Characterization and Manipulation at Nanometer Scale

Syllabus (2008)

Week 1	(2/19)	Overview
Week 2	(2/26)	STM: structure and working principles
Week 3	(3/04)	AFM: structure and working principles
Week 4	(3/11)	SPM: structure and working principles
Week 5	(3/18)	TEM: structure and working principles
Week 6	(3/25)	TEM: operations and examples
Week 7	(4/01)	X-ray and other microscopies
Week 8	(4/08)	Midterm Written Exam (50%)
Week 9	(4/15)	Spectroscopy: optical, electronic, vibrational
Week10	(4/22)	Lithography: optical, e-beam
Week11	(4/29)	Atom manipulation
Week12	(5/06)	Papers study
Week13	(5/13)	Papers study
Week14	(5/20)	Papers study
Week15	(5/27)	Papers study
Week16	(6/03)	Papers study
Week17	(6/10)	Presentation and responses (50%)

Nanoscale measurements

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http://www.phys.sinica.edu.tw/TIGP-NANO/Course/2008_Spring.htm

http://www.phys.sinica.edu.tw/~nano/

Outline

A. Introduction

B. Operational Principles:

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

C. From measuring to sensing

D. From measuring to manipulating

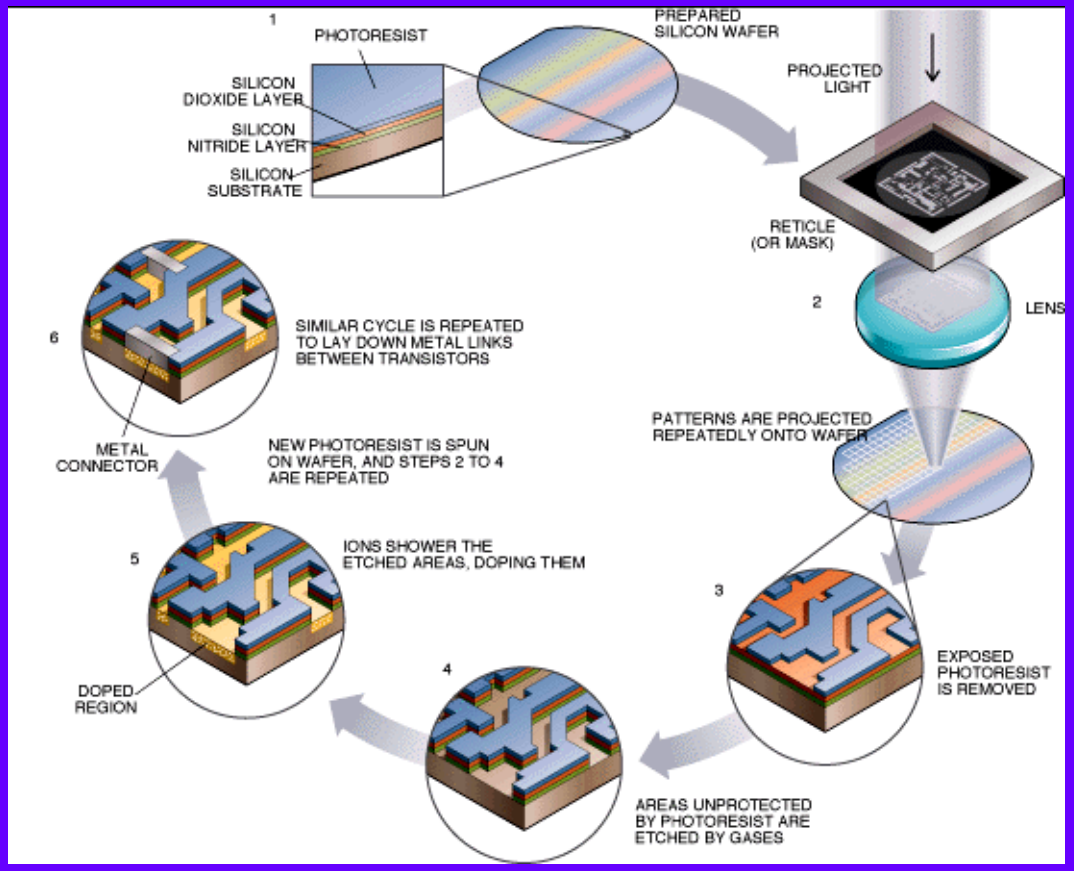
E. From measuring to fabricating

F. Considerations for making nanoscale tools

G. Future development of nanoscale measurements

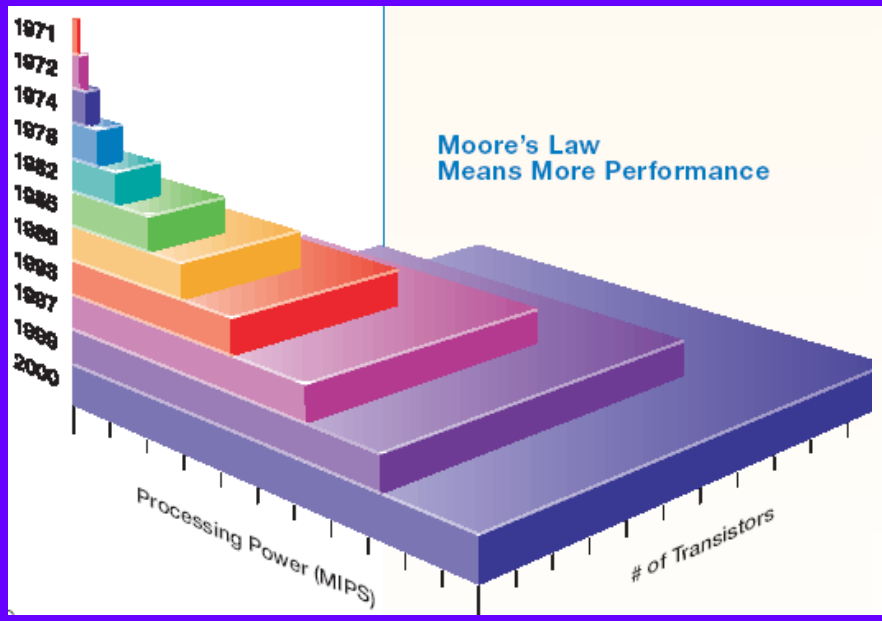
H. Conclusions

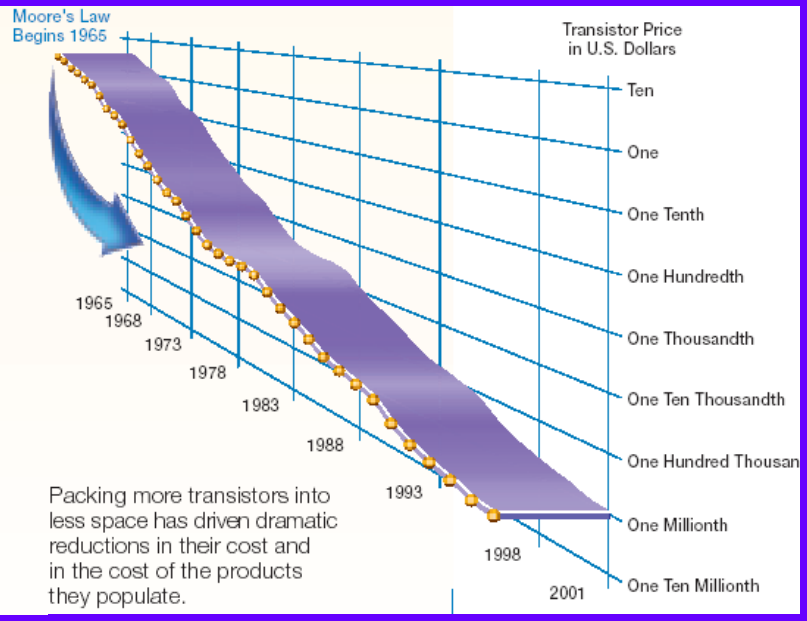
Optical lithography and planar fabrication of VLIC



Intel Corp.

Numbers of transistors in an IC

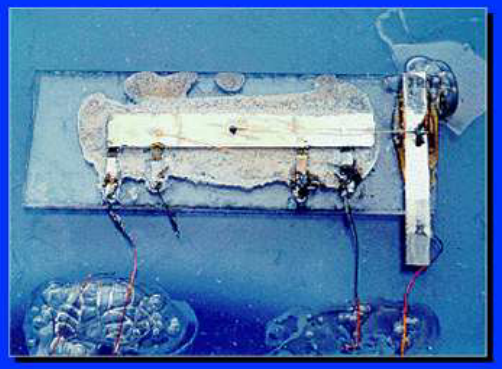




Intel Corp.

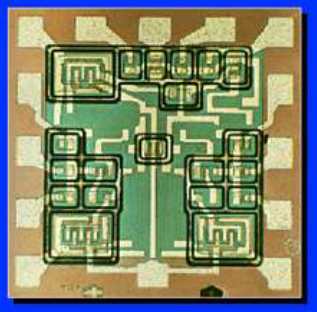
Evolution of IC industry

Kilby's First IC, 1958

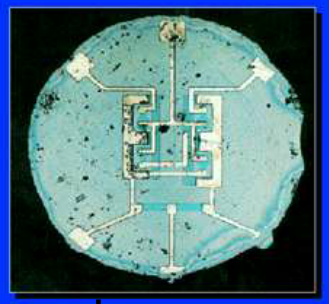


1965

- 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

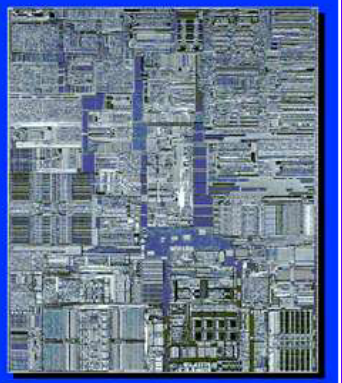


Jean Hoerni

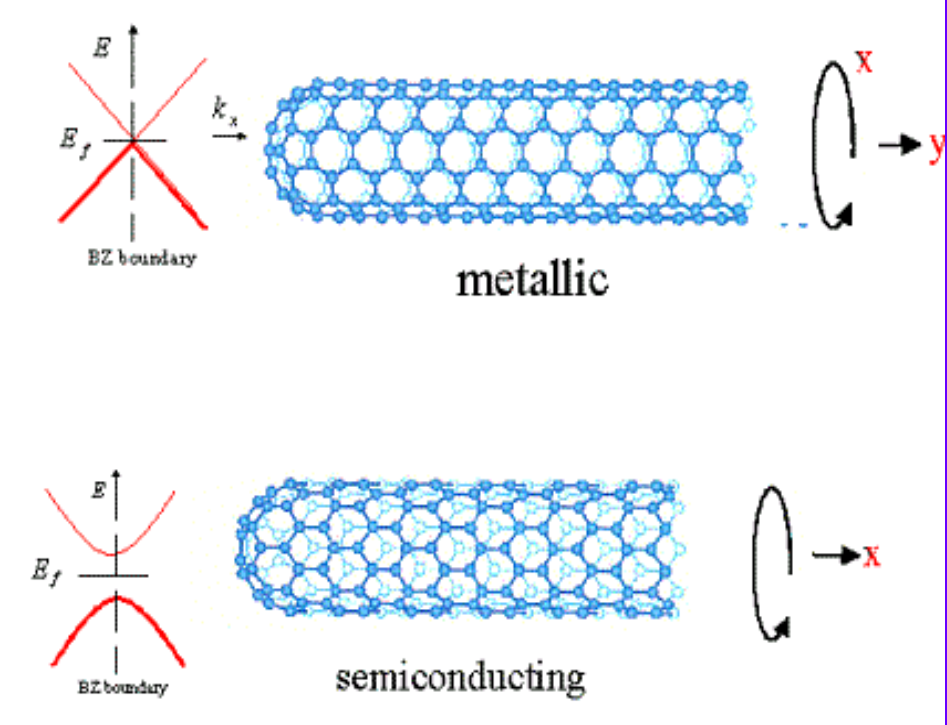
Modern IC

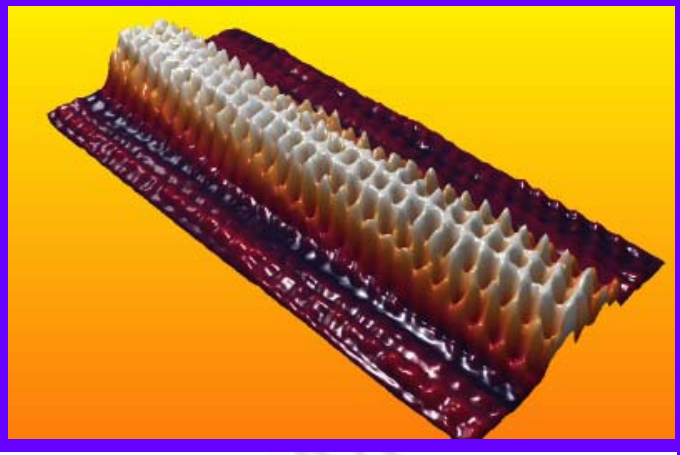
Pentium® III Processor

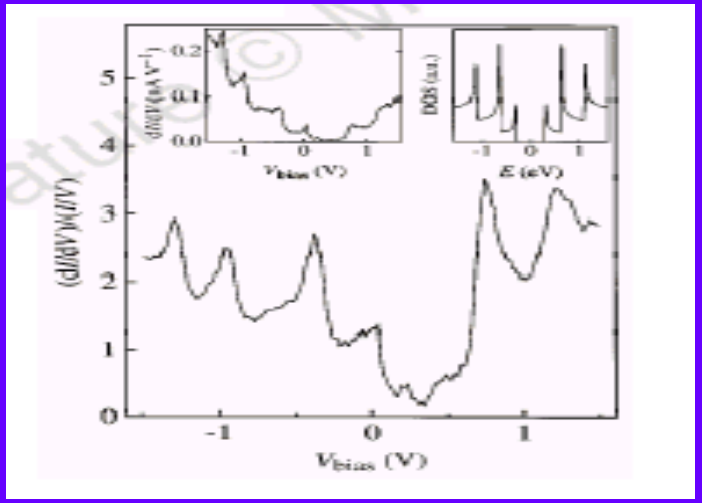
Transistors:	9,503,153
Die Size:	408.9 mils x 484.8 mils
Area:	127.9 mm²



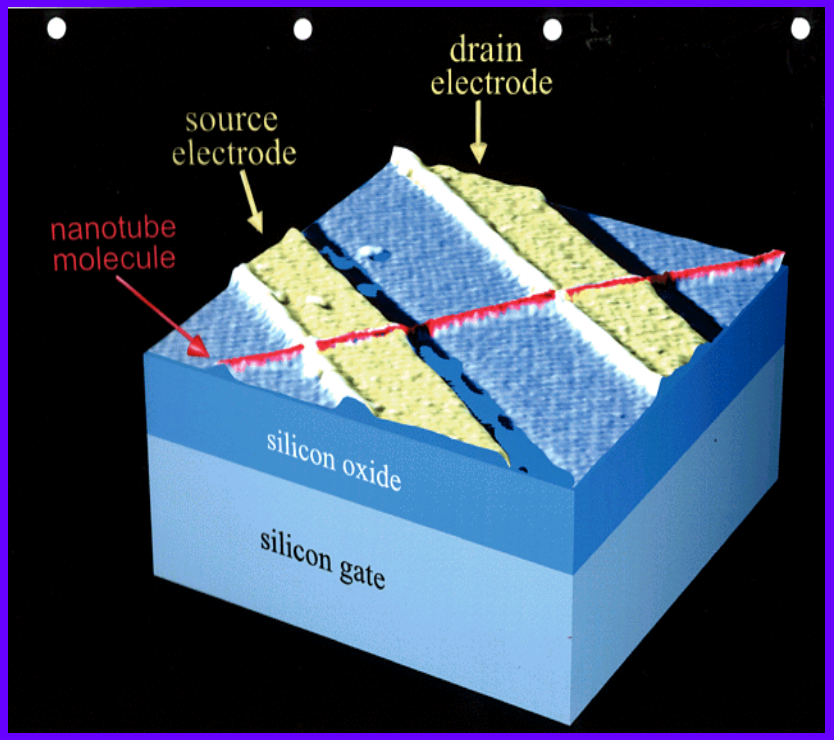
Electronic properties of a carbon nanotube

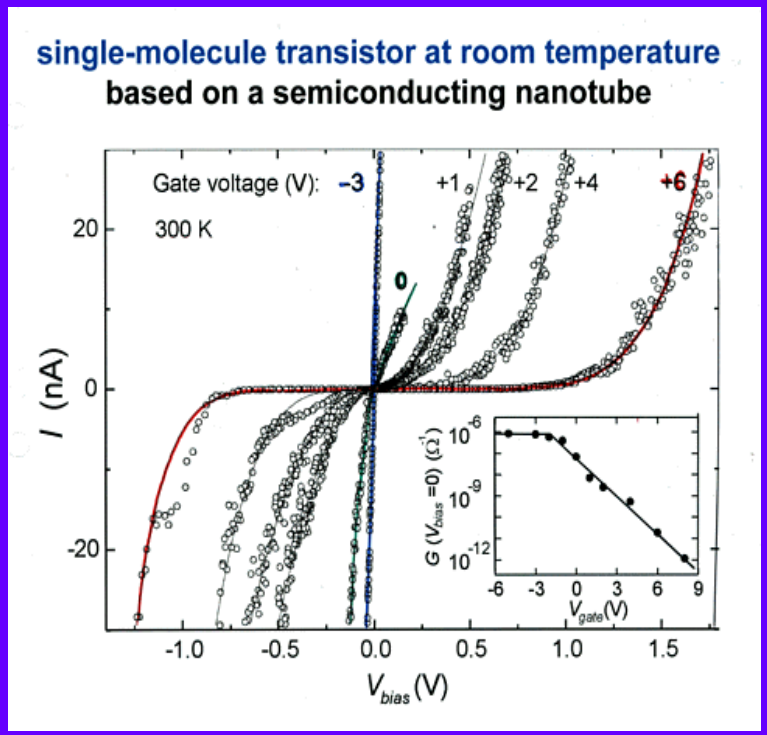






Single-walled CNT transistor





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

Definitions of nanoscience and nanotechnologies

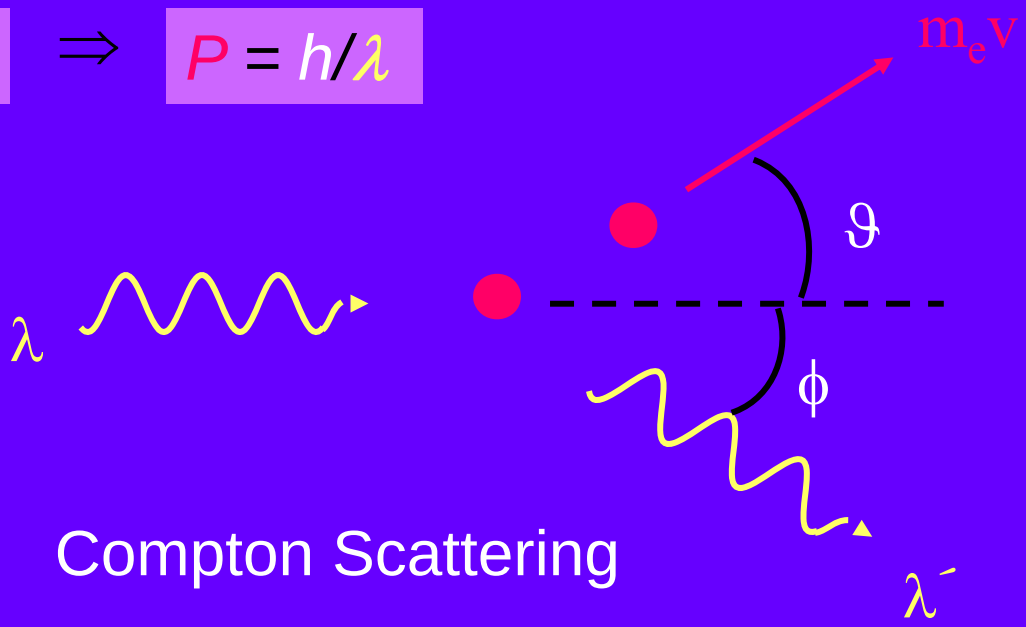
Nanoscience is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

Nanotechnologies are the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometer scale.

Photon as a particle

Einstein's proposal:

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



Compton Scattering

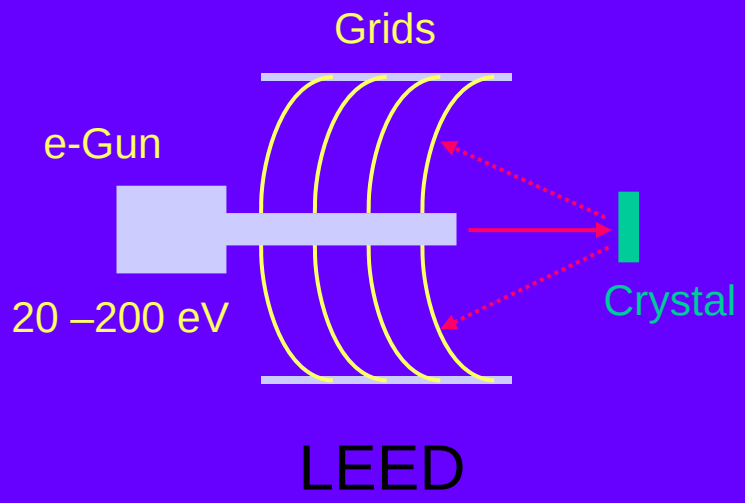
Electron as a wave

de Broglie's proposal:

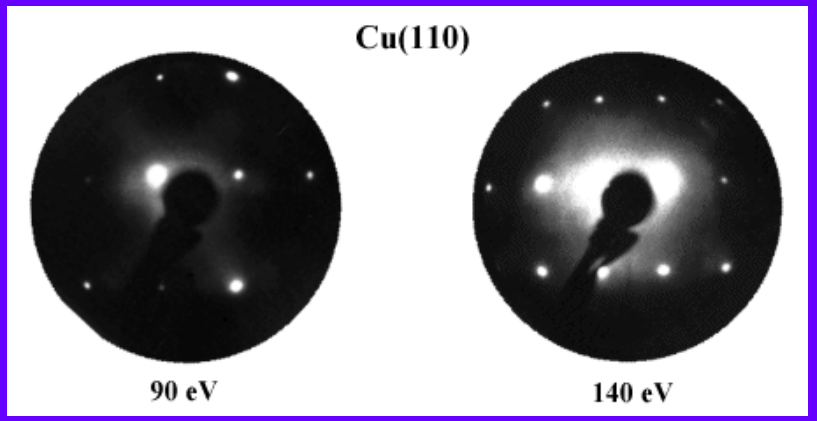
$\lambda = h/P \Rightarrow \nu = h/E$

For electrons:

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

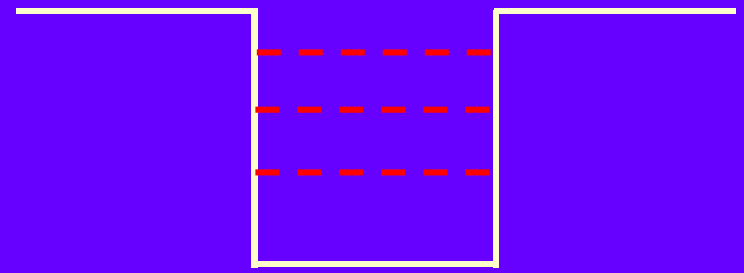


LEED

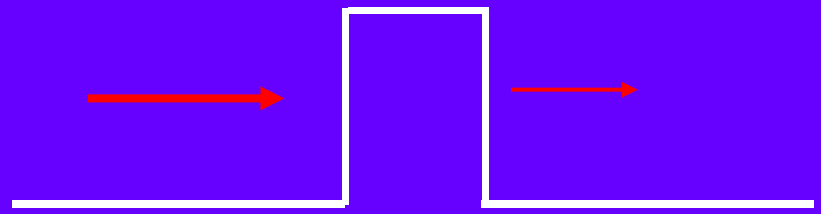


Fundamentals of Quantum Mechanics

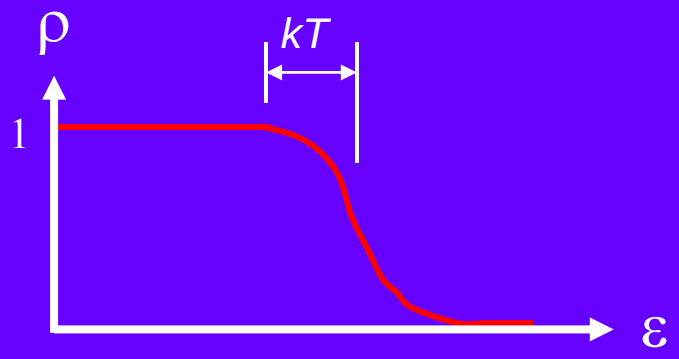
1. Quantization



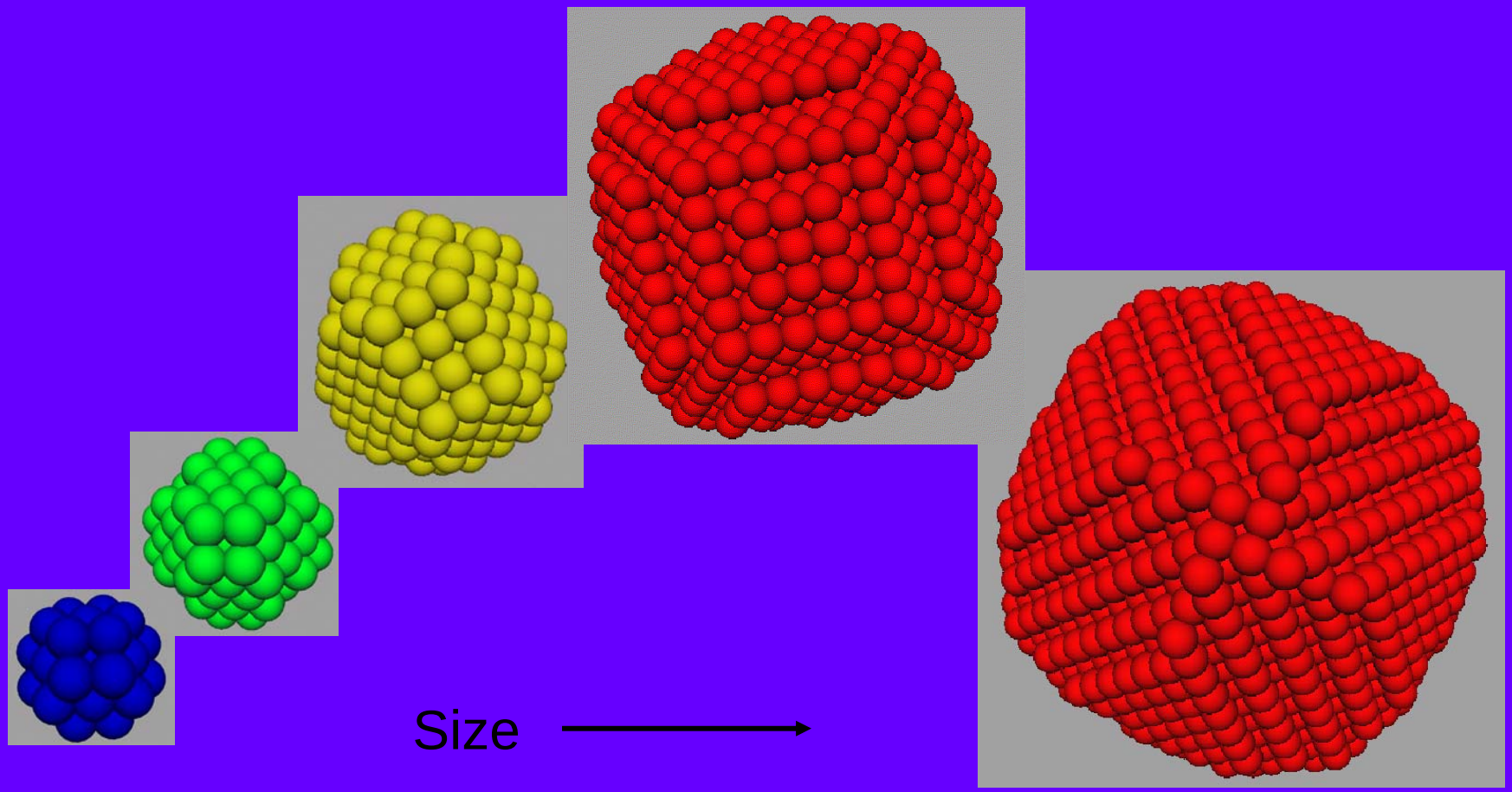
2. Tunneling



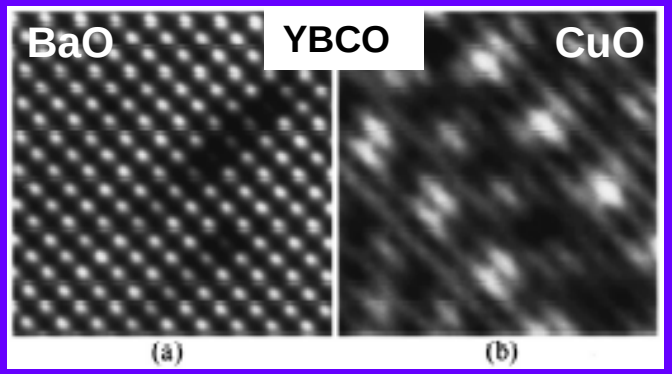
3. Statistics

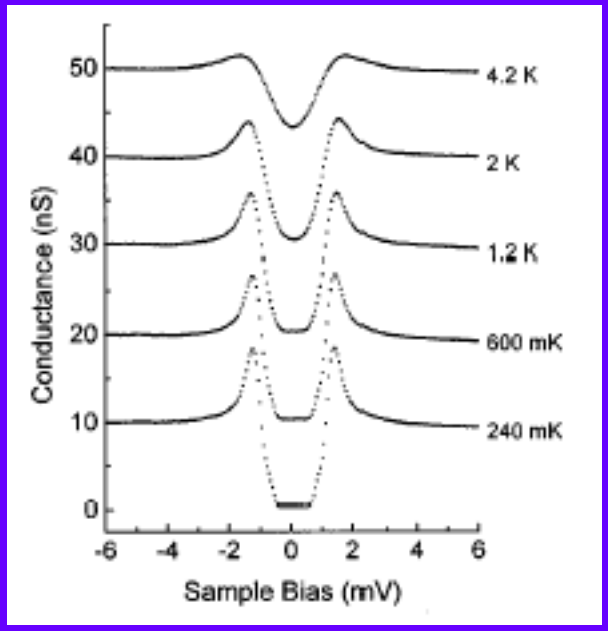


Size effect



Measurement of electronic states



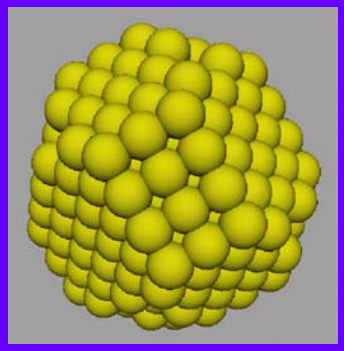


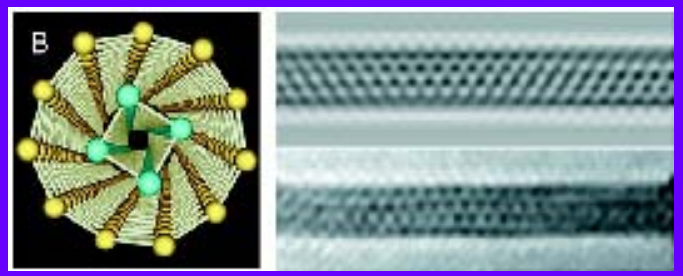
S. H. Pan *et al., Rev. Sci. Instru.* 40, 1459 (1999).

Properties of a nanostructure

Microscopic

Size
Structure
Shape
Symmetry
Domains
Defects
.
.
.



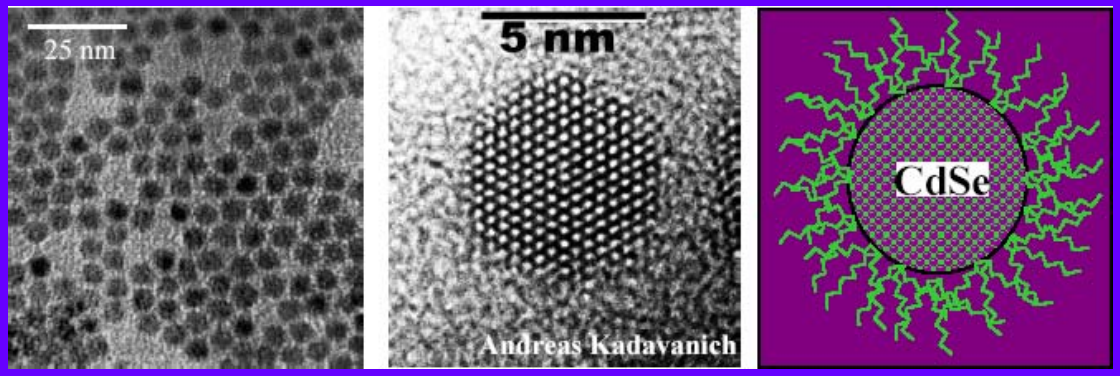


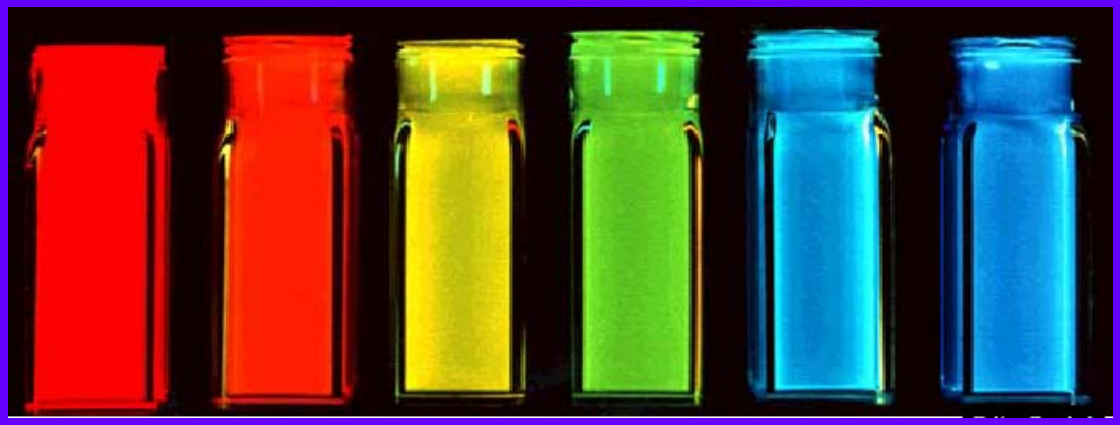
Analytical

Composition
Stoichiometry
Electronic
Magnetic
Thermal
Mechanical
.
.
.

photons, electron, ion, neutron, proximal nanoobjects …

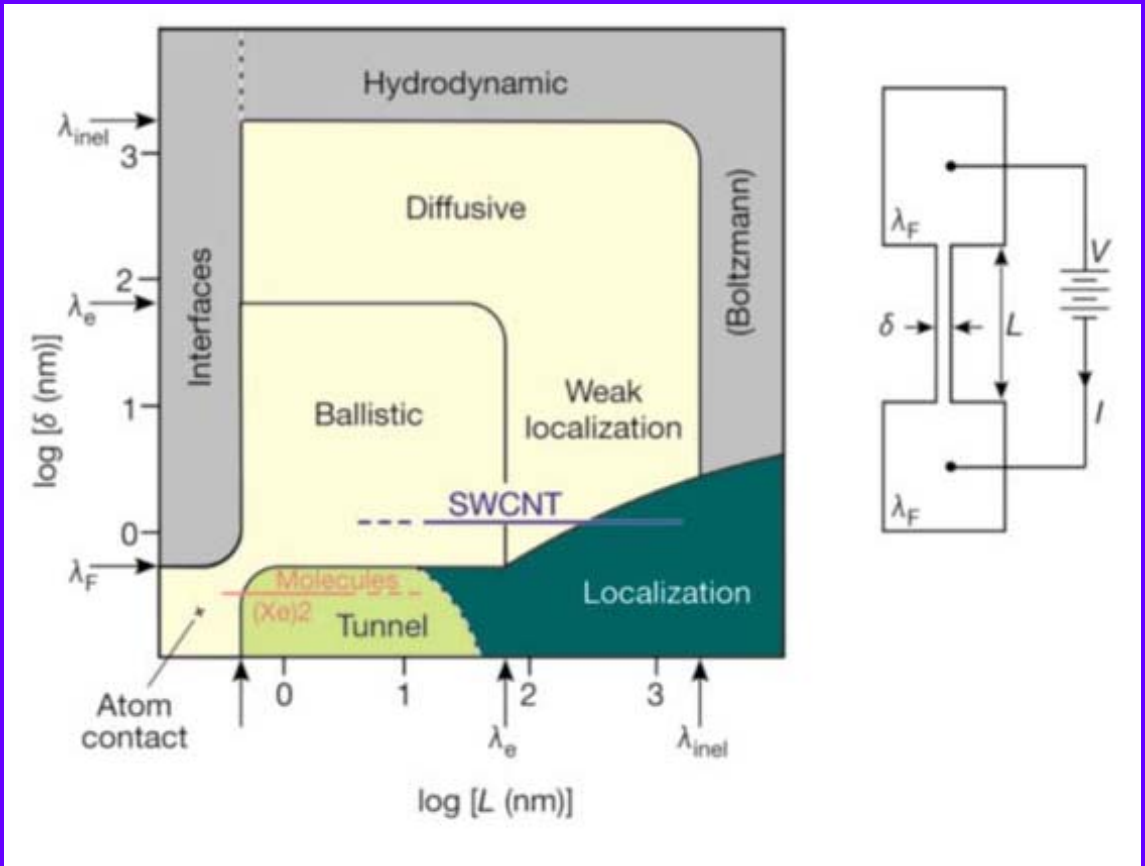
Semiconducting quantum dots





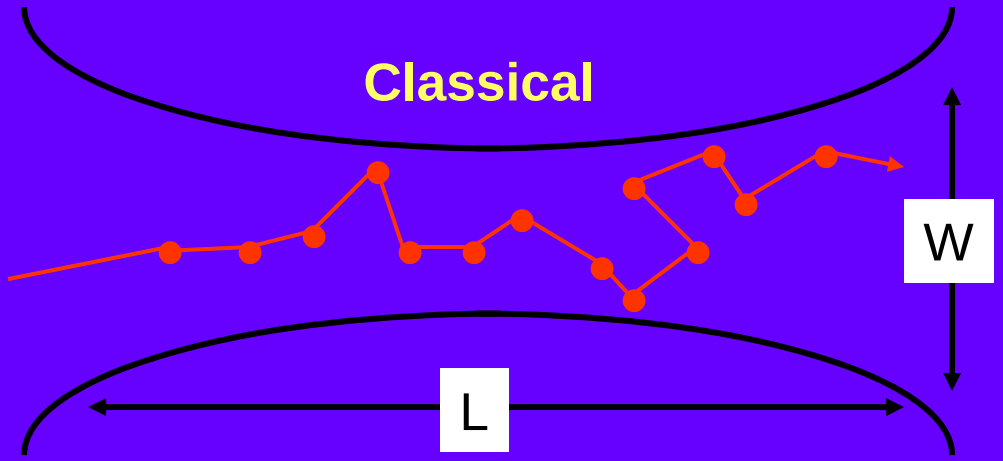
(Reproduced from Quantum Dot Co.)

Critical lengths

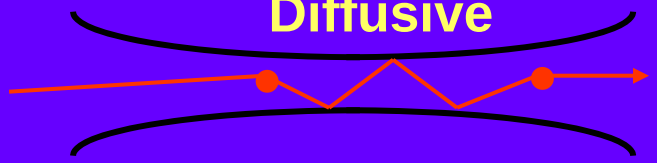


C. Joachim *et al.*, *Nature* 408, 541 (2000).

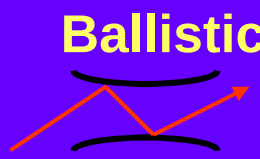
Characteristics of electron transport



$l_\varphi \ll W,L$



$l < W,L < l_\varphi$



$W,L < l$

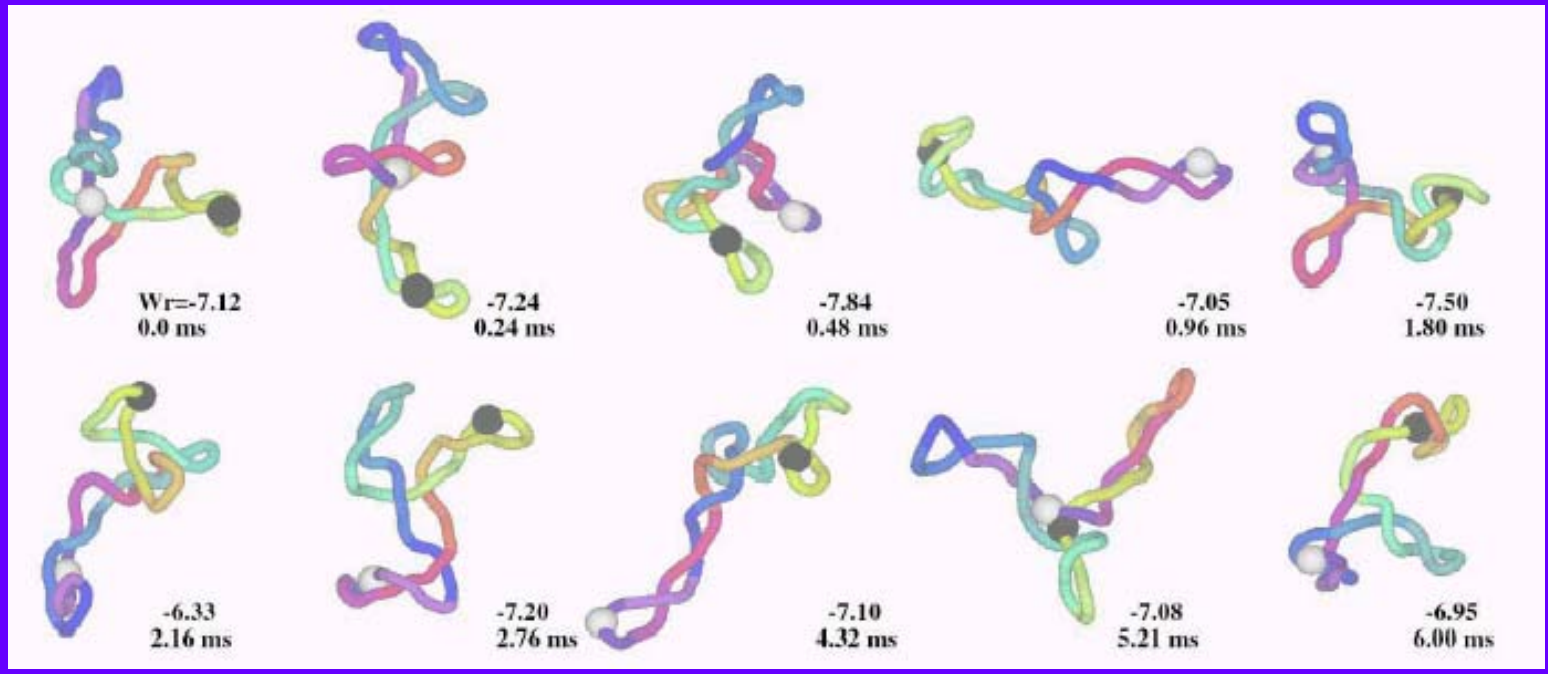
l : elastic mean free path

l_φ *: phase-breaking length*

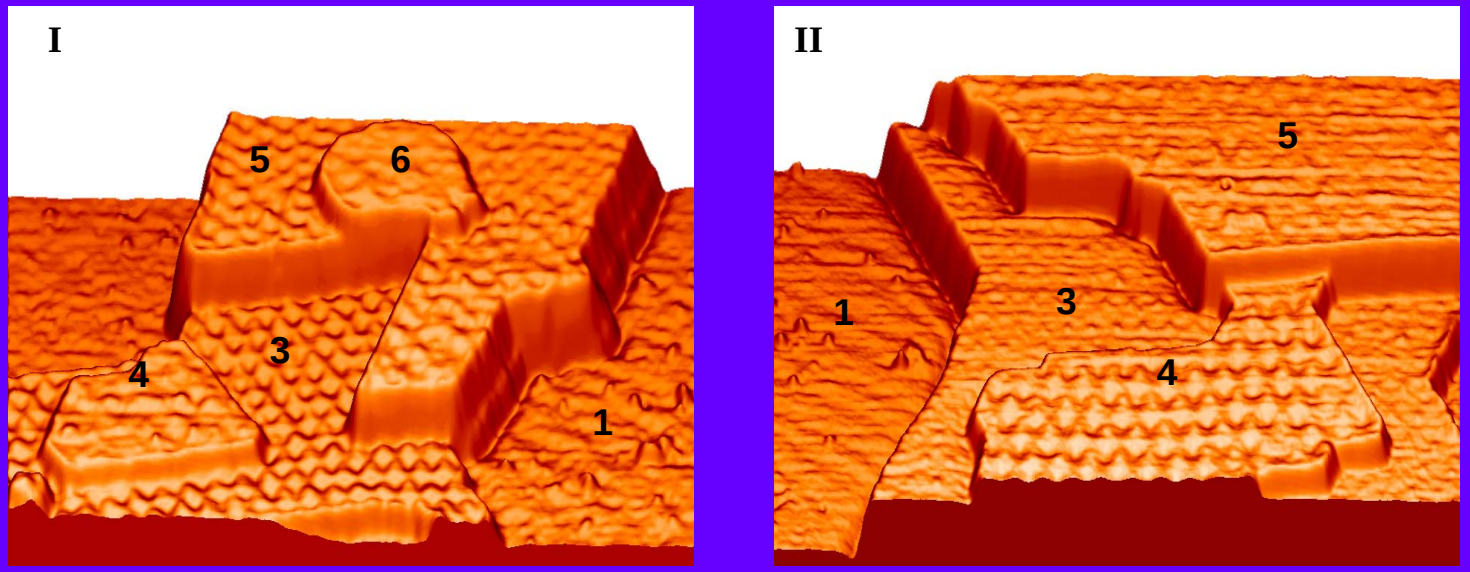
Miniturazation of length scale

Macro	Micro	Nano
continual	discrete	
scalable	nonscalable	
evolutionary	revolutionary	
classical	quantum mechanical	

Simulation of DNA dynamics

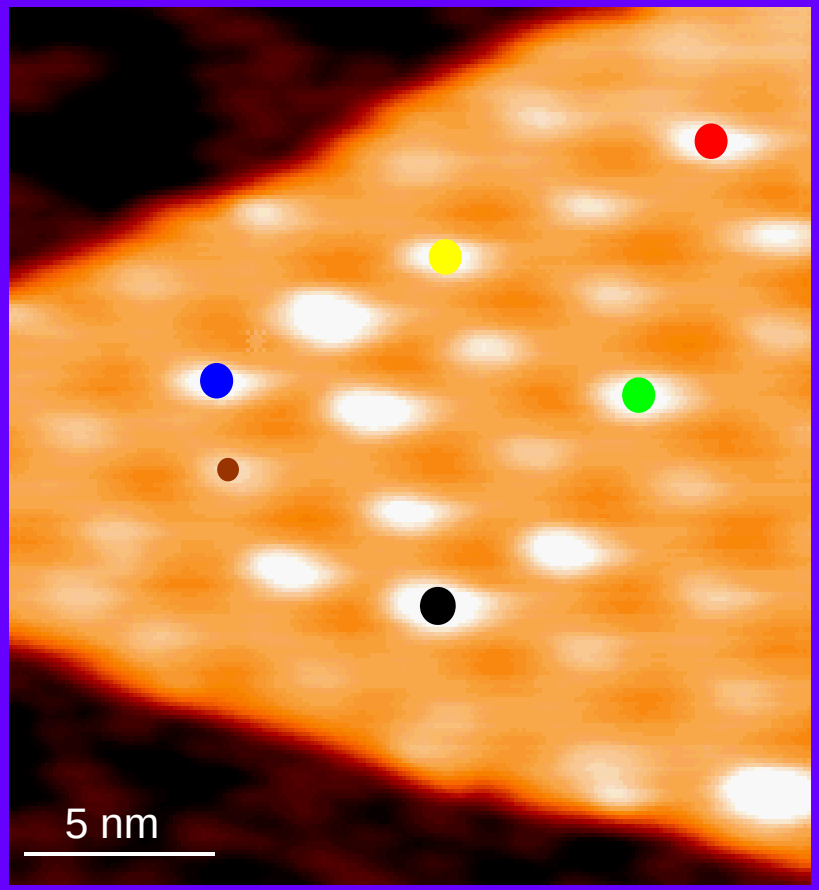


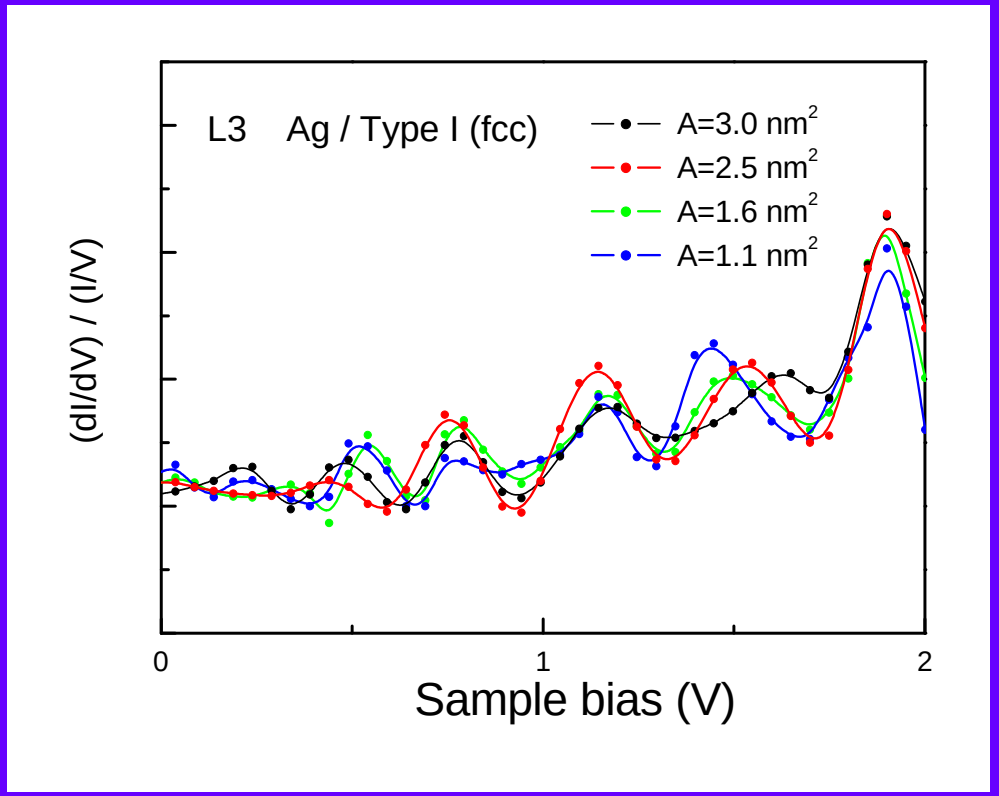
Alternating and complementary contrast



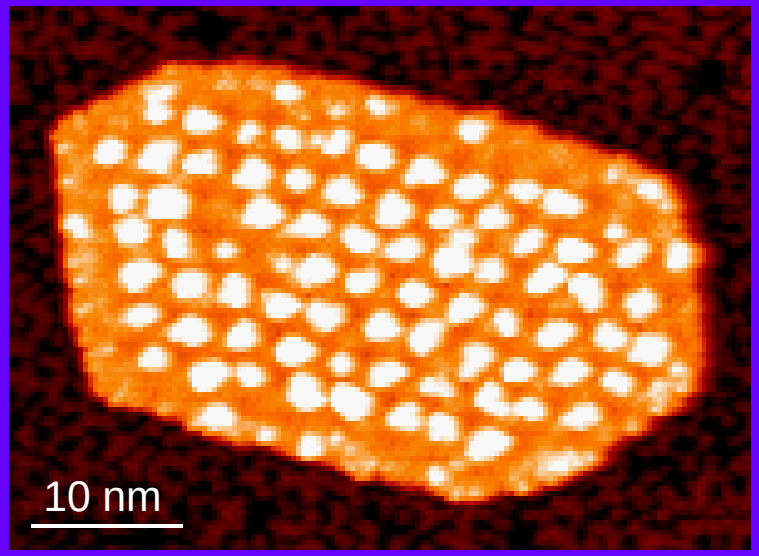
W.B. Jian *et al*. PRL **90**, 196603 (2003)

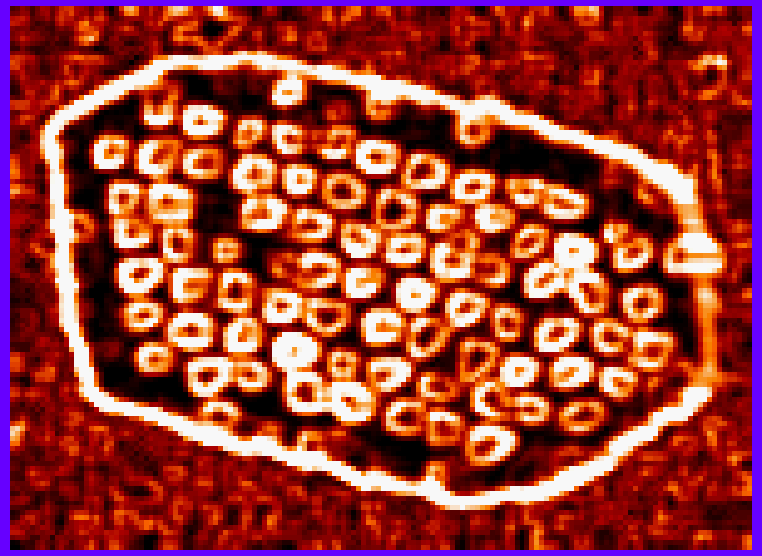
Size-dependent I/V spectra by STS



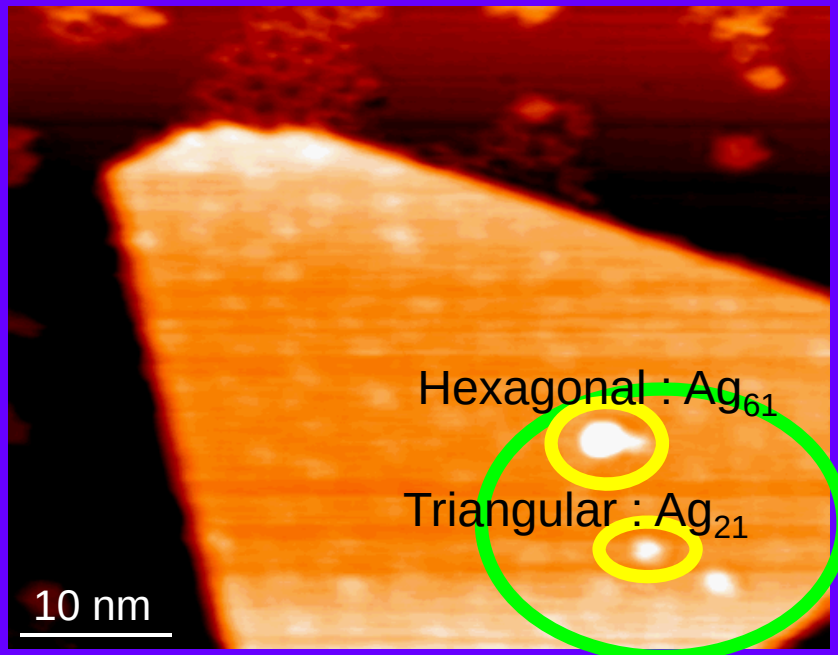


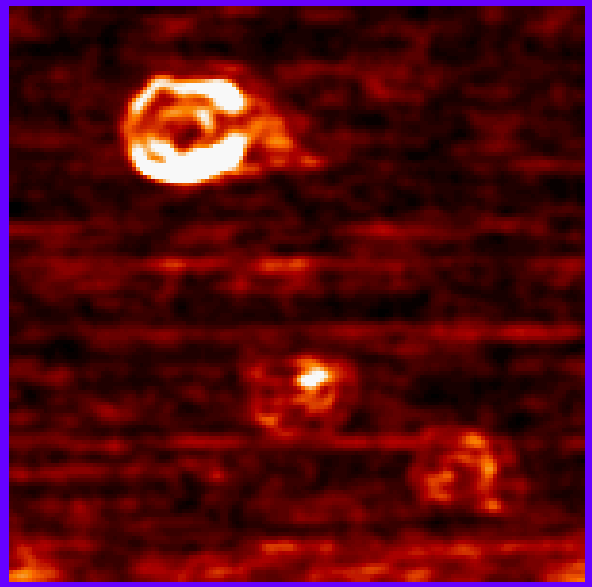
Shapes of Ag nanopucks

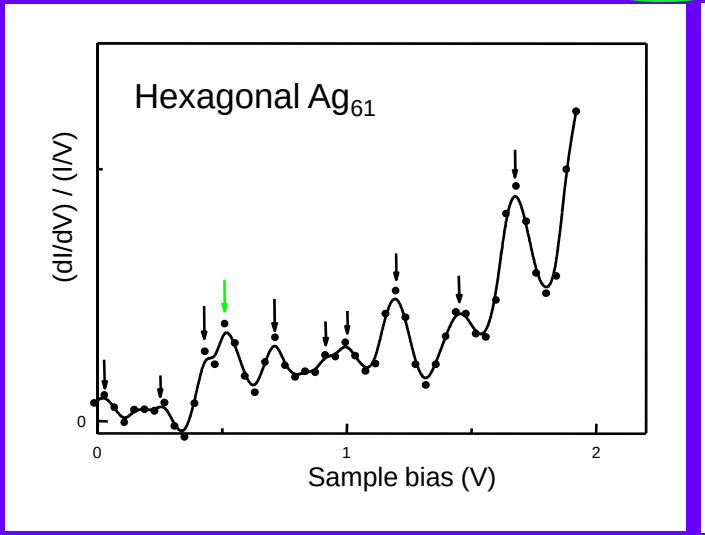


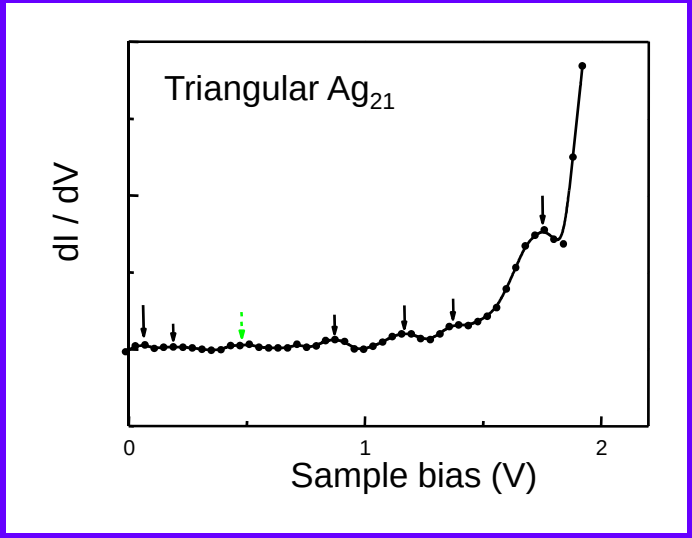


Size- and shape-dependent I/V spectra





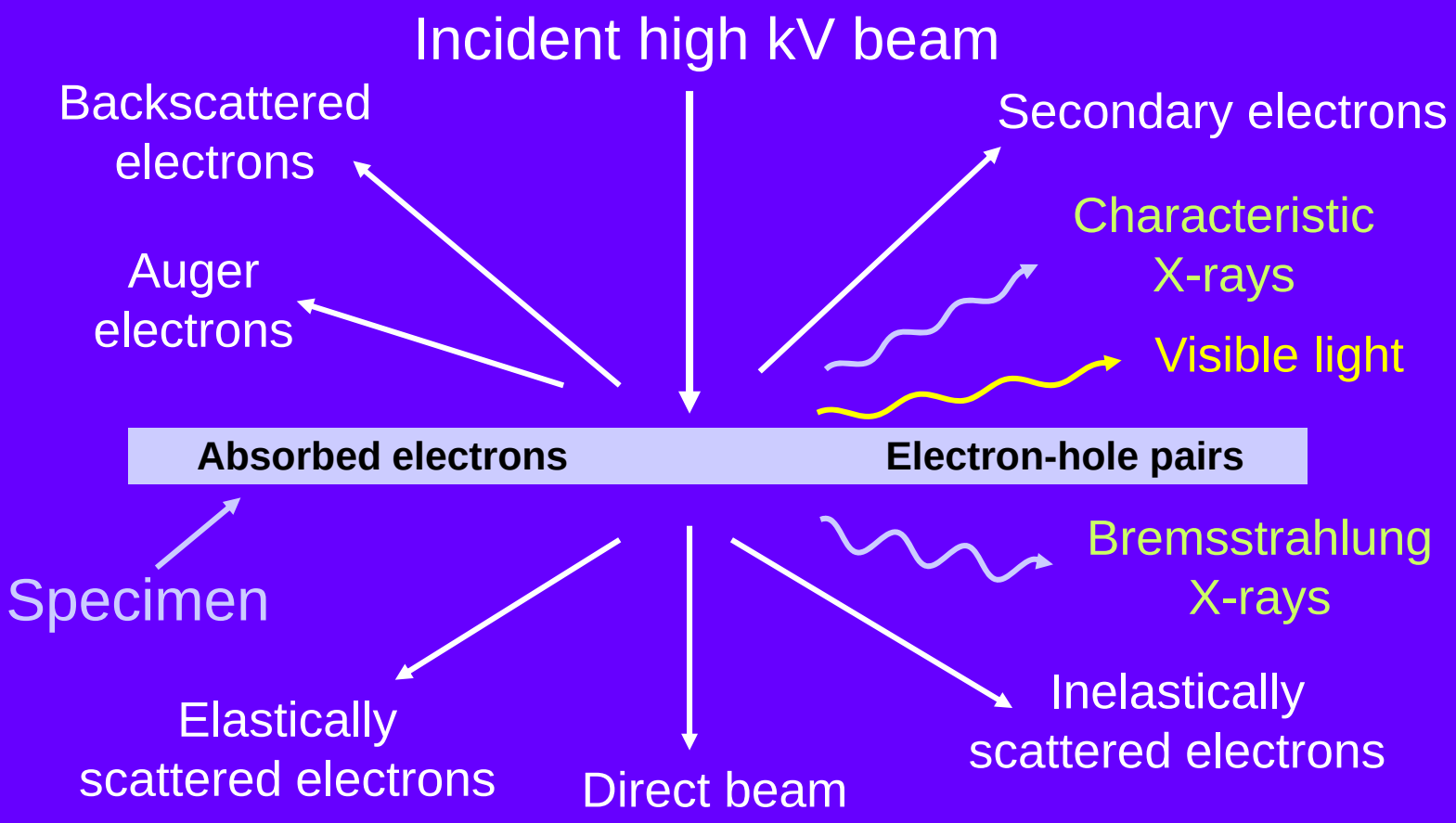




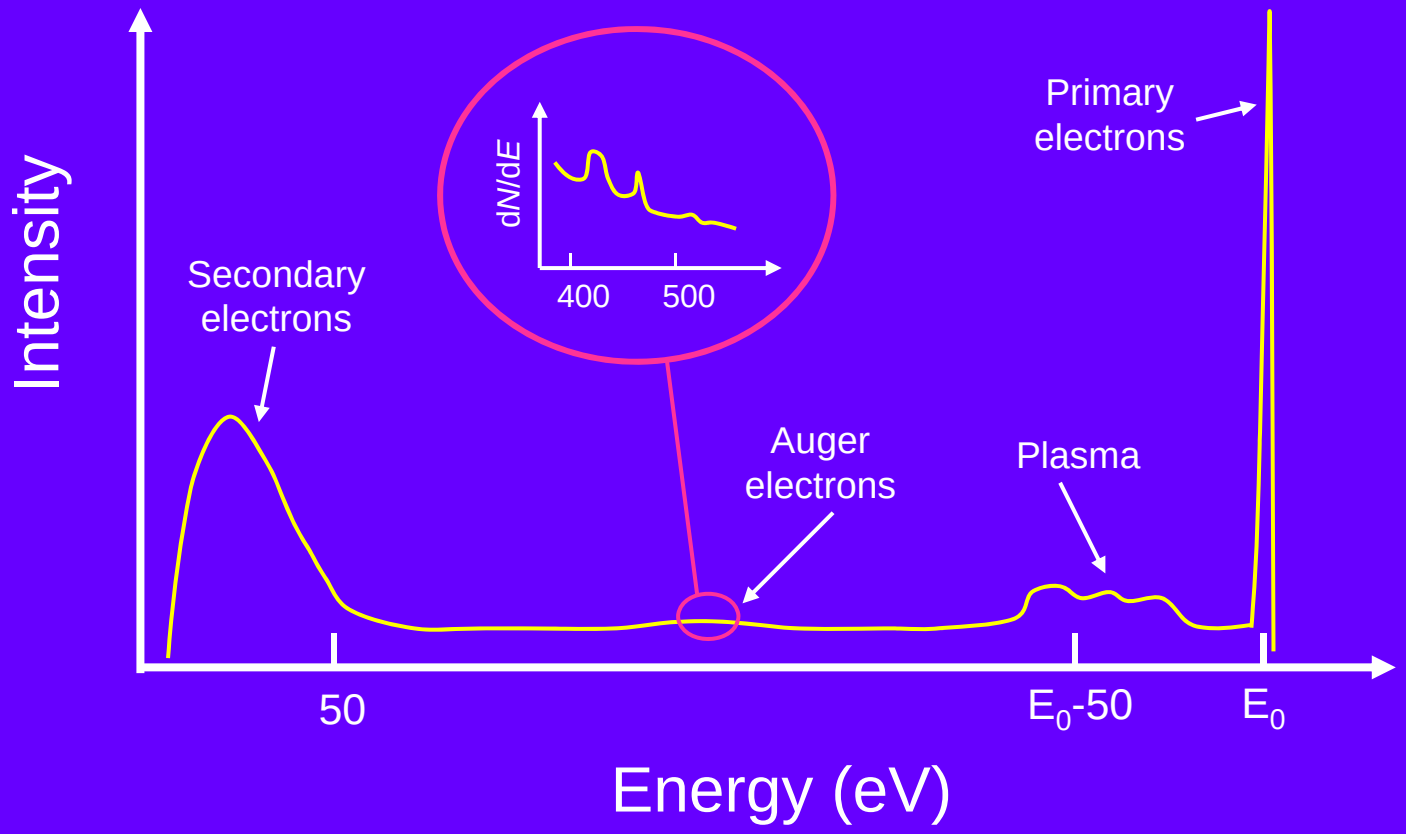
Characterization of single nanostructure

Specs	Demands
• Small size	high brightness
	small probe
• Weak signal	high sensitivity
	low interference
• High reactivity	controlled environment
	low temperature
• Flexible	high speed
functionality	*in situ* measurement

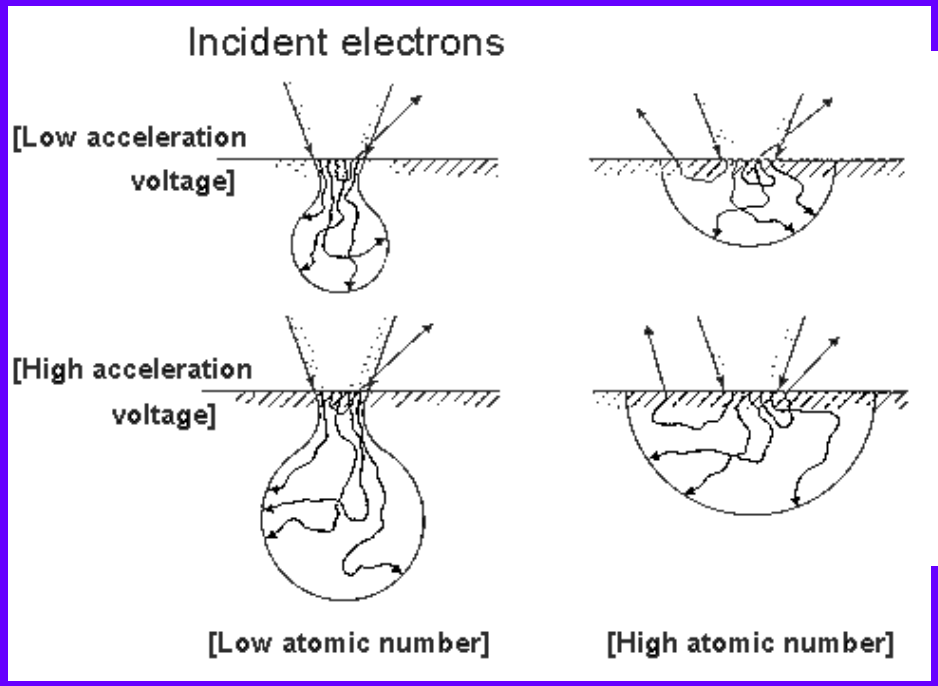
Interaction between e-beam and sample

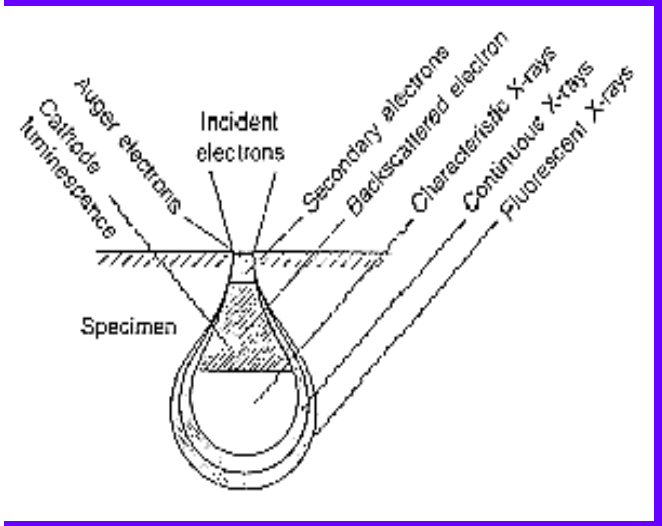


Energy distribution after interaction

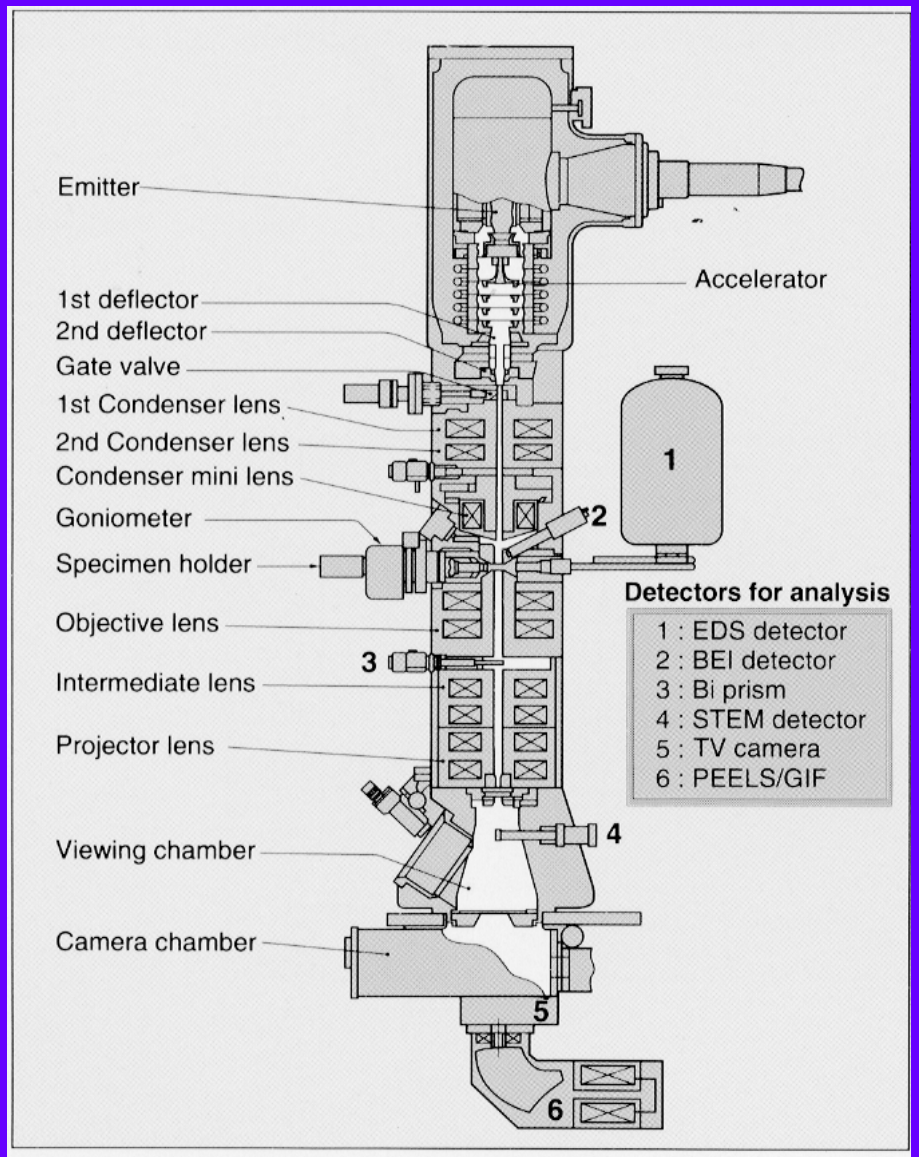


Penetration power of energetic e beam



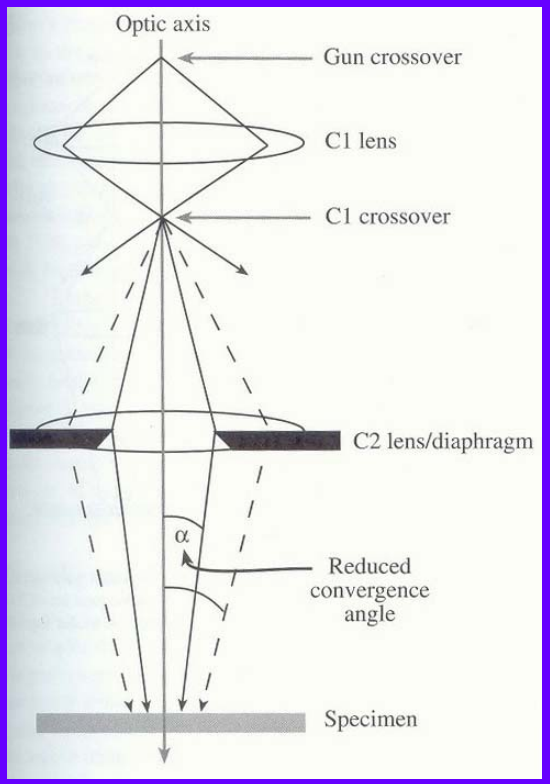


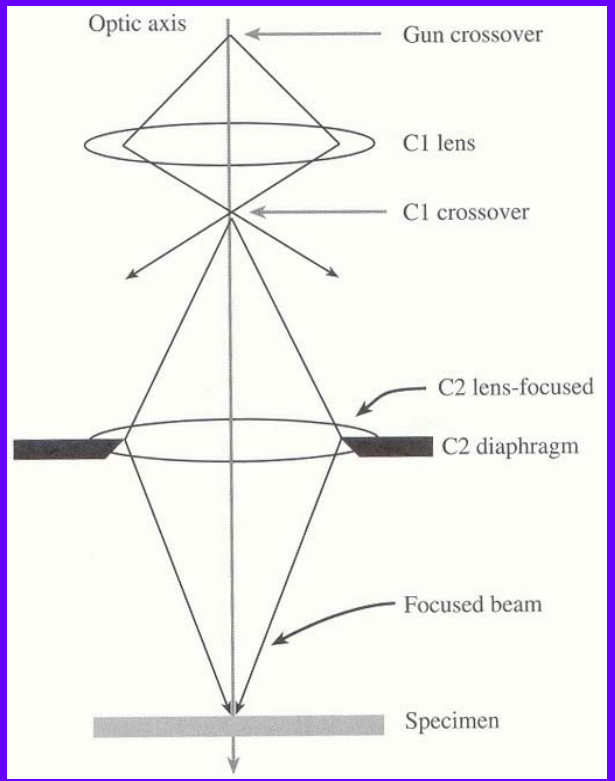
Cross section view of HRTEM



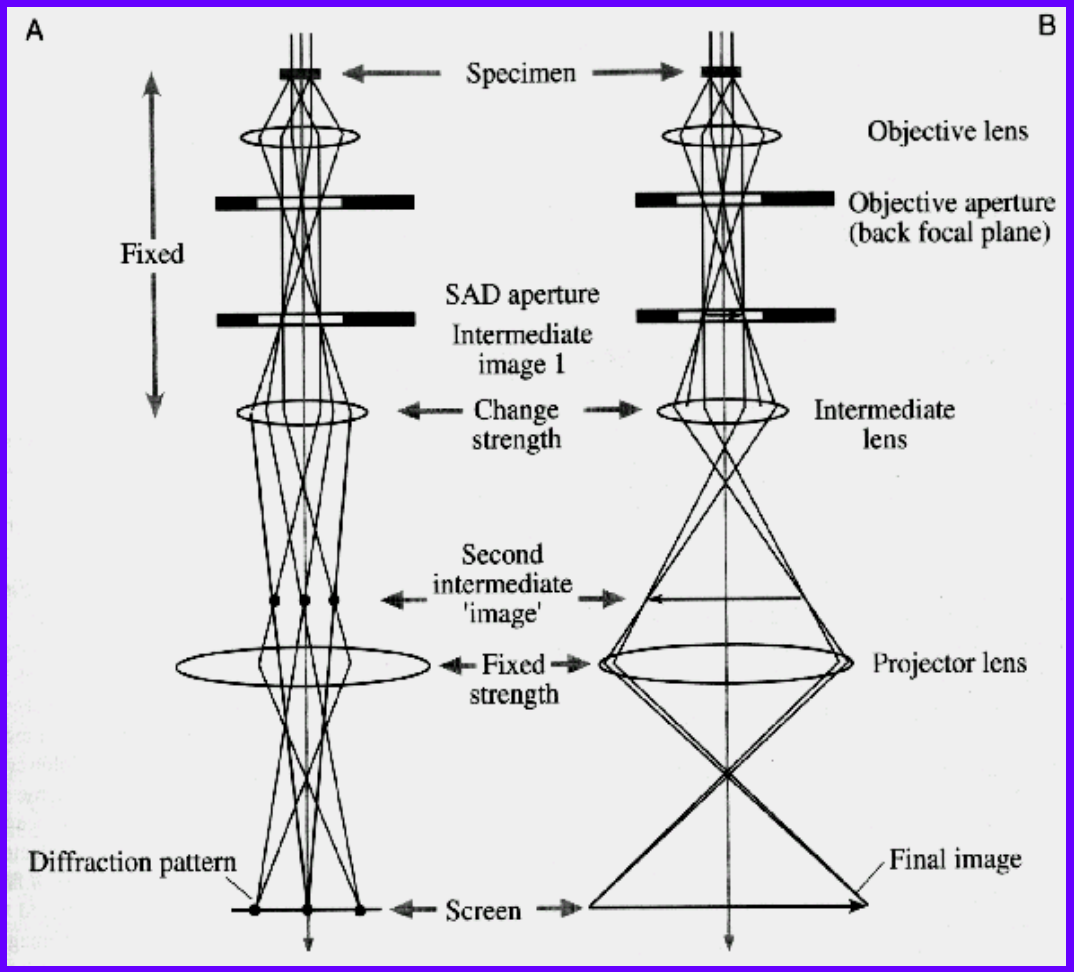
Cross section of JEM-2010F and assignment of detectors

E-beam source of TEM

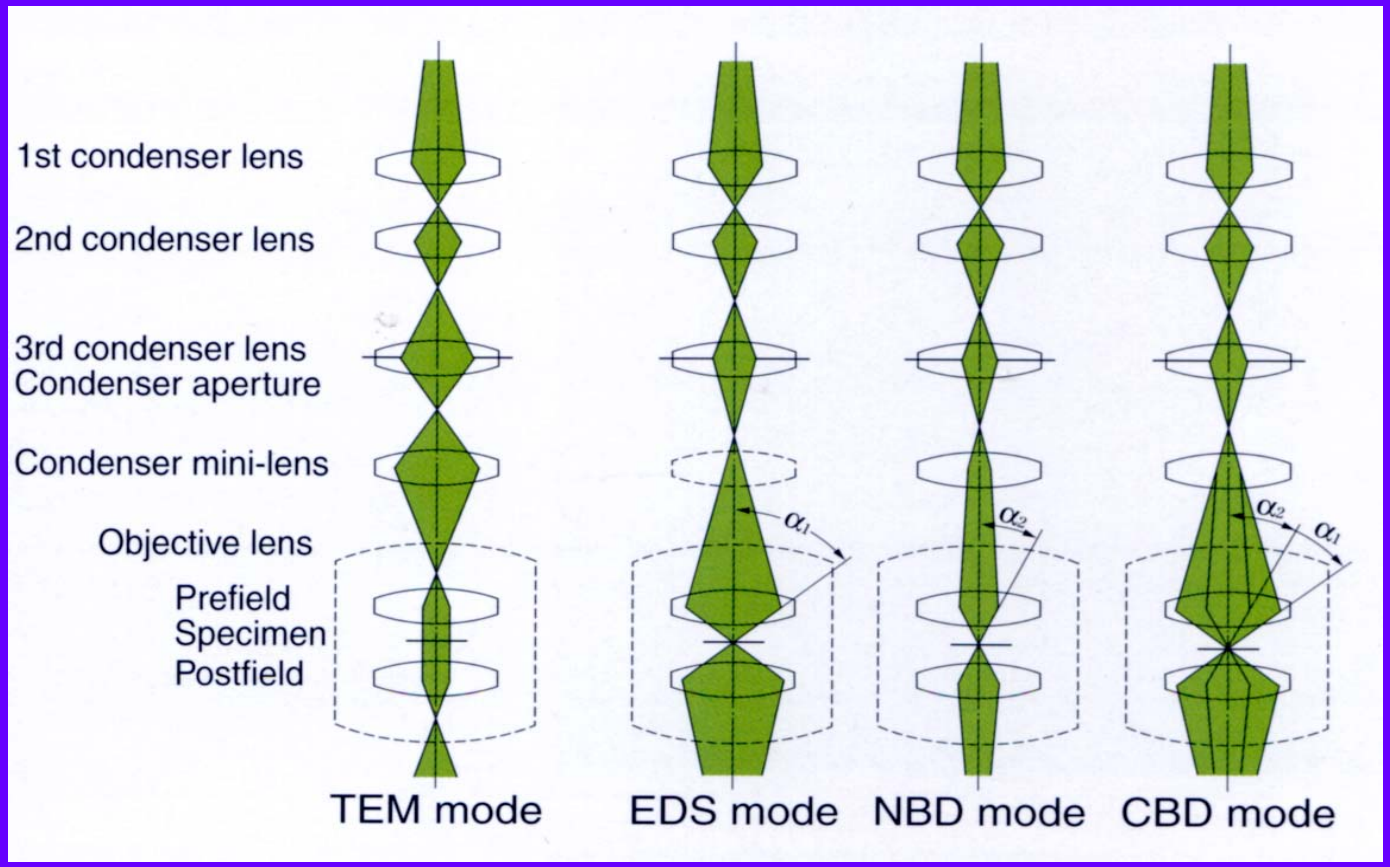


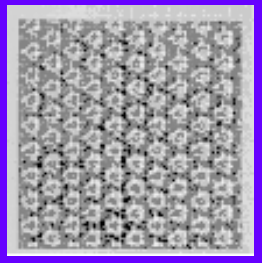


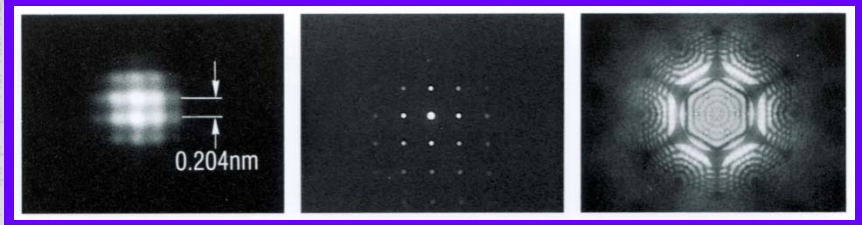
Imaging system



Quick Beam Select System

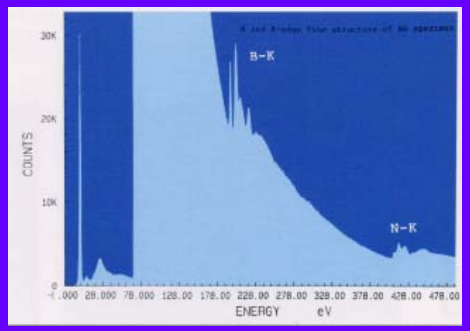




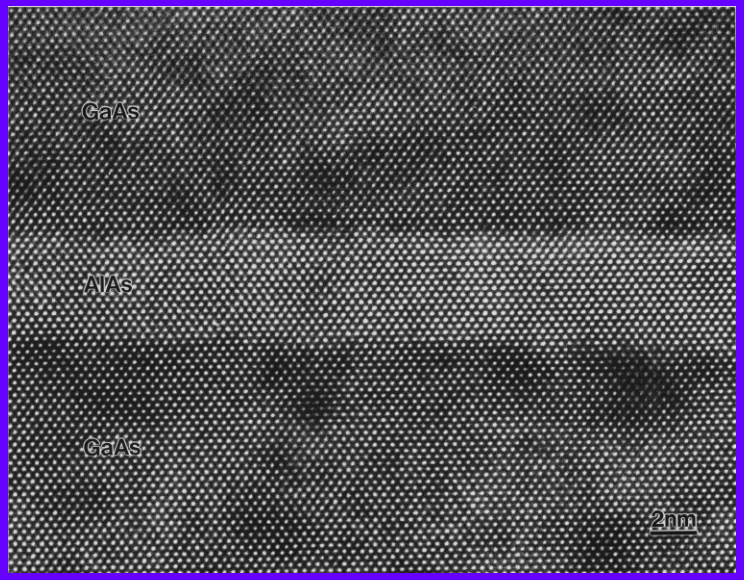


Information from TEM

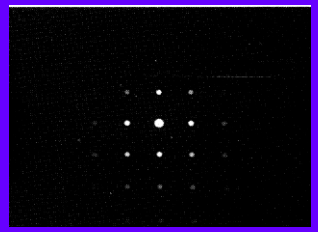
EDS



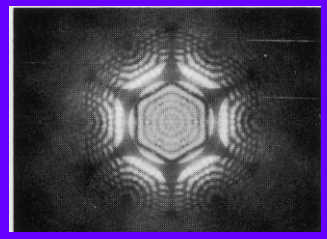
EELS or GIF



Lattice image
GaAs/AlAs



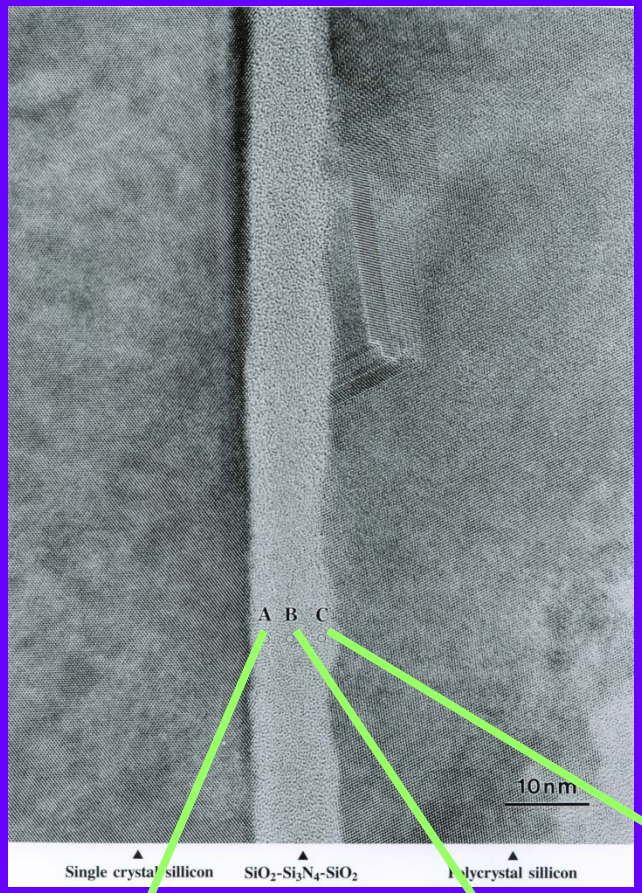
Electron Diffraction

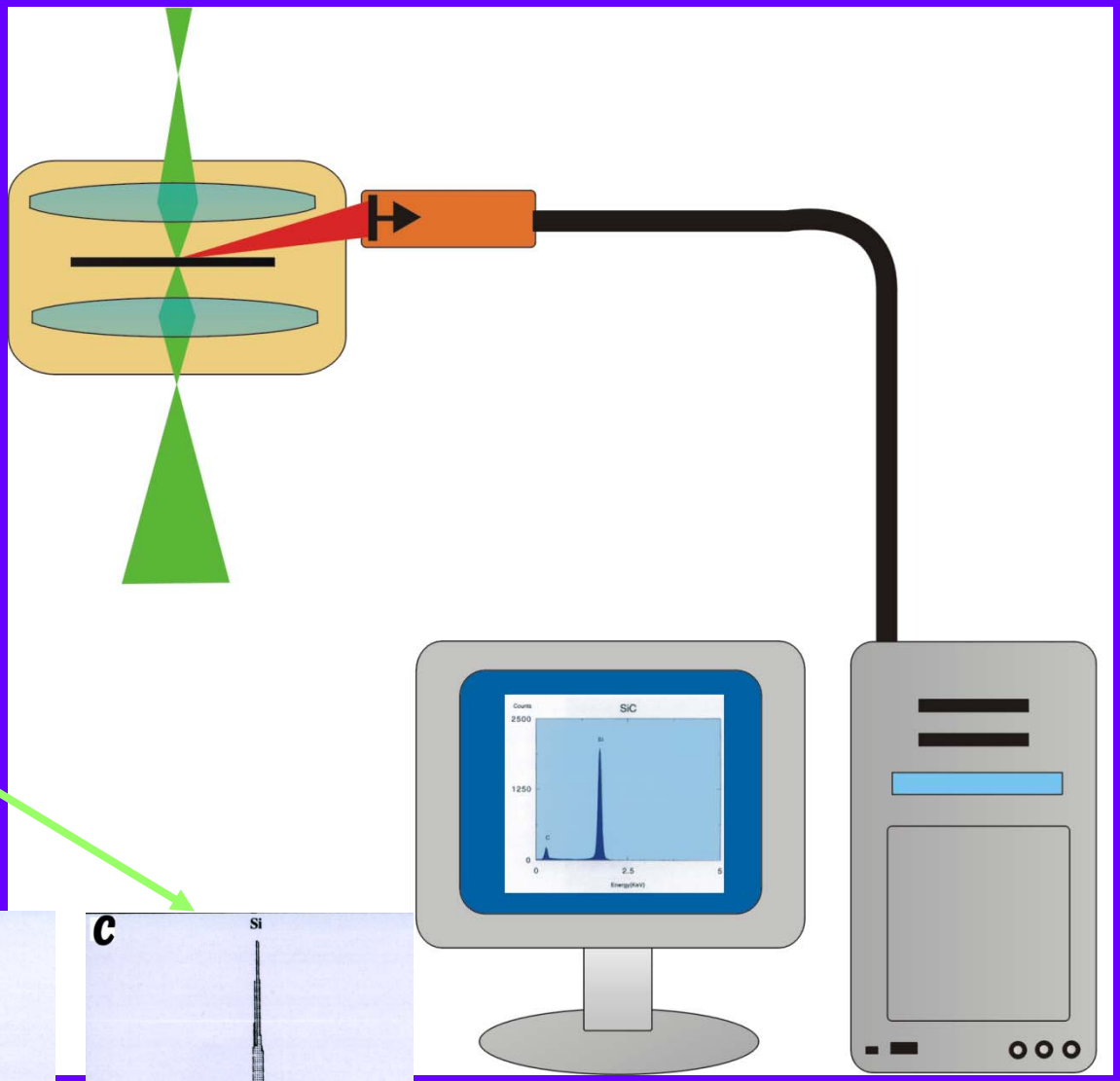


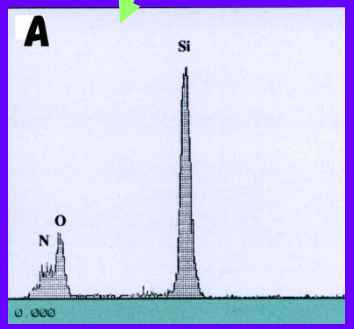
CBED

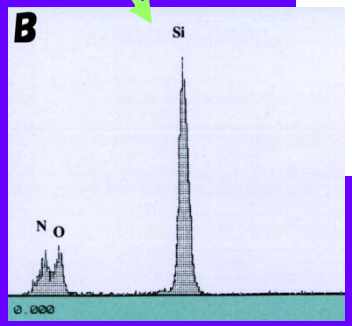
STEM+BF, HAADF →Mapping and Z-contrast image

EDS with spatial resolution

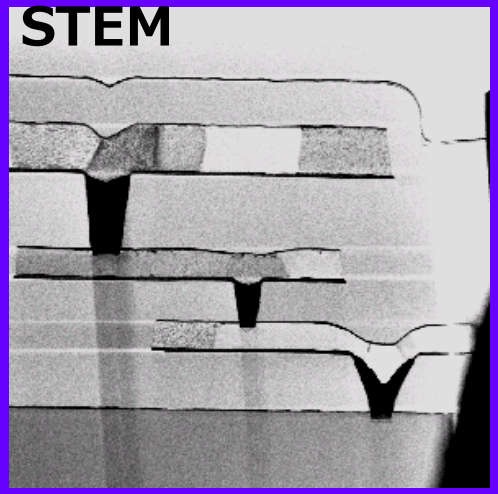


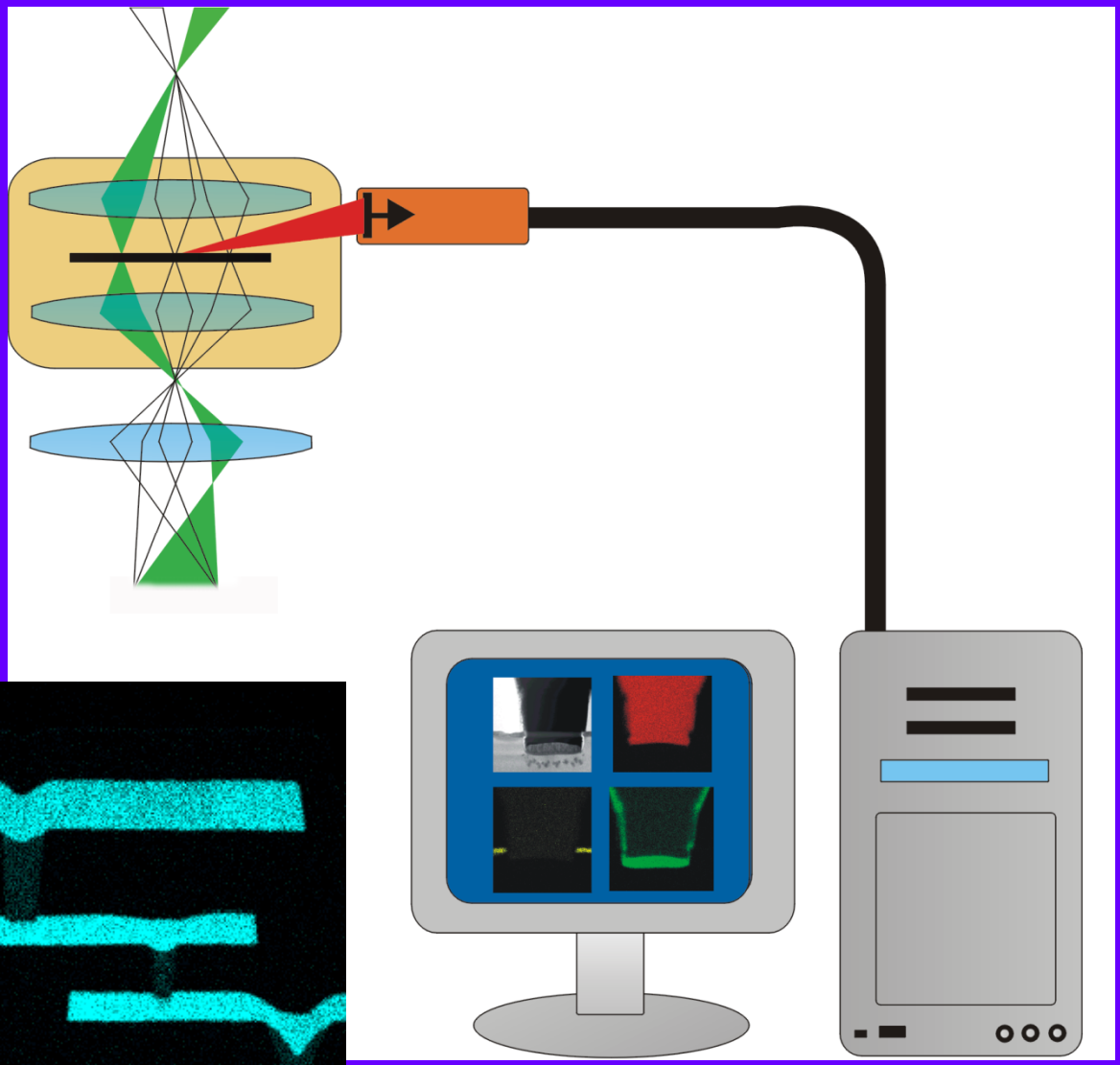


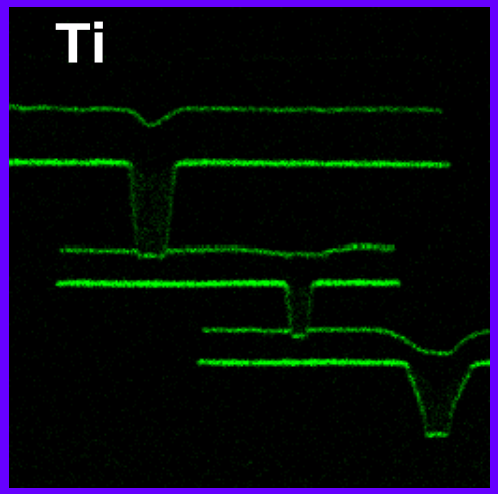




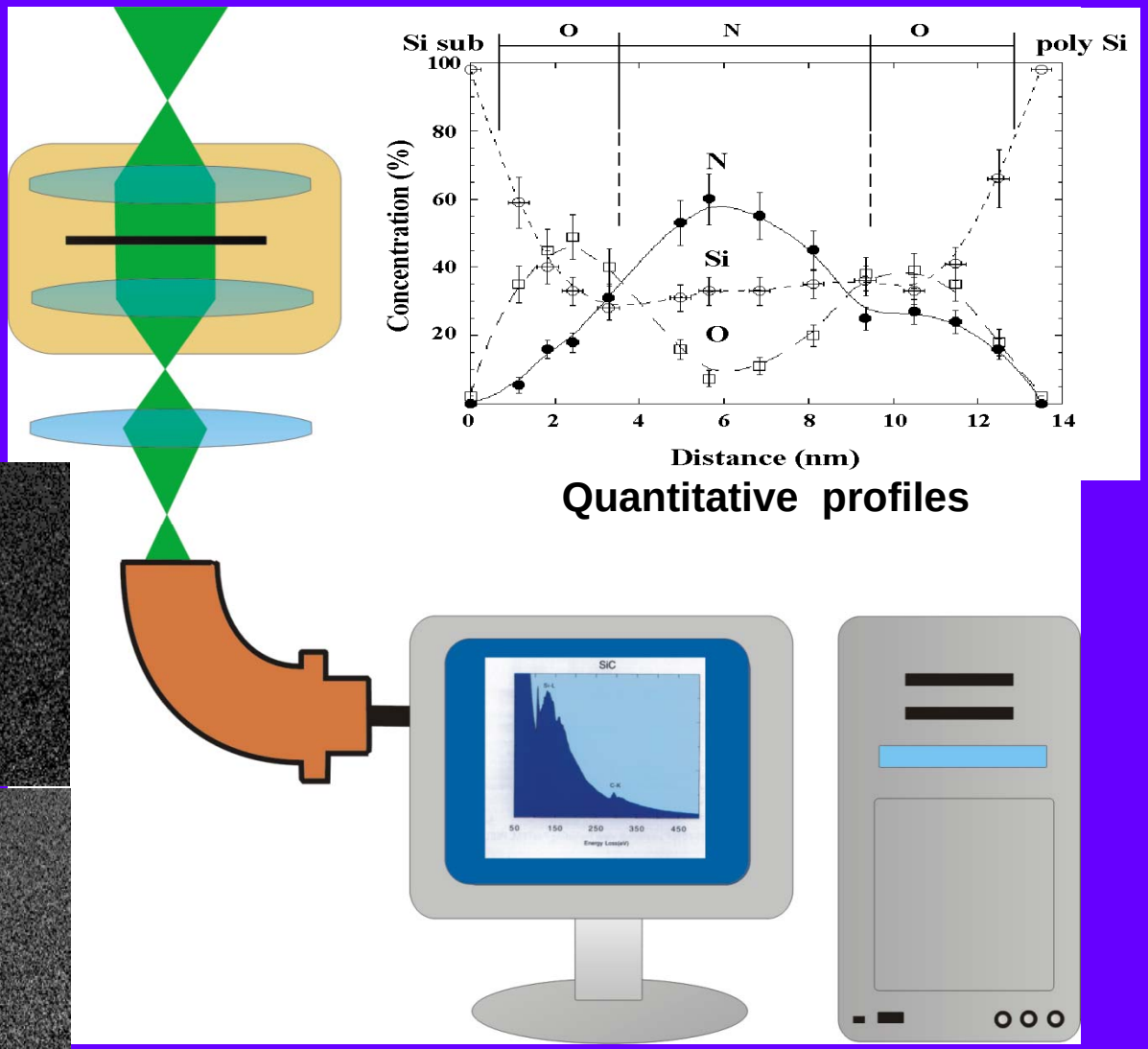
EDS mapping

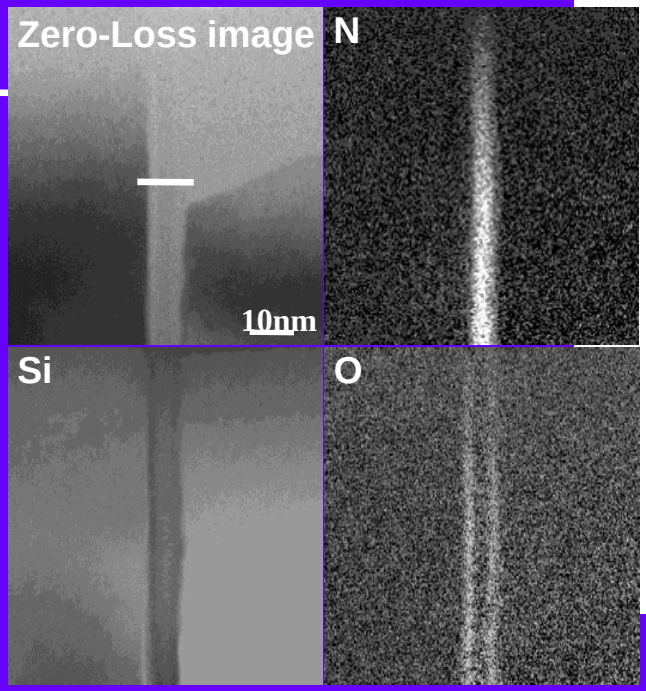






High resolution EELS

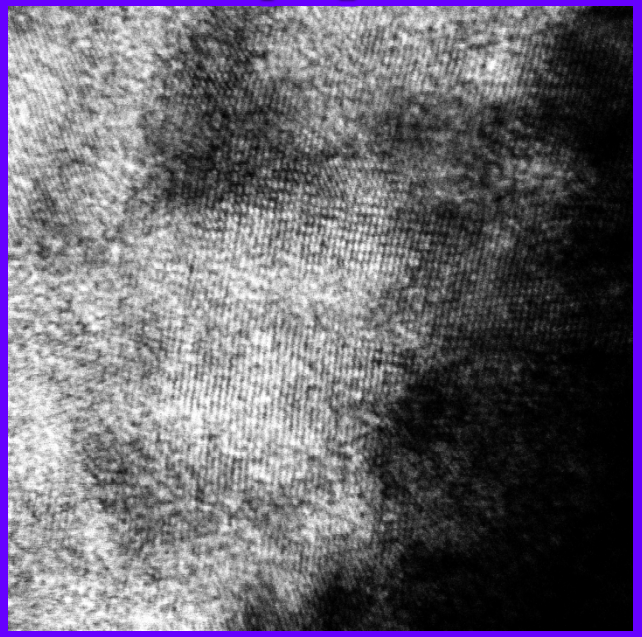


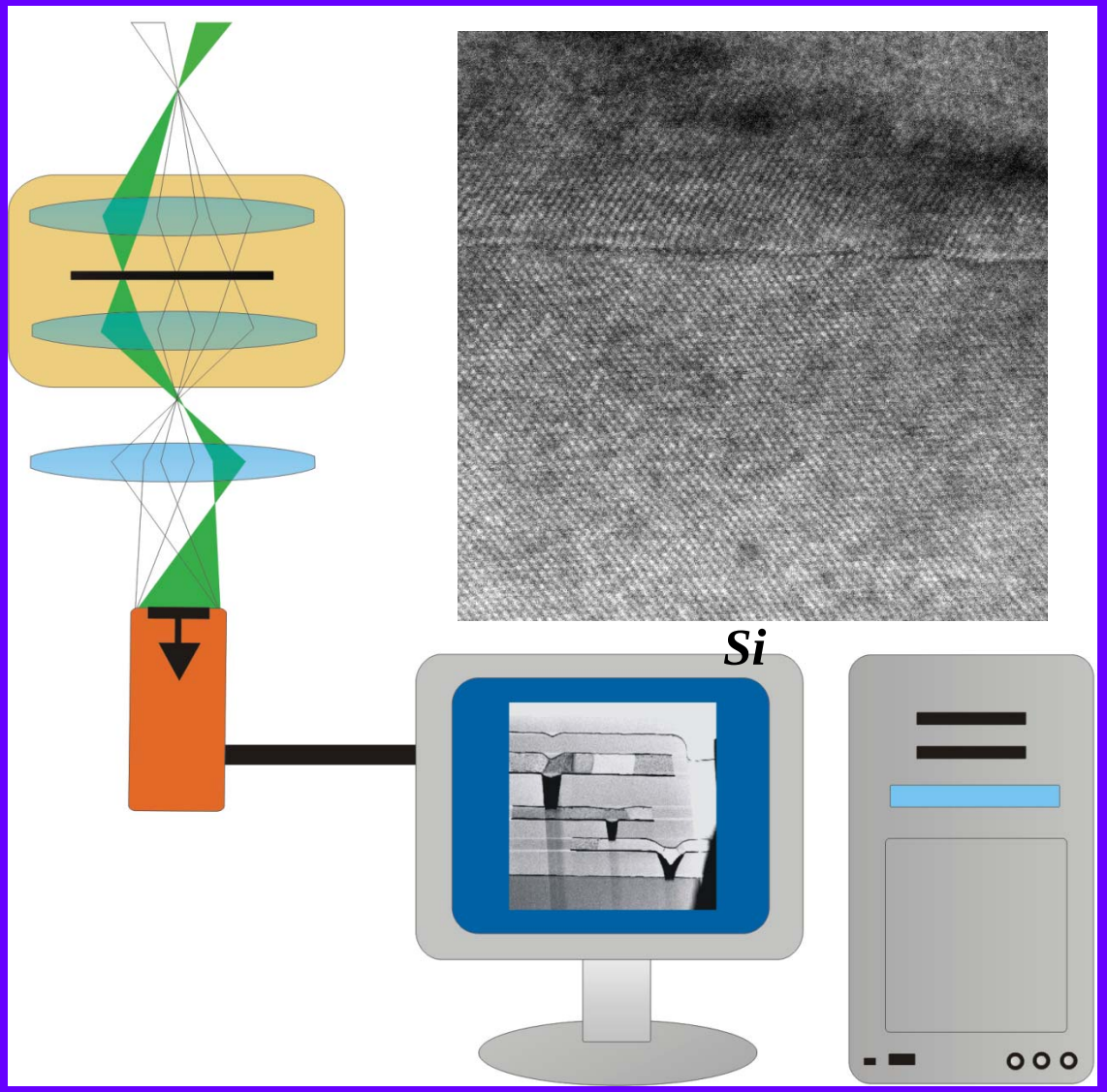


Energy Filtered images of insulating layer

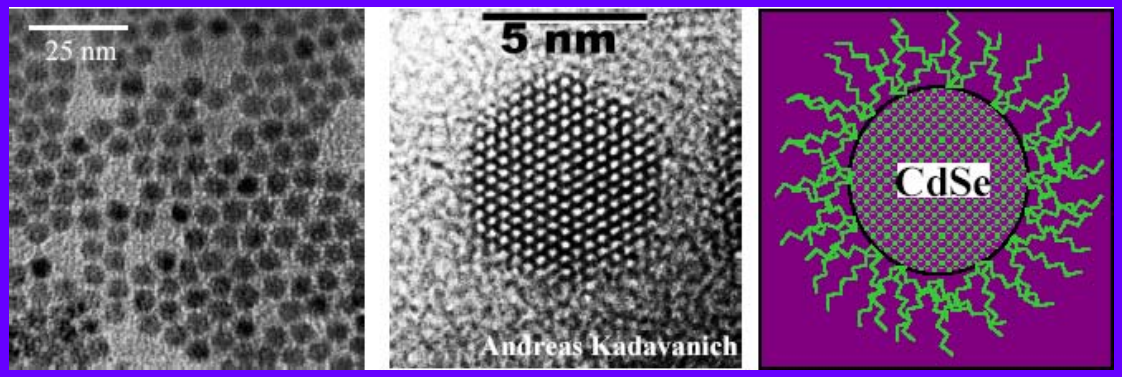
High resolution STEM image

W-plug.

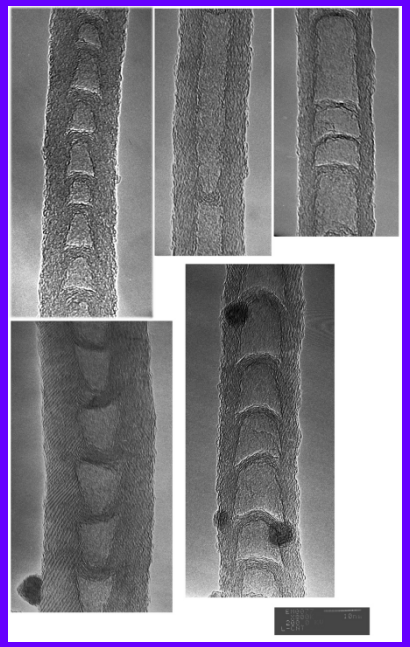




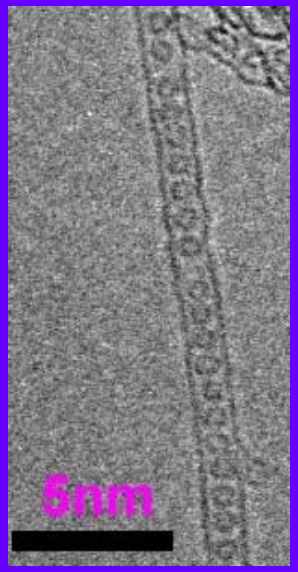
Semiconducting quantum dots and carbon nanotubes



(Reproduced from Quantum Dot Co.)

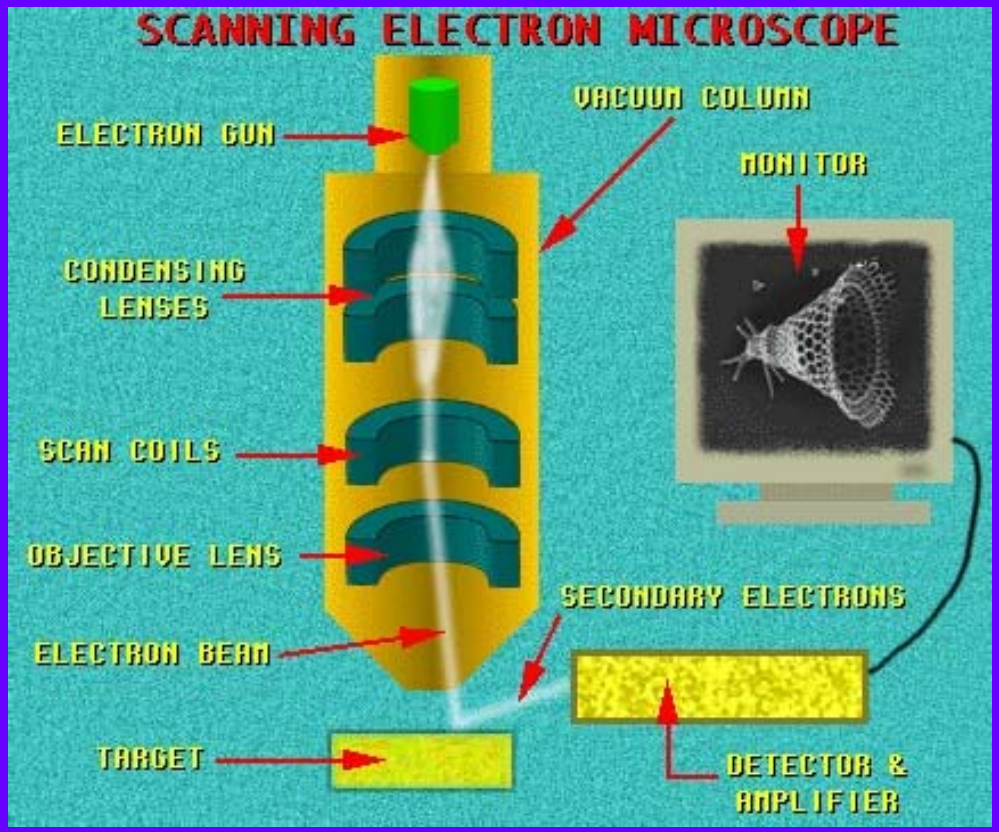


Multiwall CNT



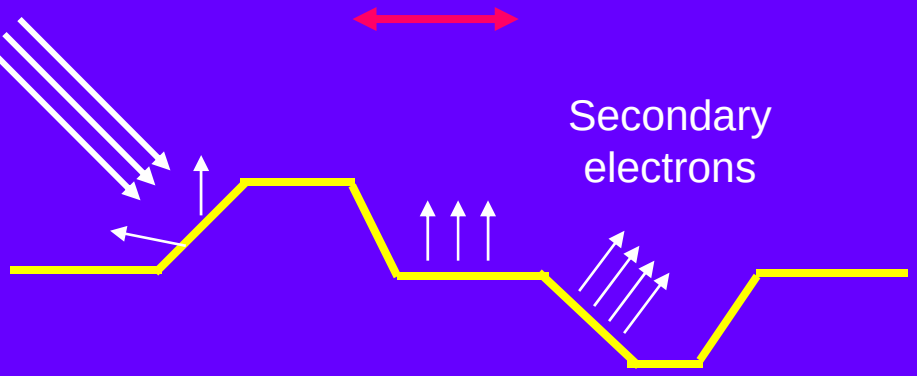
Peapod CNT

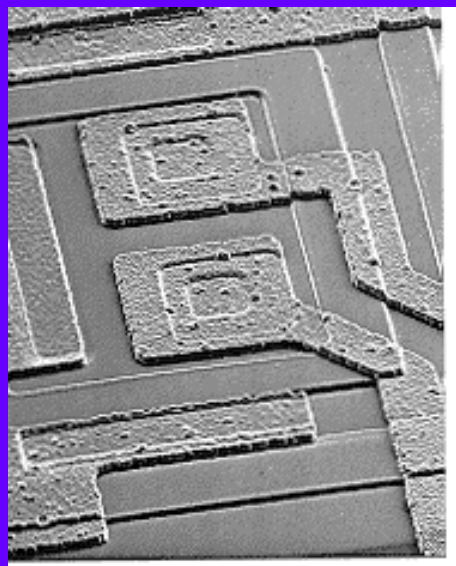
Scanning electron microscopy (SEM)



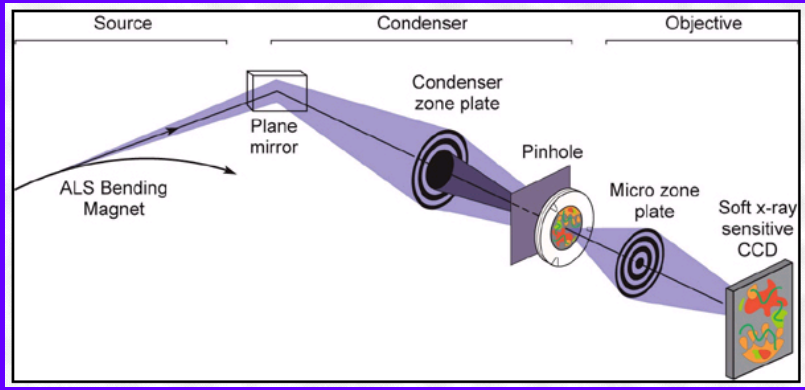
SEM contrast

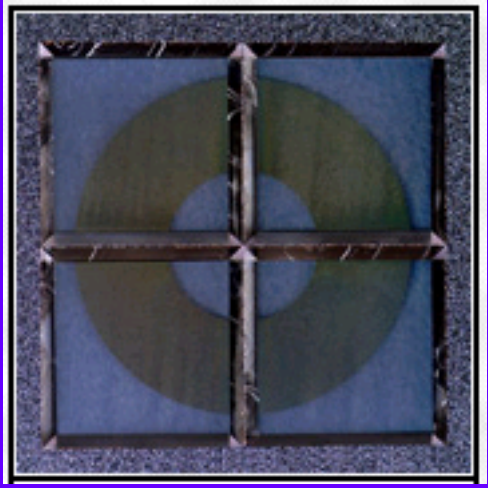
Scanning e beam

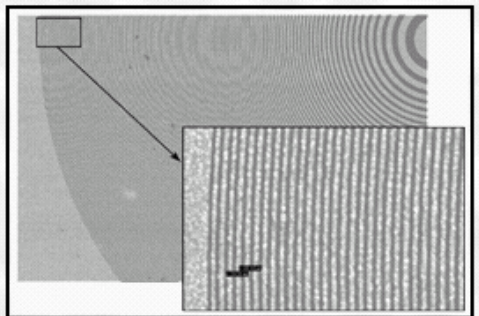




X-Ray Microscopy

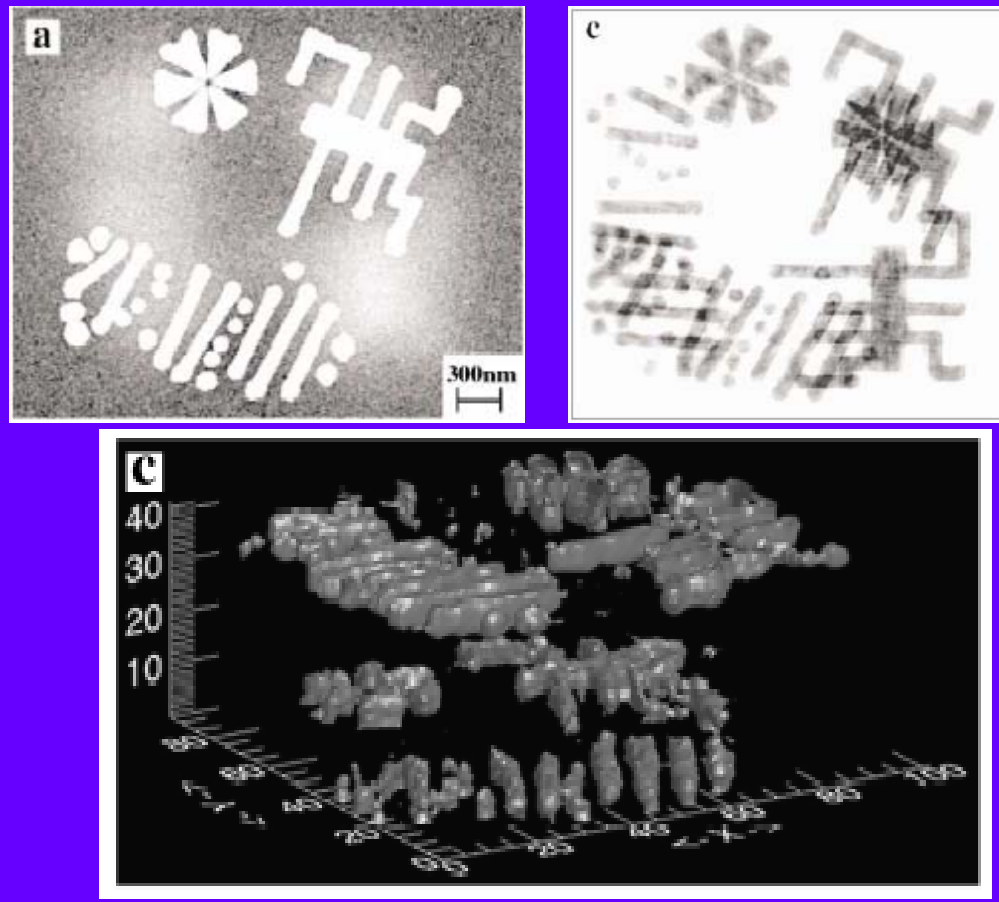






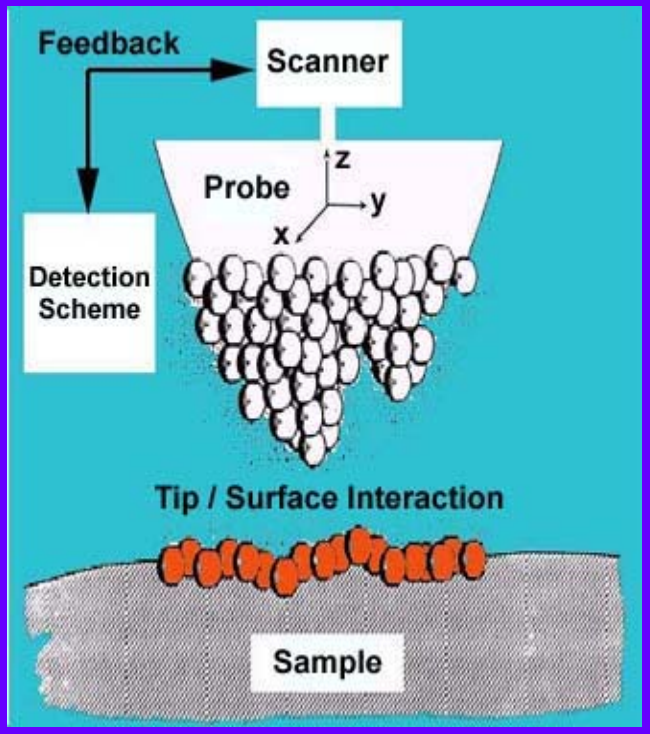
SEM micrograph of a 25-nm-outermost zone width micro zone plate. Diameter = 63mm, 628 zones, gold plated.

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)

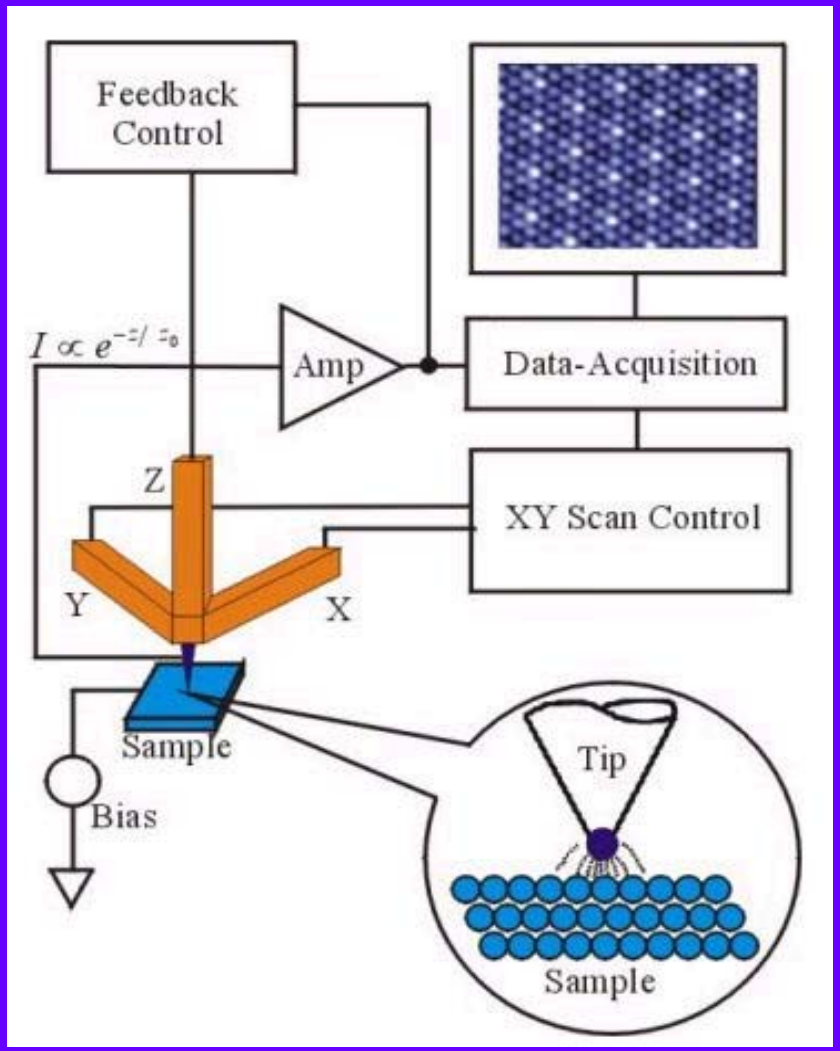
--- Y. Martin, D. W. Abraham et al (1988)

Scanning Capacitance Microscopy (SCM)

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

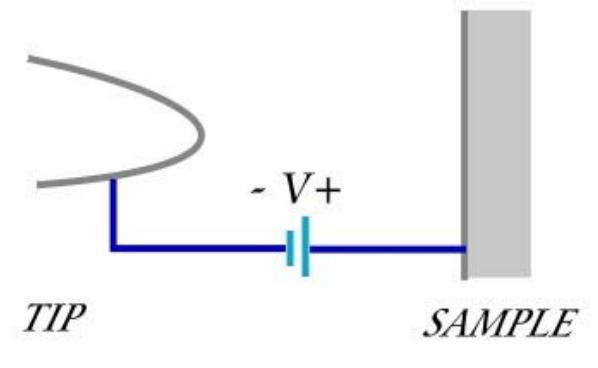
Force Modulation Microscopy (FMM)

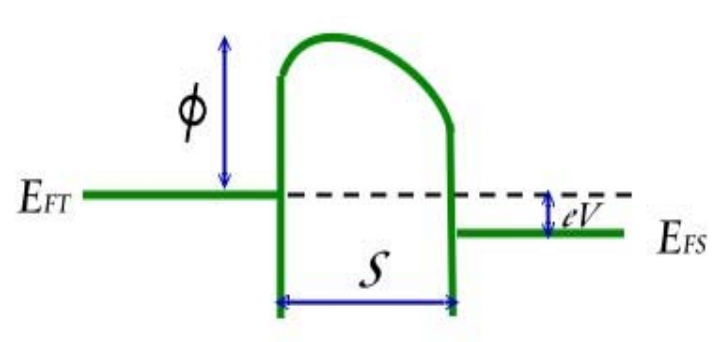
--- P. Maivald et al (1991)



Scanning Tunneling Microscopy

Theory of STM

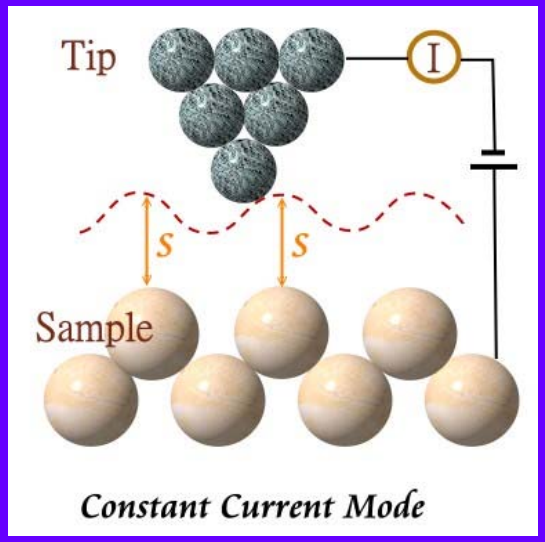




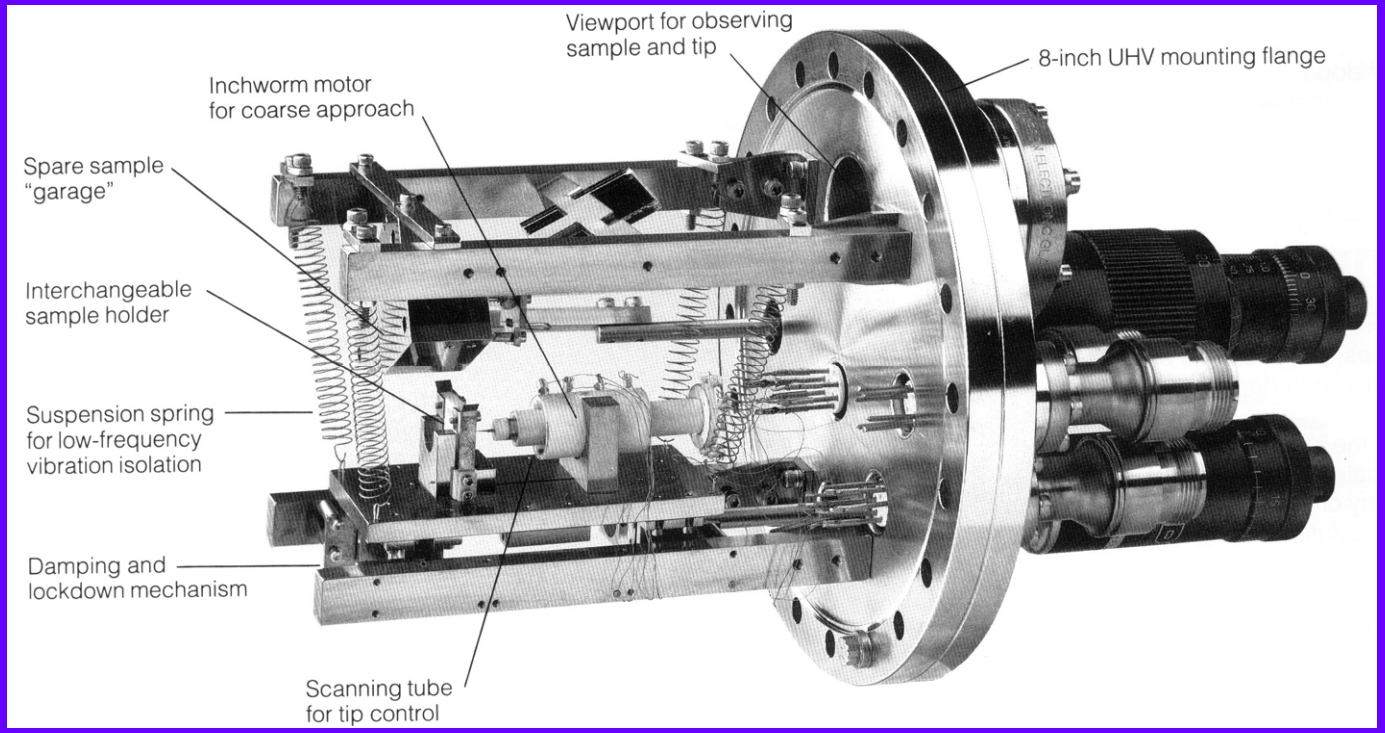
From one-dimensional tunneling problem tunneling current (eV<< ϕ)

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

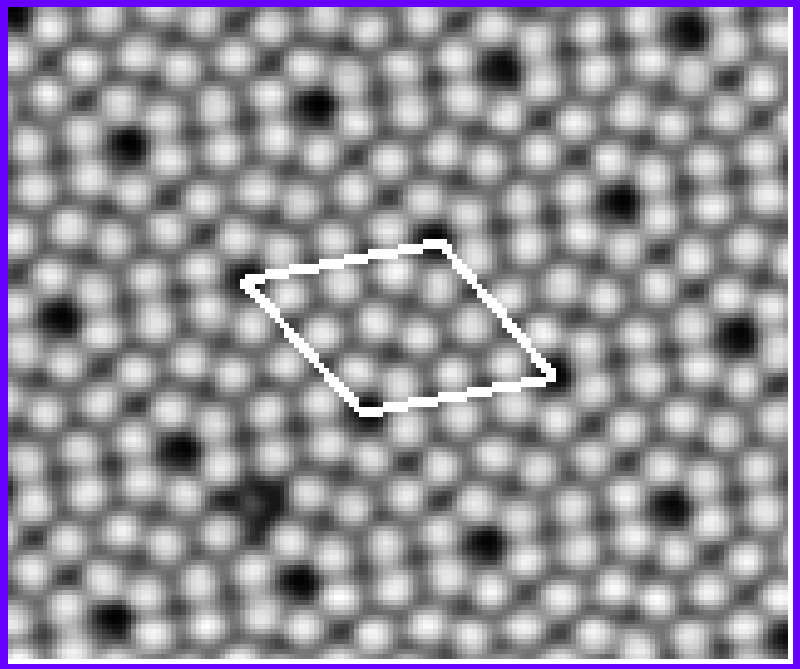
$$A = 1.025\ (eV)^{-0.5}\ \text{Å}^{-1}$$



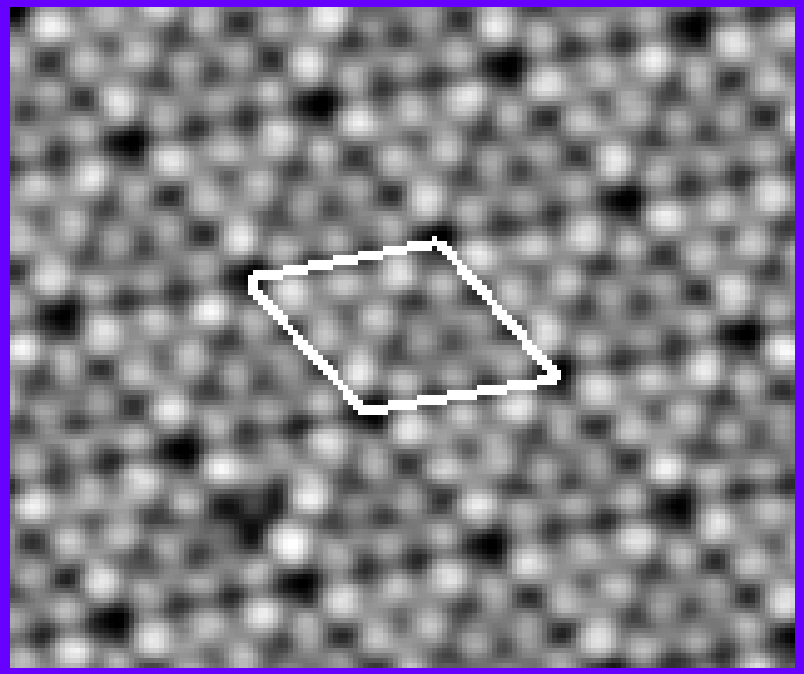
UHV STM


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)



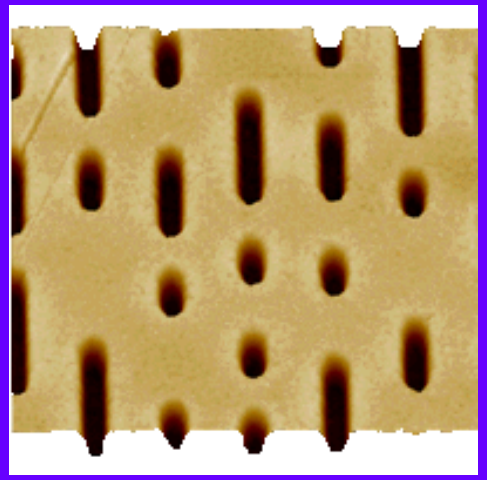
Empty-state image



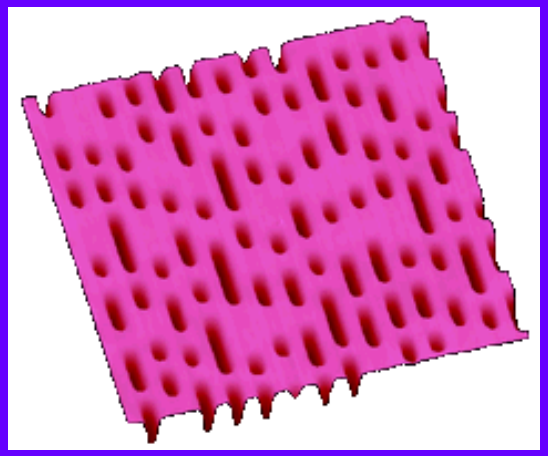
Filled-state image

AFM images

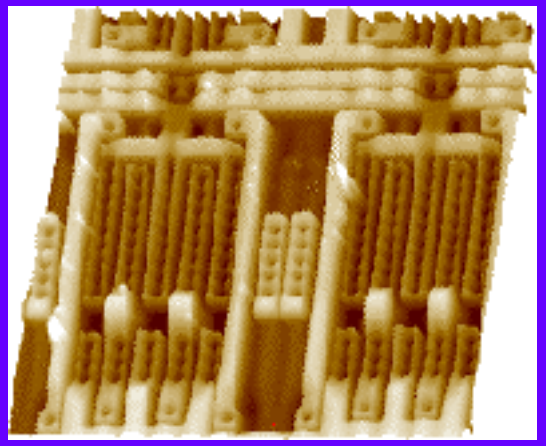
CD pits



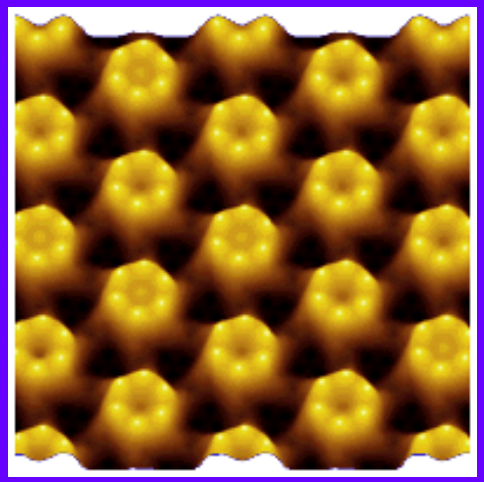
DVD pits



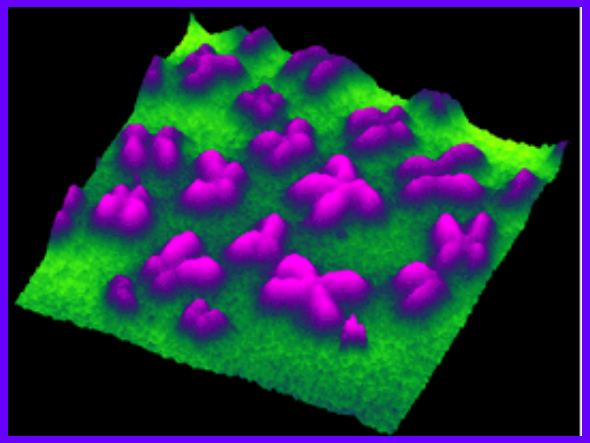
Integrated Circuit



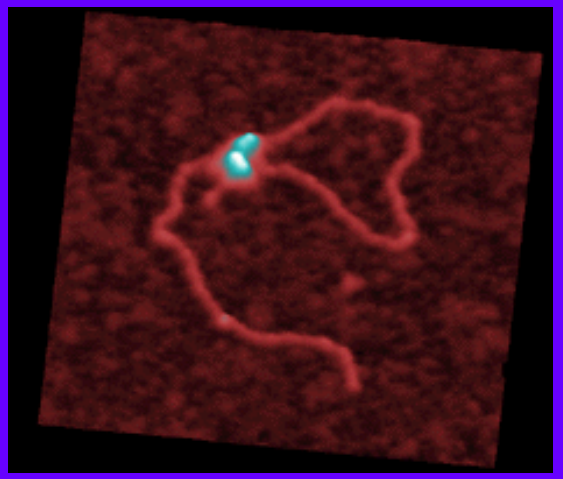
Bacteria



Chromosomes



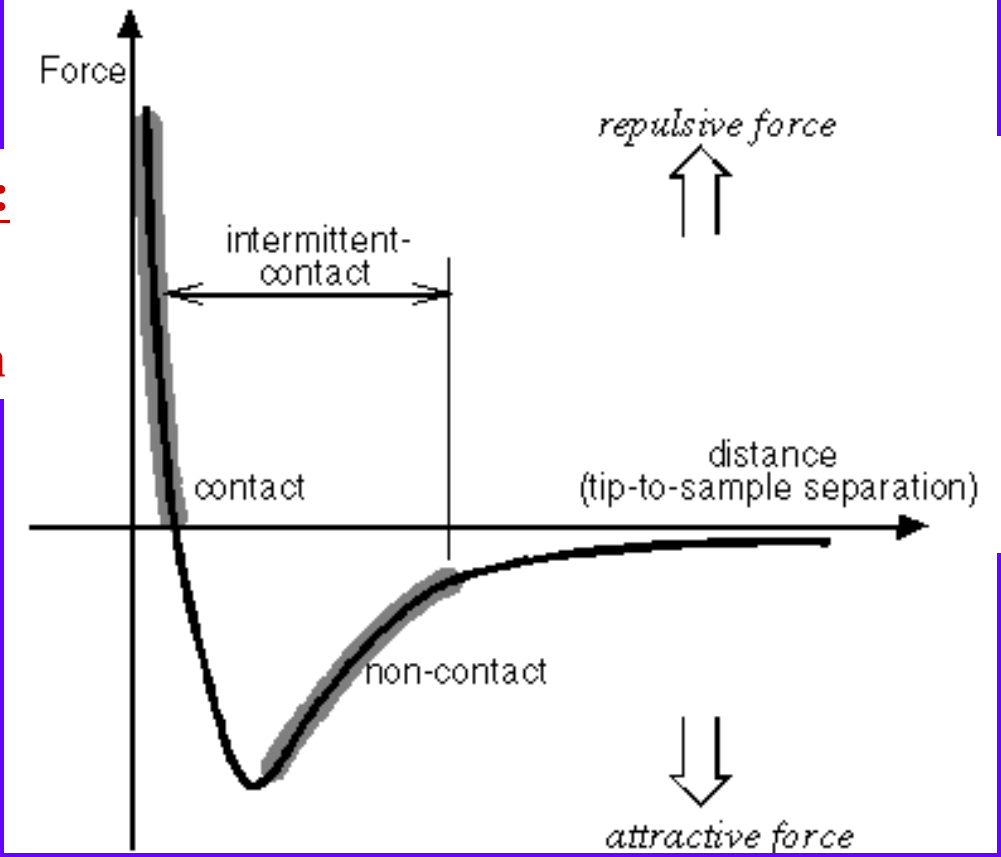
DNA



Interaction between the probe and sample

Short-range:

1) **Bonding**
2) **Repulsion**

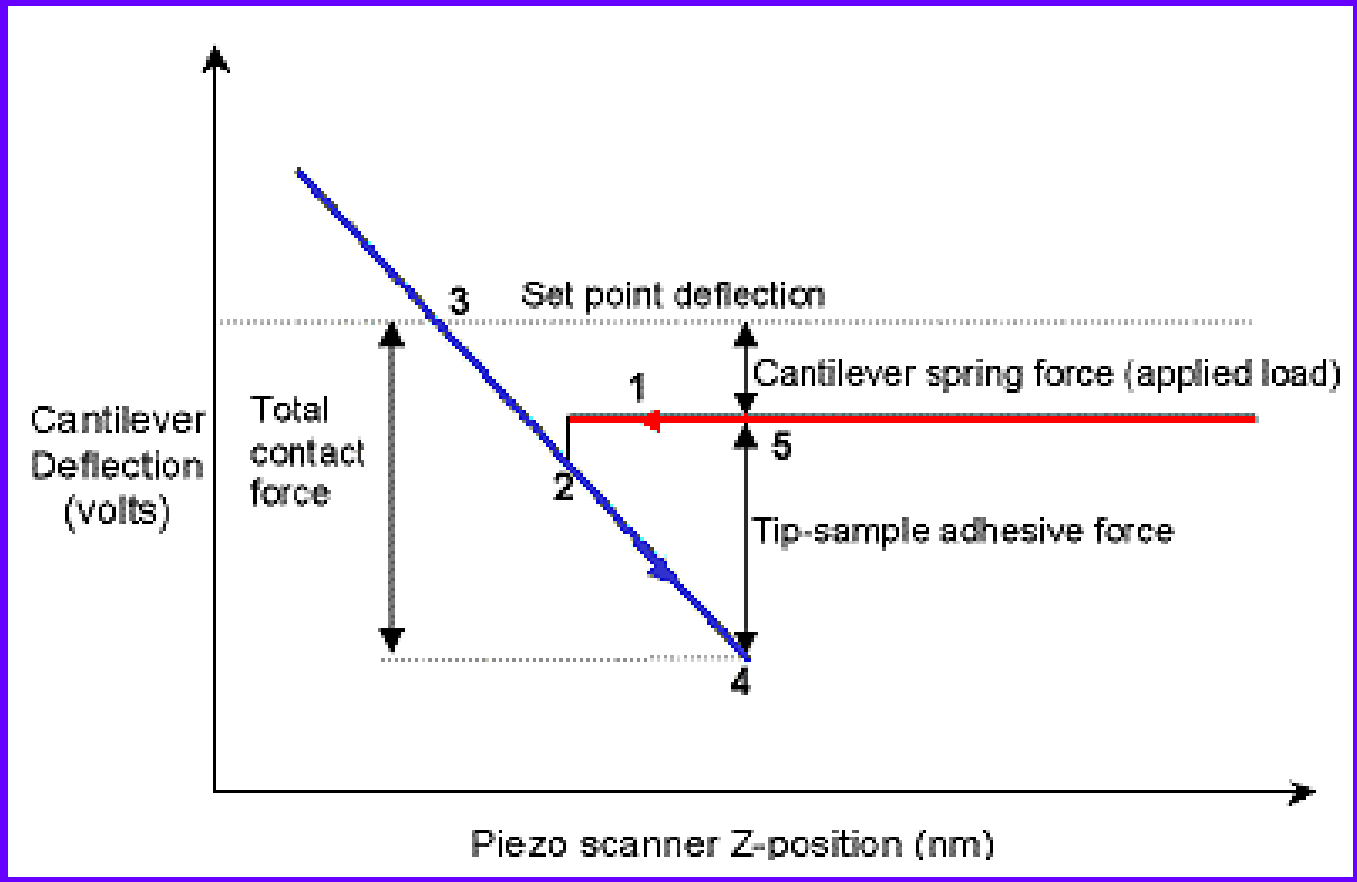


Long-range:

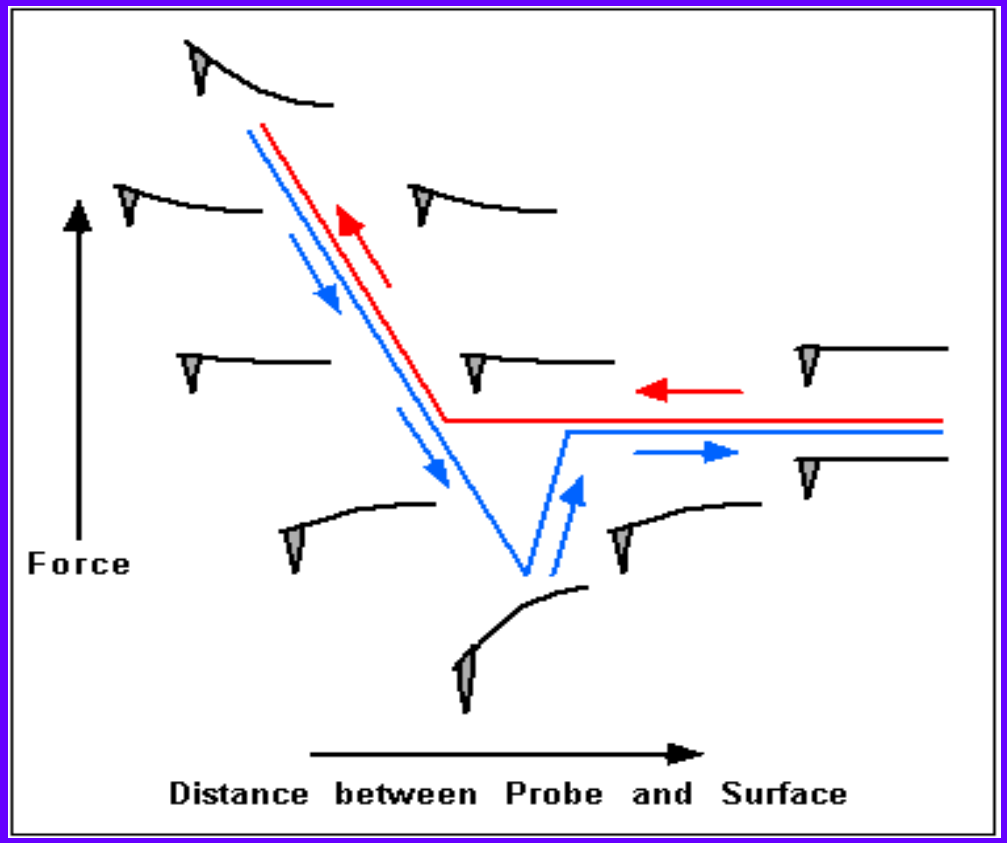
1) **Van der Waal**
2) **Capillary**
3) **Magnetic**
4) **Electrostatic**

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

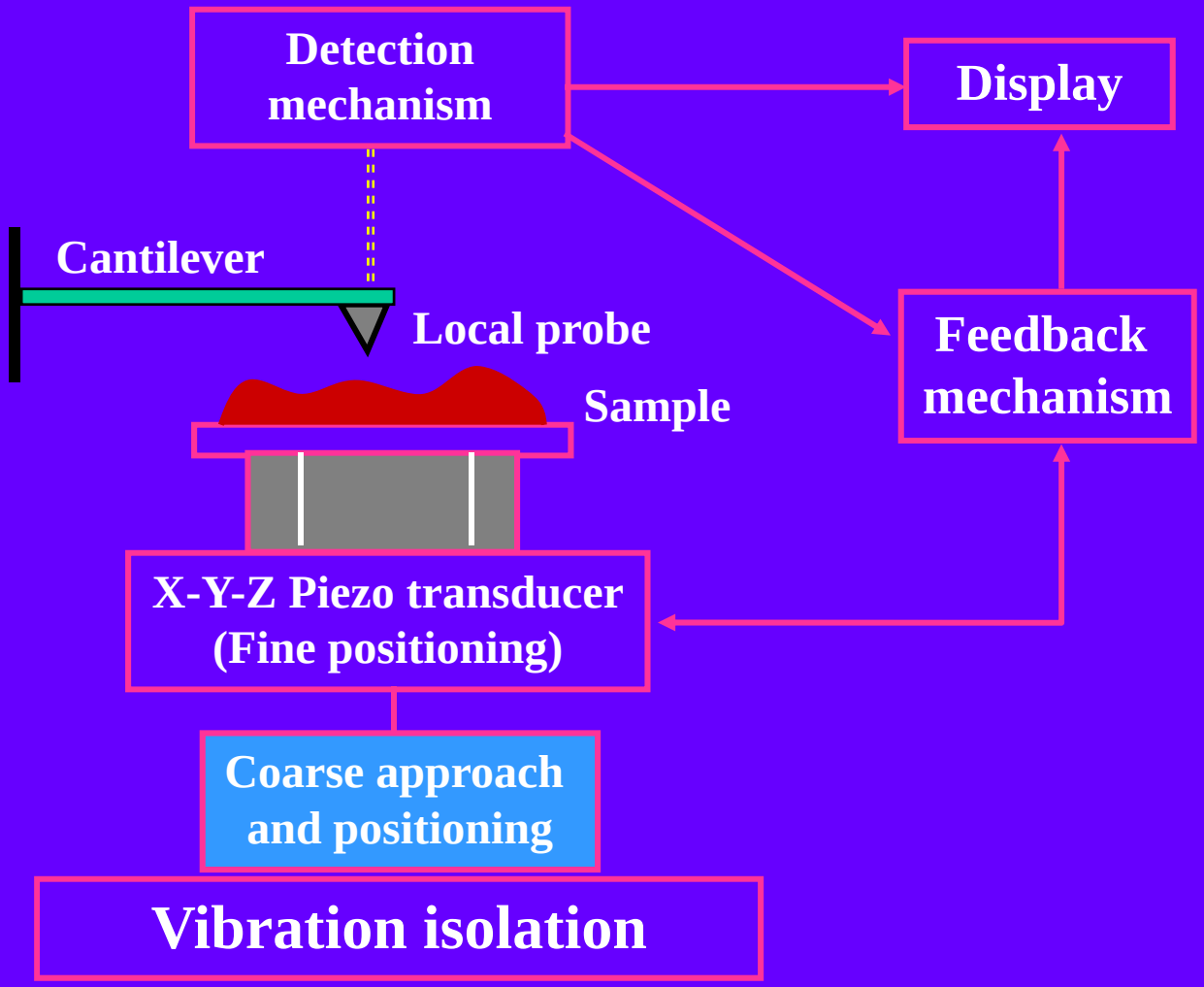
Deflection of Cantilever vs Piezo displacement



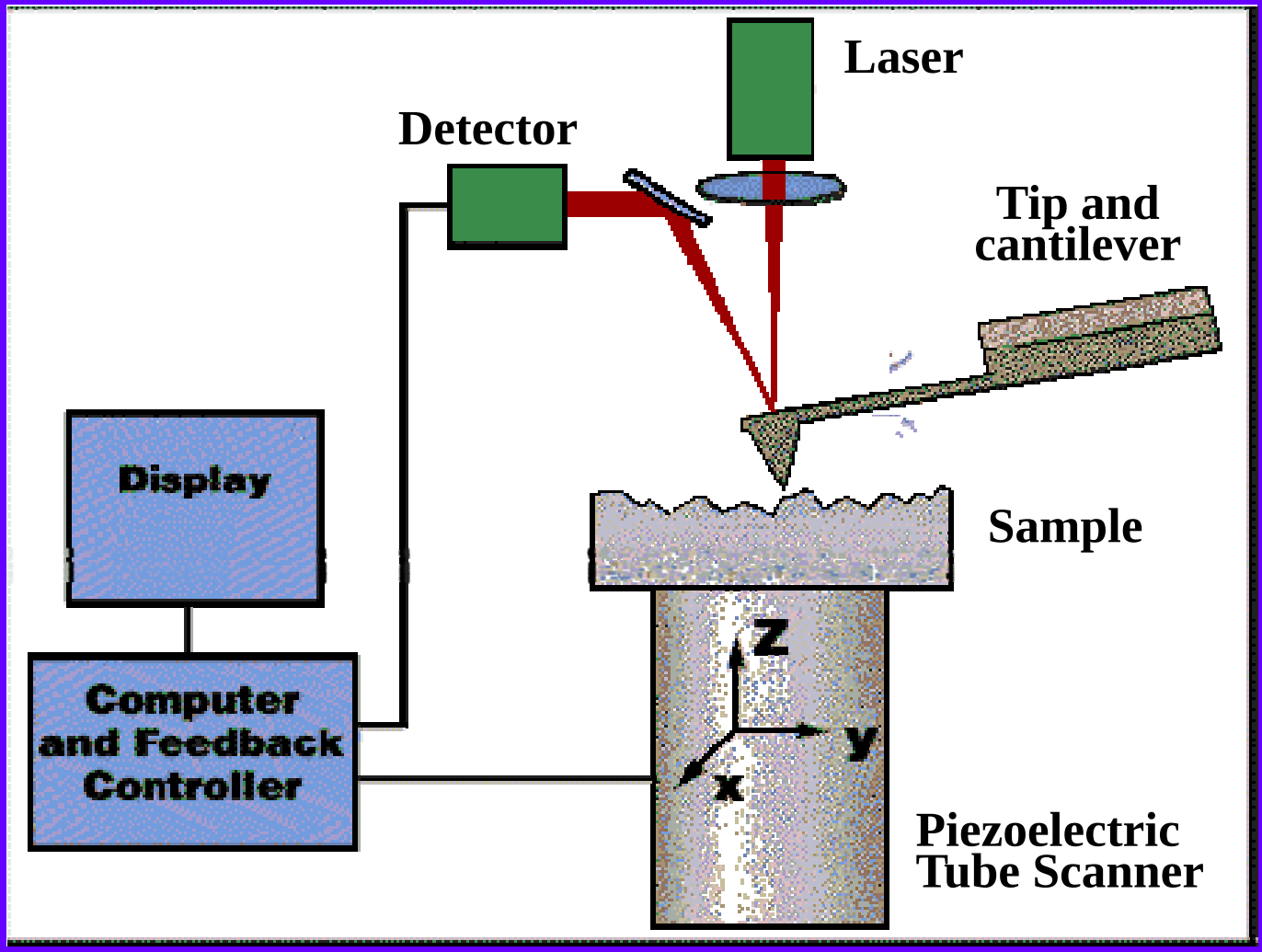
Reaction of probe to the force



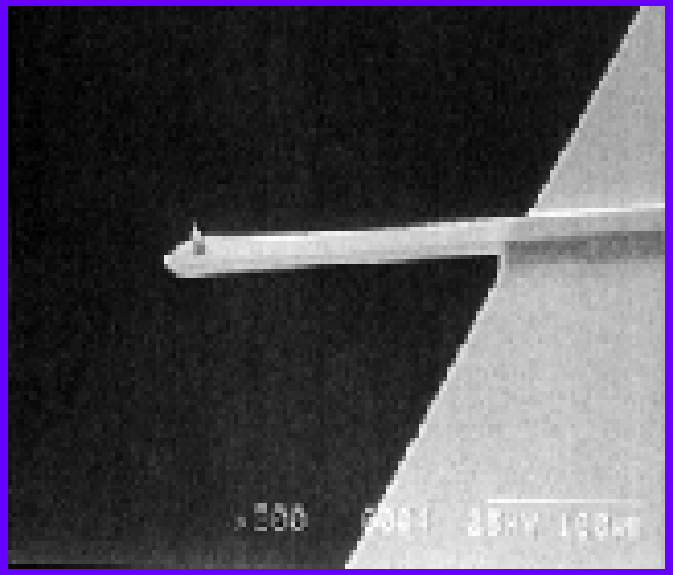
Basic configuration of AFM

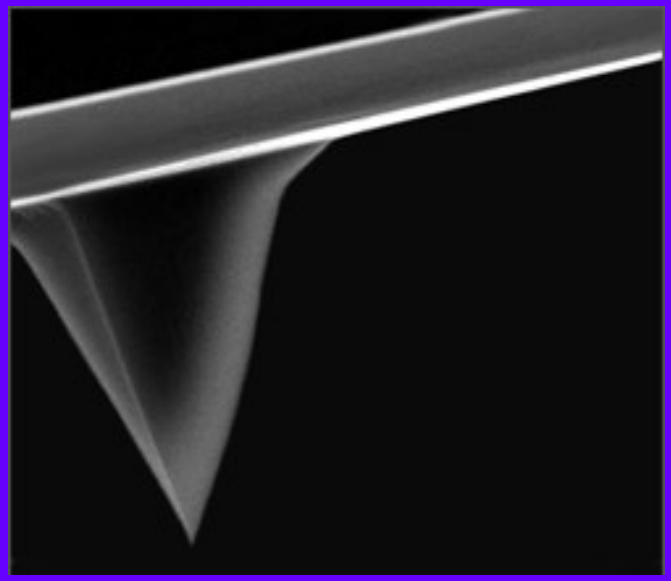


Core components of an AFM

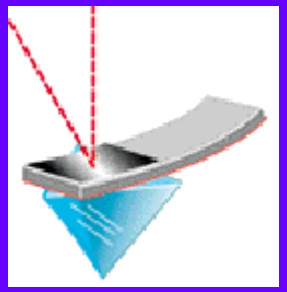


Probes for the tapping mode





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



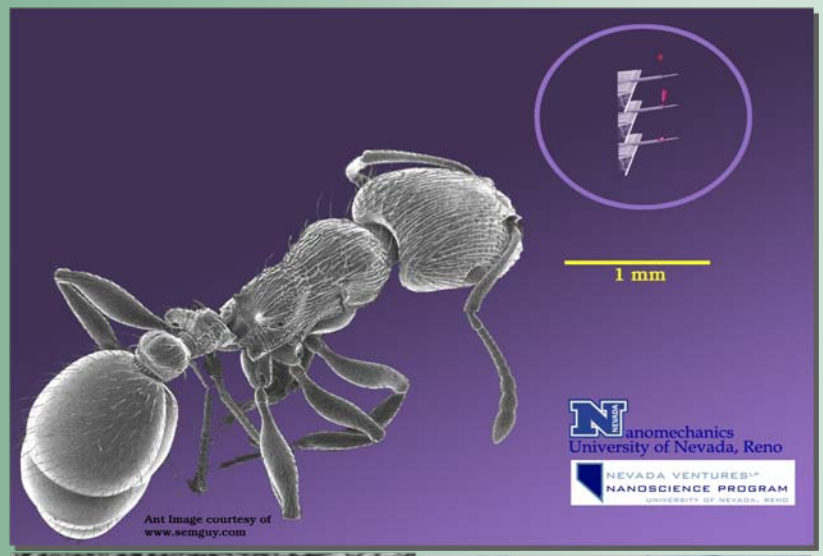
Comparisons among various microscopies

	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)
lateral	300nm	1nm	0.1nm	0.1nm
vertical	20nm	10nm		0.01nm
Imaging area	1mm	1mm	0.1mm	0.1mm
Imaging environ	none	vacuum	vacuum	none
Sample prep	no	yes	yes	no
Elemental anal	yes	yes	yes	no

Molecular Scale Nanomechanics
Driving Force in Bio-systems

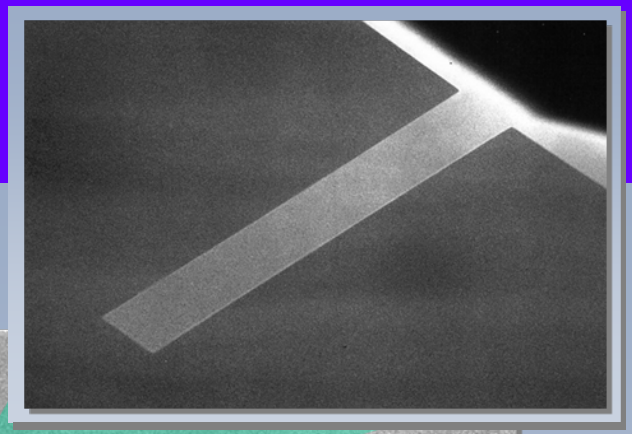
At the fundamental level, all interactions in biology and chemistry are mechanical in nature

Mechanical Sensing in Nature

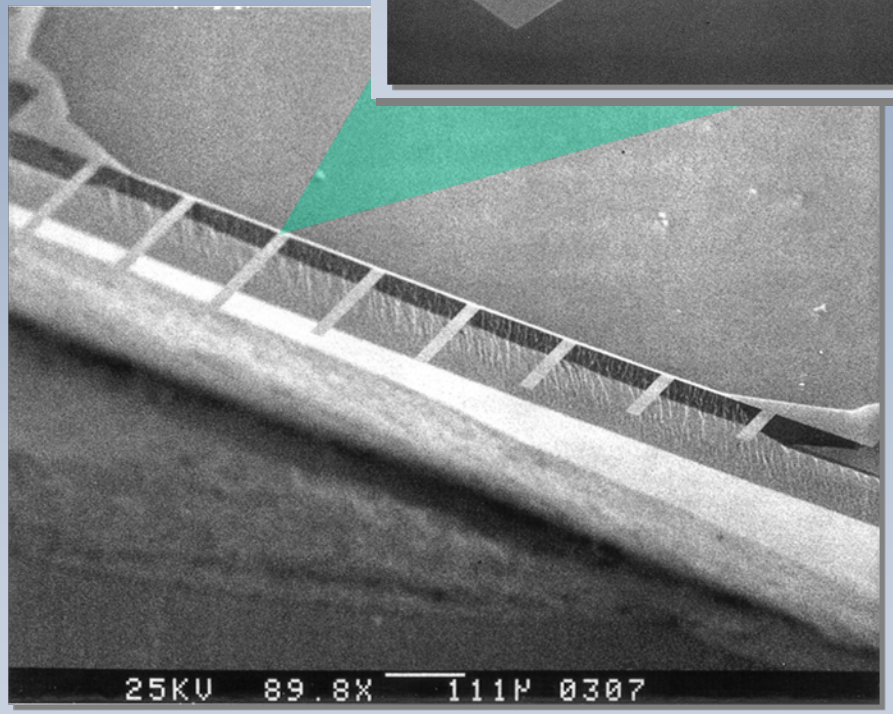


Hair bundle: frog's inner ear

Micro and Nano cantilever arrays - *Emulating nature*



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



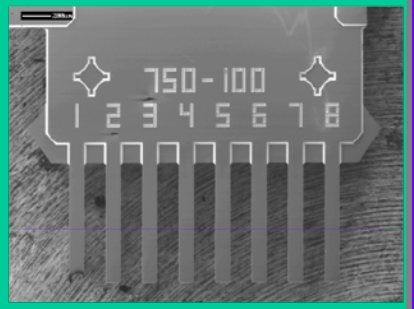
Sesitivity:
Function of dimensions

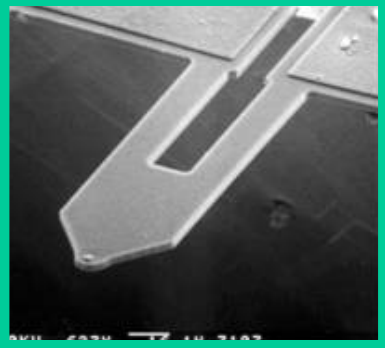
Selectivity:
Function of coatings

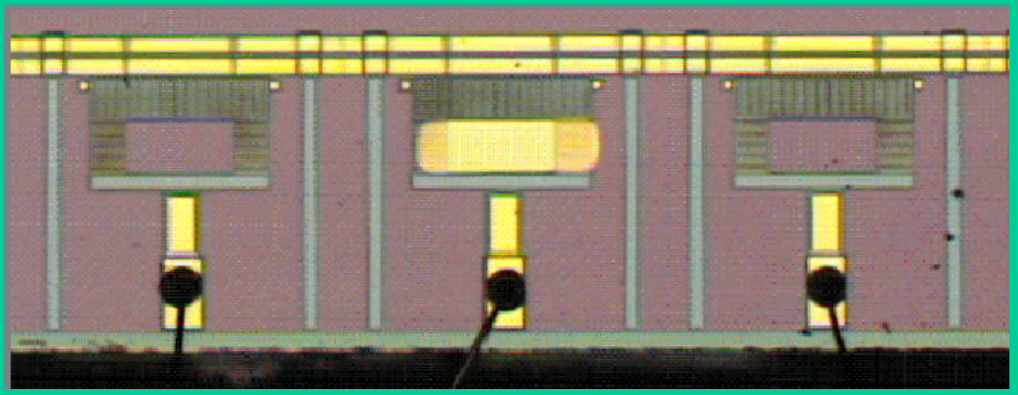
- **Mass production**

Microcantilevers:
Getting the signal out

- Optical
- Piezoresistivity
- Piezoelectricity
- Capacitance



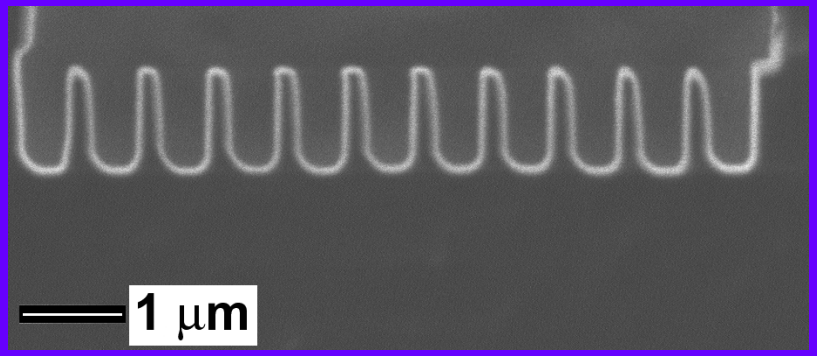


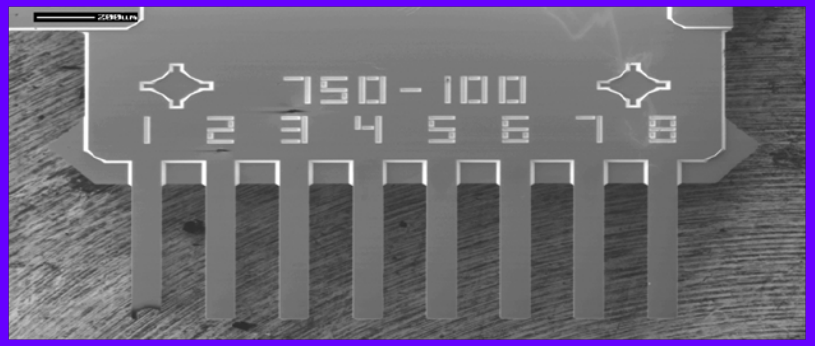


Microcantilevers To Nanocantilevers

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

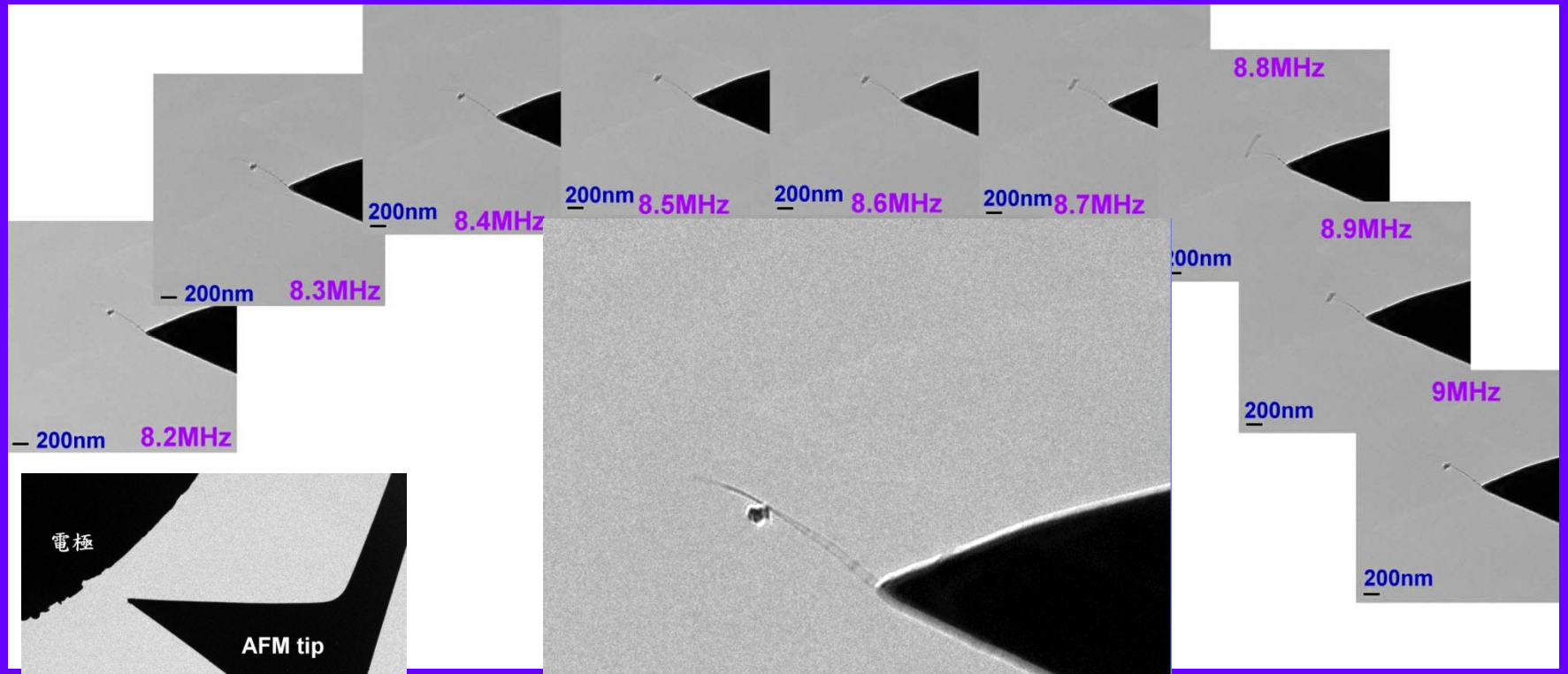
- Challenges:
  - Signal Transduction
  - Mass production



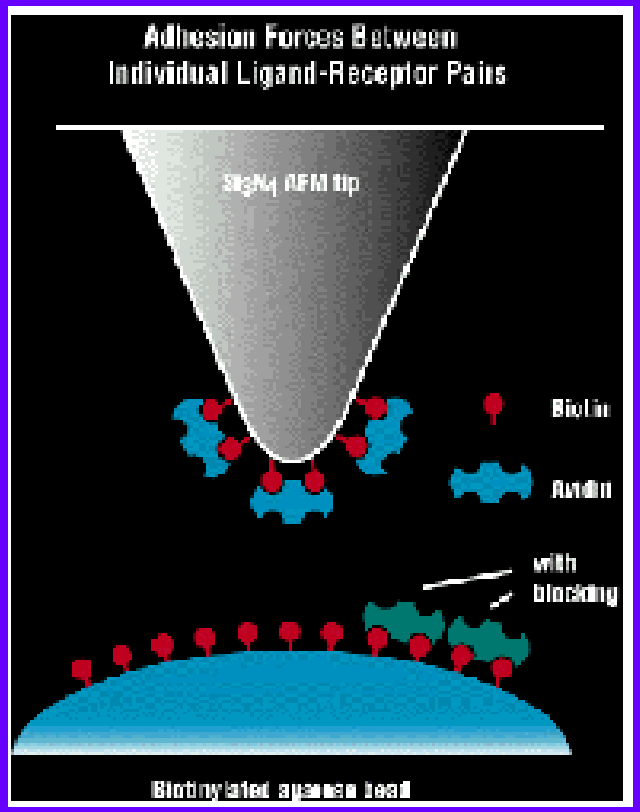


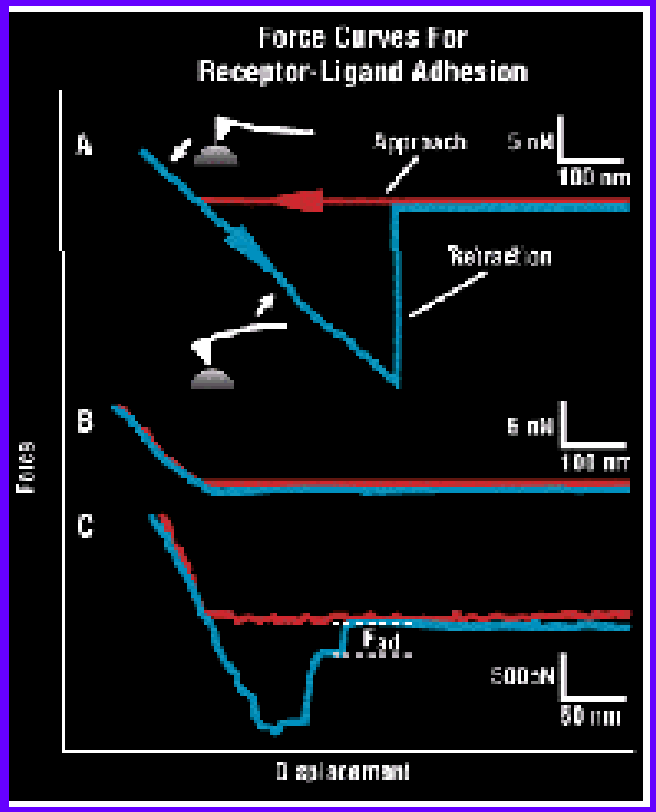
(Craig Prater, DI)

Nanoelectromechanical oscillator

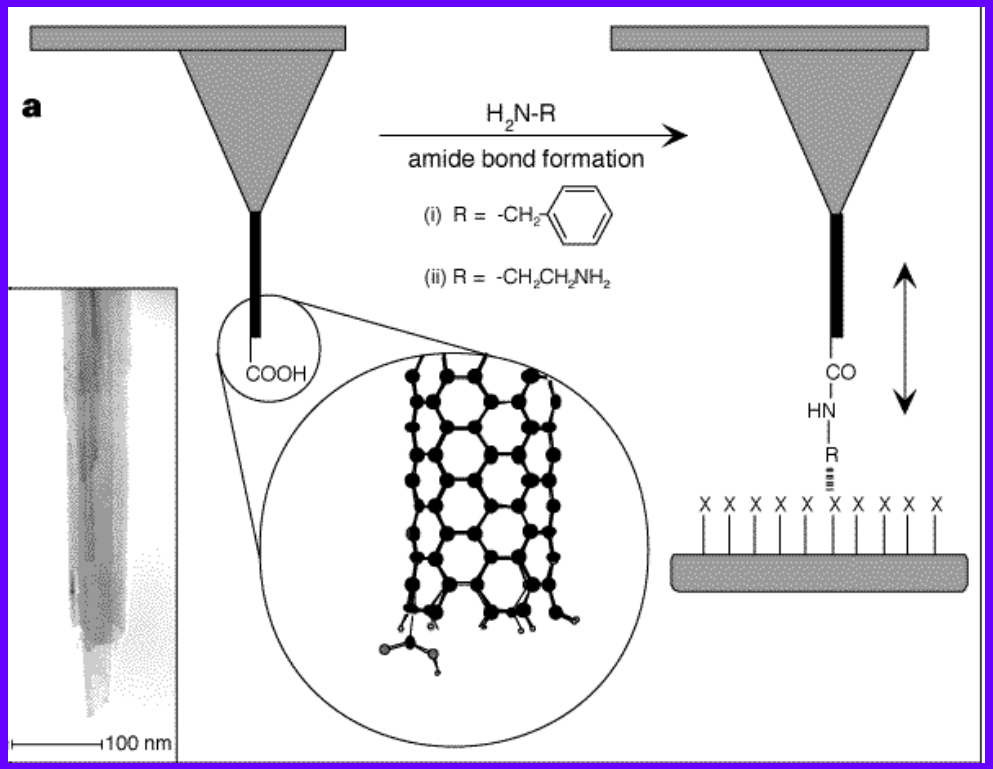


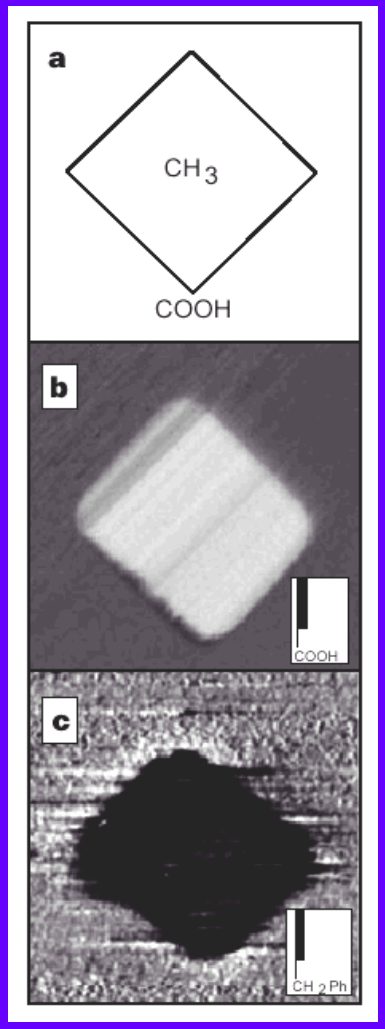
Molecular sensing





Chemical nanoprobe



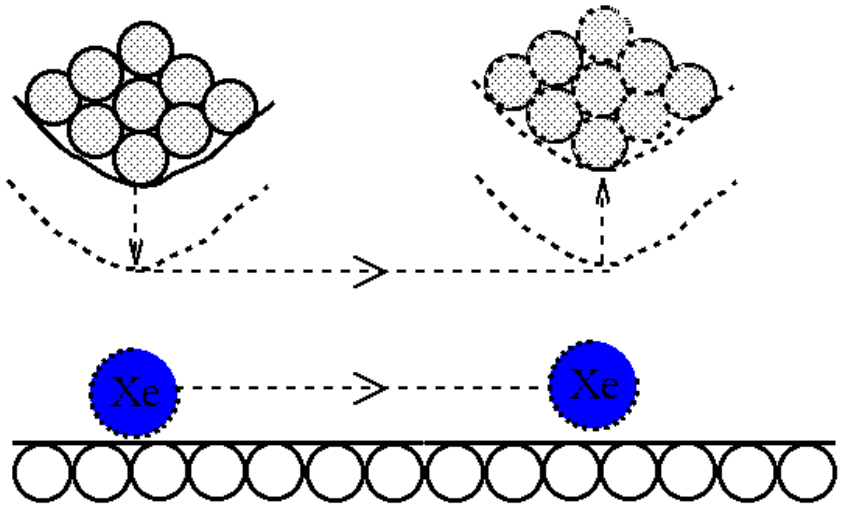


S. S. Wong *et al.*, *Nature* 394, 52 (1998).

Manipulation method

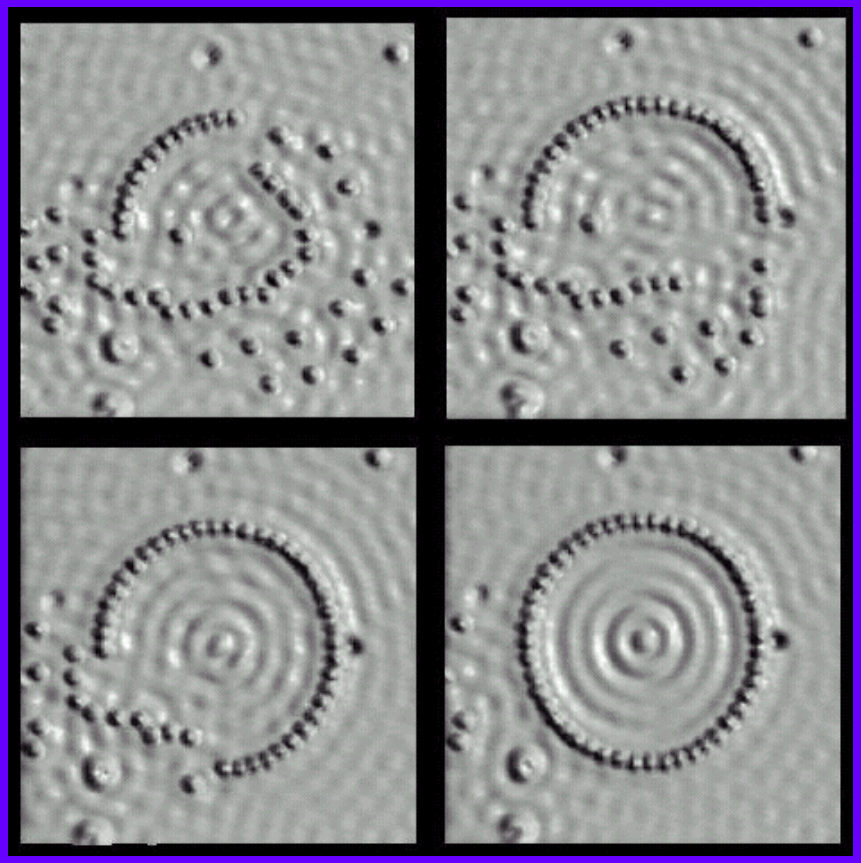
Positioning Atoms with an STM

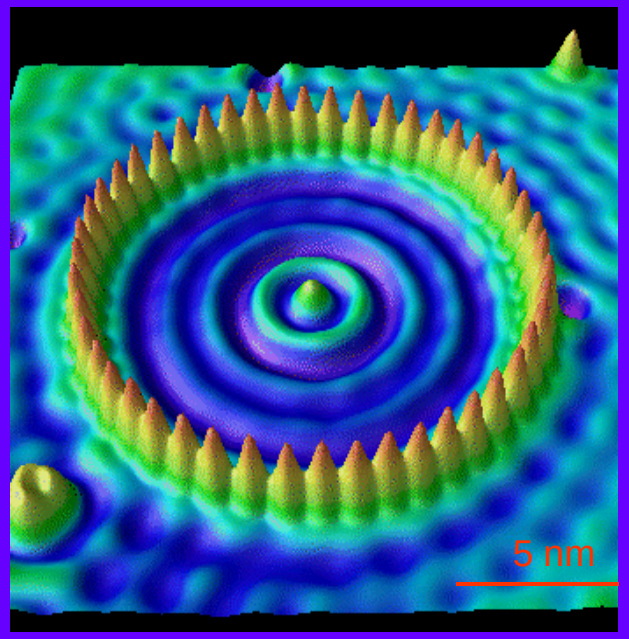
D.M. Eigler & E.K. Schweizer Nature **344** 524 (1990)



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.

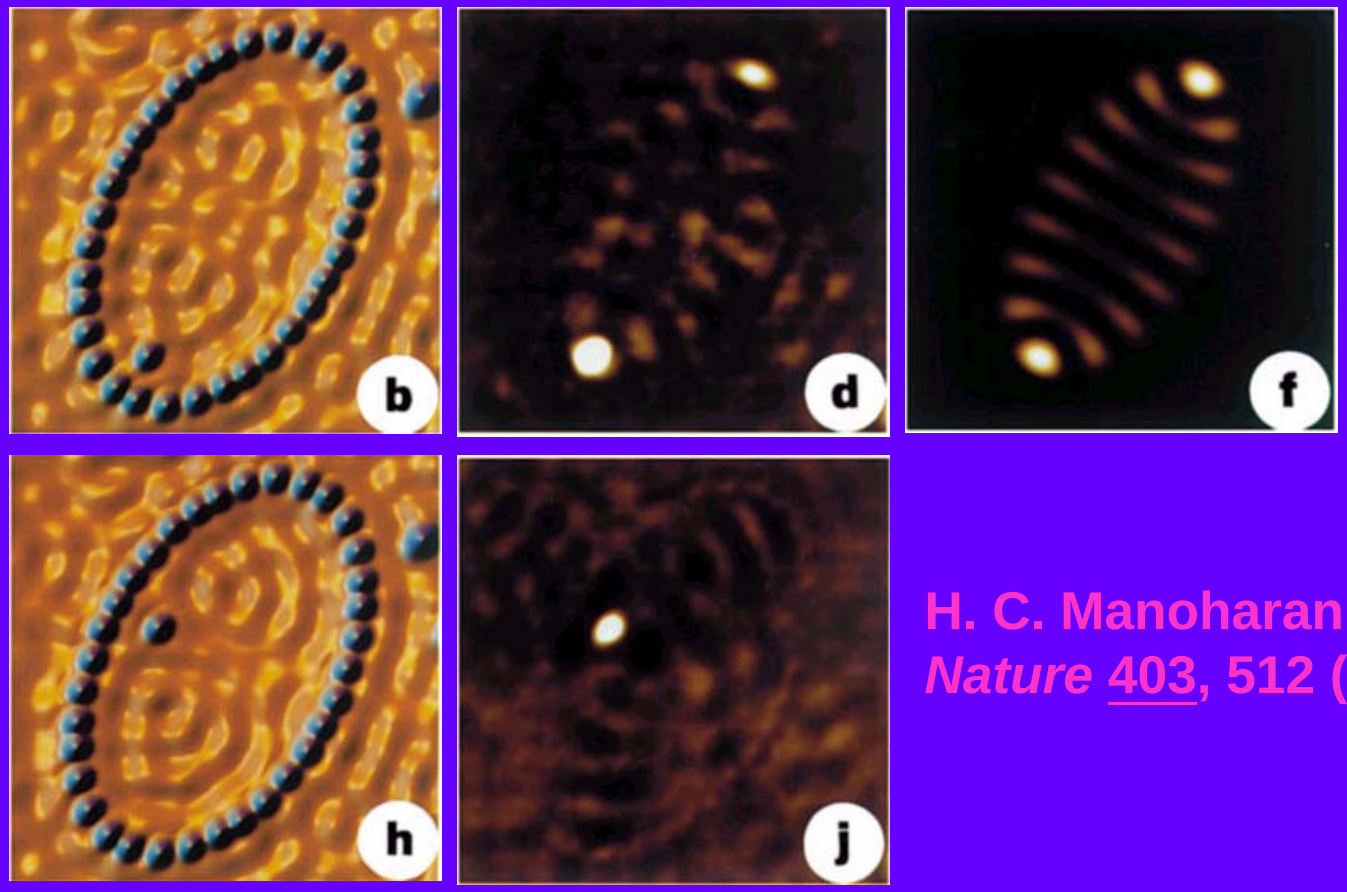
Ultimate goal of nanotechnology





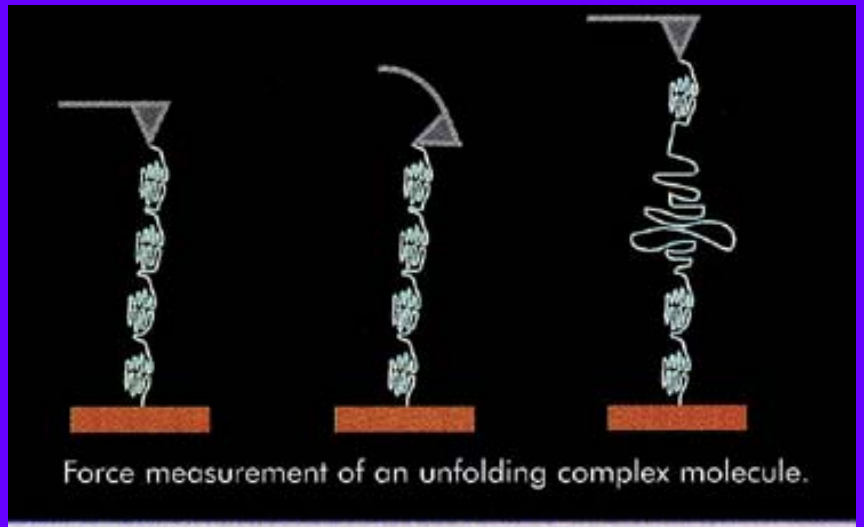
M.F. Crommie *et al.*, *Science* 262, 218 (1993).

Quantum Mirage

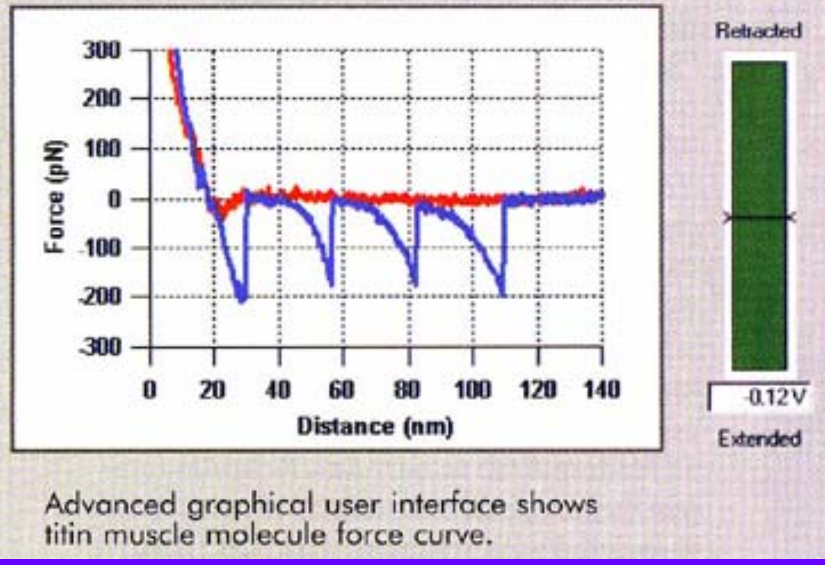


H. C. Manoharan *et al.*, *Nature* 403, 512 (2000).

Molecular unfolding

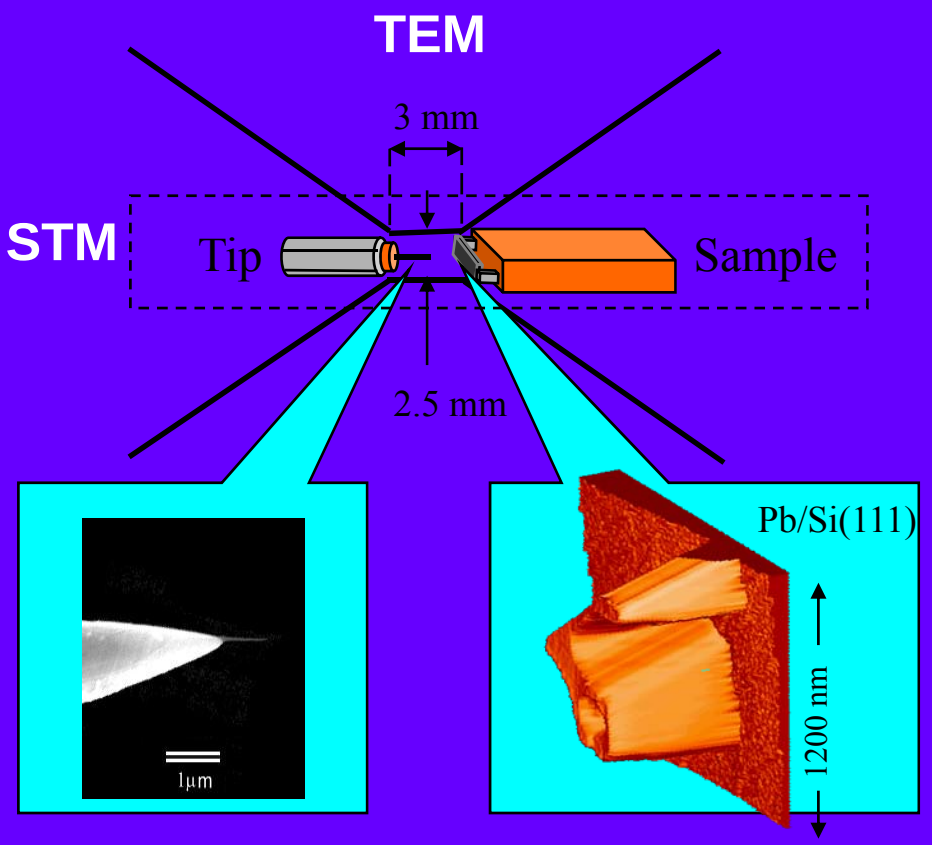


Force measurement of an unfolding complex molecule.



Advanced graphical user interface shows titin muscle molecule force curve.

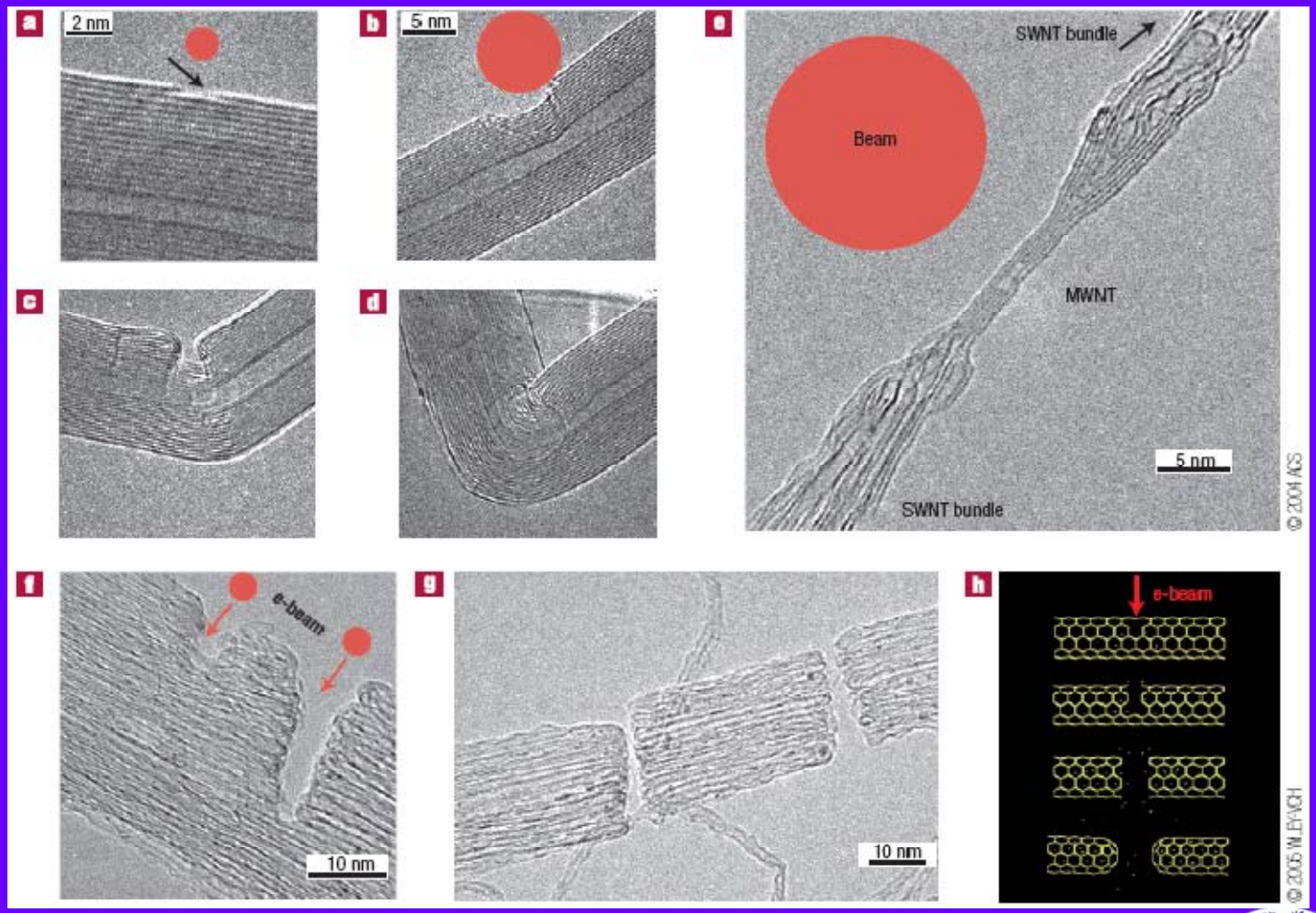
UHV HRTEM/STM



Tip with a nanotube

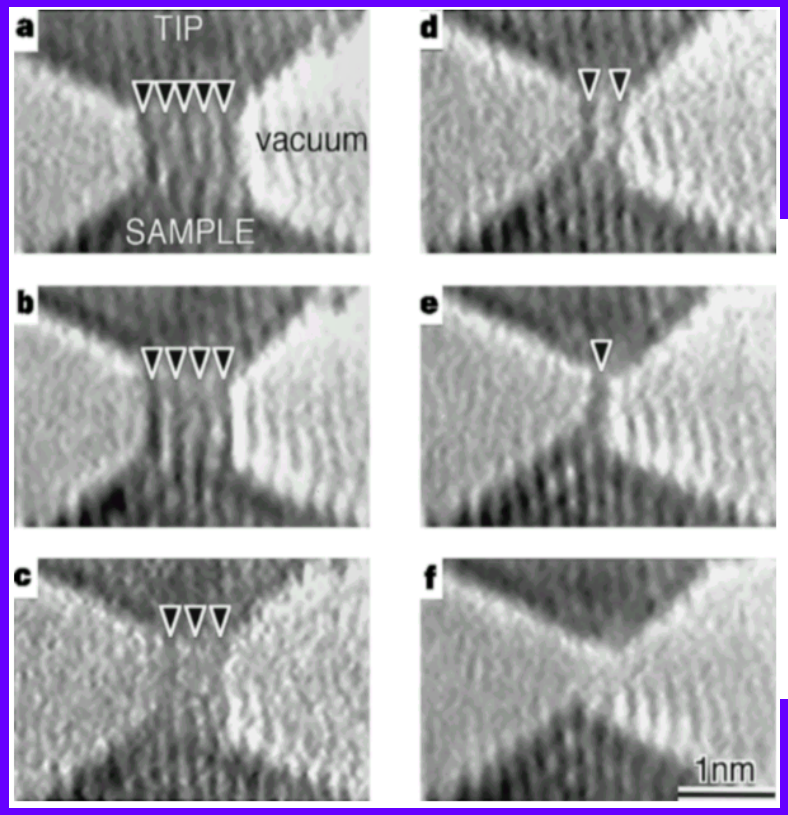
Mesa structure for holding the nano-object

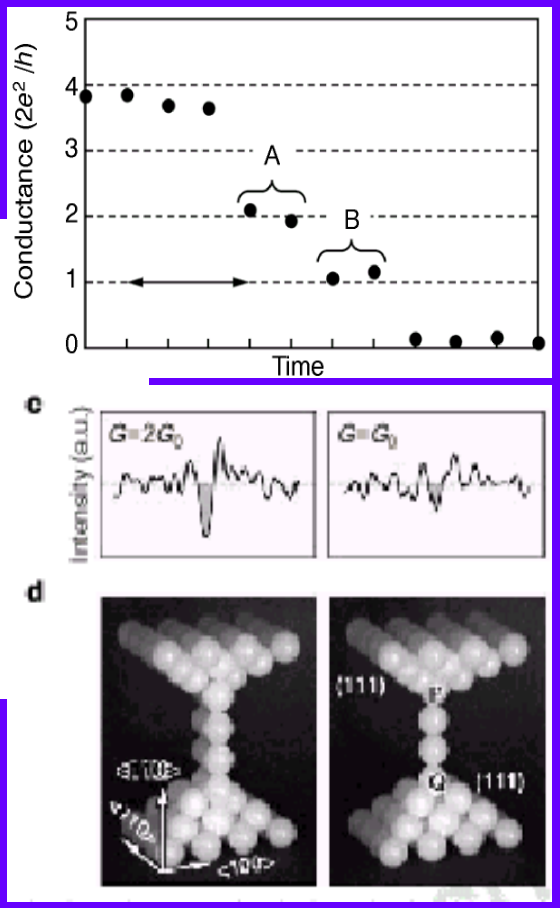
Engineering CNT with energetic e-beam



A.V. Krasheninnikov and F. Banhart
Nature Materials **6**, 723 (2007)

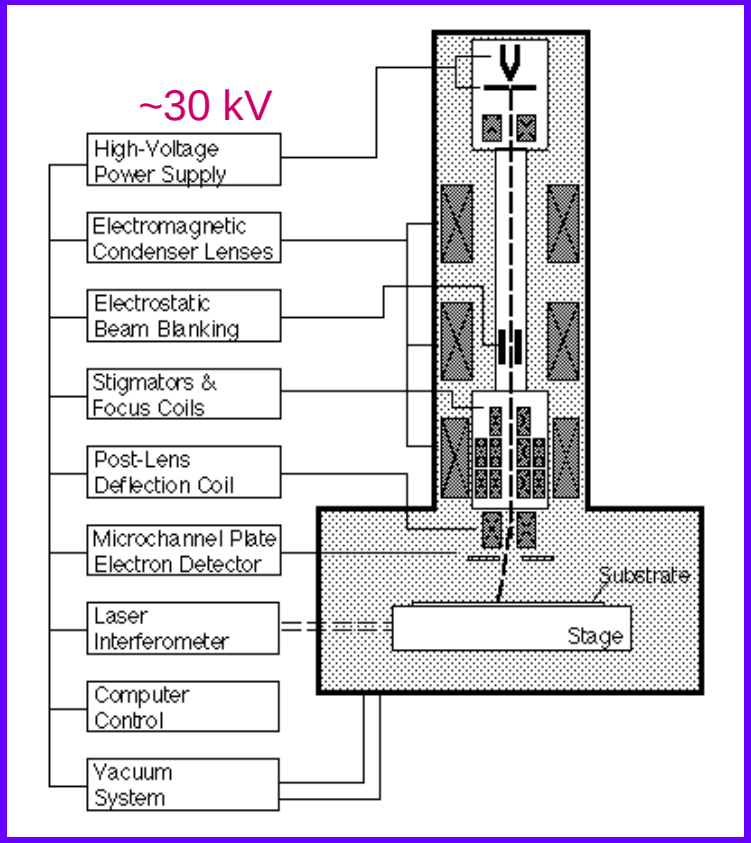
Point contact of Au wire

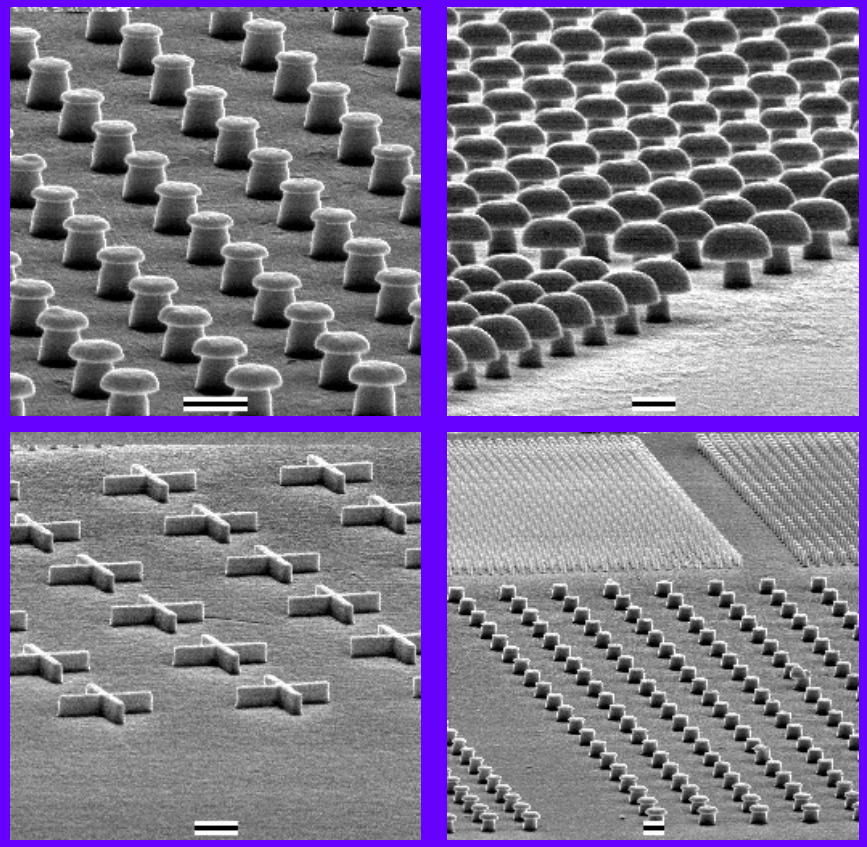




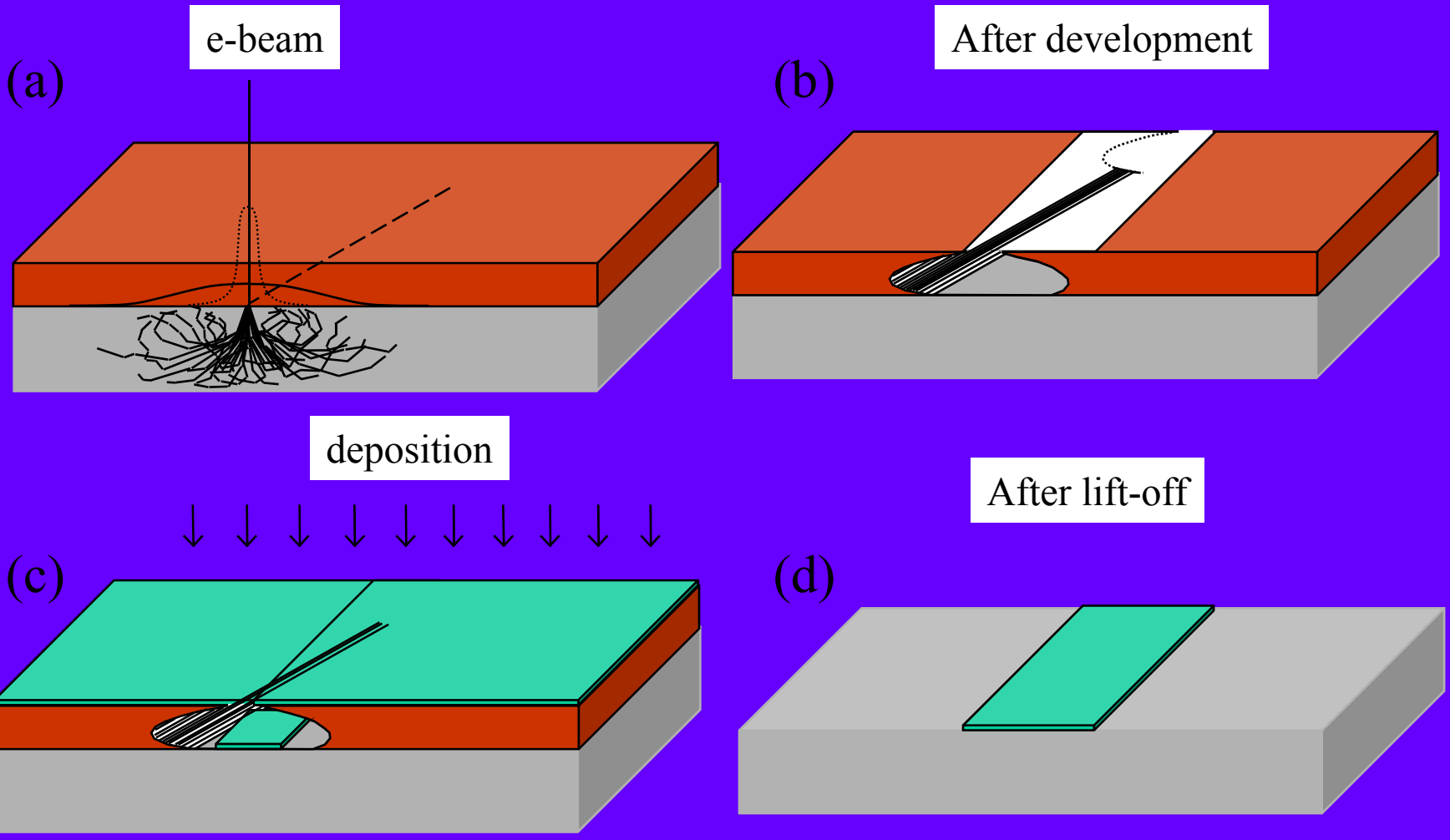
H. Ohnishi *et al.*
Nature 395, 780 (1998).

Periodic nanostructures by e-beam lithography

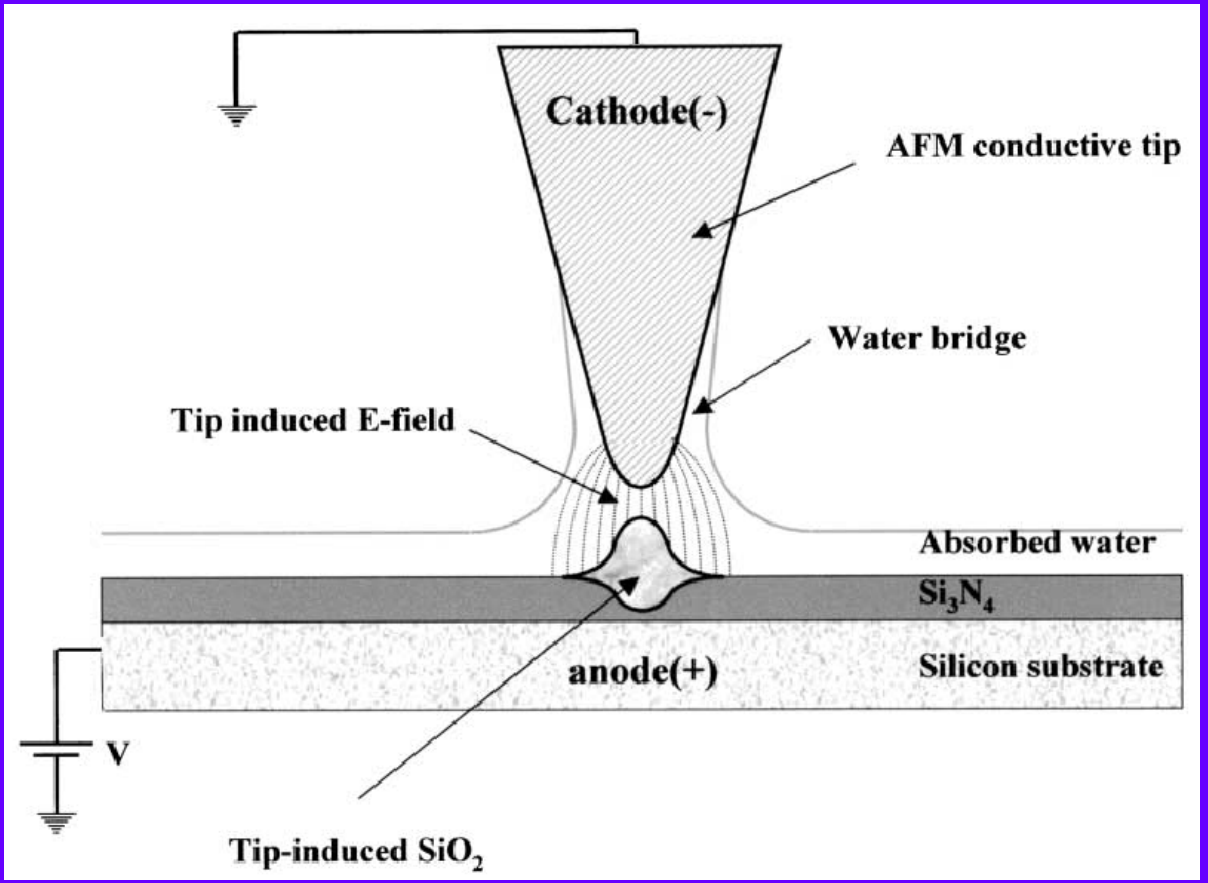




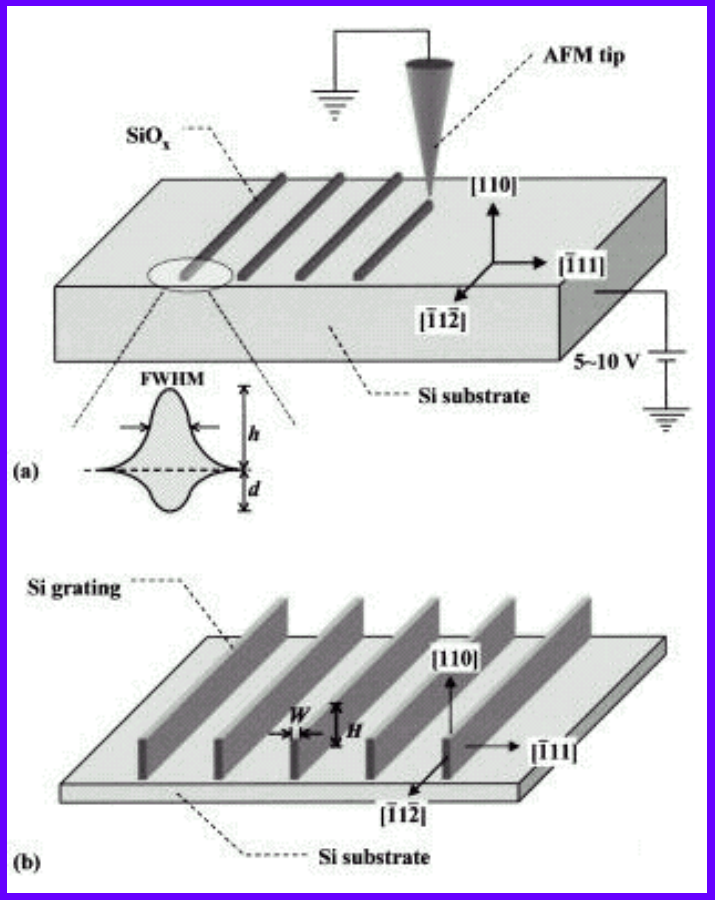
Procedures of e-beam lithography

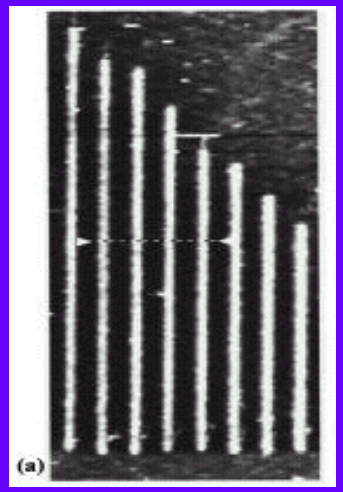


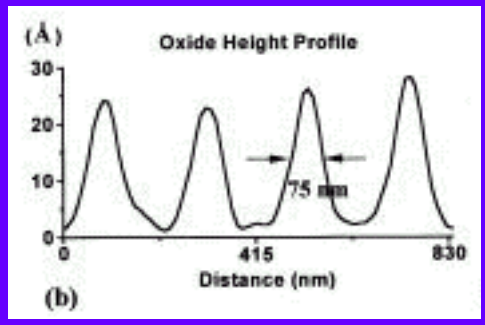
Nano-Lithography with an AFM tip



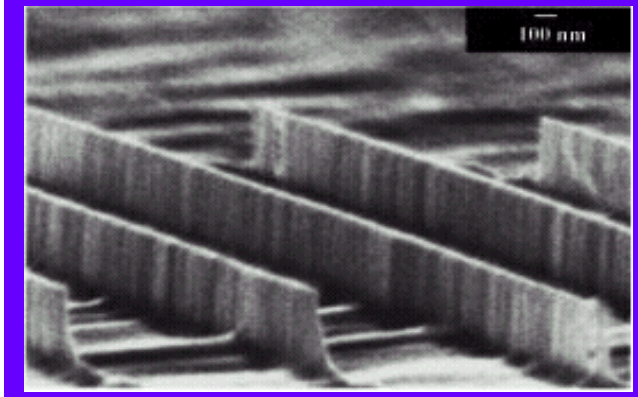
Electrical Lithography



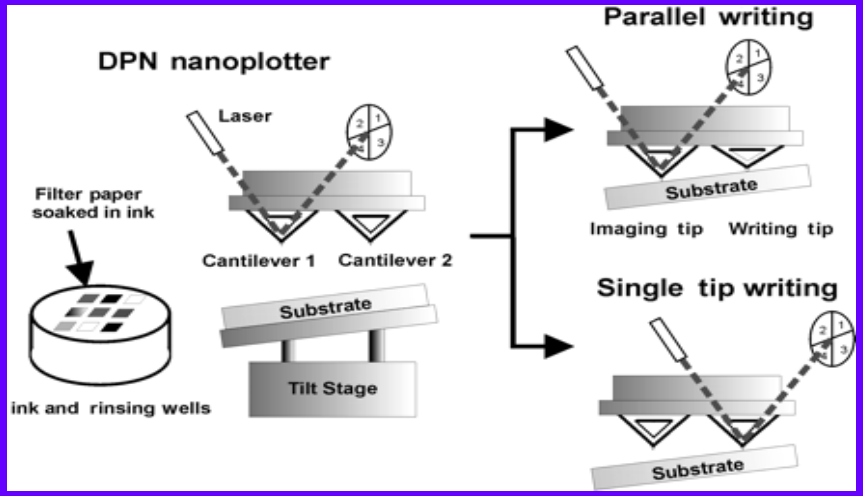


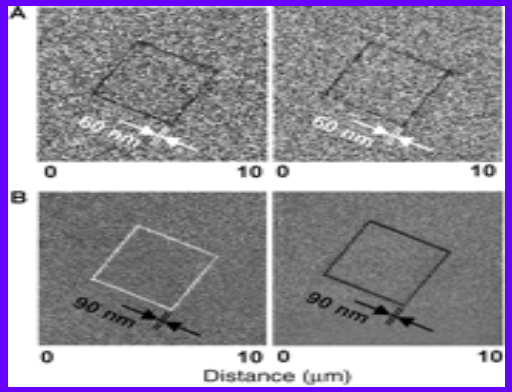


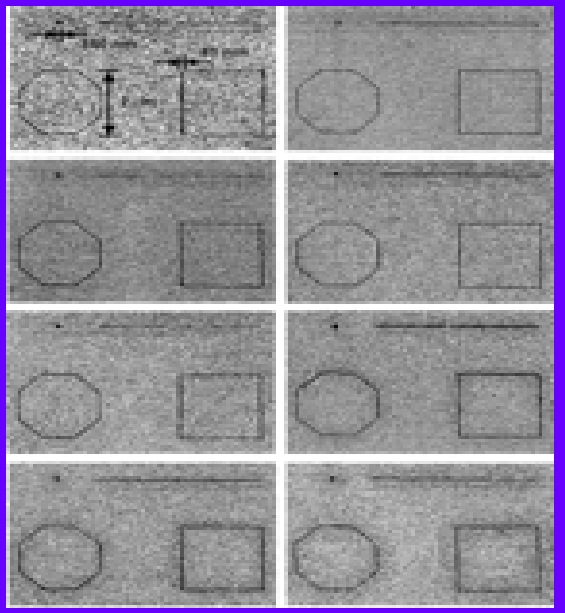
F.S.-S. Chien *et al*.
APL 75, 2429 (1999)



Nanoplotter

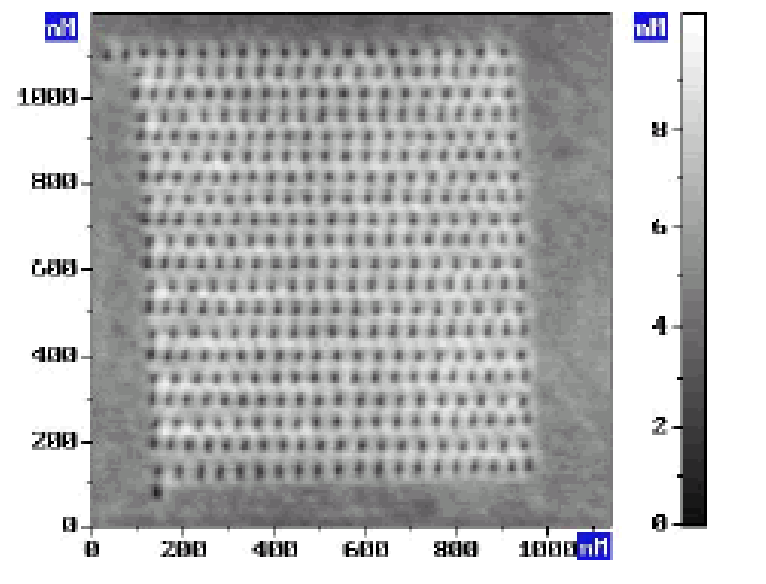




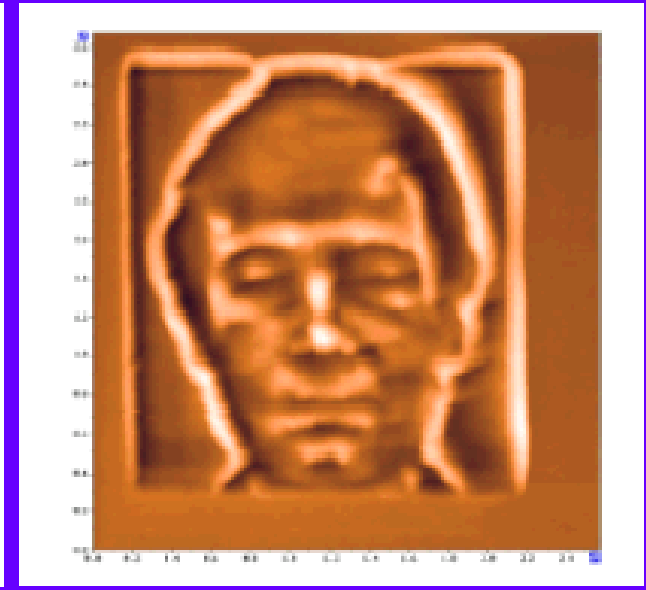


C.A. Mirkin *et al*.
Science 288, 1808 (2000)

Nanolithography of Tapping-Mode AFM



(1.2μm× 1.2μm)



(2.5μm× 2.5μm)

Image of polycarbonate film on silicon surface

Nanodrive


7,000,000-YEAR-OLD SKULL: ANCESTOR? APE? OR DEAD END?
SCIENTIFIC AMERICAN
The Nose-Tickling Science of Bubbly
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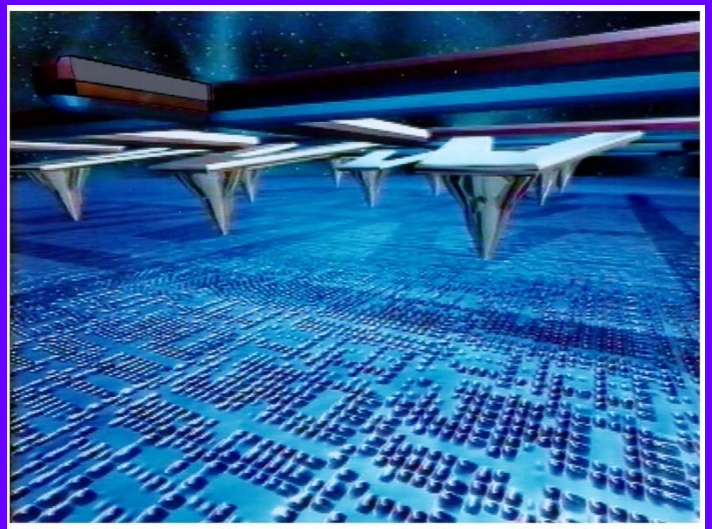
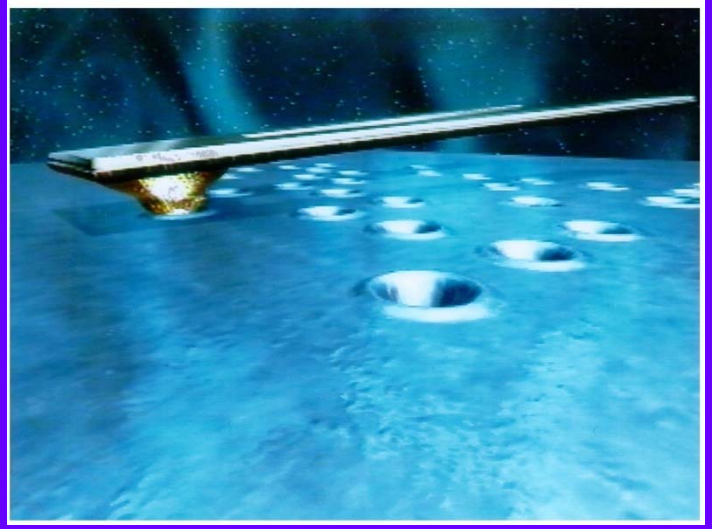
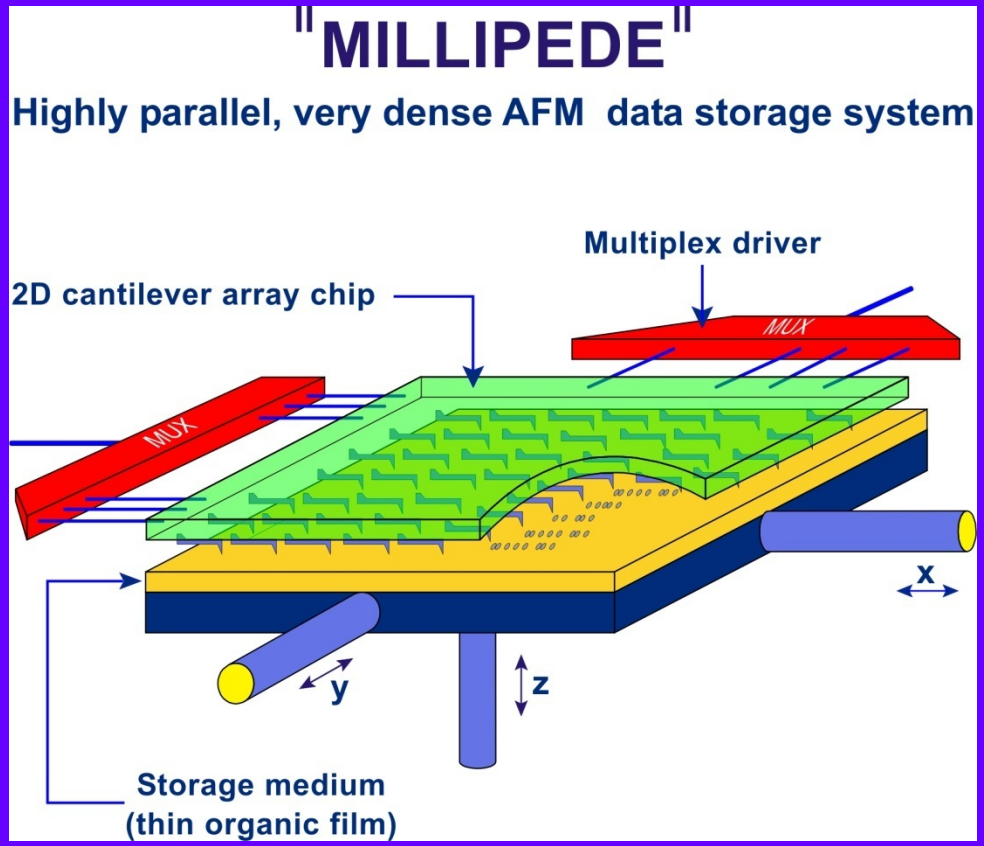




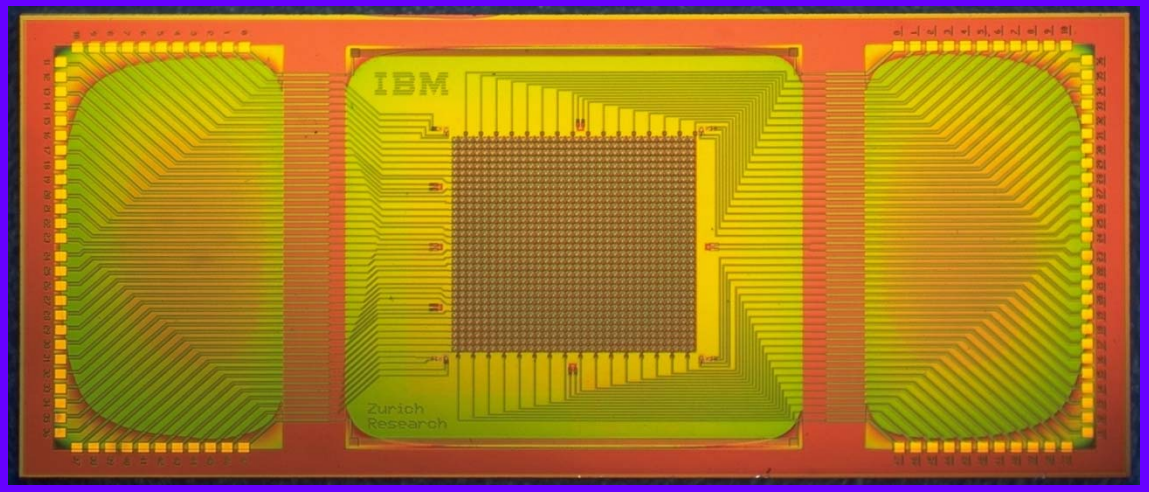
Millipede

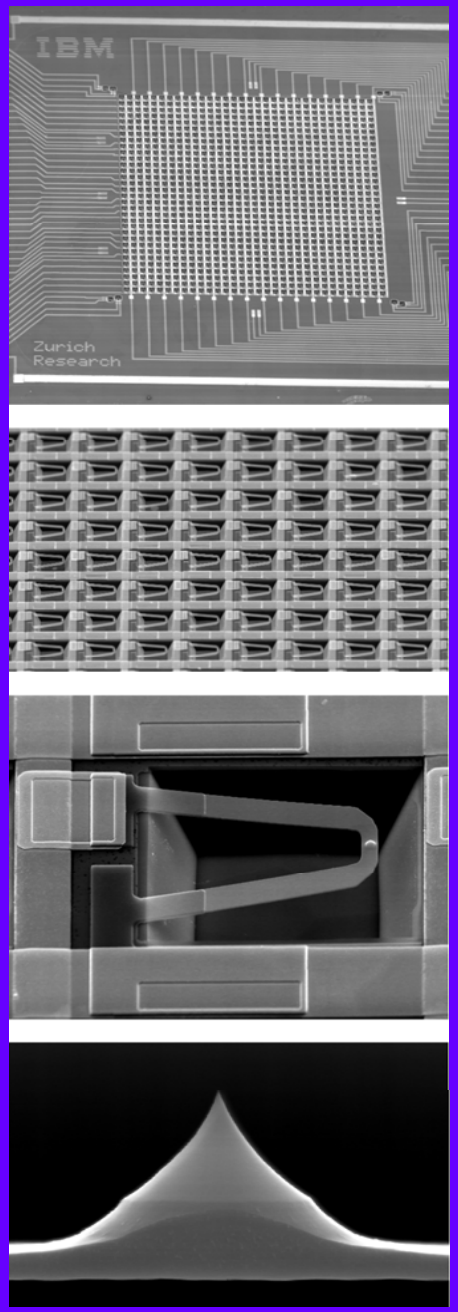


The Millipede concept: for operation of the device, the storage medium - a thin film of organic material (yellow) deposited on a silicon "table" - is brought into contact with the array of silicon tips (green) and moved in x- and y-direction for reading and writing. Multiplex drivers (red) allow addressing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

IBM-Zurich

Cantilever array



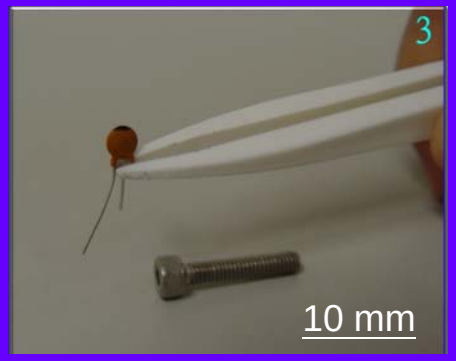


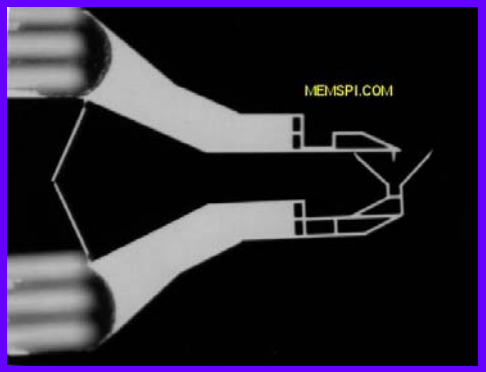
Millipede cantilevers and tips: electron microscope views of the 3 mm by 3 mm cantilever array (top), of an array section of 64 cantilevers (upper center), an individual cantilever (lower center), and an individual tip (bottom) positioned at the free end of the cantilever which is 70 micrometers (thousands 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).

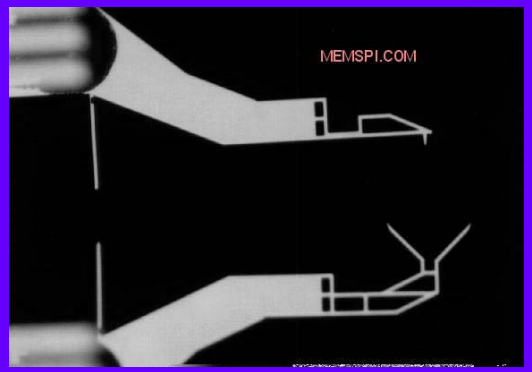
Considerations for making nanoscale tools

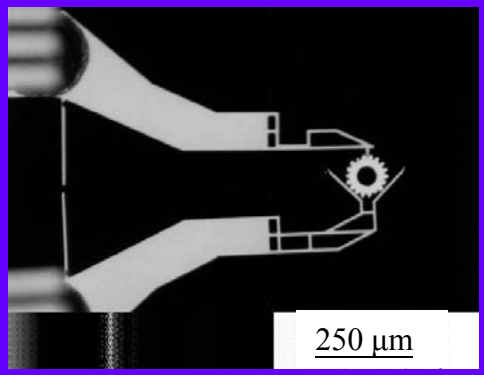
1. Size compatibility
2. Force compatibility
3. Mechanical Properties
4. Chemical Properties
5. Precision movement
6. Integratible coarse movement
7. Environment interferences

Maneuvering tools

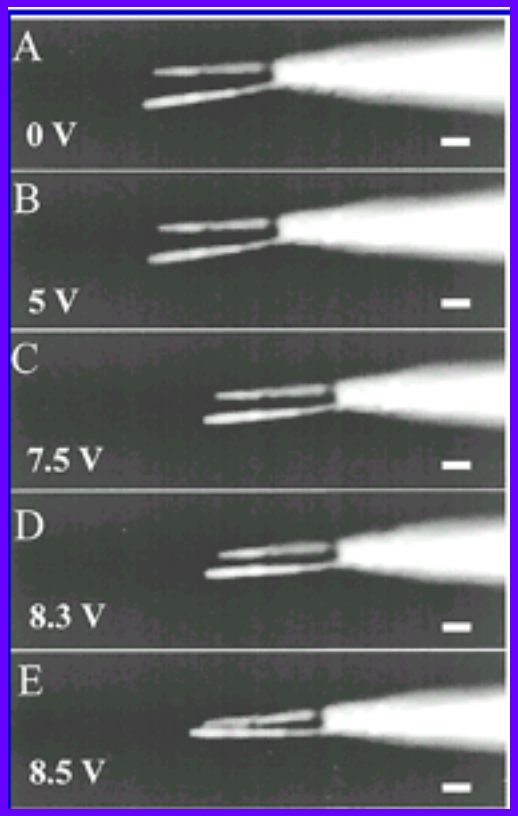


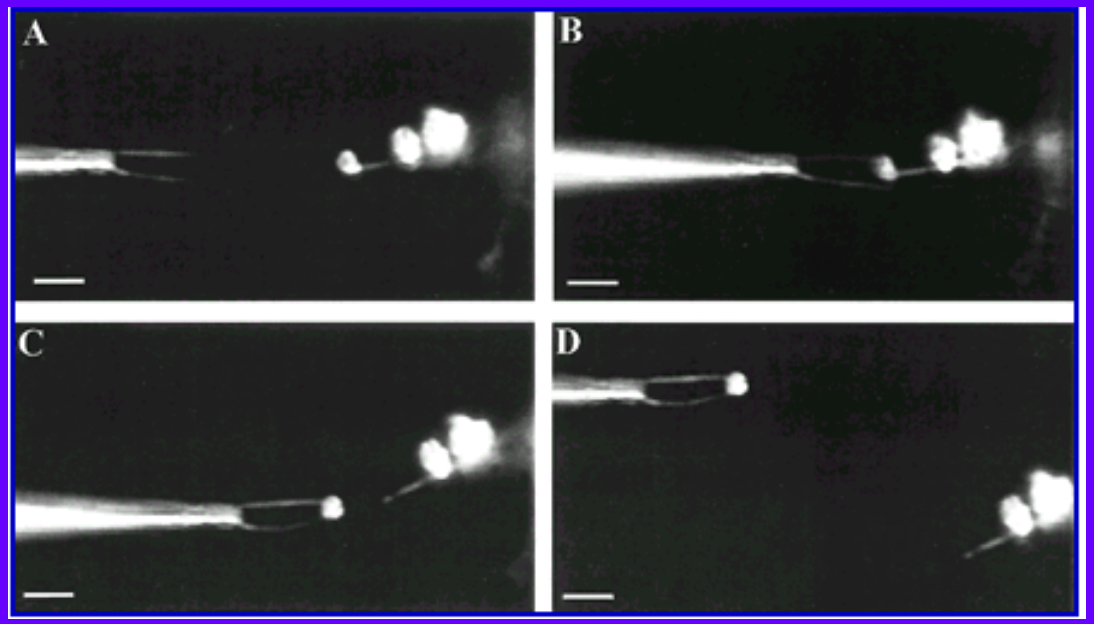






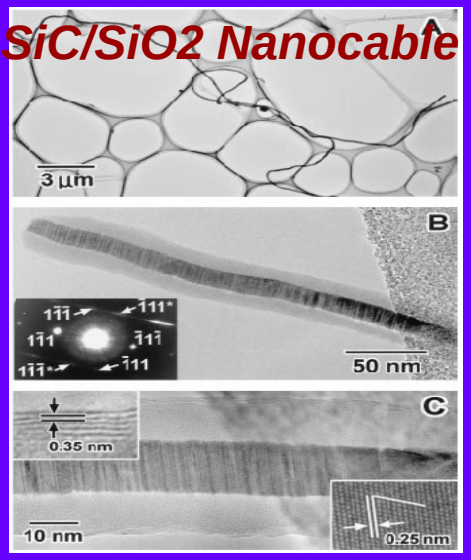
Operation of nano tweezers



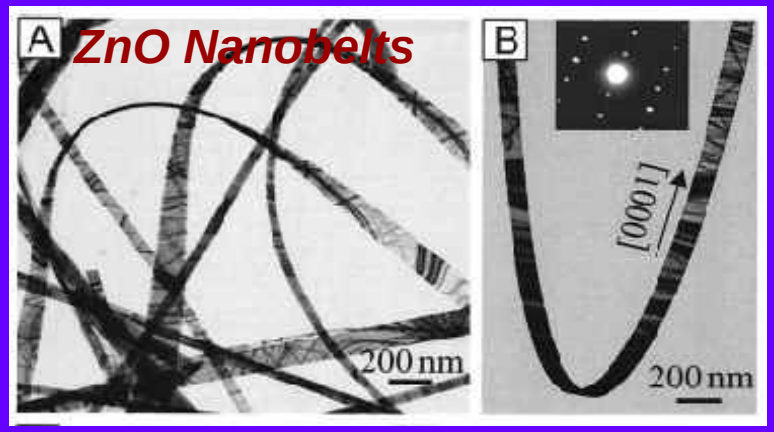


P. Kim and C.M. Lieber,
Science 286, 2148 (1999).

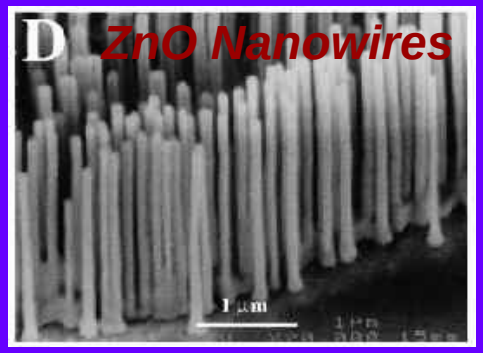
Nano wires and belts



Science 281, 973 (1998)



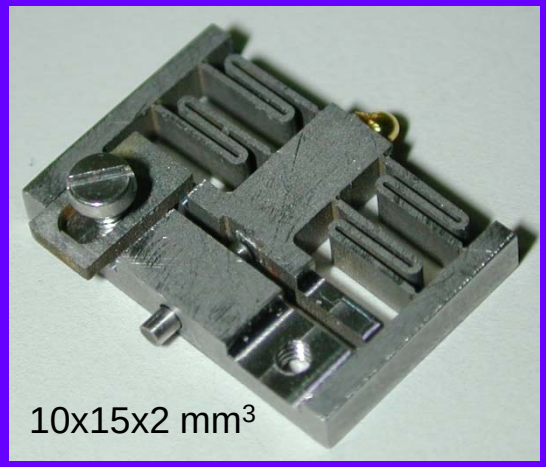
Science 291, 1947 (2001)

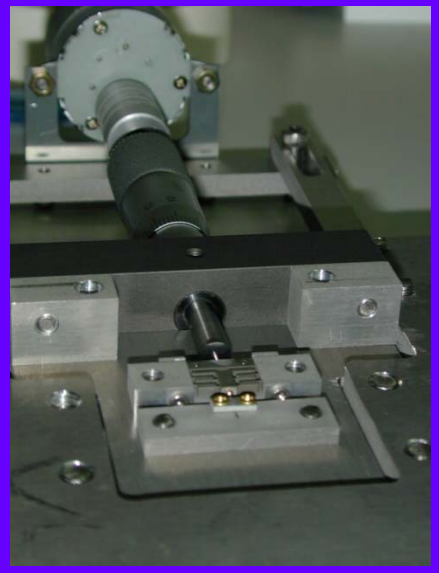


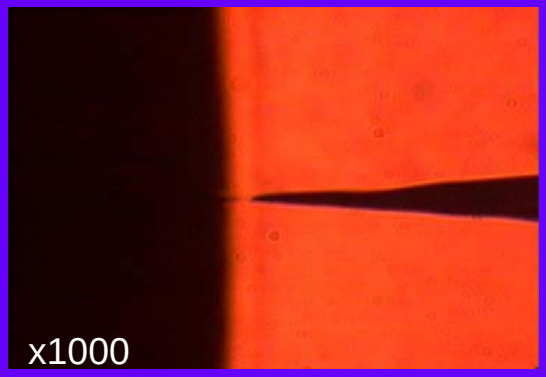
Science 292, 1897 (2001)

Nano Lett. 2, 101 (2002)

Precision stepper





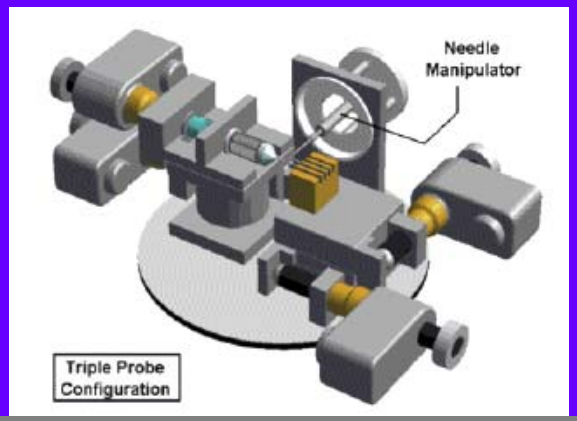


Considerations for environmental factors

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.

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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