Dictionary Definition

nano- (nan'oh)
  pref.

1. **<unit> A prefix.**
2. **Used loosely to mean “extremely small", e.g. nanotechnology.**
3. **One-billionth (10^{-9}): *nanosecond.***

[Greek nanos, nannos, little old man, dwarf, from nannas, uncle.]

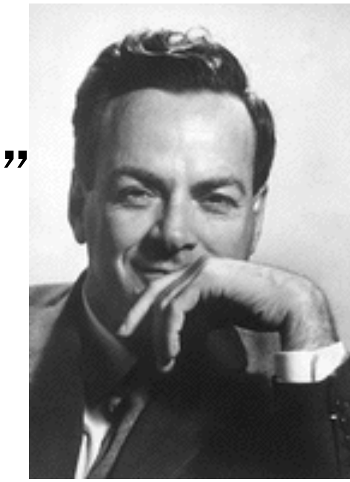
tech·nol·o·gy (tech*nol'o*gy)
  ***n. pl.* tech·nol·o·gies**

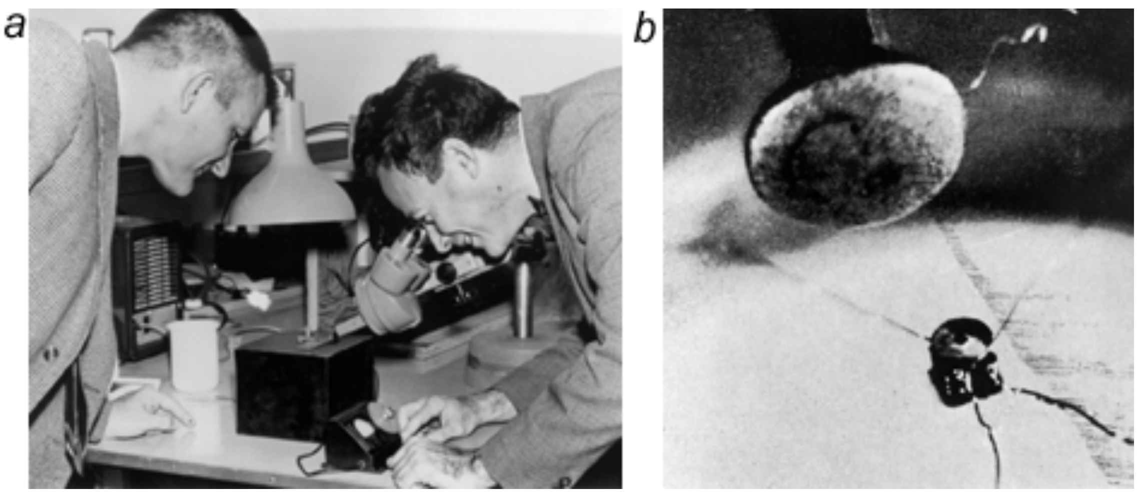
1. **The application of science, especially to industrial or commercial objectives.**
2. **The scientific method and material used to achieve a commercial or industrial objective.**
3. **Electronic or digital products and systems considered as a group: *a store specializing in office technology.***
4. ***Anthropology.* The body of knowledge available to a society that is of use in fashioning implements, practicing manual arts and skills, and extracting or collecting materials.**

[Greek tekhnologia , *systematic treatment of an art or craft* : tekhne , *skill*; see teks- in Indo-European Roots + -logia , *-logy*.]

How it all started

- **Our old friend Richard P. Feynman**
  - "There's Plenty of Room at the Bottom"
    - APS address – December 28, 1959





In the late 1950s visionary physicist Richard Feynman issued a public challenge by offering $1000 to the first person to create an electrical motor "smaller than 1/64th of an inch". Much to Feynman's consternation the young man who met this challenge, William McLellan, did so by investing many tedious and painstaking hours building the device by hand using tweezers and a microscope.

The "Futurists" get the Spotlight

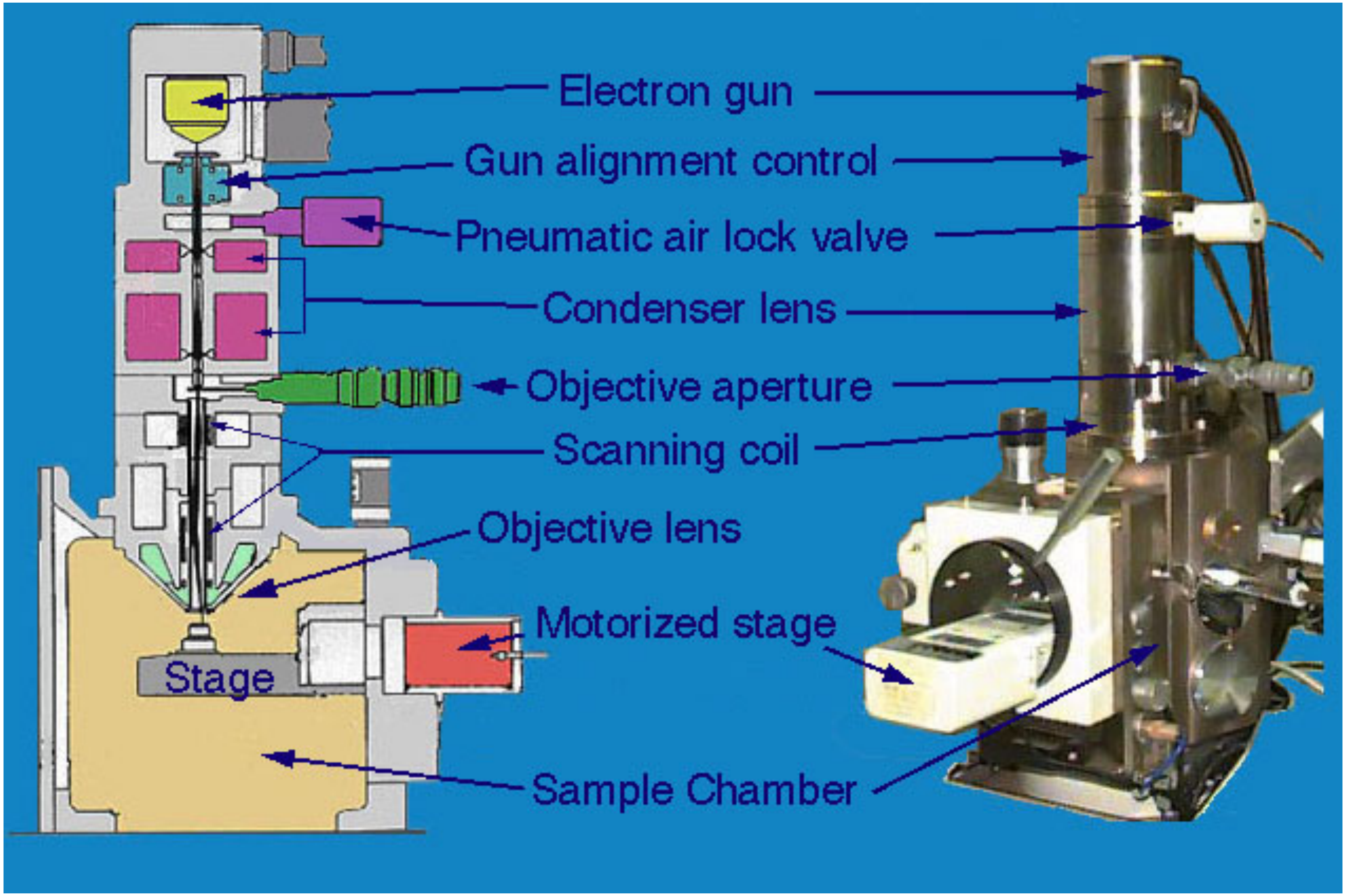
- **K. Eric Drexler**
  - ***Engines of Creation***. 1986
  - ***Nanosystems: Molecular Machinery, Manufacturing, and Computation***. 1992
  - Chairman of the "Foresight Institute"
    - Sponsor of Feynman prizes
      - Annual prizes of US$5000 for theory and experimental
      - Grand prize of US$250,000
  - Considered by most of the scientific community to be "optimistic"
  - Brought us "grey goo" and "utility fog"

Specifications for the Feynman Grand Prize require the winning entrant to:

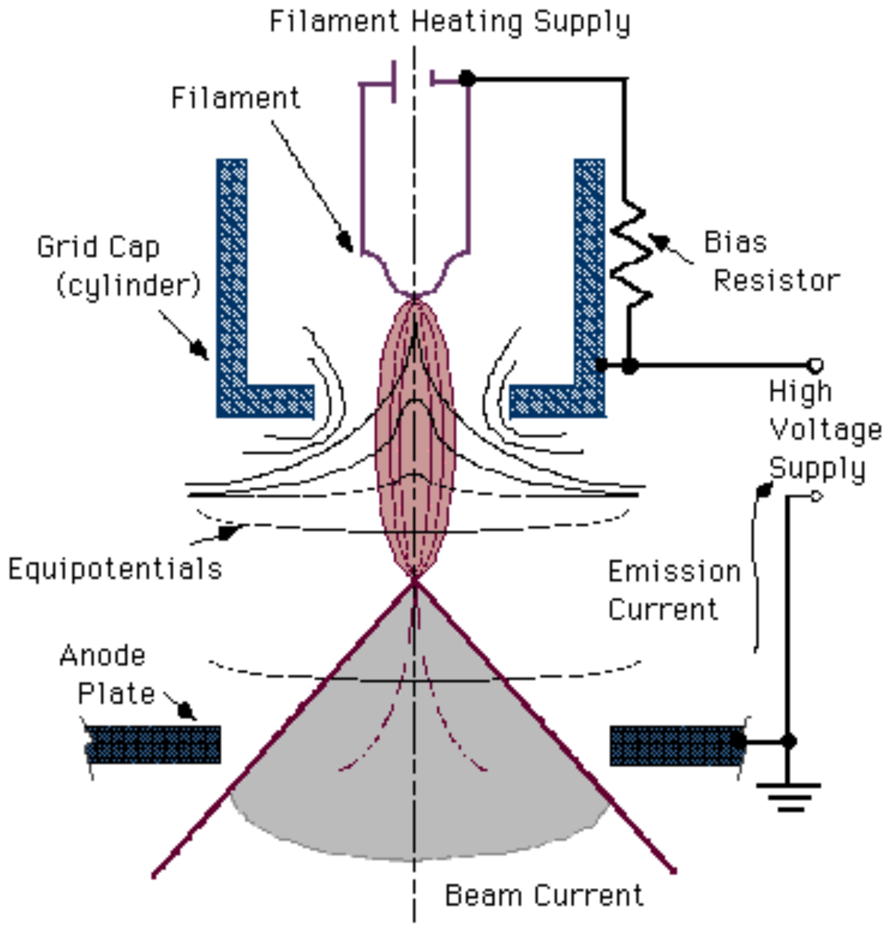
- design, construct, and demonstrate the performance of a robotic arm that initially fits into a cube no larger than 100 nanometers in any dimension, meeting certain performance specifications including means of input. The intent of this prize requirement is a device demonstrating the controlled motions needed to manipulate and assemble individual atoms or molecules into larger structures, with atomic precision; and
- design, construct, and demonstrate the performance of a computing device that fits into a cube no larger than 50 nanometers in any dimension. It must be capable of correctly adding any pair of 8-bit binary numbers, discarding overflow. The device must meet specified input and output requirements.

Tools for Nanotech

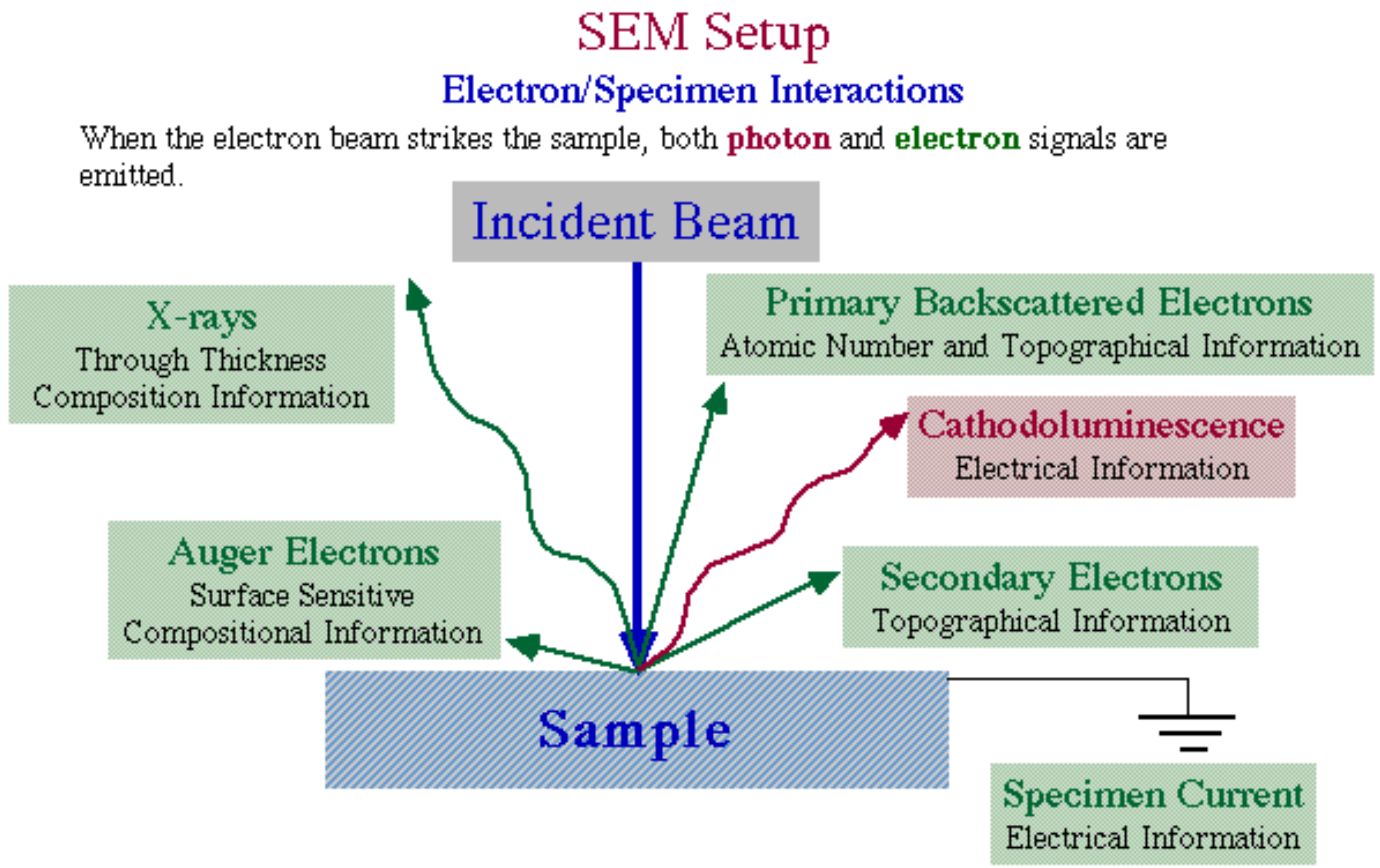
Scanning Electron Microscope (SEM)



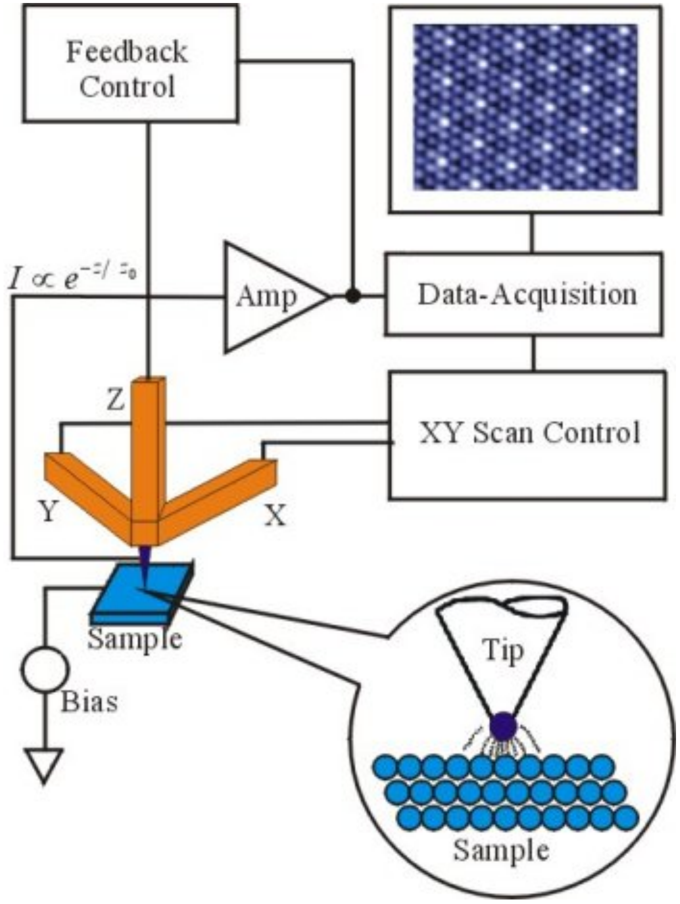
Scanning Electron Microscope (SEM)



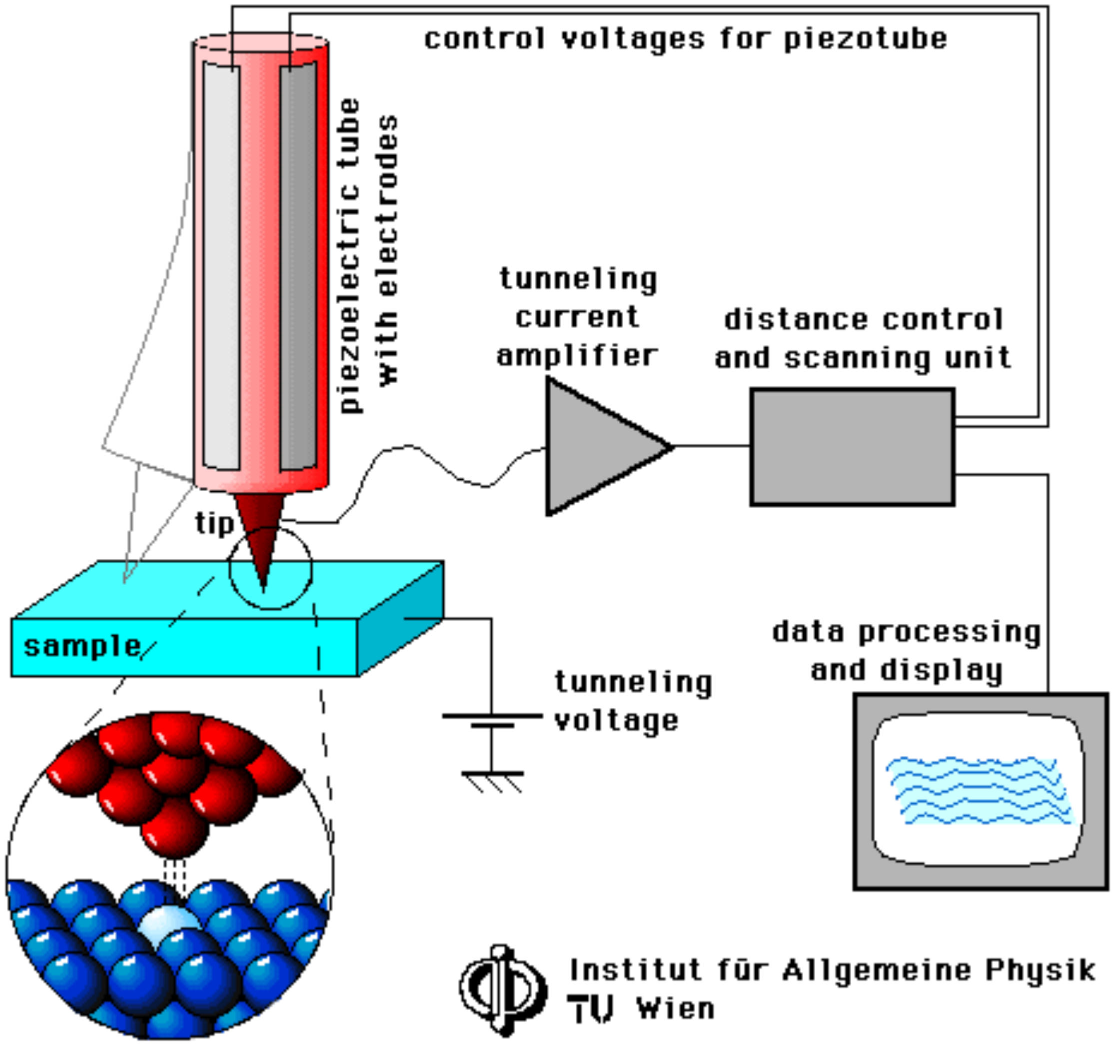
Scanning Electron Microscope (SEM)



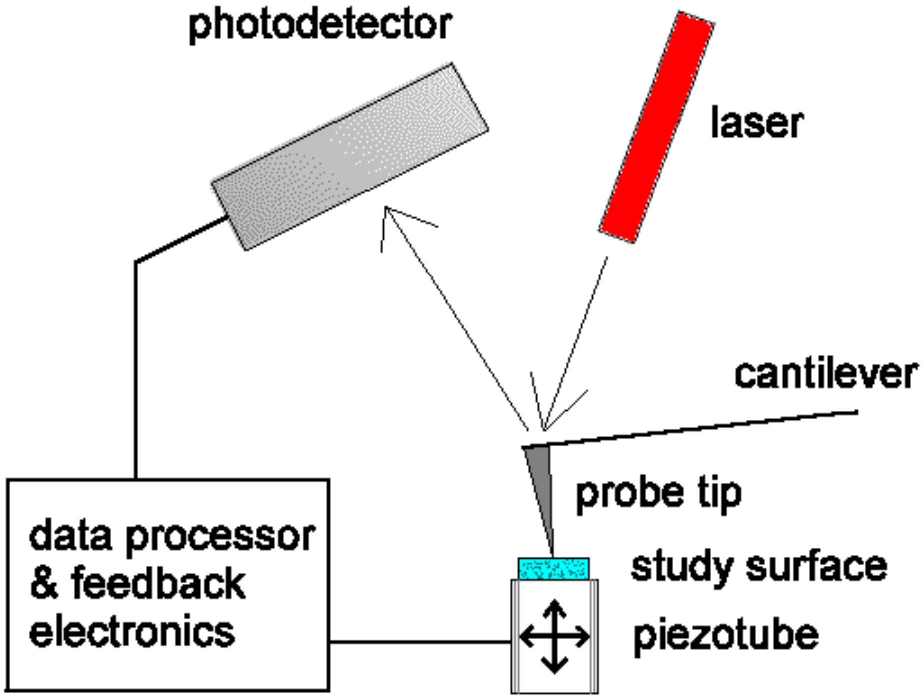
Scanning Tunneling Microscope (STM)

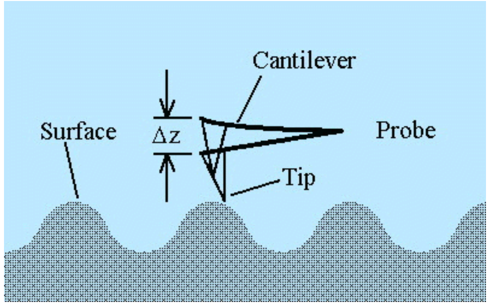


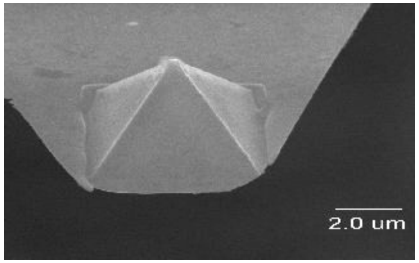
Scanning Tunneling Microscope (STM)

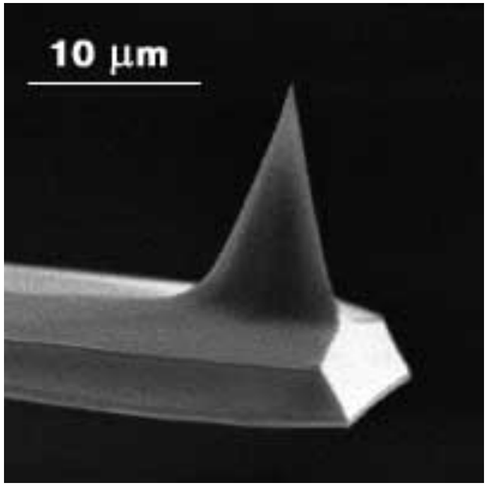


Atomic Force Microscope (AFM)



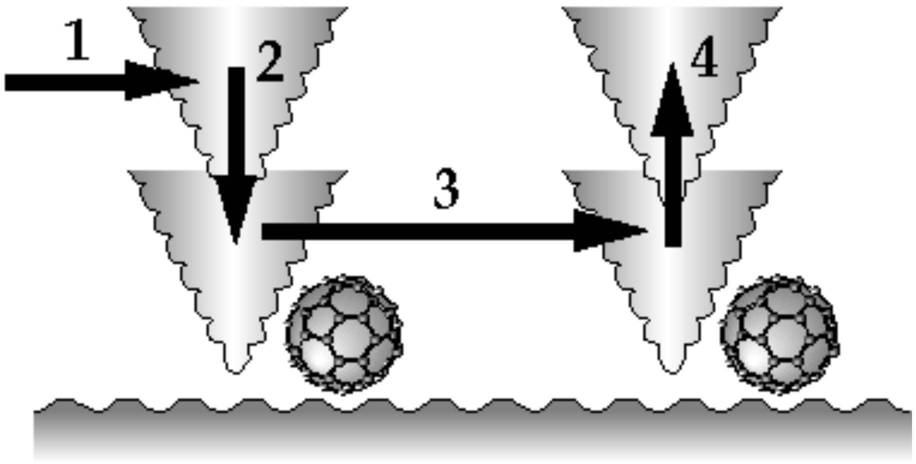






Playing with Atoms

Molecular Manipulation

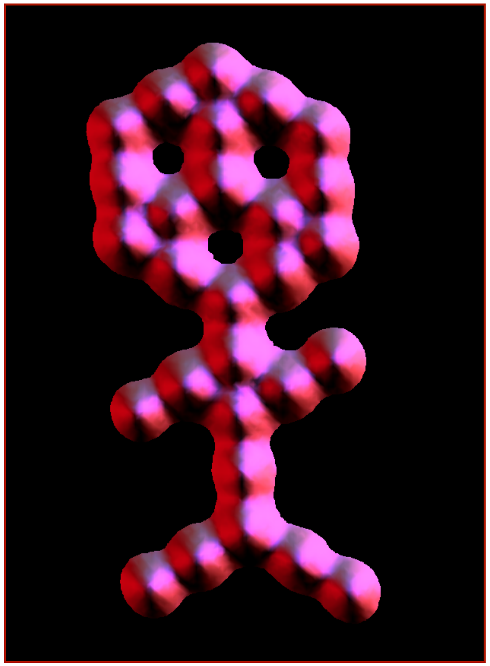


Schematic representation of the steps for molecular manipulation using a STM or AFM probe

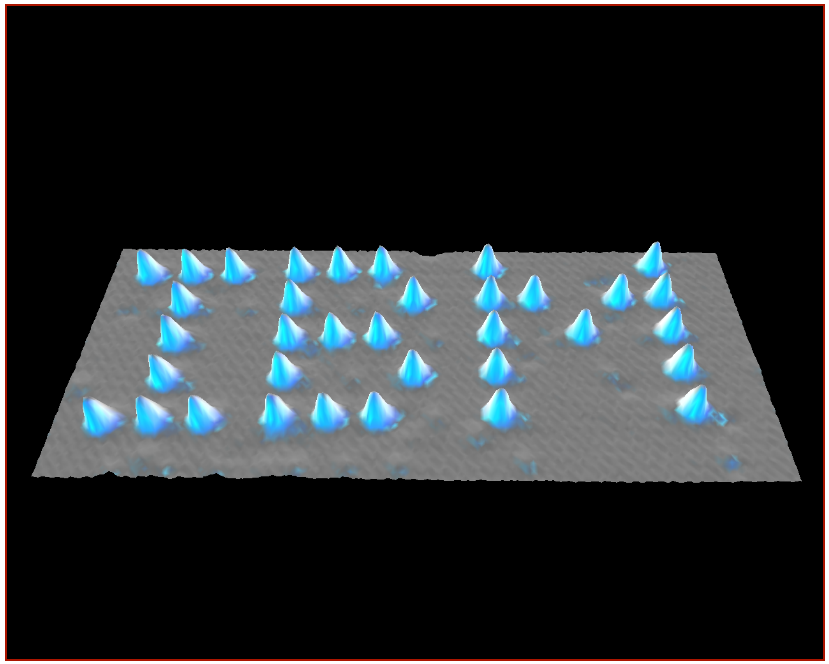
STM images of a 10nm x 10nm area near a step on Cu(100) showing the manipulation of a C60 molecule away from the step edge

http://www-g.eng.cam.ac.uk/nano/spmmeth.htm

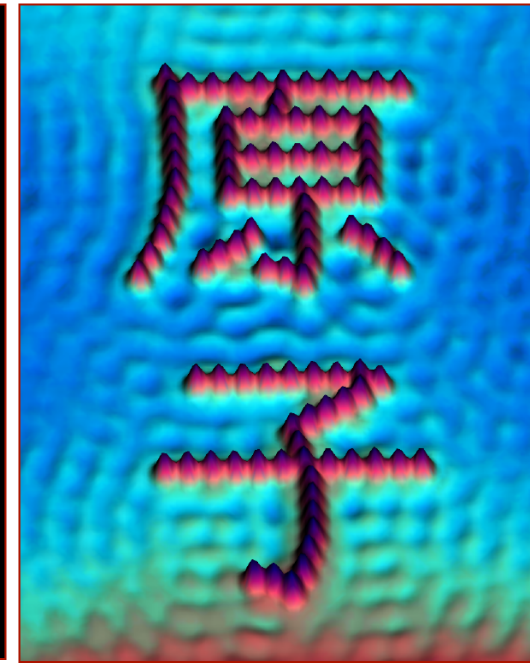
Some IBM Molecular Manipulation



Carbon Monoxide Man
Carbon Monoxide on Platinum (111)

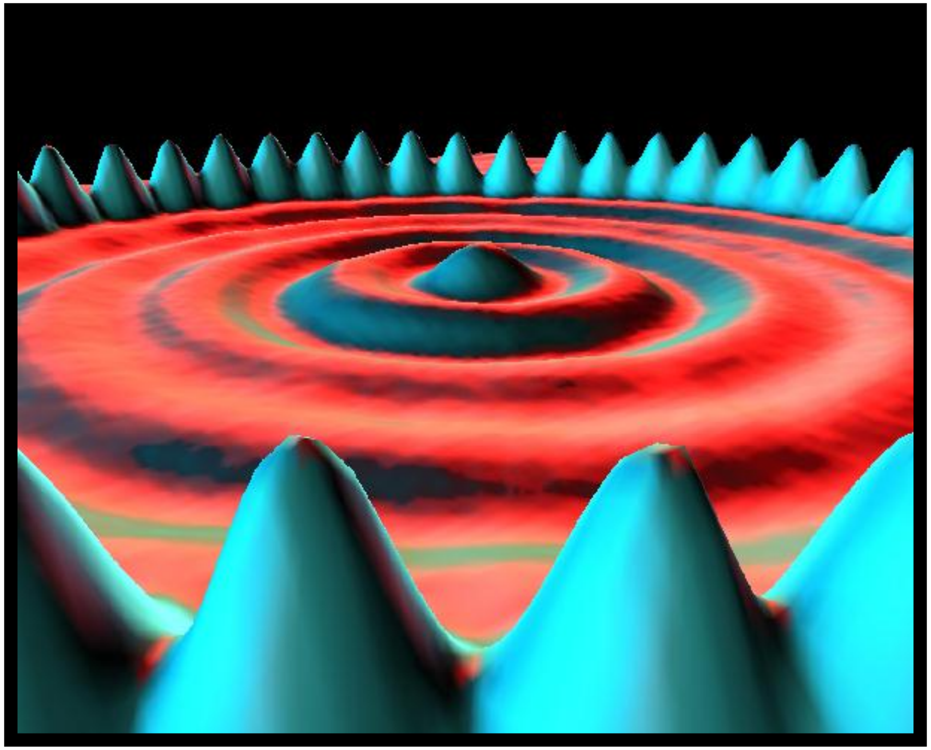


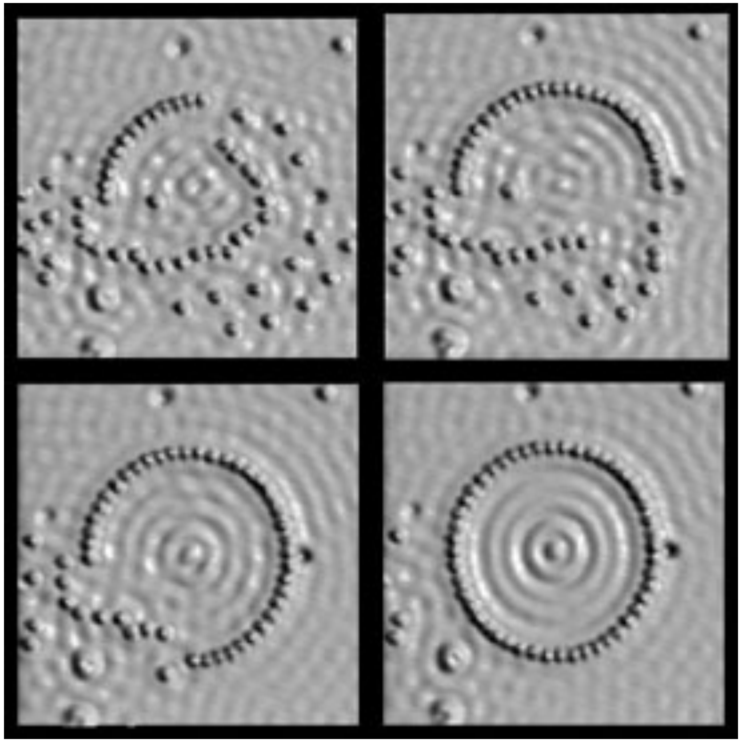
The Beginning
Xenon on Nickel (110)



Atom
Iron on Copper (111)

IBM Quantum Corrals



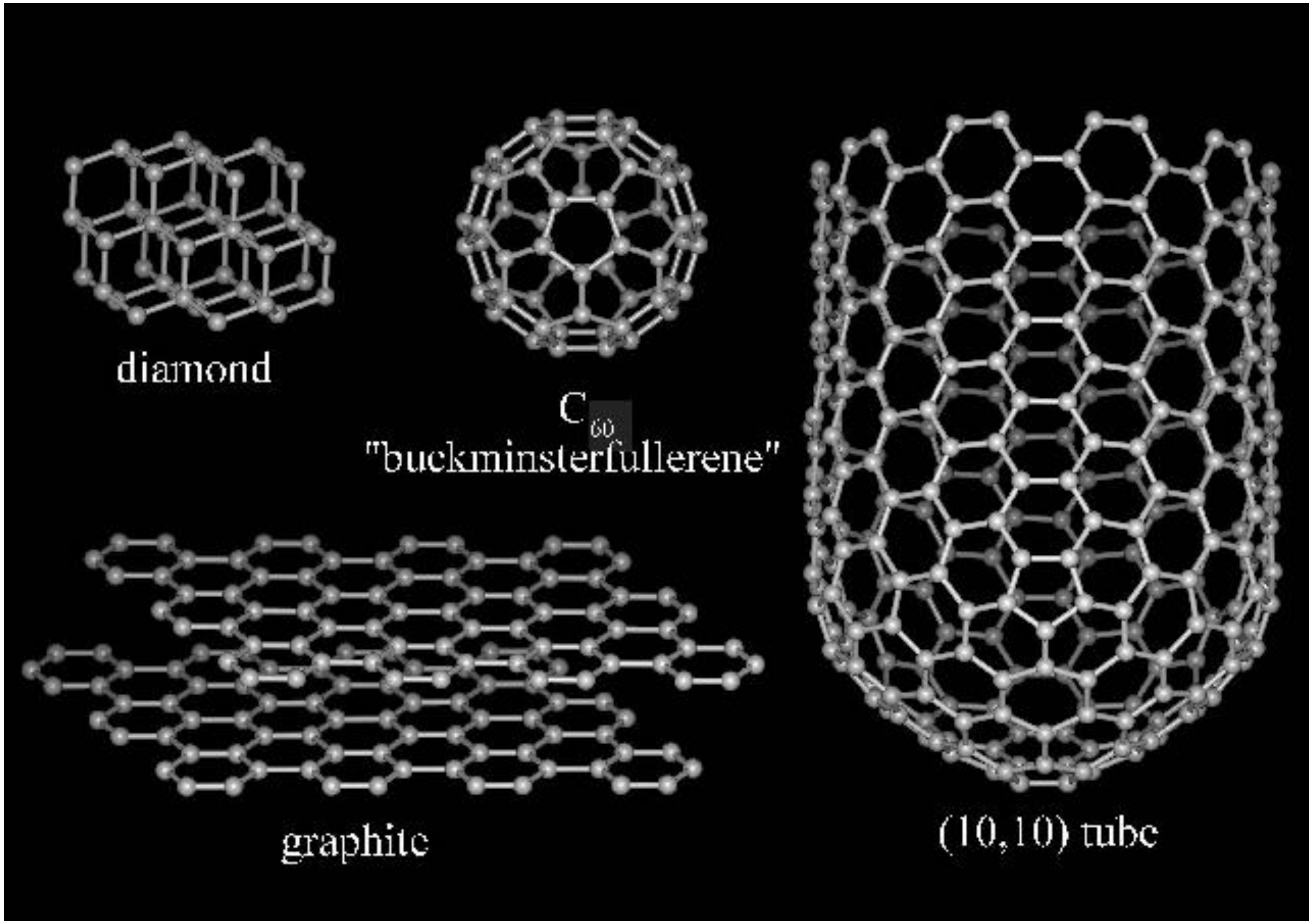


Circular Quantum Corral - Iron on Copper (111)

The discovery of the STM's ability to image variations in the density distribution of surface state electrons created in the artists a compulsion to have complete control of not only the atomic landscape, but the electronic landscape also. Here they have positioned 48 iron atoms into a circular ring in order to "corral" some surface state electrons and force them into "quantum" states of the circular structure. The ripples in the ring of atoms are the density distribution of a particular set of quantum states of the corral. The artists were delighted to discover that they could predict what goes on in the corral by solving the classic eigenvalue problem in quantum mechanics -- a particle in a hard-wall box.

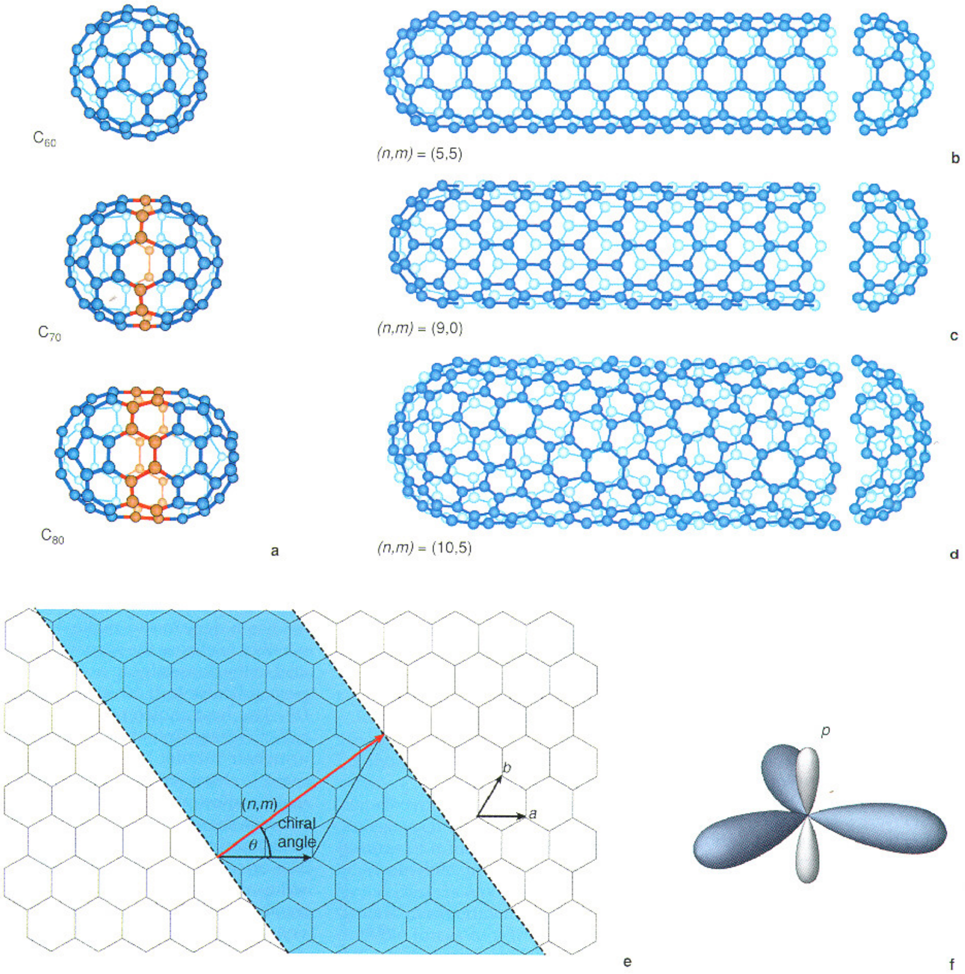
Carbon Nanotubes

Carbon Nanotube Structure



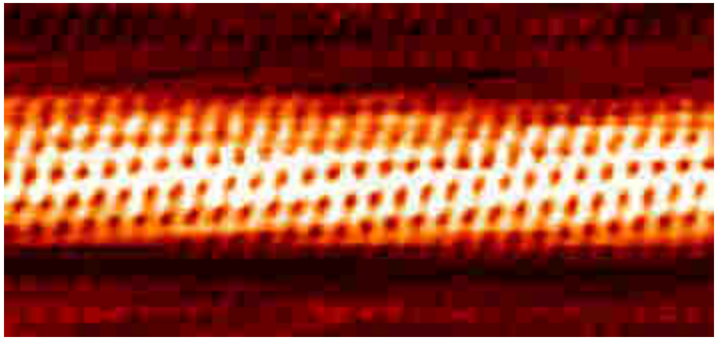
Richard E. Smalley
http://cnst.rice.edu/reshome.html

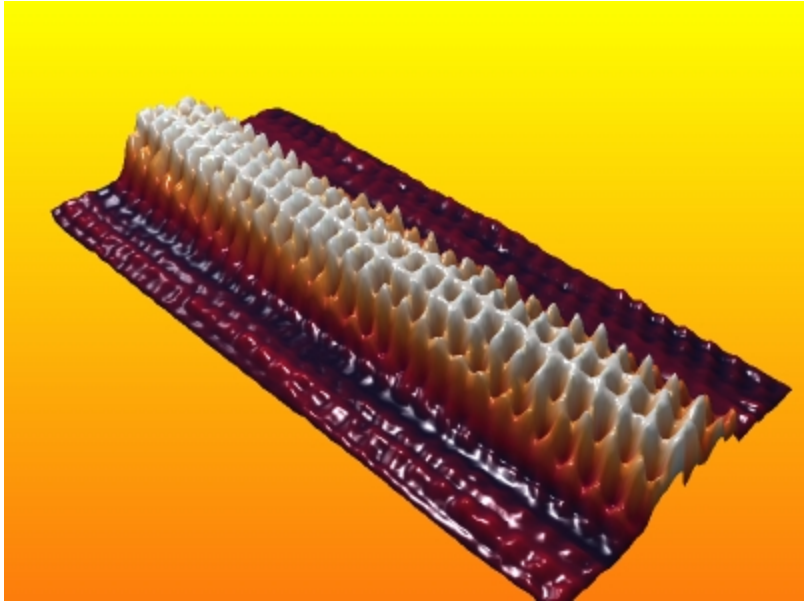
Carbon Nanotube Variations



Richard E. Smalley
http://cnst.rice.edu/reshome.html

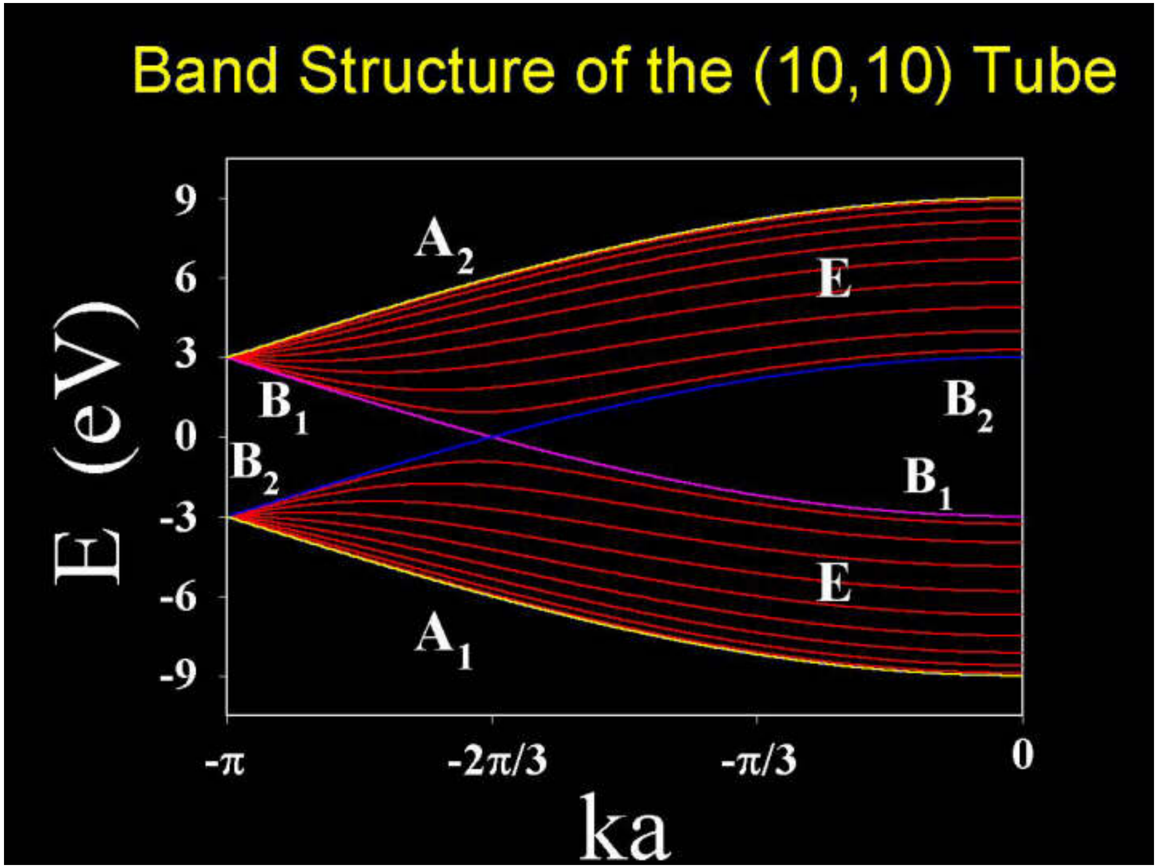
Carbon Nanotube STMs





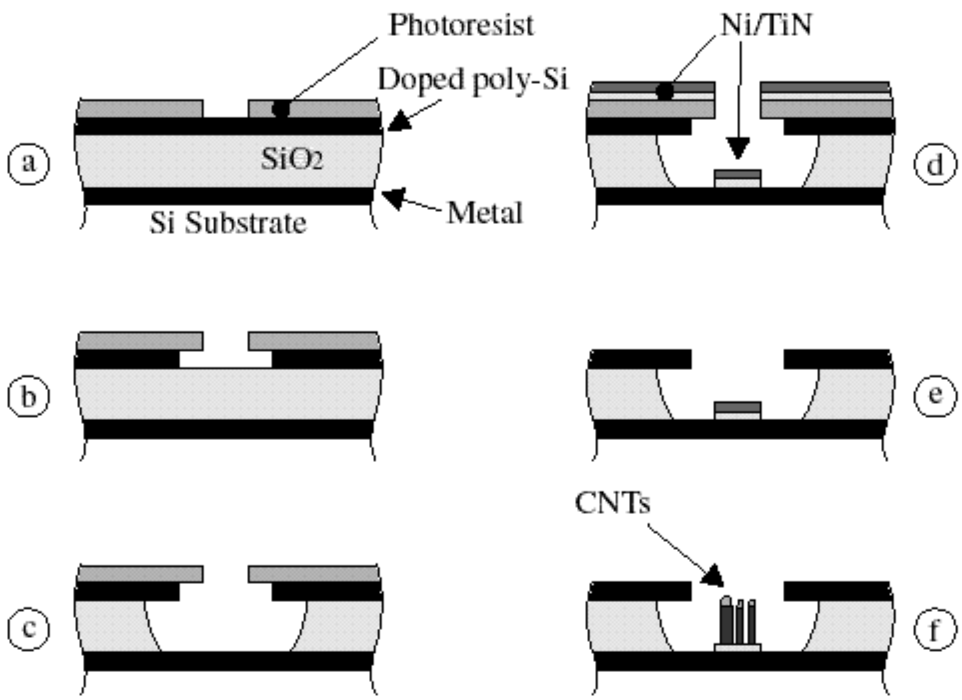
http://www.mb.tn.tudelft.nl/nanotubes.html

Carbon Nanotube Variations

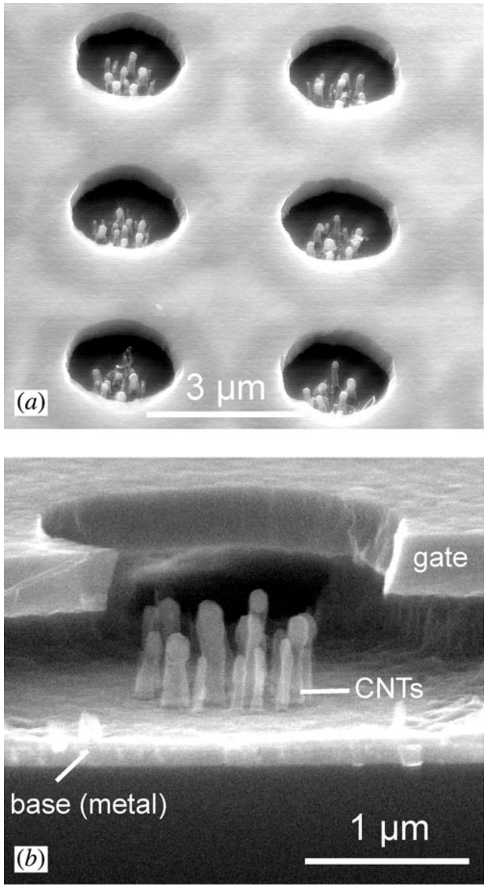


Richard E. Smalley
http://cnst.rice.edu/reshome.html

Carbon Nanotube Field-Emission



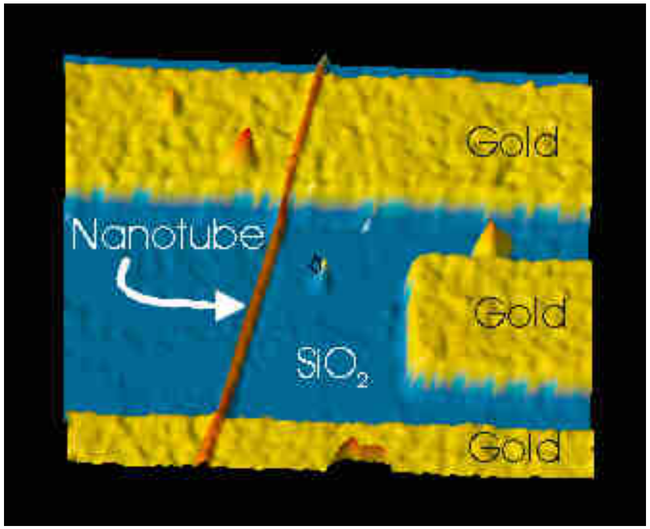
Self-aligned fabrication process for microcathodes with vertically-aligned CNTs as the emission source.

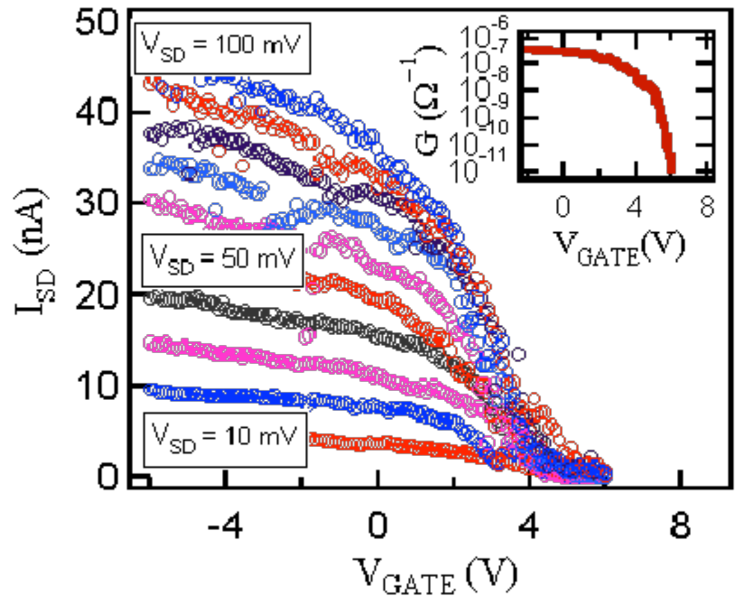


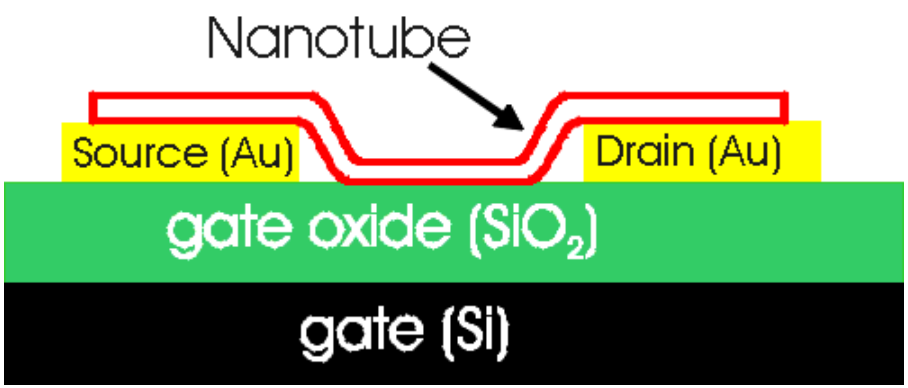
Tilted (45 .) top (*a*) and cross-sectional (*b*) SEM images of a microcathode.

Nanotechnology **13** (2002) 1–4

IBM Carbon Nanotube FET



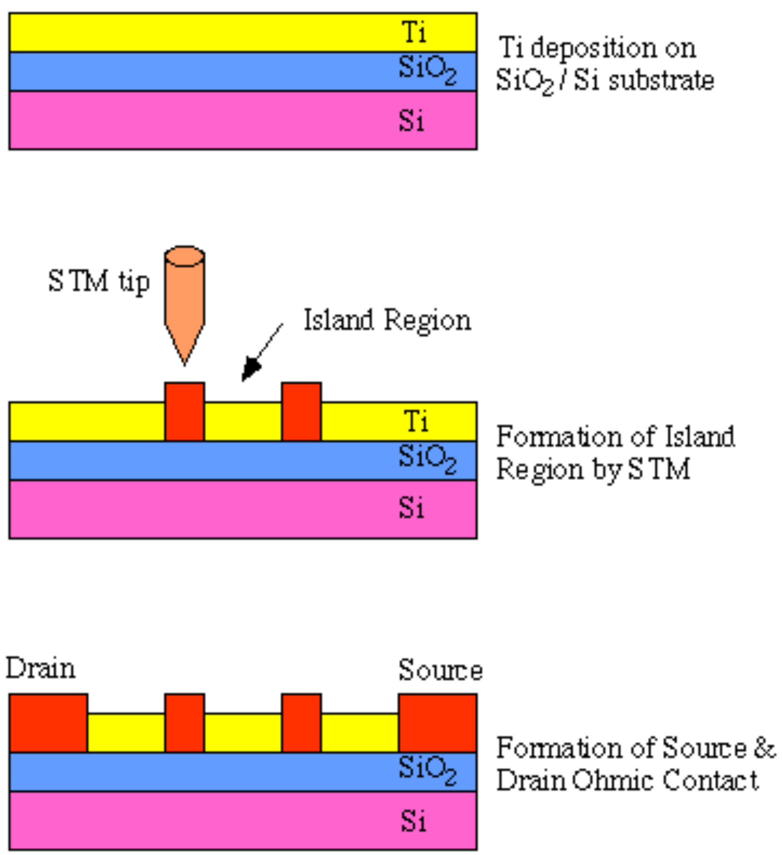


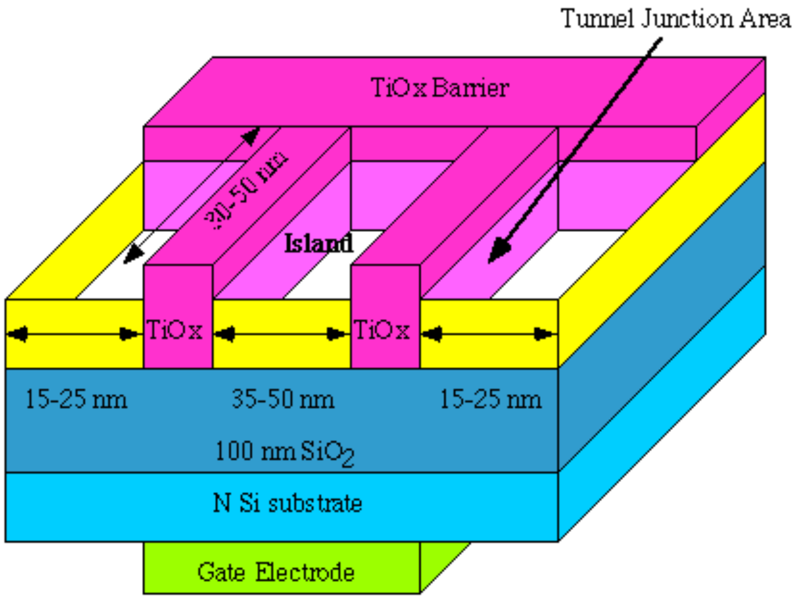


The measured electrical characteristics of the nanotube-FETs show that the amount of current (I_{SD}) flowing through the nanotube channel changes by a factor of 100,000 by changing the voltage applied to a gate (V_G), as can be seen in the data above. G is the low bias conductance of the tube.

Applied Physics Letters, vol **73**, p. 2447 (1998)

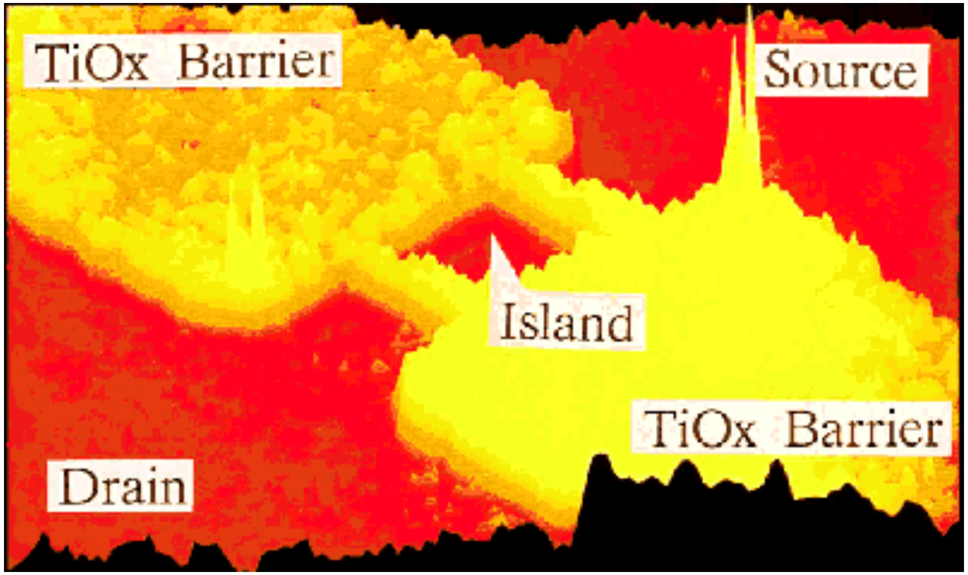
Single Electron Transistor (SET)

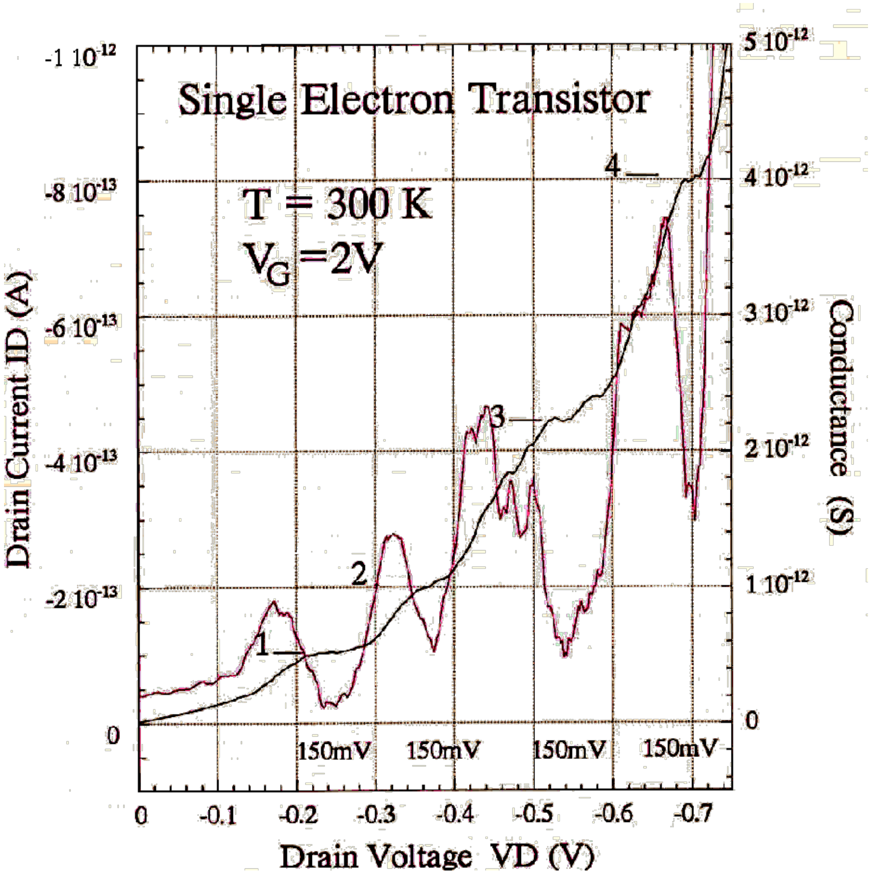




Appl. Phys. Lett. **68** (1), 1 January 1996

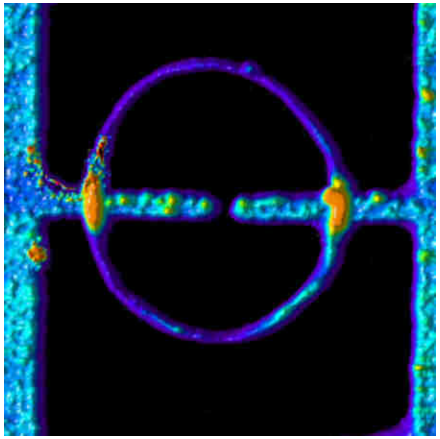
Single Electron Transistor (SET)



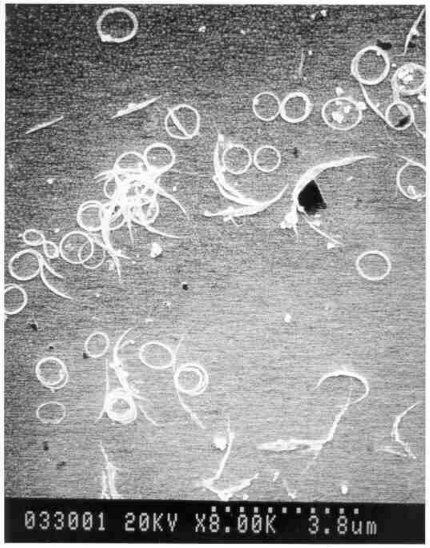


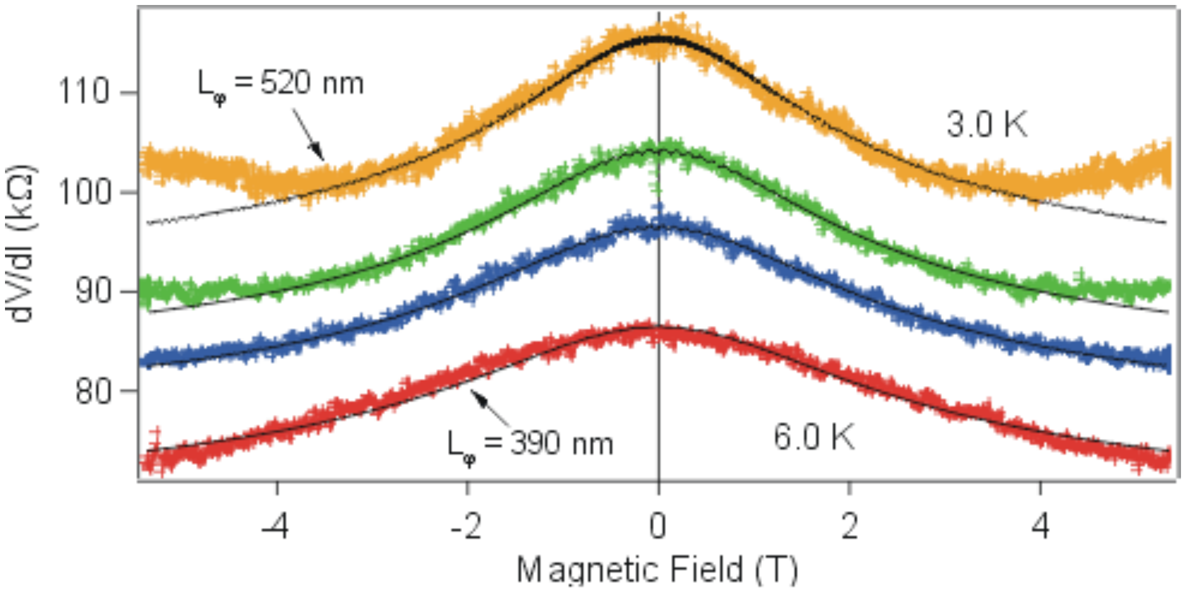
Appl. Phys. Lett. **68** (1), 1 January 1996

IBM Nanotube Rings



AFM of 1um x 1.4nm ring

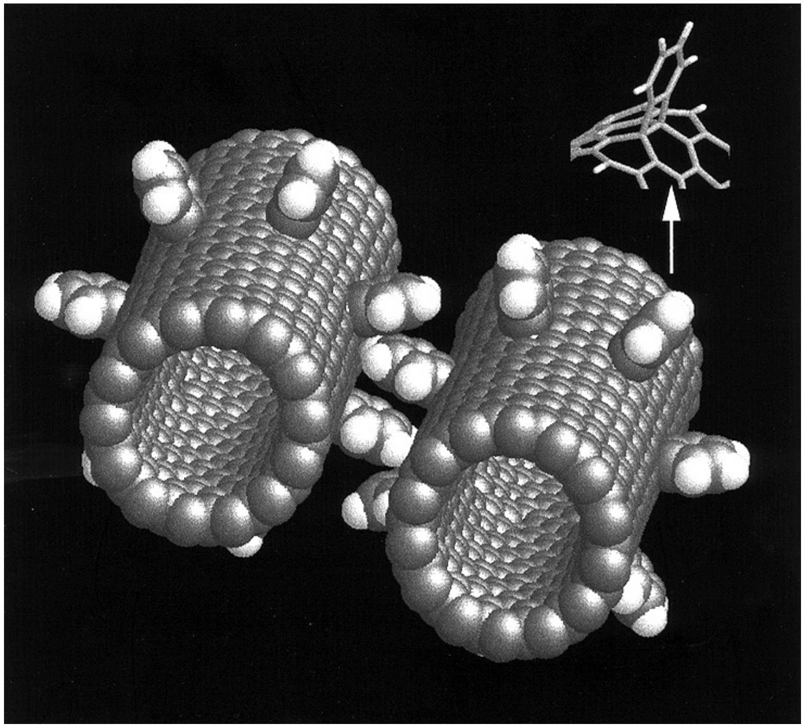




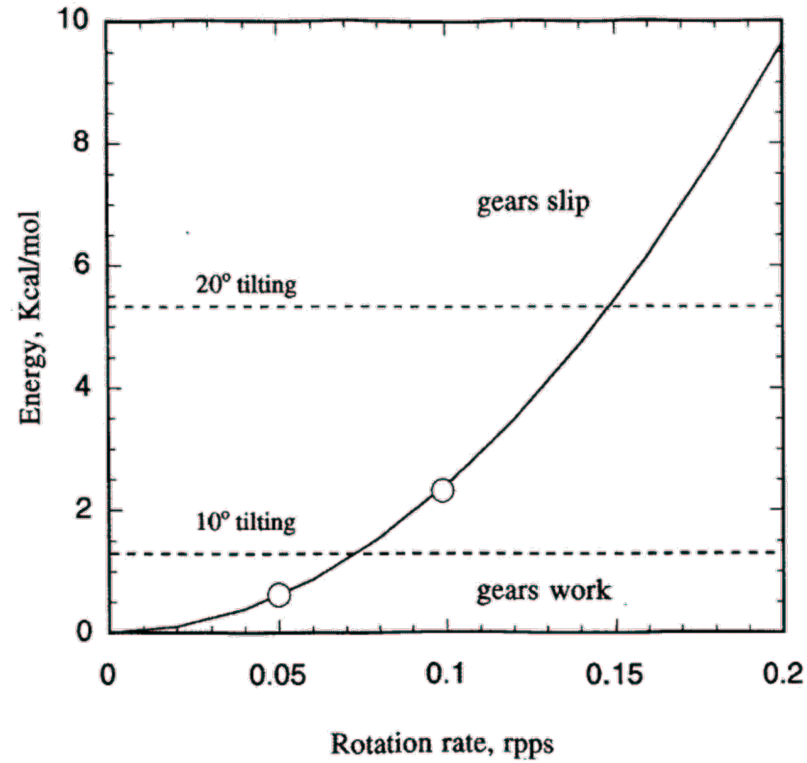
The rings are 1-D conductors and at low temperatures, quantum interference phenomena dominate electrical transport through the tubes.

The plot above shows the resistance of a ring as a function of the magnetic field applied through it. The resistance is maximum at zero field because electrons propagating around the ring in opposite directions interfere with each other constructively at the point of injection, forming a standing wave. Applying a magnetic field breaks time-reversal invariance, and the constructive interference is lost.

Carbon Nanotube Gears



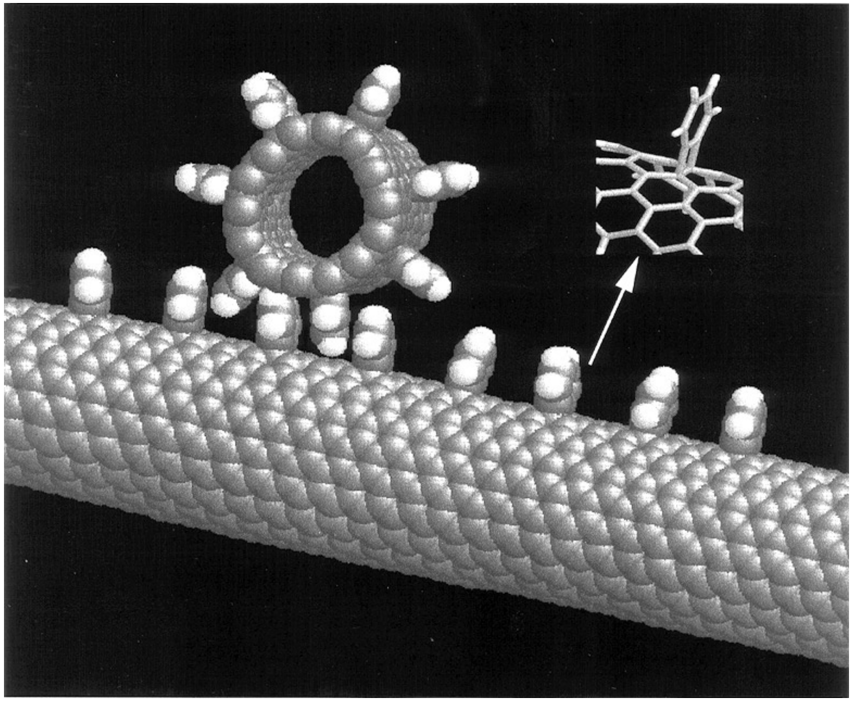
Carbon nanotube-based gears with benzene teeth.



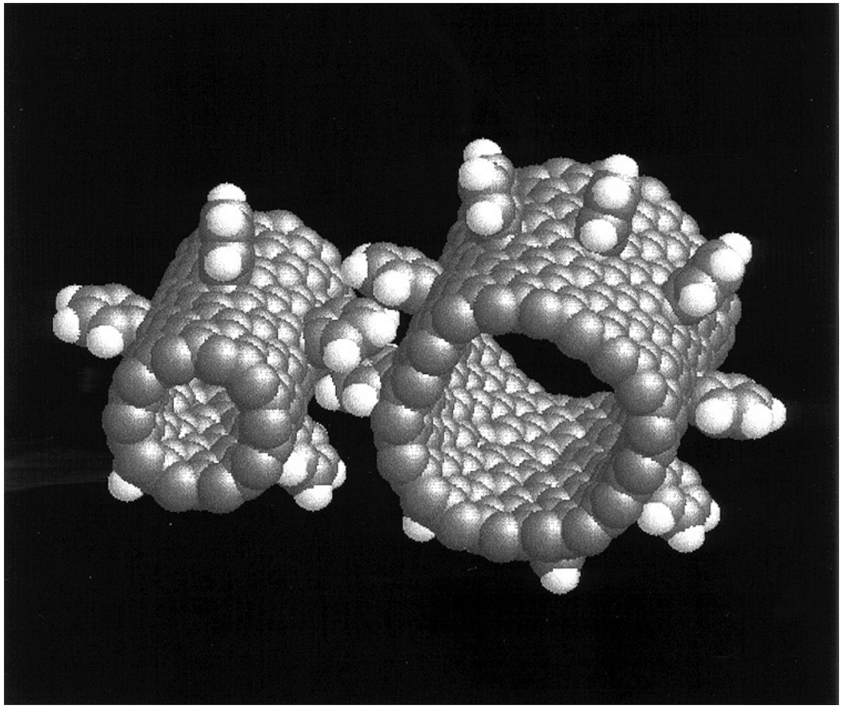
Predicting gear operations as a function of rotation rate and tooth tilting energy.

Nanotechnology **8** (1997) 95–102

Carbon Nanotube Gears



Gear and shaft system model. There are three rings between each benzyne tooth on the shaft, but only two rings between teeth in the gear.

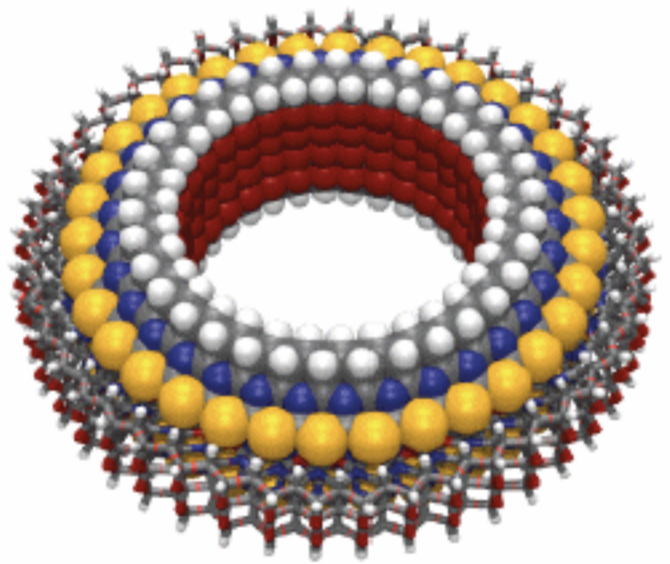


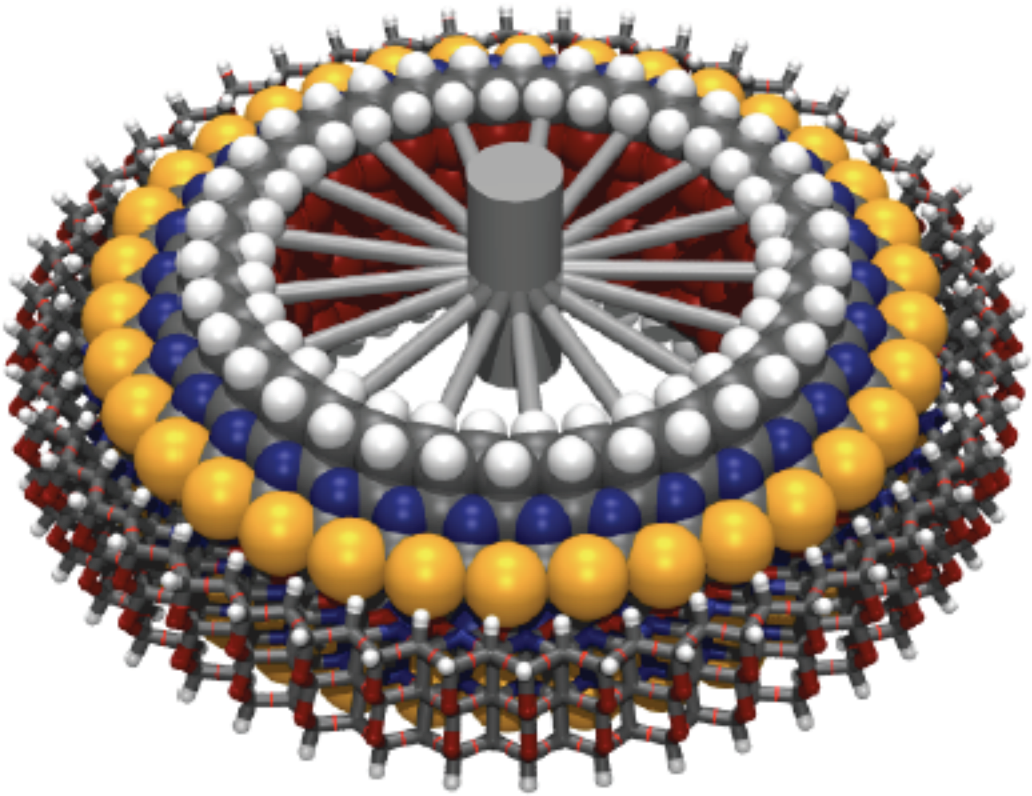
Small and large gear configuration.

Nanotechnology **8** (1997) 95–102

Foresight Institute

Sleeve Bearing



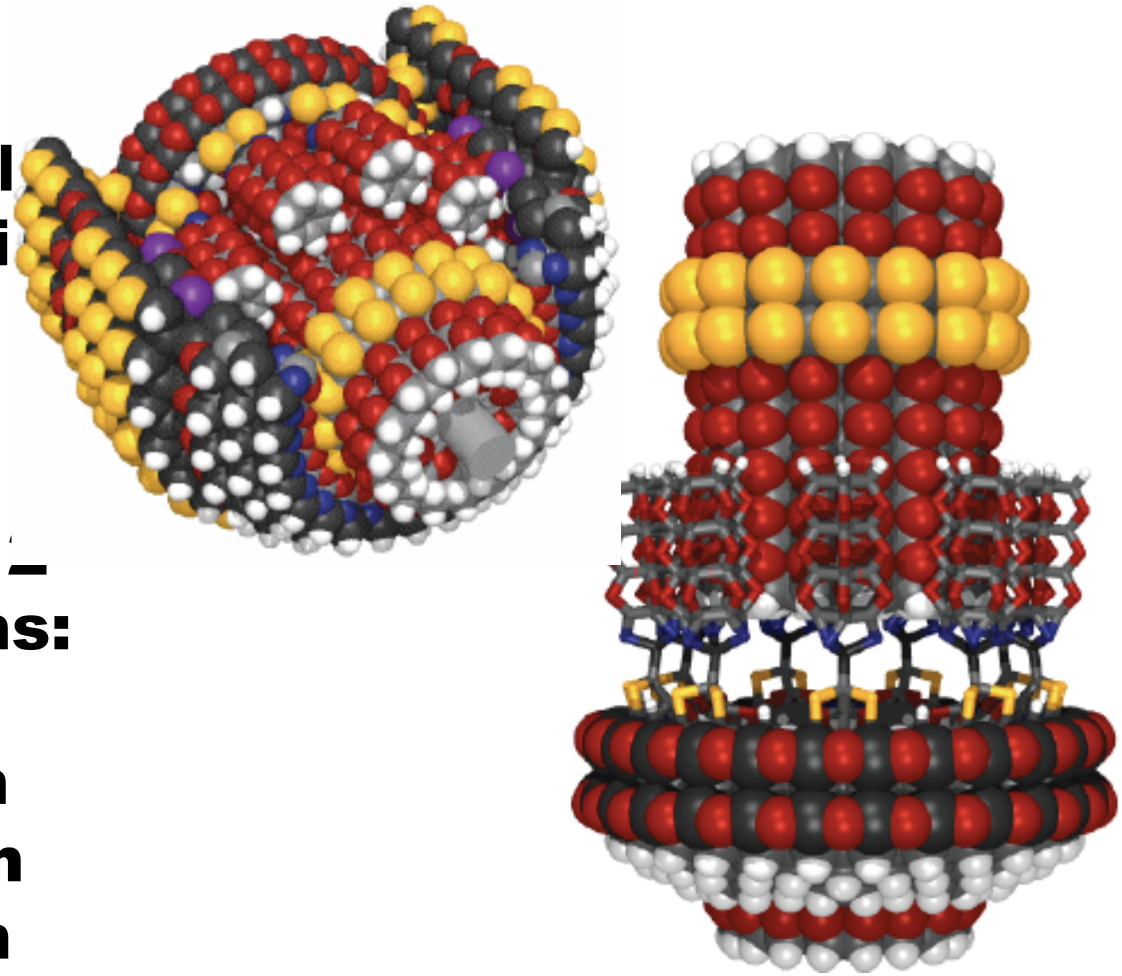


http://www.nanoengineer-1.com/mambo/
(click on Gallery)

Foresight Institute

Planetary Gear

Name: MarkIII(l
Designer: K. Eri
Drexler
Date: 2004
Number of
components: 1_
Number of atoms:
3,853
Width: 4.2 nm
Height: 4.2 nm
Depth: 4.2 nm
Gear Ratio: 45:16
Speed Ratio:
2.8125:1

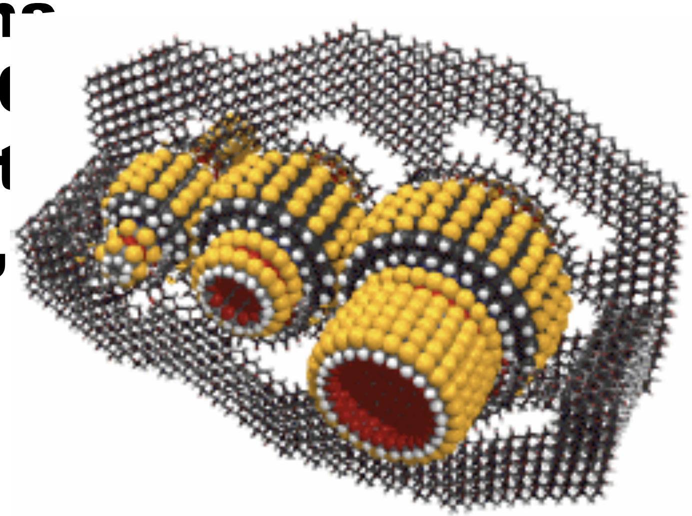


http://www.nanoengineer-1.com/mambo/ (click on Gallery)

Foresight Institute

Speed Reducer Gears

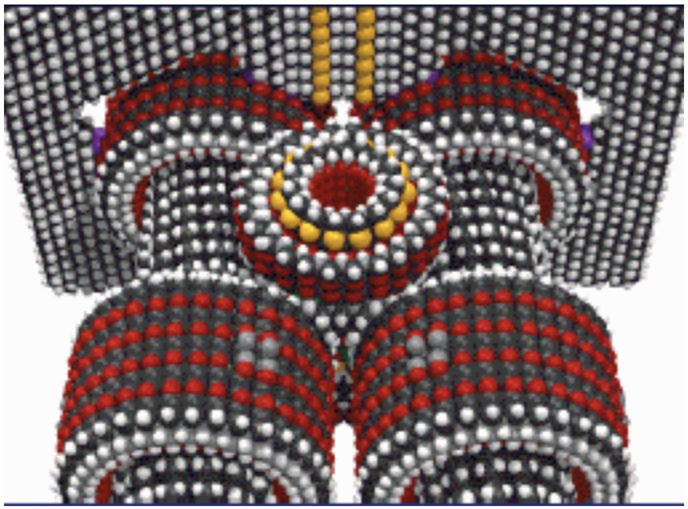
Designer: Mark Sims
Date: August 31, 200
Number of component
Number of atoms: 15,
Width: 11.3 nm
Height: 7.5 nm
Depth: 5.6 nm
Gear Ratio: 13:6
Speed Ratio: 2.167:1
Torque (large gear): 10 nN-nm

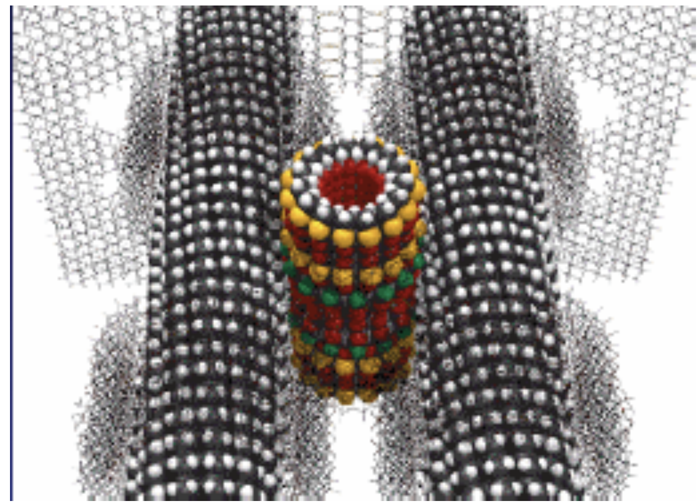


http://www.nanoengineer-1.com/mambo/ (click on Gallery)

Foresight Institute

Worm Drive Assembly

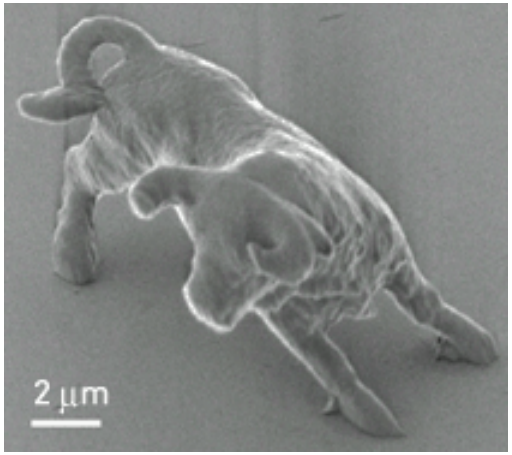


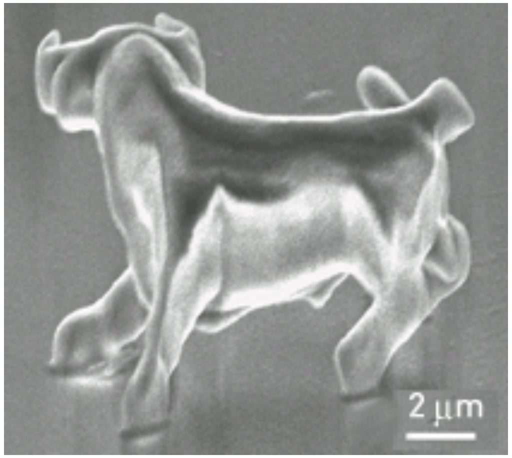


http://www.nanoengineer-1.com/mambo/ (click on Gallery)

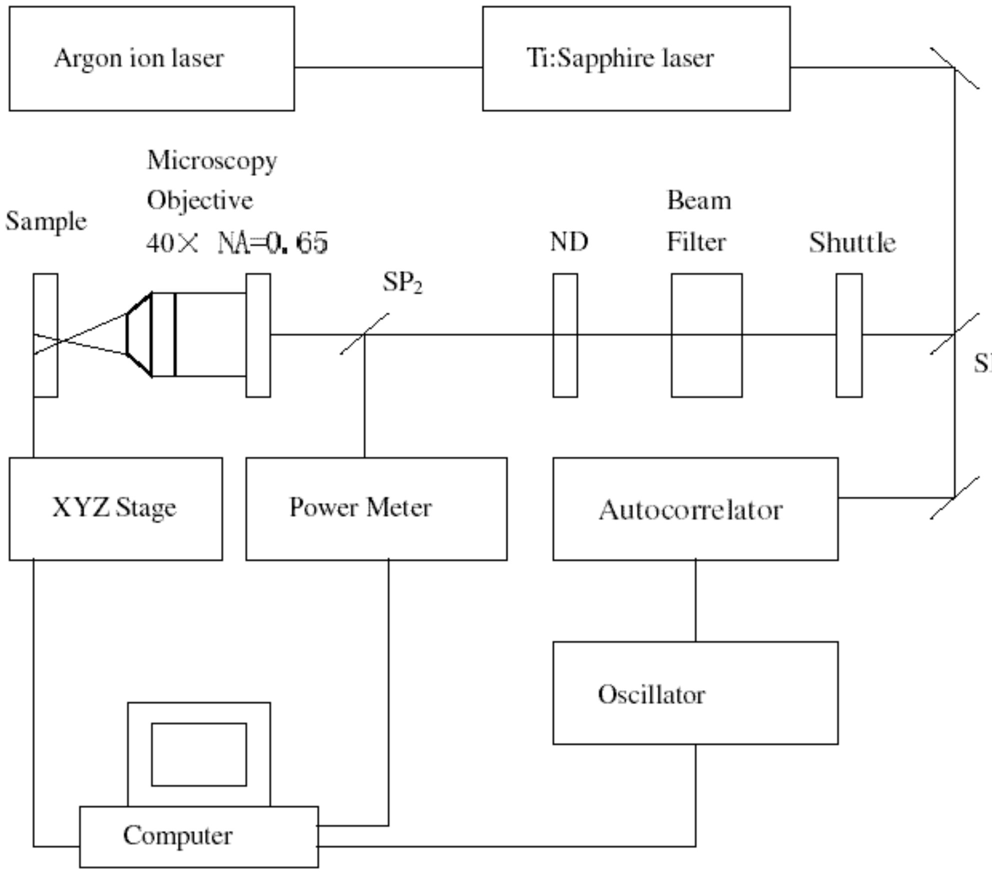
3-D Nanofabrication

"World's Smallest Bull"



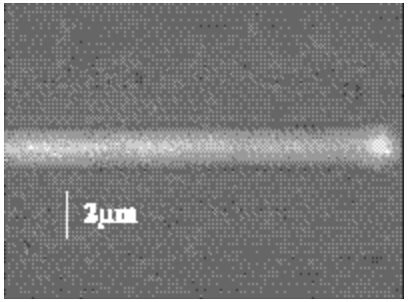


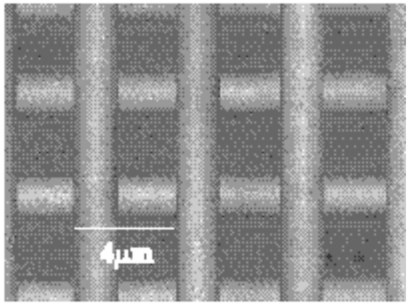
S. Kawata *et al*, Nature **412** (2001) 697



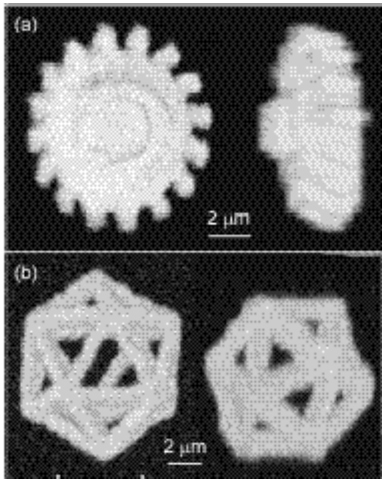
The optical system for two-photon polymerization. SP, beamsplitter.

Other 2-Photon Structures





Direct write rods using 500uW, 800nm femtosecond laser

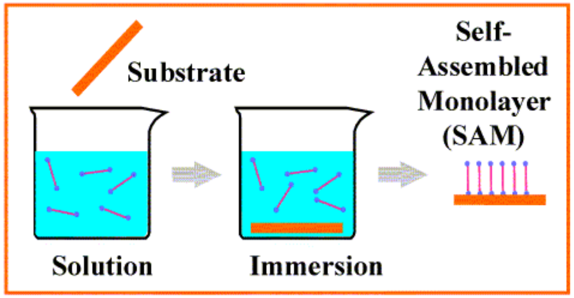


Reconstructed 3D two-photon fluorescence images of (a) a gearwheel and (b) an icosahedron.

Appl. Phys. Lett., Vol. 79, No. 10, 3 September 2001

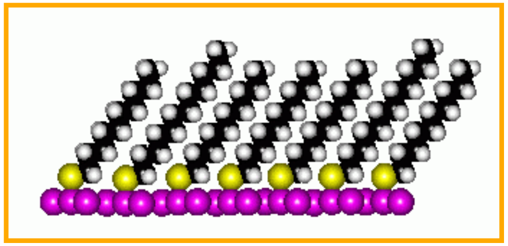
Self Assembled Monolayers (SAM)

Self-Assembled Monolayer (SAM)

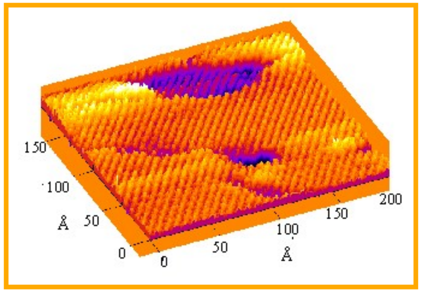


SAM is formed by soakiing a piece of sample into a solution containing molecules.

Self-assembled monolayers (SAMs) are ordered molecular structures formed by the adsorption of an active surfactant on a solid surface. For example, alkanethiol monolayer films are assembled in a close-packed structure with a nearest neighbor spacing of 5.0 Å on Au(111) lattice.



A schematic of SAM (alkanethiol molecules in this case) formation on a sample.

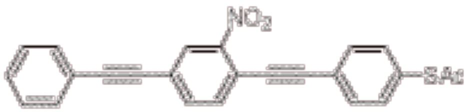


An ambient STM image of a typical alkanethiol (dodecanthiol in this case) SAM on Au(111) .

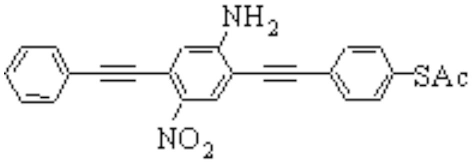
http://www.eng.yale.edu/reedlab/research/spm/spm.html

Self-Assembled Switches

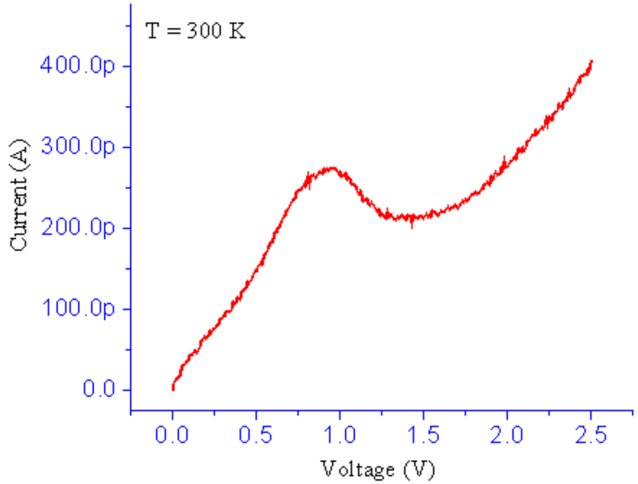
Using the nanopore process and a 2'-amino-4,4'-di(ethynylphenyl)-5'-nitro-1-benzenethiolate SAM we have demonstrated low temperature negative differential resistance (NDR) and using a 4,4'-di(ethynylphenyl)-2'-nitro-1-benzenethiolate SAM we have demonstrated room temperature NDR. These devices work as two terminal switches: at a specific applied voltage current will flow (device ON) at all other voltage values current does not flow (device OFF).



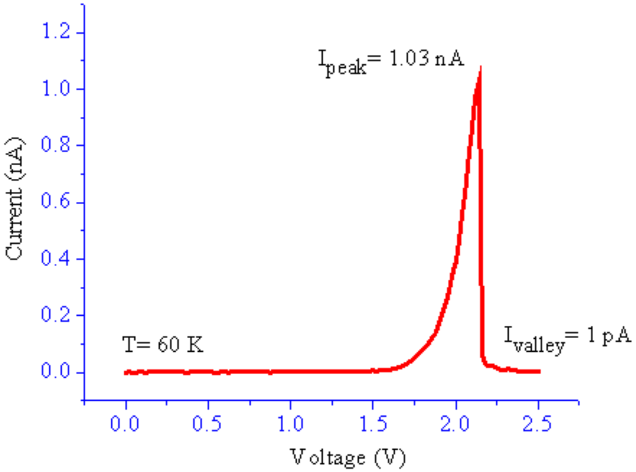
4,4'-di(ethynylphenyl)-2'-nitro-1-benzenethiolate ("nitro" for short)



2'-amino-4,4'-di(ethynylphenyl)-5'-nitro-1-benzenethiolate ("nitro-amine" for short)



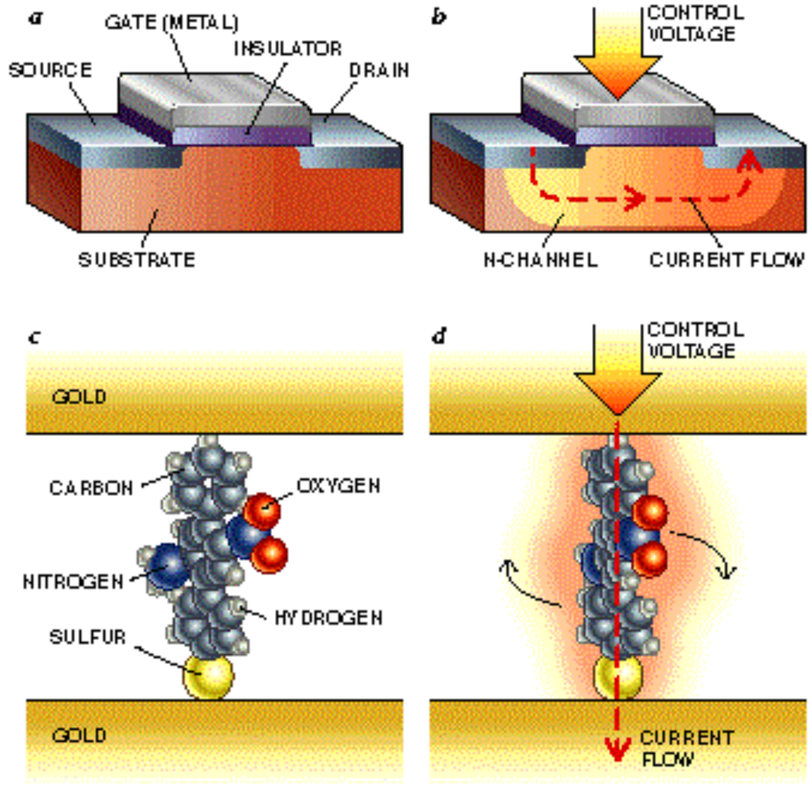
I-V plot of nitro nanopore at 300K.
Shows NDR with a peak to valley ratio of 1.5:1 and a current density of 16 Amps/cm^2.



I-V plot of nitro-amine nanopore at 60K.
Shows very strong NDR with a peak to valley ratio of 1000:1 and a current density of 50 Amps/cm^2.

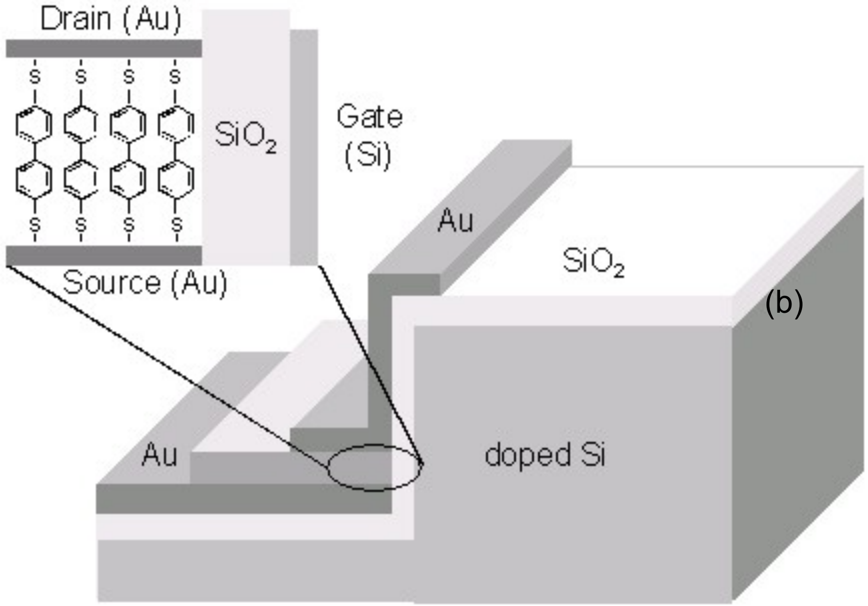
http://www.eng.yale.edu/reedlab/research/device/mol_devices.html

The Switching Mechanism:



In a conventional microelectronics transistor (a) the conduction path is turned on using an applied voltage at the gate electrode (b). Similarly, the conduction path thru a molecular switch (c) is turned on by an applied voltage. The applied voltage is believed to cause a conformational shift which, in concert with the charging of the molecule, opens the conduction pathway (d).

Bell Labs SAM Molecular Transistor



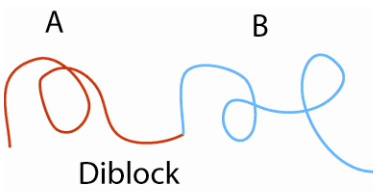
- mobility of >300 cm^2/V-s
- gm of 120 mA/V (large device)
- demonstrated inverter gain of 8

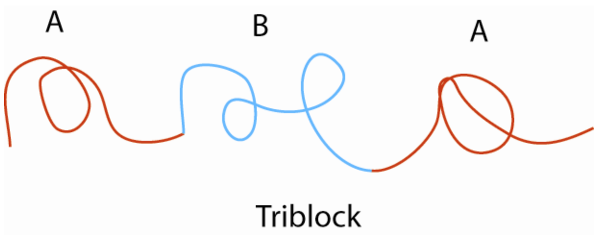
Nature **413**, 713 - 716 (18 Oct 2001)

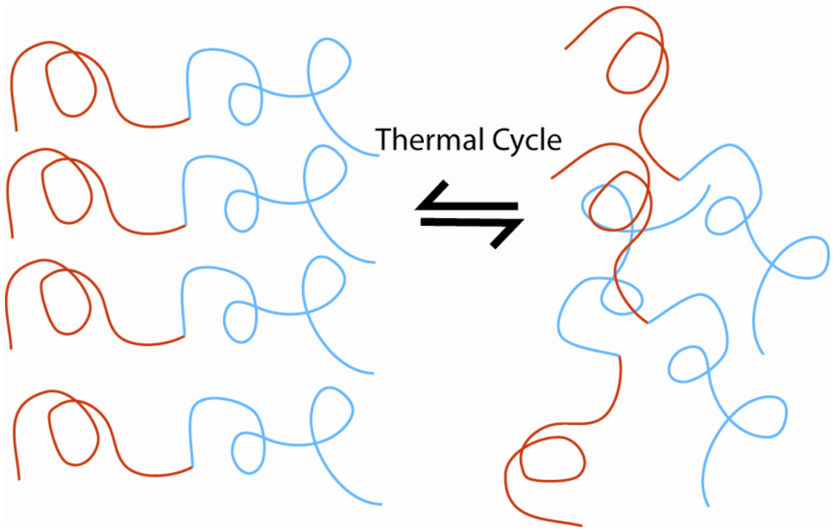
Polymer Self-Assembed Masking

Block copolymer masks

- Phase separation of incompatible block copolymers

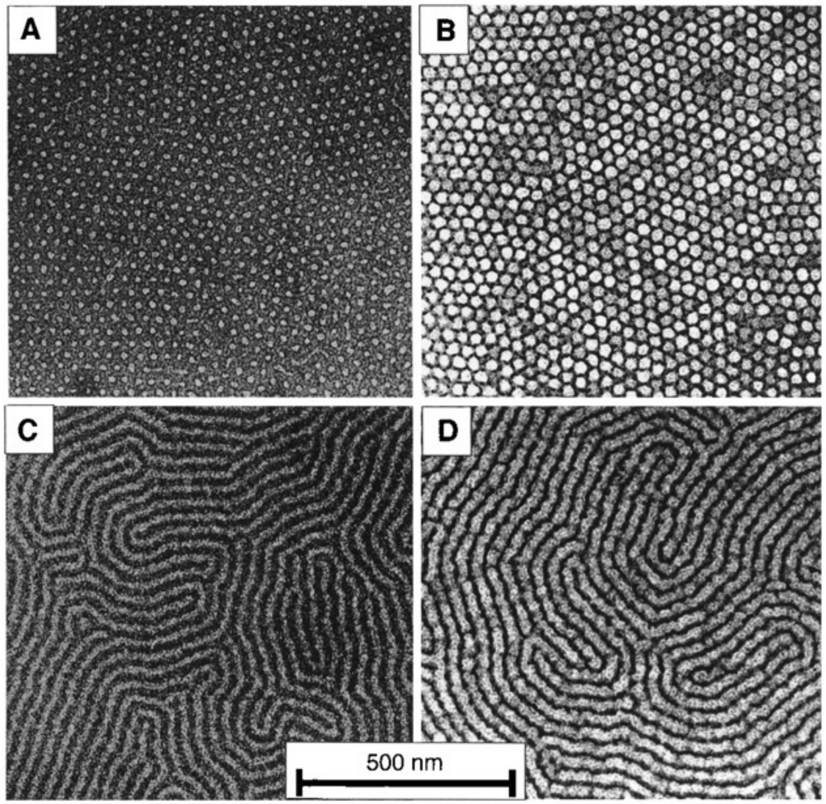






e.g., polystyrene and polybutadiene

Self-assembled masks



TEM images showing:

(A) a spherical micro-domain monolayer film after removal of poly butadiene by ozone treatment

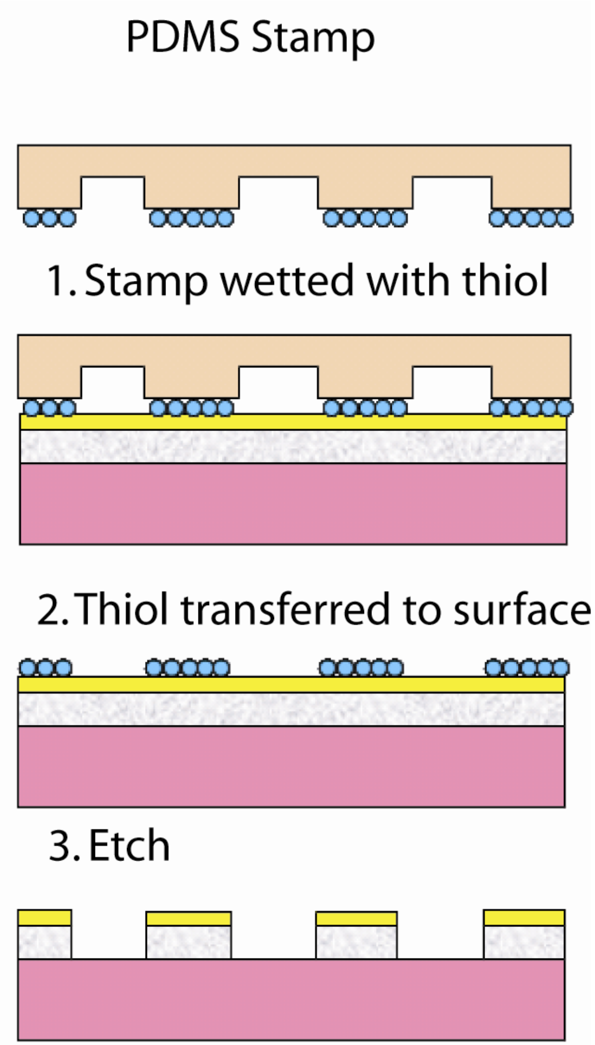
(B) the resulting array of holes in silicon nitride after RIE

(C) cylindrical microdomains in which the darker regions are osmium stained poly butadiene domains

(D) the resulting cylindrical pattern etched into the silicon nitride surface

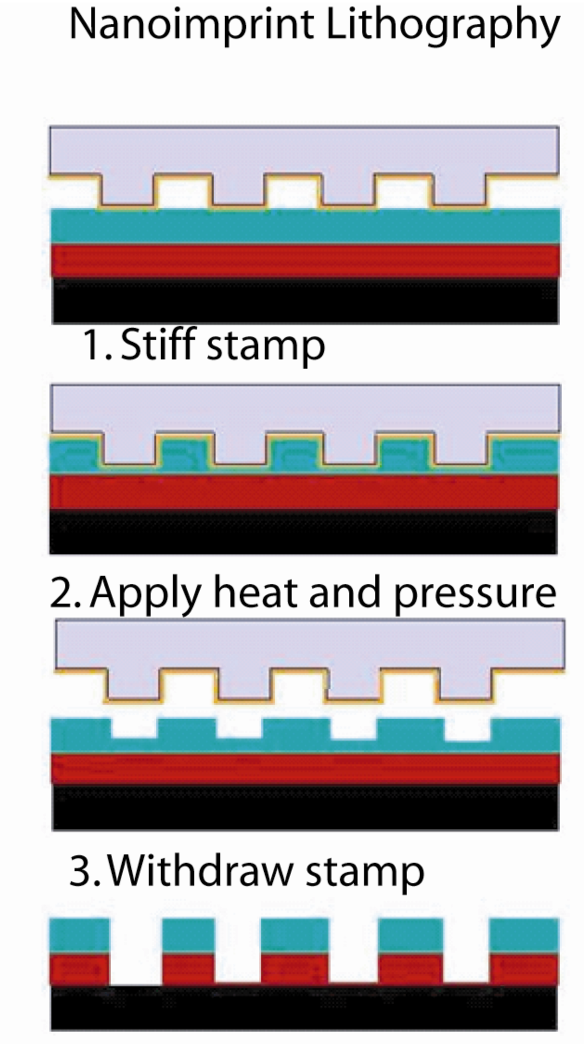
Stamp-Based Lithography

PDMS Stamp Lithography



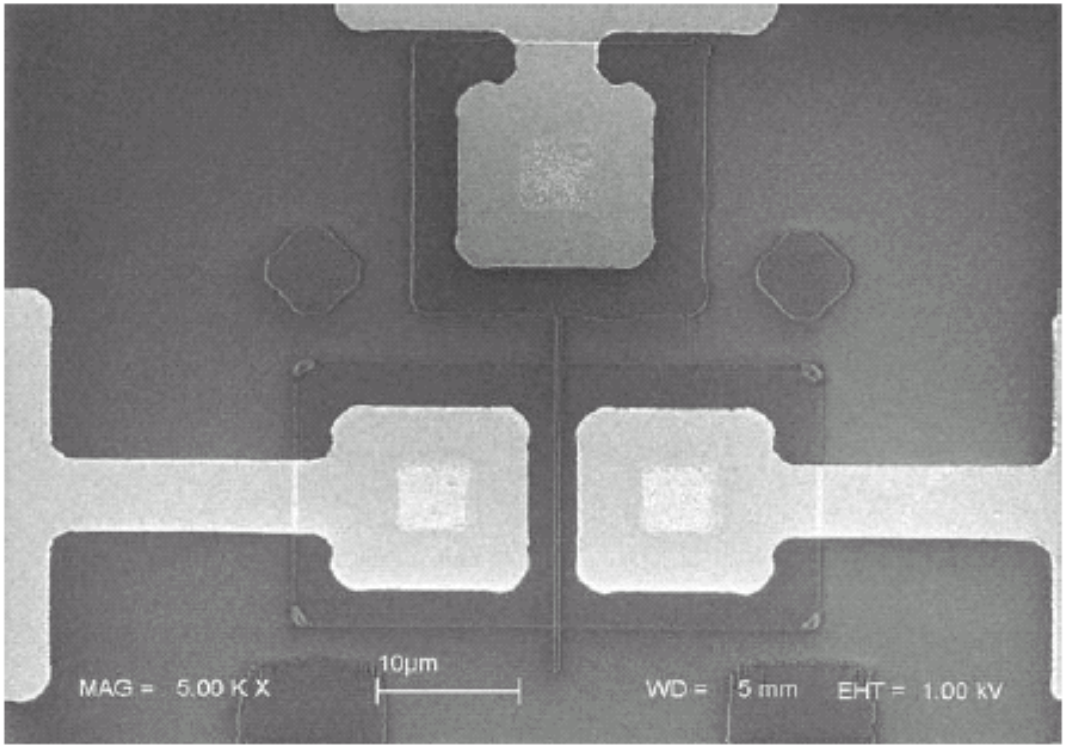
Soft imprint lithography using a polydimethylsiloxane stamp to transfer chemicals to the surface of a wafer to be etched. Here the material acts as an etch resist but it could also form other functions such as a DNA molecule for a "gene chip".

Nanoimprint Lithography



Nanoimprint lithography with a hard stamp. The stamp is pressed into a heated thermoplastic on the surface of the wafer at a temperature above the glass transition temperature of the plastic. The plastic is then cooled and the stamp removed to leave a patterned resist.

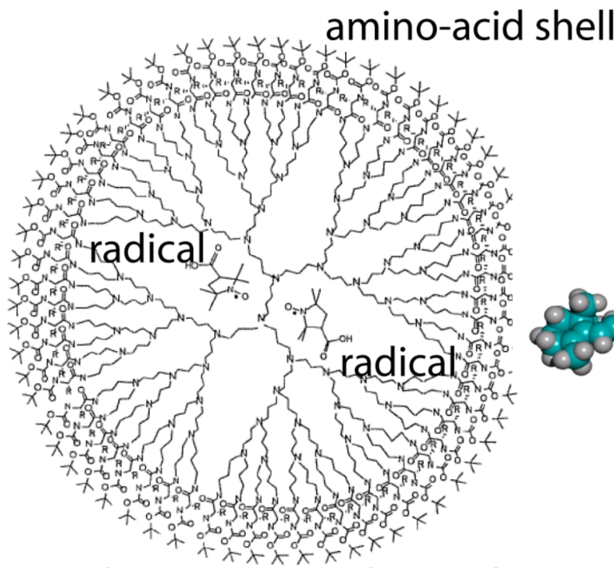
Nanoprinted Transistor



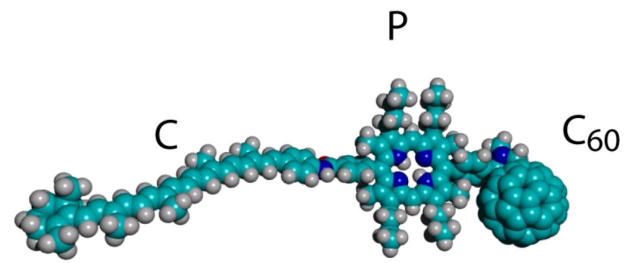
MOSFET with 60nm gate length. All steps were carried out using nanoprint methods.

Organic Synthesis

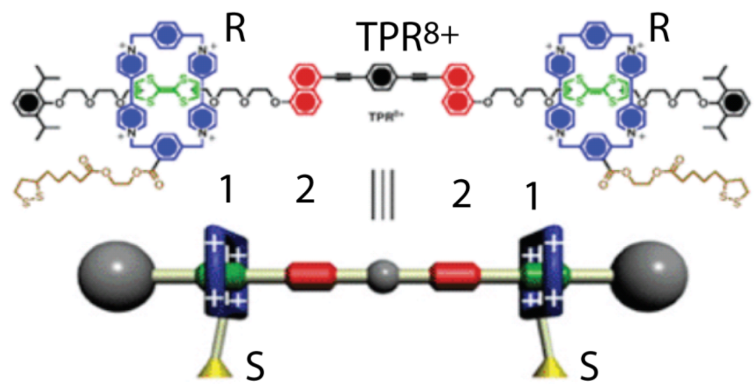
Organic Synthesis



Dendrimer encapsulating dyes

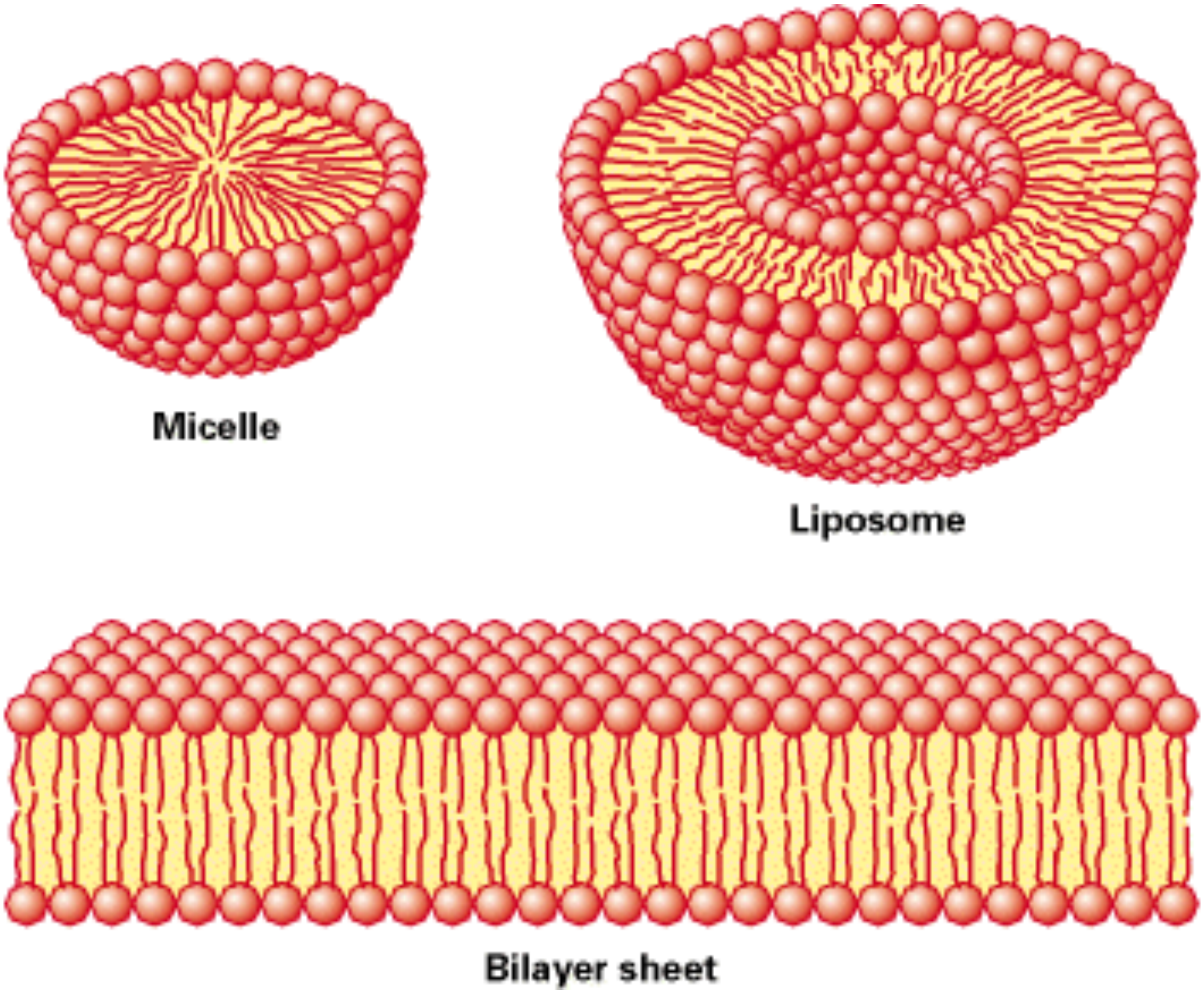


Light-to-charge converter

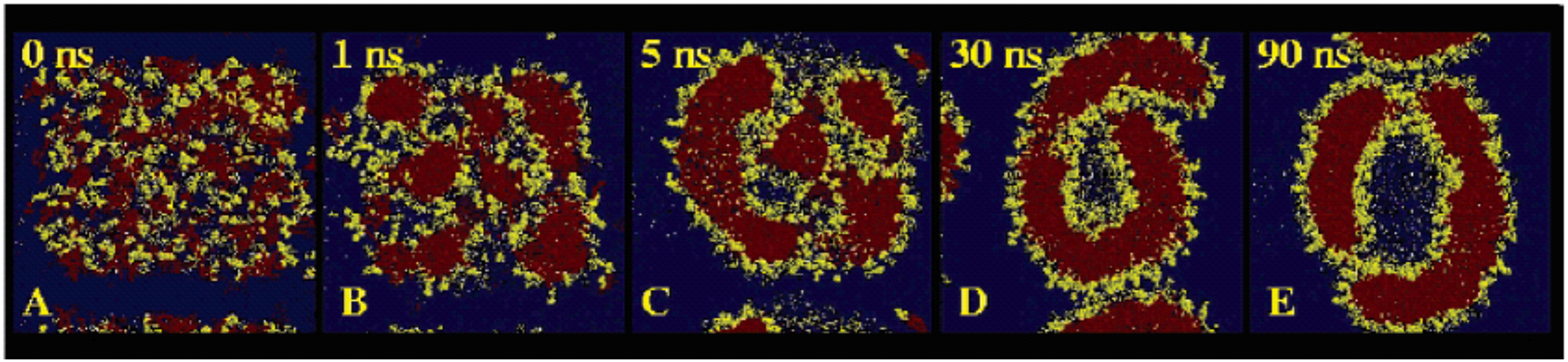


"Nano-muscle" actuator based on rotaxanes

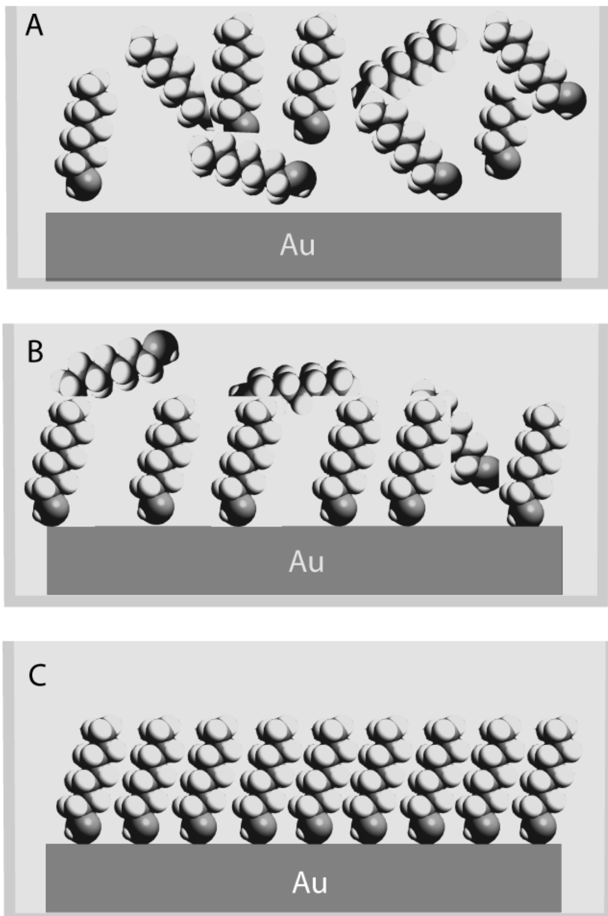
Self-assembled amphiphilic structures



MD Simulation of vesicle formation



Self-assembled monolayers



Preparation of alkanethiol self-assembled monolayers.

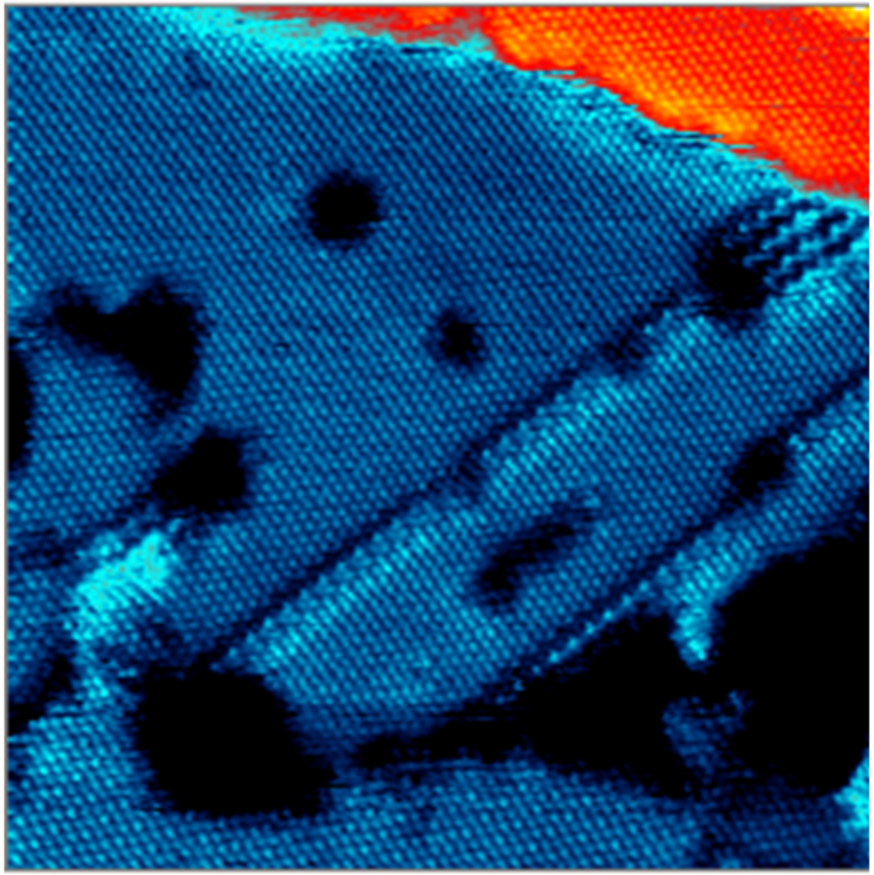
A) A flat gold substrate is immersed in solution

B) Containing alkane molecules terminated in a thiol (S-H) group. The sulfur binds to the gold pulling the molecule down.

C) After diffusion on the surface they form into an organized monolayer

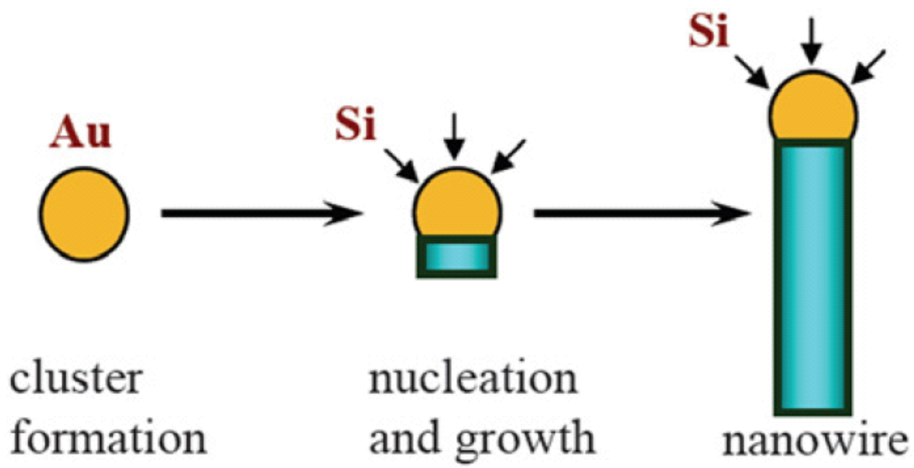
Different head groups or mixtures can be used on the alkanethiol.

Self-assembled monolayers



High-resolution STM image of dodecanethiol monolayer on a Au(111) surface. The image size is 40nmx40nm.
Note the hexagonal packing of the individual molecules.

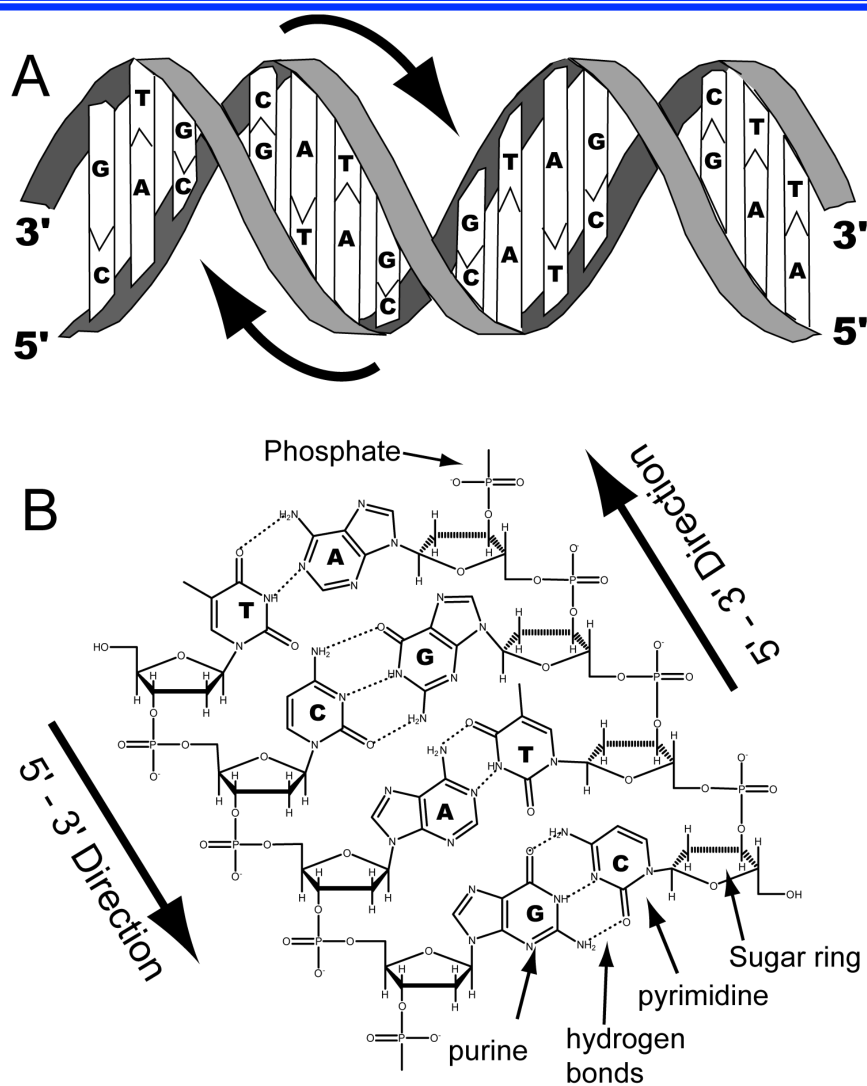
Growth of silicon nanowires



A gold nanoparticle serves as the nucleation site for growth of the nanowire. The gold is heated to a temperature such that when bombarded with Si (by CVD) it forms a Au-Si eutectic (having a lower melting point than either). This results in the growth of a Si nanowire from the base of the nanoparticle.

DNA

DNA Technology

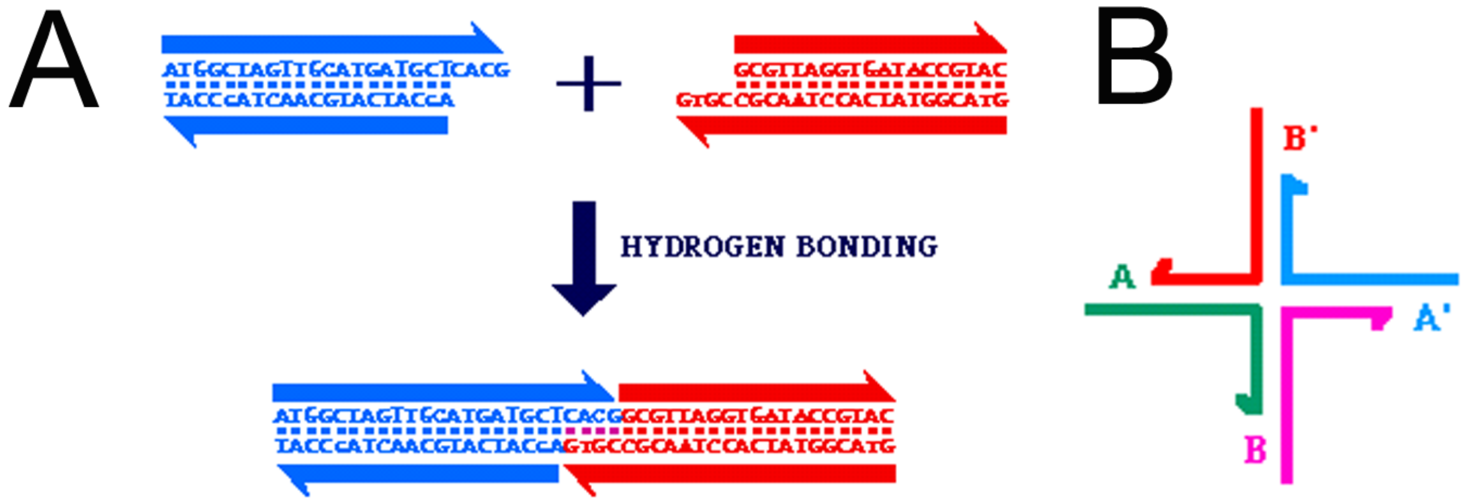


Structure of the DNA double helix.

A) Consists of two phosphate-sugar polymers running in opposite directions coupled by pairs of bases which hydrogen bond together as A-T and C-G precisely filling the gap. Results in a helix with a repeat distance of 3.4nm corresponding to 10 base pairs.

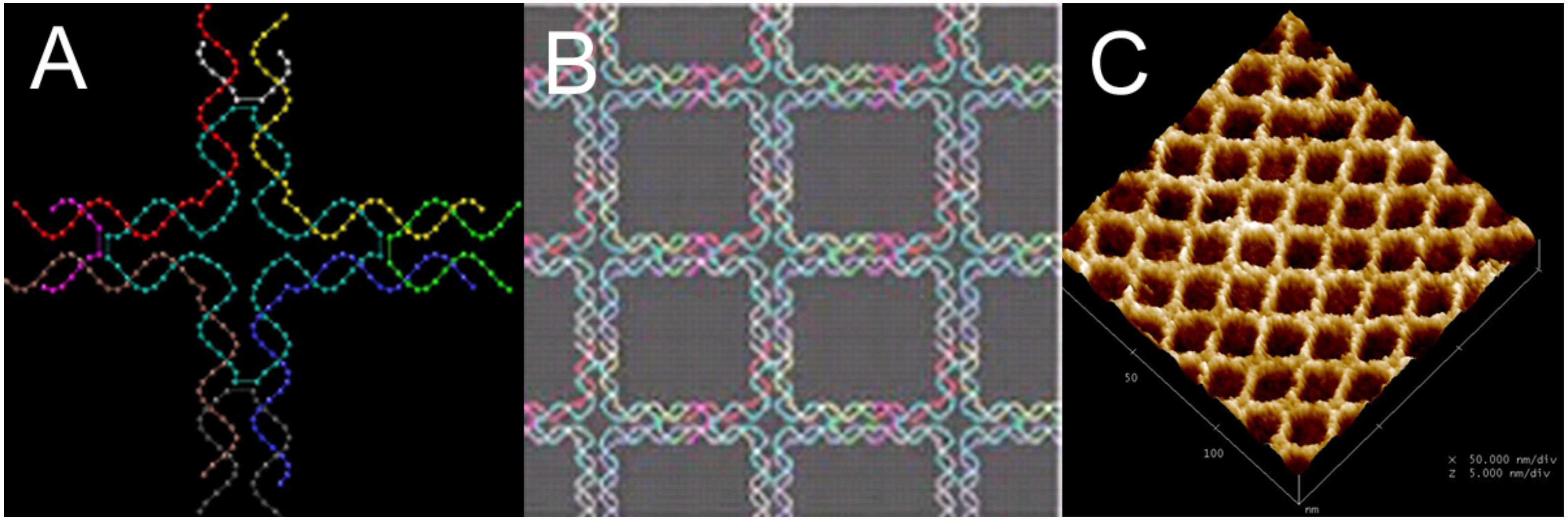
B) Note that Adenine-Thymine has two H-bonds while Gaunine-Cytosine has three.

Structural basis for DNA technology



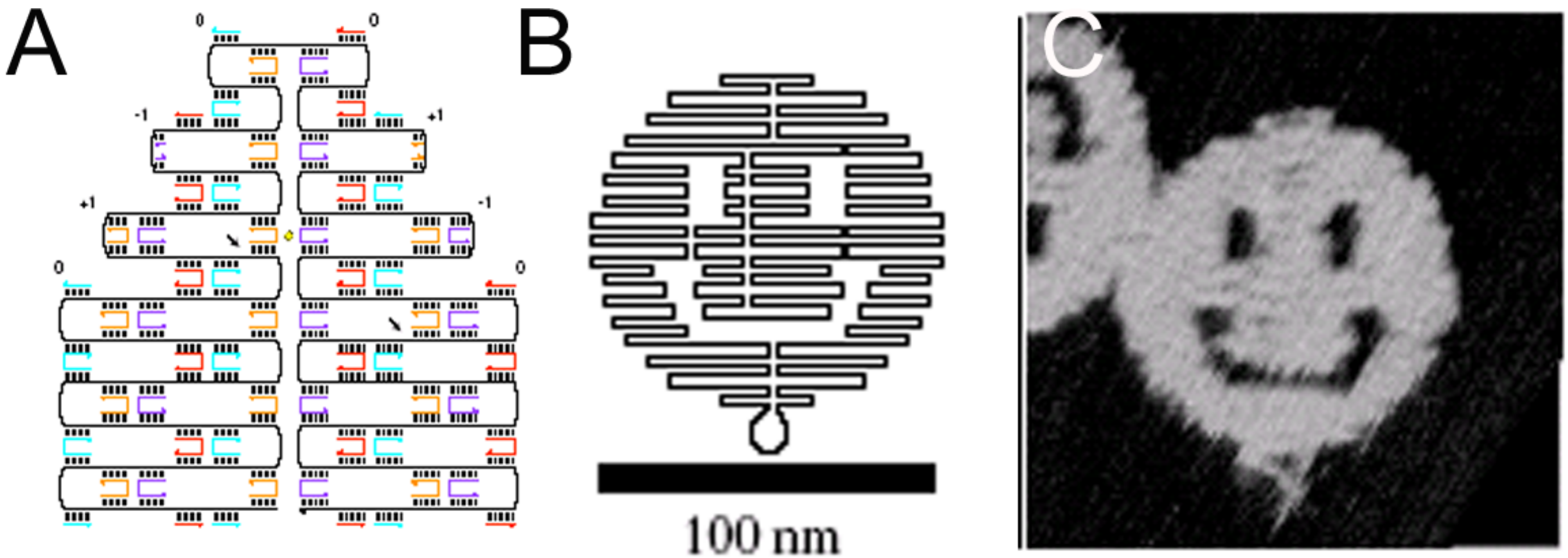
Segment A and B have complementary overhangs allowing them to bond. Using this many geometric structure can be assembled using various combinations of base pairs.

DNA technology



Design of a 4-way crossover structure that results in a rigid planar structure, A. With appropriate end sequences these self-assemble into lattice structure B, having a repeat distance of 20nm. C is an AFM of a such a structure formed by annealing a solution containing the approriate DNA strands.

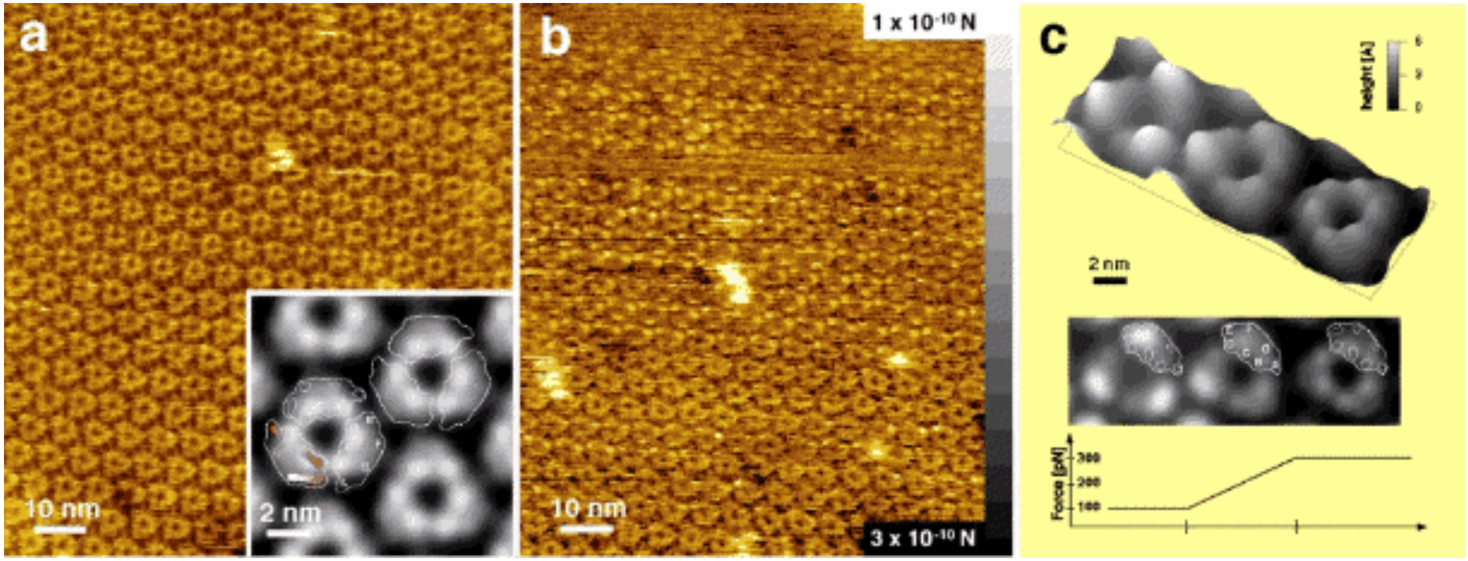
DNA Origami



Design of a more complex structure is illustrated in A. By choosing the appropriate DNA base pair sequence the folding of the chain can be controlled as in B. C illustrates an AFM image of a DNA nanoscale smiley face made using this technique.

Proteins

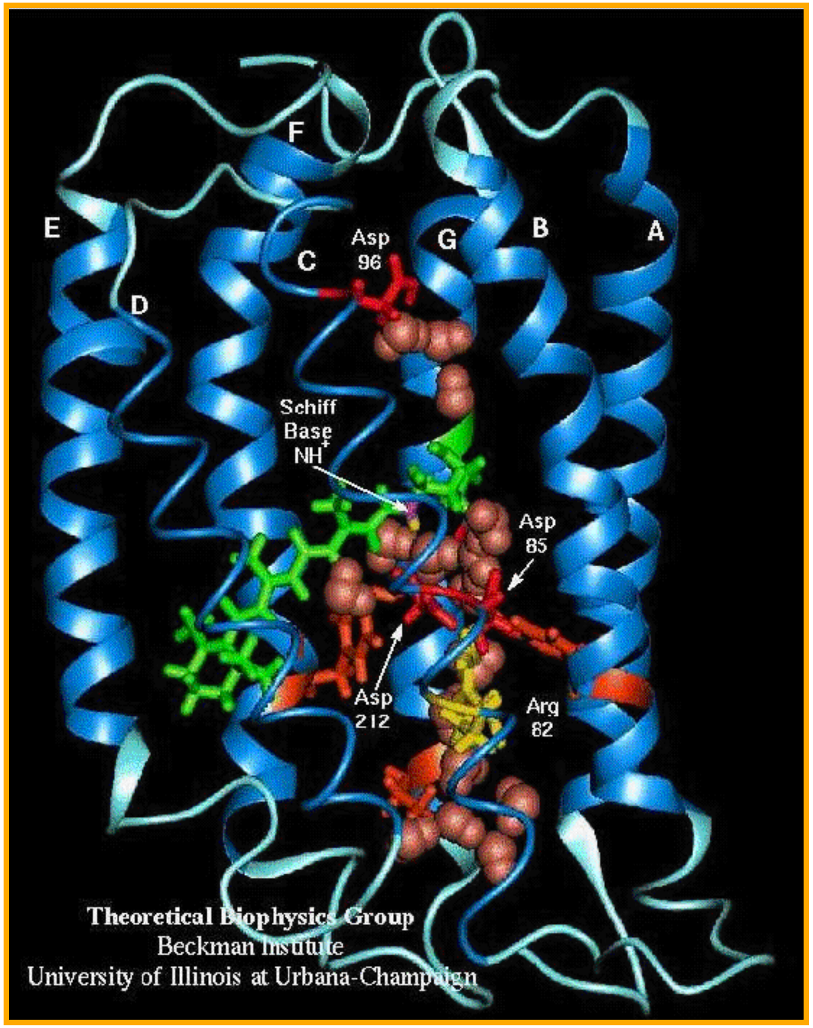
AFM of Bacteriorhodopsin (bR)

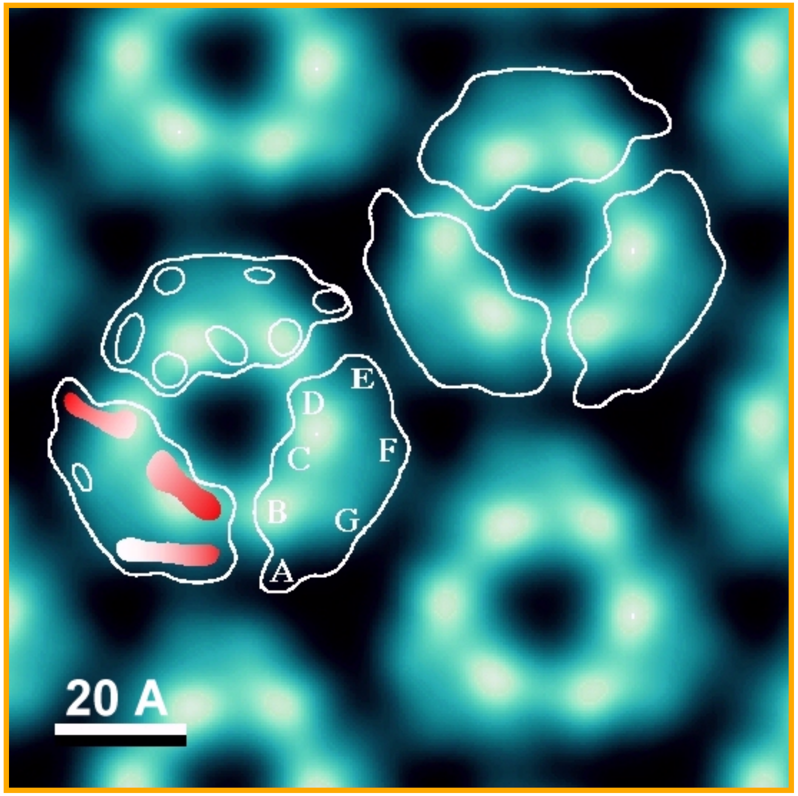


AFM topographs of purple membrane from Halobacterium salinarium. Purple membrane consists of 25% lipids and 75% bacteriorhodopsin. This light driven proton pump comprises 7 transmembrane a-helices which surround the photoactive retinal. (a) Imaged at forces of about 3x10 -10 N two of the three loops connecting the a-helices are visible on the cytoplasmic surface (inset). (b) When the applied force is reduced during imaging (from 3x10 -10 N at the beginning (bottom) to 1x10-10 N at the end (top) of the scan), the proteins undergo a conformational change. (c) The most prominent loop connecting the a-helices E and F is imaged at 1x10 -10 N, but is bent toward the membrane surface at higher forces.

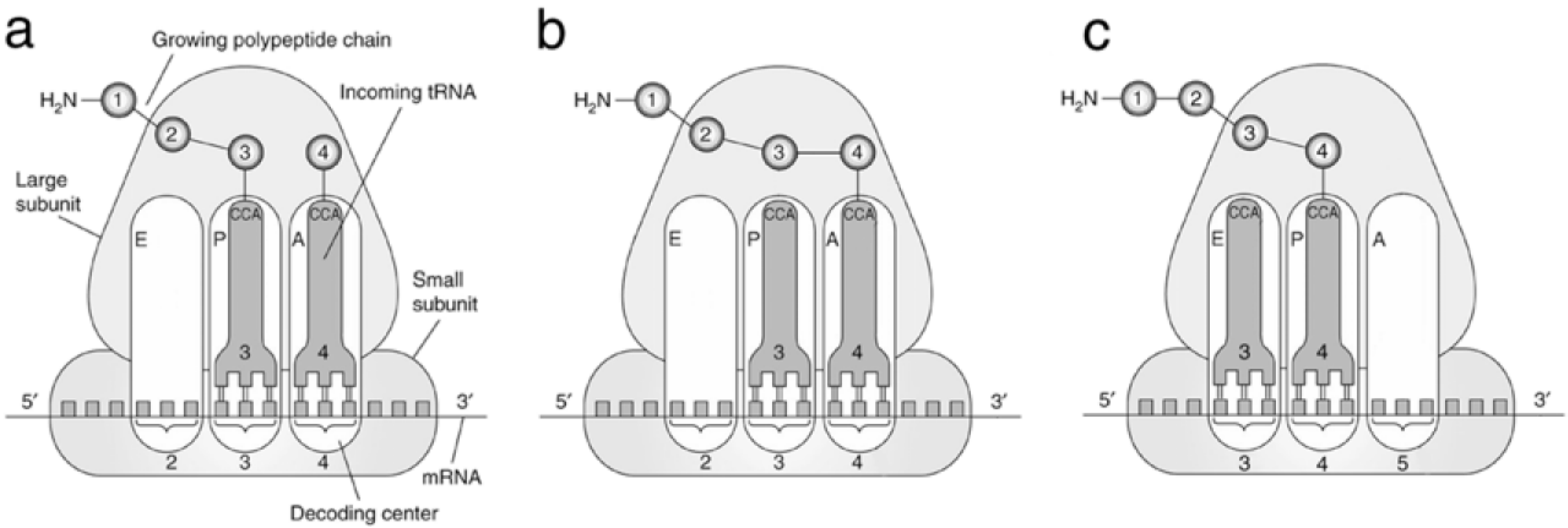
http://www.mih.unibas.ch/Booklet/Booklet96/

Structure of bR



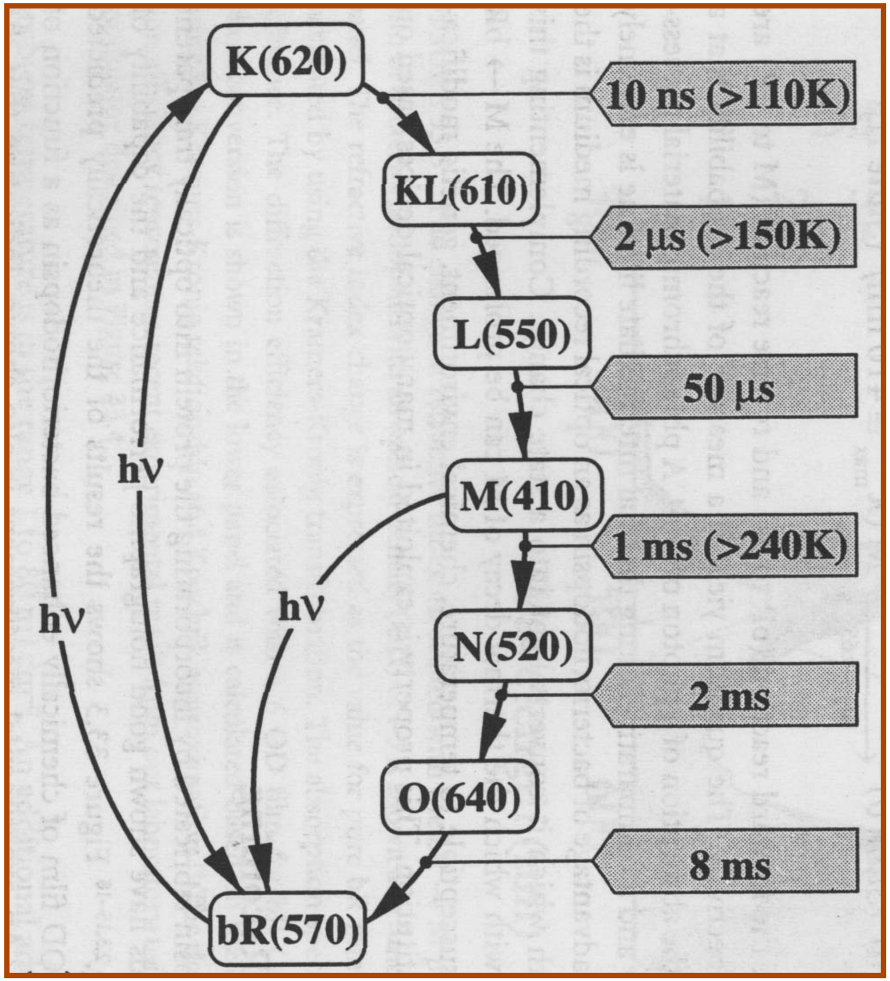


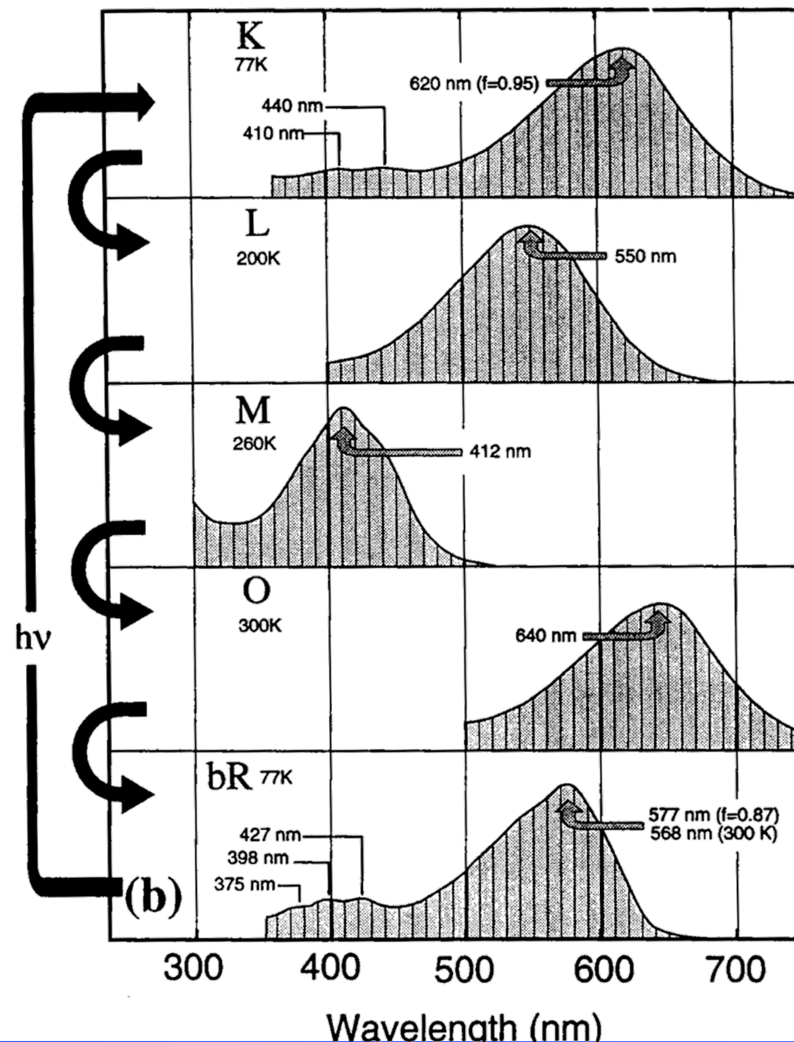
Ribosome



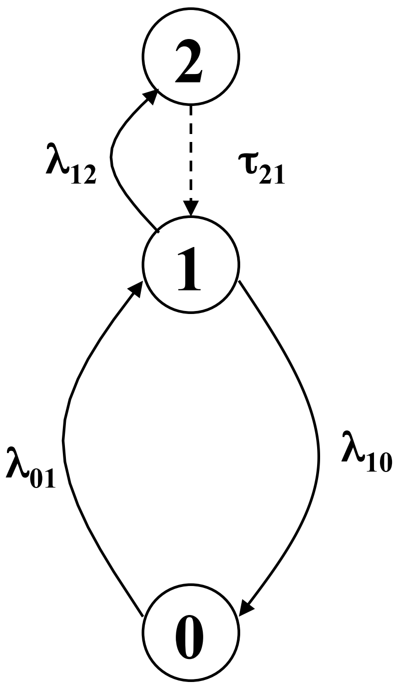
J. Frank1,2,4 & C.M.T. Spahn, Rep. Prog. Phys. **69** 1383 (2006)

Photocycle of bR (sans P-Q)





Idealized 2-D PC Display State Machine



Wavelengths

λ_{01} - write wavelength
- invisible or filtered

λ_{10} - erase wavelength
- invisible or filtered

λ_{12} - display or read wavelength
- visible
- possibly three bands for colour

$\lambda_{01}, \lambda_{10}, \lambda_{12}$ - mutually exclusive wavelengths

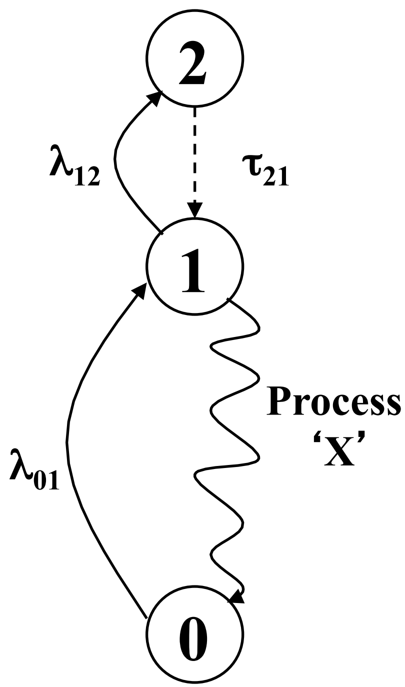
States

0 - stable ground state

1 - stable active state

2 - unstable excited display state
- thermal transition to 1 with time constant τ_{21}

Alternate 2-D PC Display State Machine



Wavelengths

λ_{01} - write wavelength
- invisible or filtered

λ_{12} - display or read wavelength
- visible
- possibly three bands for colour

λ_{01}, λ_{12} - mutually exclusive wavelengths

Process 'X' - non-optical, switchable process which returns all in state 1 to state 0
- could be a negative process

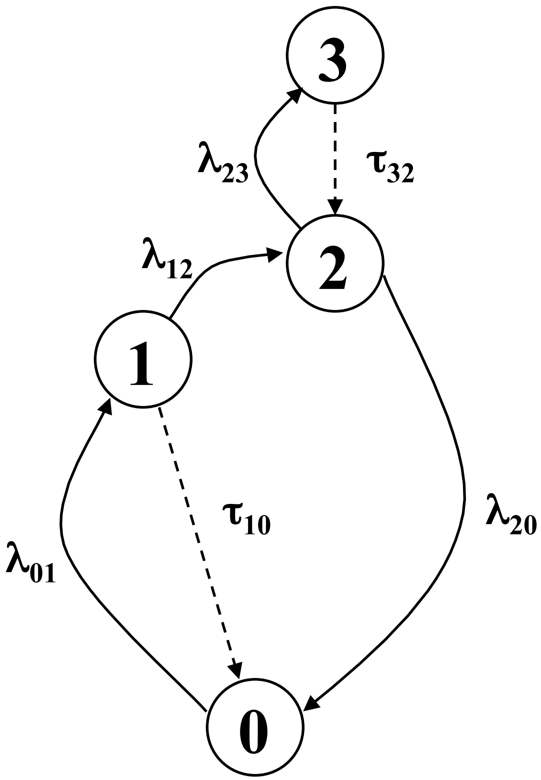
States

0 - stable ground state

1 - stable active state

2 - unstable excited display state
- thermal transition to 1 with time constant τ_{21}

Idealized 3-D PC Display State Machine



Wavelengths

Similar to 2-D version but requires added wavelength to facilitate writing in Z using intersecting beams.

Process 'X' can be used to replace λ_{20} as an alternate erase mechanism.

States

0 - stable ground state

1 - unstable transition state

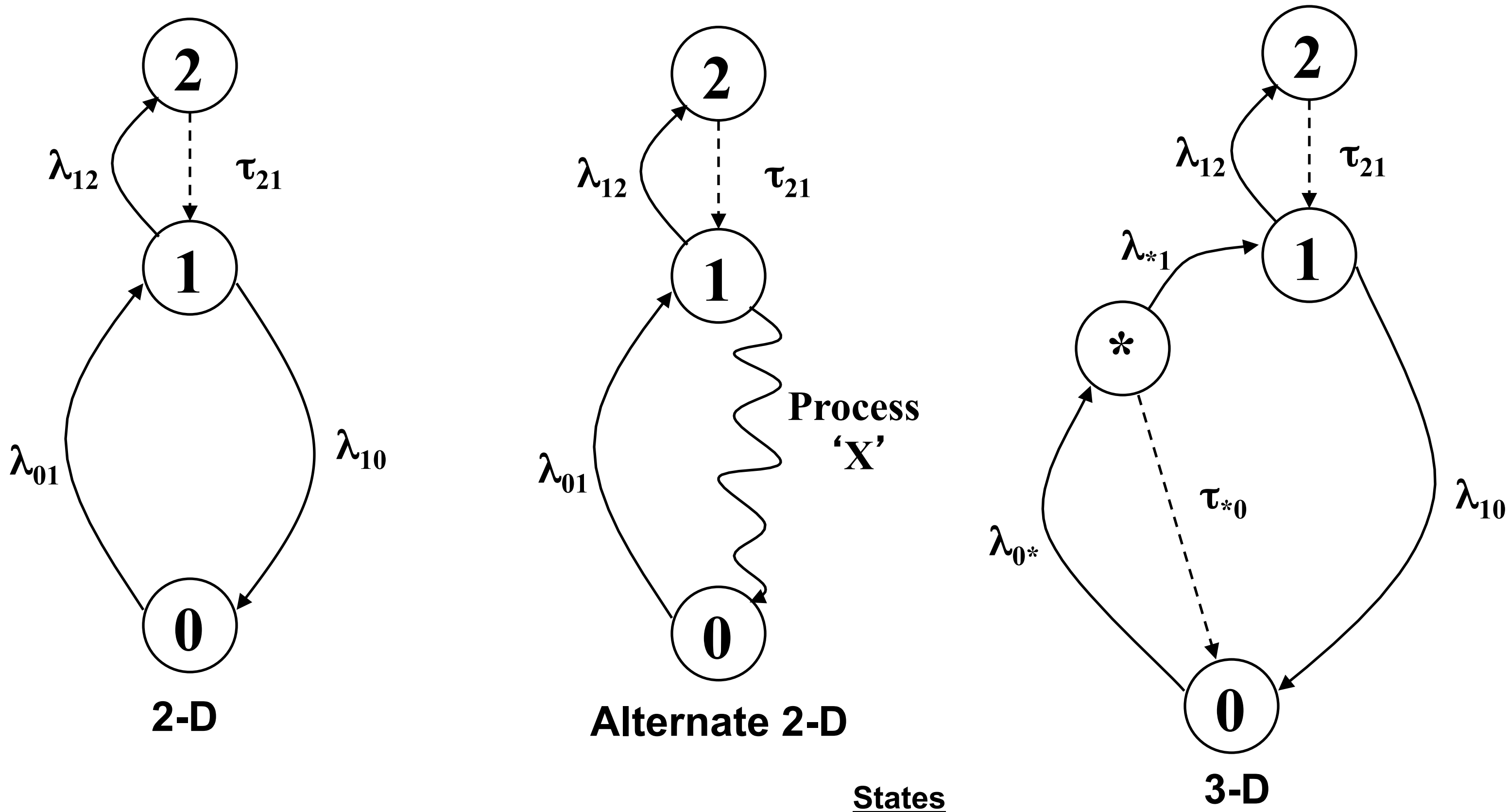
- thermal decay to 1 with time constant τ_{10}

2 - stable active state

3 - unstable excited display state

- thermal decay to 2 with time constant τ_{32}

Possible bR State Machines



Wavelengths

λ_{01}, (λ_{0*}, λ_{*1}) - write wavelength (s)

λ_{10} - erase wavelength

λ_{12} - display or read wavelength

States

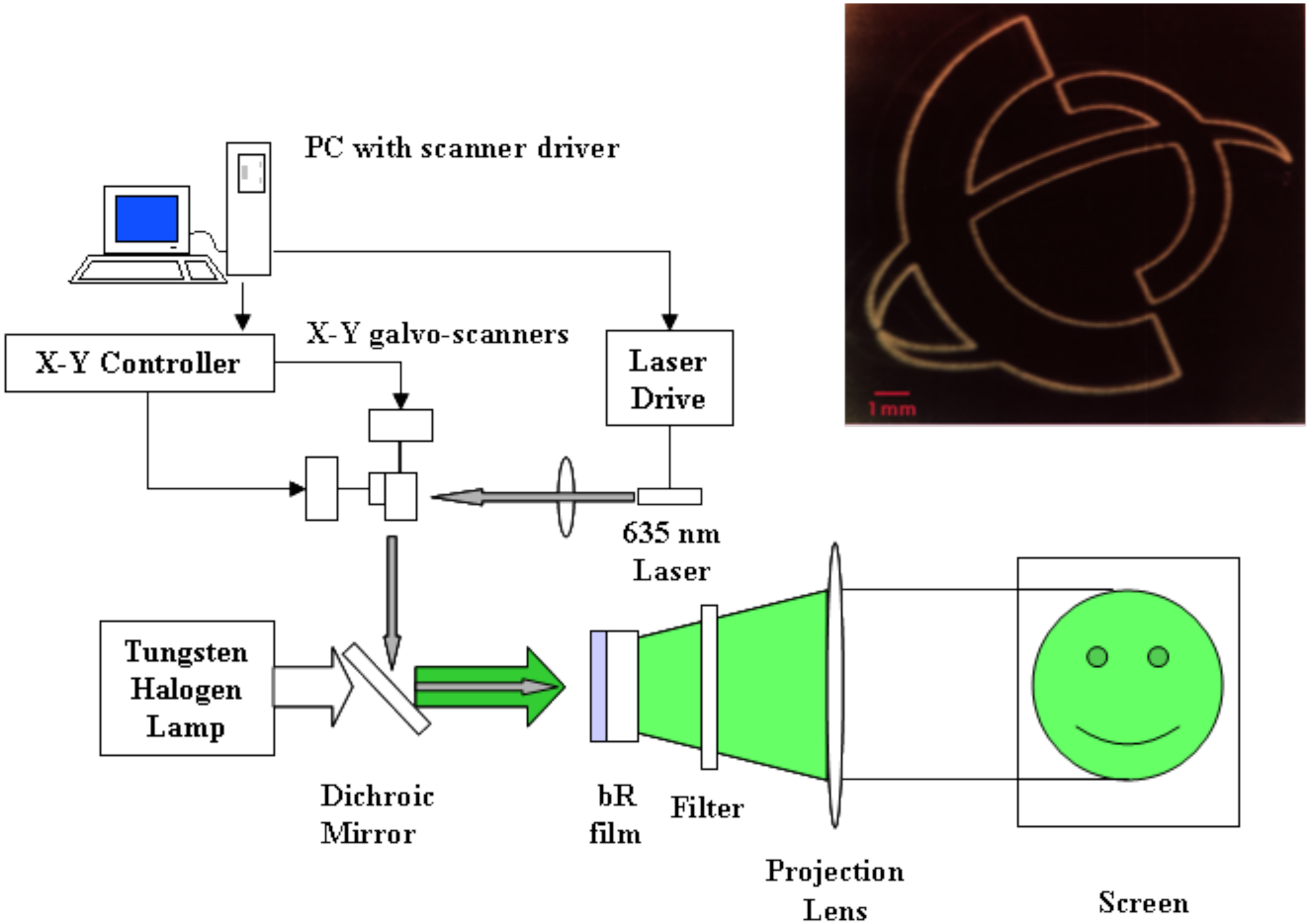
0 - stable ground state

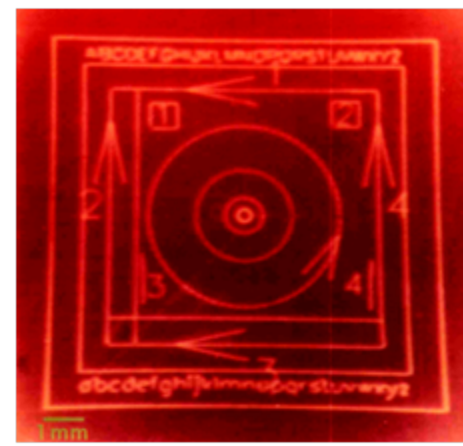
1 - stable active state

2 - unstable excited display state
- thermal transition to 1 with time constant τ_{21}

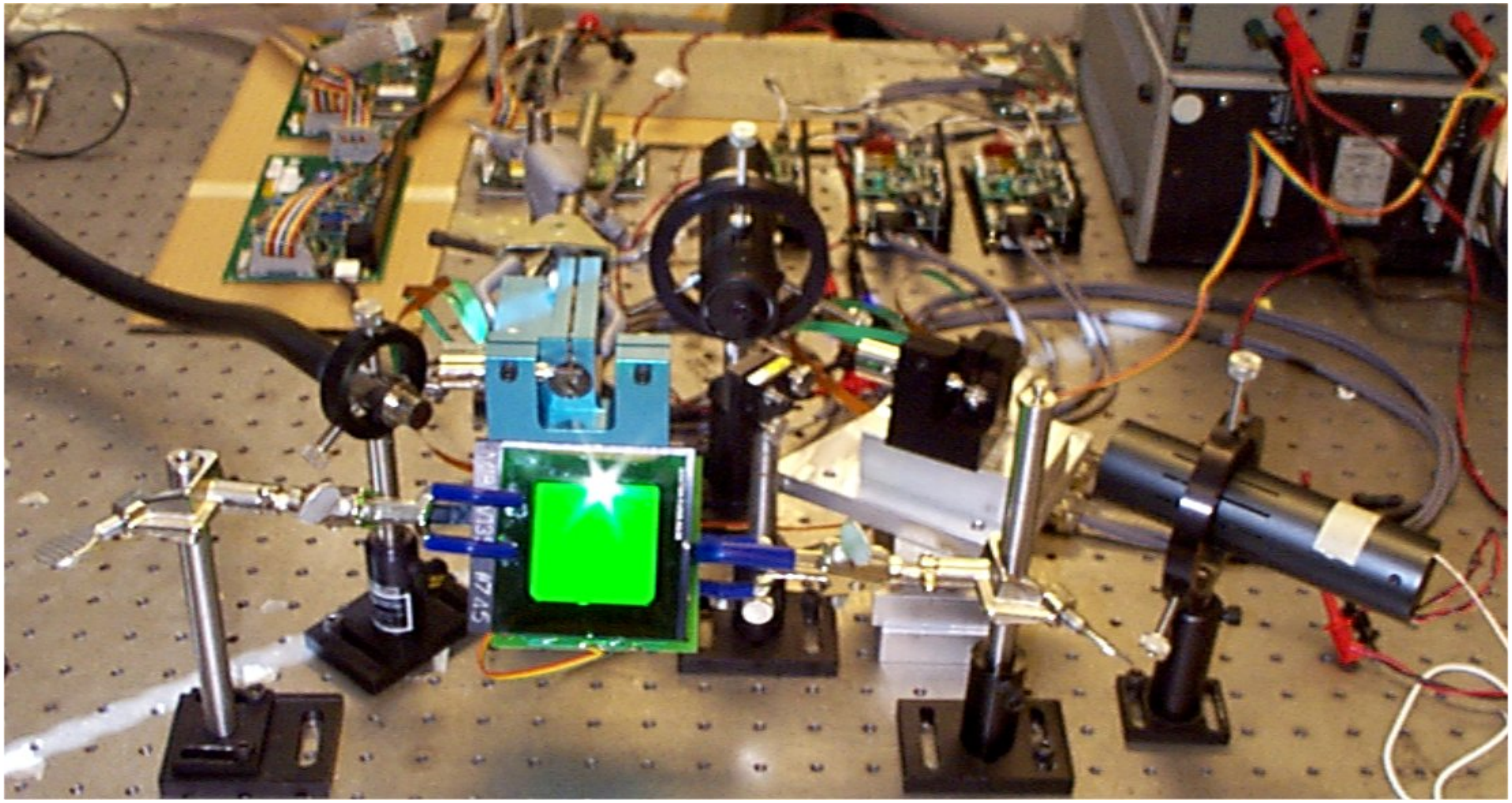
* - unstable mid-write state
- thermal transition to 0 with time constant τ_{*0}

bR Projection Vector Display

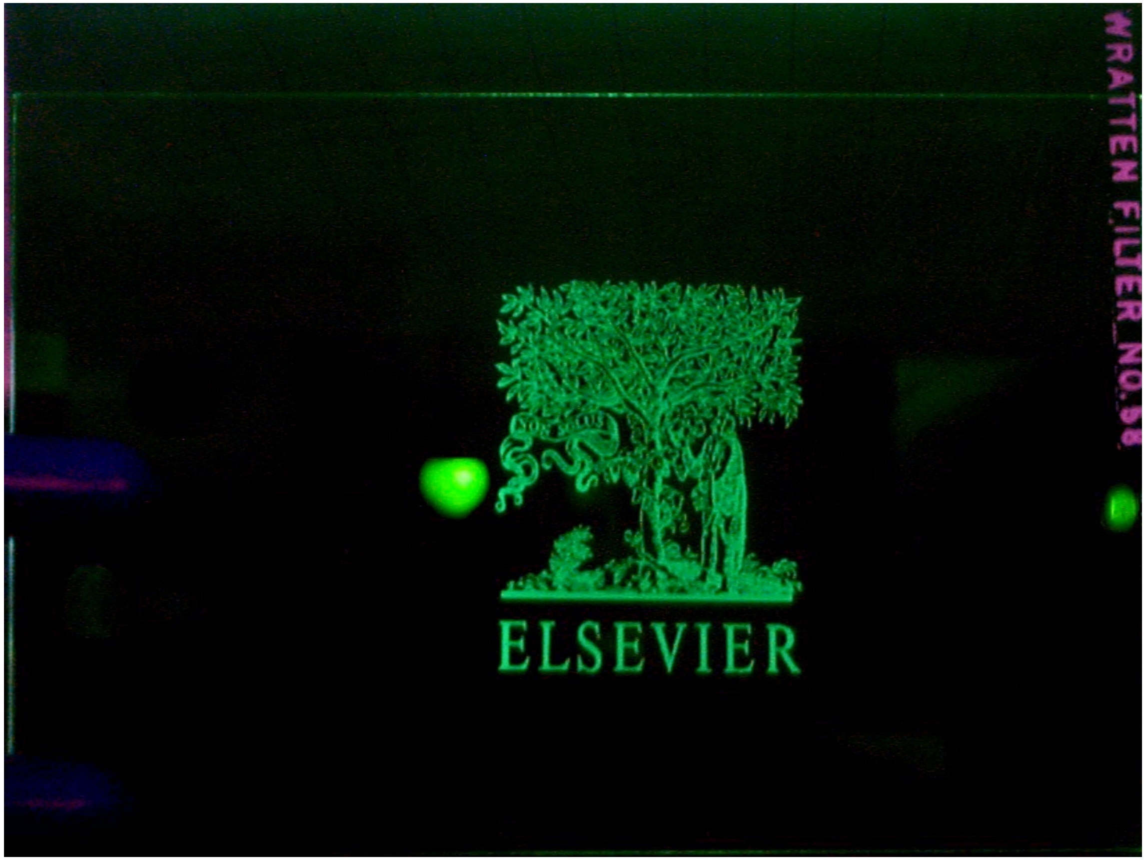




bR Projection Raster Display Setup



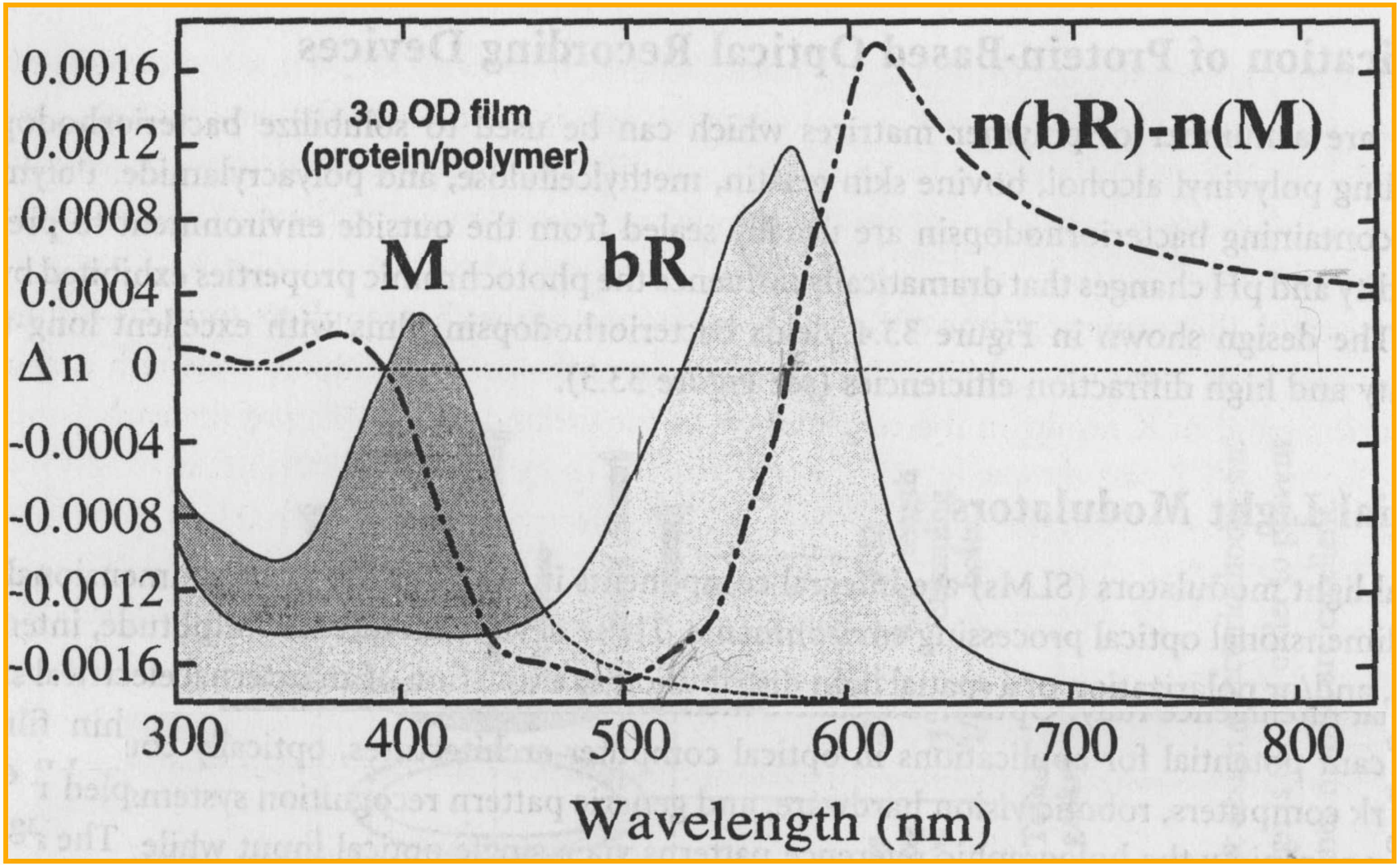
bR Hi-Res Raster Image



Mapping bR onto ideal state machines

- **possible to narrow absorption bands**
  - **both chemically and genetically**
- **significant change is possible in the state positions**
  - **chromophore substitution, chemical or genetic alteration of protein**
- **state lifetimes can be engineered**
  - **proton accessibility, chemical or genetic alterations**
- **possible to change photocycle with field**
  - **very little study to date**
  - **may enable hybrid addressing**
- **ultimate resolution very high**
  - **holographic -> limited by matrix scattering to date**
- **visual properties acceptable**
  - **optical density of 4-6 with dynamic range of >300**
  - **material purity and high clarity matrix required (less so than memories)**

Absorption & Index Spectrum of bR



Adaptive Waveguide Router

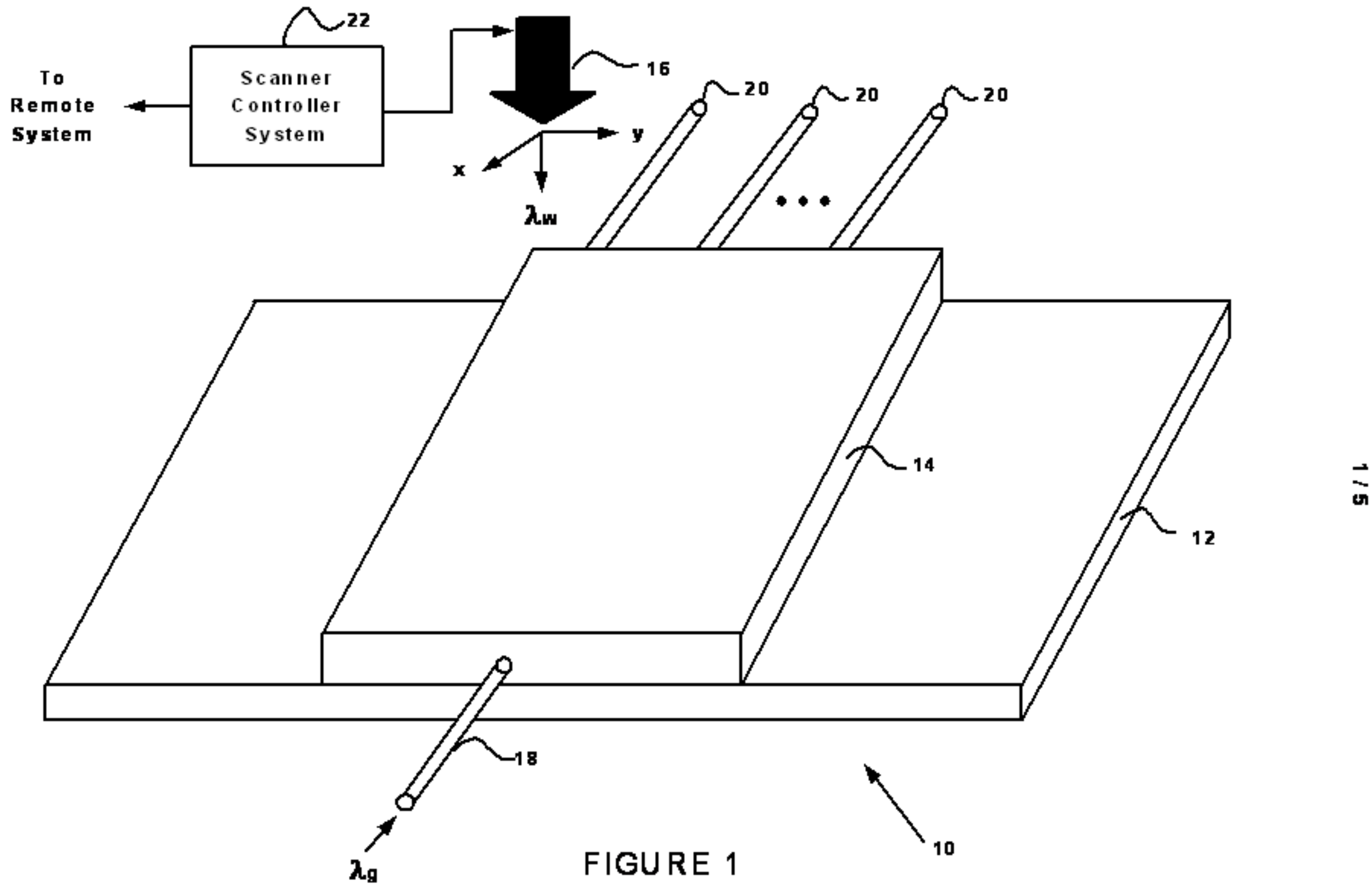


FIGURE 1

Adaptive WG Router – X-section

Activated Core

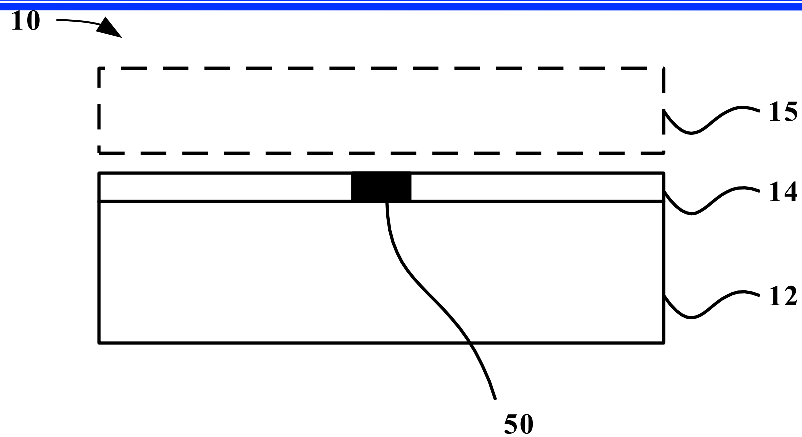


Figure 2A

Activated Clad

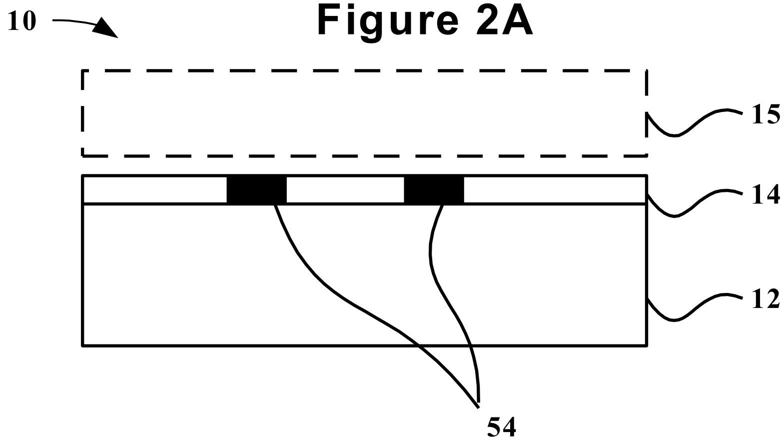


Figure 2B

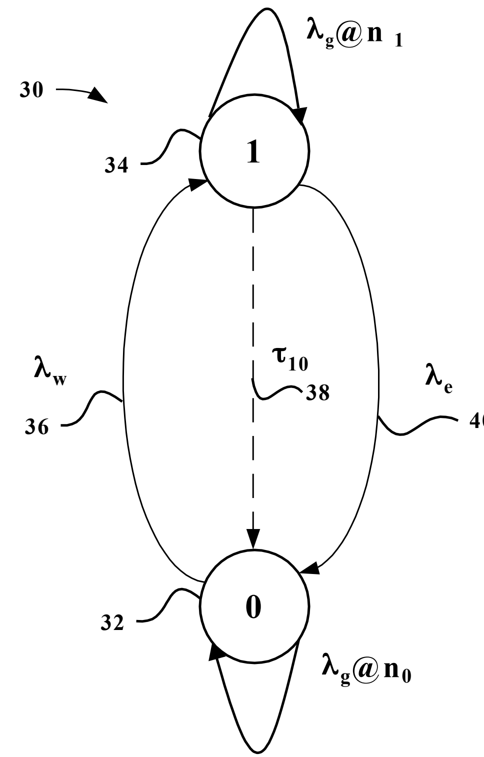


Figure 3