

Characterization and Manipulation at Nanometer Scale

Syllabus (2009)

Week 1 (2/17)	Overview
Week 2 (2/24)	STM: structure and working principles
Week 3 (3/03)	AFM: structure and working principles
Week 4 (3/10)	SPM: structure and working principles
Week 5 (3/17)	EM: structure and working principles (Prof. Hsu, NTHU)
Week 6 (3/24)	EM: operations and examples (Prof. Hsu, NTHU)
Week 7 (3/31)	X-ray and other microscopies (Prof. Hwu, AS)
Week 8 (4/07)	Spectroscopy: optical, electronic, vibrational
Week 9 (4/14)	Midterm Written Exam (50%)
Week10 (4/21)	Optical imaging (Prof. Kao, NYMU)
Week11 (4/28)	Lithography: optical, e-beam (Prof. Chen, AS)
Week12 (5/05)	Atom manipulation
Week13 (5/12)	Papers study ()
Week14 (5/19)	Papers study ()
Week15 (5/26)	Papers study ()
Week16 (6/02)	Papers study ()
Week17 (6/09)	Papers study ()
Week18 (6/16)	Presentation and responses (50%)



Nanoscale measurements and manipulation

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

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



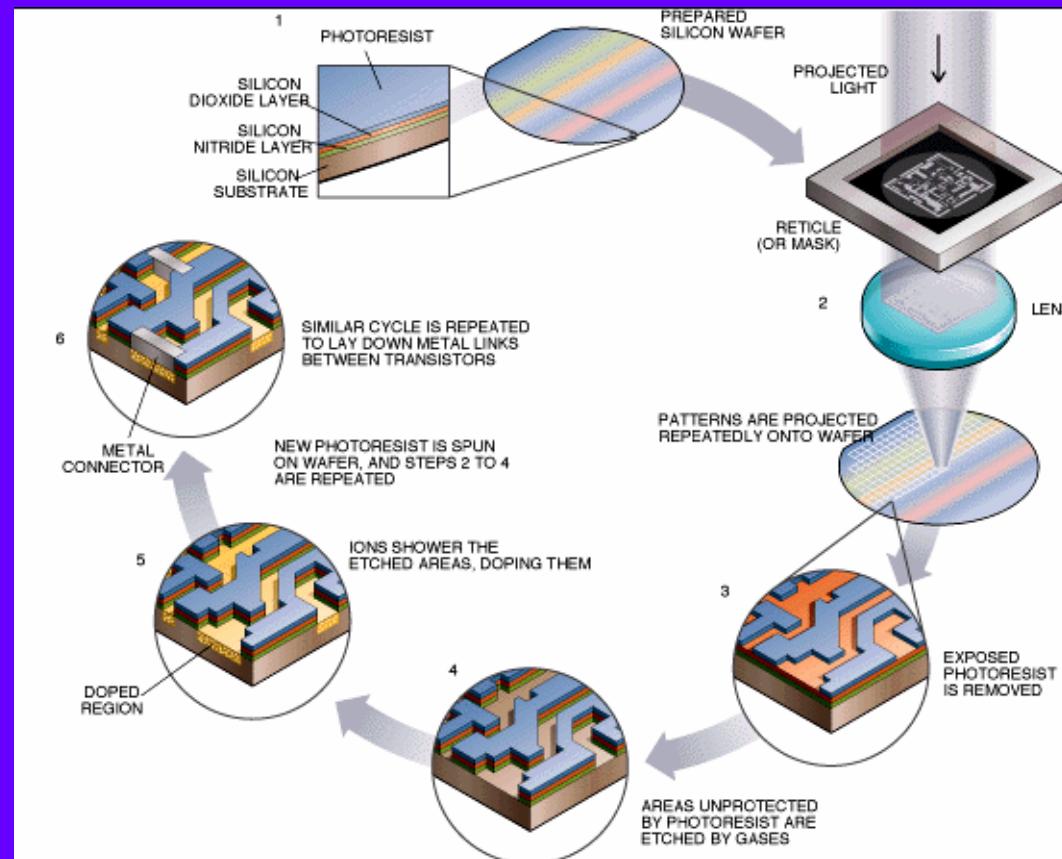
Outline

- 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**

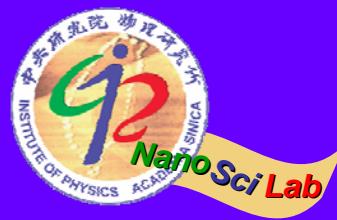


Nano Sci Lab

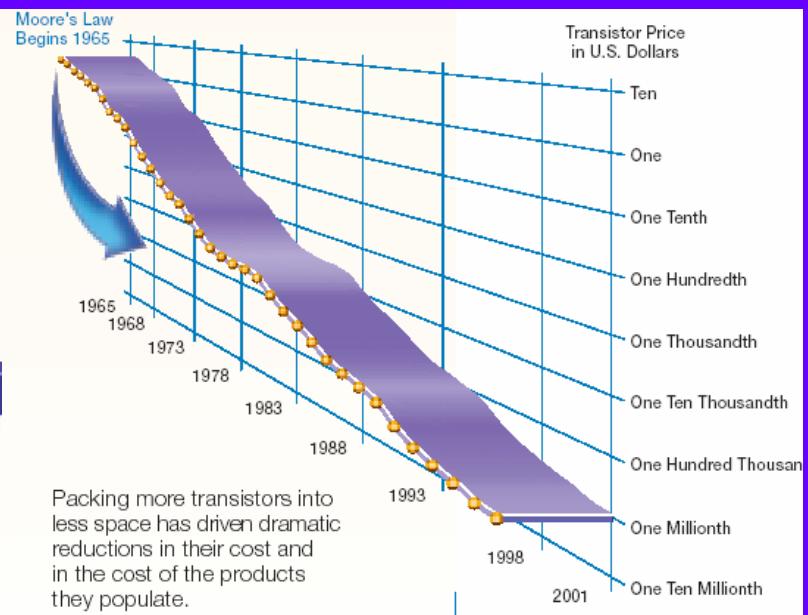
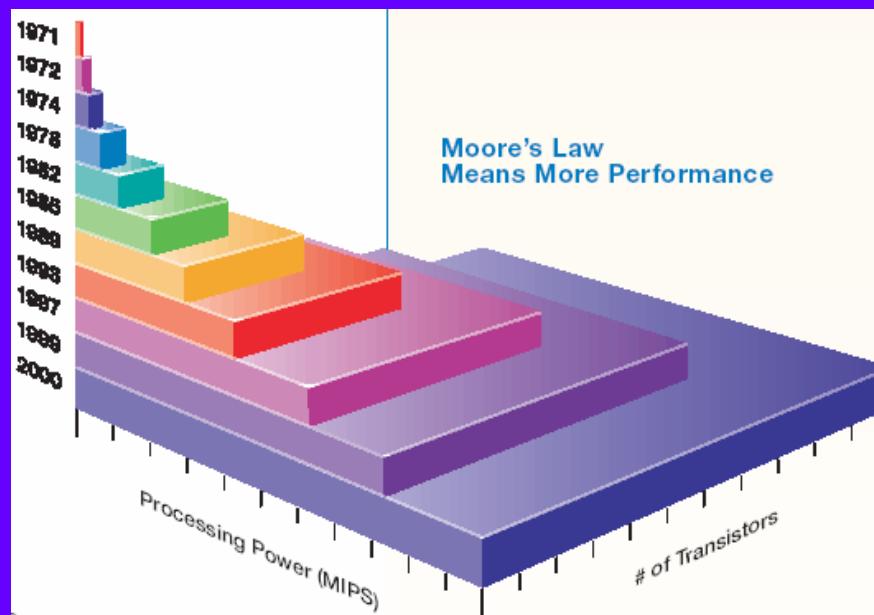
Optical lithography and planar fabrication of VLIC



Intel Corp.



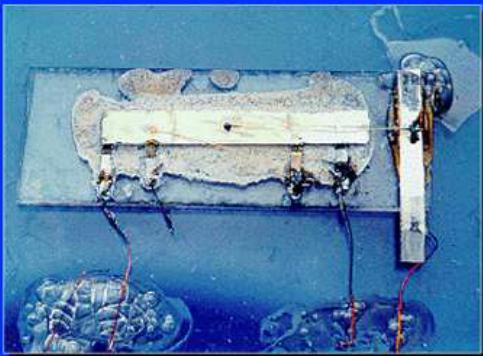
Numbers of transistors in an IC



Intel Corp.

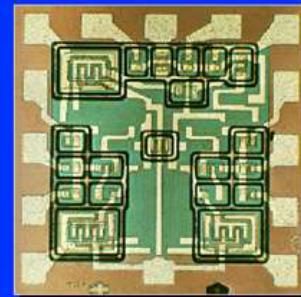
Evolution of IC industry

Kilby's First IC, 1958

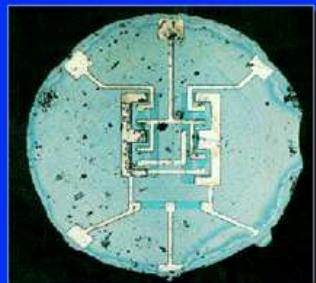


1965

- 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

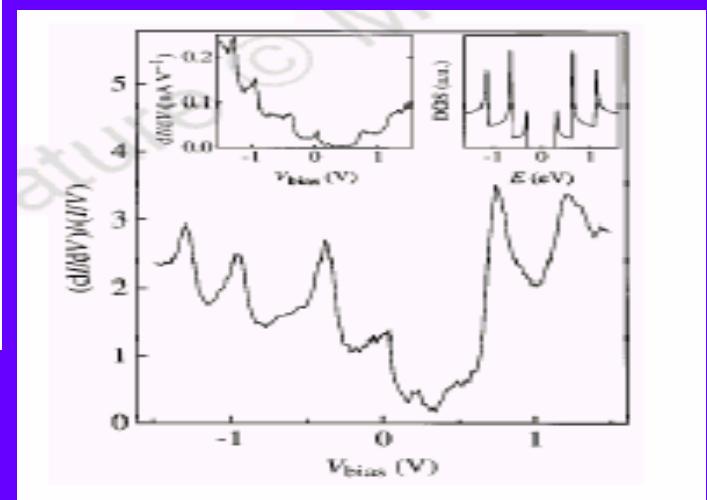
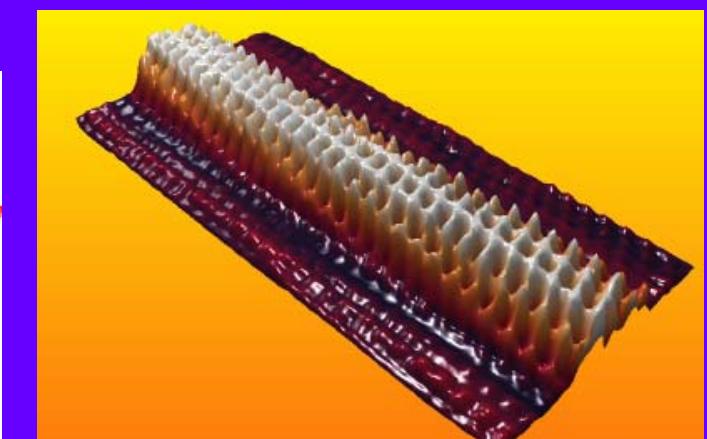
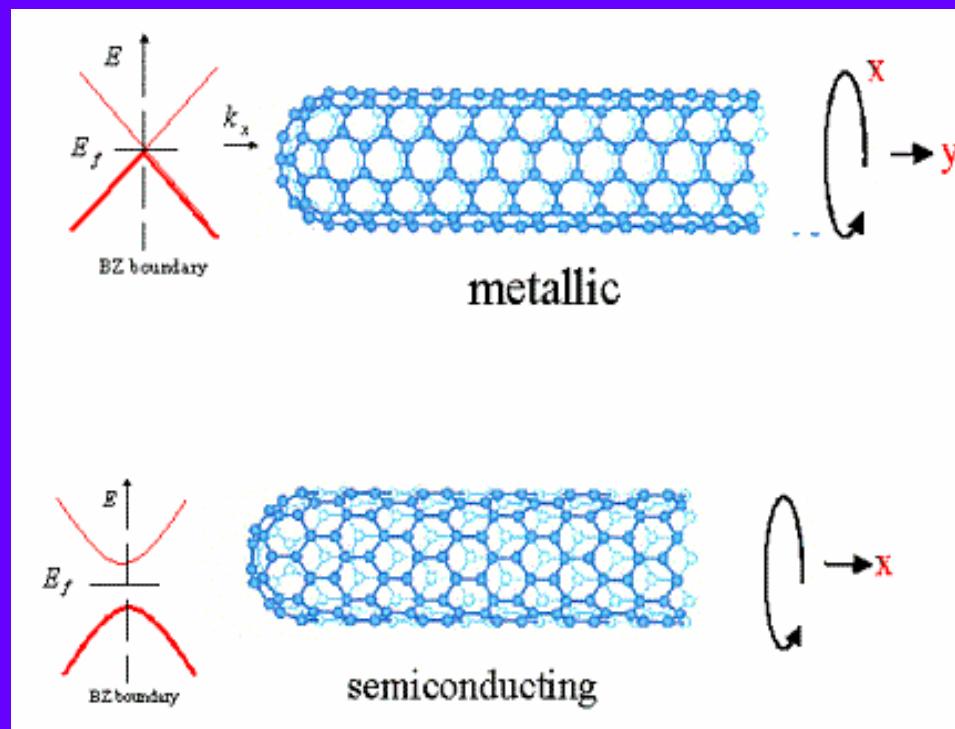
Pentium® III Processor

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

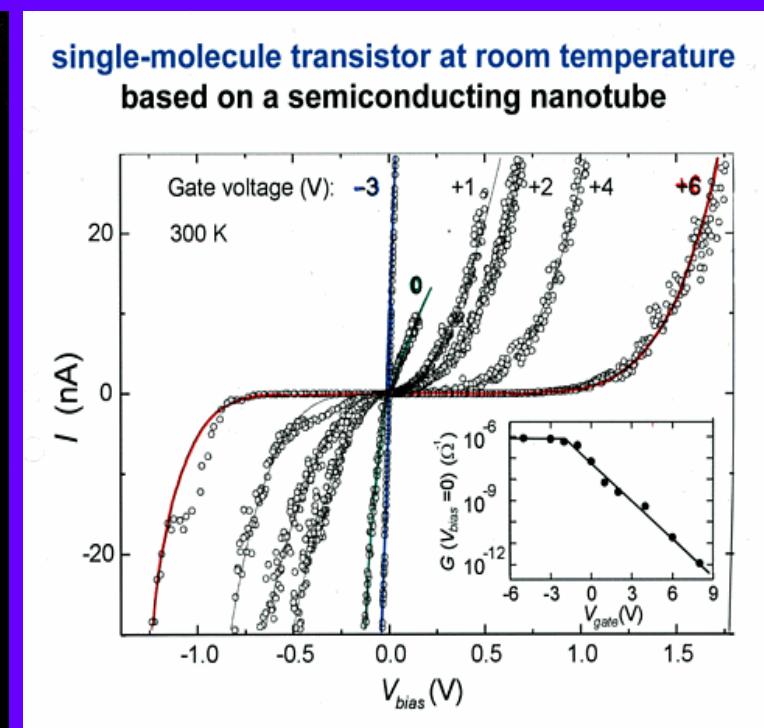
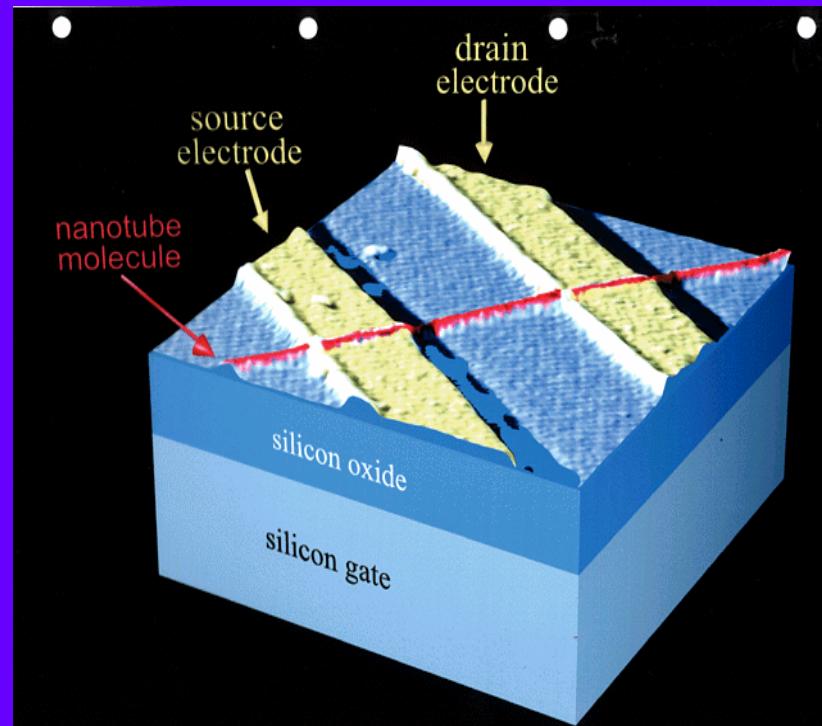




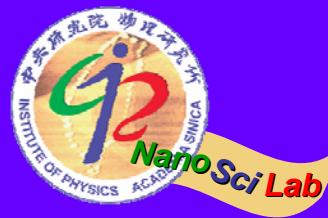
Electronic properties of a carbon nanotube



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.

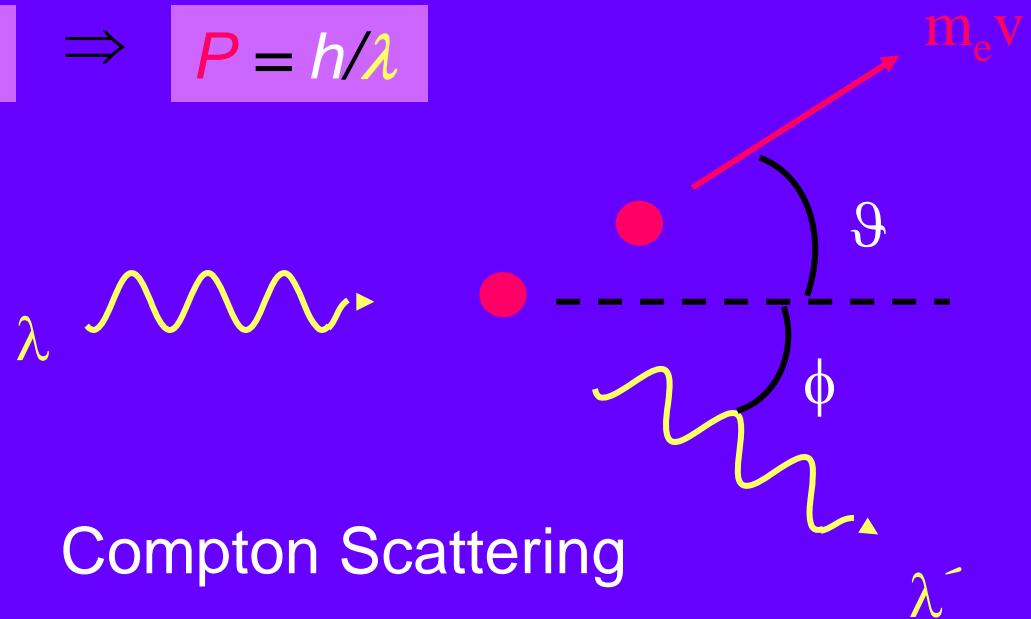
Nanotechnologies are the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometer scale.



Photon as a particle

Einstein's proposal:

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





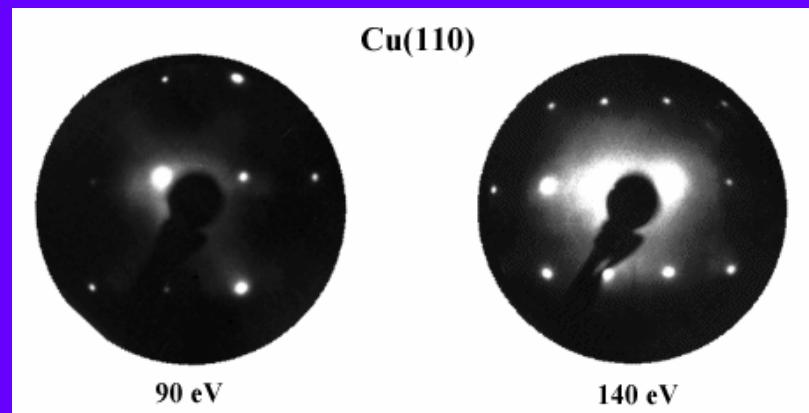
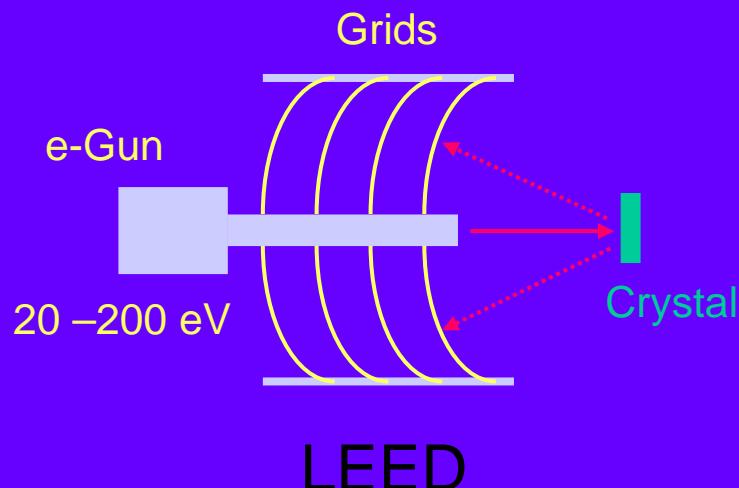
Electron as a wave

de Broglie's proposal:

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

For electrons:

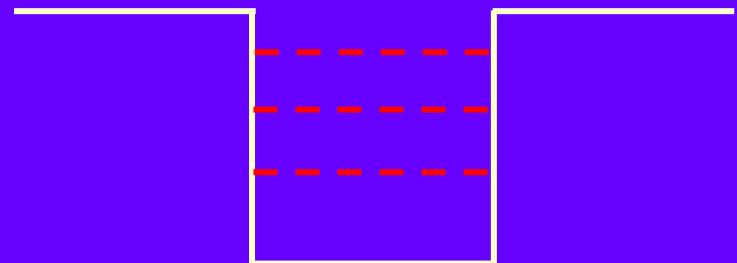
$$\lambda \text{ (nm)} = 1.22/E^{1/2} \text{ (eV)}$$



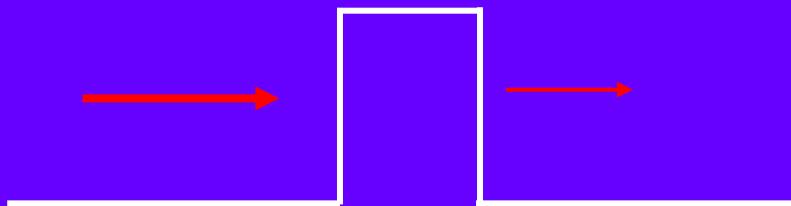


Fundamentals of Quantum Mechanics

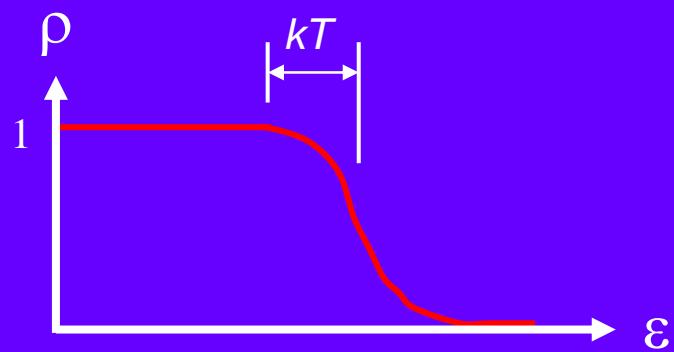
1. Quantization



2. Tunneling

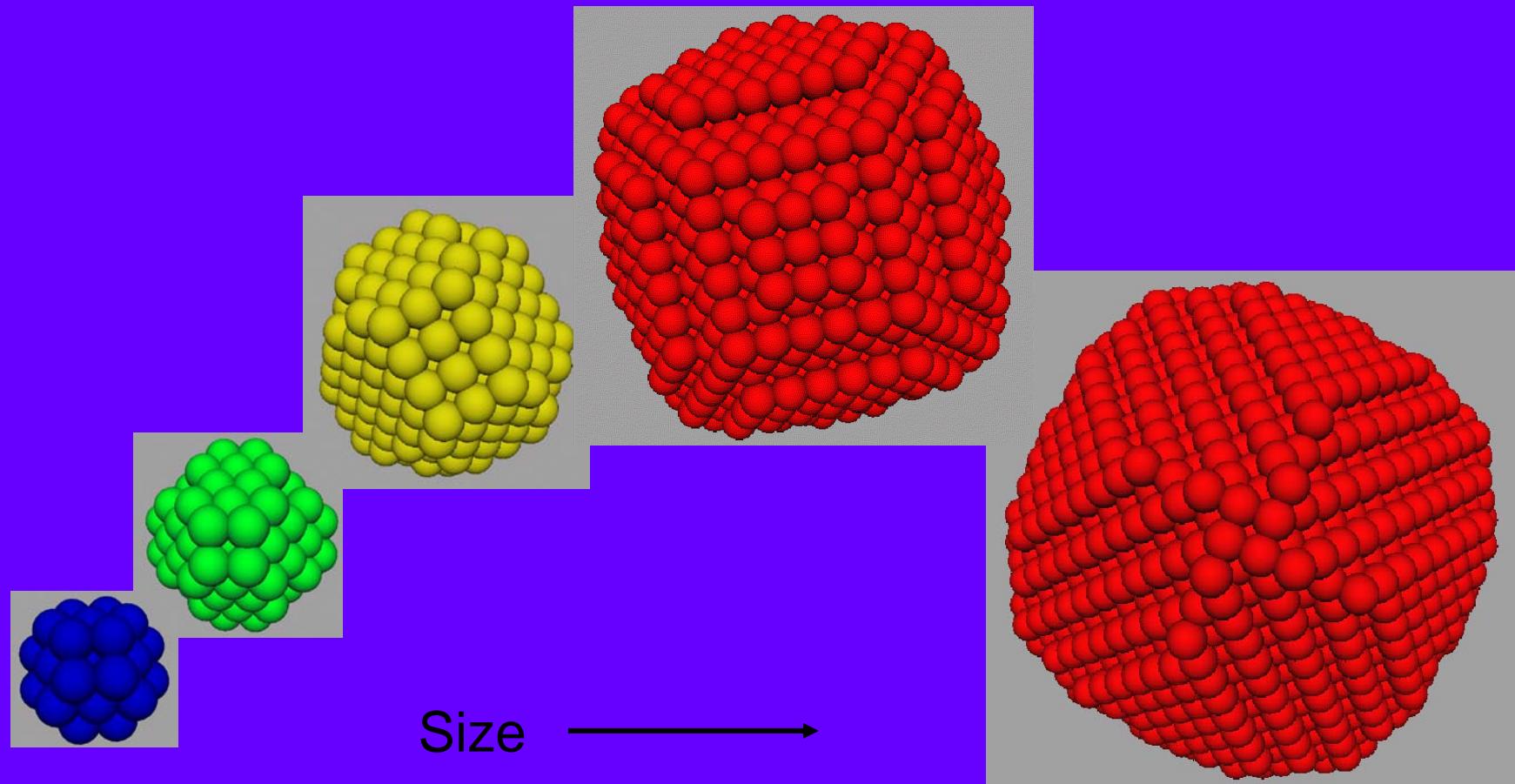


3. Statistics



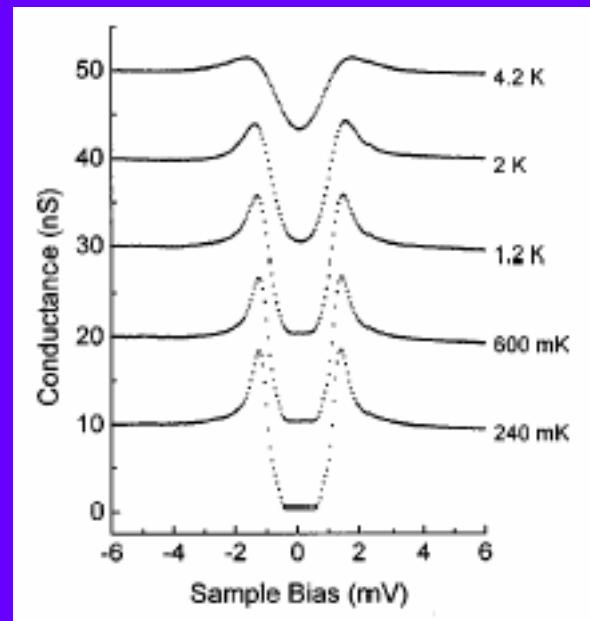
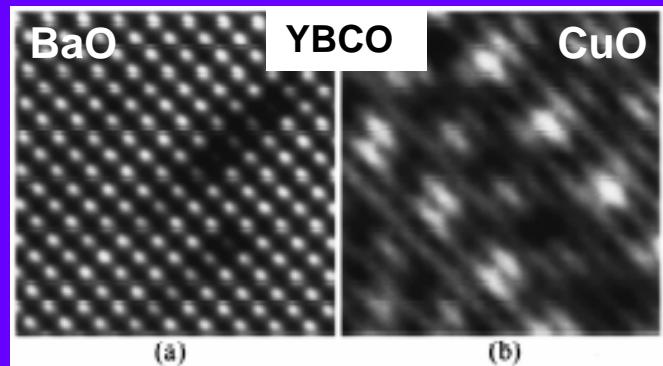


Size effect





Measurement of electronic states



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

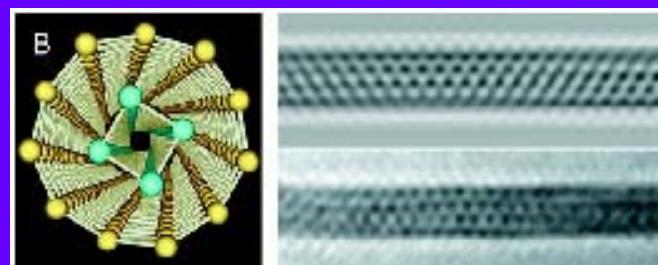
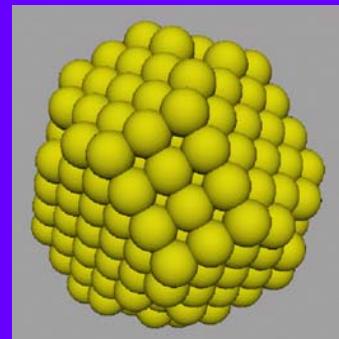


Properties of a nanostructure

Microscopic

Size
Structure
Shape
Symmetry
Domains
Defects

·
·
·

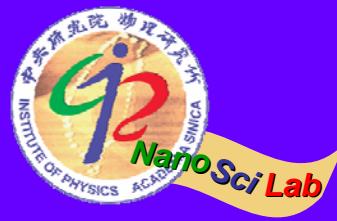


Analytical

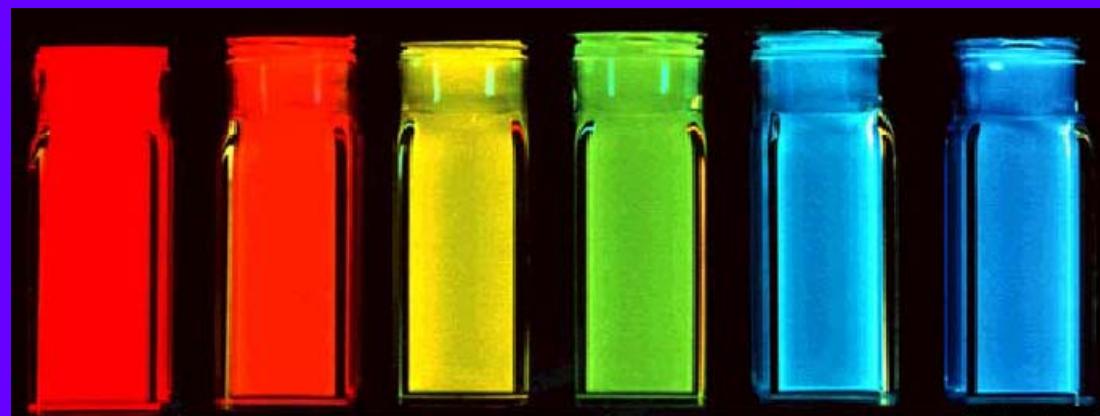
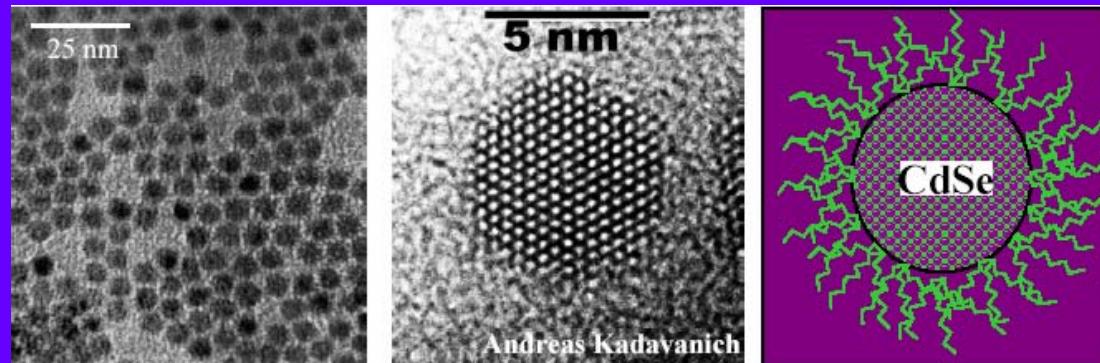
Composition
Stoichiometry
Electronic
Magnetic
Thermal
Mechanical

·
·
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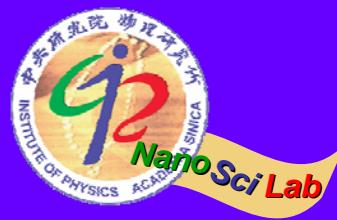
photons, electron, ion, neutron, proximal nanoobjects ...



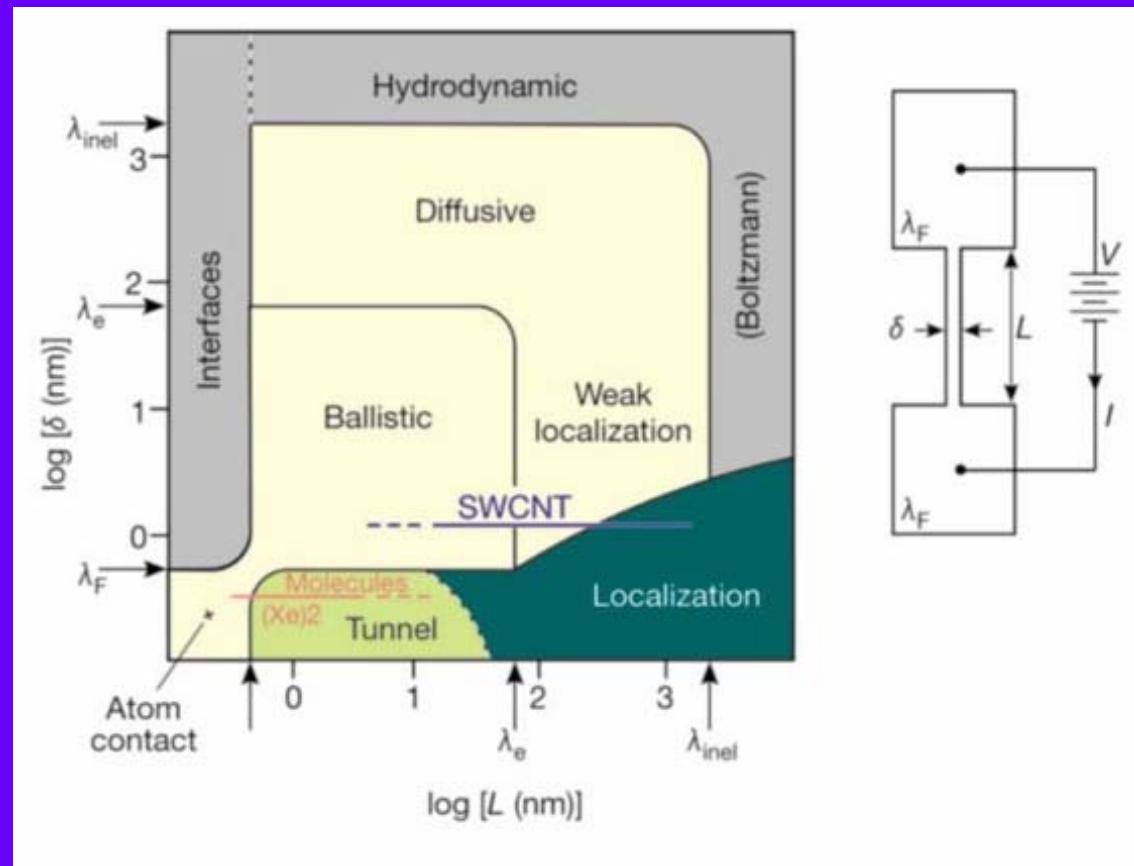
Semiconducting quantum dots



(Reproduced from Quantum Dot Co.)



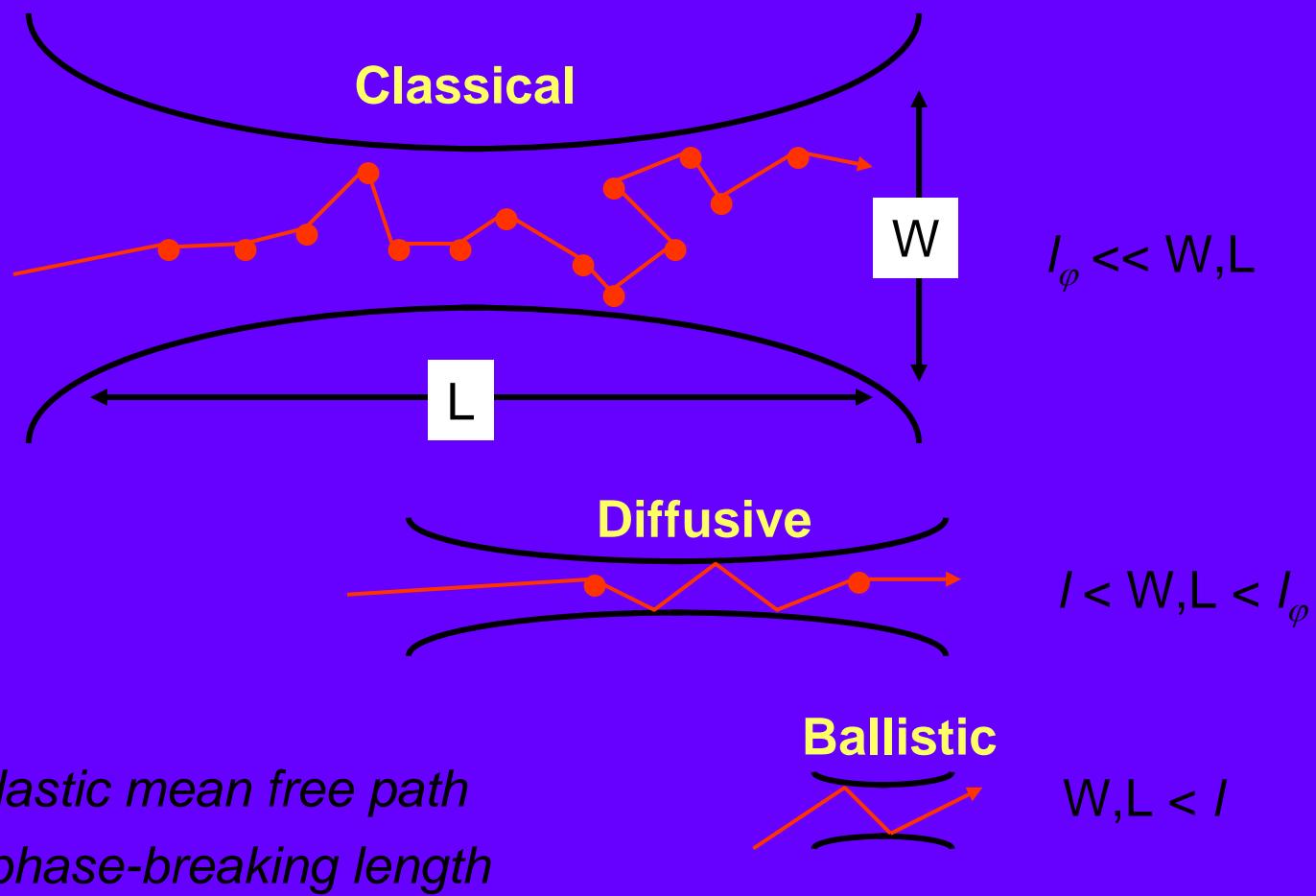
Critical lengths



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



Characteristics of electron transport



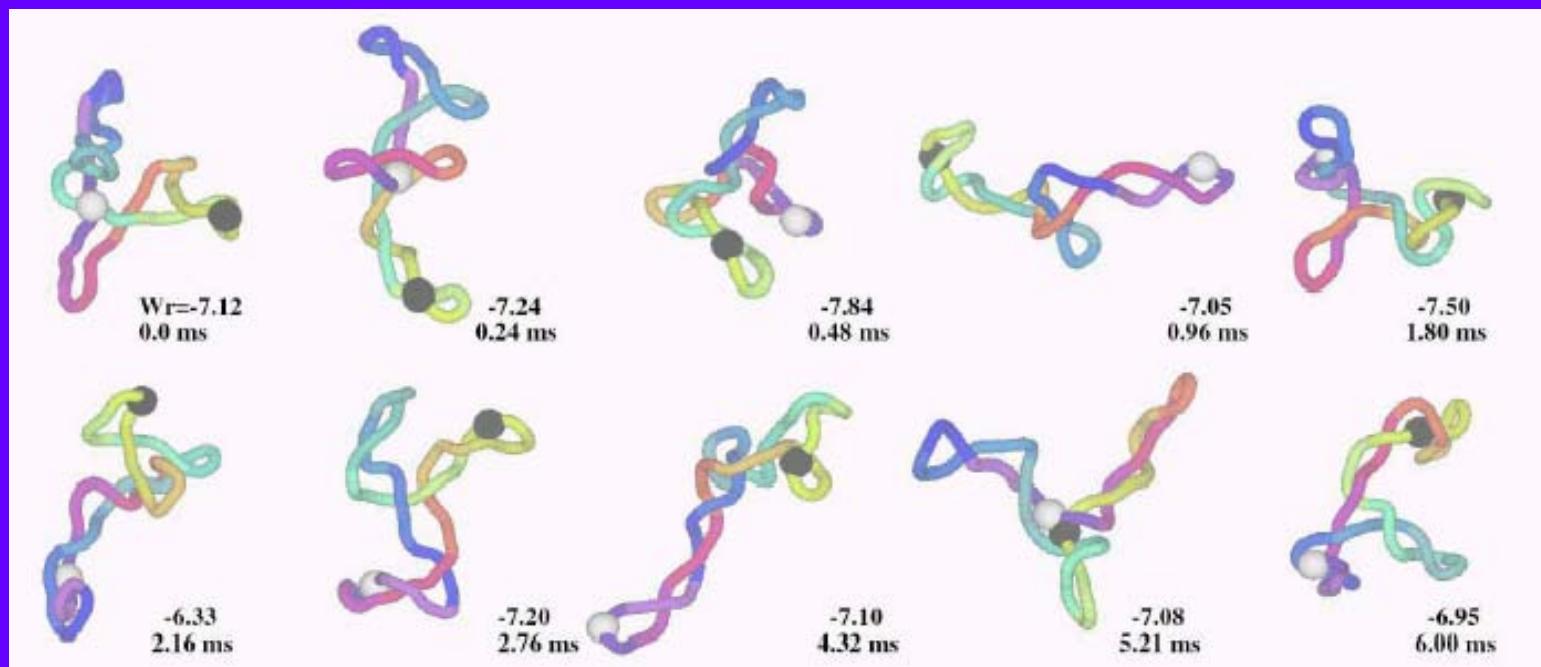


Minituralization of length scale

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

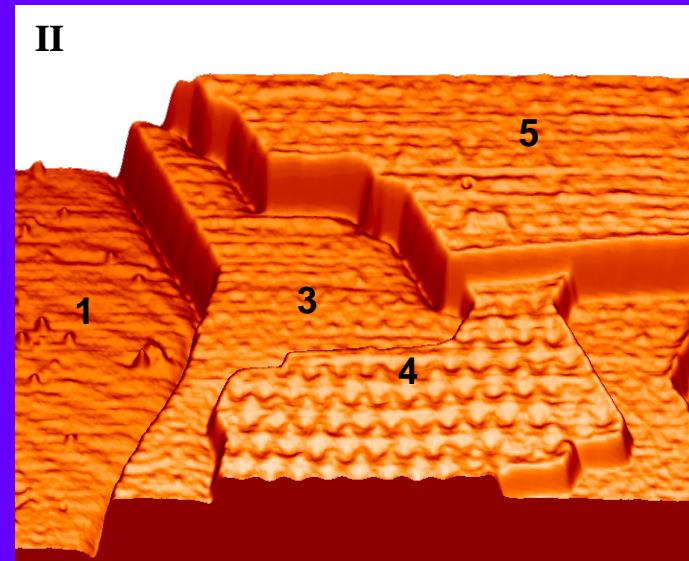
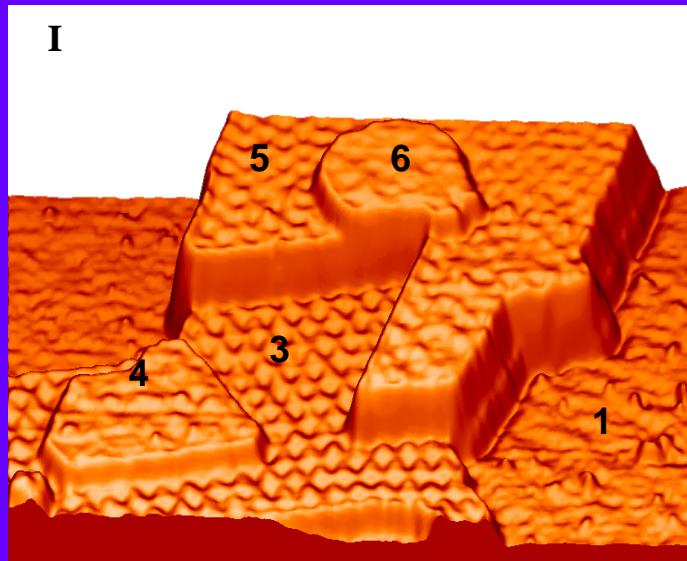


Simulation of DNA dynamics



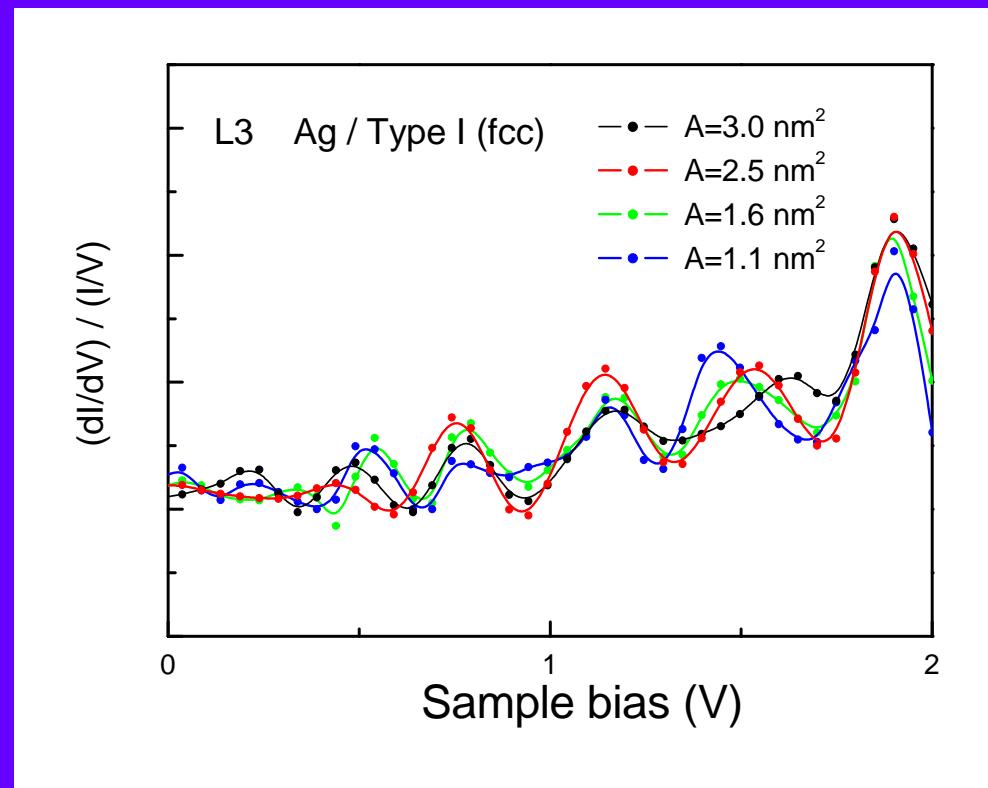
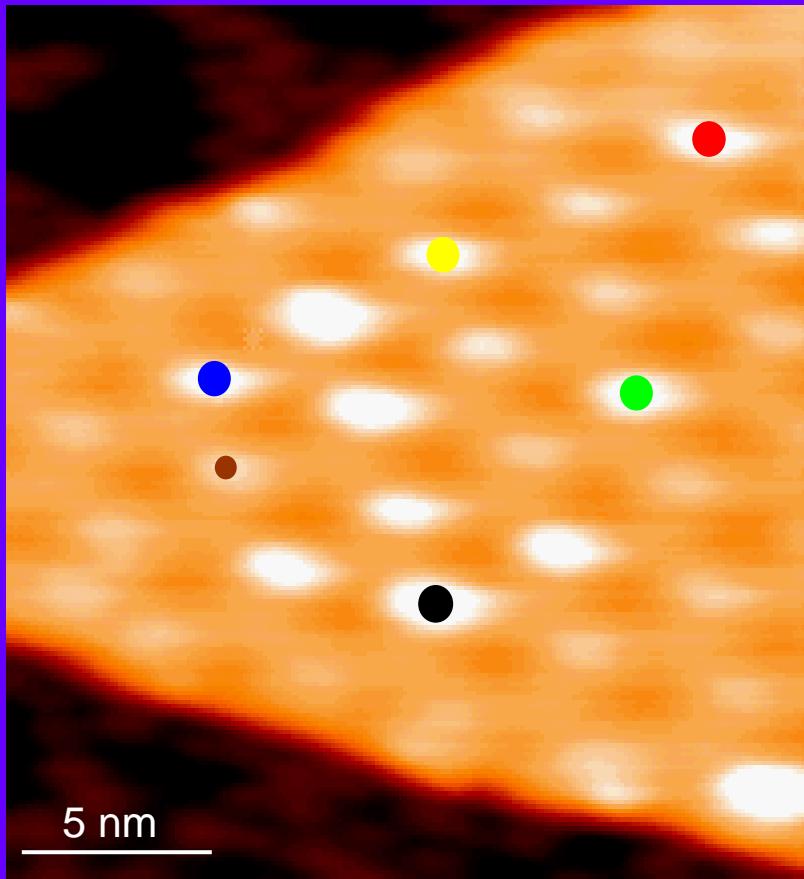


Alternating and complementary contrast

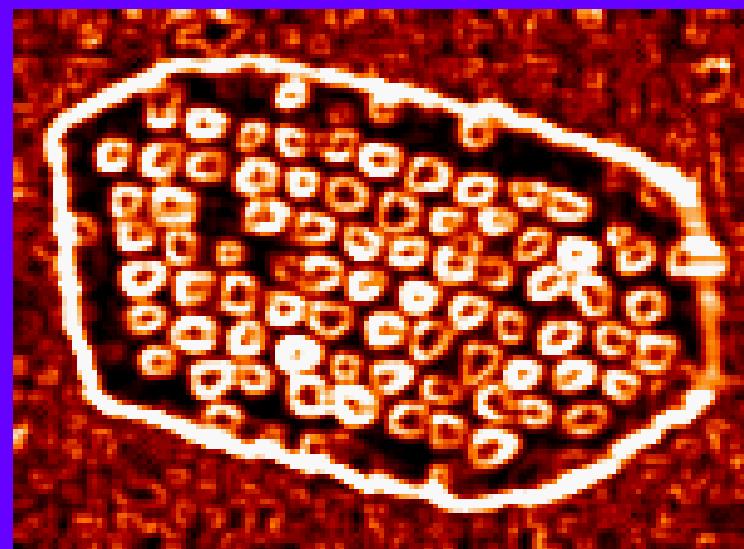
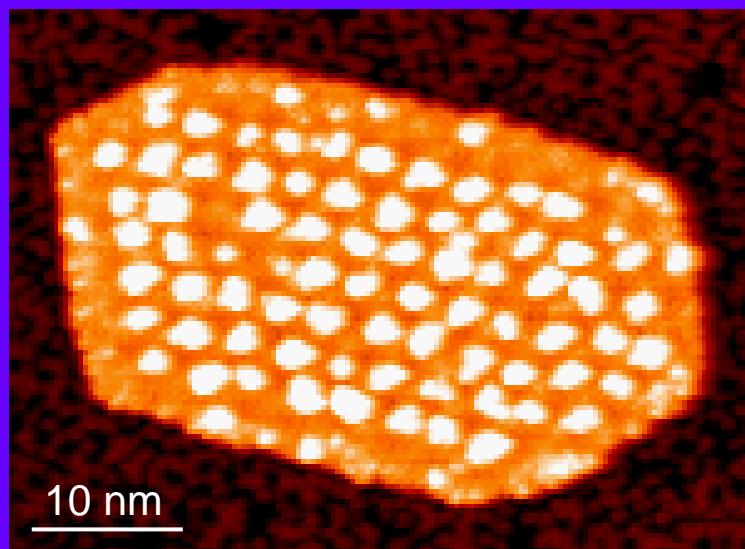


W.B. Jian *et al.* PRL 90, 196603 (2003)

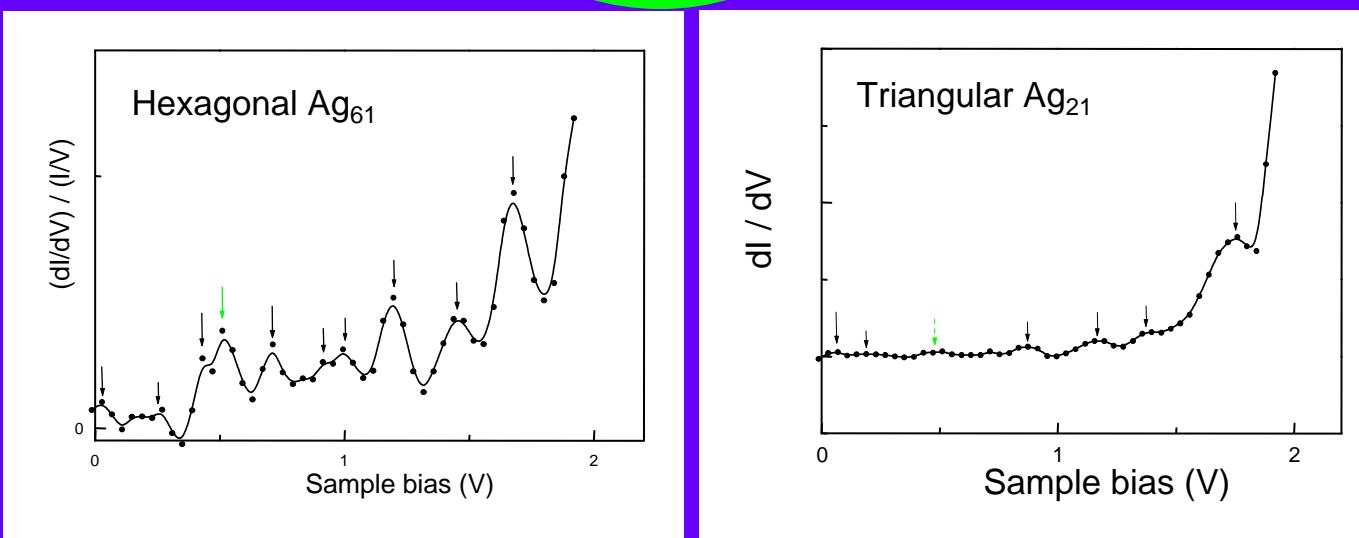
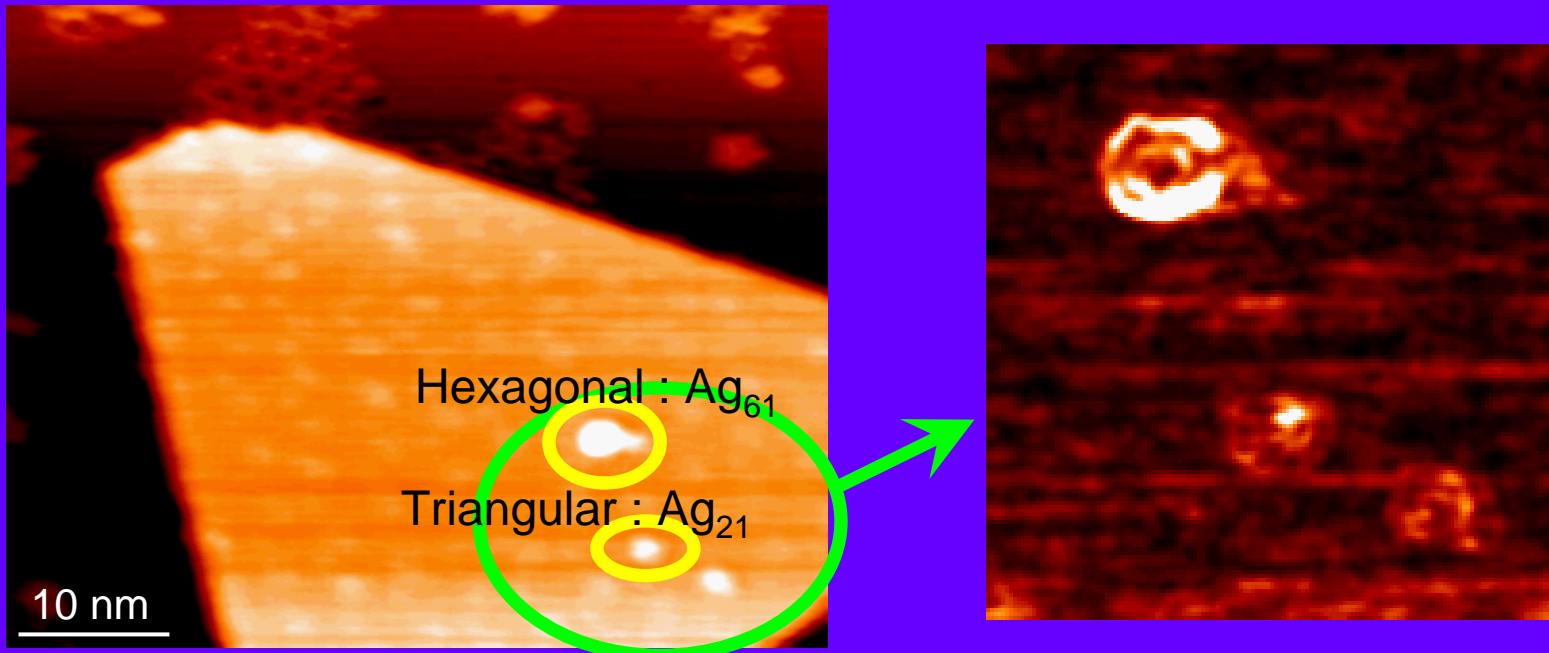
Size-dependent I/V spectra by STS



Shapes of Ag nanopucks



Size- and shape-dependent I/V spectra



Characterization of single nanostructure

Specs

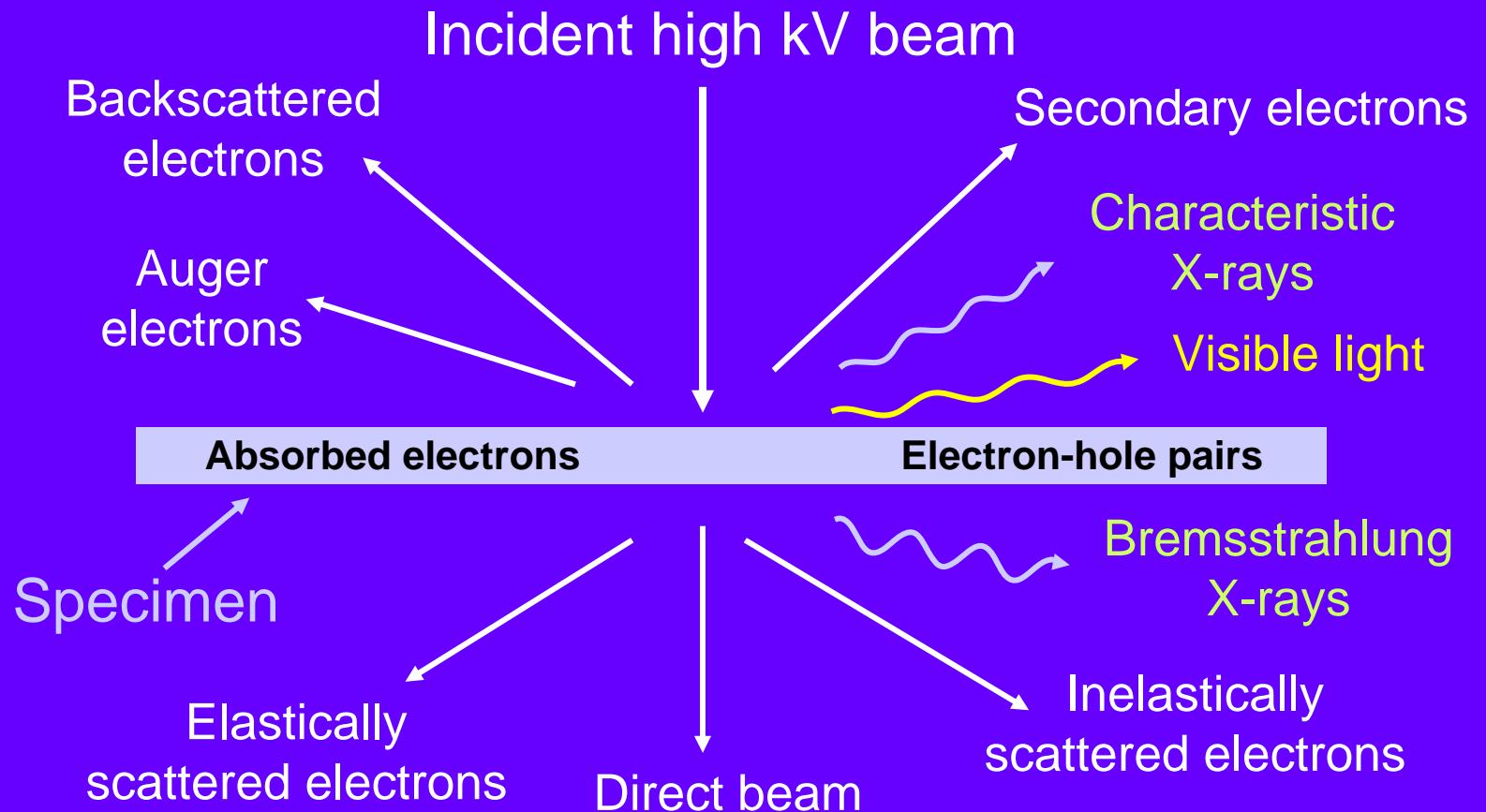
- Small size
- Weak signal
- High reactivity
- Flexible functionality

Demands

- high brightness
- small probe
- high sensitivity
- low interference
- controlled environment
- low temperature
- high speed
- in situ* measurement

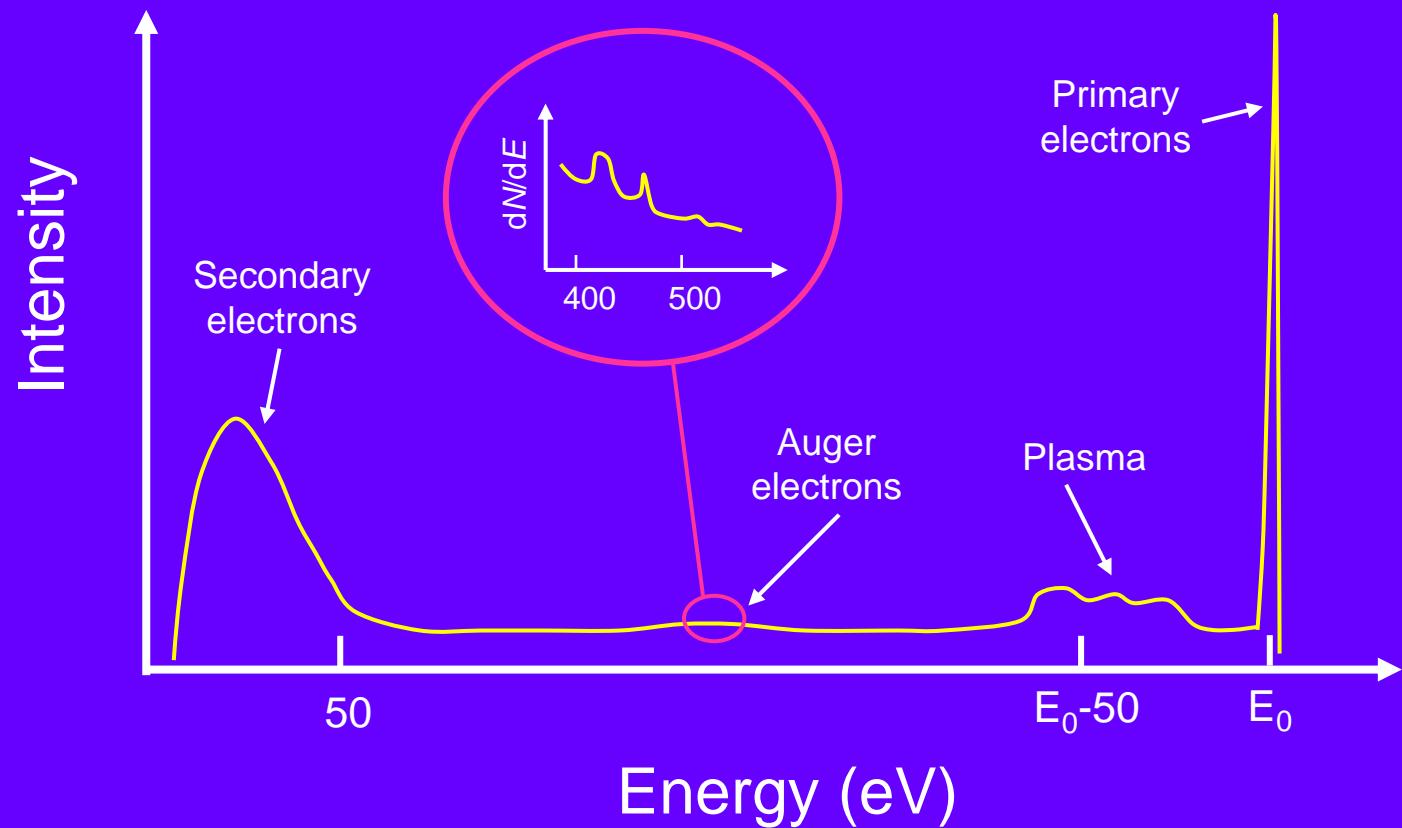


Interaction between e-beam and sample



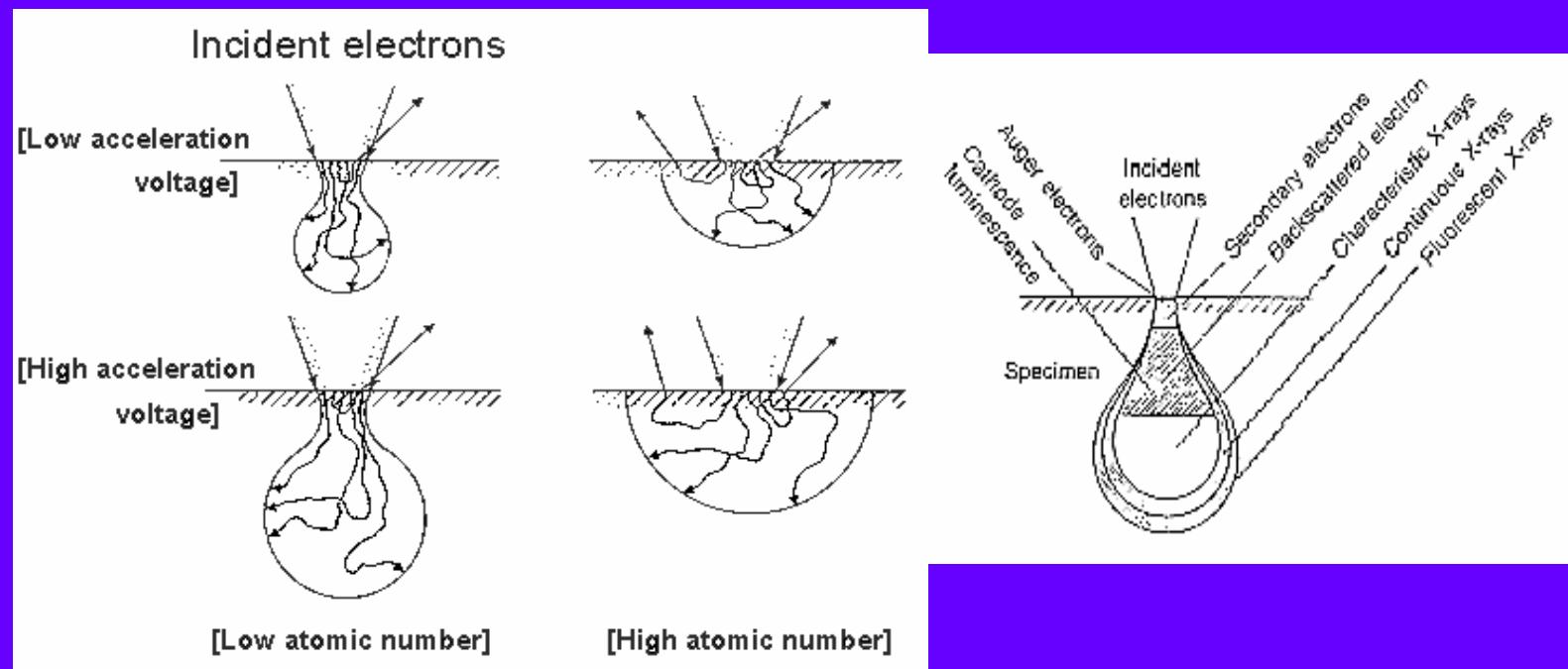


Energy distribution after interaction

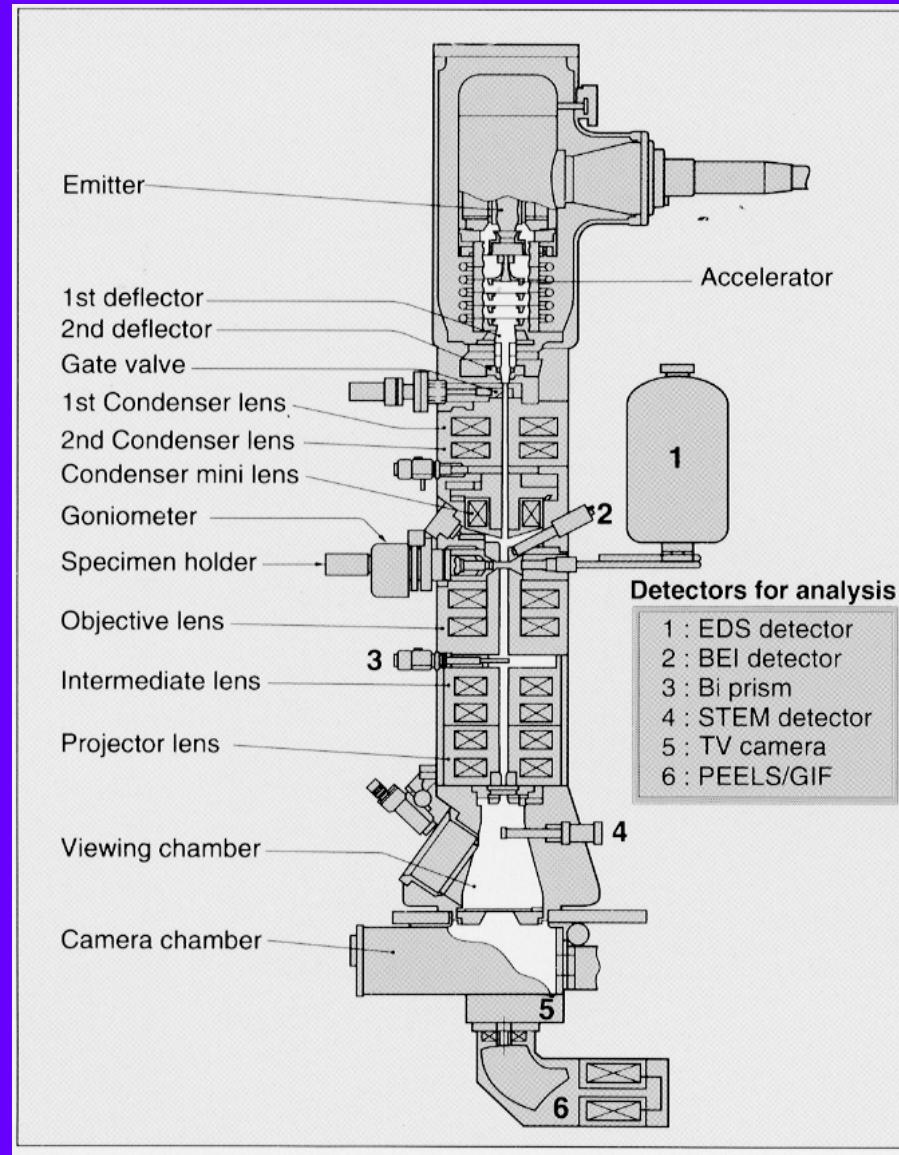




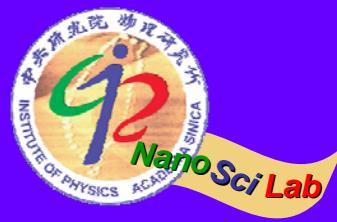
Penetration power of energetic e beam



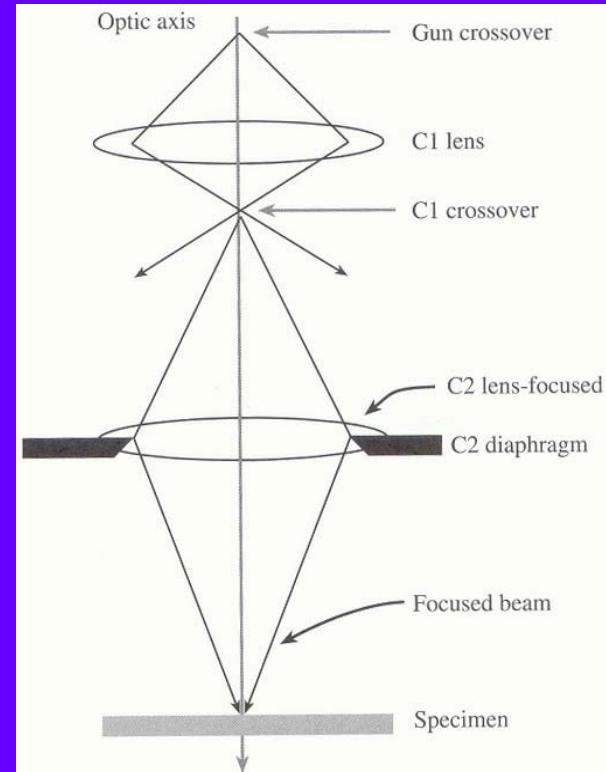
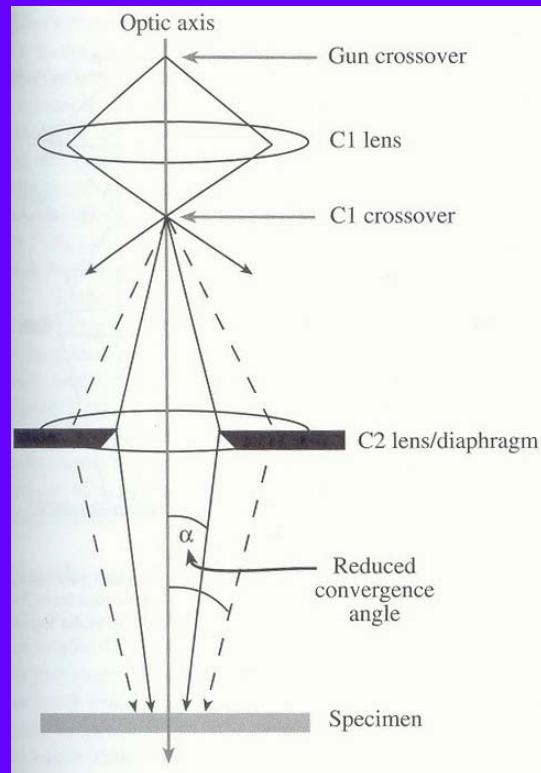
Cross section view of HRTEM



Cross section of JEM-2010F and assignment of detectors

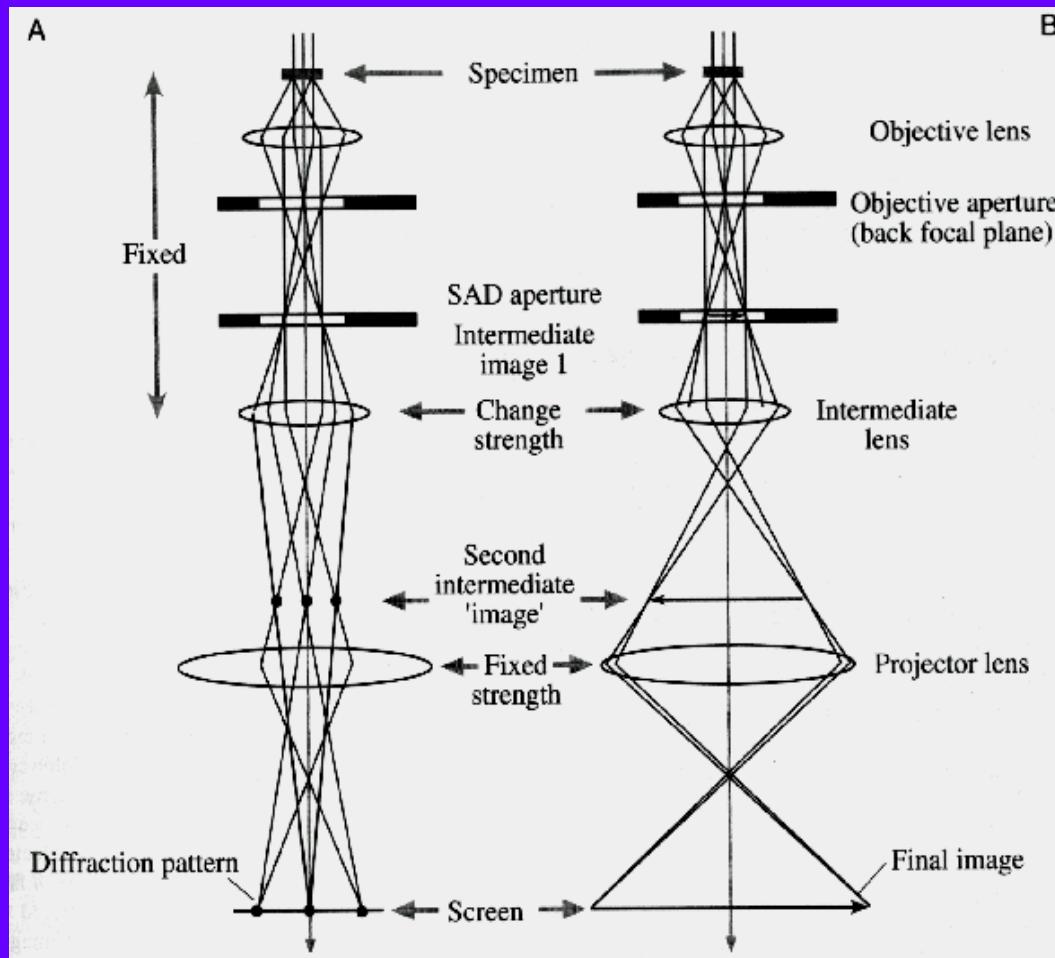


E-beam source of TEM

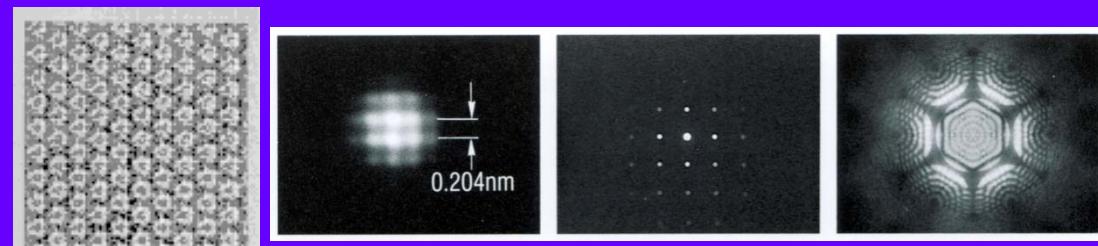
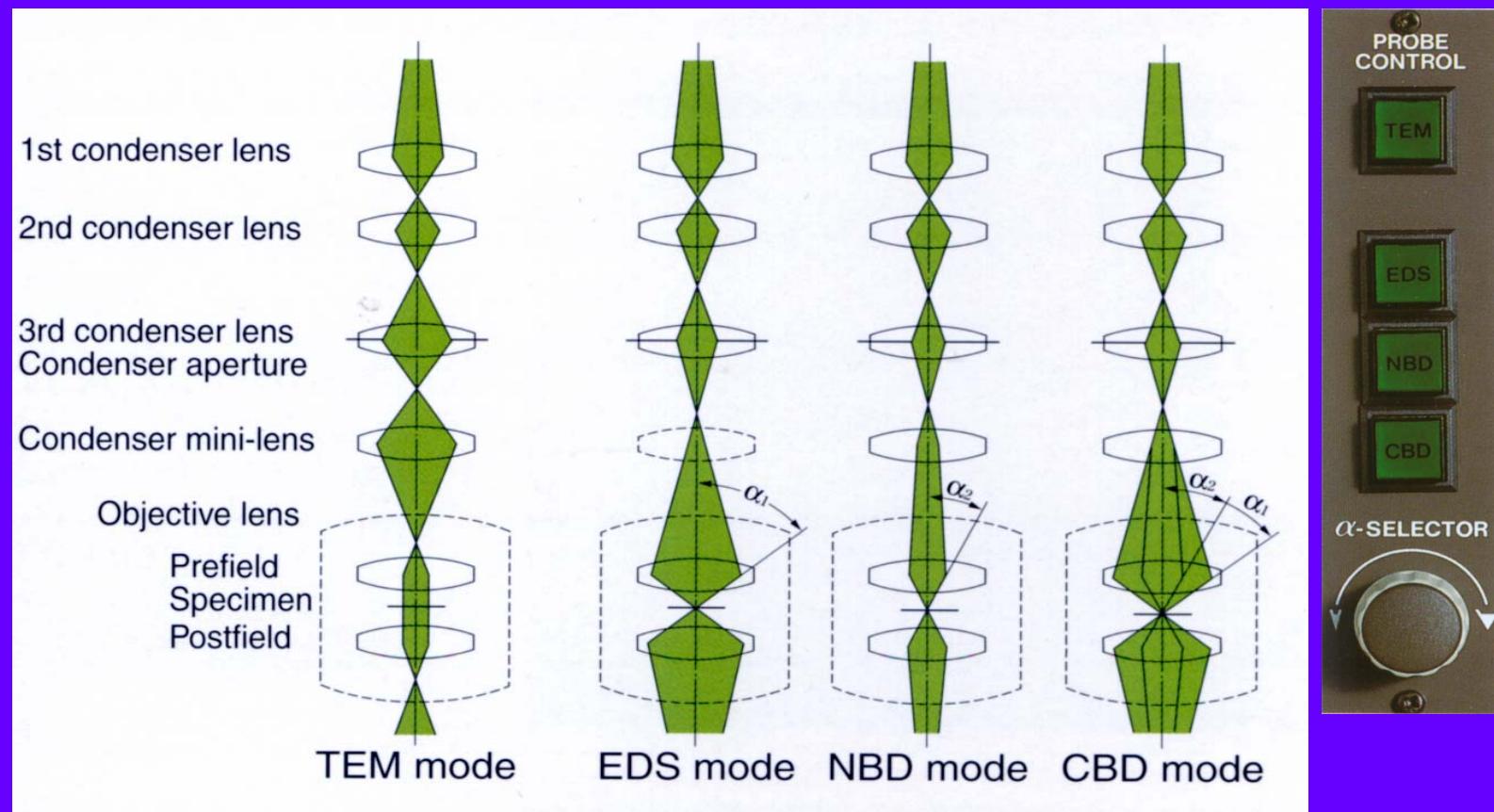




Imaging system



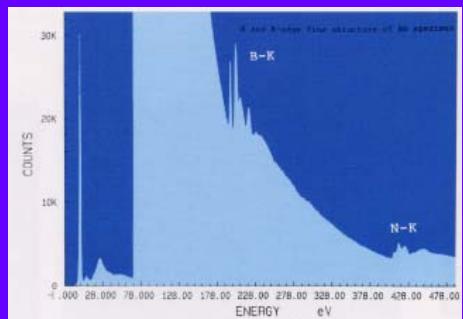
Quick Beam Select System



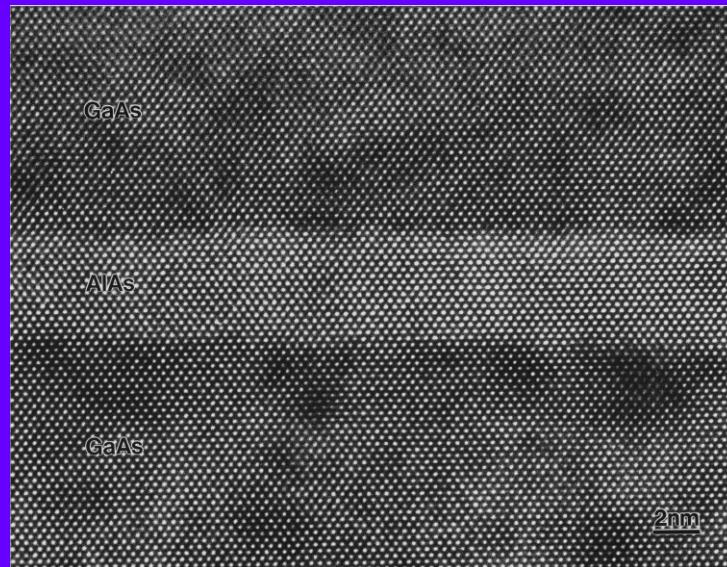
Information from TEM



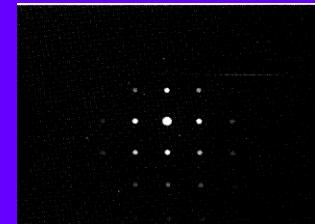
EDS



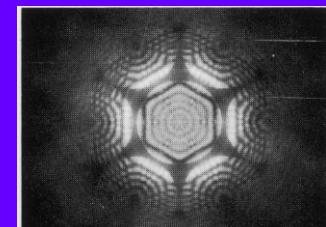
EELS or GIF



Lattice image
GaAs/AlAs



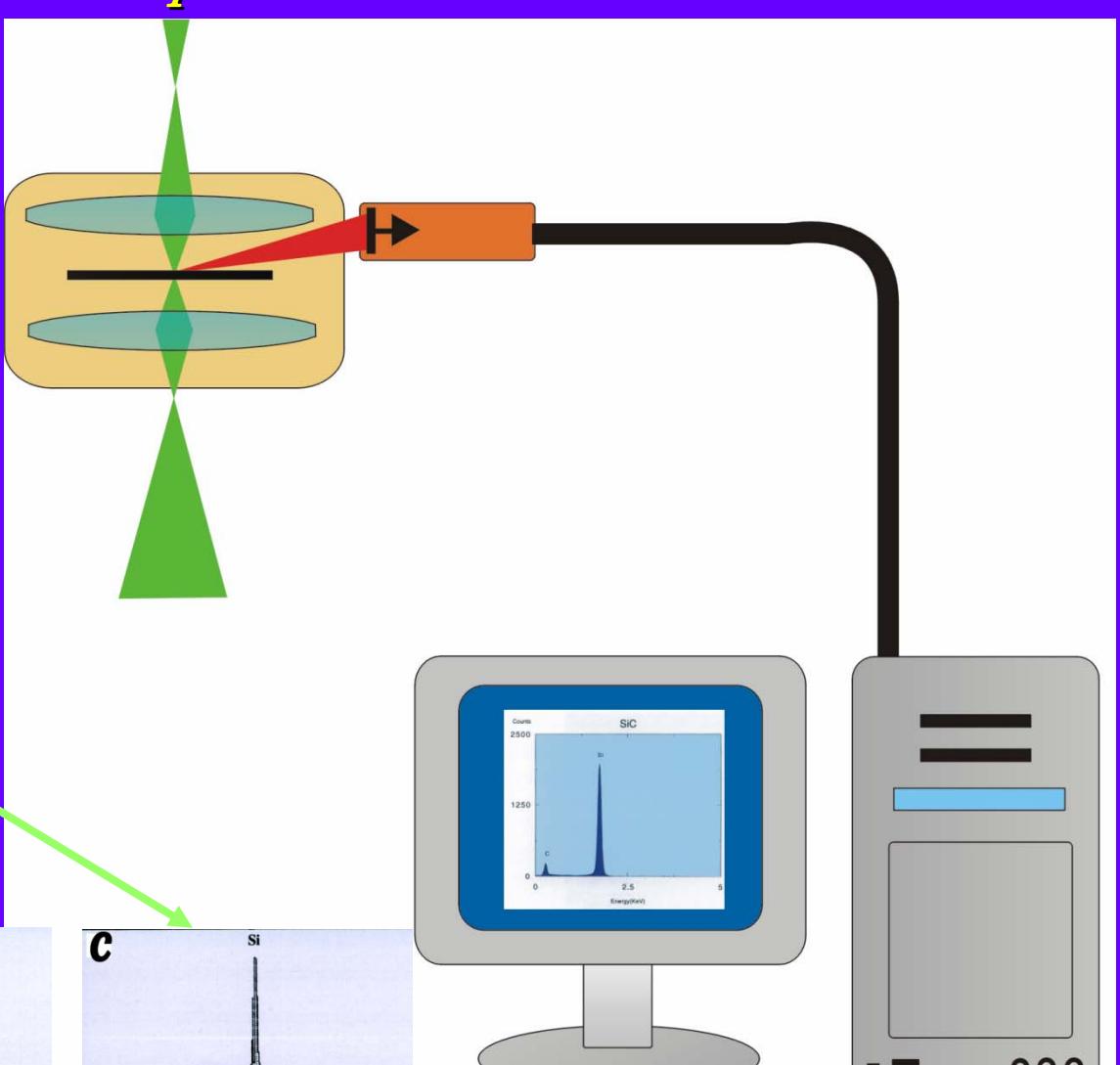
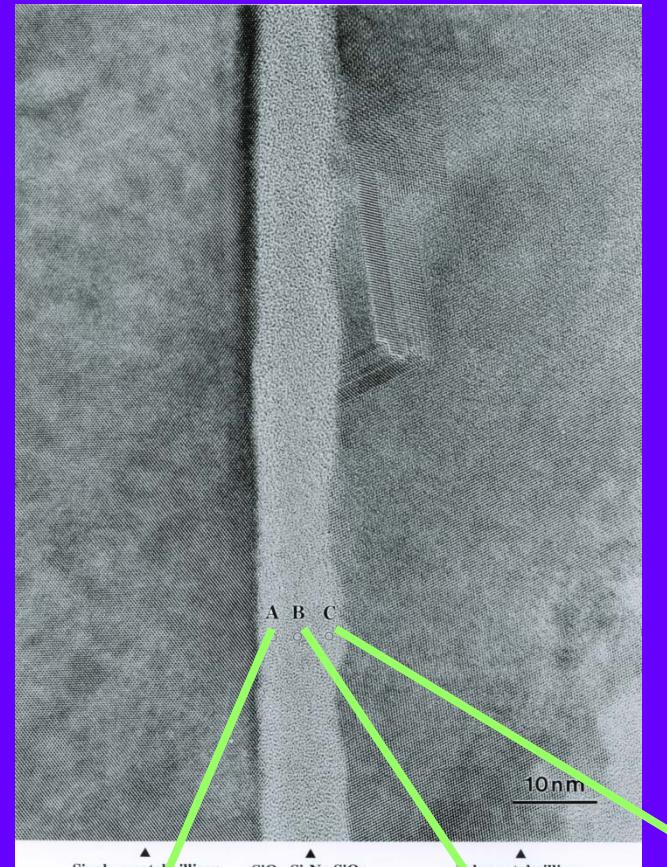
Electron Diffraction



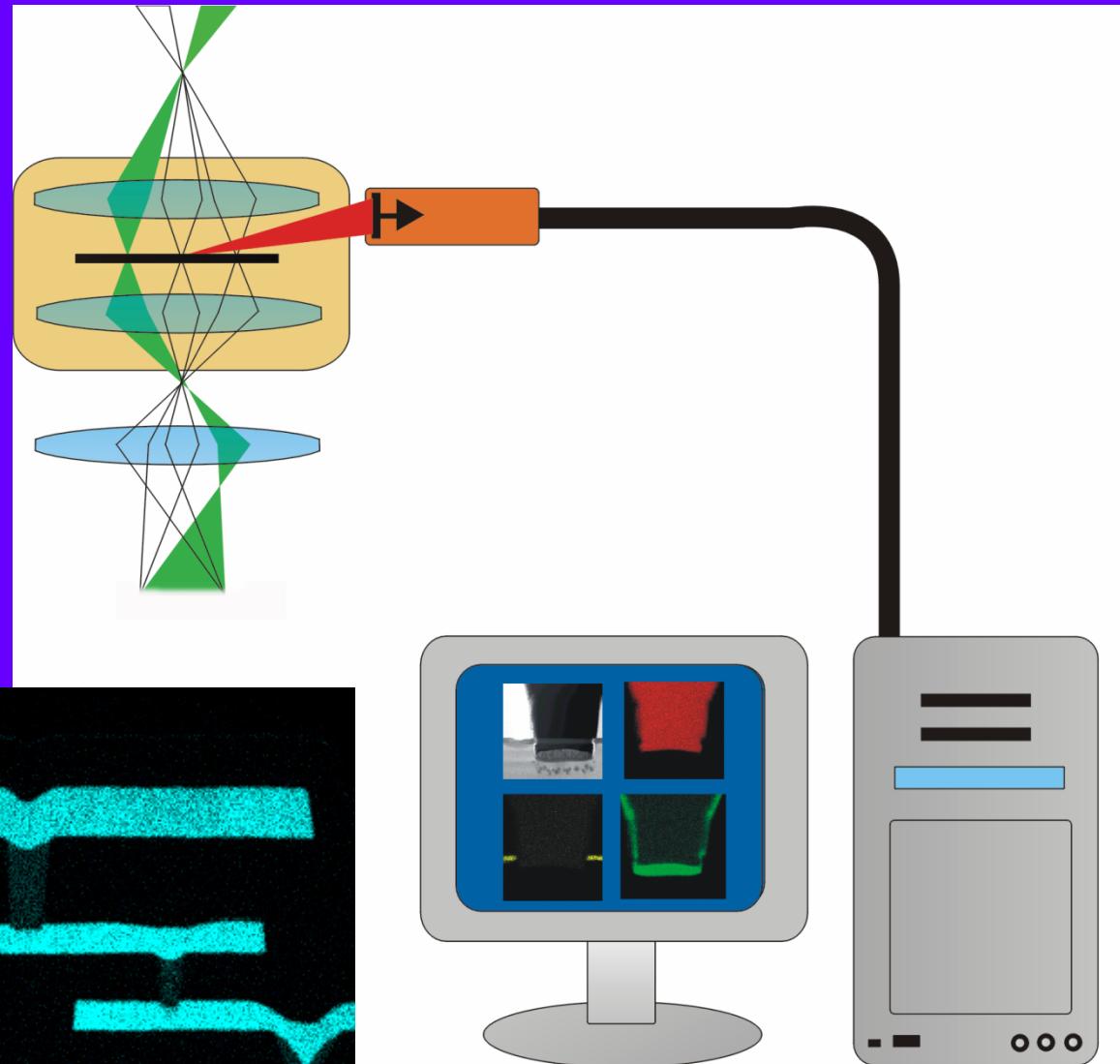
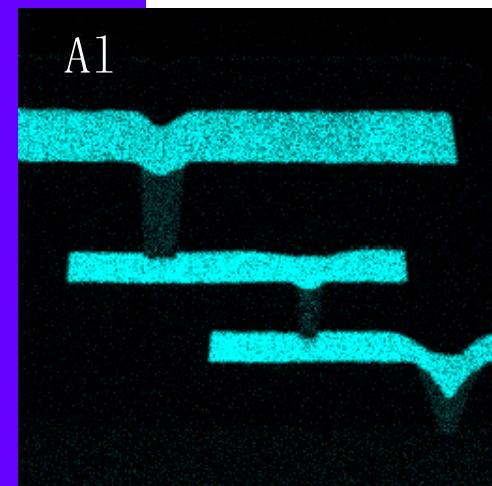
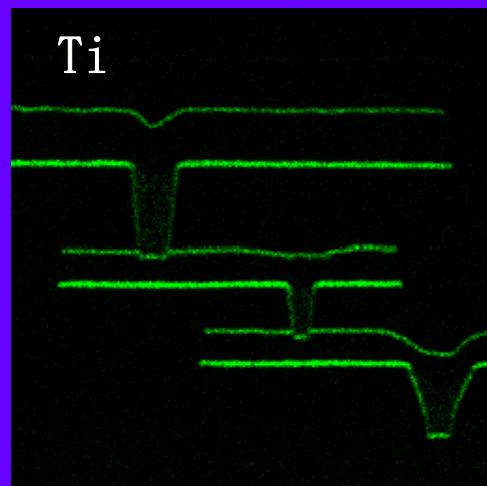
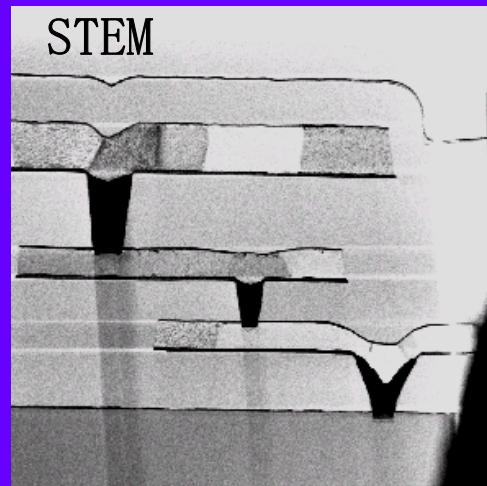
CBED

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

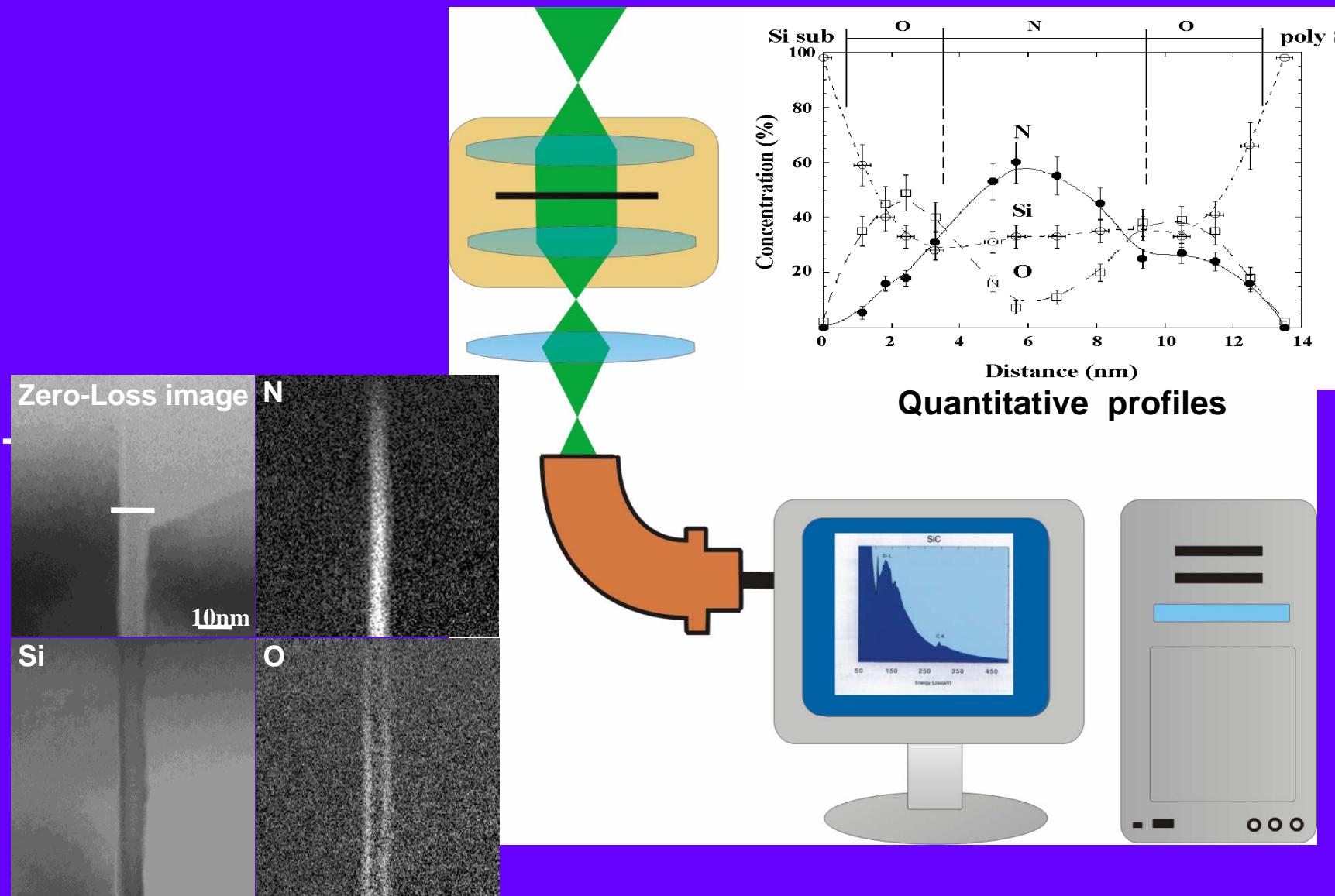
EDS with spatial resolution



EDS mapping

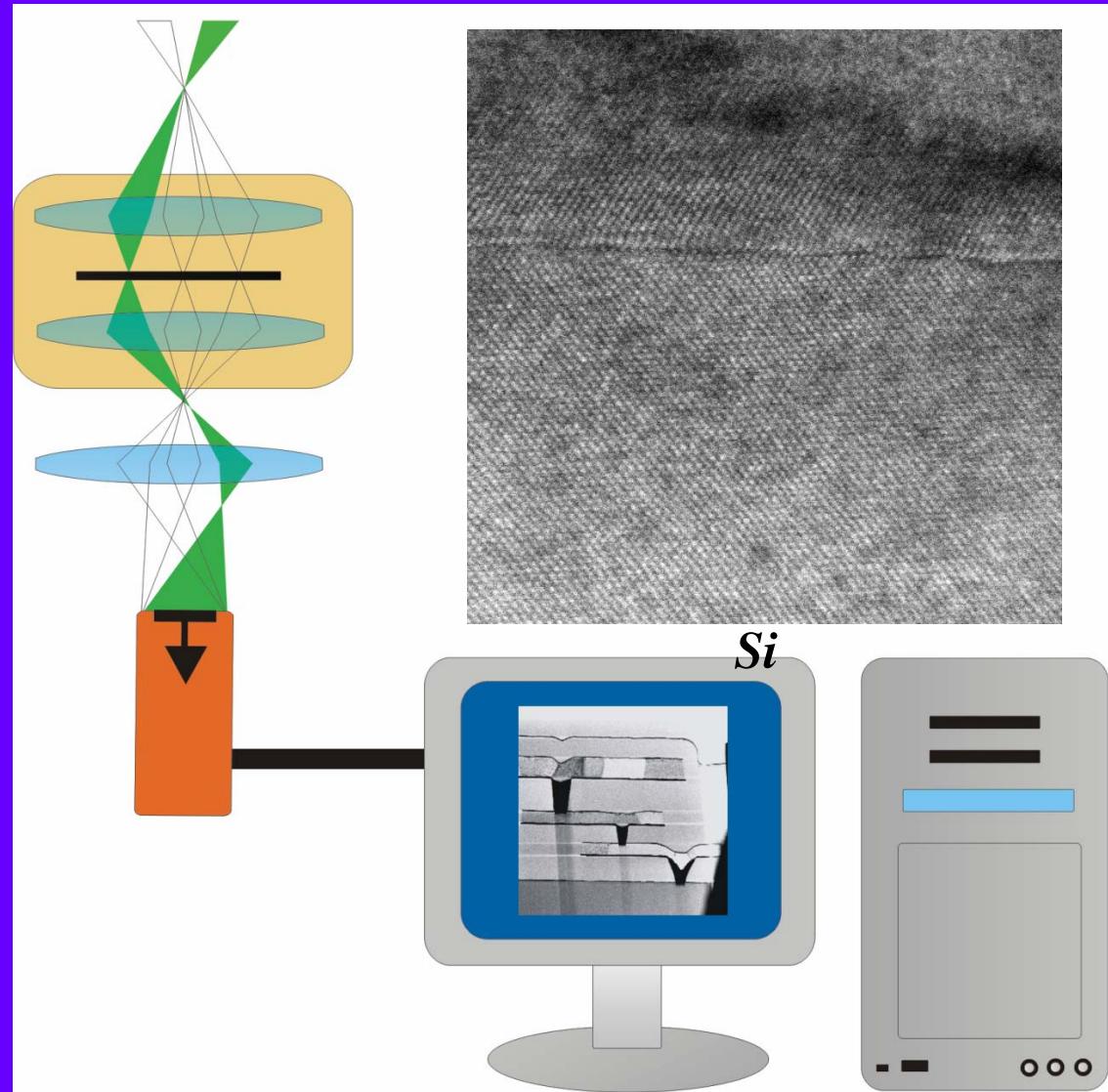
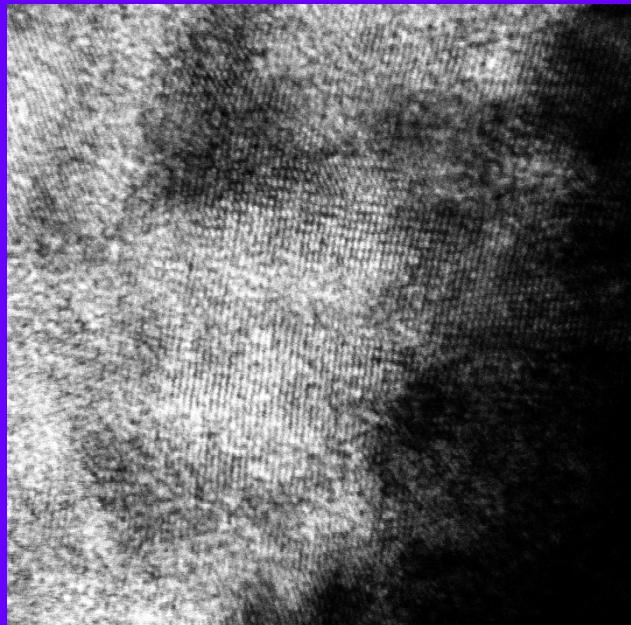


High resolution EELS



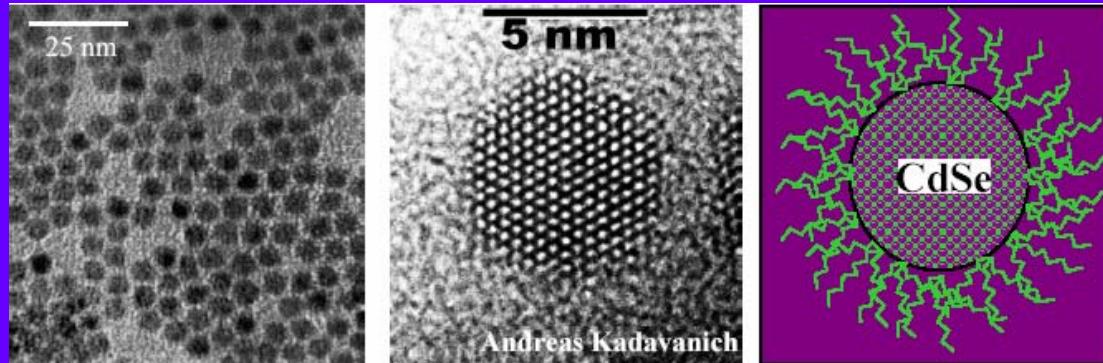
High resolution STEM image

W-plug.

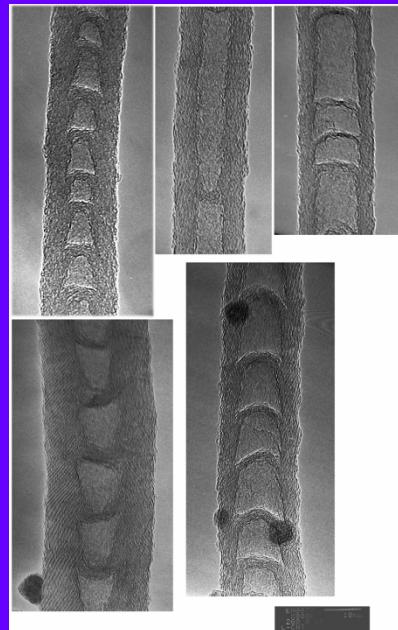




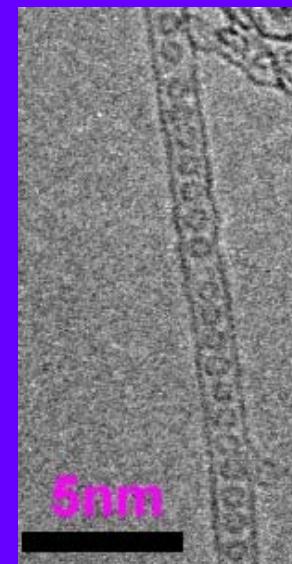
Semiconducting quantum dots and carbon nanotubes



(Reproduced from Quantum Dot Co.)



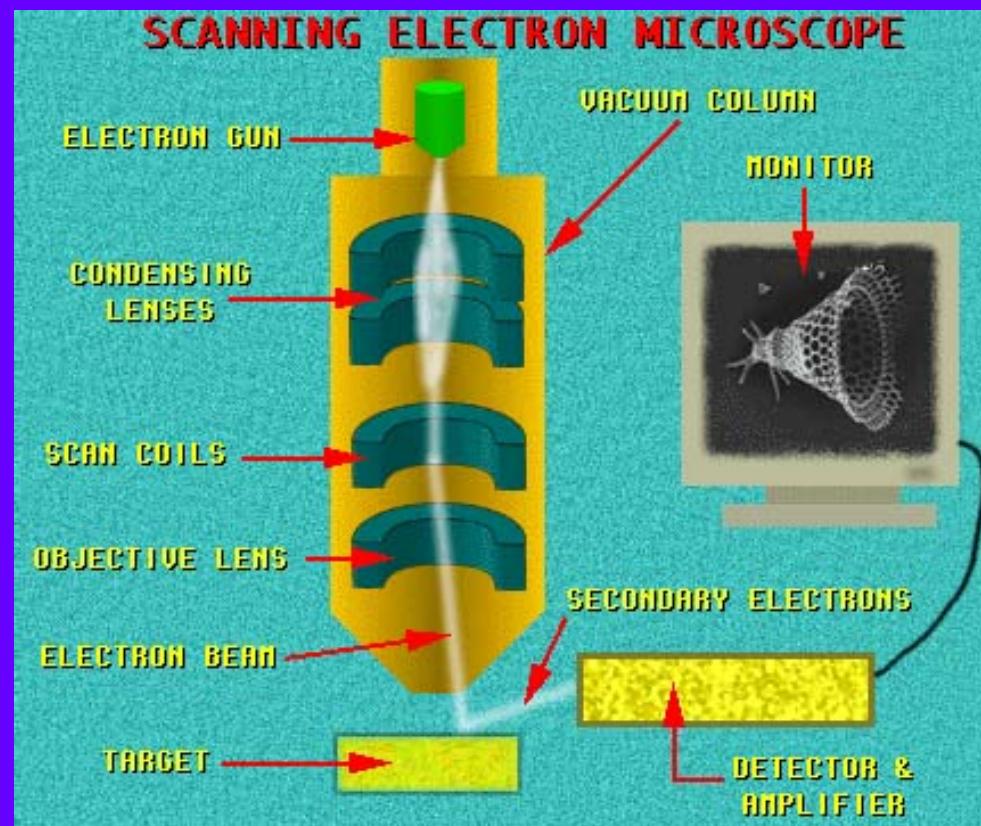
Multiwall CNT



Peapod CNT



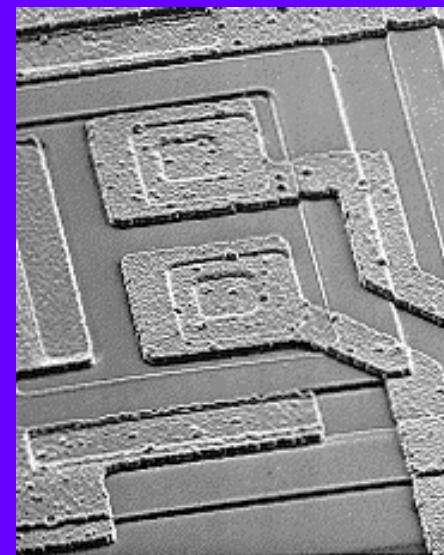
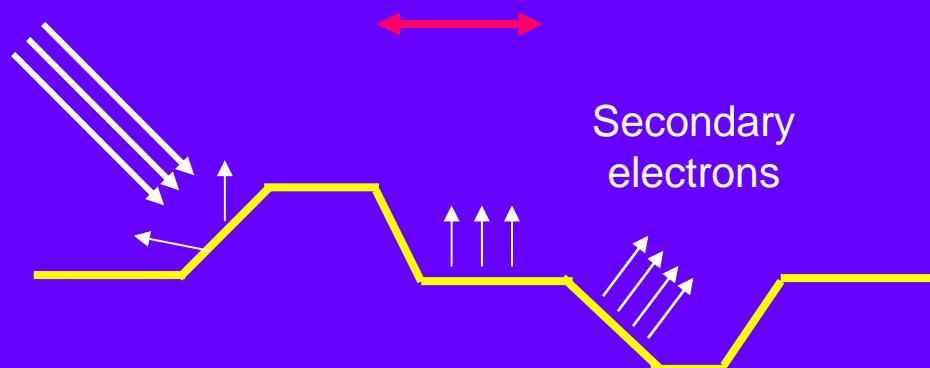
Scanning electron microscopy (SEM)





SEM contrast

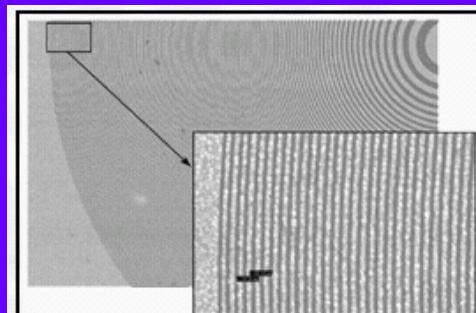
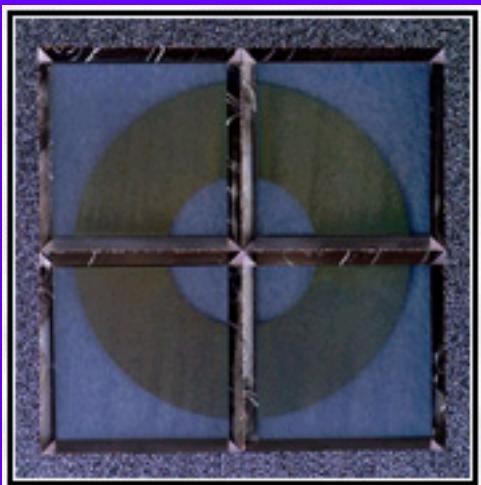
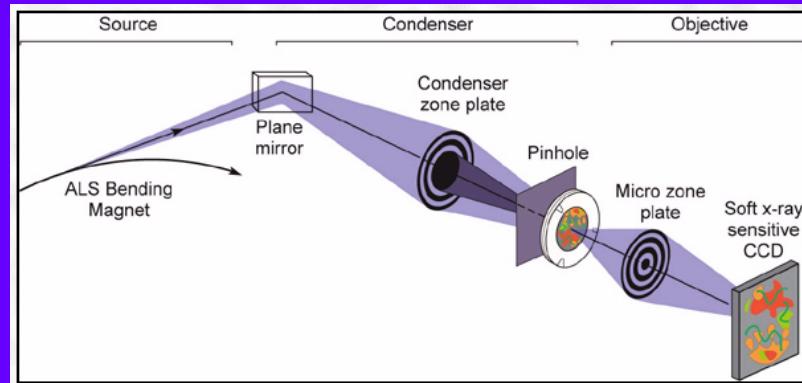
Scanning e beam



(a) 5 kV x720
Tilt angle: 50°



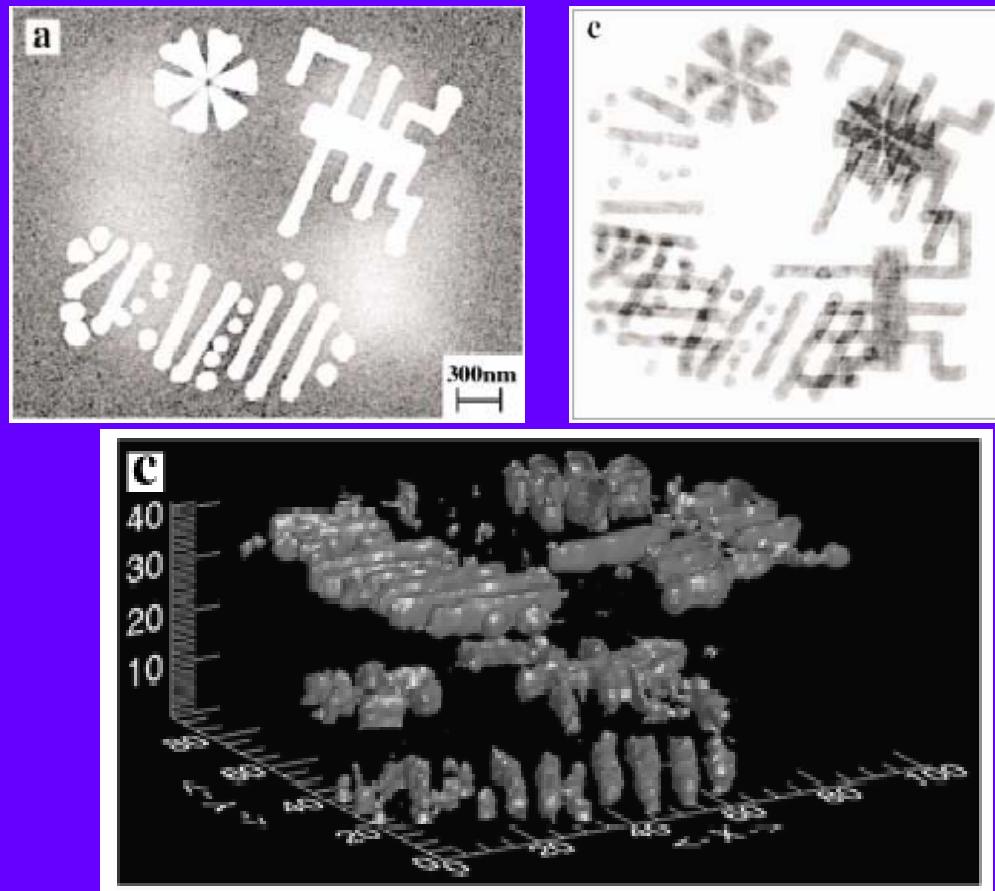
X-Ray Microscopy



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



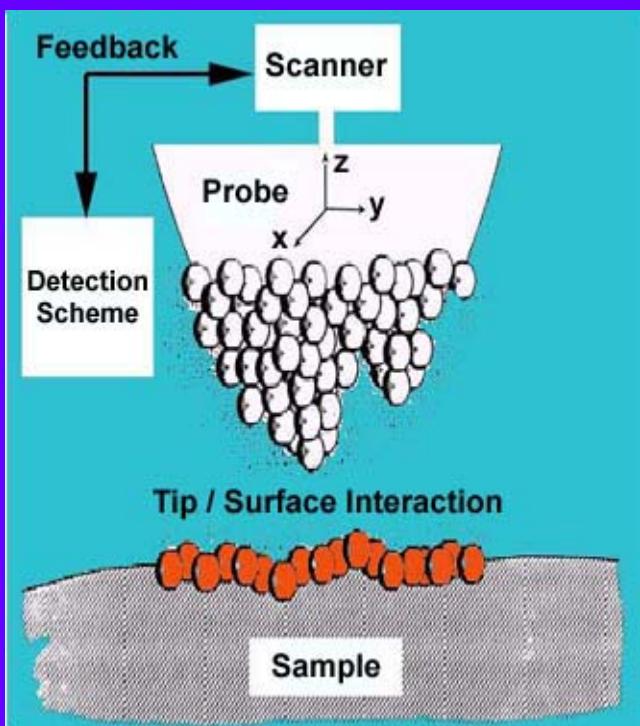
3D X-Ray Image



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)

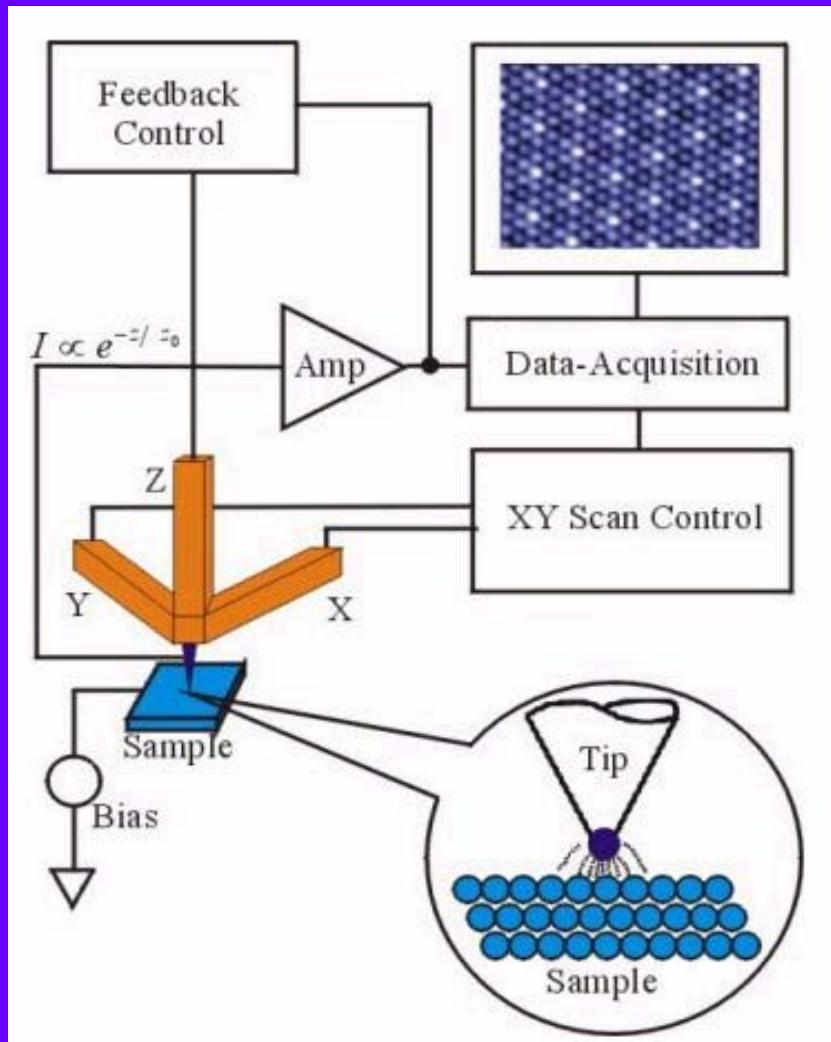
--- Y. Martin, D. W. Abraham et al (1988)

Scanning Capacitance Microscopy (SCM)

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

Force Modulation Microscopy (FMM)

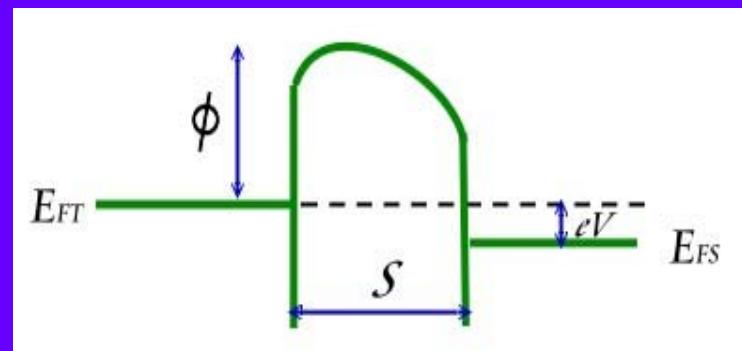
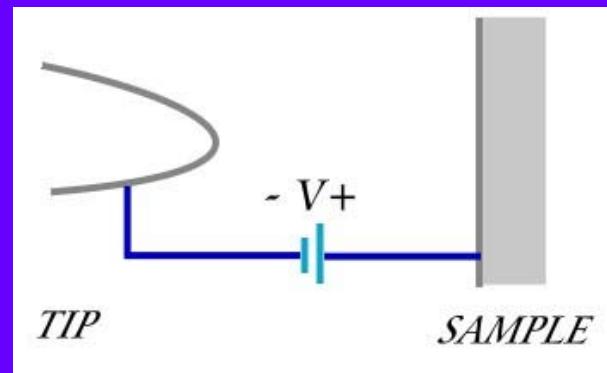
--- P. Maivald et al (1991)



Scanning Tunneling Microscopy



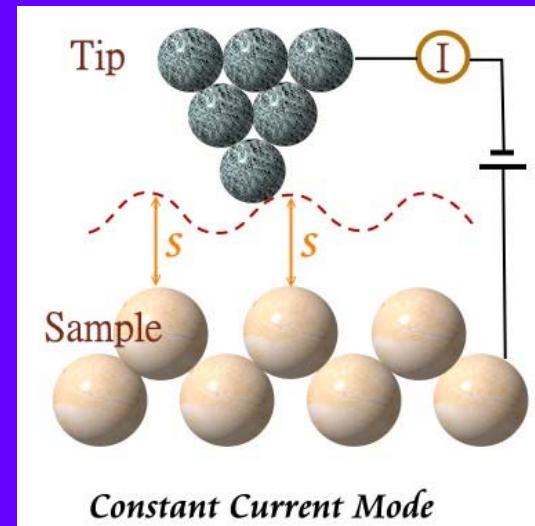
Theory of STM



From one-dimensional tunneling
problem tunneling current ($eV \ll \phi$)

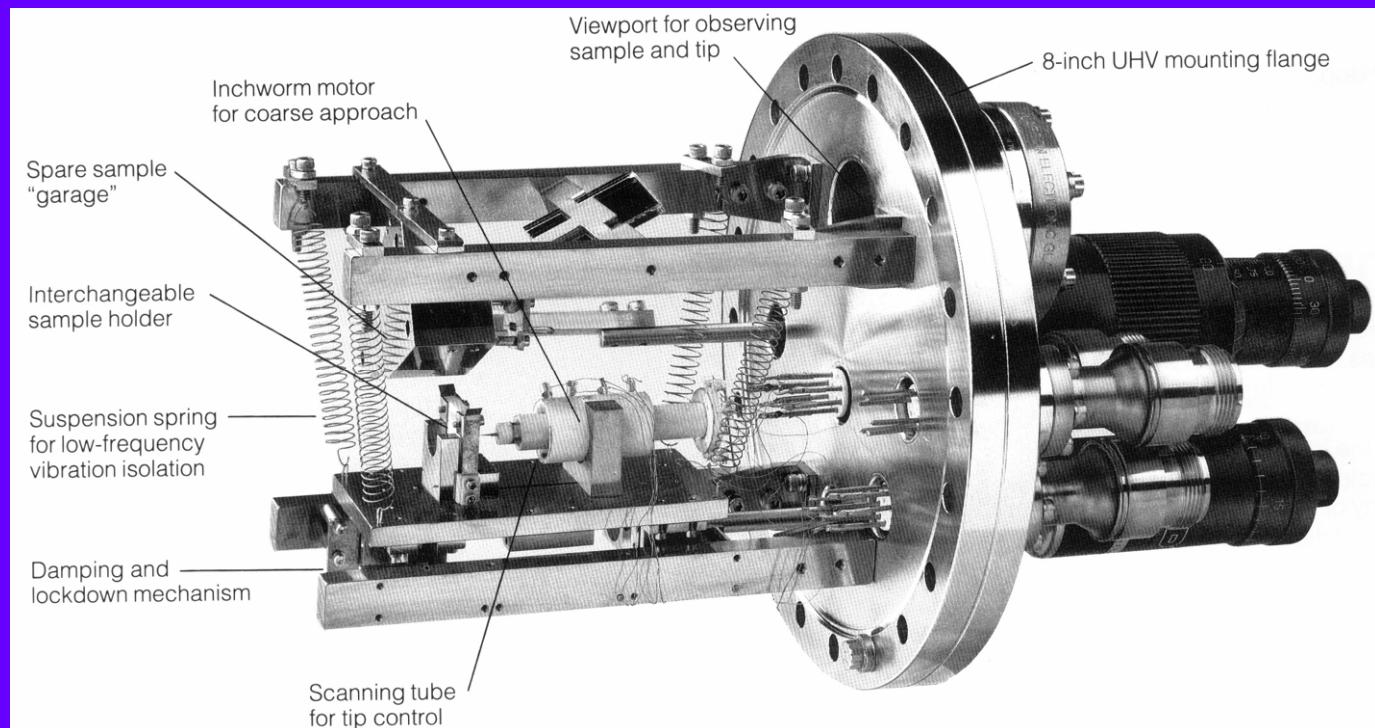
$$I \propto \frac{V}{S} \exp\left(-A\phi^{\frac{1}{2}}S\right)$$

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



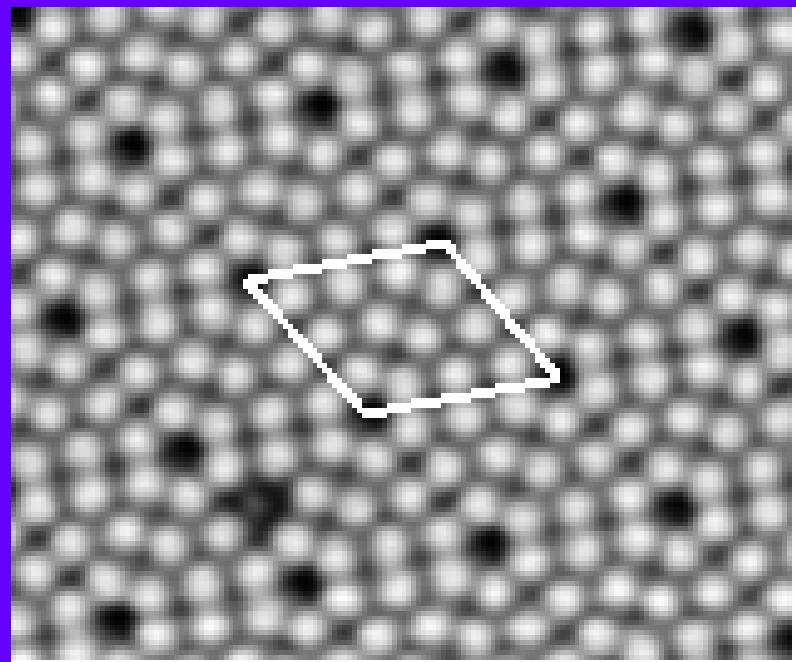


UHV STM

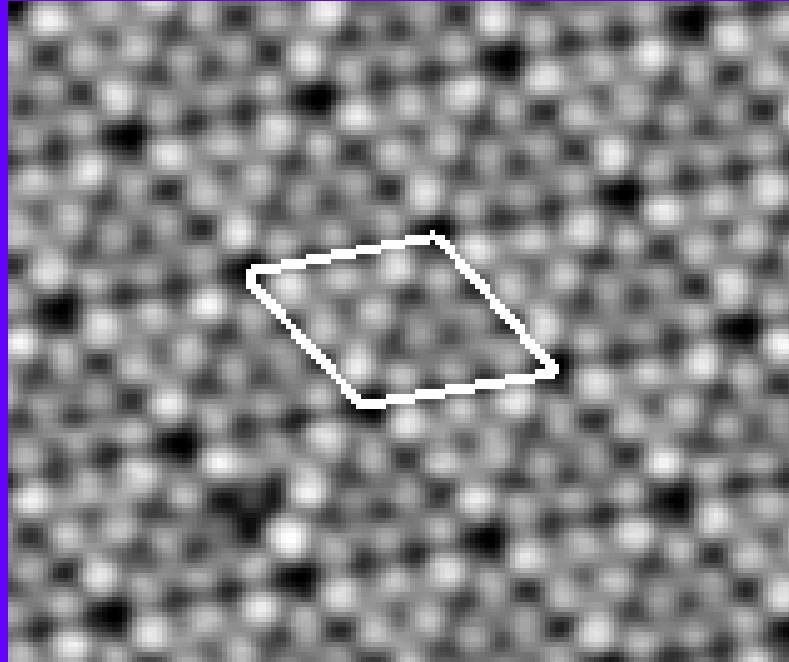




STM Images of Si(111)-(7×7)



Empty-state image

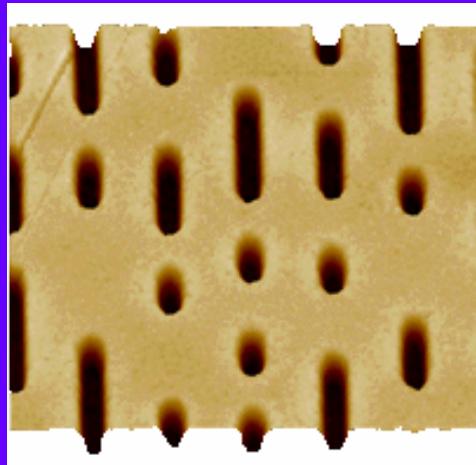


Filled-state image

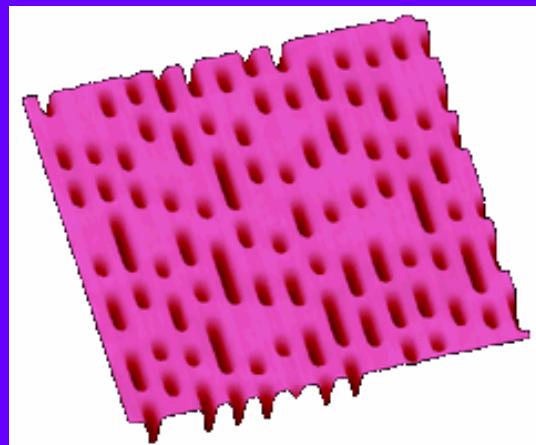


AFM images

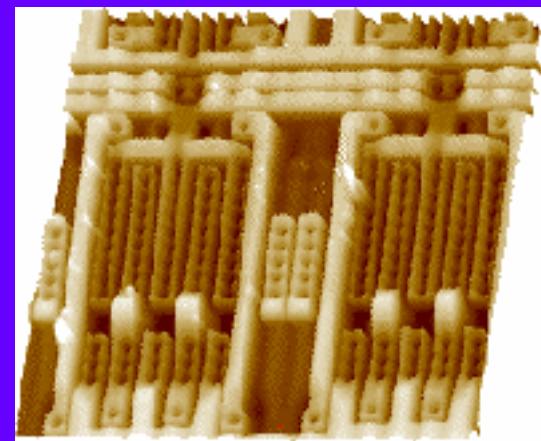
CD pits



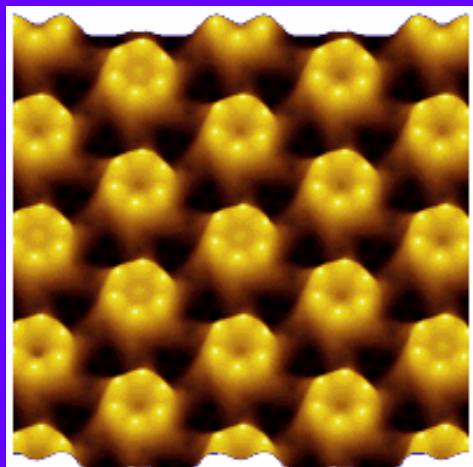
DVD pits



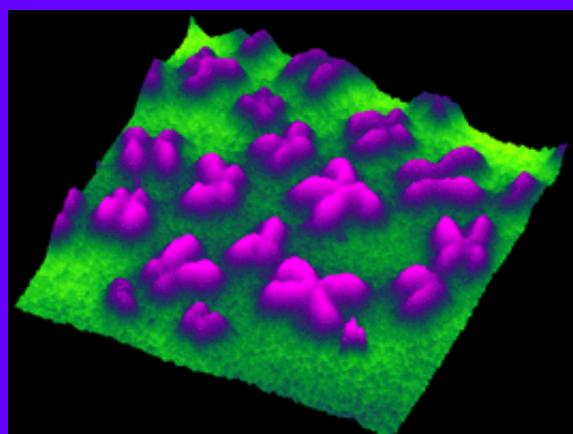
Integrated Circuit



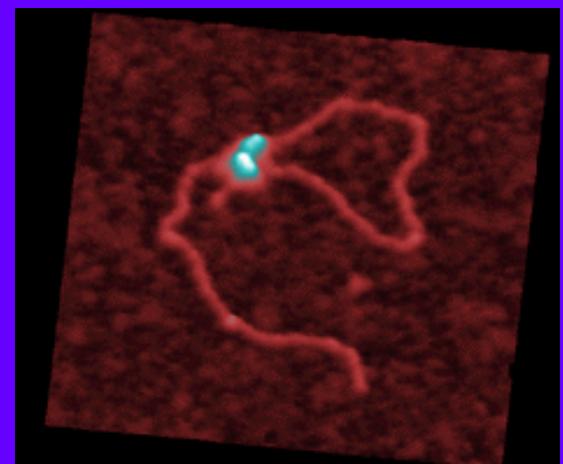
Bacteria



Chromosomes



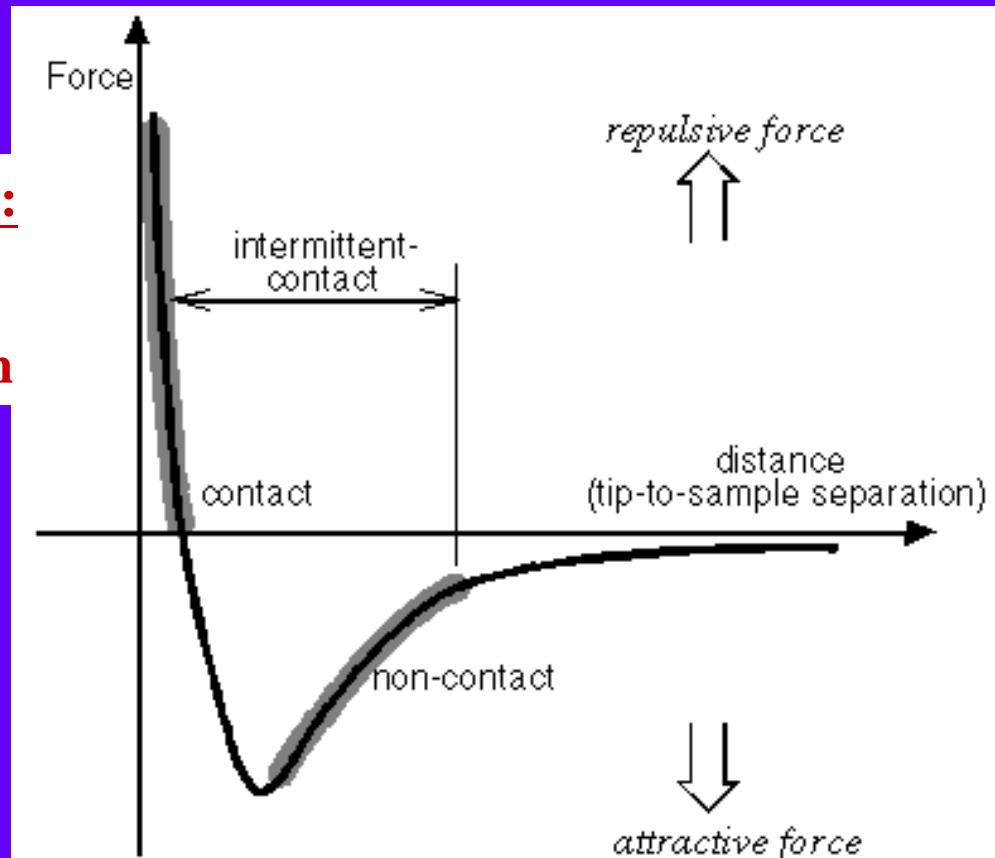
DNA



Interaction between the probe and sample

Short-range:

- 1) Bonding
- 2) Repulsion



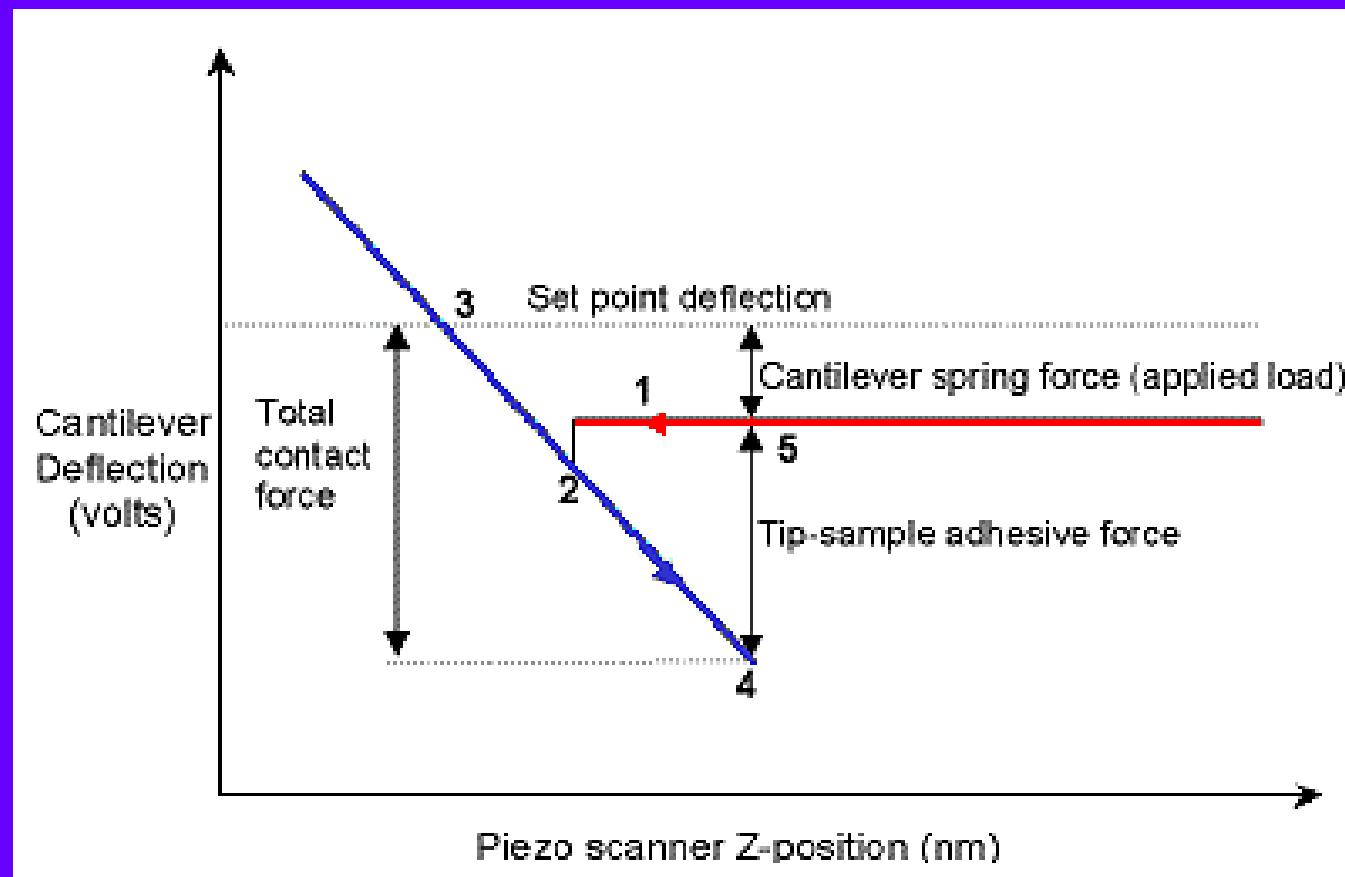
Long-range:

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

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

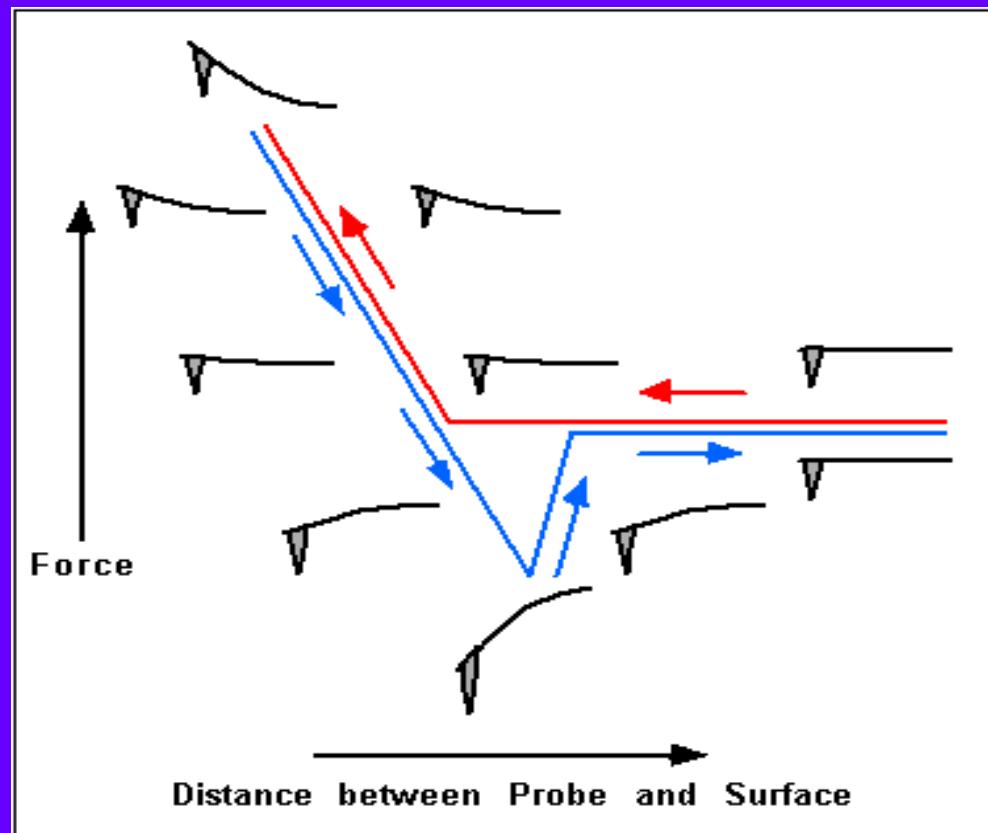


Deflection of Cantilever vs Piezo displacement



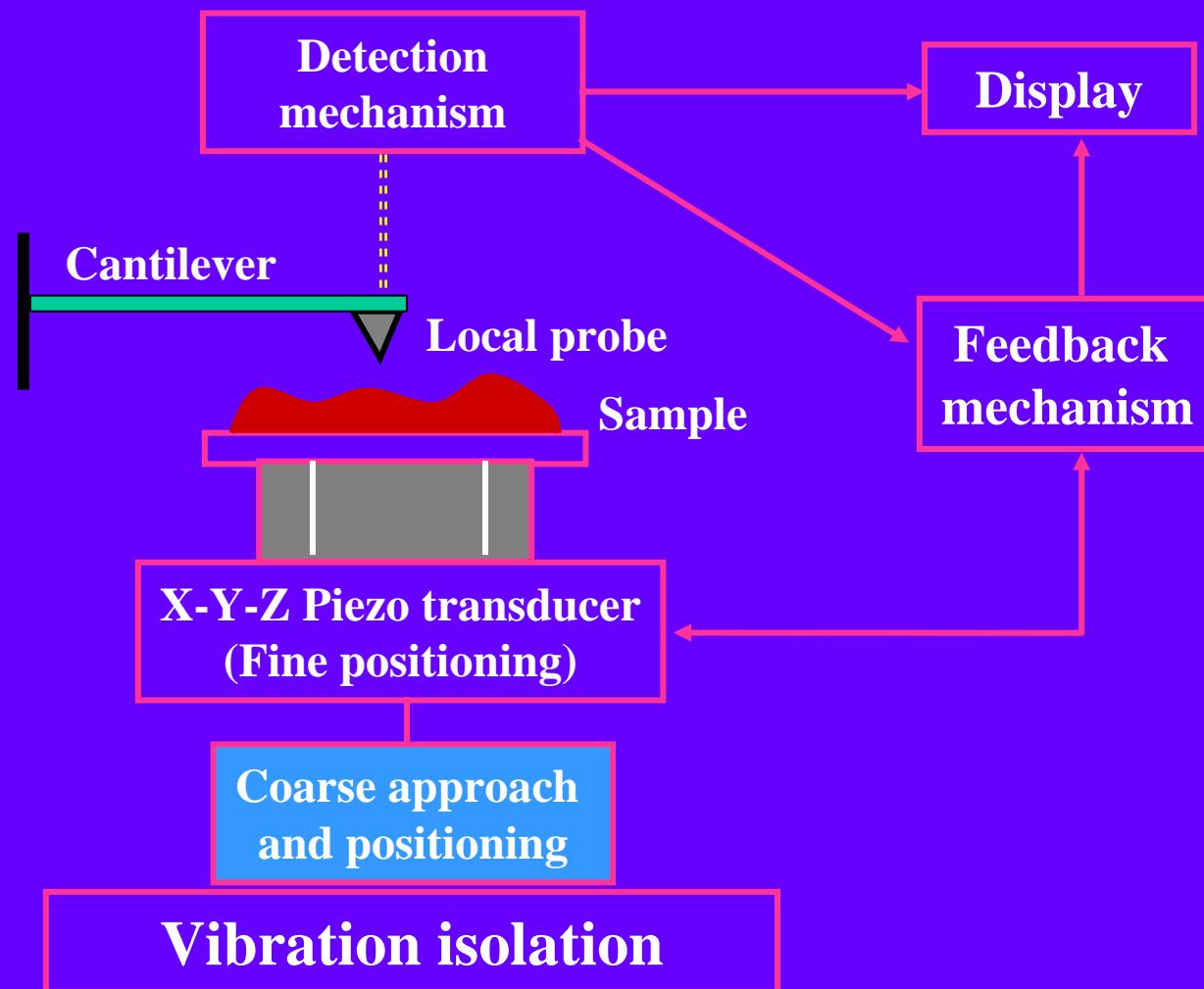


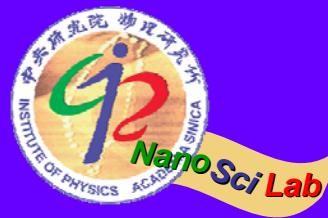
Reaction of probe to the force



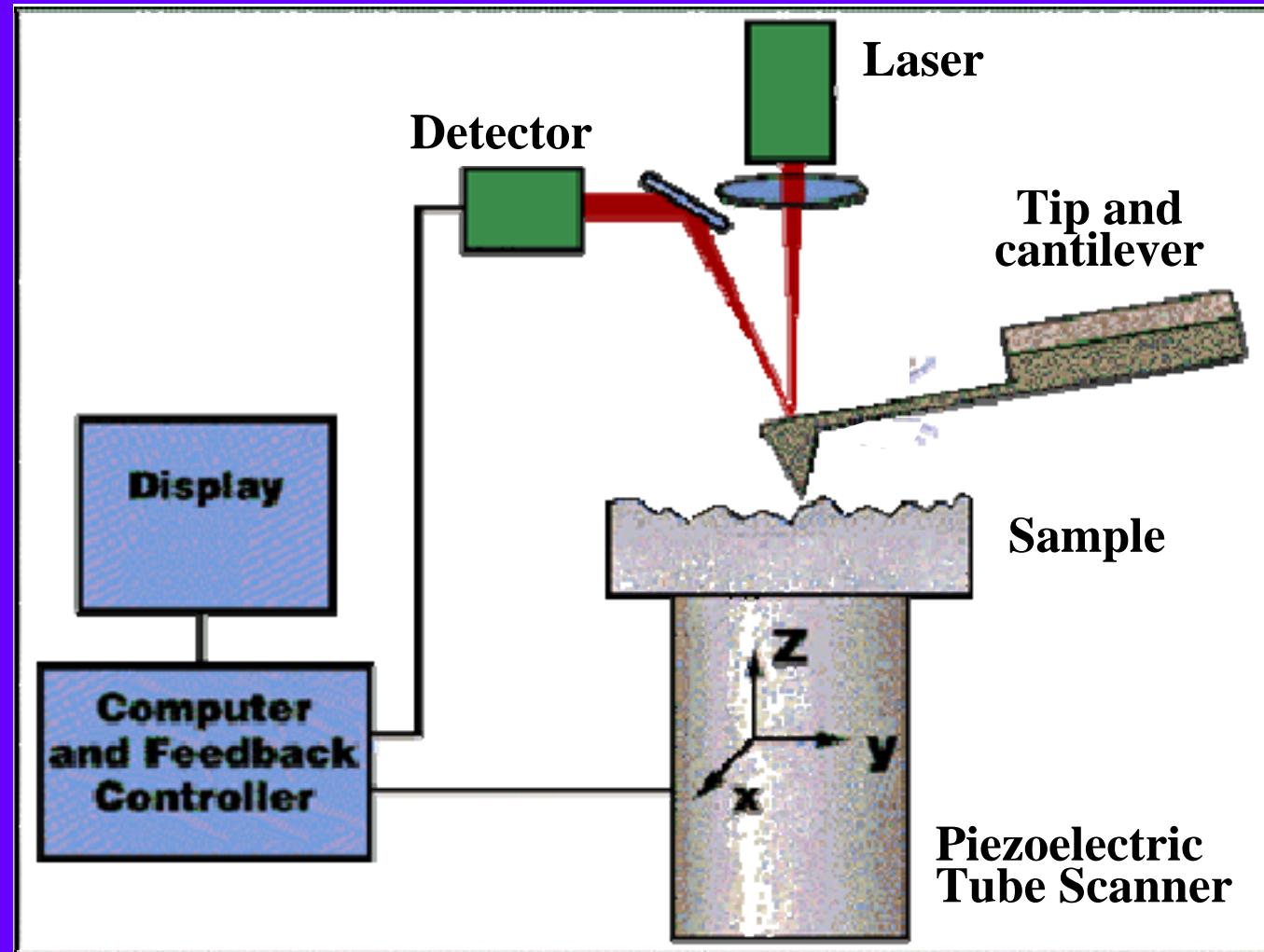


Basic configuration of AFM



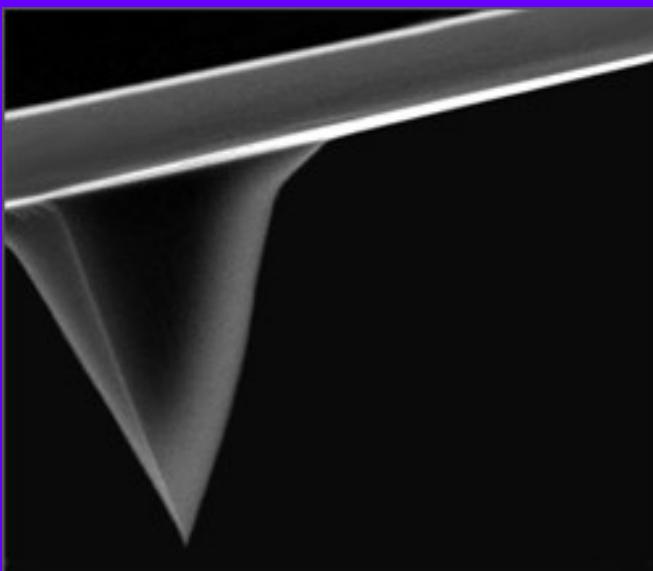
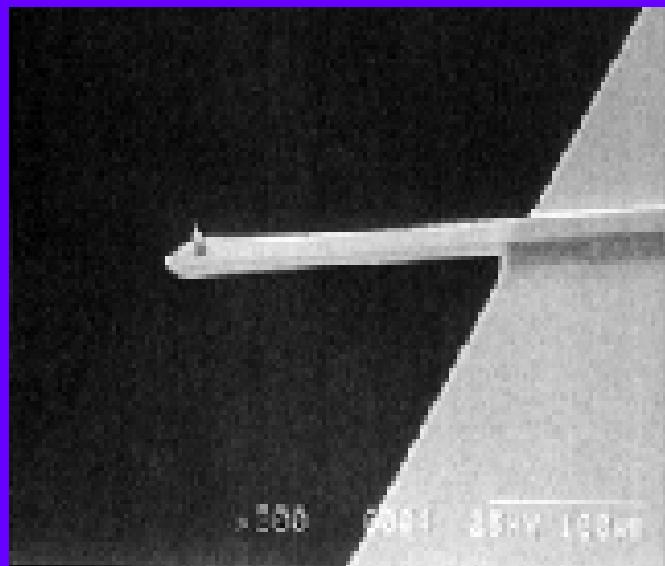


Core components of an AFM

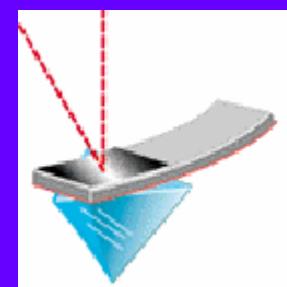




Probes for the tapping mode



Typical Tip Dimension:
150 μ m x 30 μ m x 3 μ m
 $f_r \sim 100$ kHz
Materials: Si





Comparisons among various microscopies

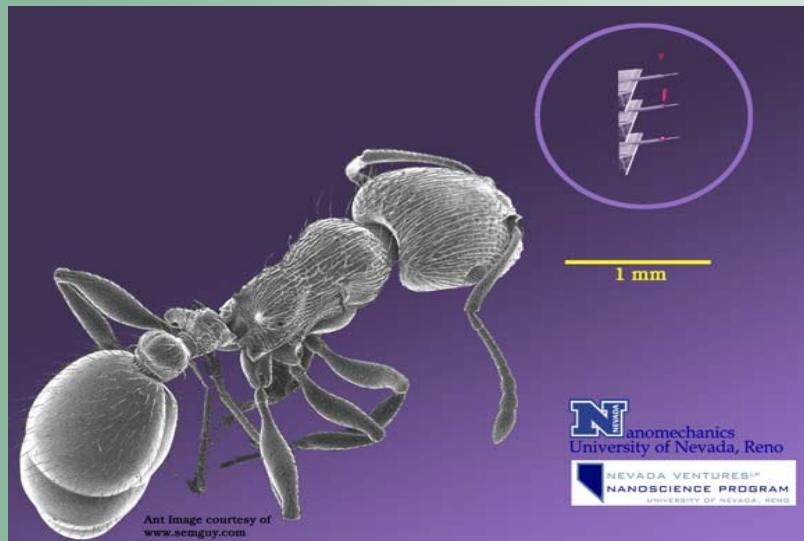
	光學顯微術 (OM)	掃描電子顯微術 (SEM)	穿透電子顯微術 (TEM)	掃描探針顯微術 (SPM)
lateral	300nm	1nm	0.1nm	0.1nm
vertical	20nm	10nm		0.01nm
Imaging area	1mm	1mm	0.1mm	0.1mm
Imaging environ	none	vacuum	vacuum	none
Sample prep	no	yes	yes	no
Elemental anal	yes	yes	yes	no

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



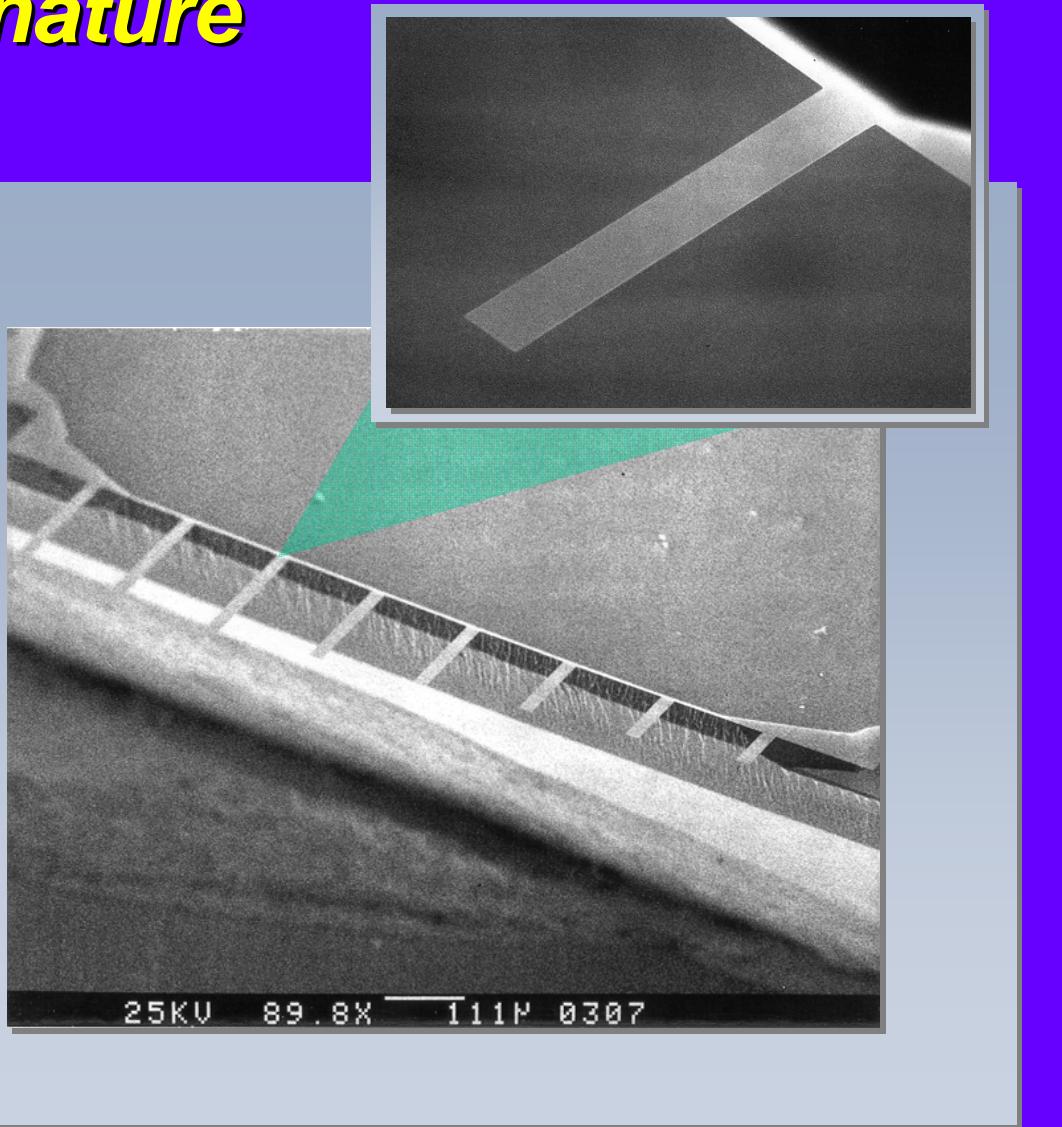
Micro and Nano cantilever arrays - *Emulating nature*

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

Sensitivity:
Function of dimensions

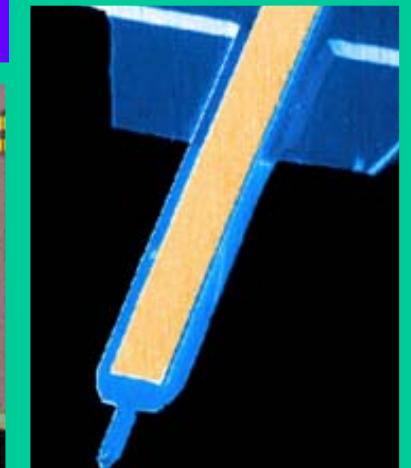
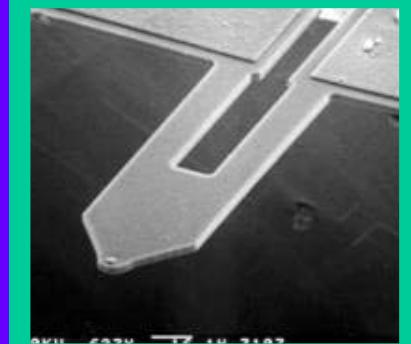
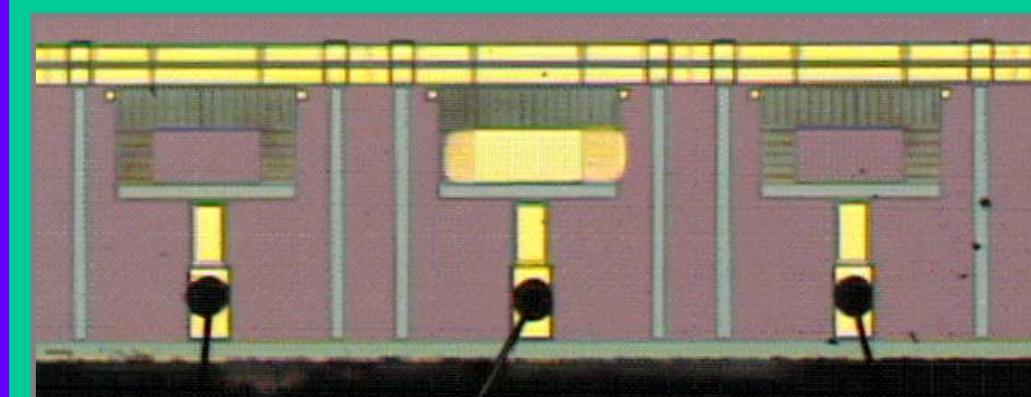
Selectivity:
Function of coatings

- Mass production



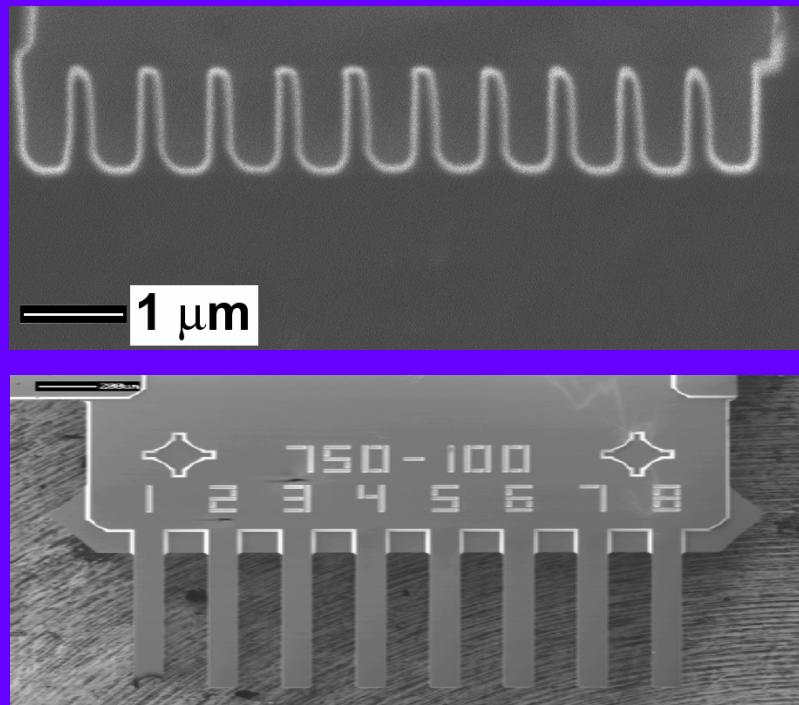
Microcantilevers: Getting the signal out

- Optical
- Piezoresistivity
- Piezoelectricity
- Capacitance



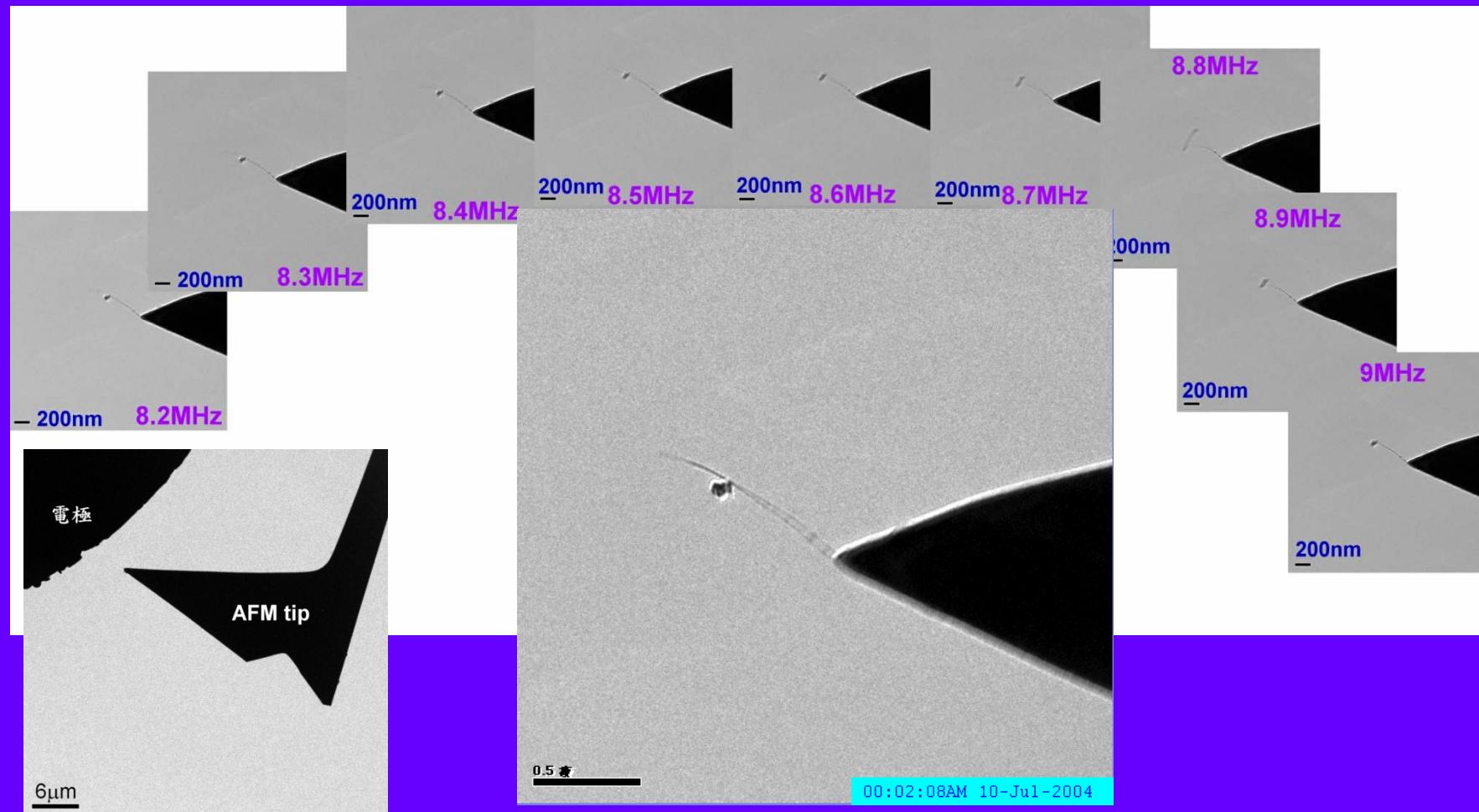
Microcantilevers To Nanocantilevers

- Increased Sensitivity
- High Resonance Frequency
- Small Spring Constants
- Single Molecule Detection
- Challenges:
 - Signal Transduction
 - Mass production



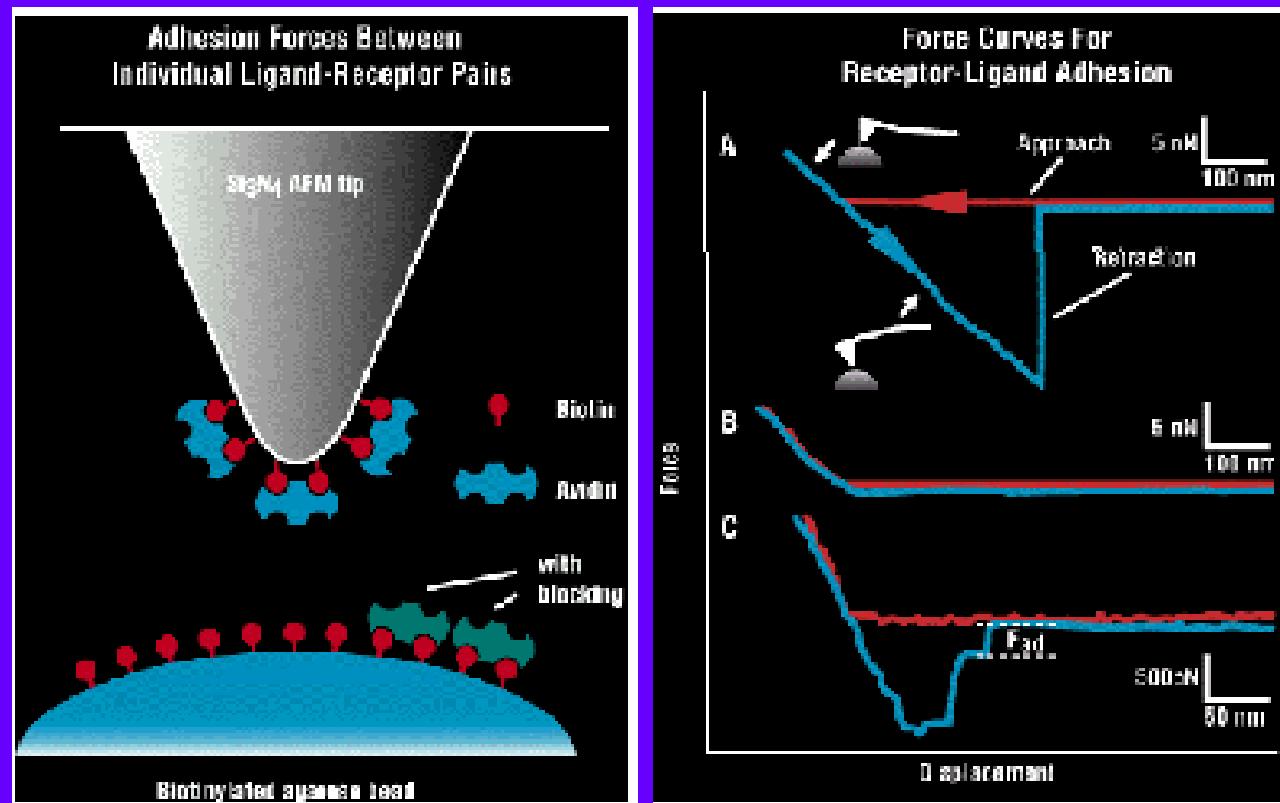
(Craig Prater, DI)

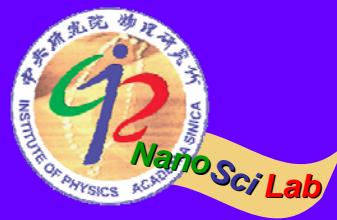
Nanoelectromechanical oscillator



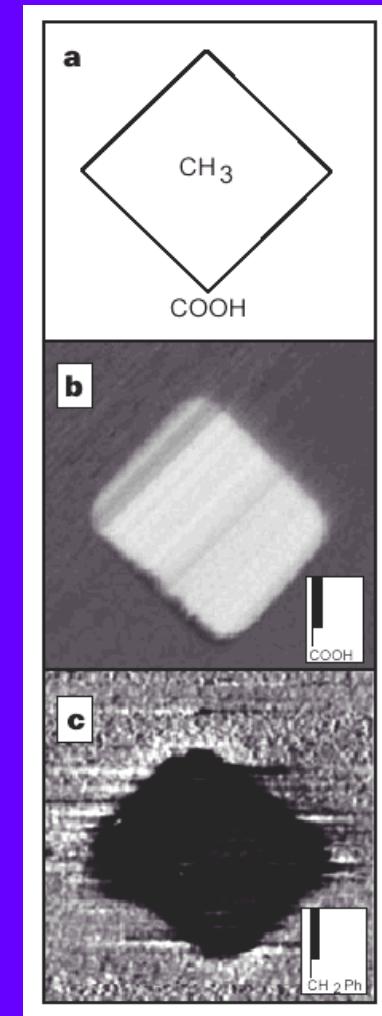
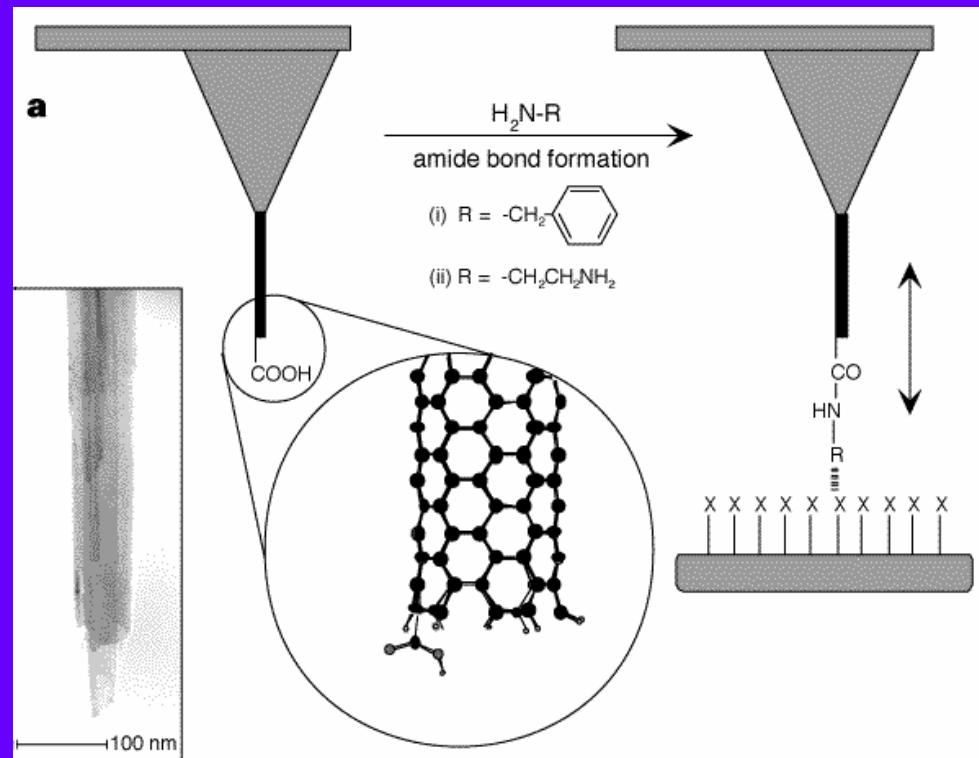


Molecular sensing

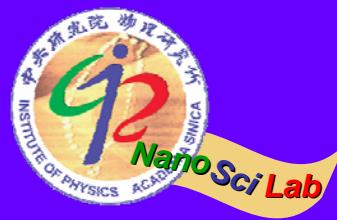




Chemical nanoprobe



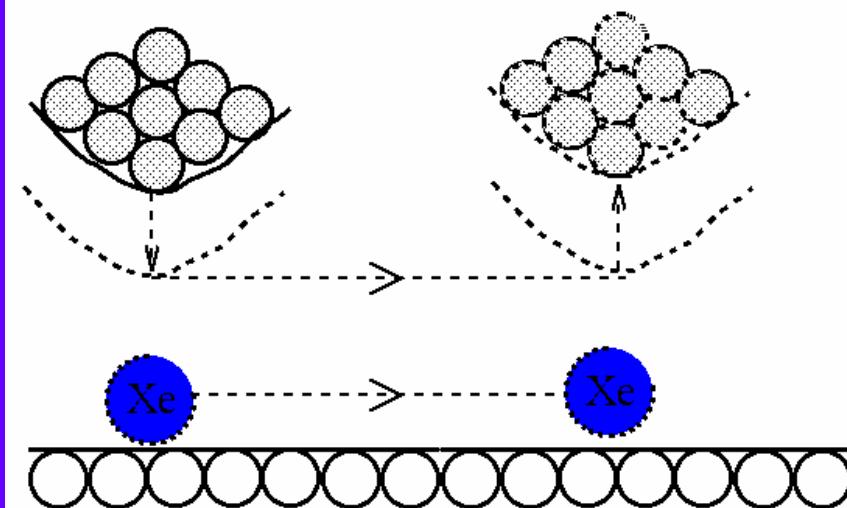
S. S. Wong *et al.*, *Nature* **394**, 52 (1998).



Manipulation method

Positioning Atoms with an STM

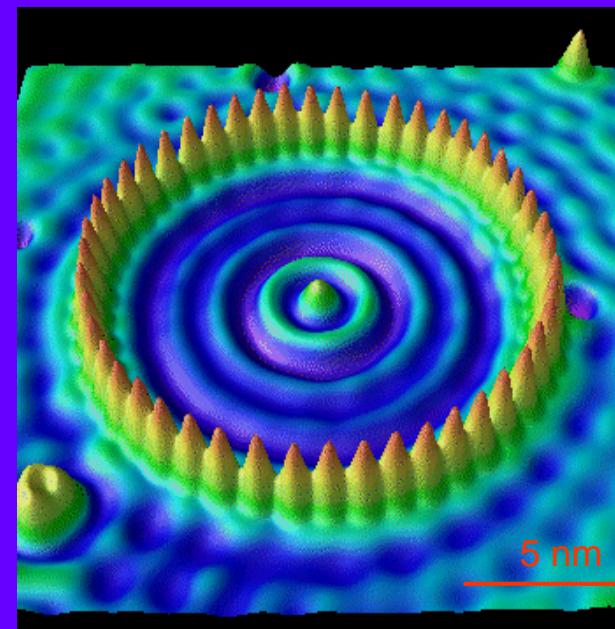
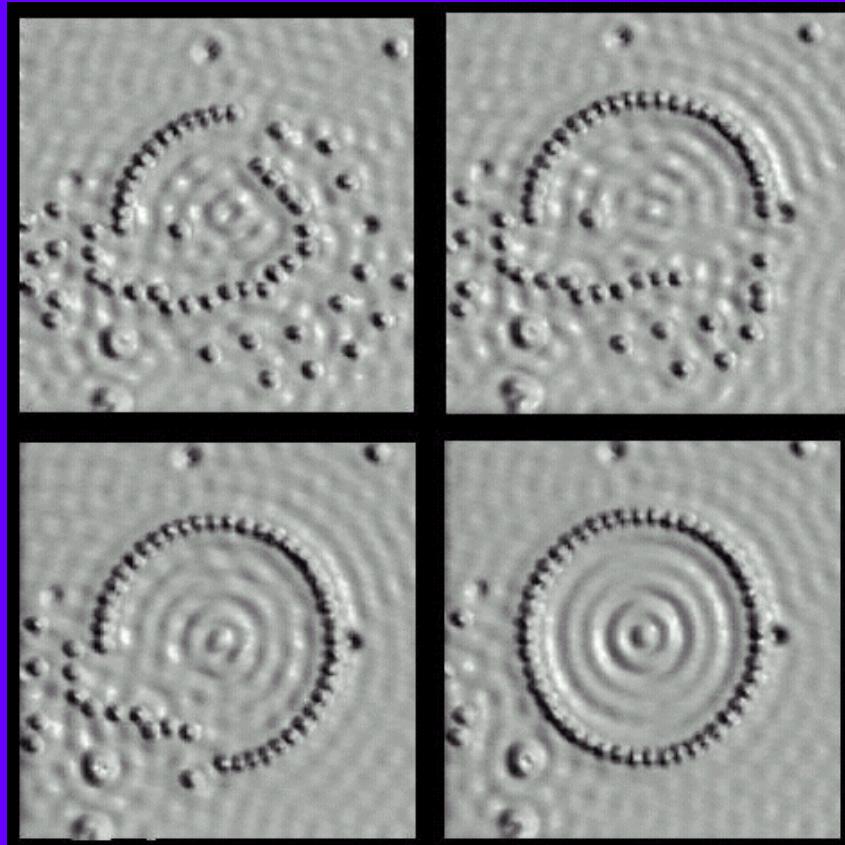
D.M. Eigler & E.K. Schweizer *Nature* **344** 524 (1990)



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.



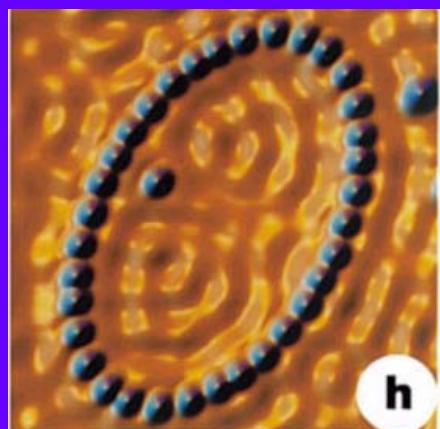
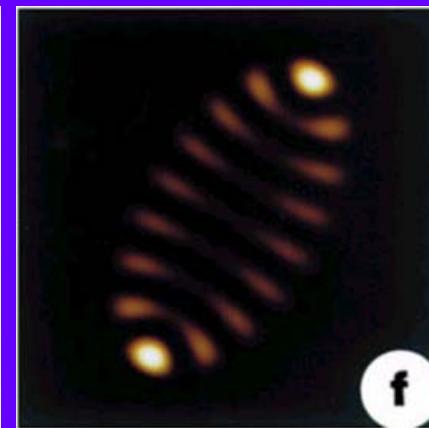
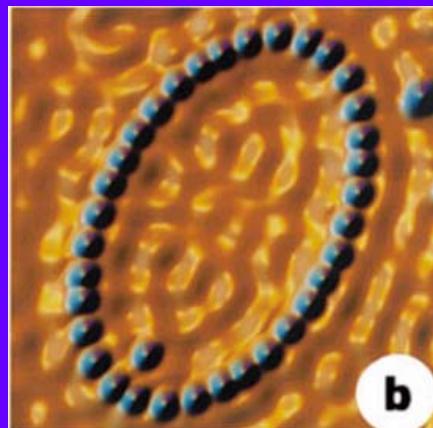
Ultimate goal of nanotechnology



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



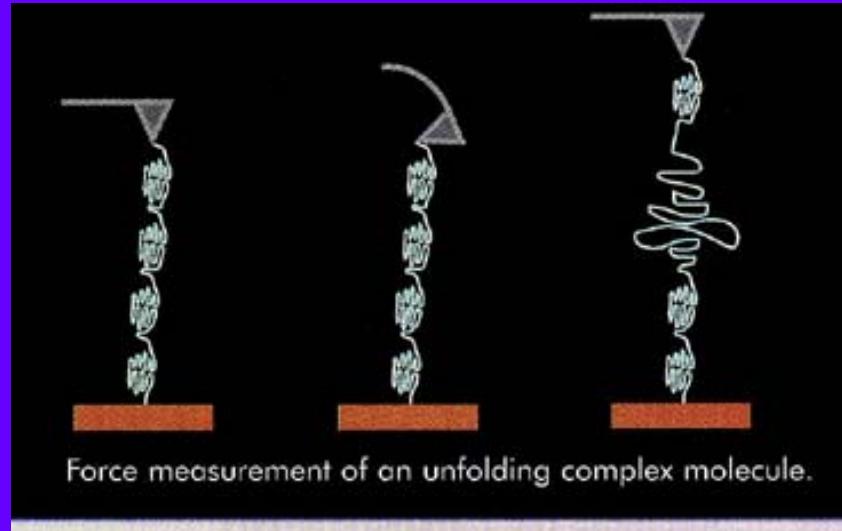
Quantum Mirage



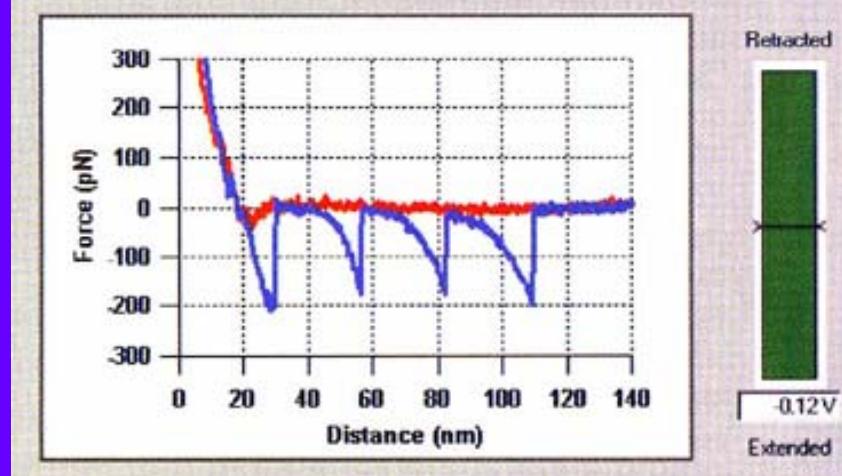
H. C. Manoharan *et al.*,
Nature 403, 512 (2000).



Molecular unfolding



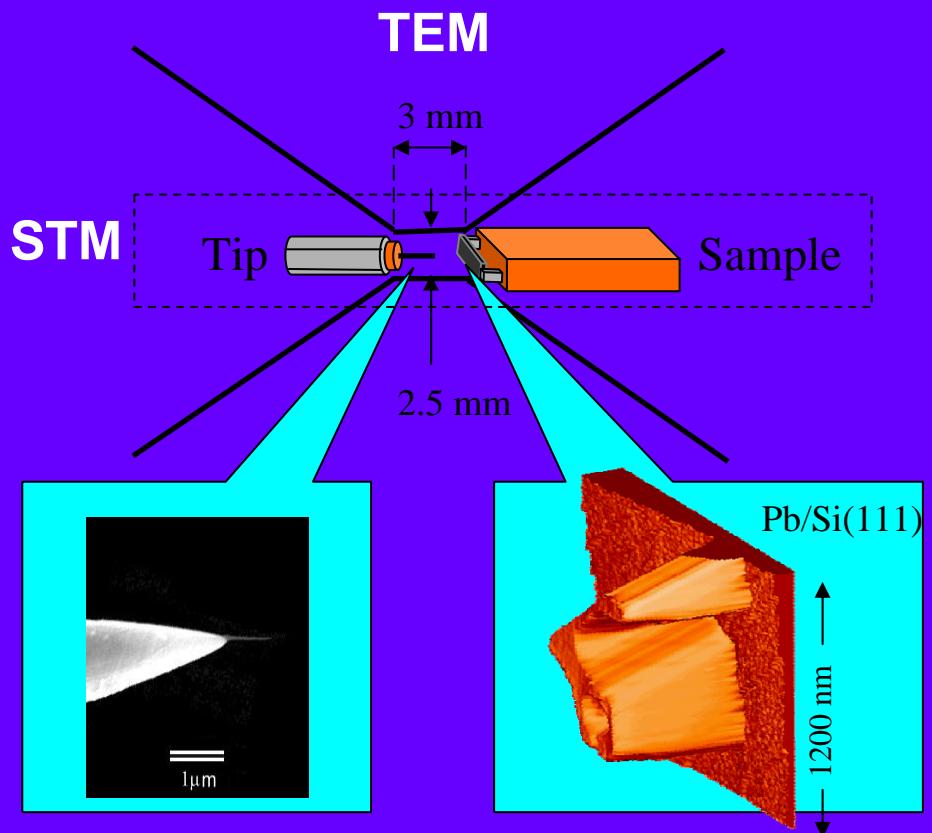
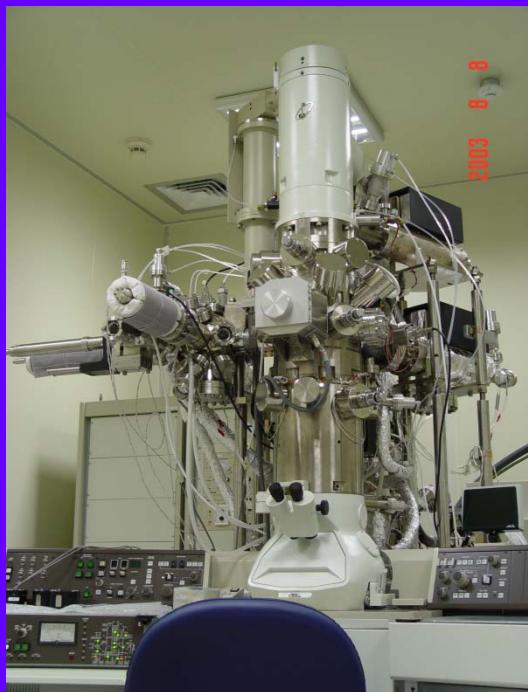
Force measurement of an unfolding complex molecule.



Advanced graphical user interface shows titin muscle molecule force curve.



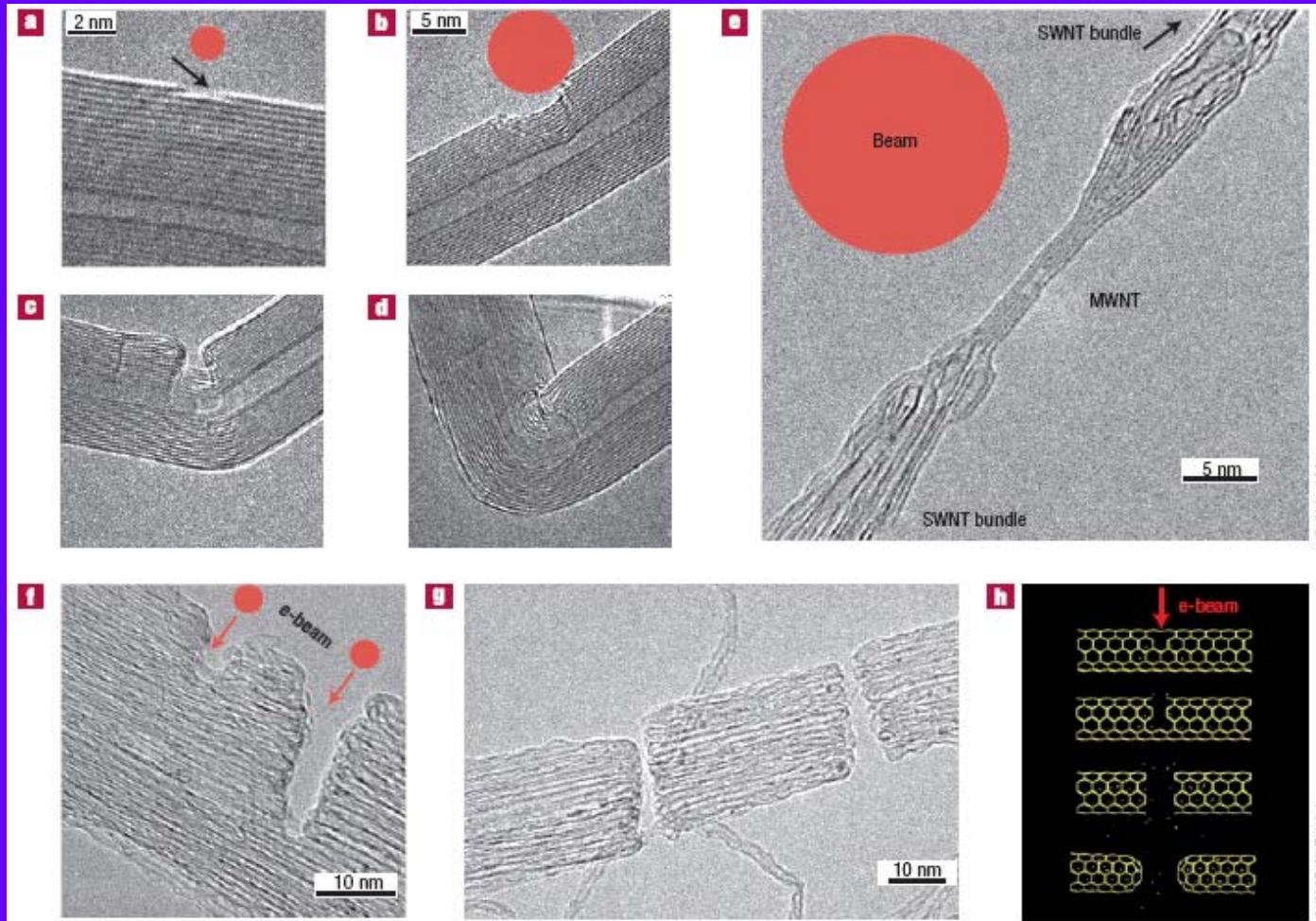
UHV HRTEM/STM



Tip with a nanotube

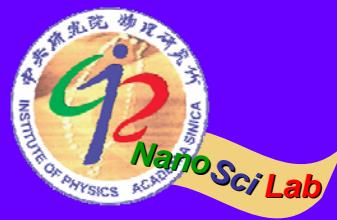
Mesa structure for holding the nano-object

Engineering CNT with energetic e-beam

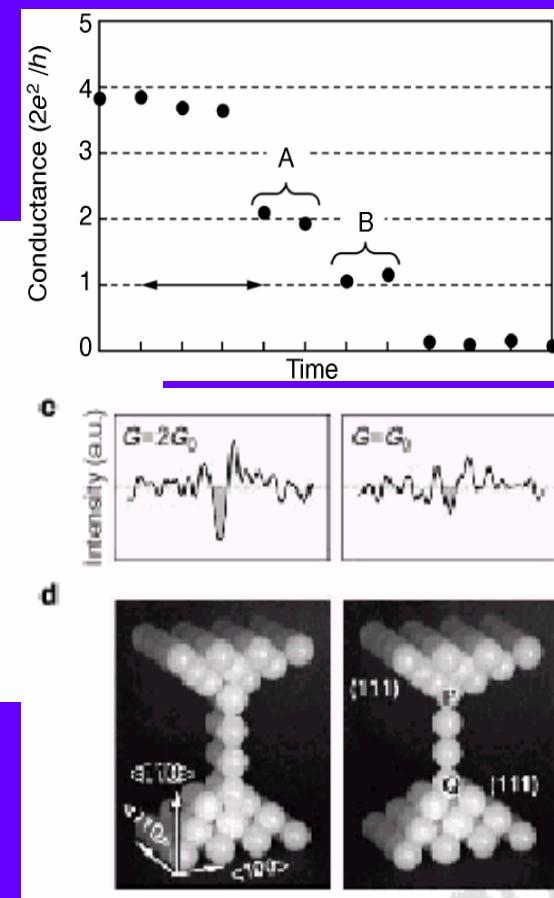
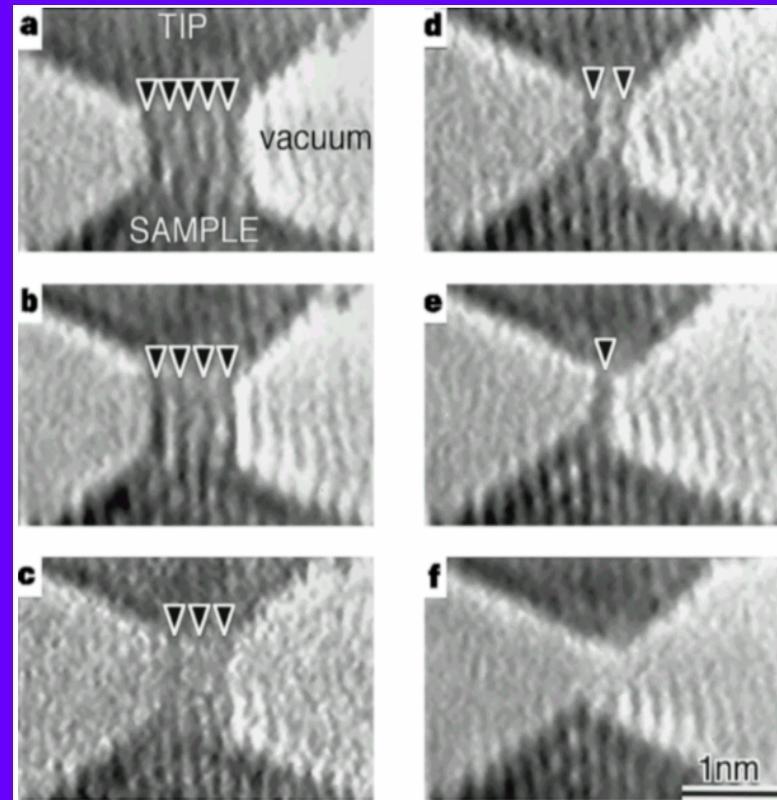


A.V. Krasheninnikov and F. Banhart
Nature Materials **6**, 723 (2007)





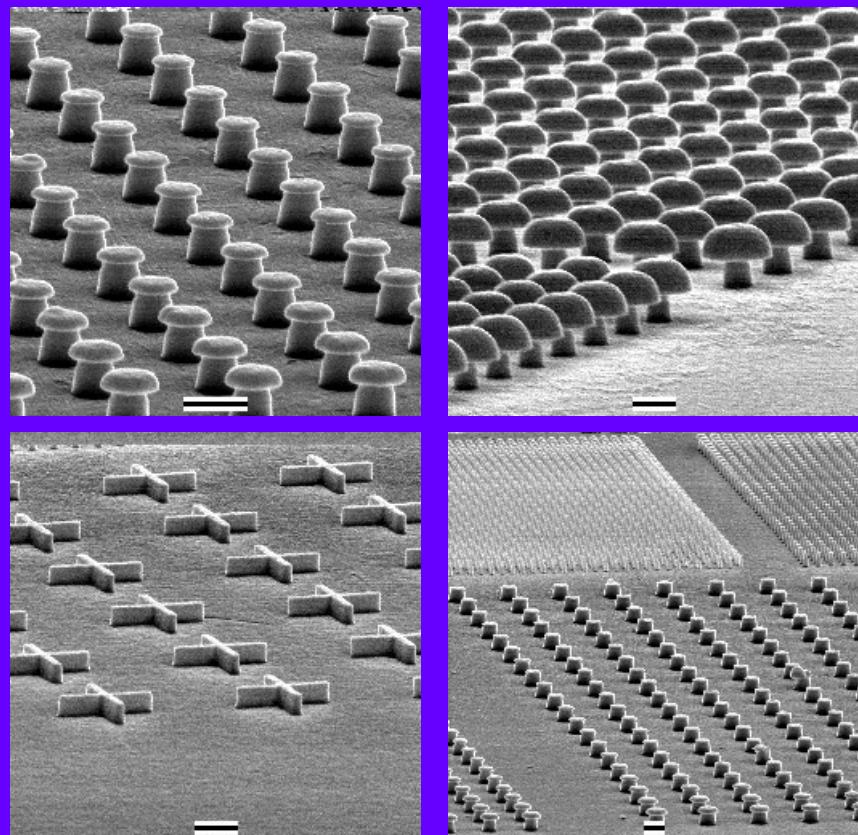
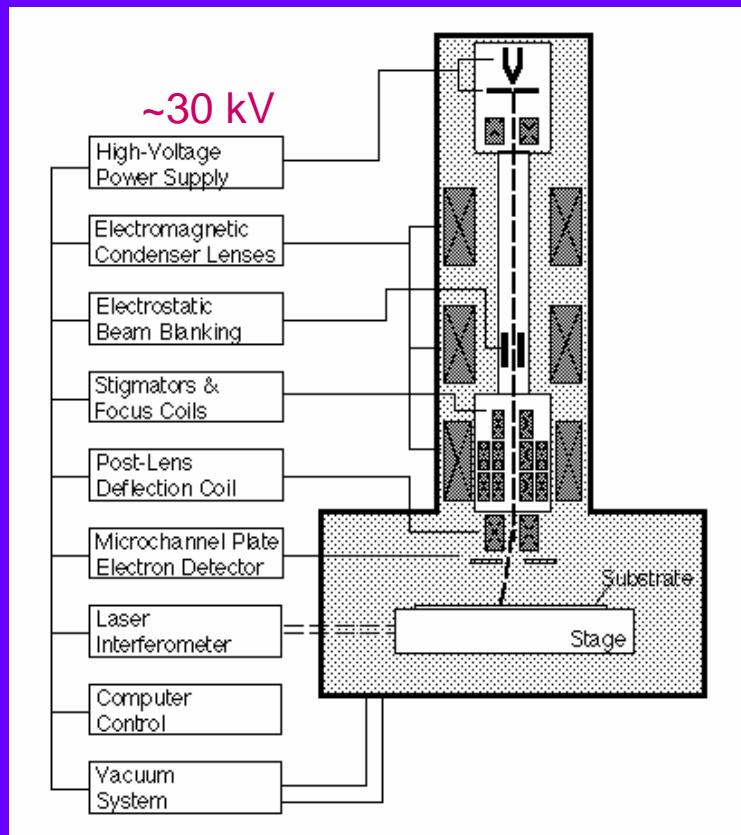
Point contact of Au wire

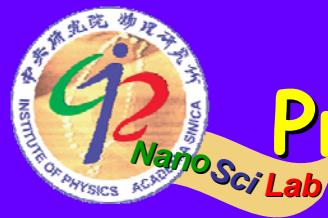


H. Ohnishi *et al.*
Nature 395, 780 (1998).

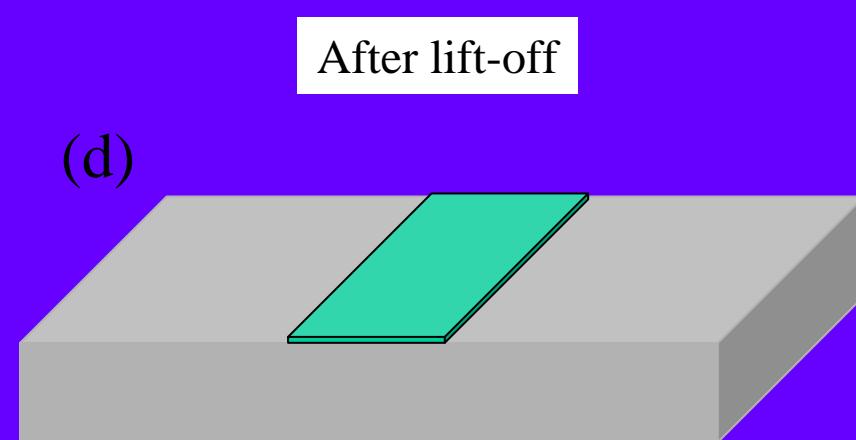
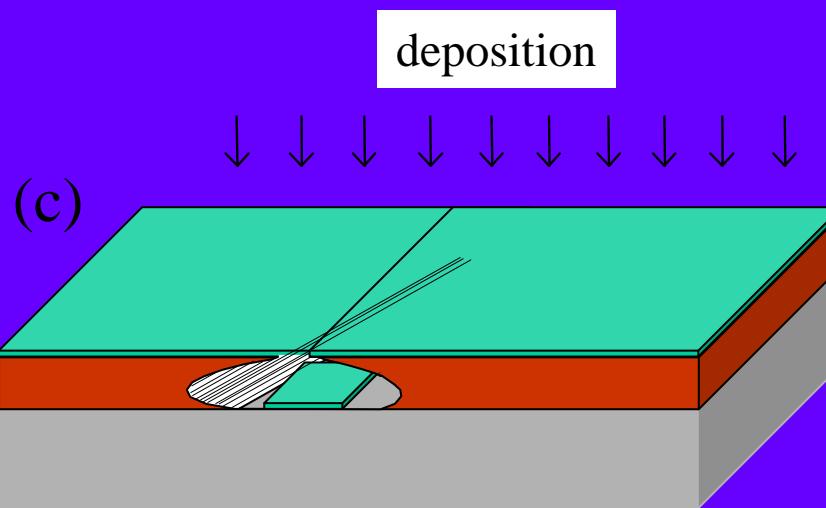
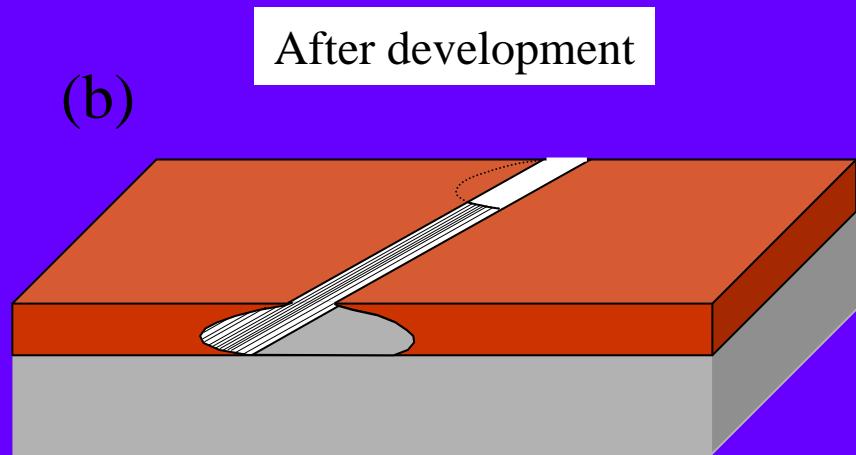
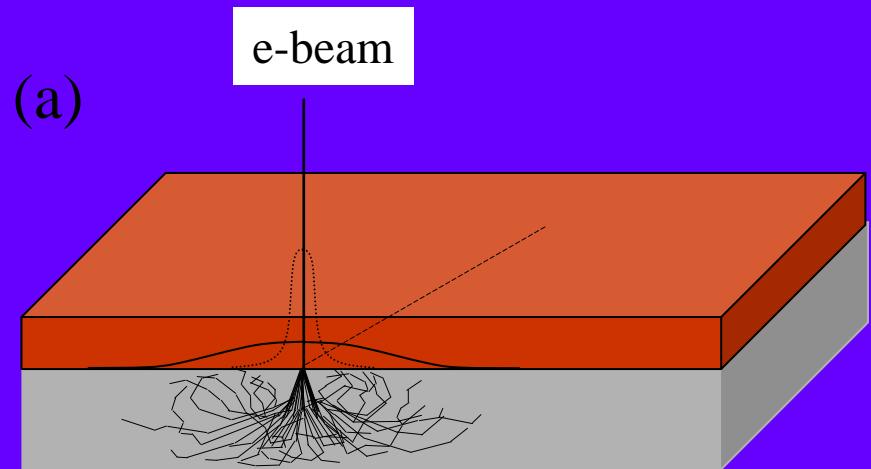


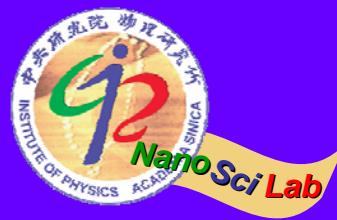
Periodic nanostructures by e-beam lithography



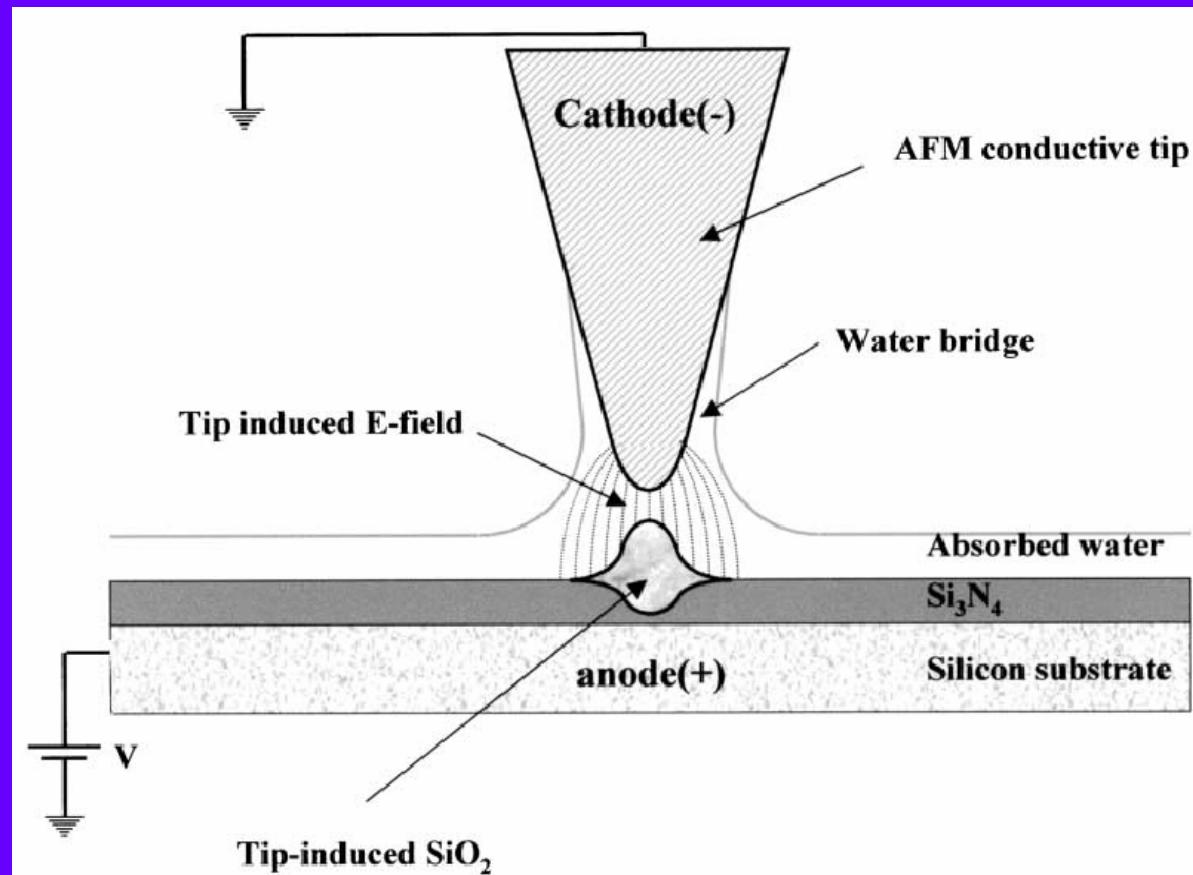


Procedures of e-beam lithography

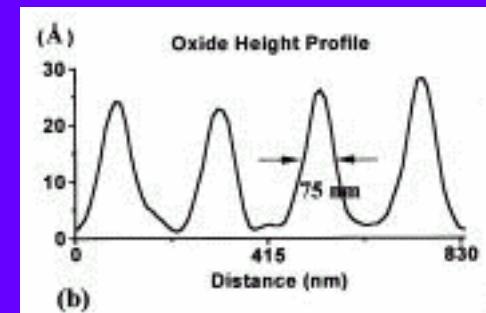
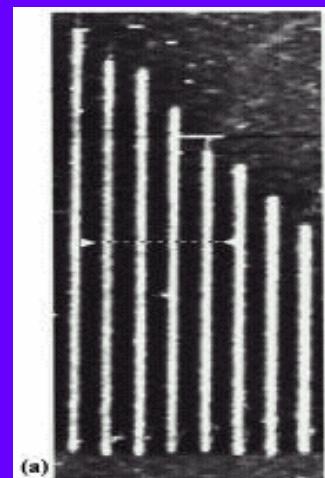
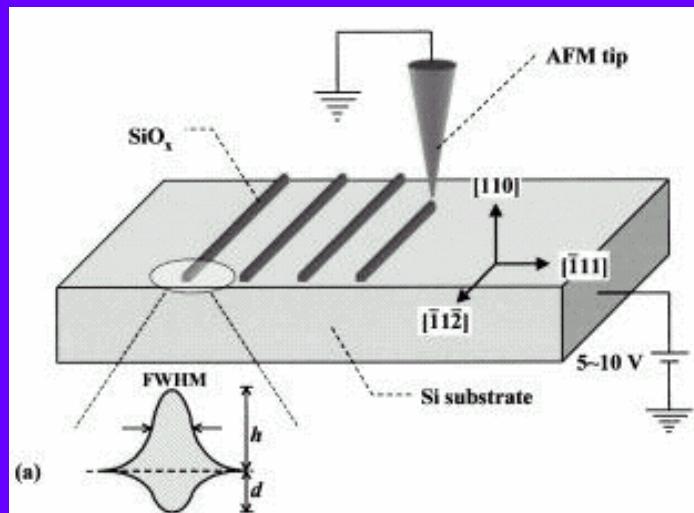




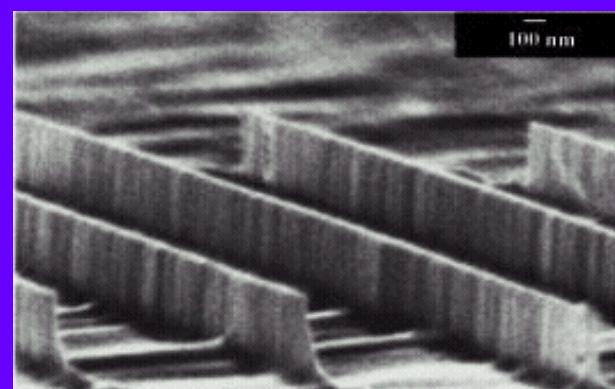
Nano-Lithography with an AFM tip



Electrical Lithography

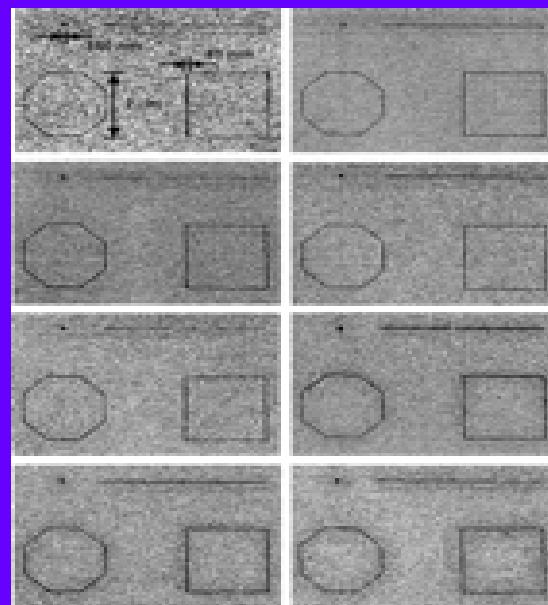
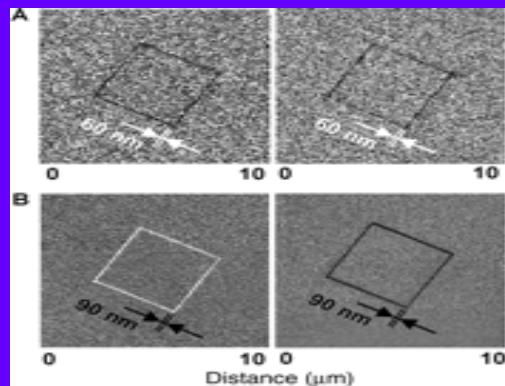
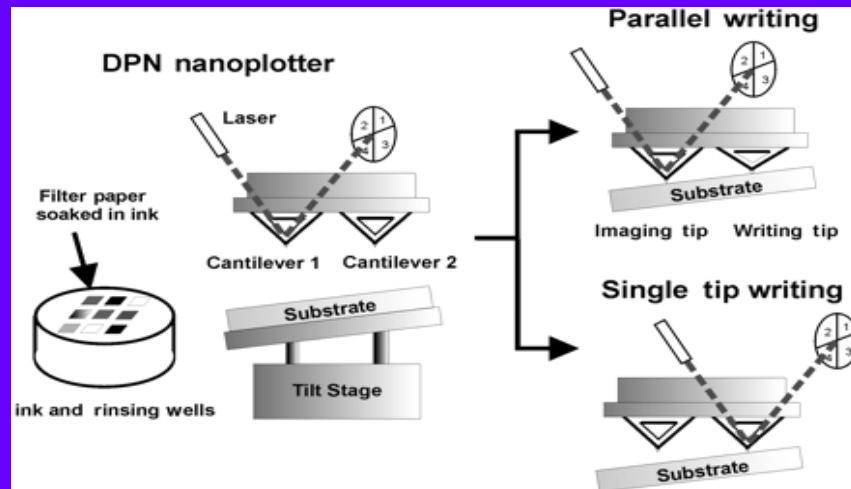


F.S.-S. Chien *et al.*
APL 75, 2429 (1999)





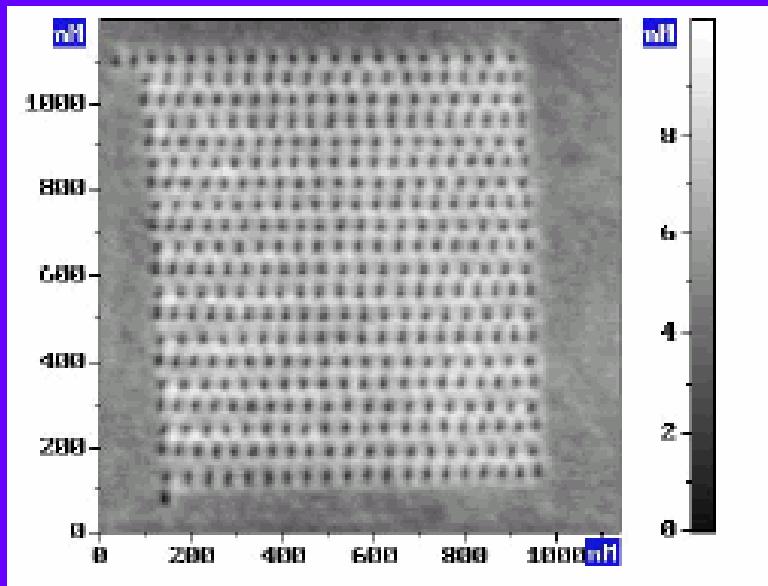
Nanoplotter



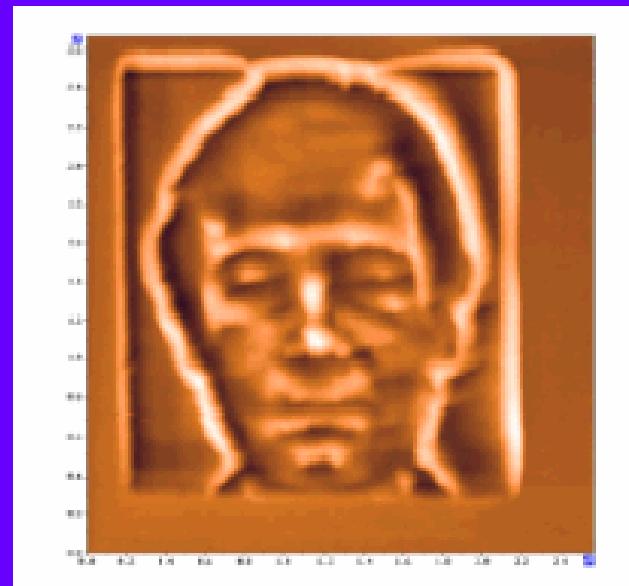
**C.A. Mirkin *et al.*
Science 288, 1808 (2000)**



Nanolithography of Tapping-Mode AFM



$(1.2 \mu\text{m} \times 1.2 \mu\text{m})$

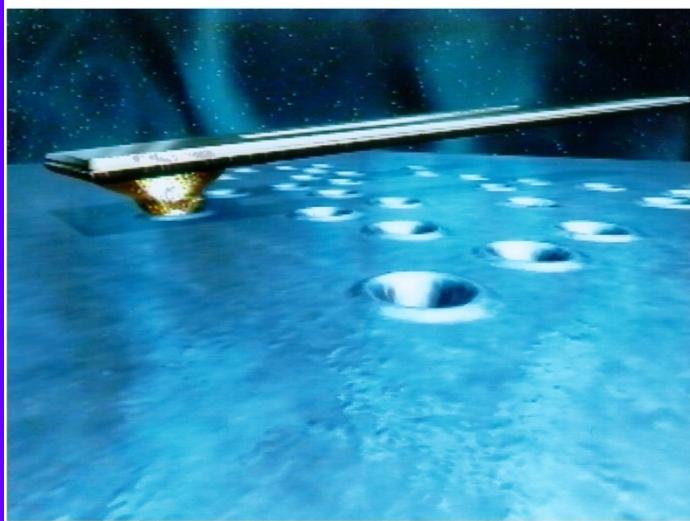
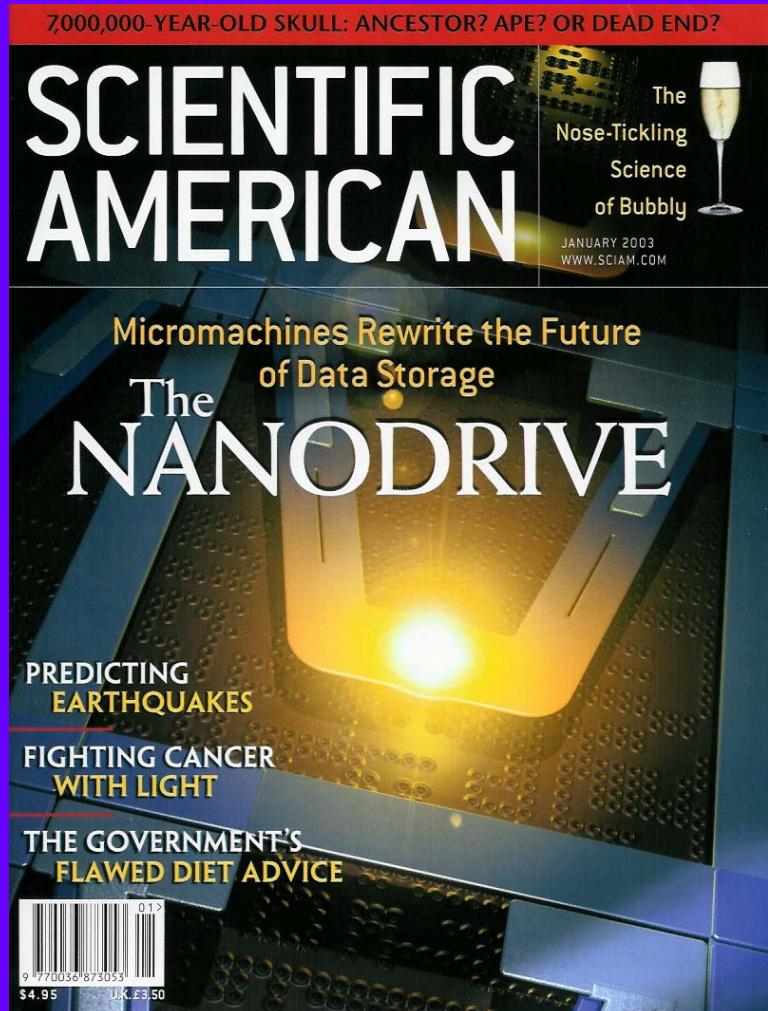


$(2.5 \mu\text{m} \times 2.5 \mu\text{m})$

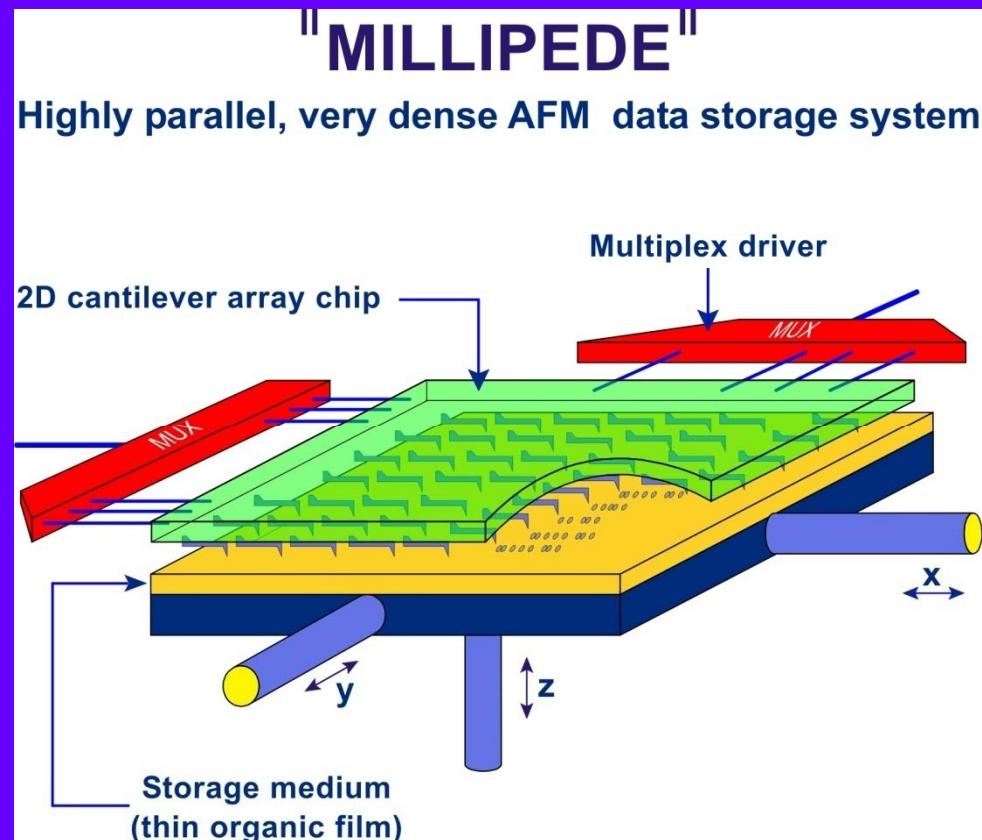
Image of polycarbonate film on silicon surface



Nanodrive



Millipede

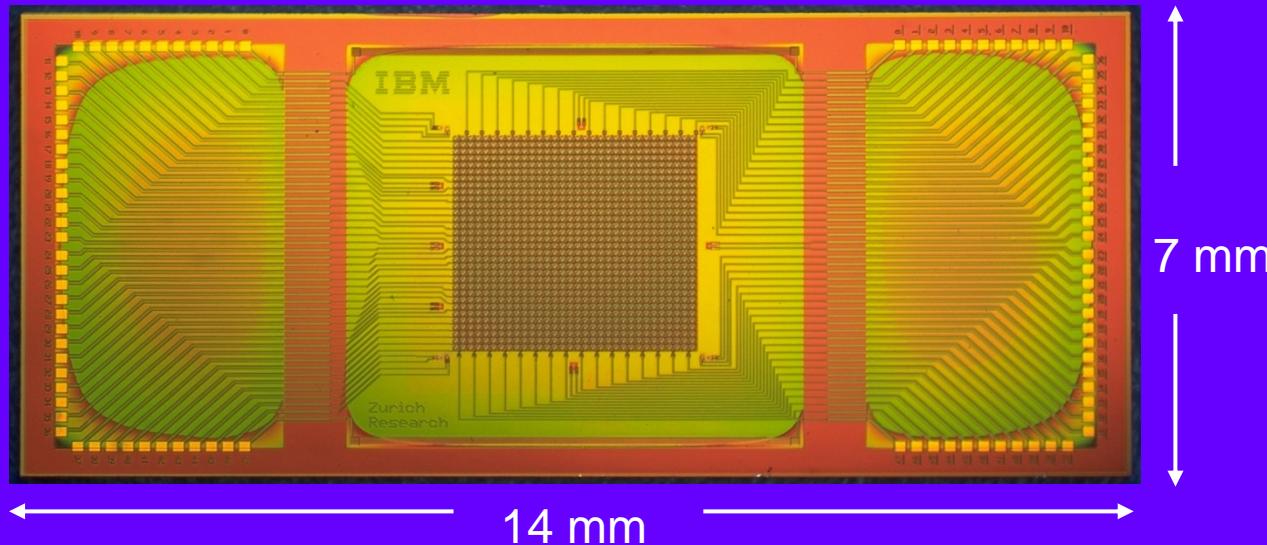


The Millipede concept: for operation of the device, the storage medium - a thin film of organic material (yellow) deposited on a silicon "table" - is brought into contact with the array of silicon tips (green) and moved in x- and y-direction for reading and writing. Multiplex drivers (red) allow addressing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

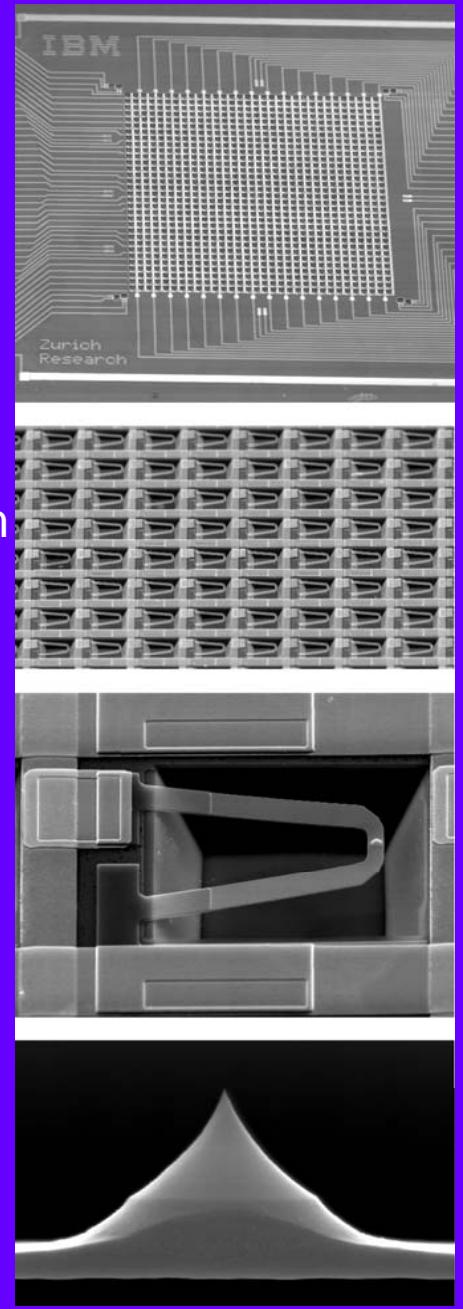
IBM-Zurich



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).



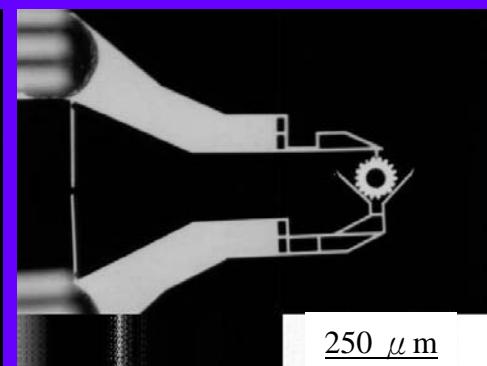
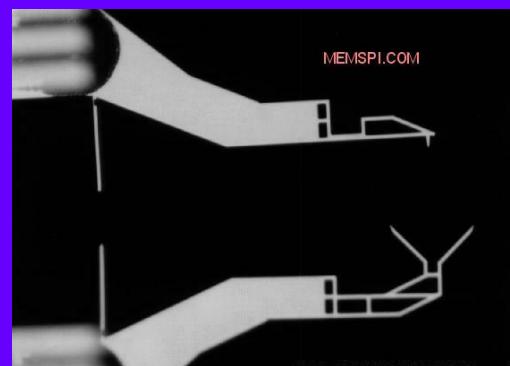
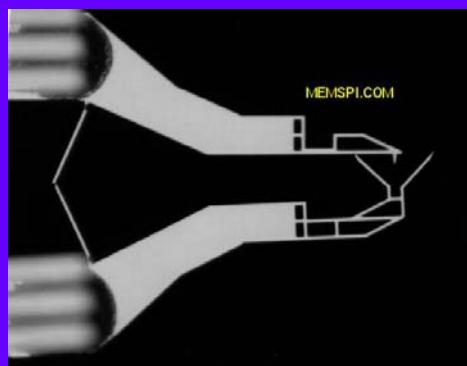
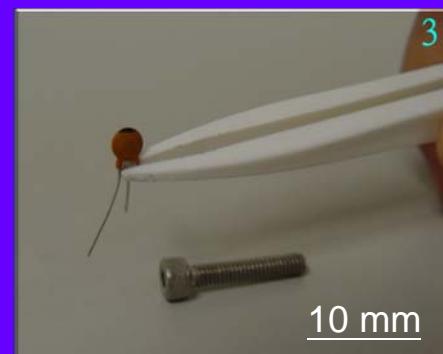
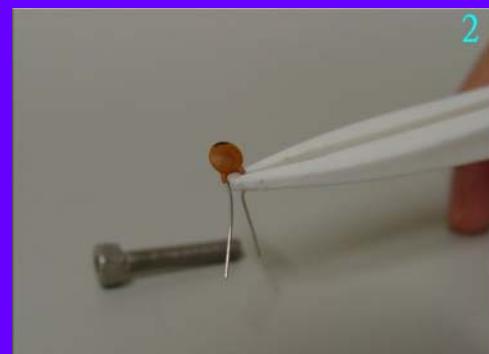


Considerations for making nanoscale tools

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

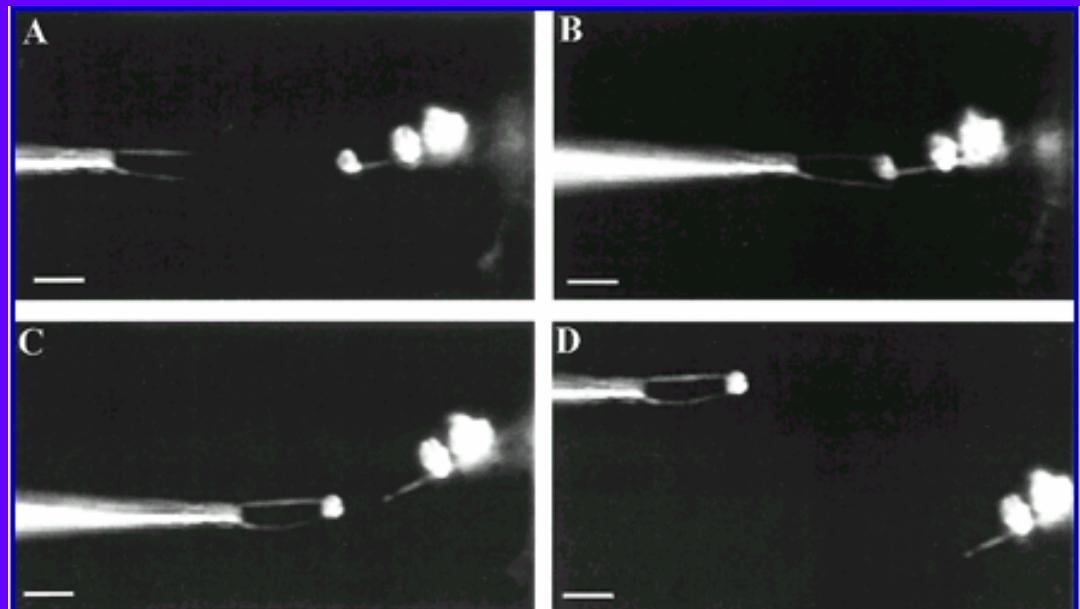
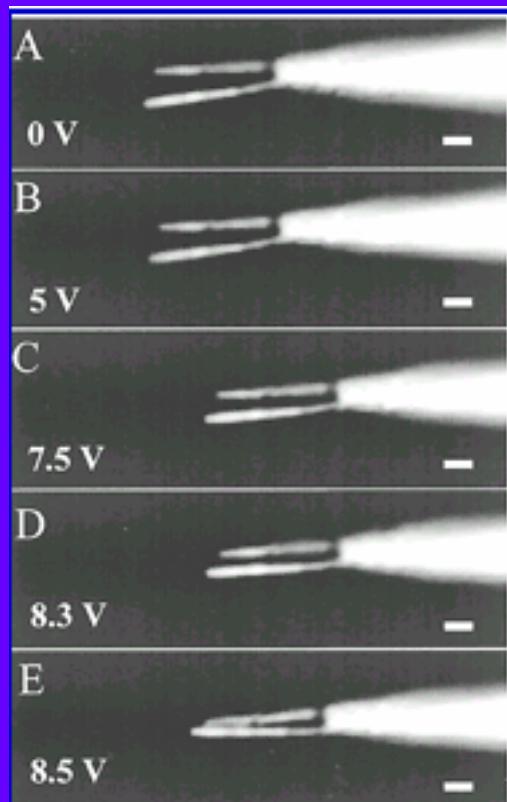


Maneuvering tools





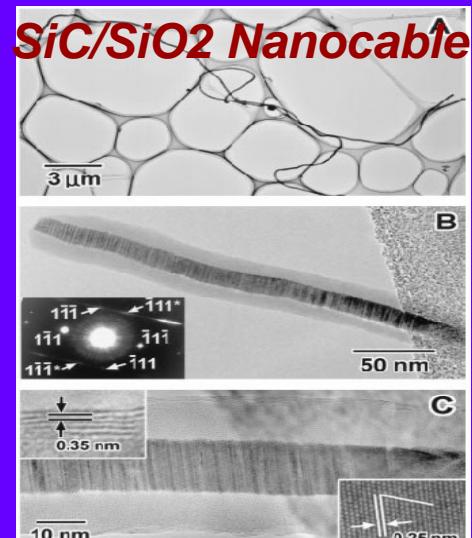
Operation of nano tweezers



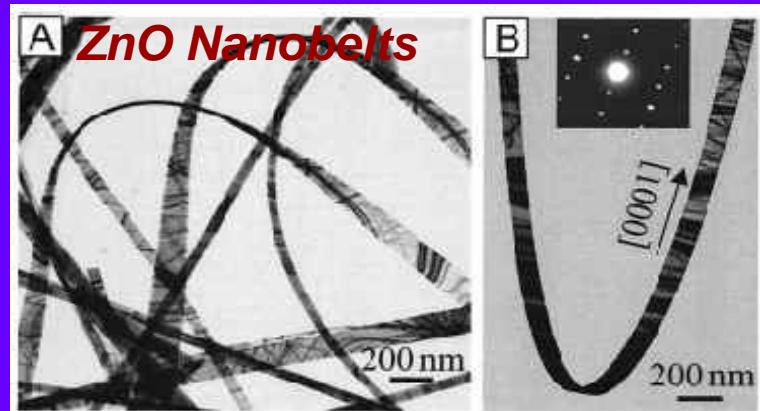
P. Kim and C.M. Lieber,
Science 286, 2148 (1999).



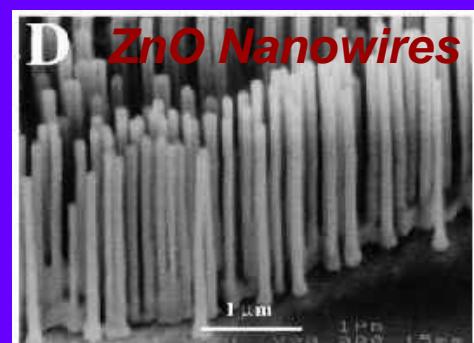
Nano wires and belts



Science 281, 973 (1998)



Science 291, 1947 (2001)



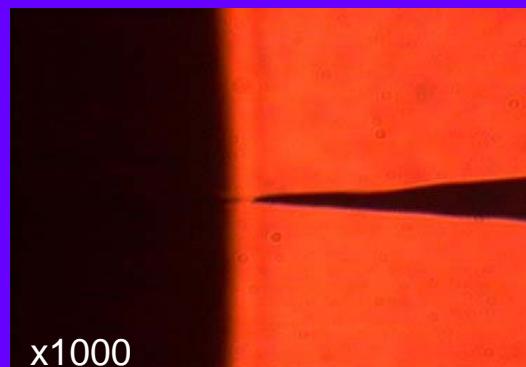
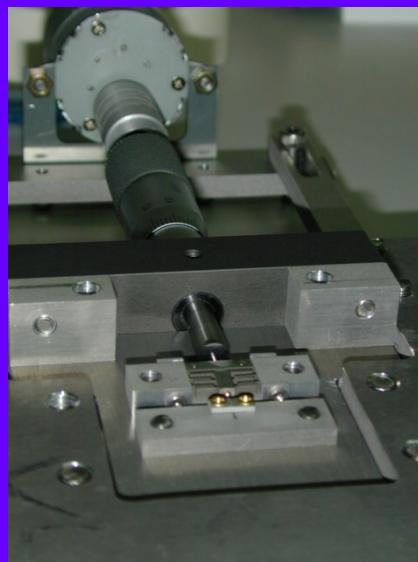
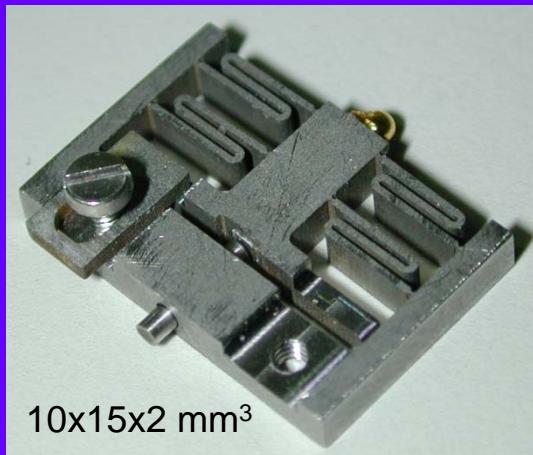
Science 292, 1897 (2001)



Nano Lett. 2, 101 (2002)



Precision stepper





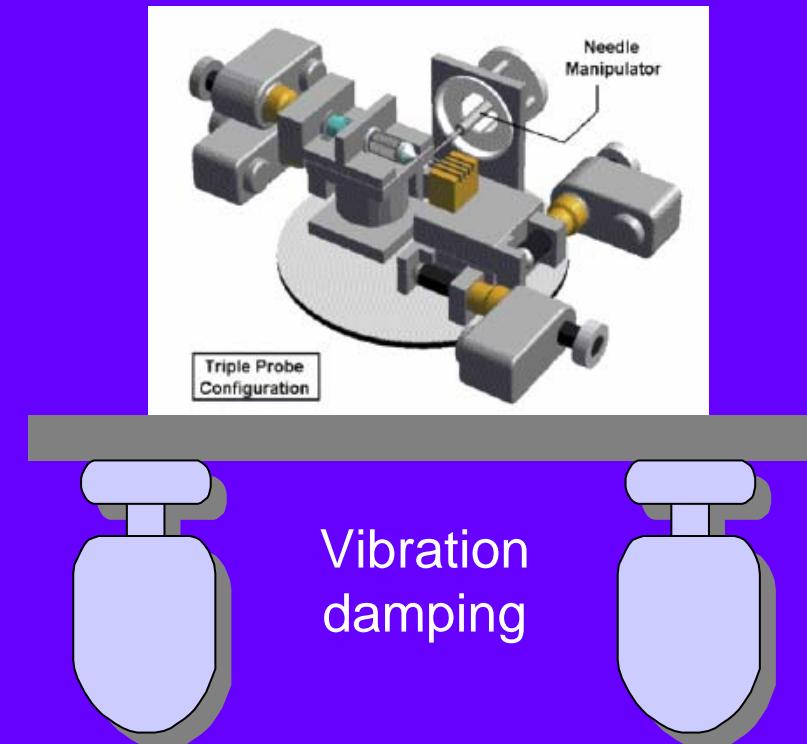
Considerations for environmental factors

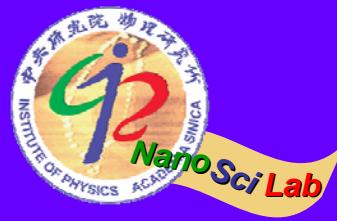
EMI
shield

Temp.,humidity &
ventilation control

Dust filtering

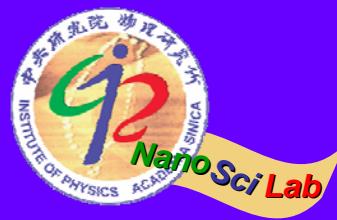
Acoustic
isolation





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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National Chung-Cheng University
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National Cheng-Kung University

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