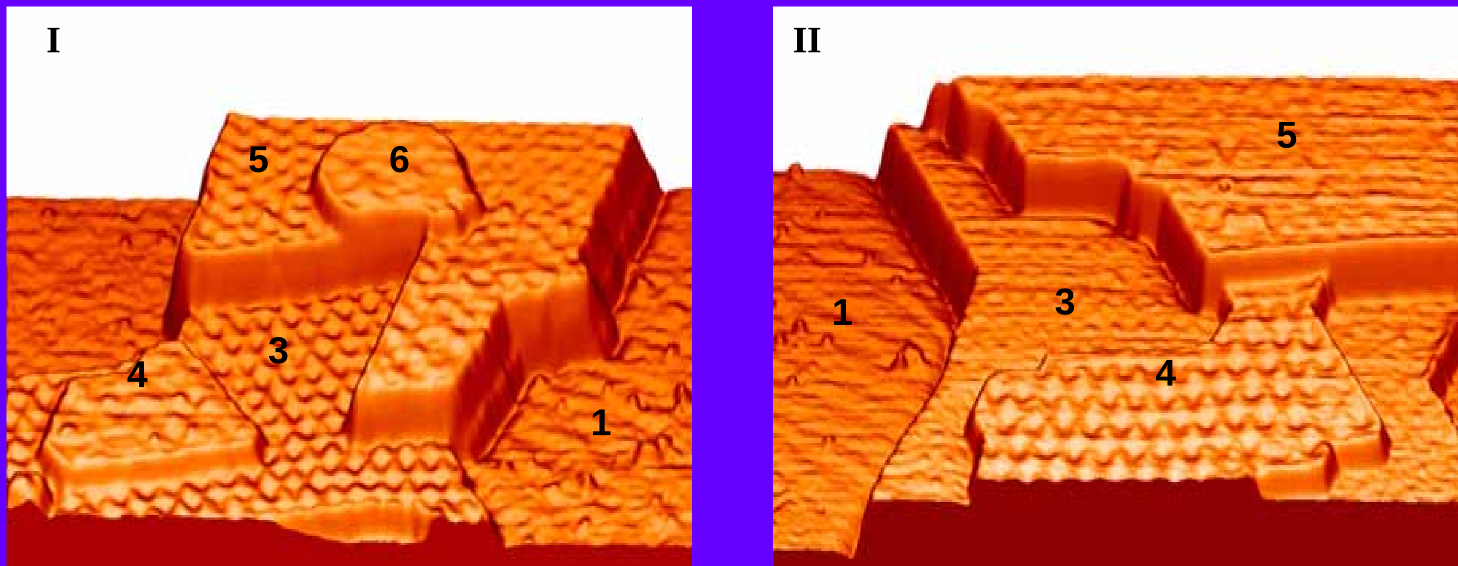
Macro → Micro → Nano

continual	discrete
scalable	nonscalable
evolutionary	revolutionary
classical	quantum mechanical

Simulation of DNA dynamics

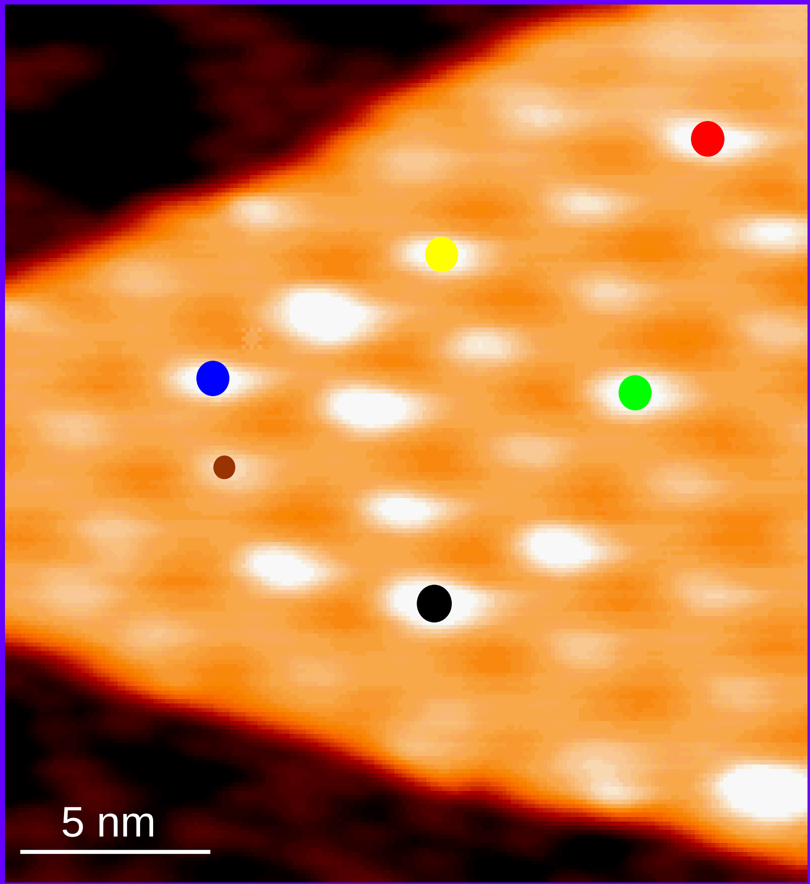


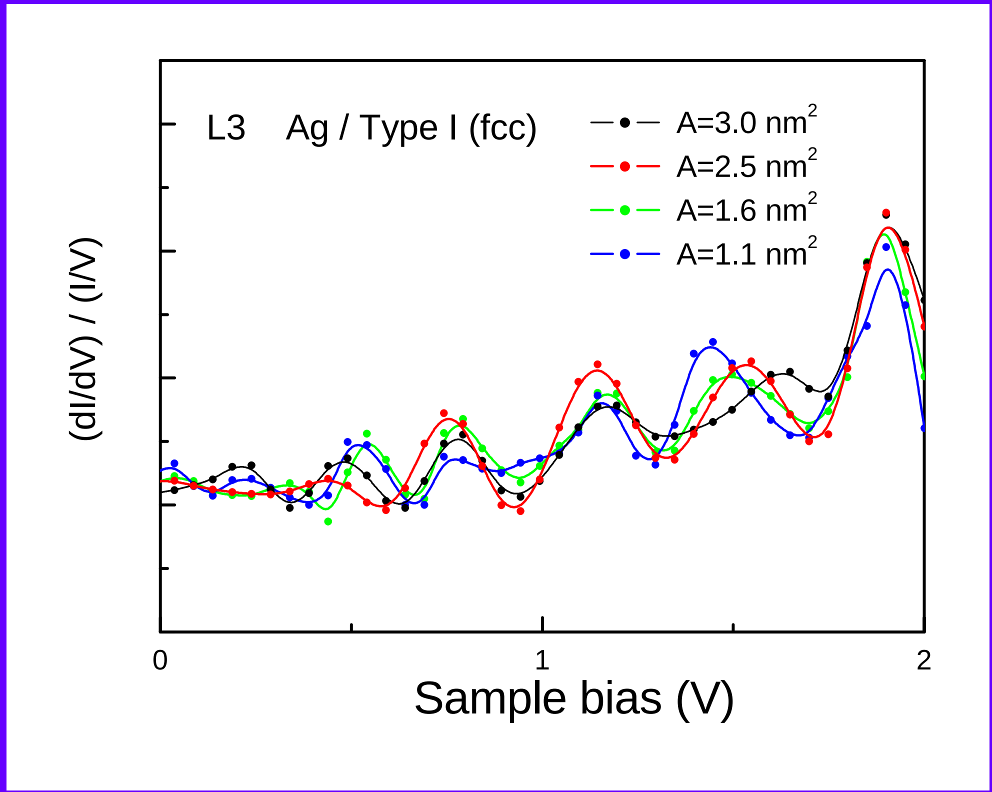
Alternating and complementary contrast



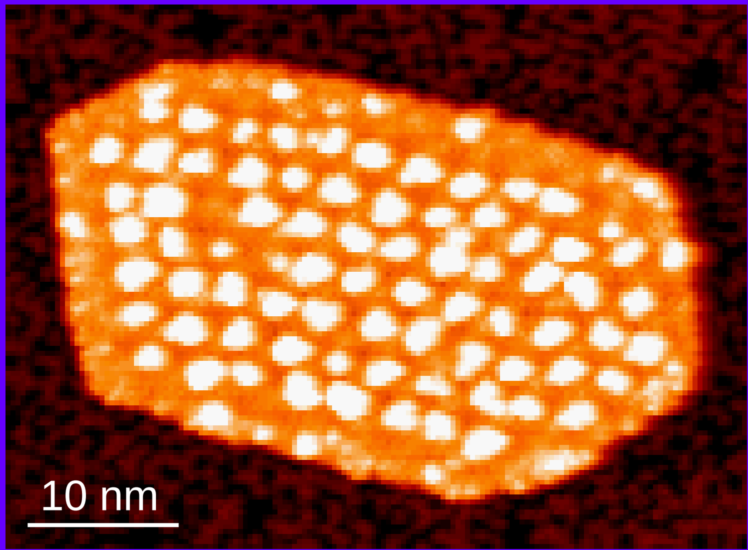
W.B. Jian *et al*. PRL **90**, 196603 (2003)

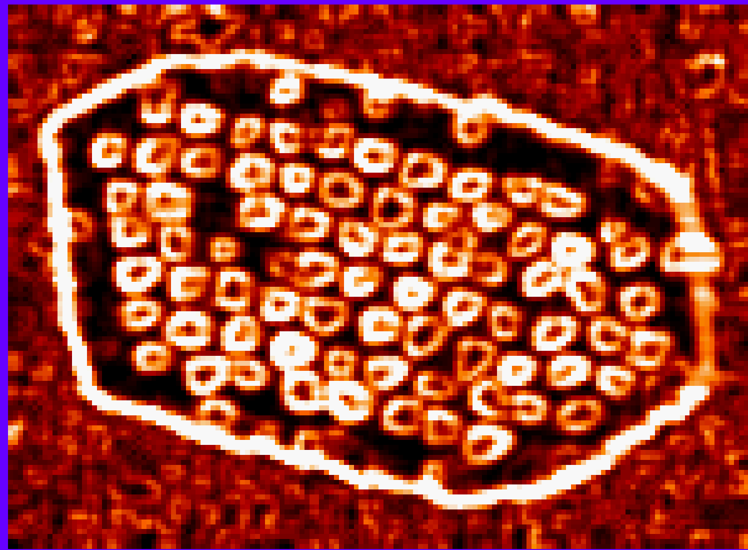
Size-dependent I/V spectra by STS



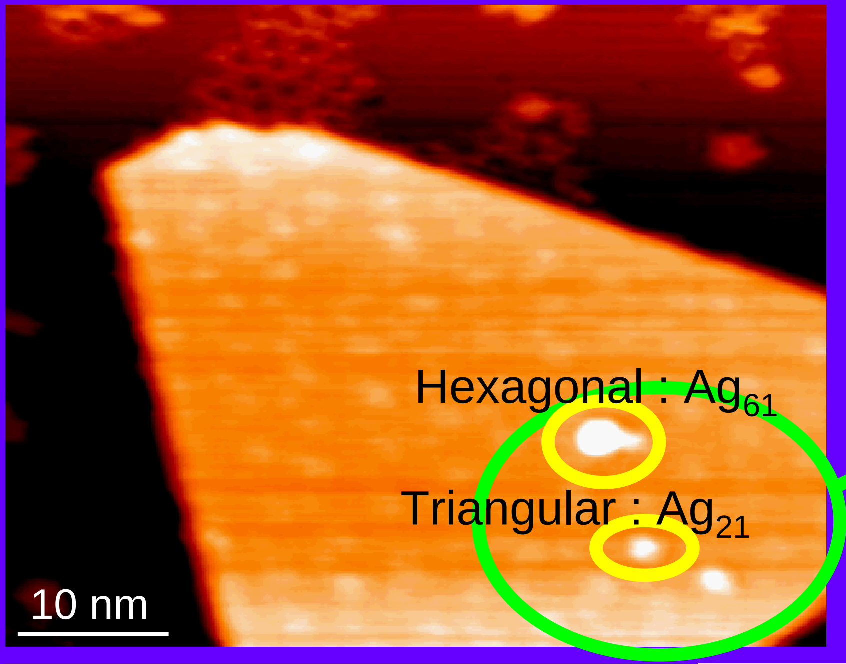


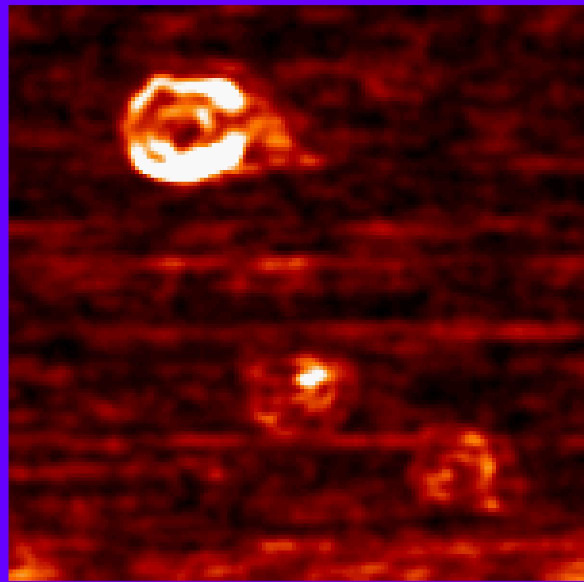
Shapes of Ag nanopucks

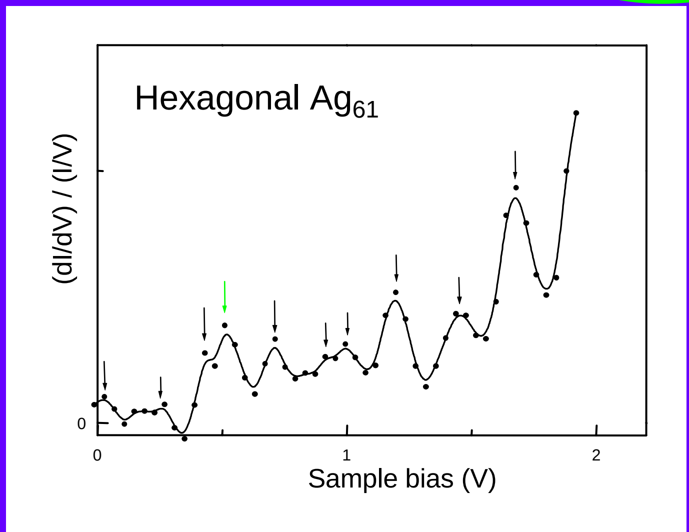


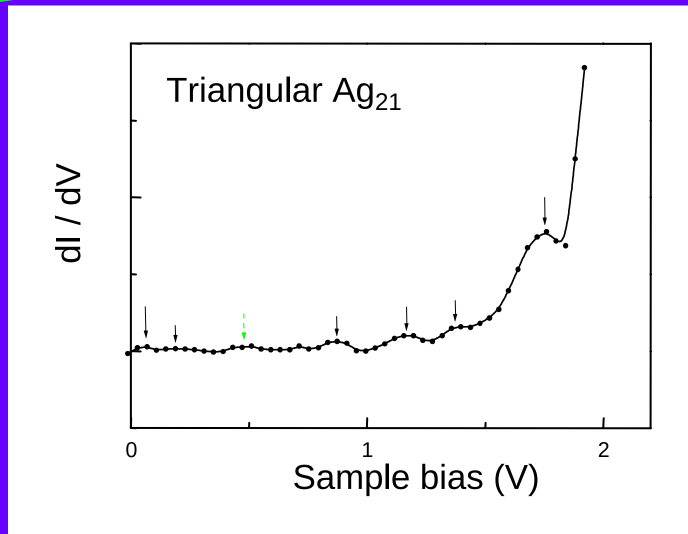


Size- and shape-dependent I/V spectra









單一奈米結構檢測

特色

- 體積小
- 信號弱
- 活性強
- 結構影響性能

需求

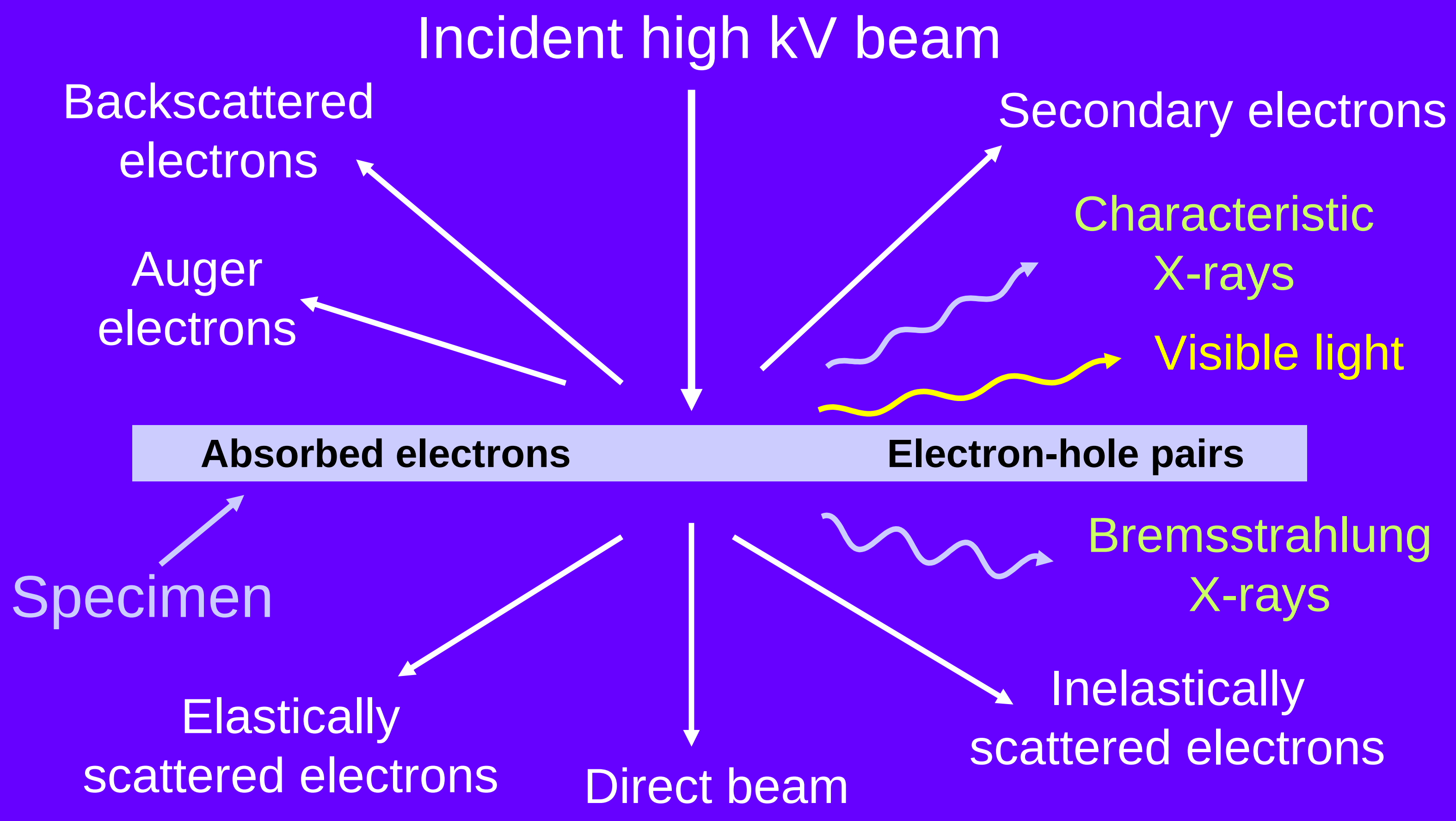
高解析、小探針

高靈敏、低干擾

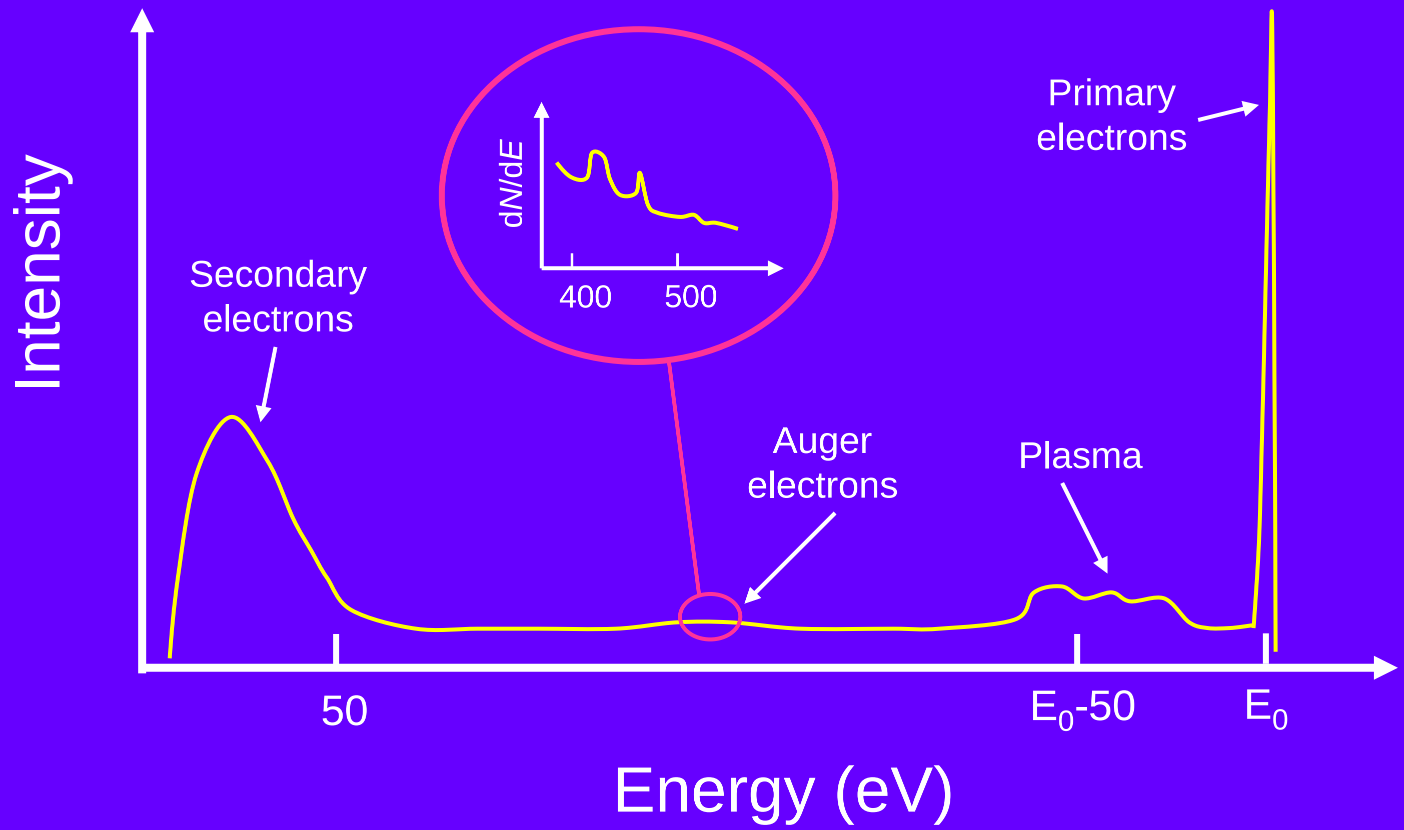
高真空、低溫

高速度、現場

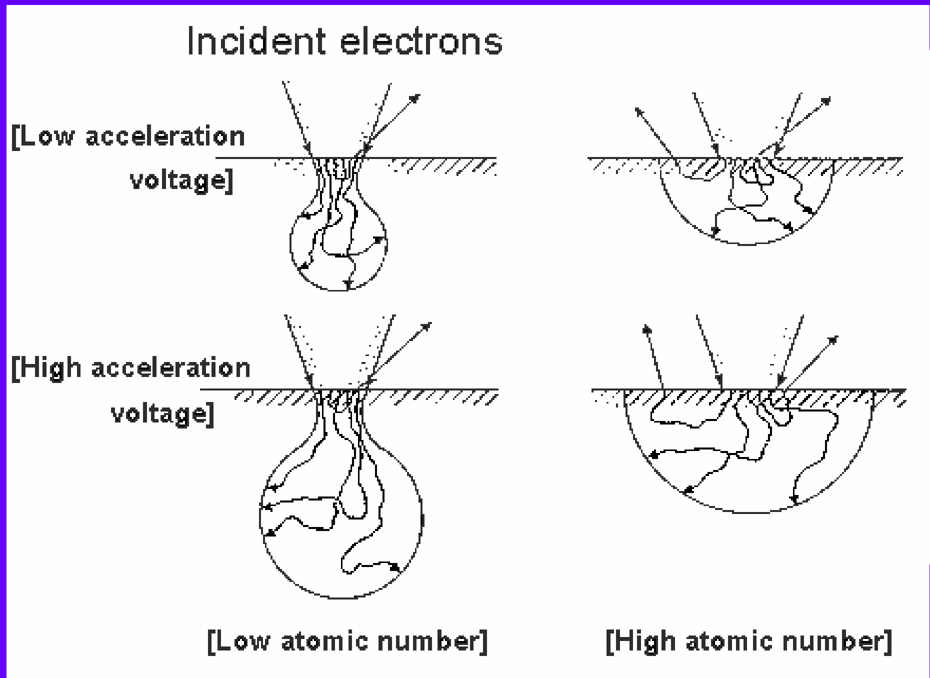
Interaction between e-beam and sample

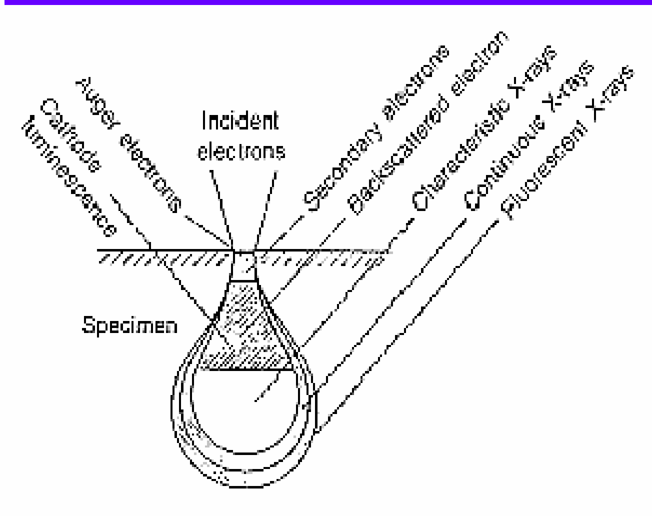


作用後電子束的能量分佈

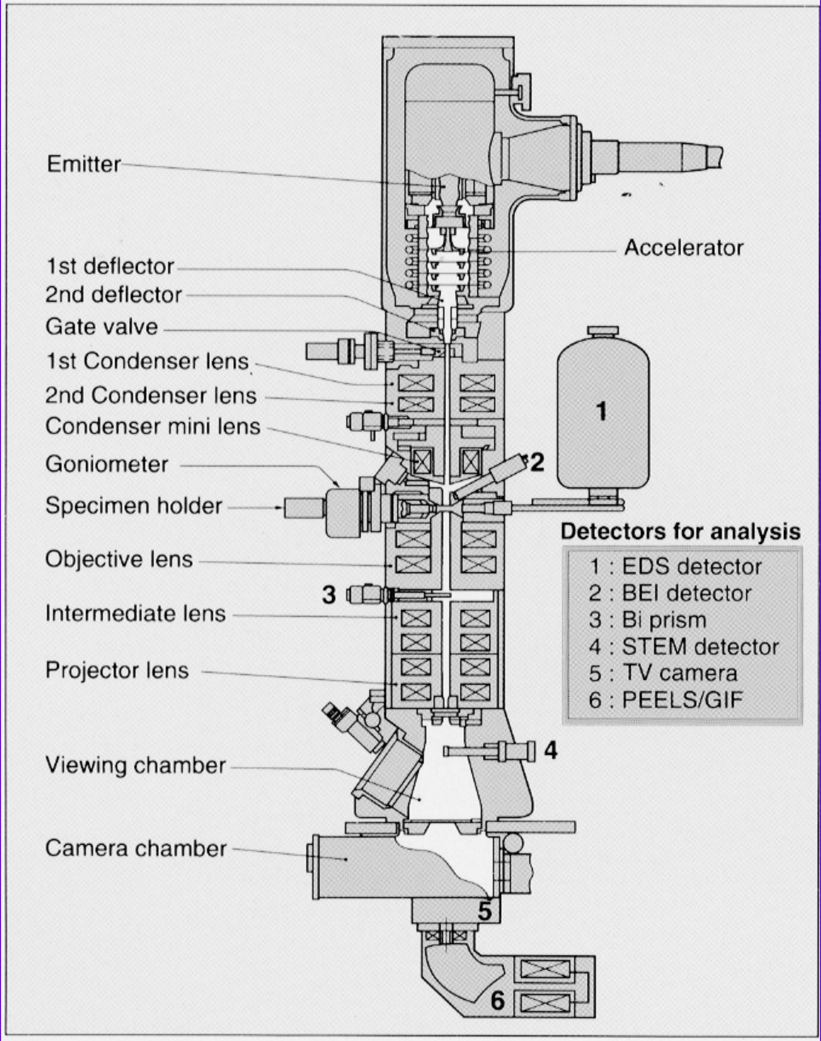


電子束的穿透能力


Incident electrons
[Low acceleration voltage]
[High acceleration voltage]
[Low atomic number]
[High atomic number]

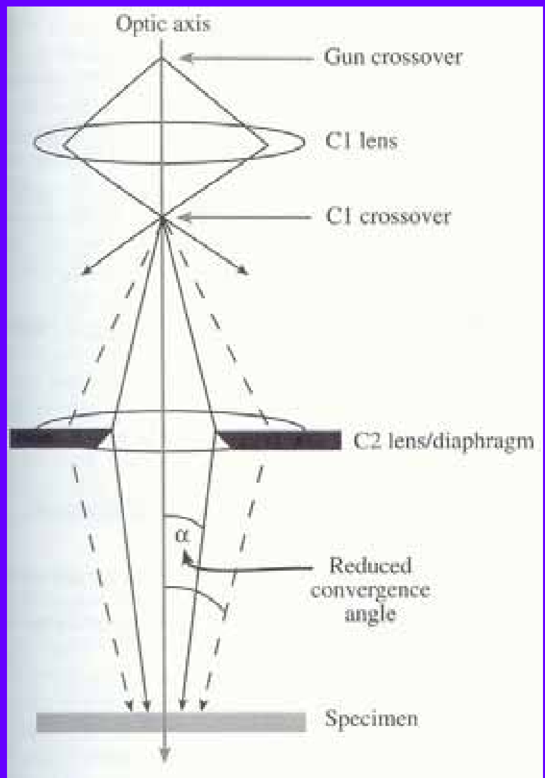

Auger electrons
Cathode luminescence
Incident electrons
Secondary electrons
Backscattered electron
Characteristic X-rays
Continuous X-rays
Fluorescent X-rays
Specimen

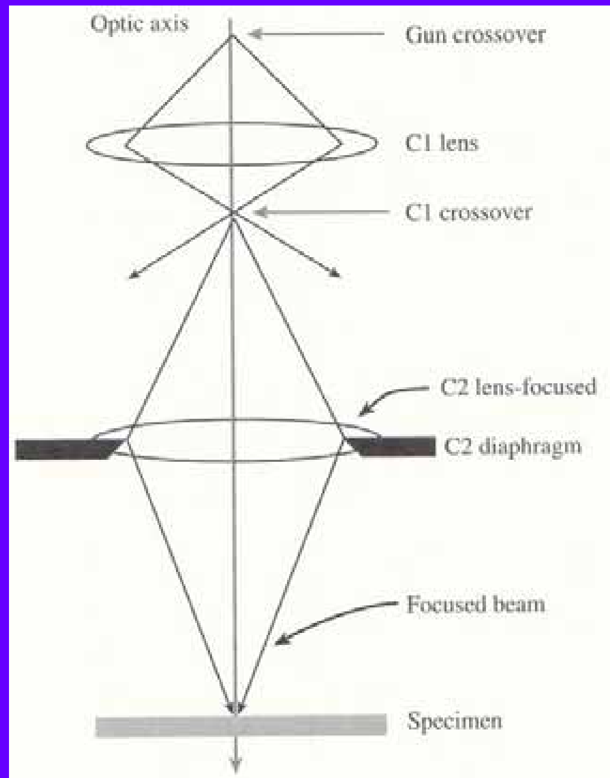
Cross section view of HRTEM



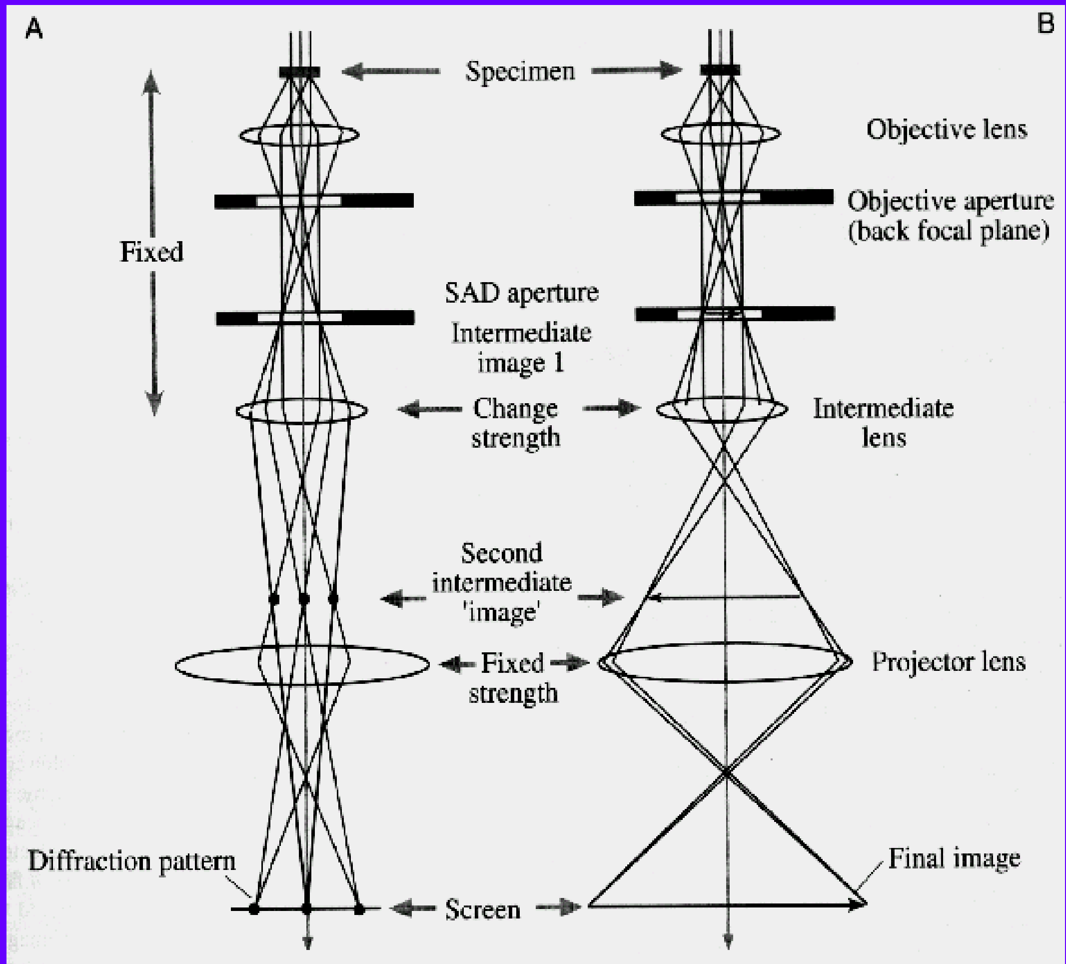
Cross section of JEM-2010F and assignrnent of detectors

穿透電子顯微術(TEM)光源

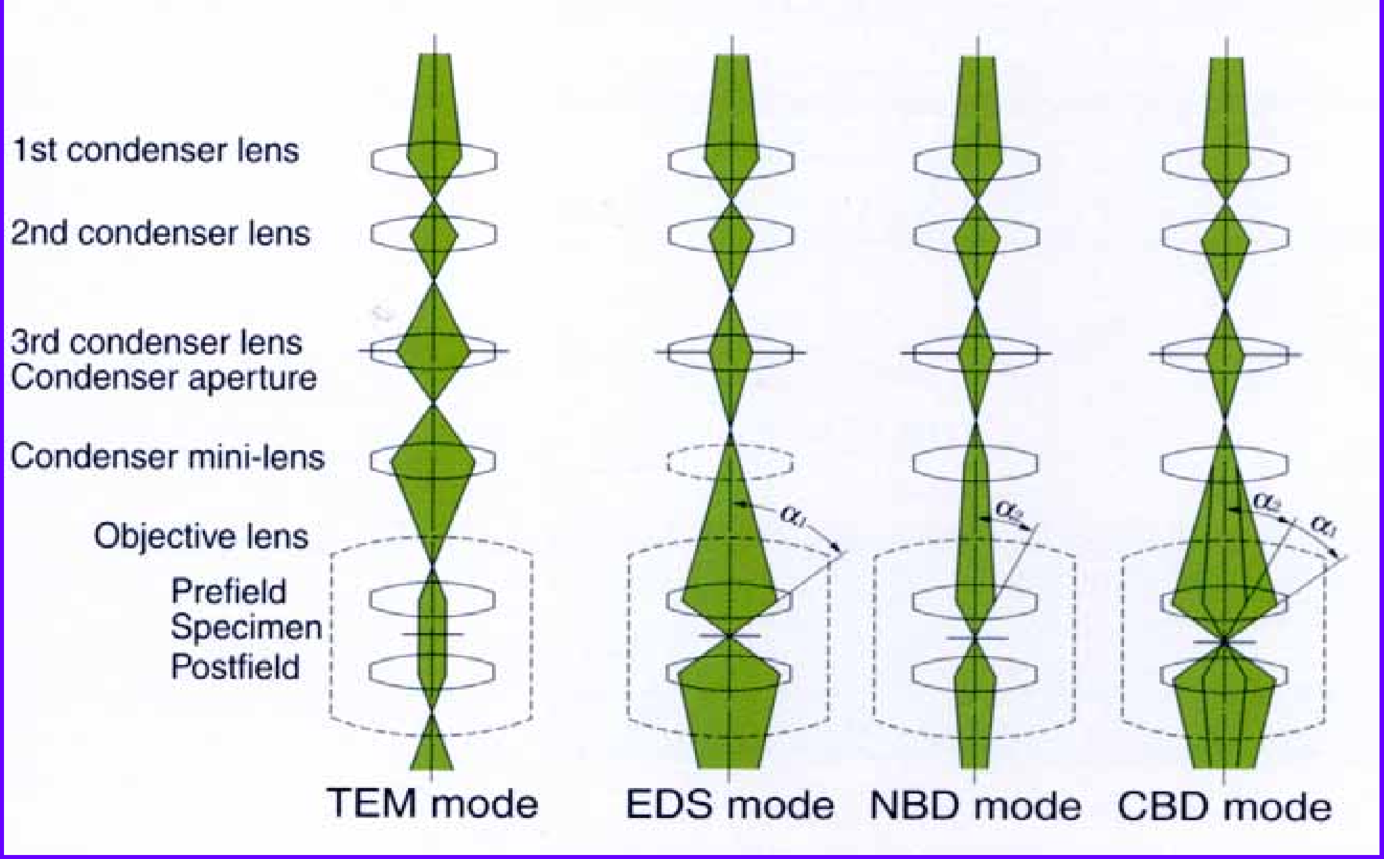


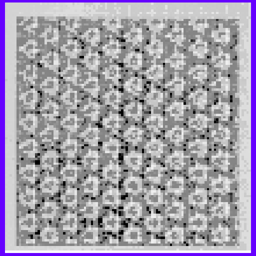


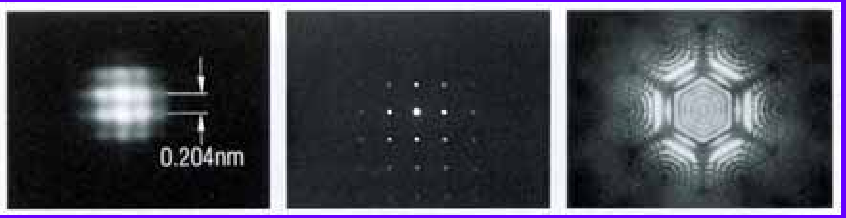
TEM 成像系統


A
B
Specimen
Objective lens
Objective aperture
(back focal plane)
Fixed
SAD aperture
Intermediate
image 1
Change
strength
Intermediate
lens
Second
intermediate
'image'
Fixed
strength
Projector lens
Diffraction pattern
Final image
Screen

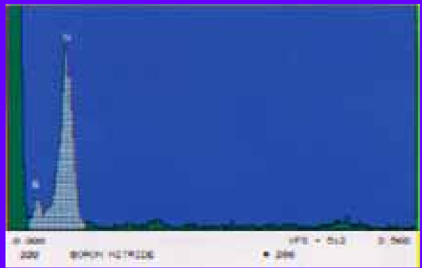
Quick Beam Select System



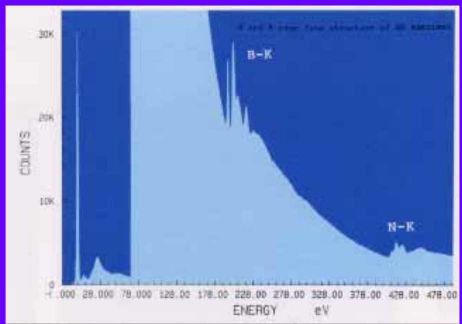




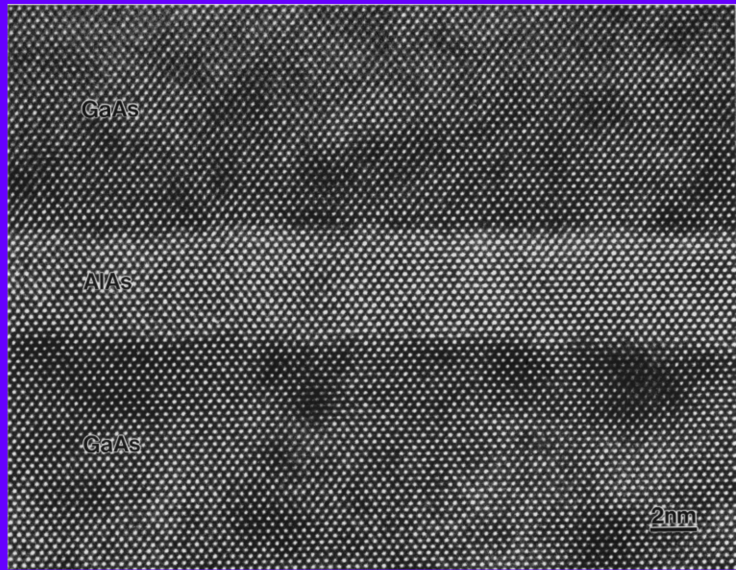
Information from TEM



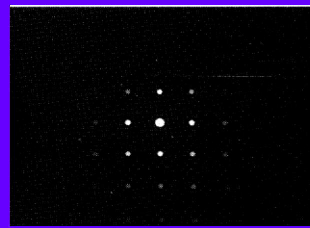
EDS



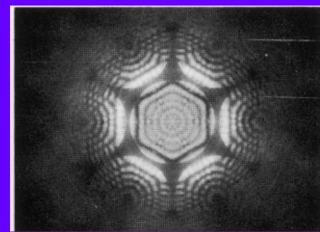
EELS or GIF



Lattice image
GaAs/AlAs



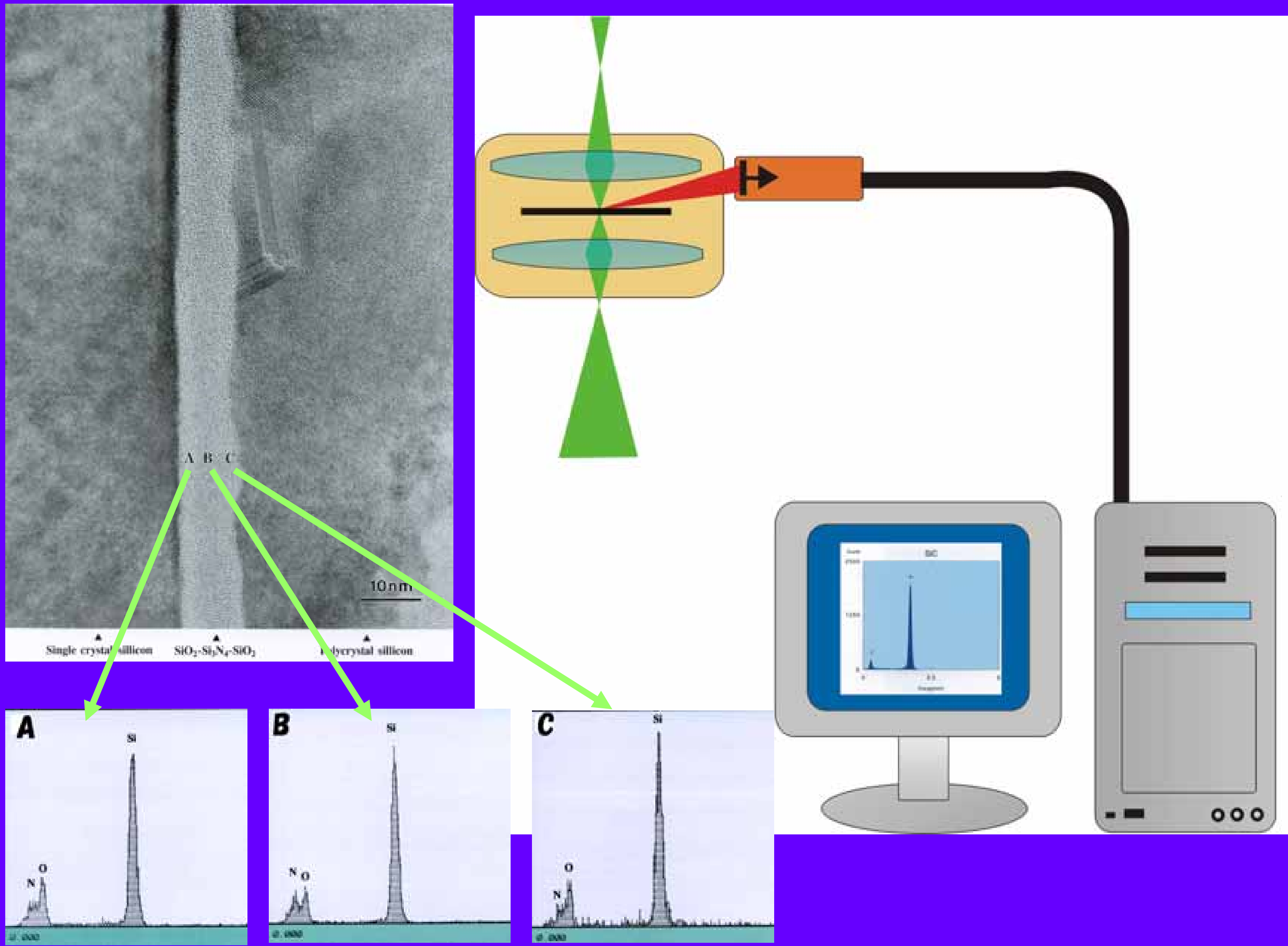
Electron Diffraction



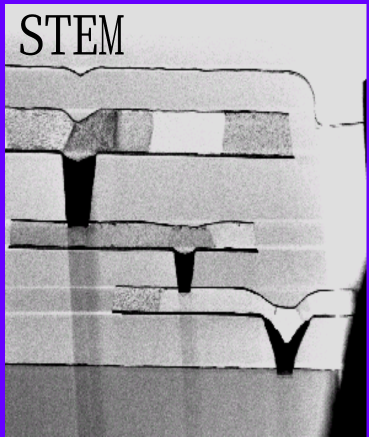
CBED

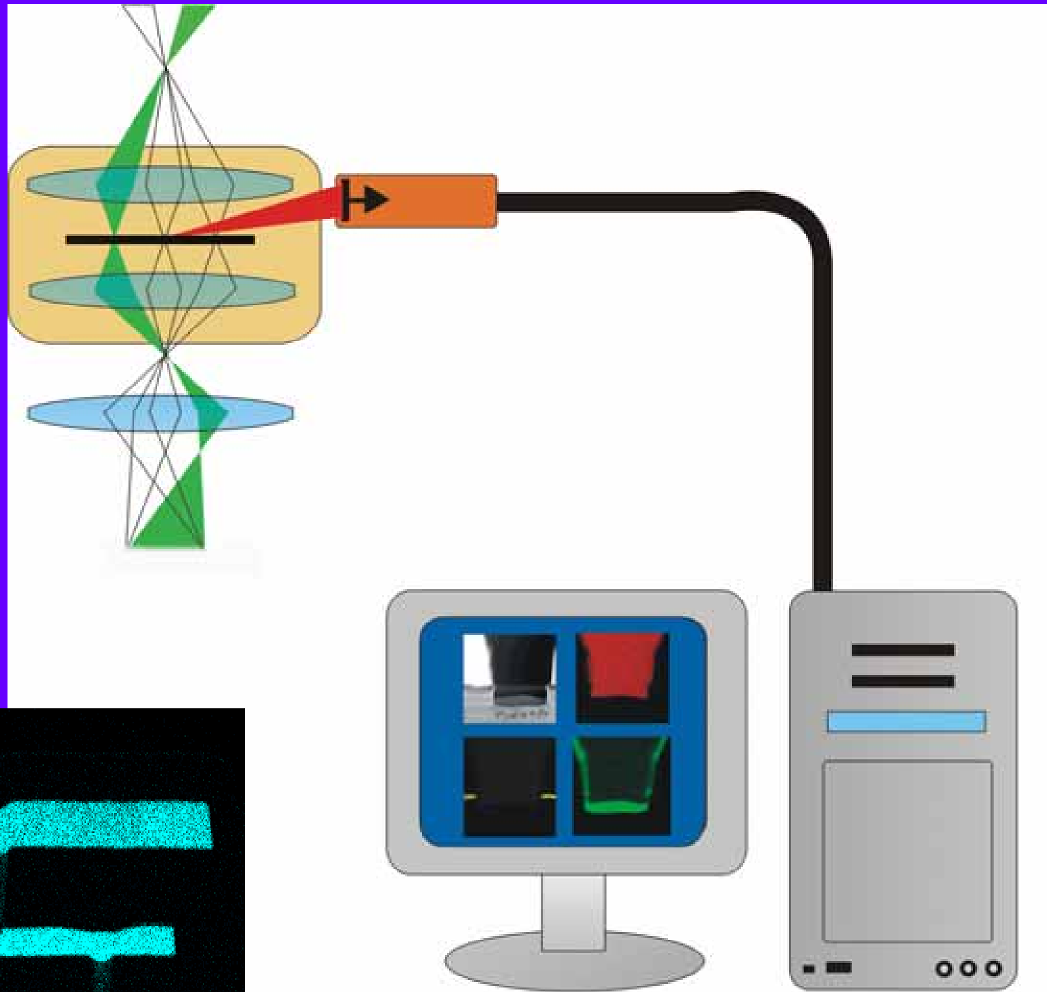
STEM+BF, HAADF →Mapping and Z-contrast image

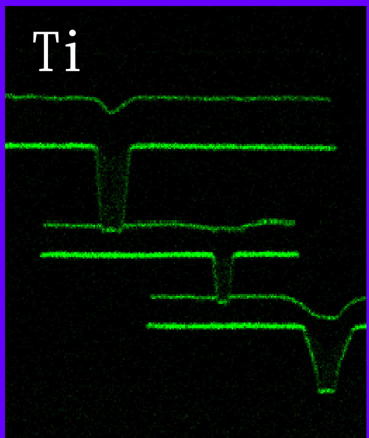
EDS with spatial resolution

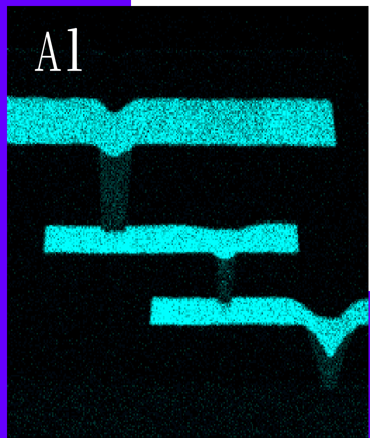


EDS mapping

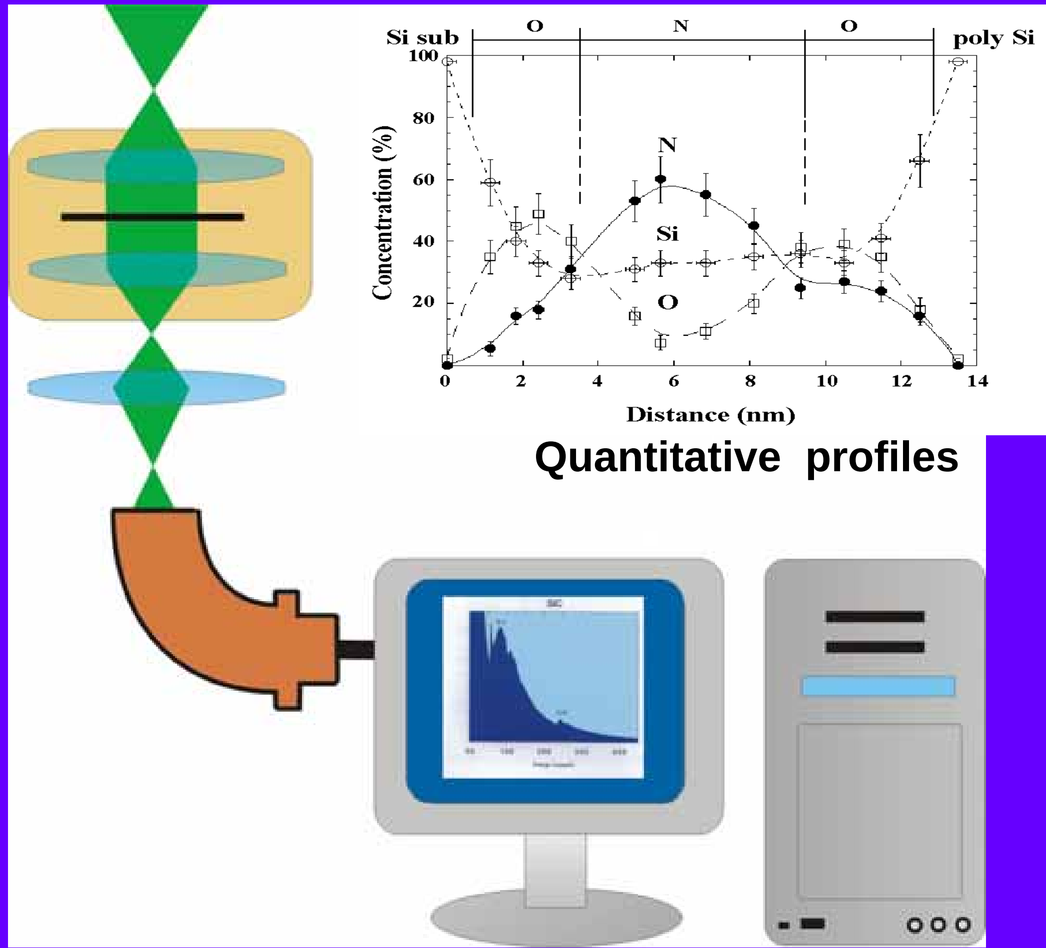


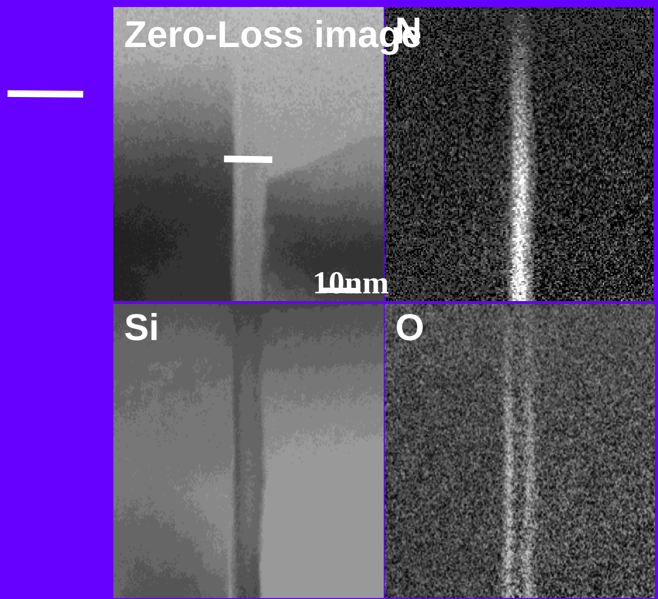






High resolution EELS

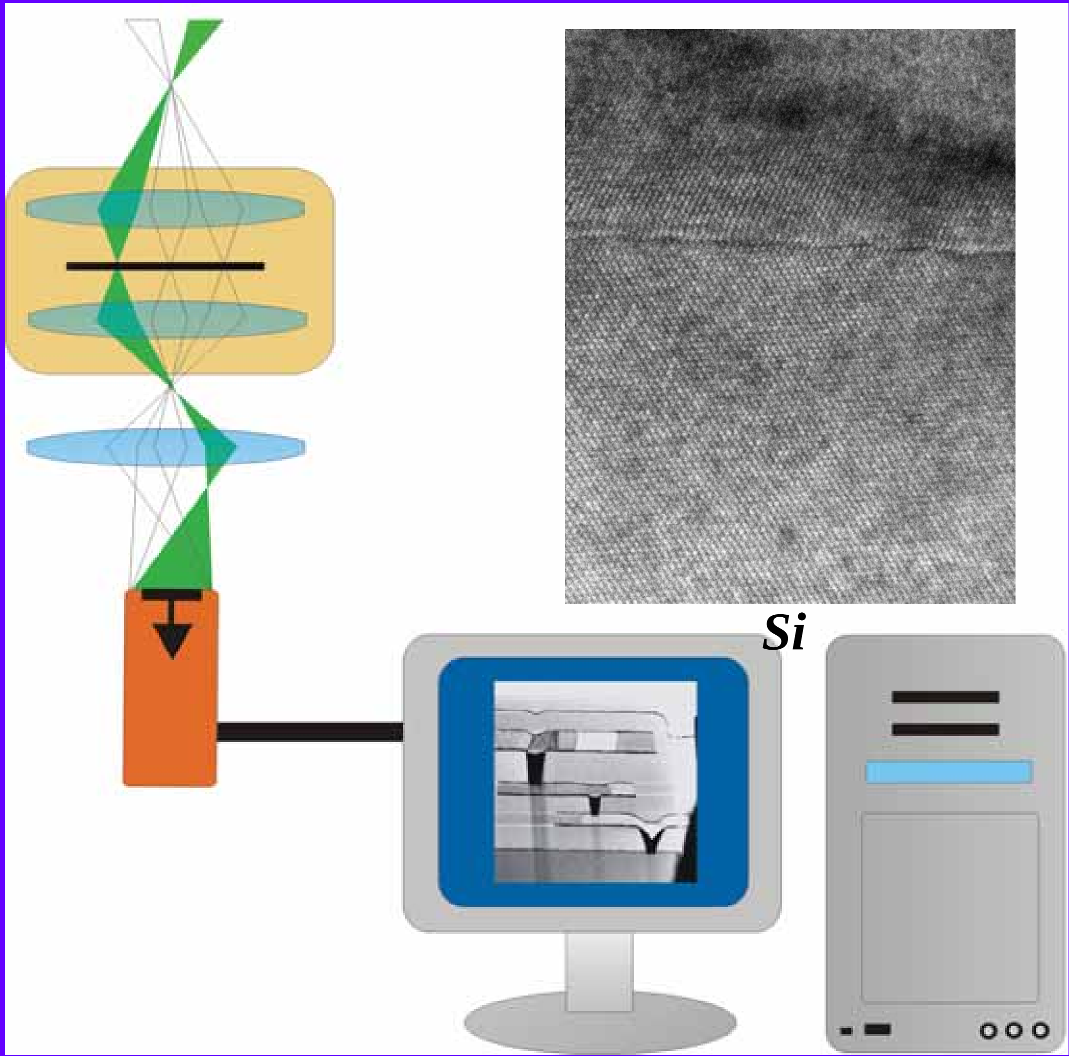




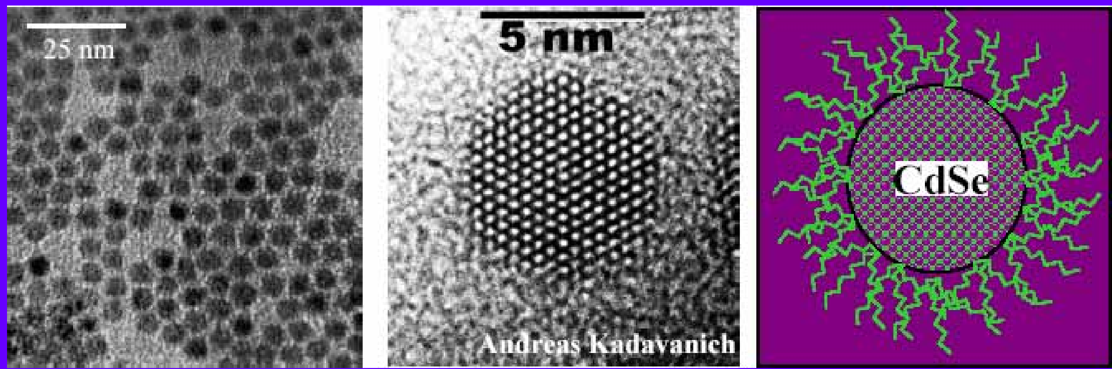
Energy Filtered images of insulating layer

High resolution STEM image

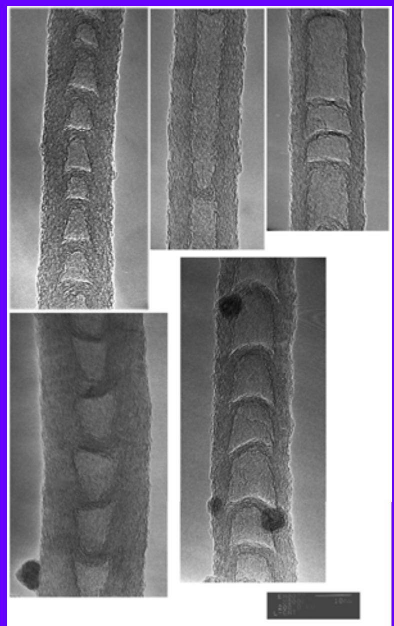
W-plug.



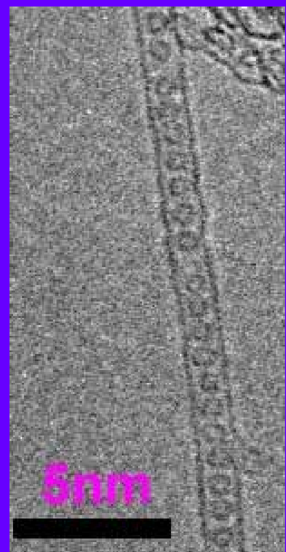
Semiconducting quantum dots and carbon nanotubes



(Reproduced from Quantum Dot Co.)

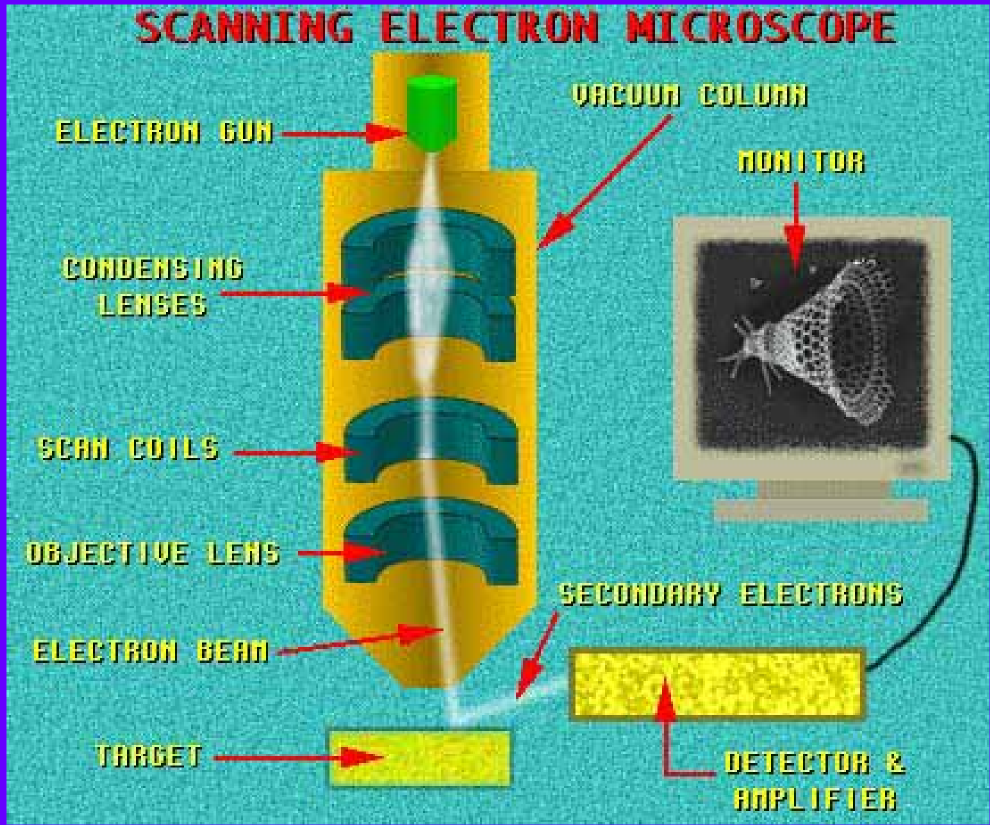


Multiwall CNT



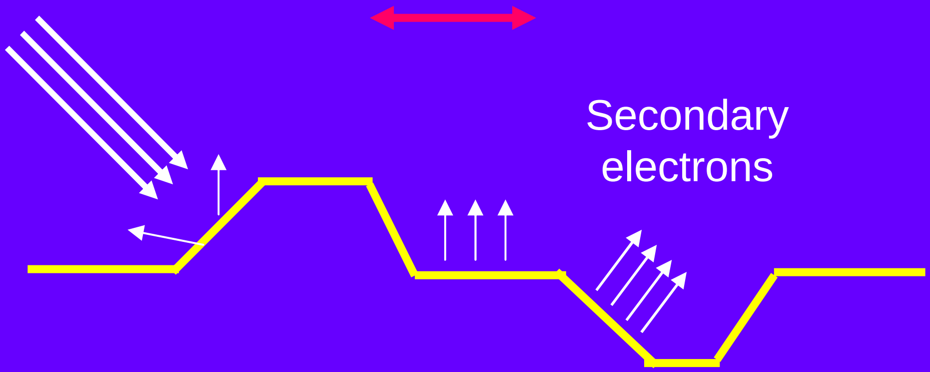
Peapod CNT

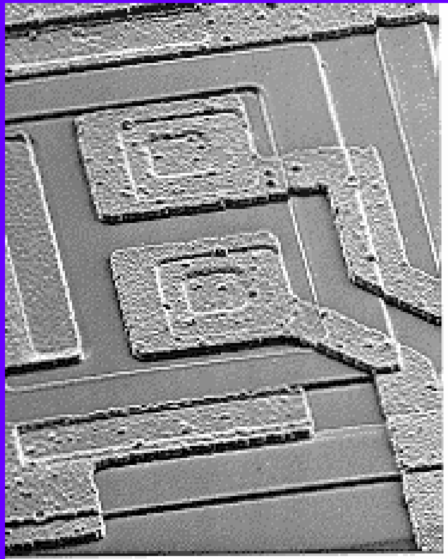
Scanning electron microscopy (SEM)



SEM contrast

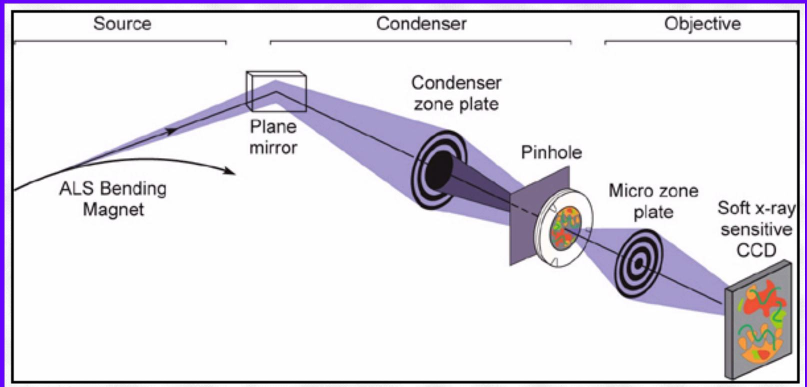
Scanning e beam

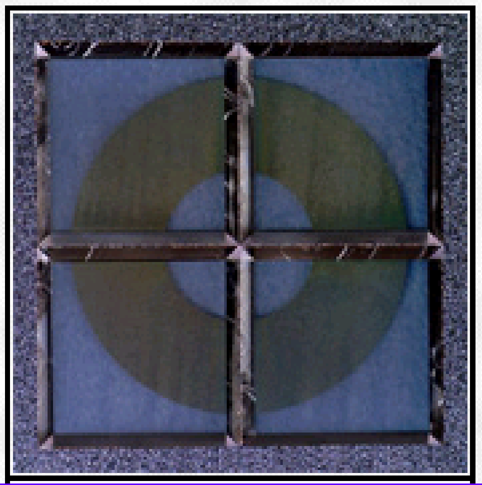


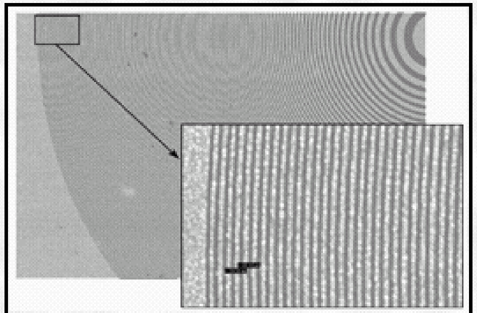


(a) 5 kV x720
Tilt angle: 50°

X-Ray Microscopy

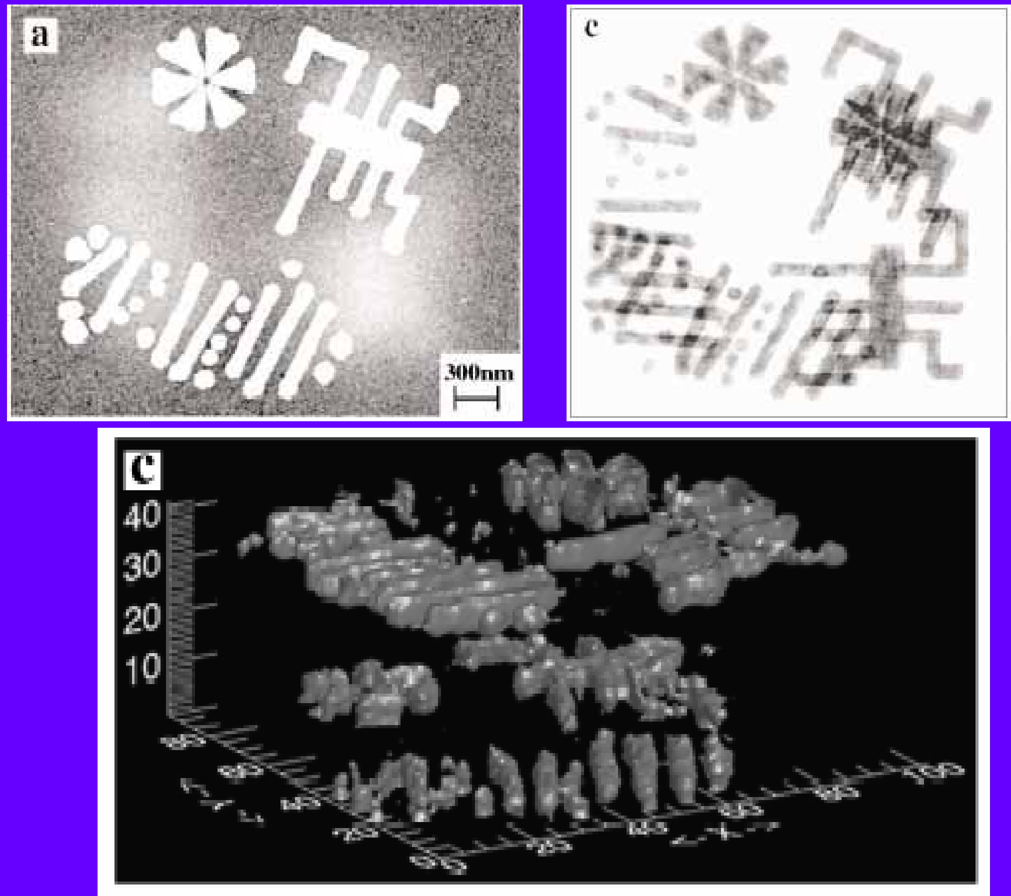






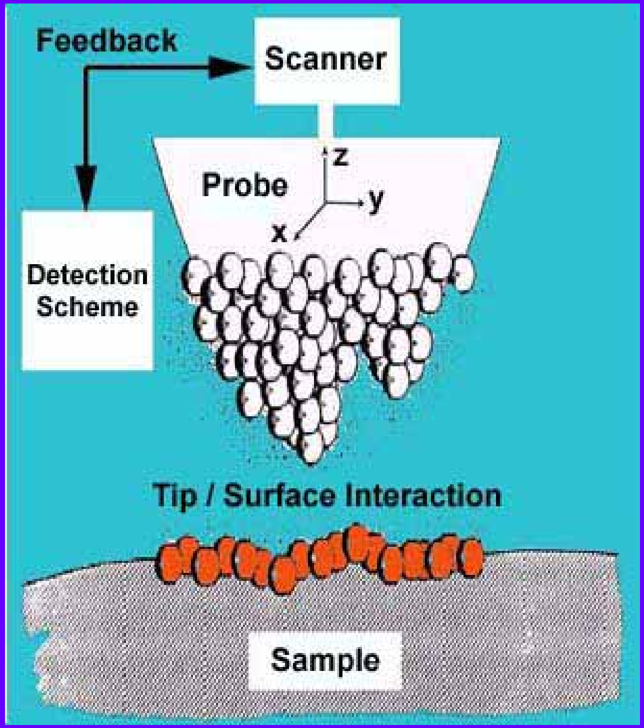
SEM micrograph of a 25-nm-outermost zone width micro zone plate. Diameter = 63mm, 628 zones, gold plated.

3D X-Ray Image



J. Miao et al., PRL 89, 088303 (2002).

Historical development of SPMs



Scanning Tunneling Microscopy (STM)

--- G. Binnig, H. Rohrer et al, (1982)

Near-Field Scanning Optical Microscopy (NSOM)

--- D. W. Pohl (1982)

Atomic Force Microscopy (AFM)

--- G. Binnig, C. F. Quate, C. Gerber (1986)

Scanning Thermal Microscopy (SThM)

--- C. C. Williams, H. Wickramasinghe (1986))

Magnetic Force Microscopy (MFM)

--- Y. Martin, H. K. Wickramasinghe (1987)

Friction Force Microscopy (FFM or LFM)

--- C. M. Mate et al (1987)

Electrostatic Force Microscopy (EFM)

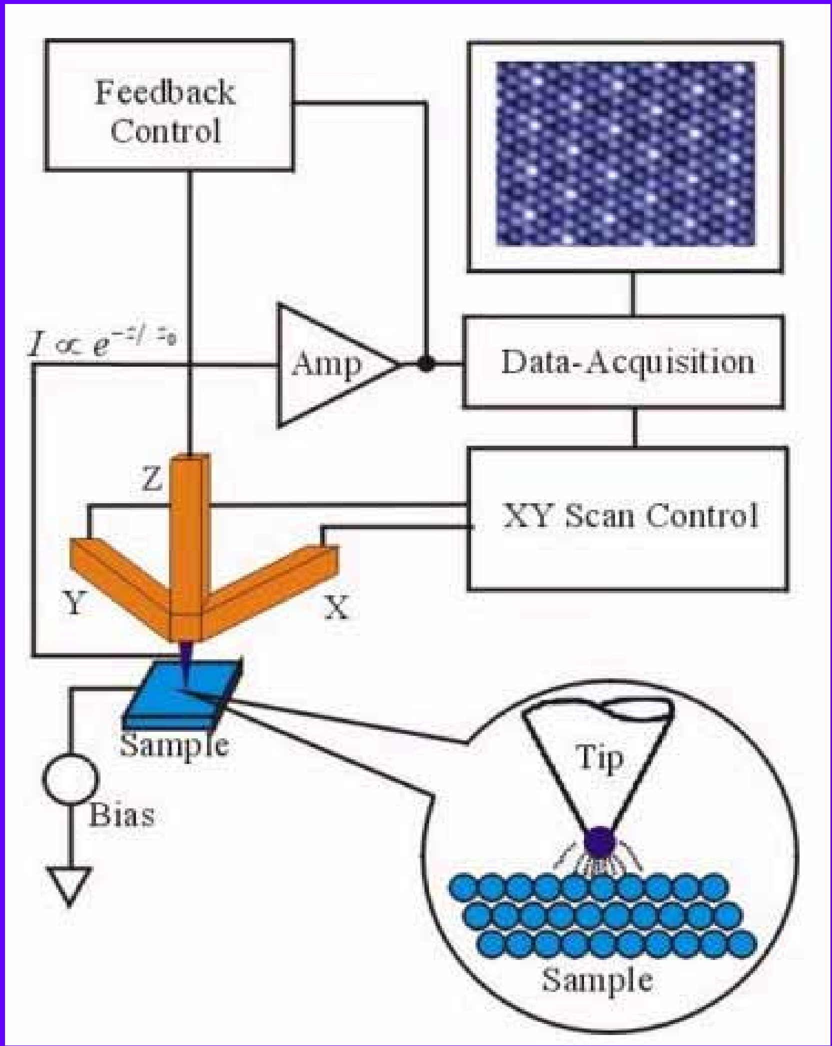
--- Y. Martin, D. W. Abraham et al (1988)

Scanning Capacitance Microscopy (SCM)

--- C. C. Williams, J. Slinkman et al (1989)

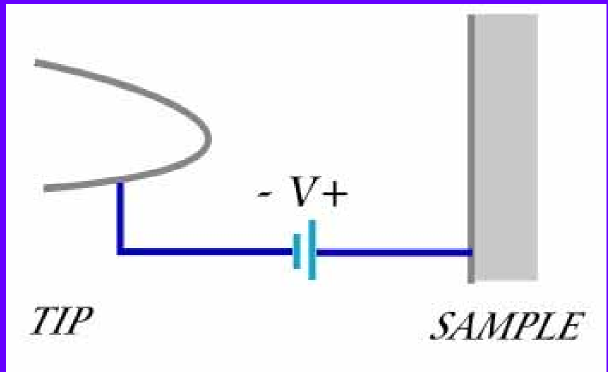
Force Modulation Microscopy (FMM)

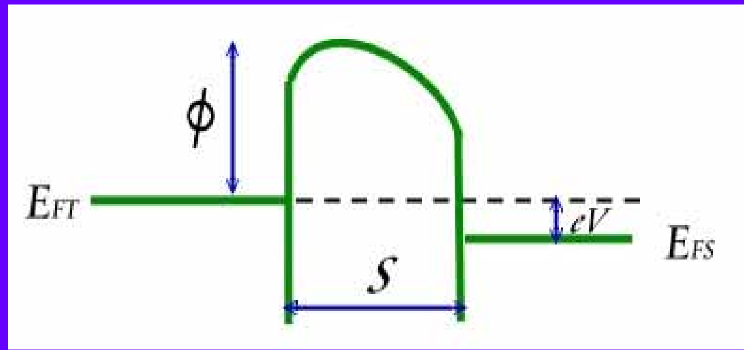
--- P. Maivald et al (1991)



掃描穿隧顯微儀 (Scanning Tunneling Microscopy)

Theory of STM

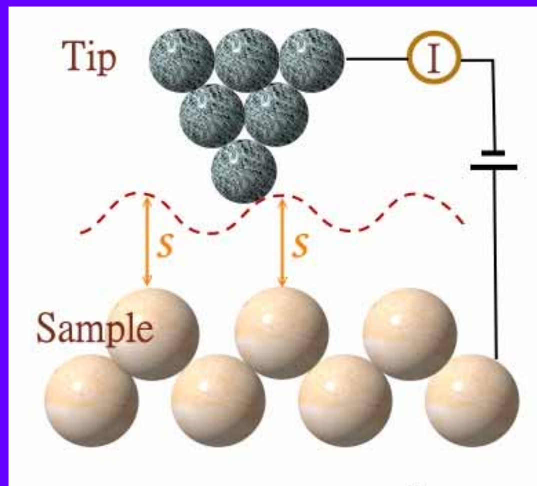




From one-dimensional tunneling problem tunneling current (eV<< ϕ)

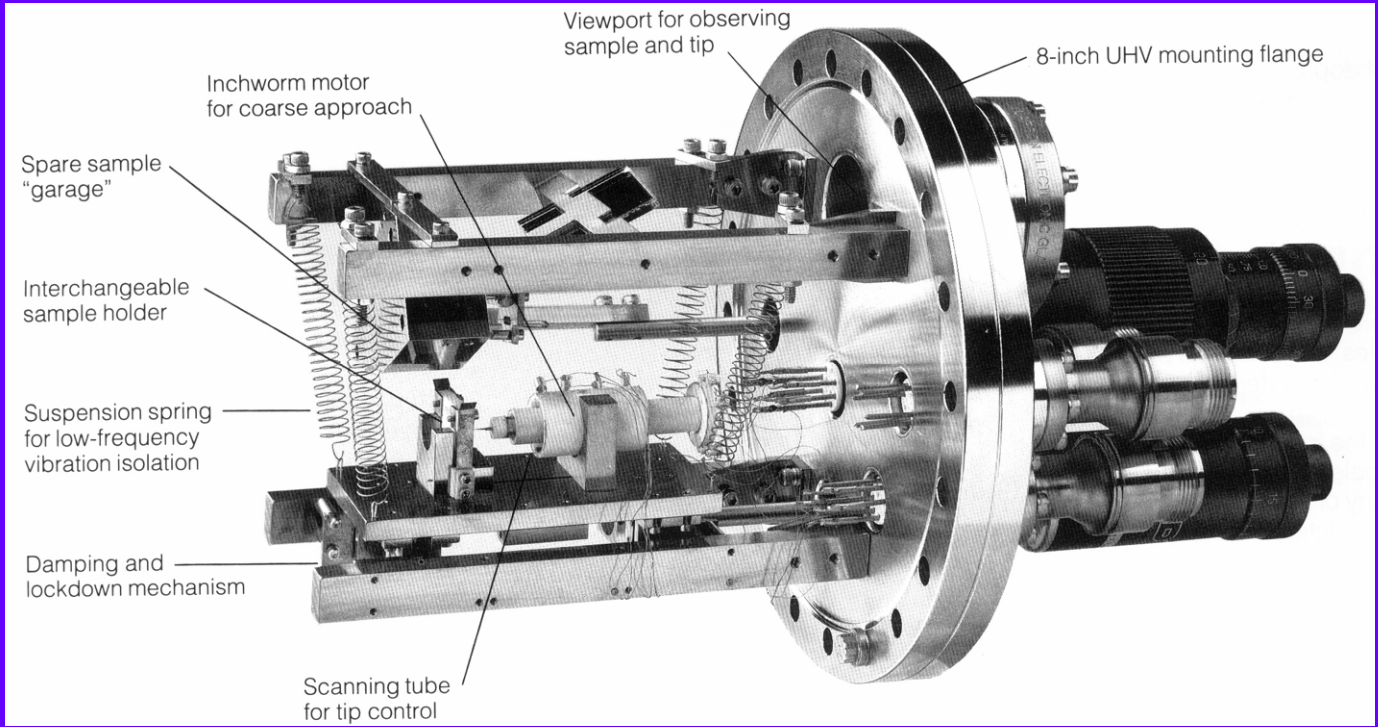
$$I \propto \frac{V}{S} \exp\left(-A\phi^{\frac{1}{2}} S \right)$$

$$A = 1.025\ (eV)^{-0.5}\ \text{Å}^{-1}$$



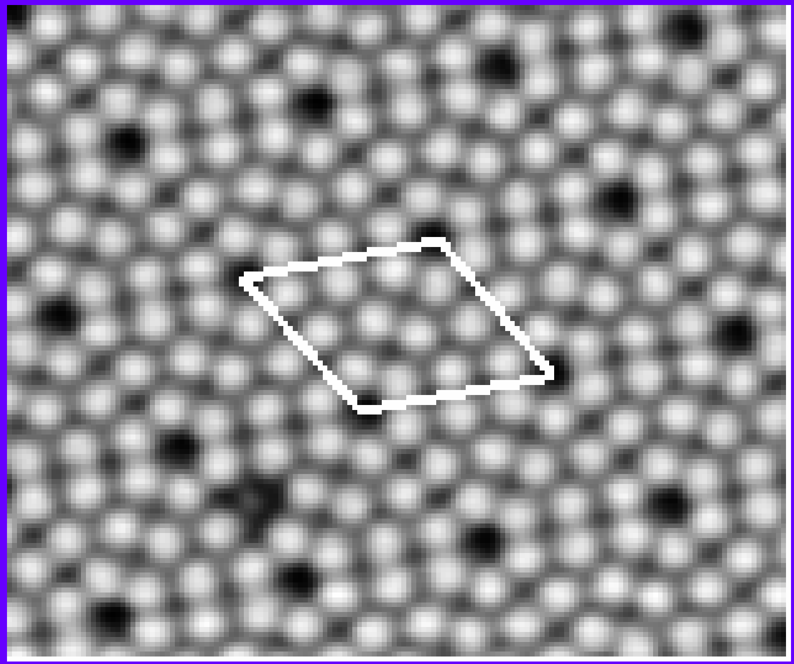
Constant Current Mode

UHV STM

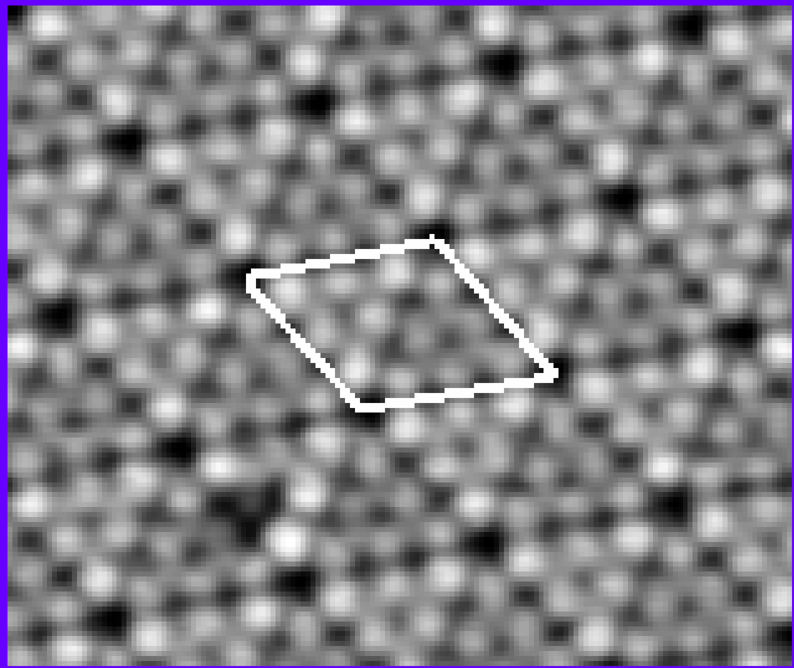


Viewport for observing
sample and tip
8-inch UHV mounting flange
Inchworm motor
for coarse approach
Spare sample
"garage"
Interchangeable
sample holder
Suspension spring
for low-frequency
vibration isolation
Damping and
lockdown mechanism
Scanning tube
for tip control

STM Images of Si(111)-(7×7)



Empty-state image



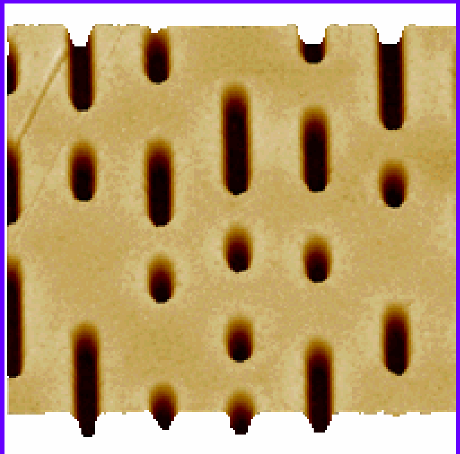
Filled-state image

原子力顯微術
(Atomic Force Microscopy, AFM)

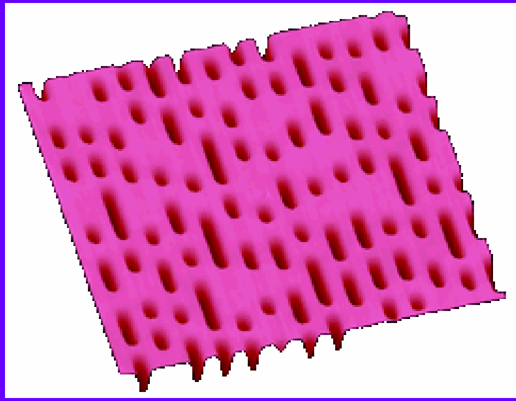
- 探針一般由成份為Si或SiN_4懸臂樑及針尖組成，尖端直徑20至100nm，藉著針尖與樣品間的原子作用力，使懸臂樑產生位移，而測得表面結構形狀，具有原子解析度。光偏折為最常用之距離控制機制。
- 操作上分接觸式(DC式)、非接觸式及暫接觸式(AC式)。
- 應用於奈米級表面形狀量測，粗糙度分析、生醫樣品檢測等。

AFM images

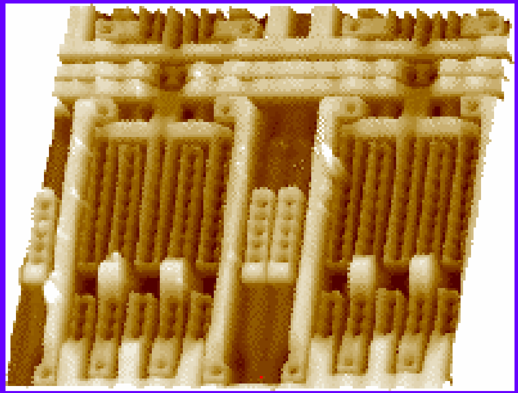
CD pits



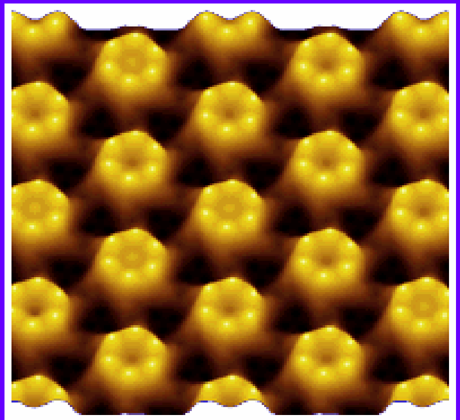
DVD pits



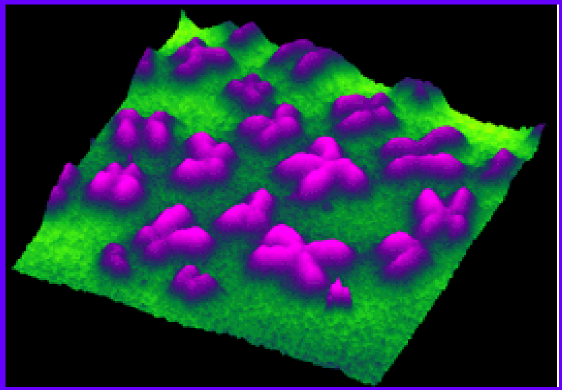
Integrated Circuit



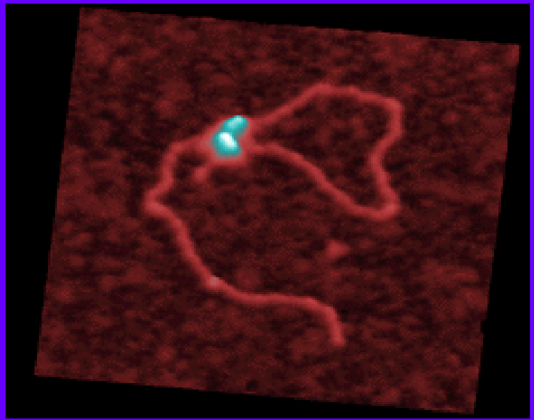
Bacteria



Chromosomes



DNA

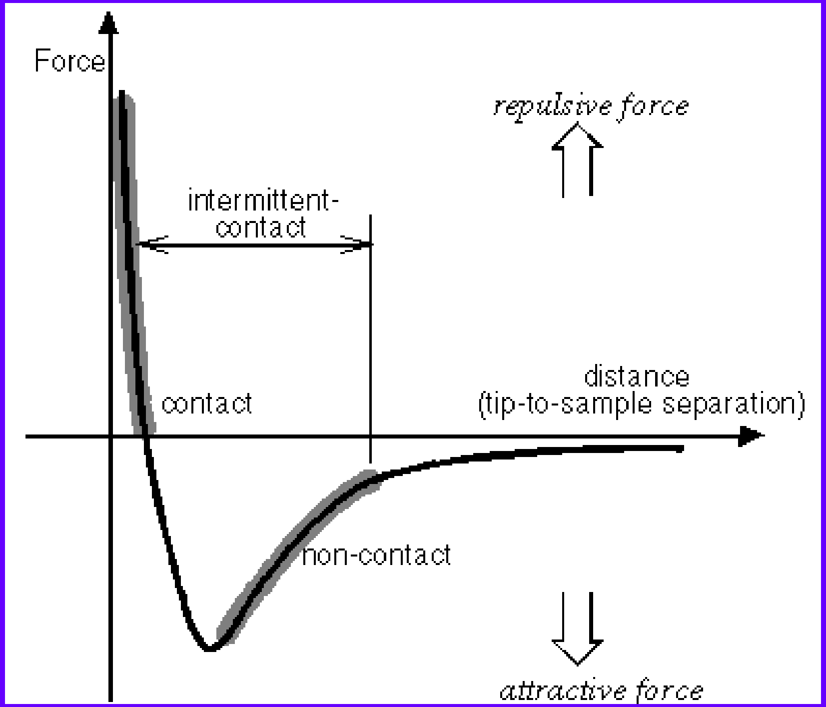


Probe/sample interaction as function of distance

短程力：

1) 鍵結力

2) 排斥力



長程力：

1) 范德瓦力

2) 毛細作用力

3) 磁力

4) 靜電力

Lennard-Jones potential $\phi(r) = -A/r^6 + B/r^{12}$

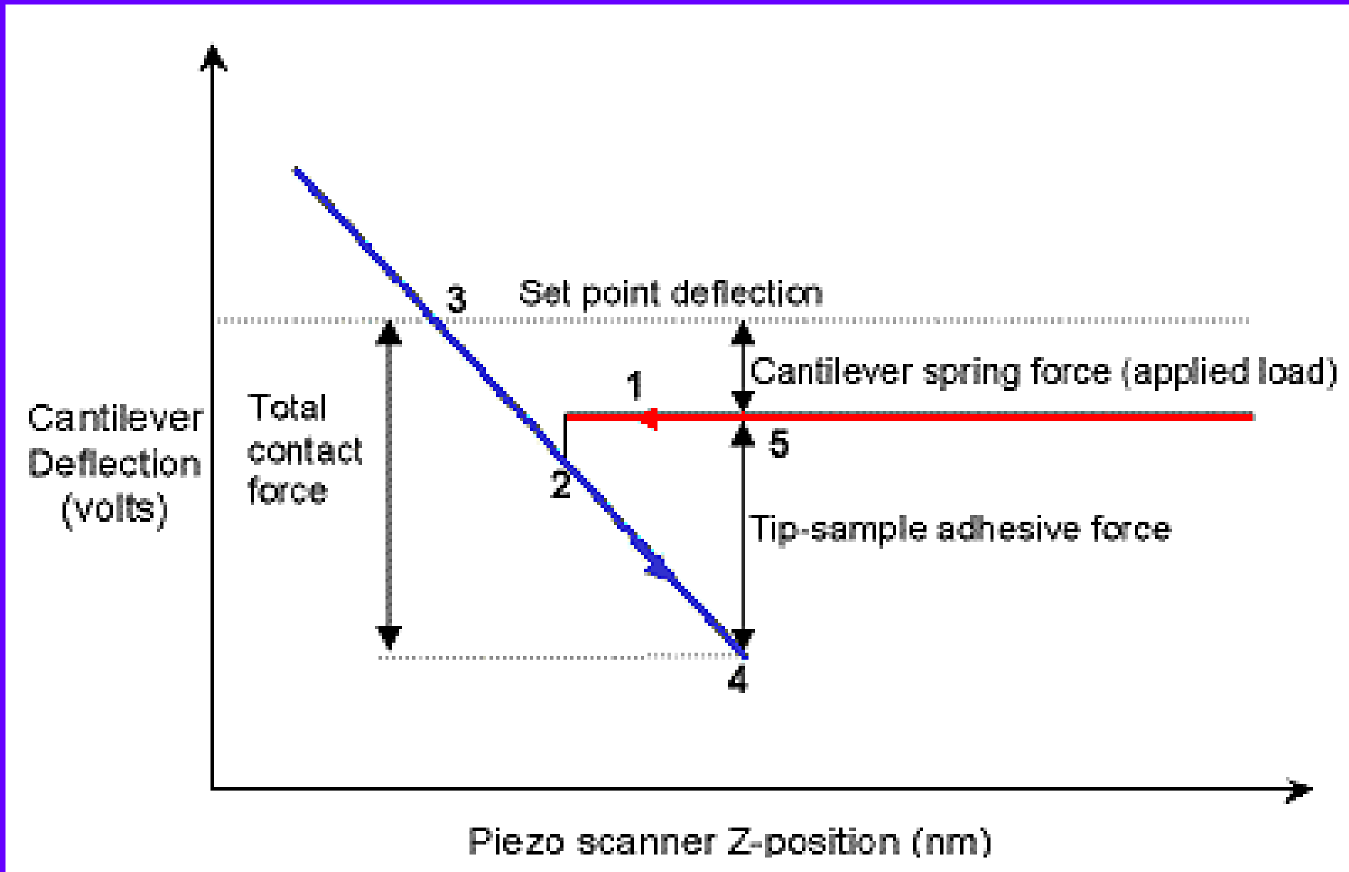
幾種力的起源

- 排斥力：
  1) Pauli 不相容原理；
  2) 原子核間庫倫排斥力。

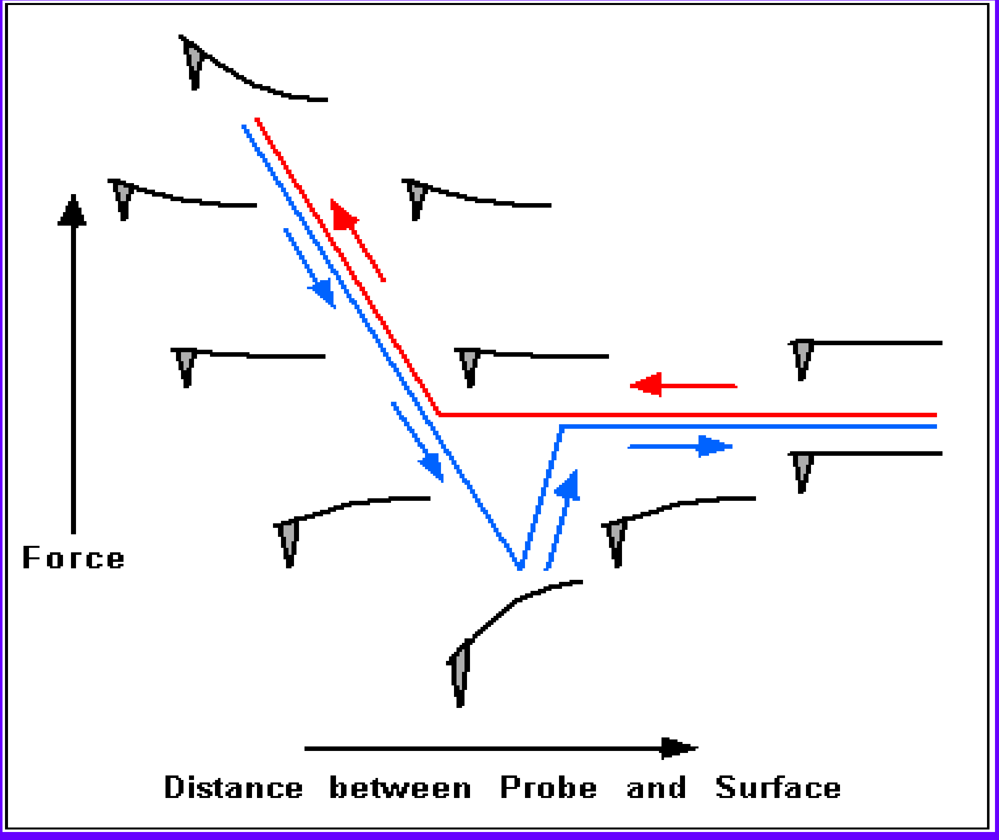
- 范德瓦力：
  主要是由電偶矩間的作用產生的。

- 毛細作用力：
  主要是由於水膜在探針和樣品間形成所造成的。

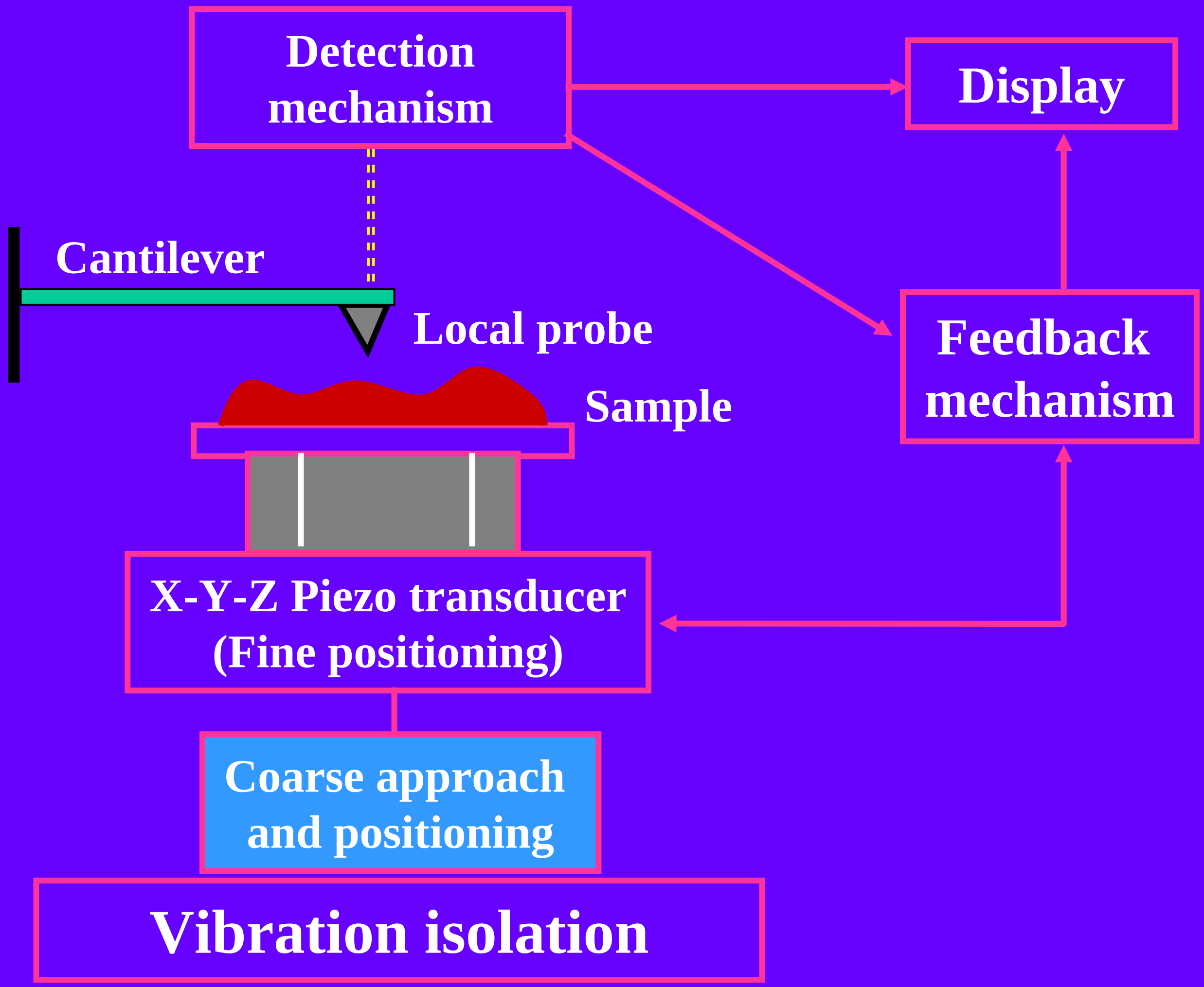
探針偏移與其位移的關係



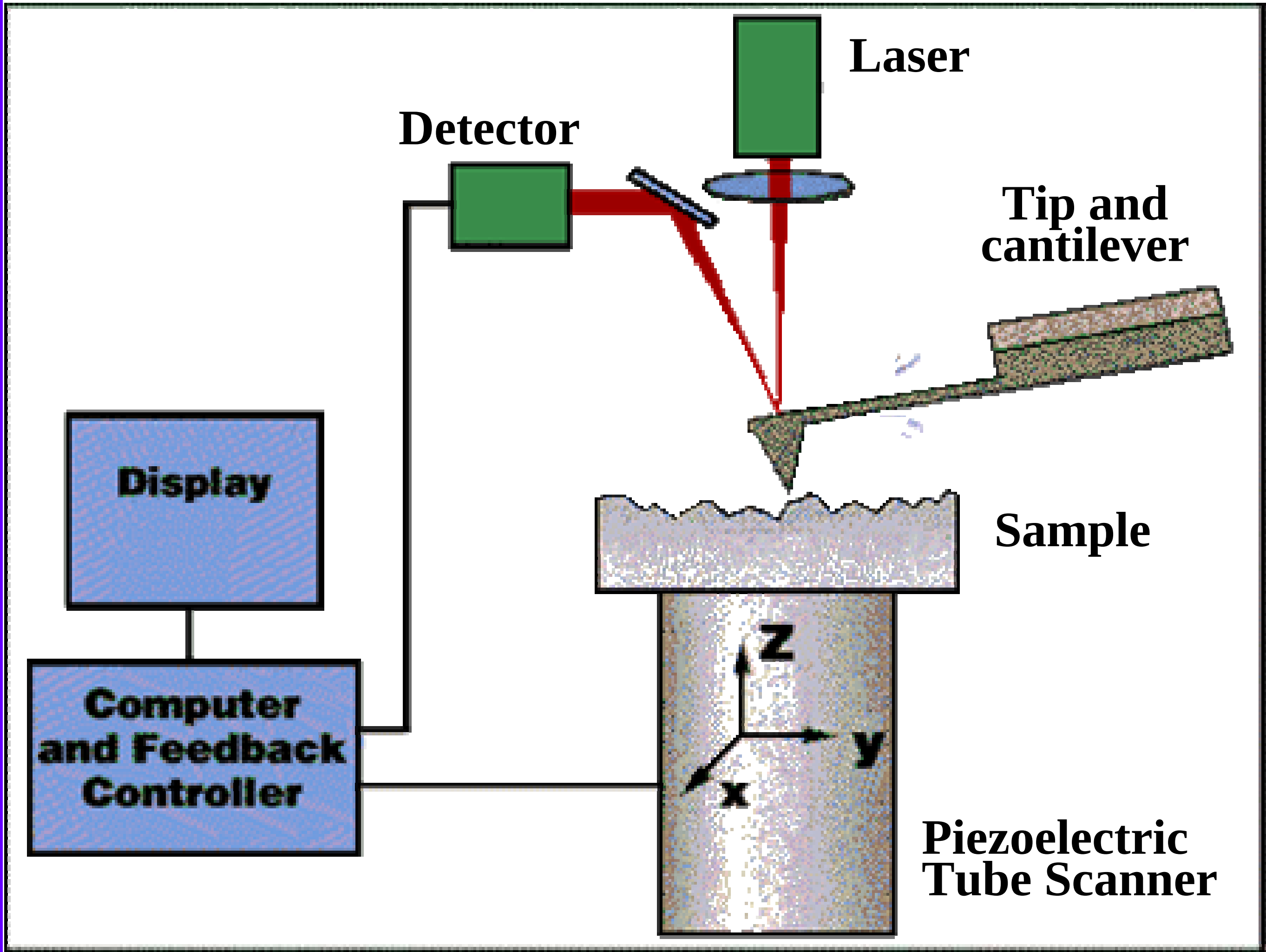
Reaction of probe to the force



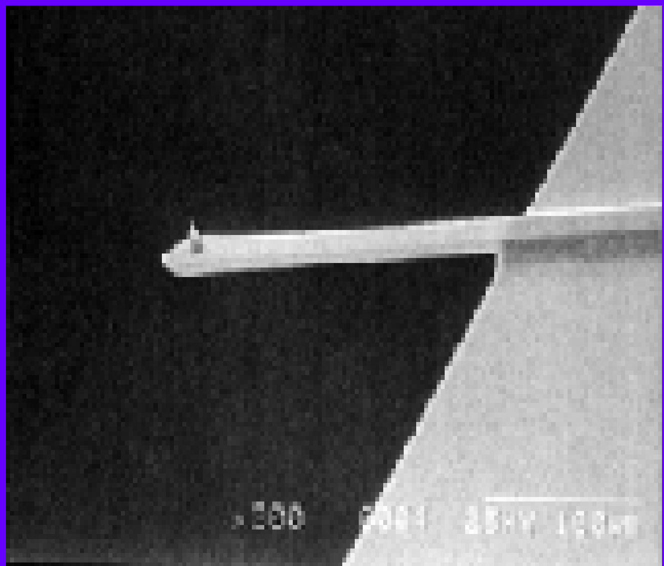
Basic configuration of AFM

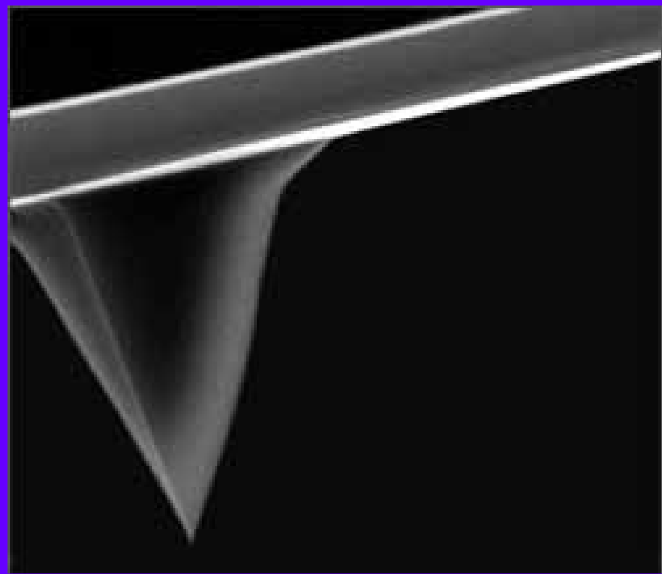


Core components of an AFM

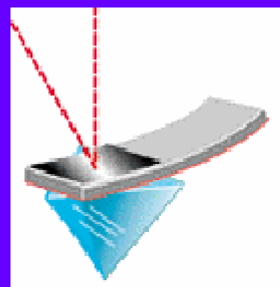


Probes for the tapping mode





Typical Tip Dimension:
150μm x 30μm x 3μm
f_r ~ 100 kHz
Materials: Si



掃描探針顯微術的重要性

一般而言，奈米技術所涉及的尺寸是在100 nm以下到原子尺度(0.2 ~ 0.3 nm)，因此對於量測儀器的準確度要求也相對地日趨嚴苛。掃描探針顯微鏡（Scanning Probe Microscope，SPM）是在80年代所發展的一種材料表面特性檢測儀器之總稱，主要用來觀察材料表面的各種特性。由於其檢測的解析度可以達到奈米或甚至原子級的程度，且可在大氣環境下進行檢測，並且提供操縱能力，故其應用領域不斷地擴大。

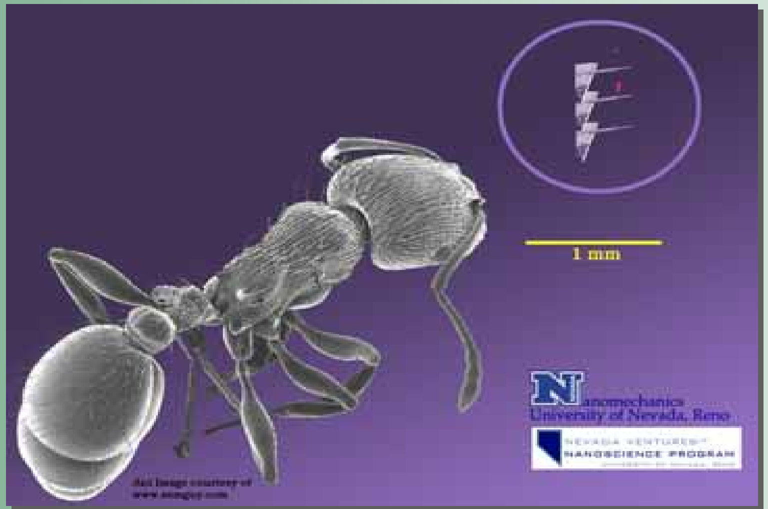
常用顯微術性能比較表

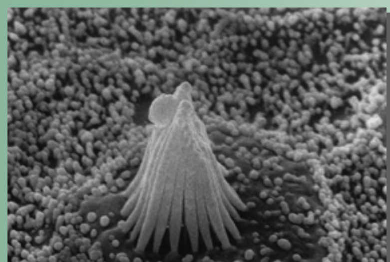
	光學顯微術（OM）	掃描電子顯微術（SEM）	穿透電子顯微術（TEM）	掃描探針顯微術（SPM）
橫向解析	300奈米	1奈米	原子級	原子級
縱向解析	20奈米	10奈米	無	原子級
成像範圍	1毫米	1毫米	0.1毫米	0.1毫米
成像環境	無限制	真空	真空	無限制
樣品準備	無	鍍導電膜	手續繁複	無
成份分析	有	有	有	無

Molecular Scale Nanomechanics
Driving Force in Bio-systems

At the fundamental level, all interactions in biology and chemistry are mechanical in nature

Mechanical Sensing in Nature

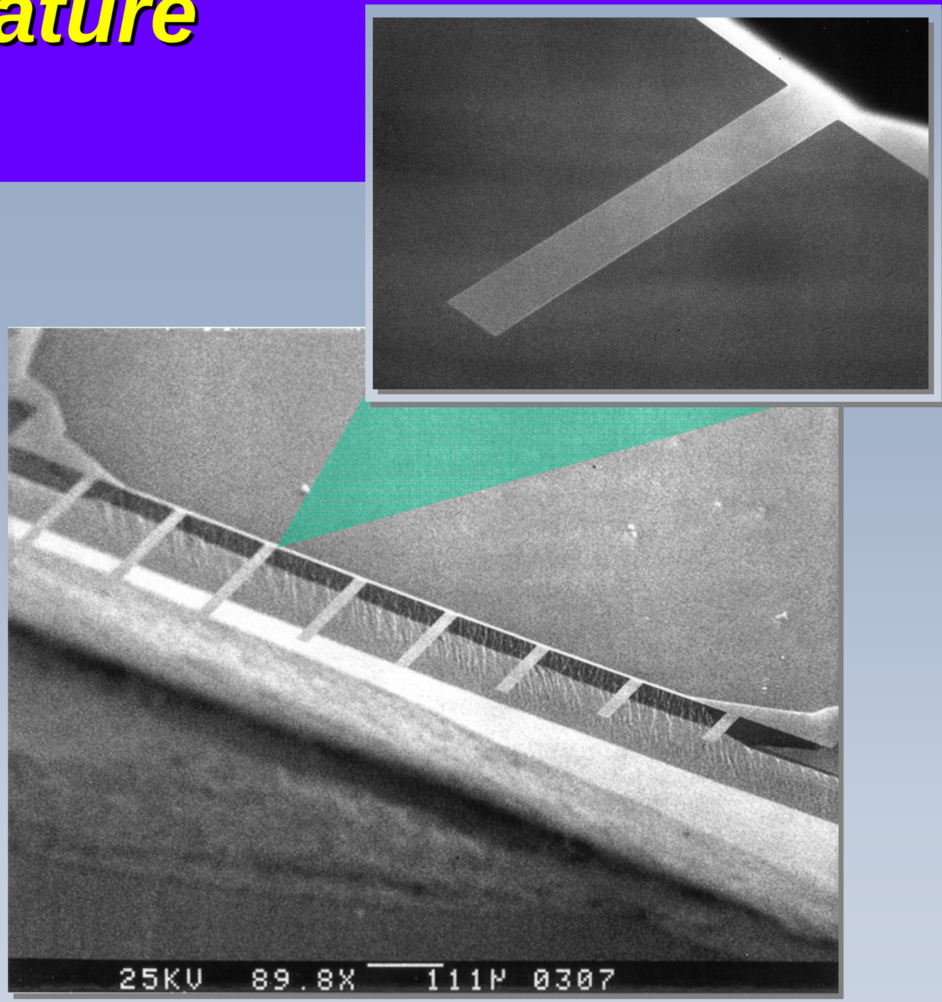




Hair bundle: frog's inner ear

Micro and Nano cantilever arrays - *Emulating nature*

- **Ideal displacement sensor**
  - **Sub nm sensitivity**
- **Displacement ~ force**
- **Surface stress, temperature**
- **Mass loading**



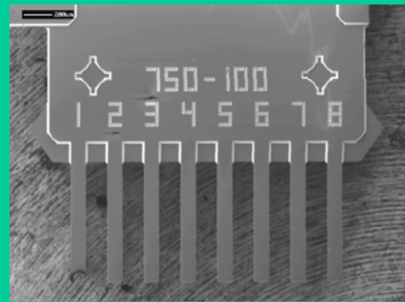
Sesitivity:
Function of dimensions

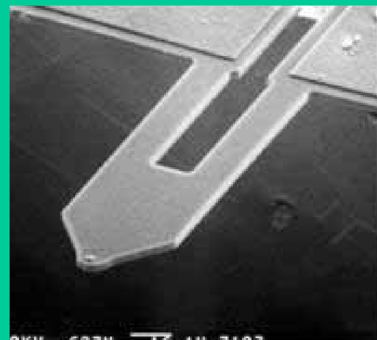
Selectivity:
Function of coatings

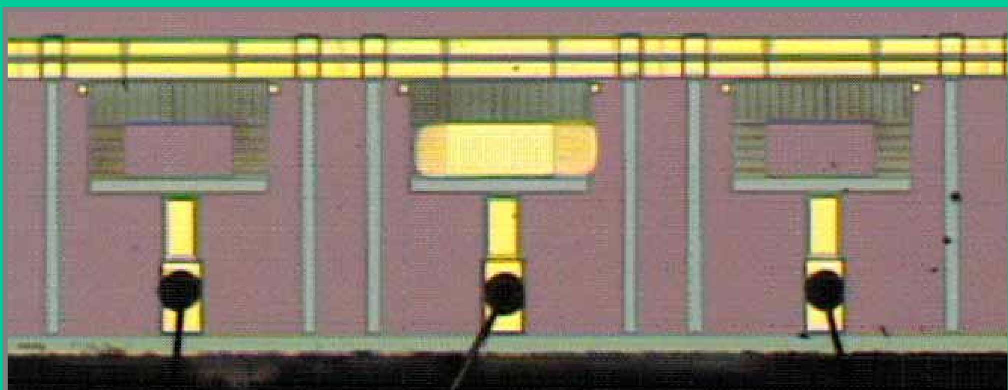
- **Mass production**

Microcantilevers:
Getting the signal out

- **Optical**
- **Piezoresistivity**
- **Piezoelectricity**
- **Capacitance**



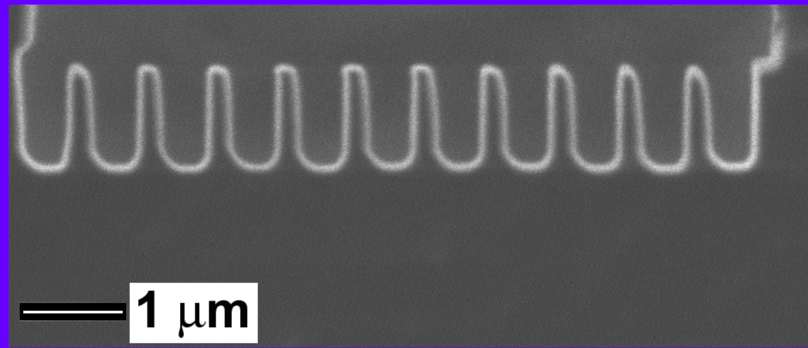


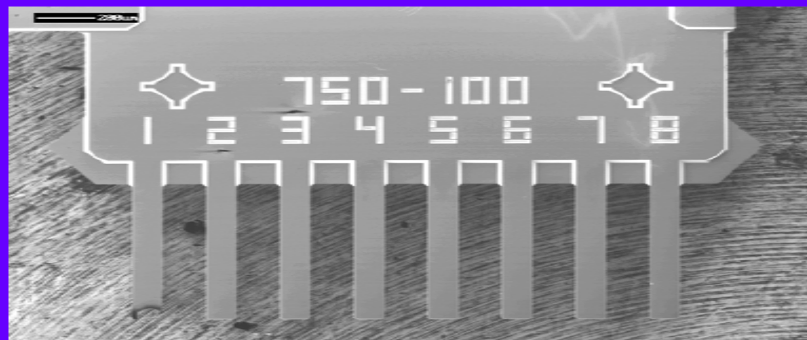


Microcantilevers To Nanocantilevers

- Increased Sensitivity
- High Resonance Frequency
- Small Spring Constants
- Single Molecule Detection

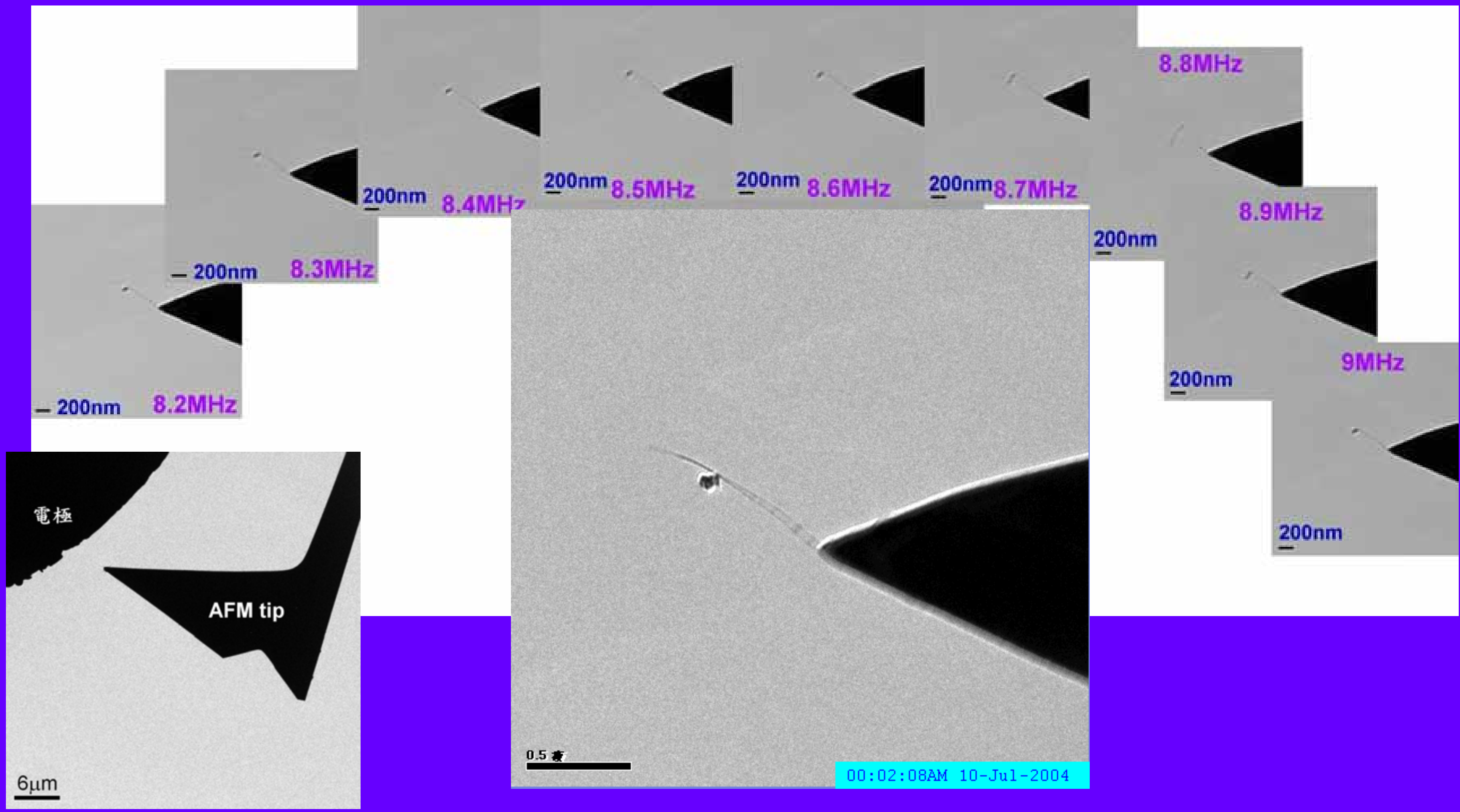
- Challenges:
  - Signal Transduction
  - Mass production



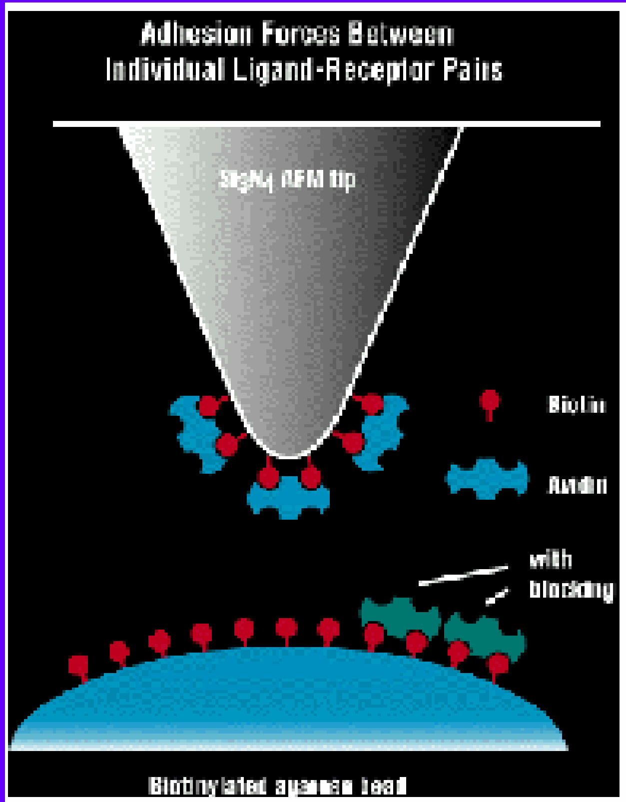


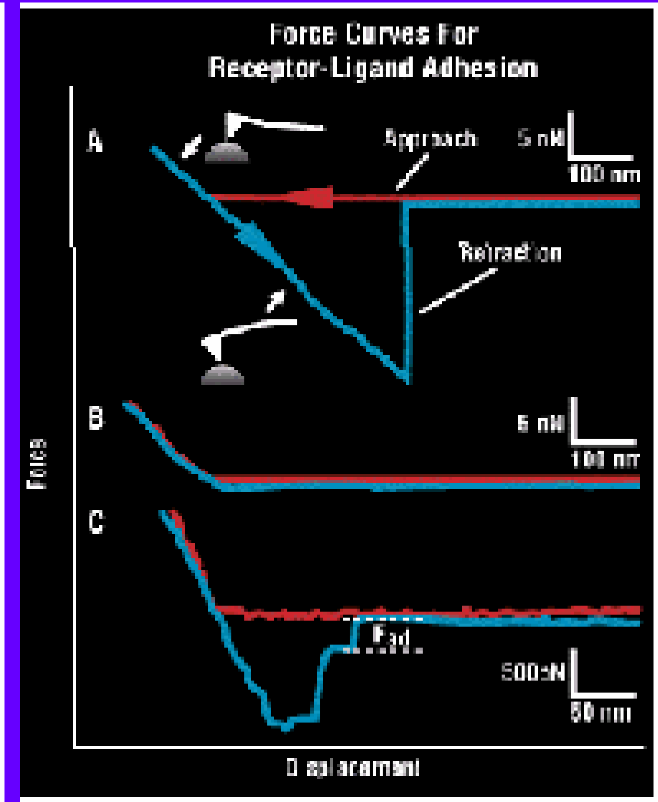
(Craig Prater, DI)

Nanoelectromechanical oscillator

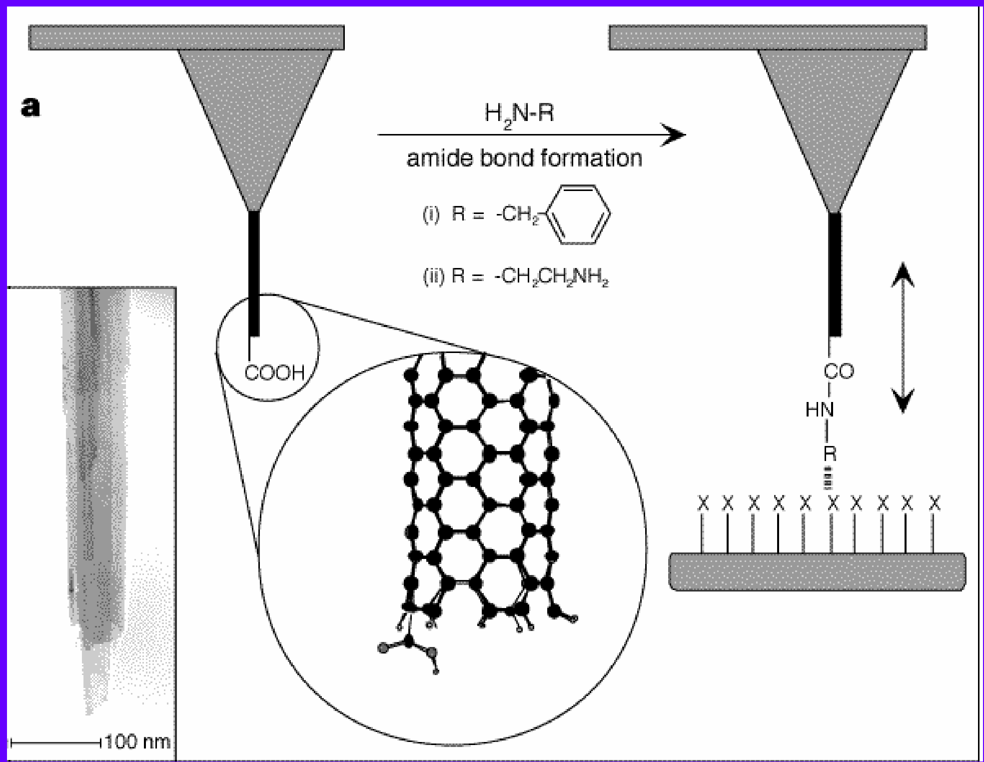


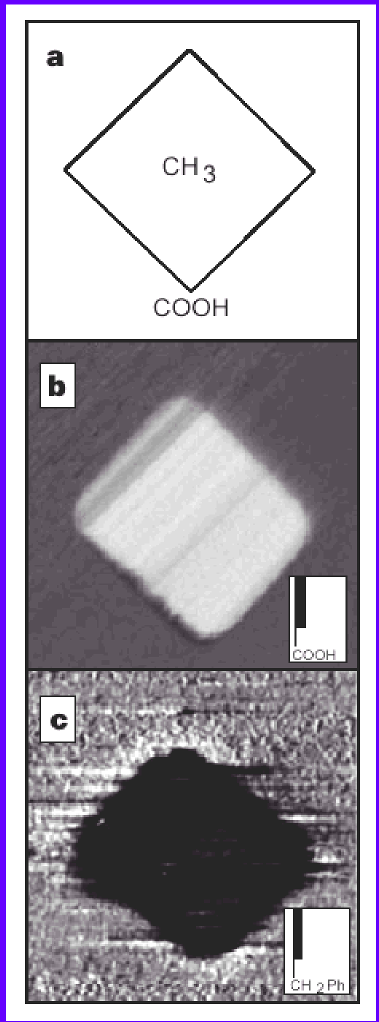
Molecular sensing





Chemical nanoprobe



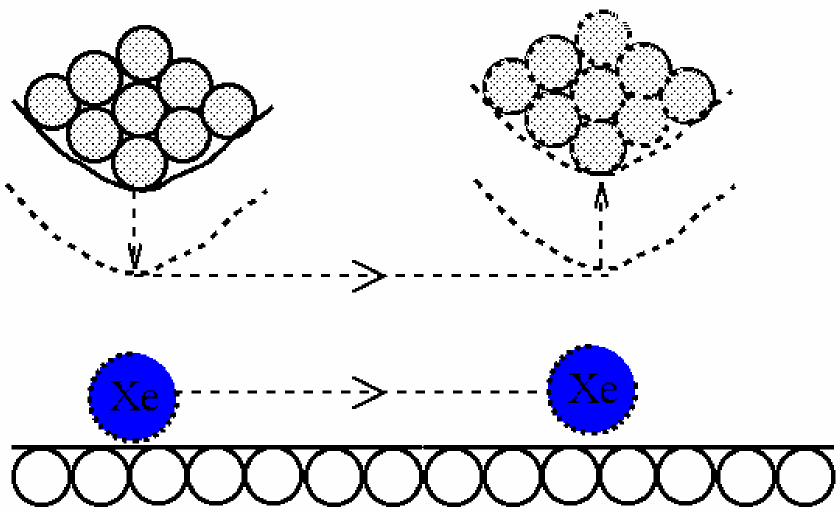


S. S. Wong *et al., Nature* 394, 52 (1998).

Manipulation method

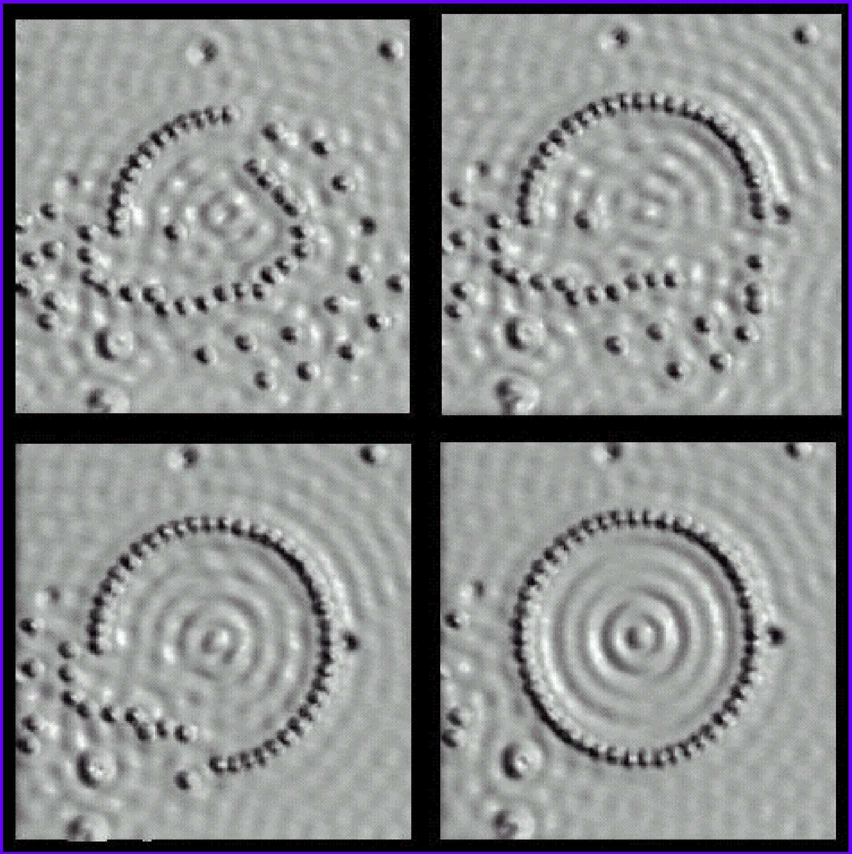
Positioning Atoms with an STM

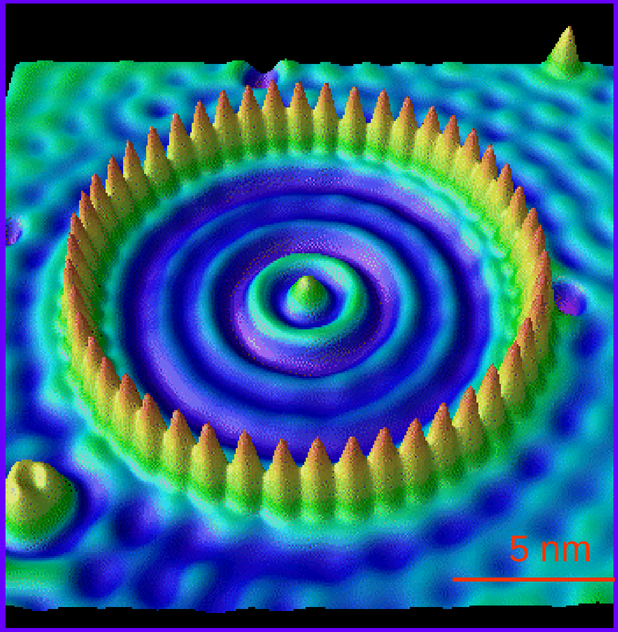
D.M. Eigler & E.K. Schweizer Nature **344** 524 (1990)



The STM tip is brought down near the atom, until the attraction is enough to hold it as the atom is dragged across the surface to a new position.

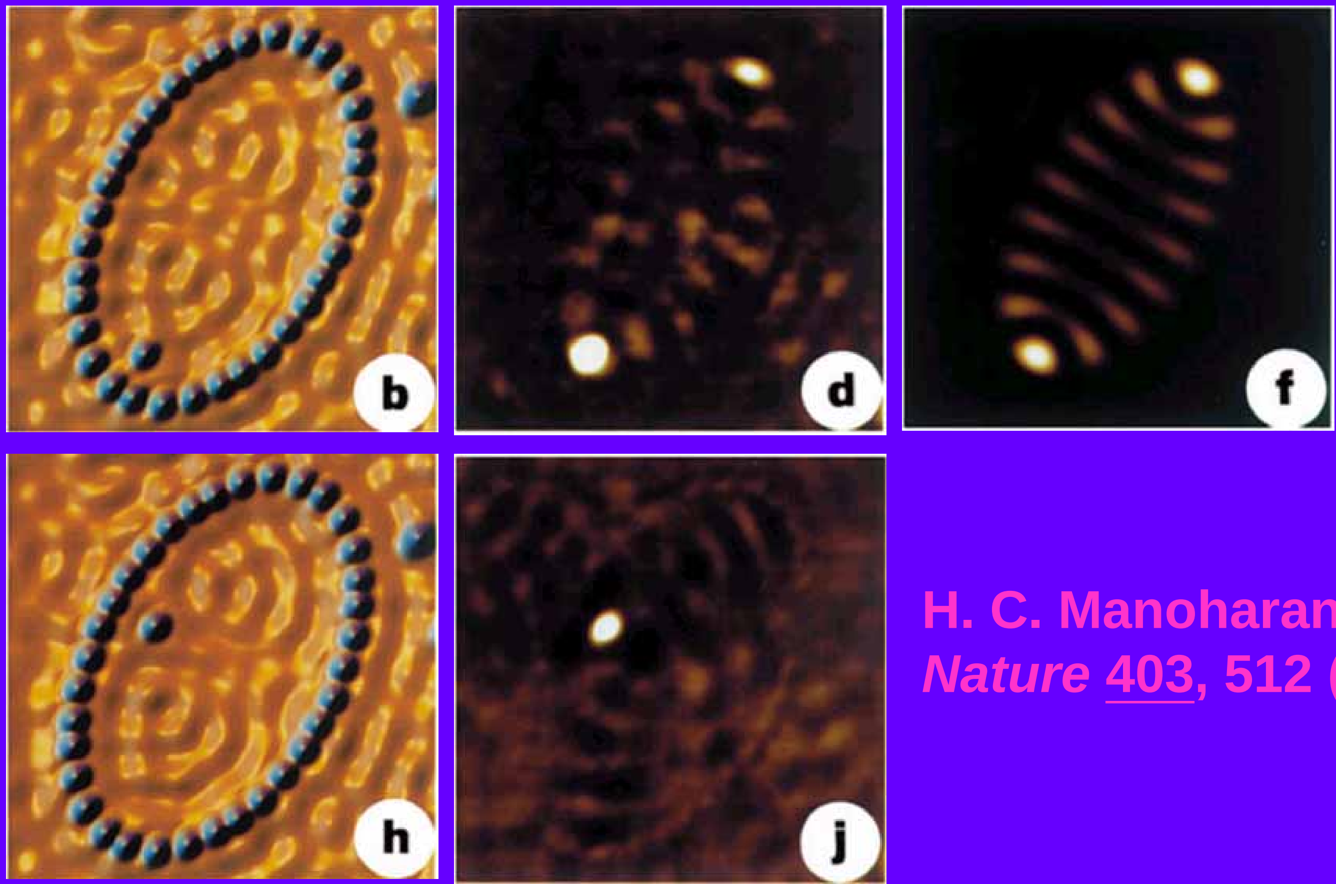
Ultimate goal of nanotechnology





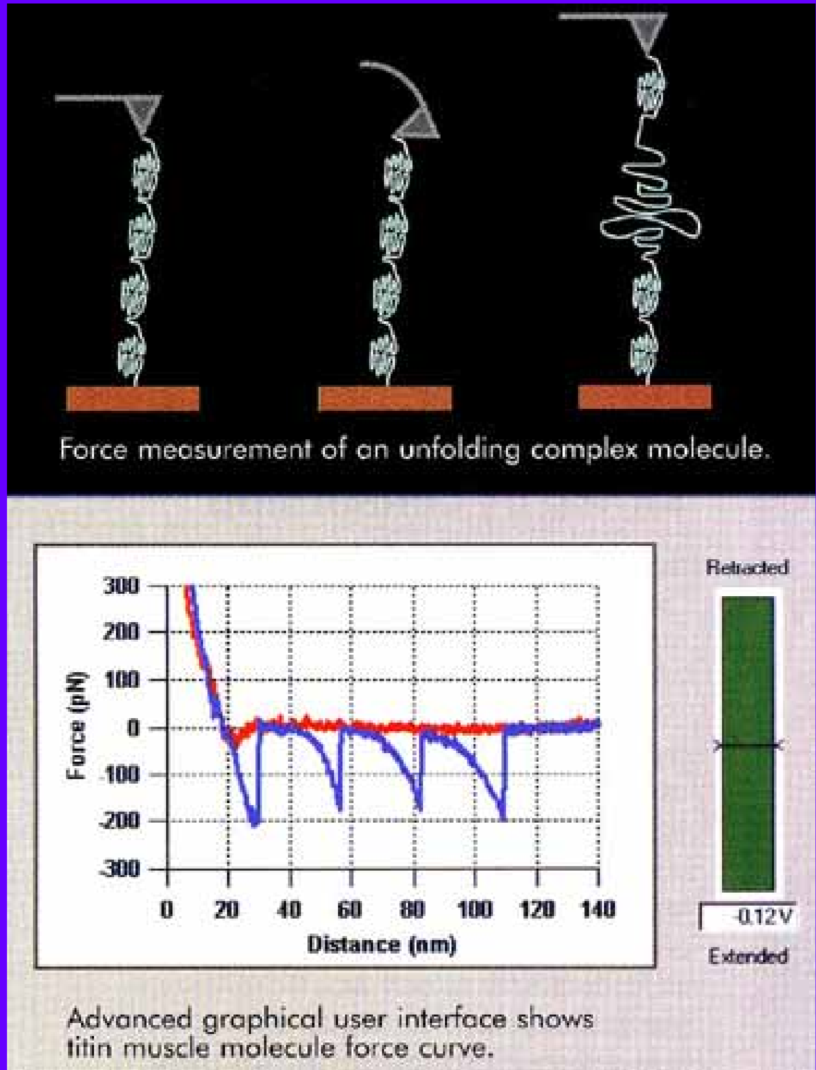
M.F. Crommie *et al.*, *Science* 262, 218 (1993).

Quantum Mirage

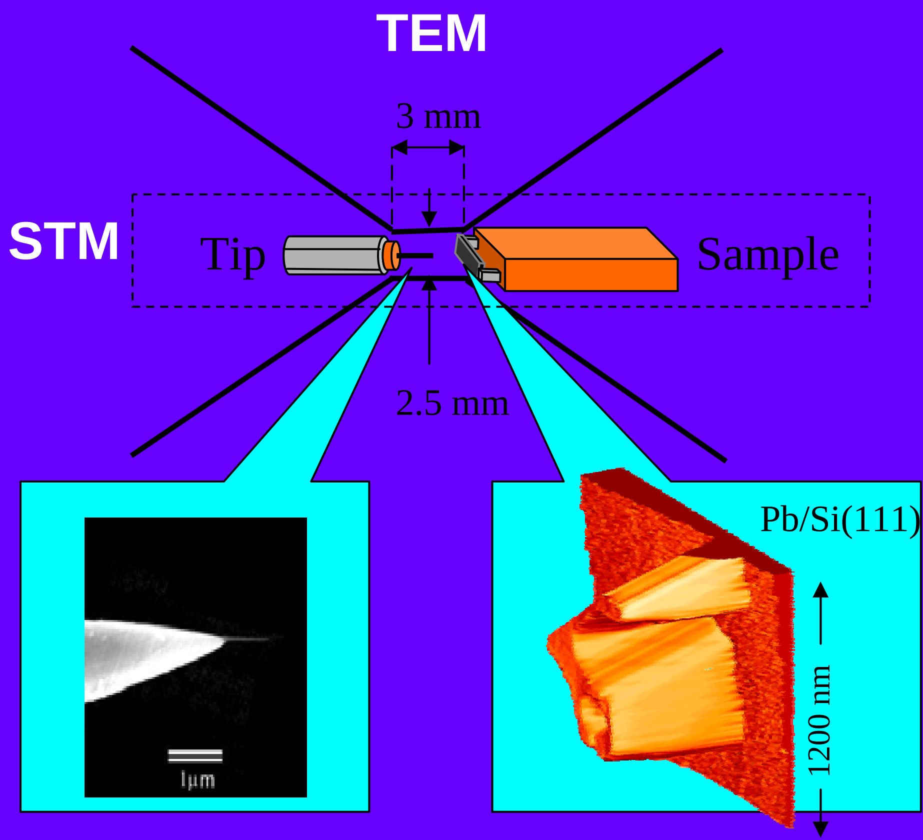


H. C. Manoharan *et al.*, *Nature* 403, 512 (2000).

Molecular unfolding



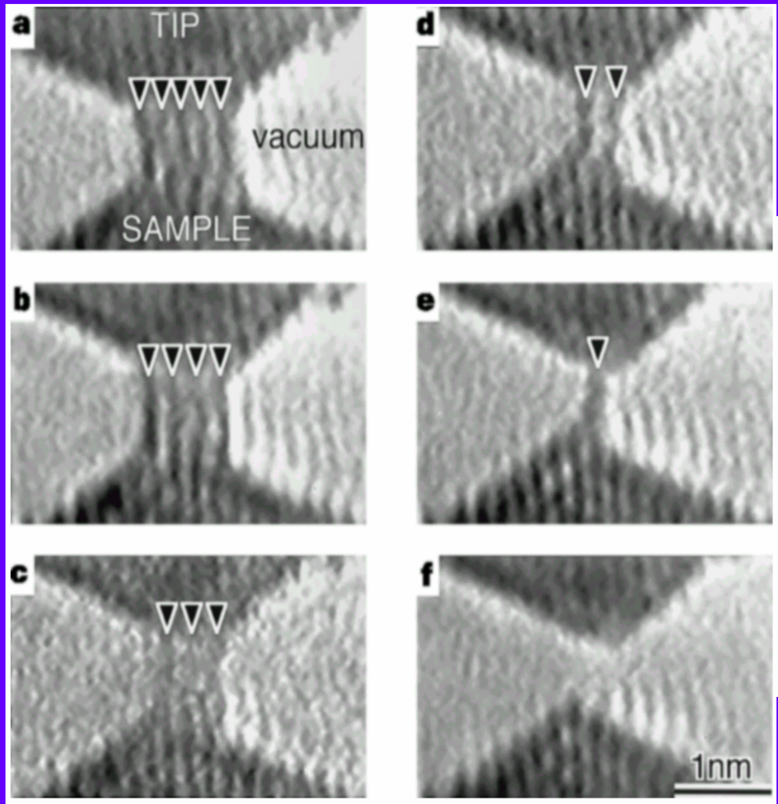
UHV HRTEM/STM

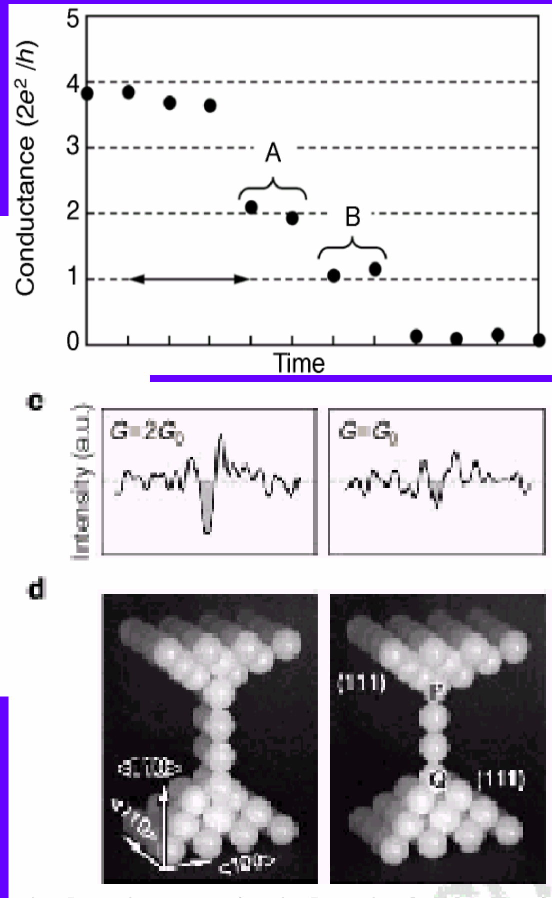


Tip with a nanotube

Mesa structure for holding the nano-object

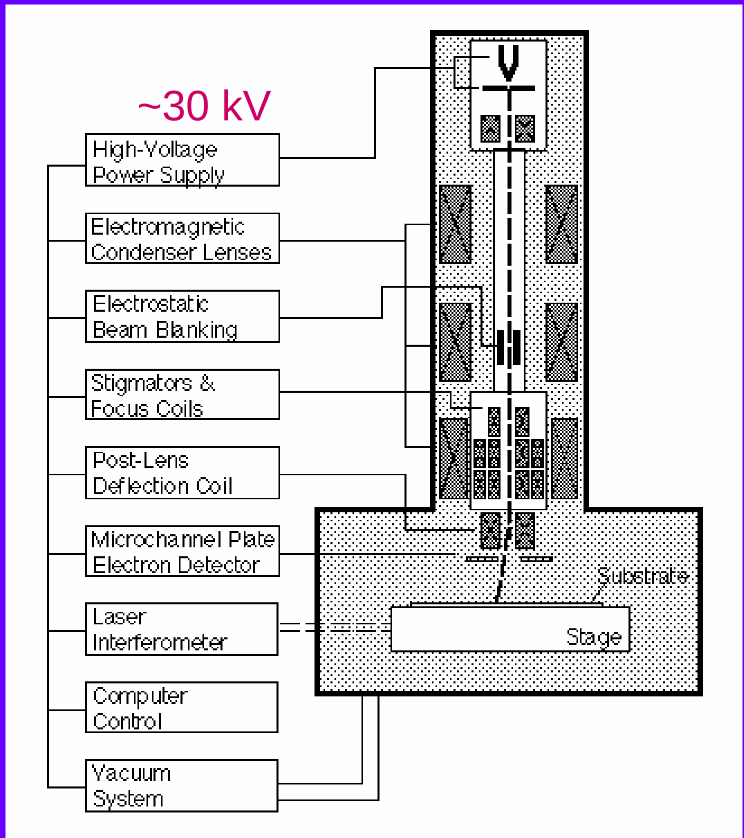
Point contact of Au wire

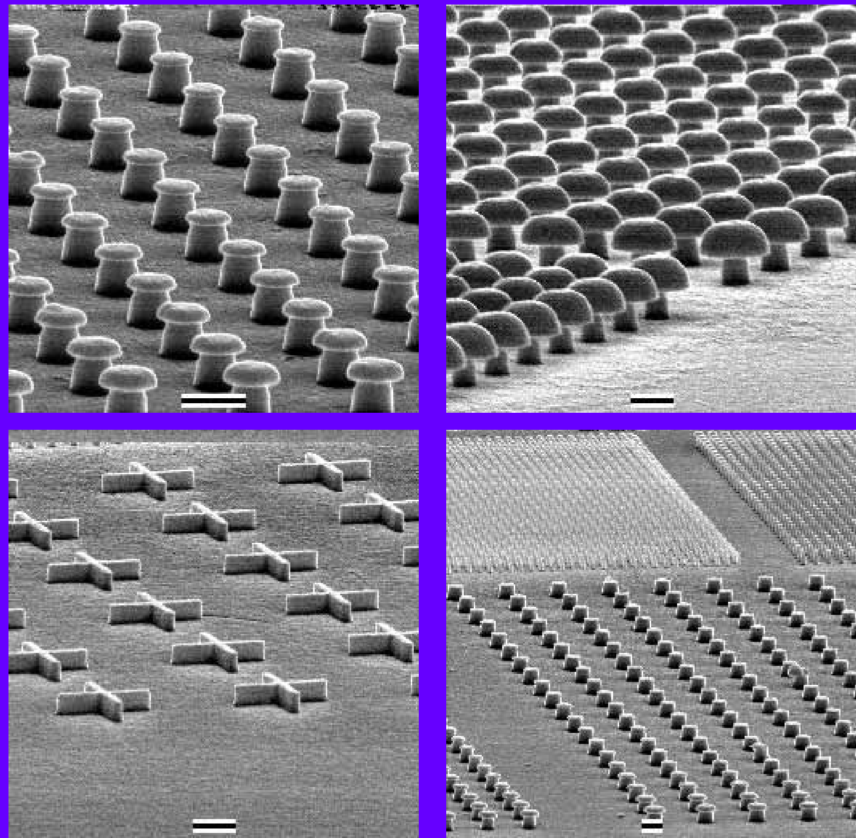




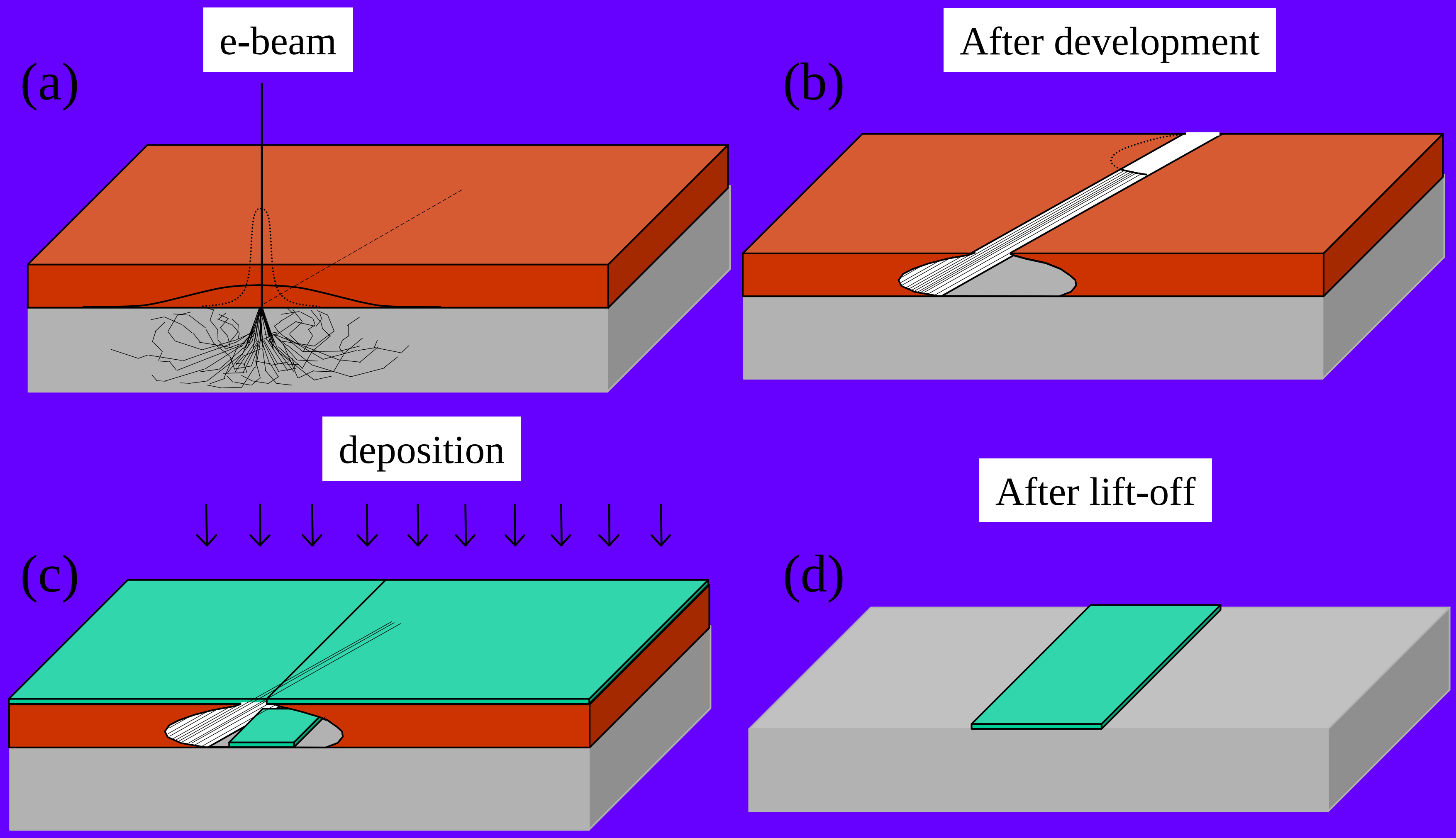
H. Ohnishi *et al.*
Nature 395, 780 (1998).

Periodic nanostructures by e-beam lithography

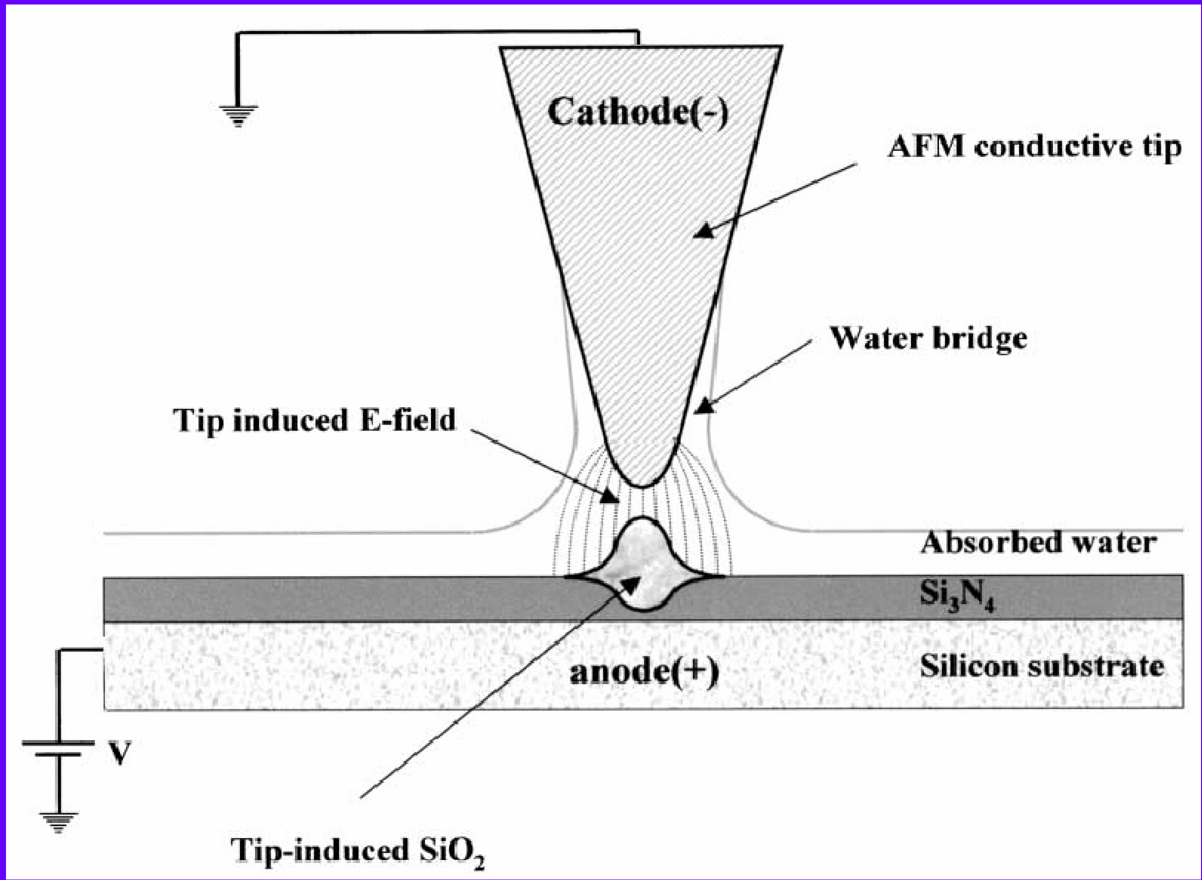




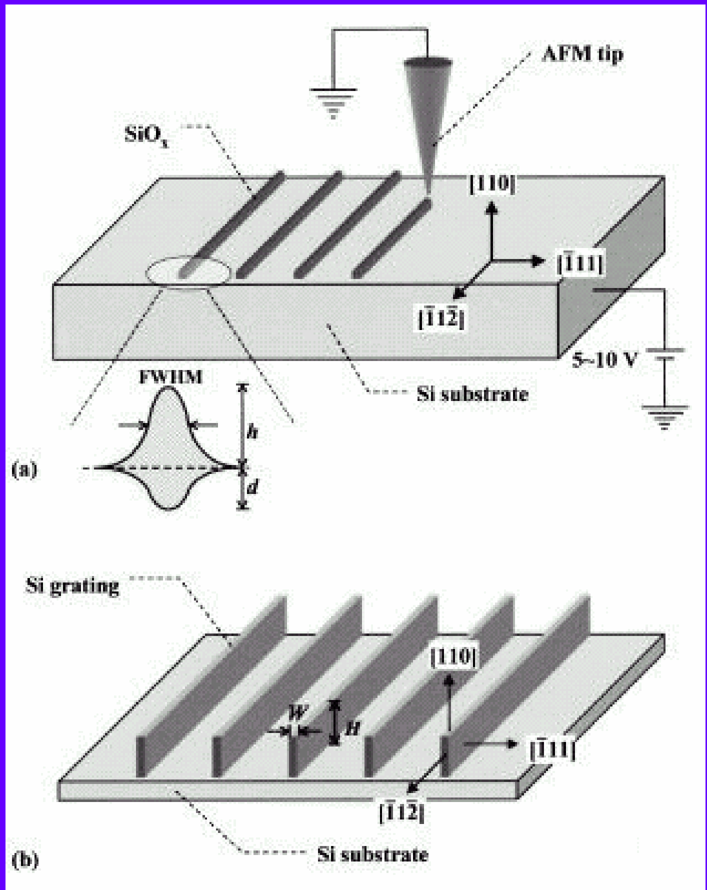
Procedures of e-beam lithography

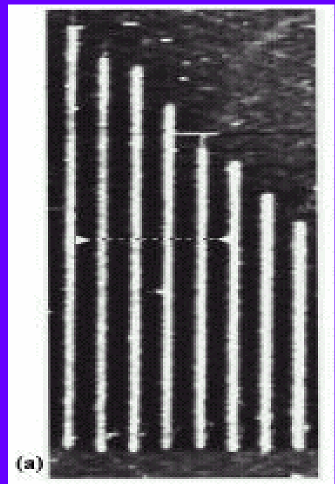


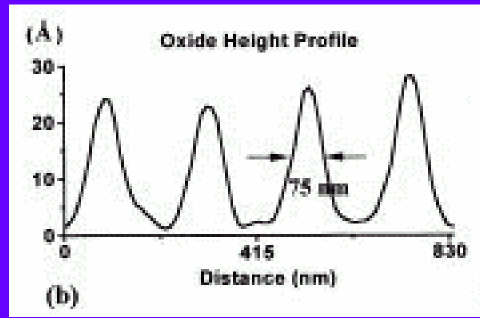
Nano-Lithography with an AFM tip



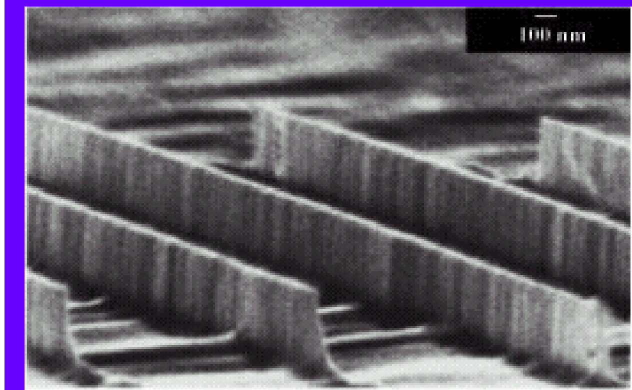
Electrical Lithography



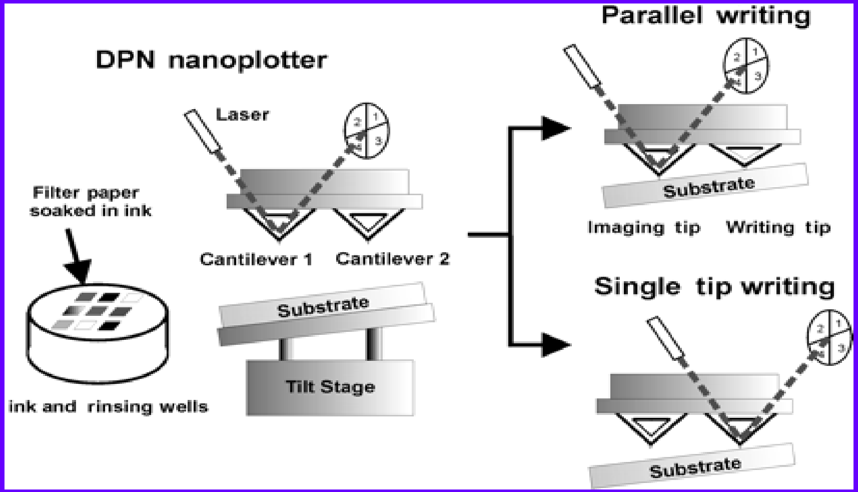


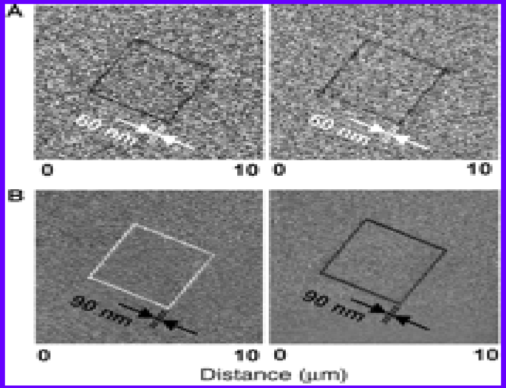


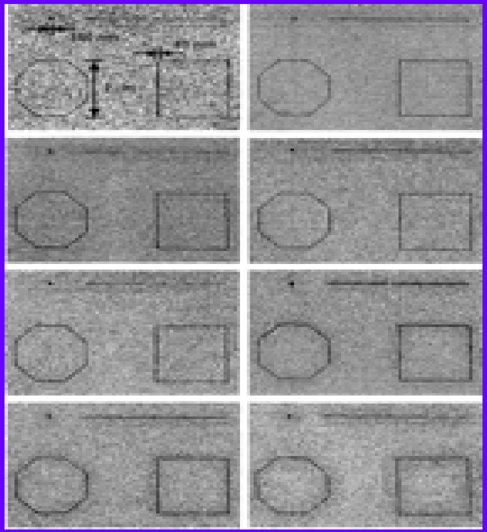
F.S.-S. Chien *et al*.
APL 75, 2429 (1999)



Nanoplotter

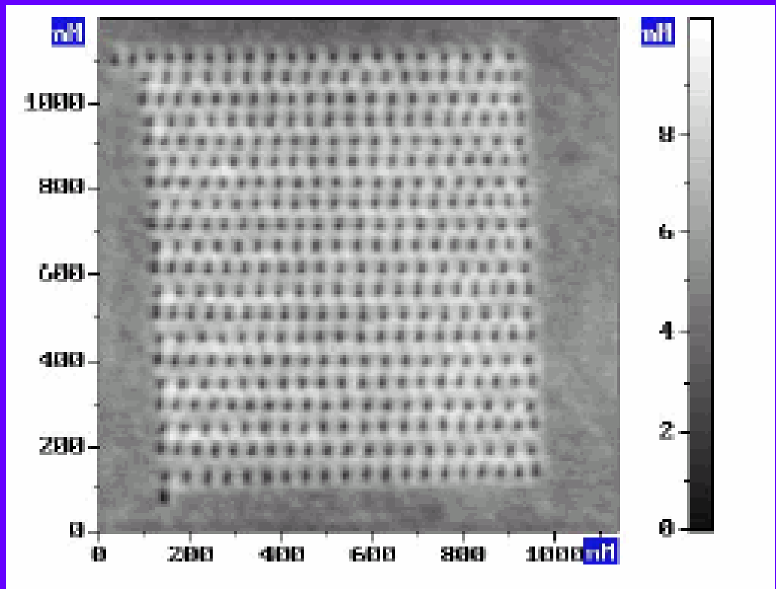


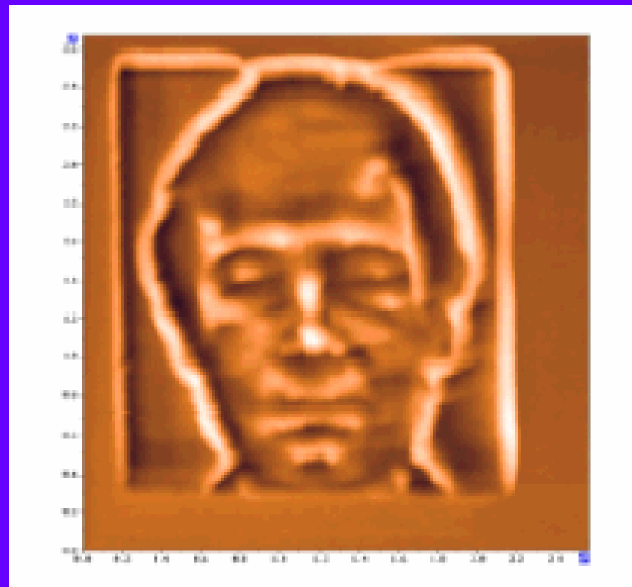




C.A. Mirkin *et al*.
Science 288, 1808 (2000)

Nanolithography of Tapping-Mode AFM

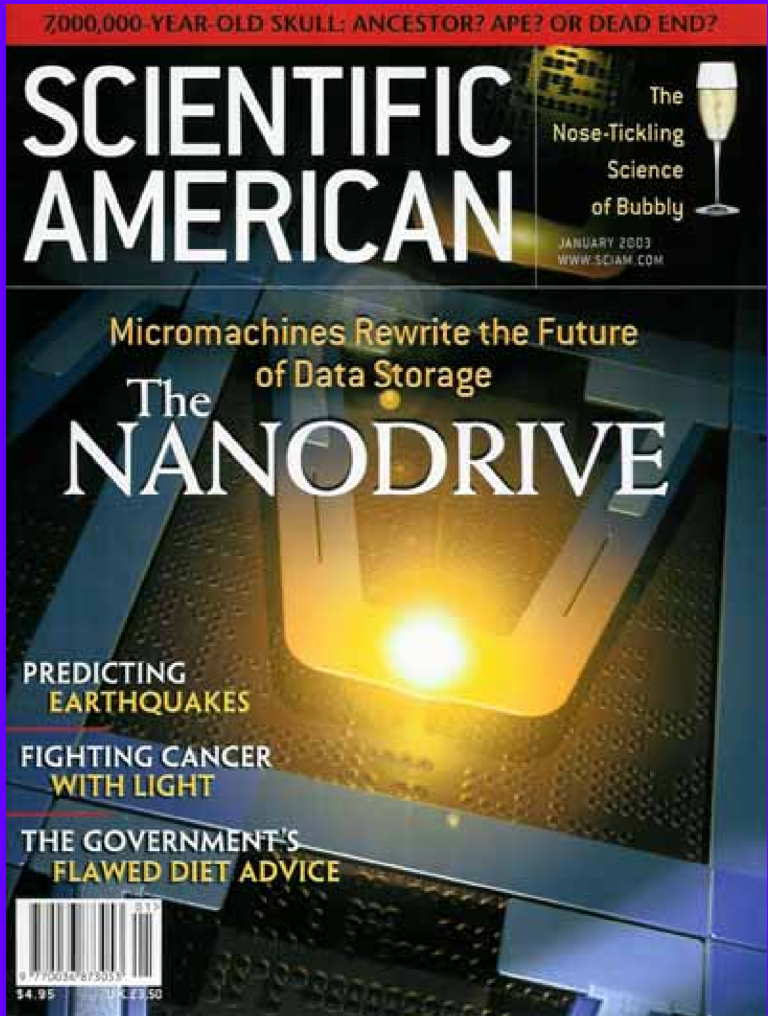




(1.2 μ m× 1.2 μ m) (2.5 μ m× 2.5 μ m)

Image of polycarbonate film on silicon surface

Nanodrive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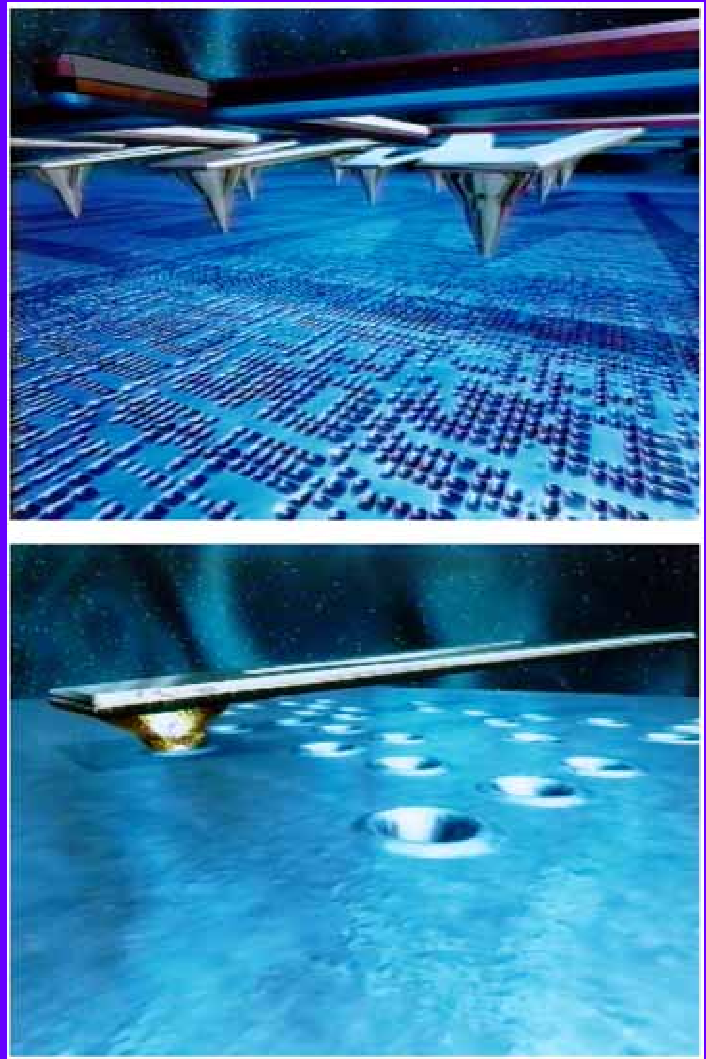
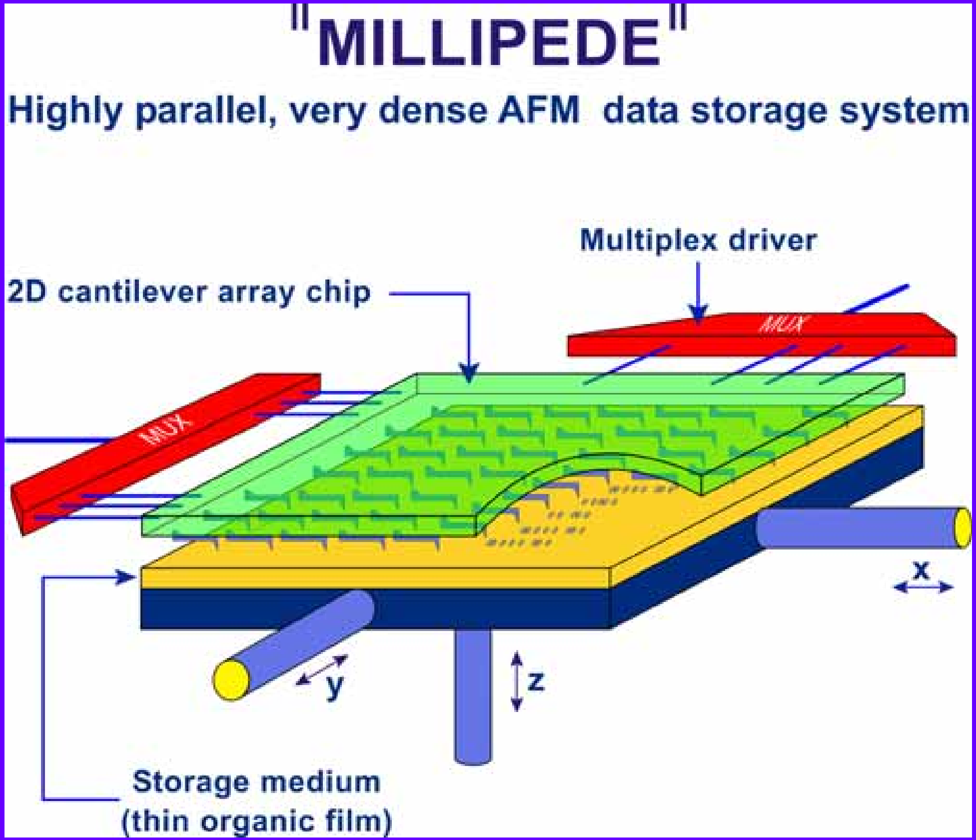


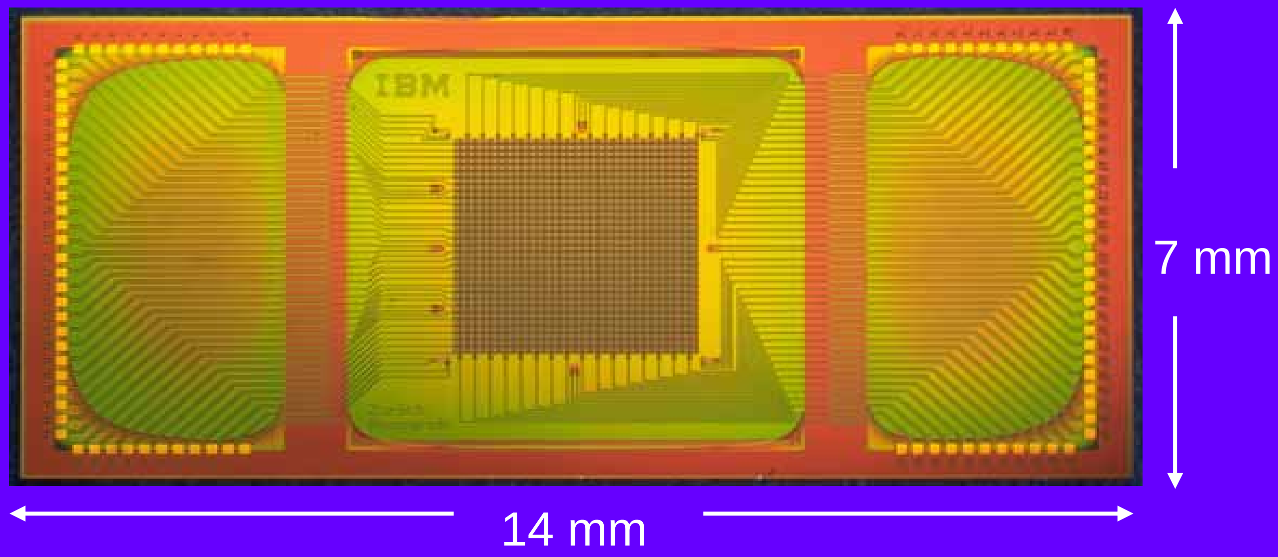
Millipede



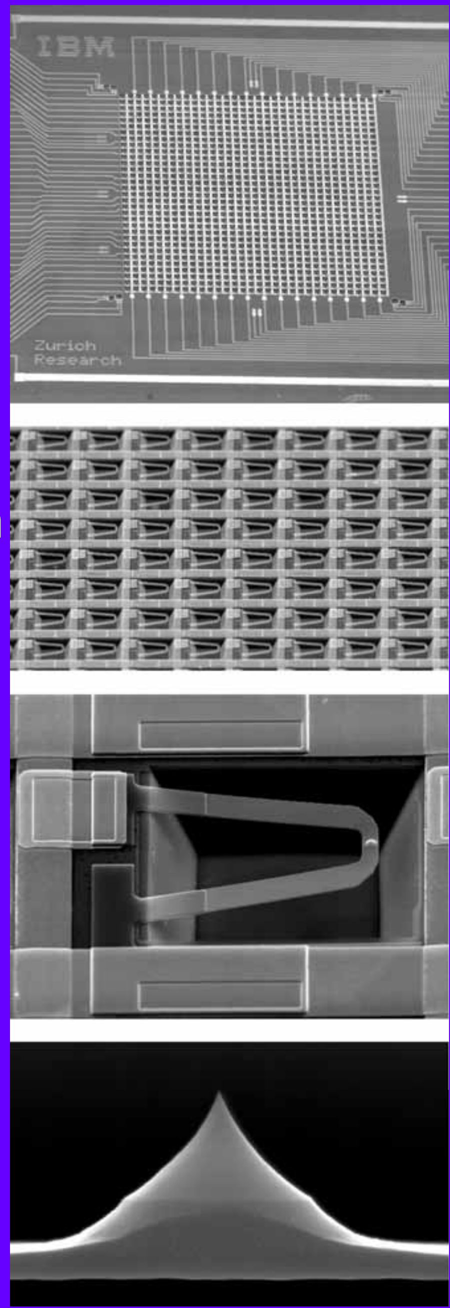
The Millipede concept: for operation of the device, the storage medium - a thin film of organic material (yellow) deposited on a silicon "table" - is brought into contact with the array of silicon tips (green) and moved in x- and y-direction for reading and writing. Multiplex drivers (red) allow addressing of each tip individually.

IBM-Zurich

Cantilever array



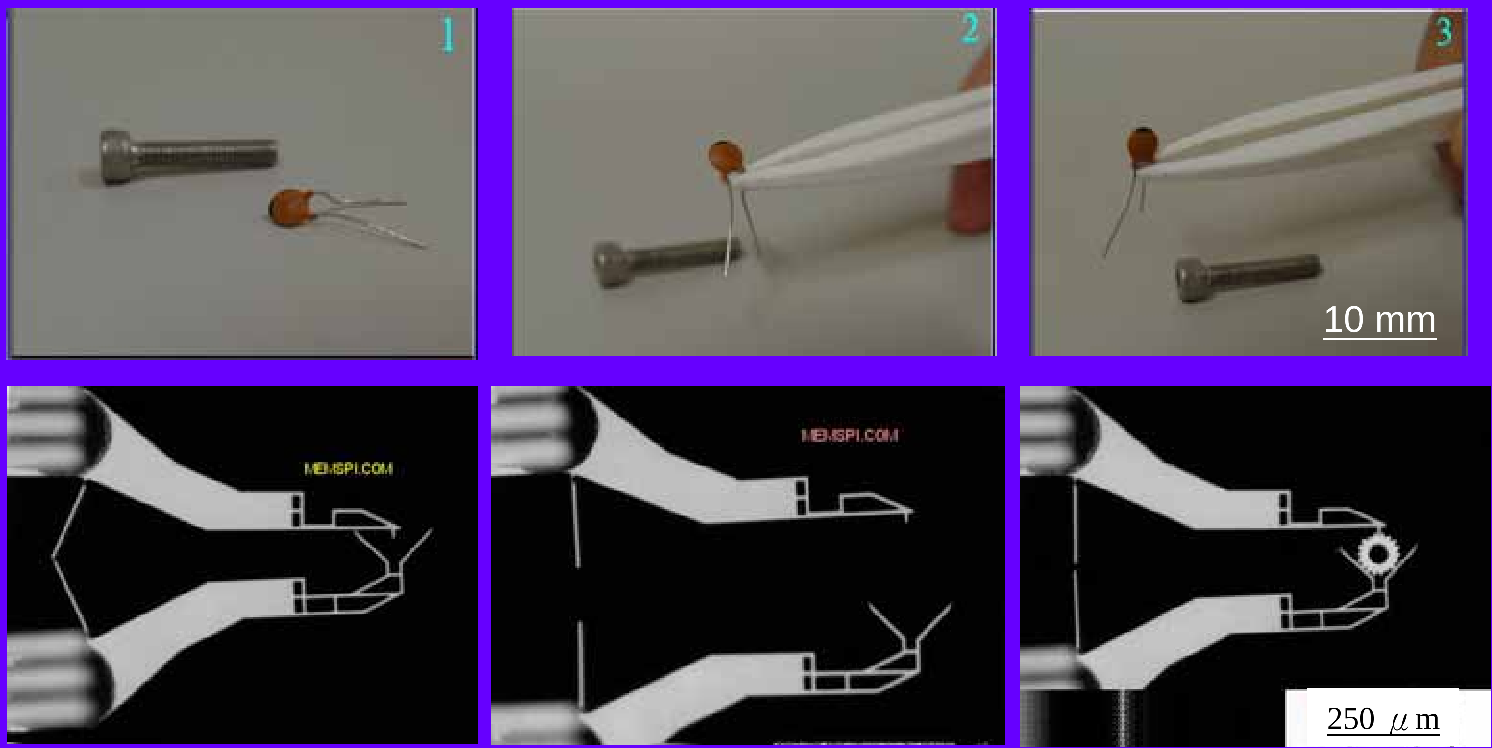
Millipede cantilevers and tips: electron microscope views of the 3 mm by 3 mm cantilever array (top), of an array section of 64 cantilevers (upper center), an individual cantilever (lower center), and an individual tip (bottom) positioned at the free end of the cantilever which is 70 micrometers (thousands of a millimeter) long, 10 micrometers wide, and 0.5 micrometers thick. The tip is less than 2 micrometers high and the radius at its apex smaller than 20 nanometers (millionths of a millimeter).



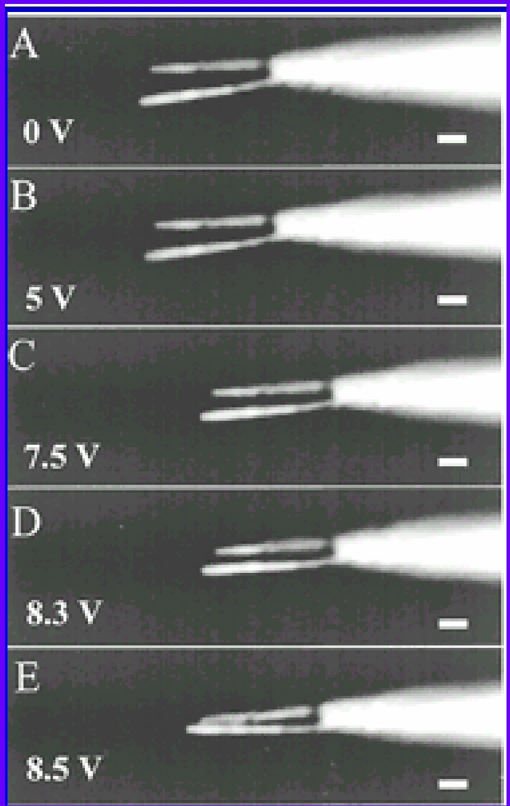
Considerations for making nanoscale tools

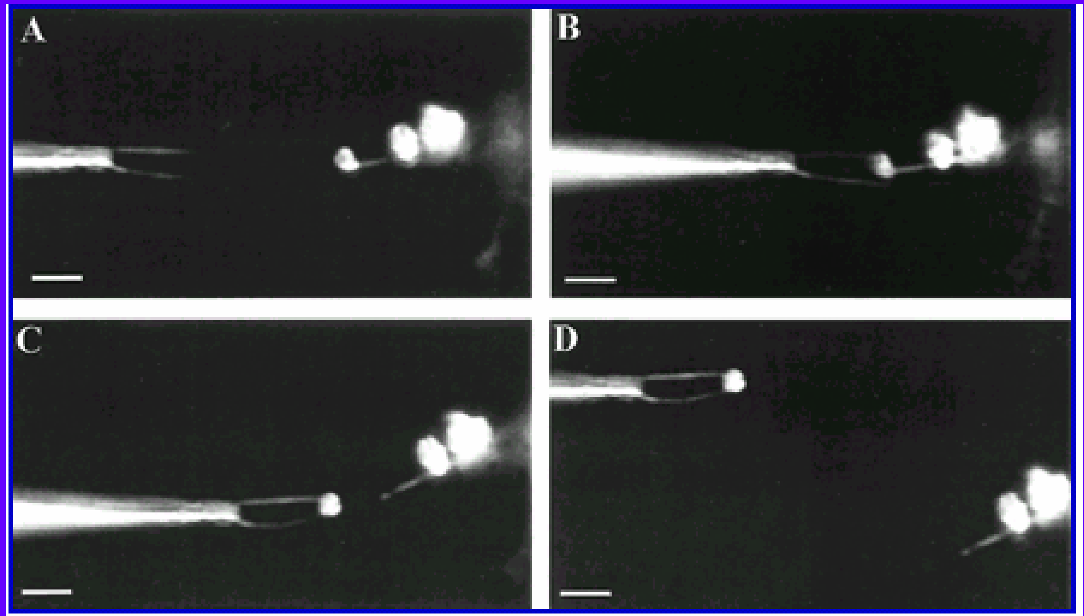
1. Size compatibility
2. Force compatibility
3. Mechanical Properties
4. Chemical Properties
5. Precision movement
6. Integratible coarse movement
7. Environment interferences

Maneuvering tools



Operation of nano tweezers

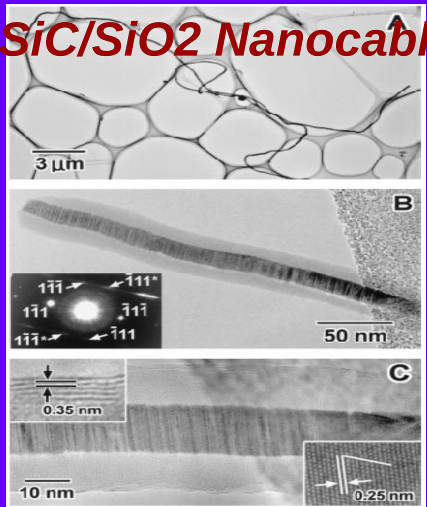




P. Kim and C.M. Lieber,
Science 286, 2148 (1999).

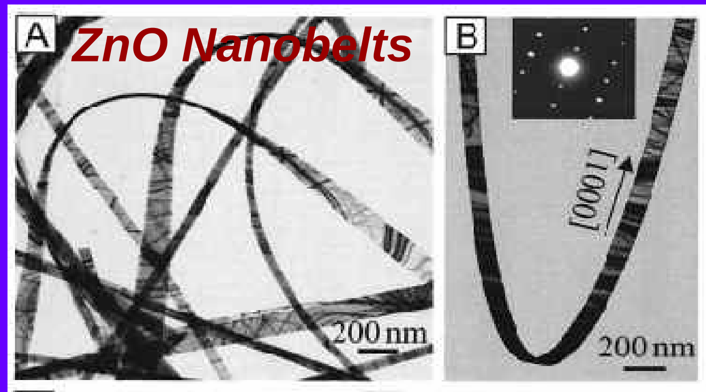
Nano wires and belts

SiC/SiO2 Nanocable



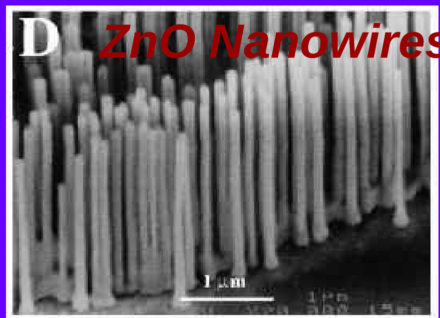
Science 281, 973 (1998)

ZnO Nanobelts



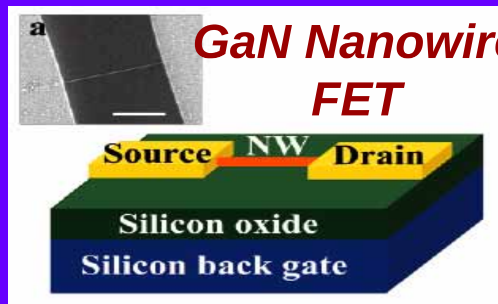
Science 291, 1947 (2001)

ZnO Nanowires



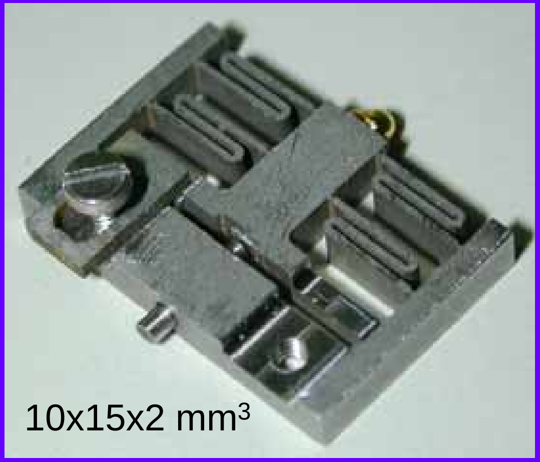
Science 292, 1897 (2001)

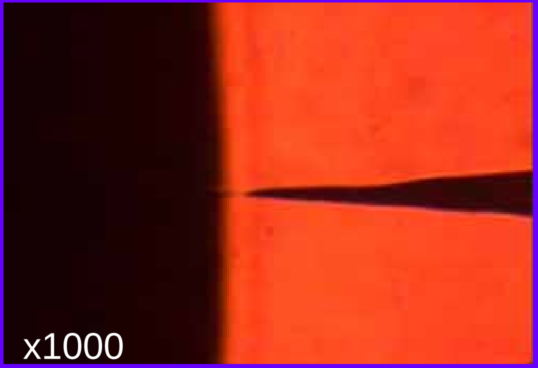
GaN Nanowire FET



Nano Lett. 2, 101 (2002)

Precision stepper





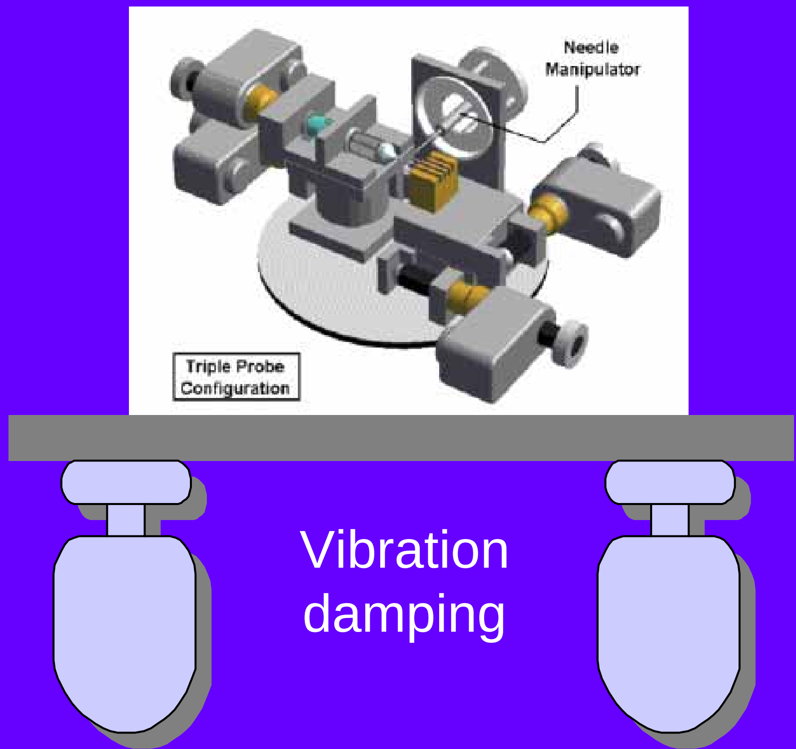
Considerations for environmental factors

Temp.,humidity & ventilation control

Dust filtering

EMI shield

Acoustic isolation



Vibration damping

Goals for next 5-10 years

- Instruments for analysis of supramolecules, biomolecules, and polymers.
- 3-D structure determination.
- Nanostructure chemical identification.
- *In situ* functional measurements.
- Functional parallel probe arrays.
- Standardization and metrology.
- New nano-manipulators.

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- 中區核心設施中心
- 南區核心設施中心
- 東區核心設施中心

References

1. ***Scanning Tunneling Microscopy II***, **eds. R. Wiesendanger and H.-J. Guntherodt (Springer-Verlag, Berlin, 1992).**
2. **M. Stark and R. Guckenberger, Rev. Sci. Instru. 70, 3614 (1999).**

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