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Directed Assembly of Nanostructures for Nanoelectronics

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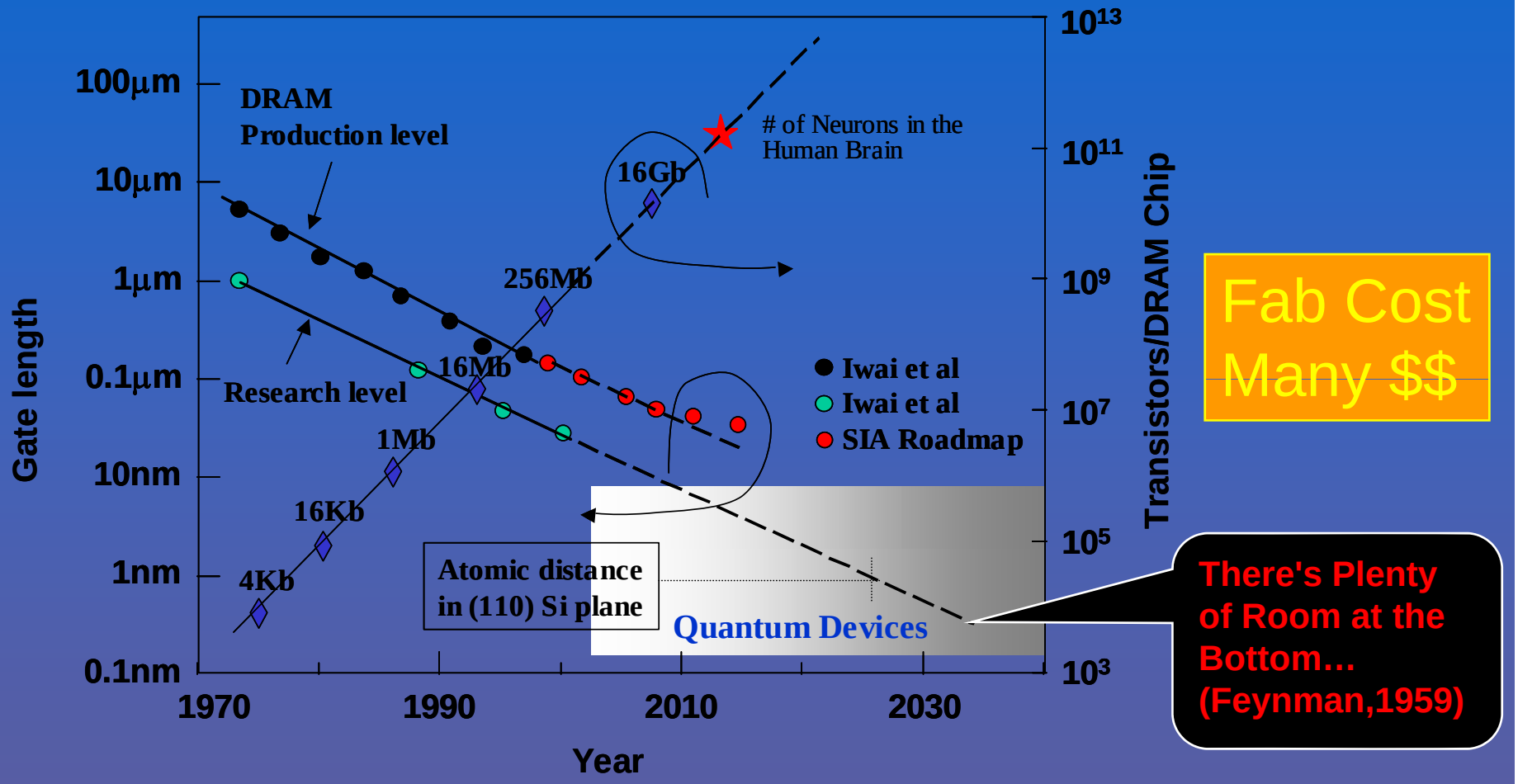
Scaling Trend in Si – Moore's Law



Moore's law: Functionality per cost goes up 2x every 18 months

In 25 years: we will approach the inter-atomic distance

One has to pay for it: Moore's second Law: Every two generations, Fab cost goes up 2x

Challenge: Reaching the physical limit; the excessive cost (what is the future of computing?)

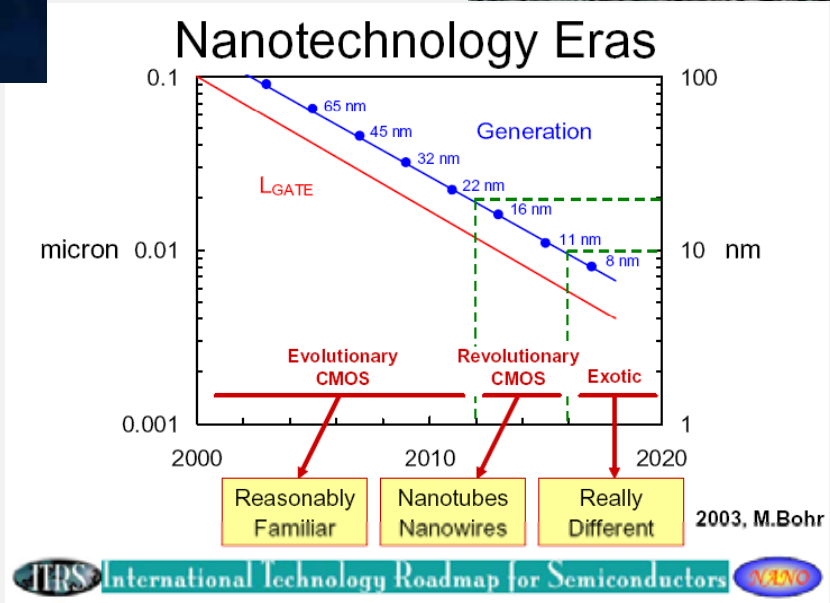
Opportunity: maneuvering and building things bottom-up

Nanopatterning…

- 1959 – Richard Feynman
  – "there´s plenty of room at the bottom"

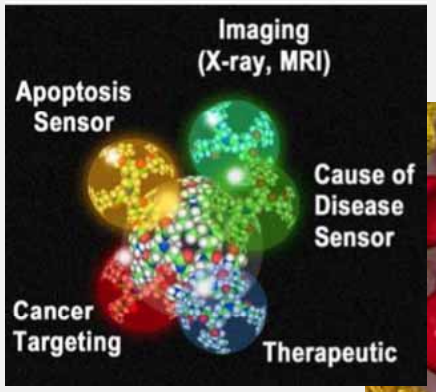
•C^3 in the IC industry

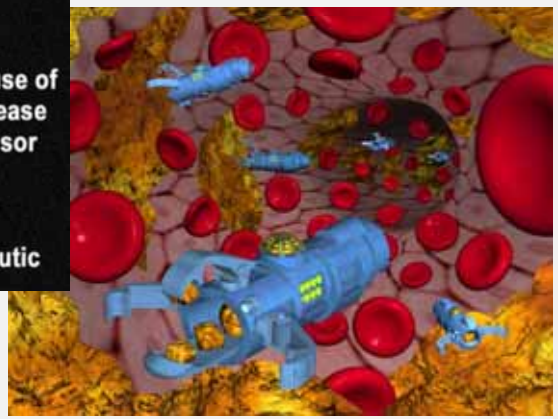
- •Competitiveness
- •Cost Effectiveness
- •Collaboration and Co-development



•D^3 in the Biotech industry

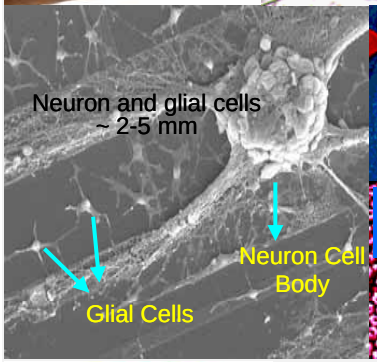
- •Detection of first diseased cell
- •Diagnosis of diseases
- •Delivery of targeted treatment

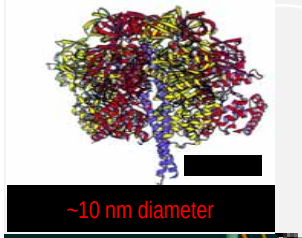


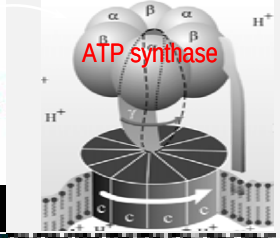


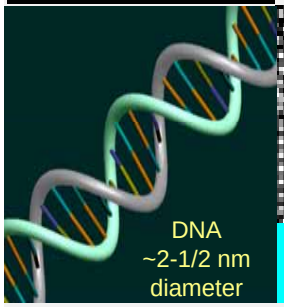
Scale of Natural and Artificial Structures

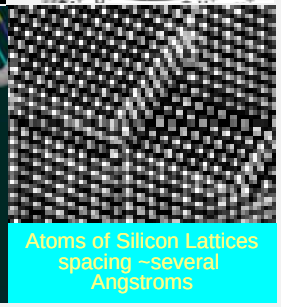
Structures From Nature

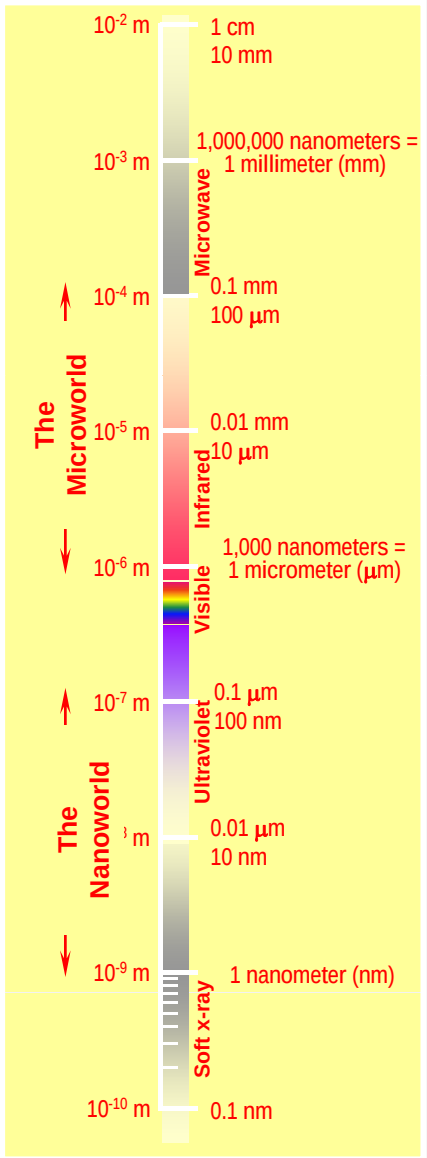




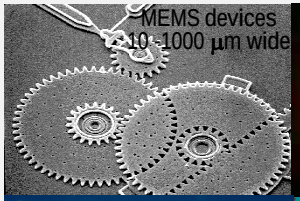


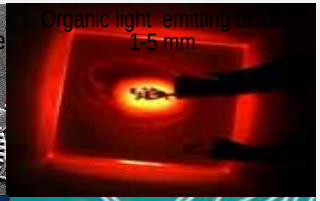


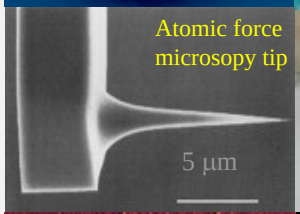


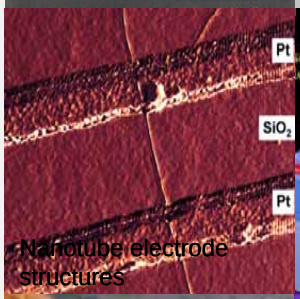


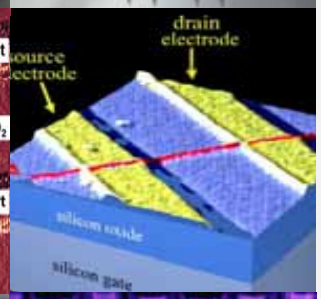
Engineered Micro/Nano Structures

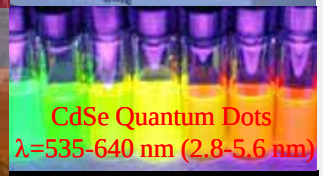


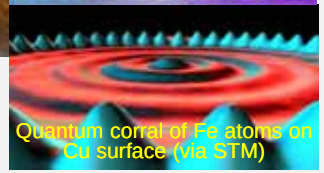




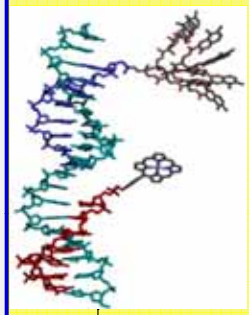


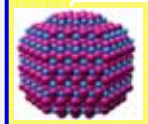






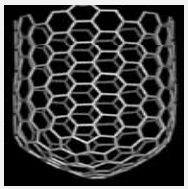
Challenge: 3-D Hierarchical Assembly of Structures (Bottom-up Assembly)



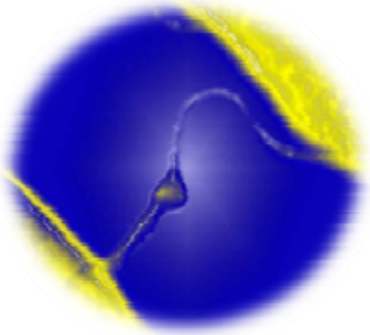


DNA, protein, Nanotubes, Quantum dots

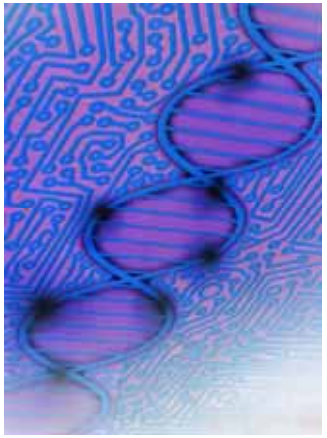
Combine nanoscale building blocks into novel devices and structures

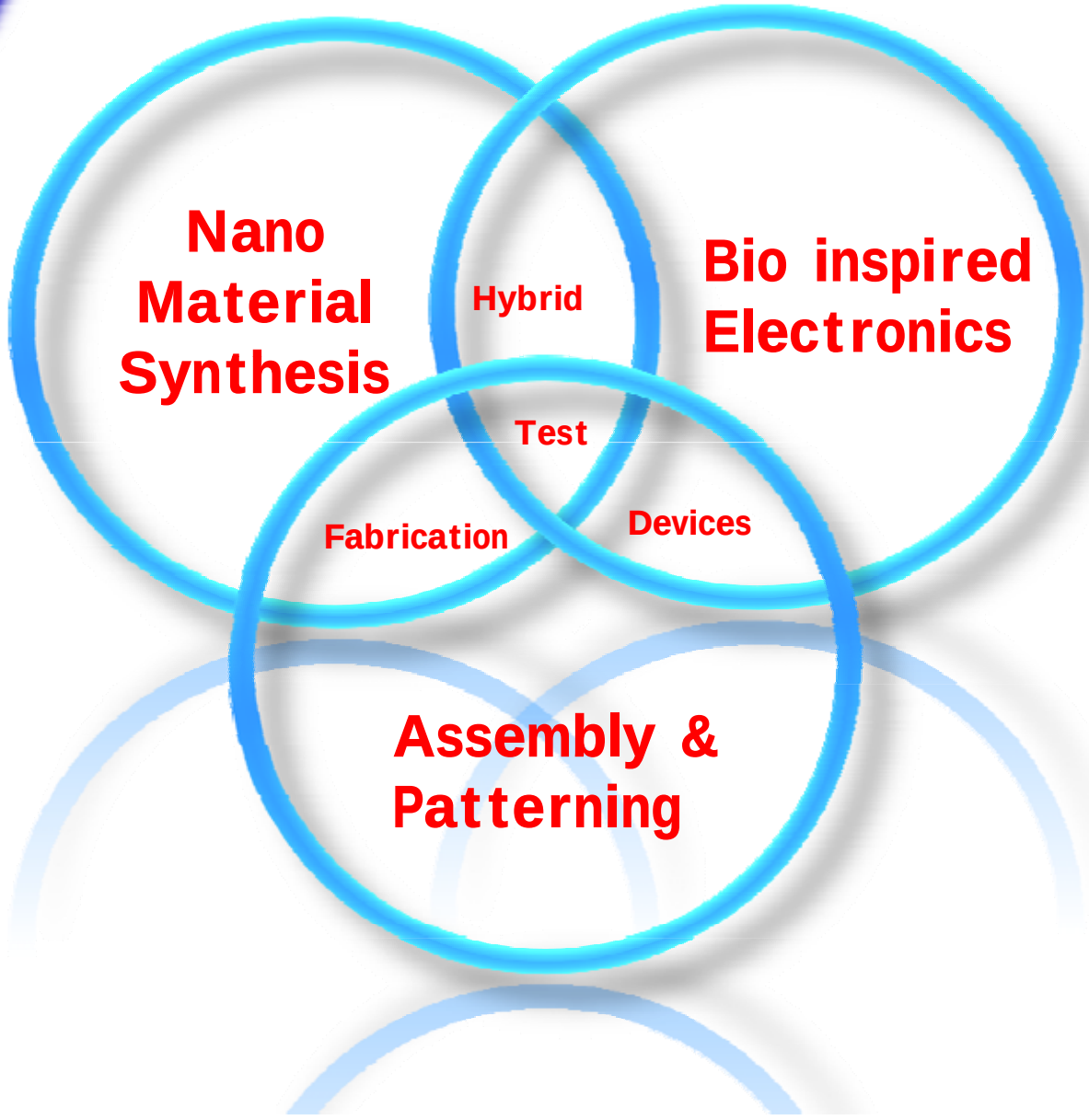


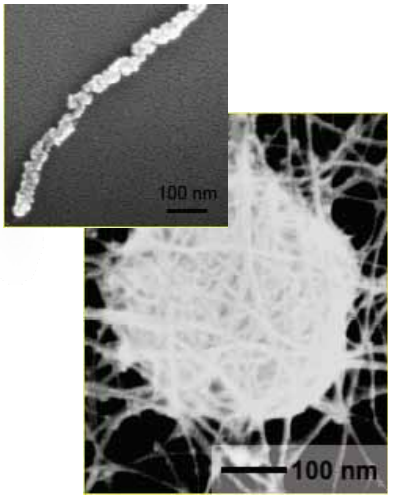
SW Carbon Nanotube
~1-2 nm diameter



Ozkan Research Group



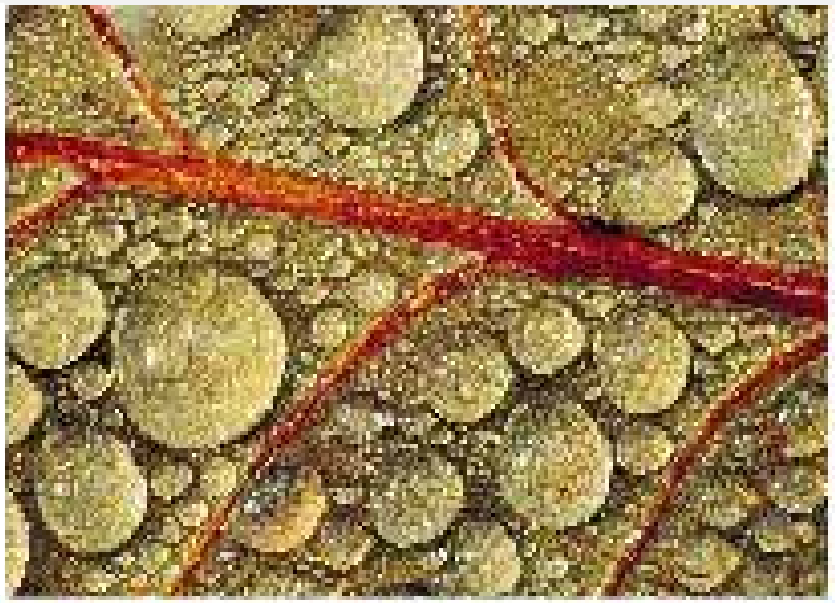




Self Assembly

SELF-assembly involves the spontaneous and autonomous organization of disorganized interacting components into an organized pattern without direct human or mechanical interference.

RAINDROPS on a leaf illustrate thermodynamic self-assembly



The laws of thermodynamics require that a raindrop take the form that maximizes its energetic stability. The smooth, curved shape does so by minimizing the area of the unstable surface.

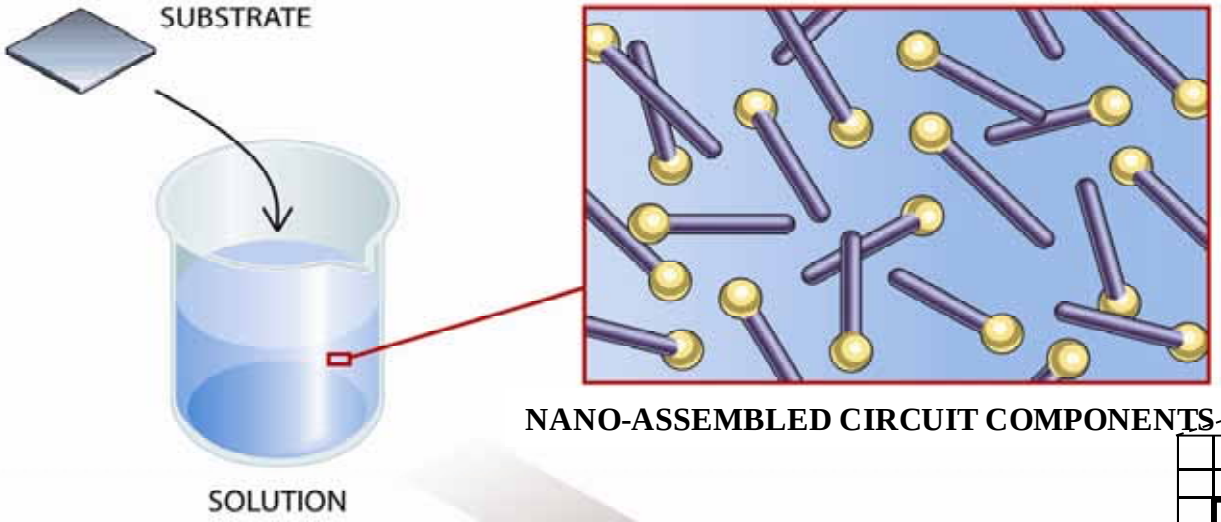
EMBRYO exemplifies coded self-assembly

The kind of self-assembly embodied by life is called coded self-assembly because instructions for the design of the system are built into its components.

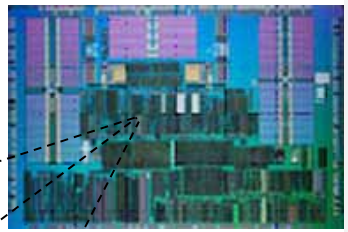
Self Assembly and Intermolecular Forces: Molecular Recognition

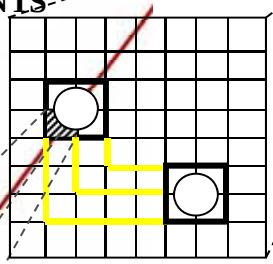
Type of Force	Strength (kJ/mol)	Example
Covalent	>210	C--C bond
Electrostatic	>190	Li^{+}--F^{-}
Dipole-dipole	5-40	H^{+}-Cl^{-}--H^{+}-Cl^{-}
π-π interaction	10-20	CNT--CNT*
Hydrogen bonding	5-40	ssDNA--ssDNA**
Dispersion	<5	H^{+}-$O^{=}$-H^{+}--$Cl^{—}Cl^{+}$
Hydrophobic	5-40	H_2O--Metal
Dative	20-380	S--Au

OUR APPROACH: BOTTOM-UP ASSEMBLY

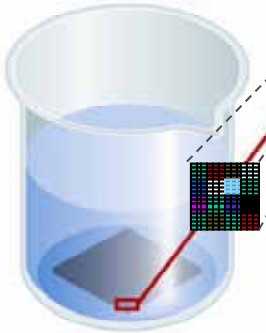


NANO-ASSEMBLED CIRCUIT COMPONENTS



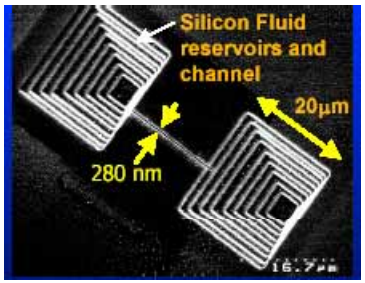


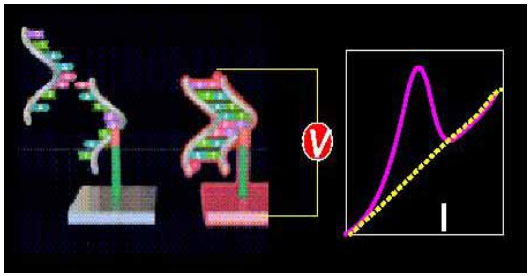
A circuit block

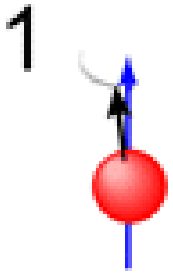


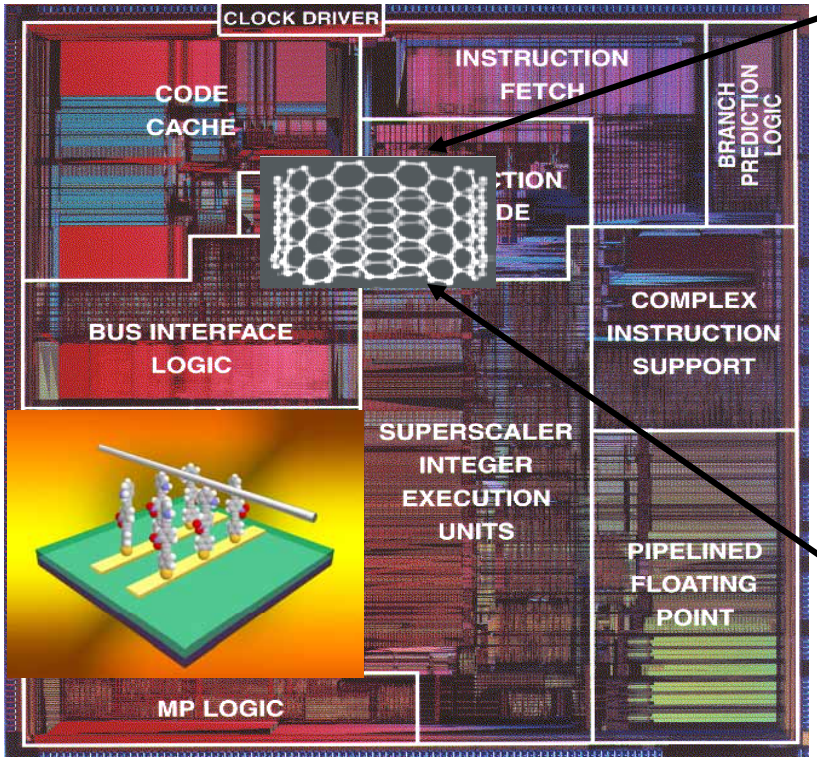
- **SYNTHESIS OF CIRCUIT BUILDING BLOCKS**
- **DROP-IN ONTO EXISTING TECHNOLOGY**

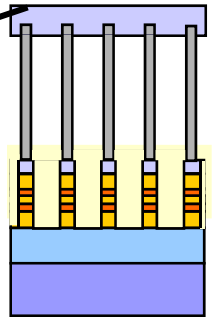
Heterogeneous Integration by Self Assembly

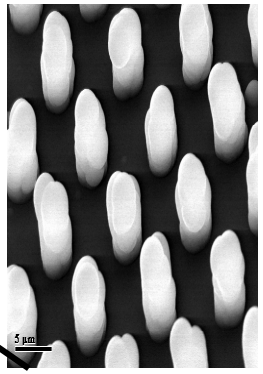


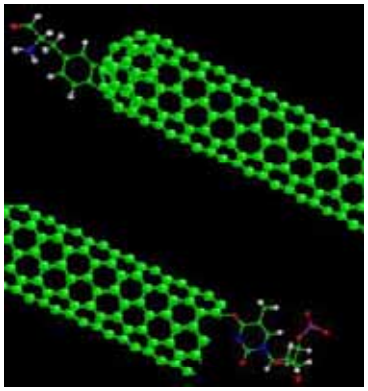












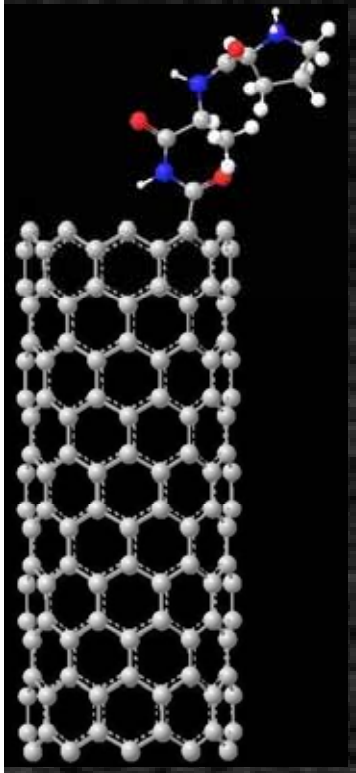
- Drop-in technology
- Biomolecules, nanowires, nanotubes
- Built into back-end processing
- Massively parallel integration?
- Compatibility issues?

A new paradigm for synthesizing devices and integrated circuits

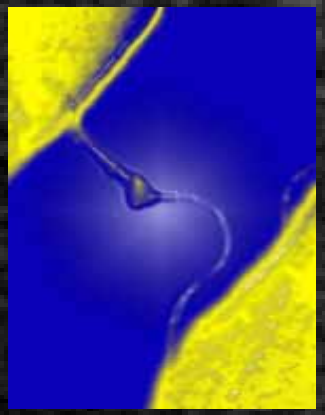
Biological assembly of Devices

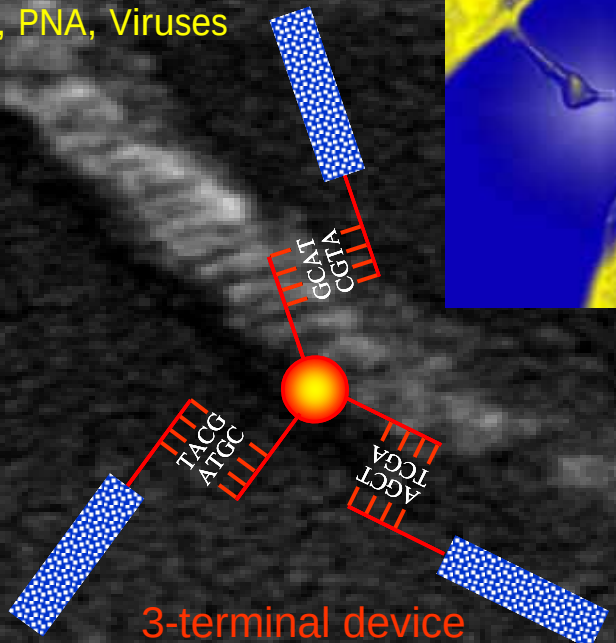
Nanocrystals, carbon nanotubes, nanowires

Linkers: Peptides, DNA, PNA, Viruses

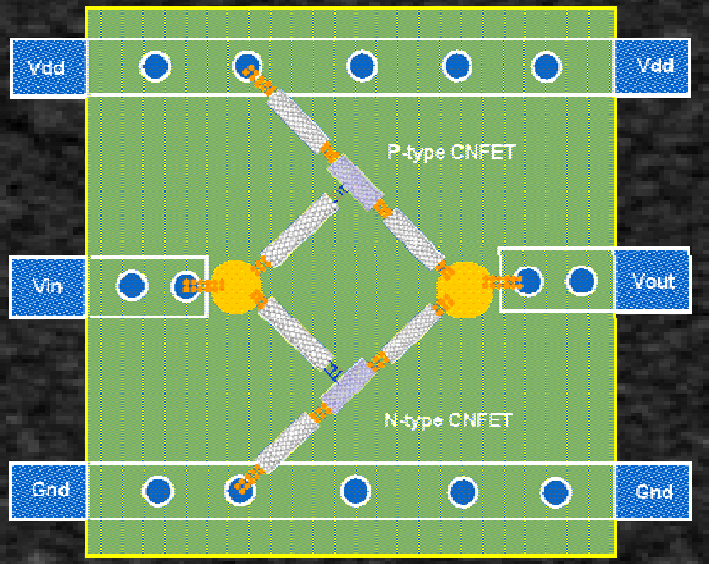


CNT-peptide complex

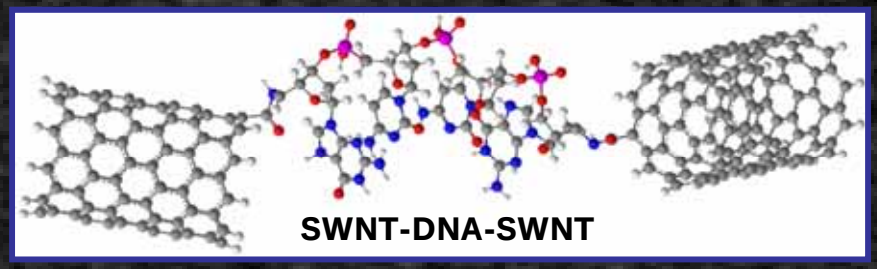




3-terminal device



Synthesized inverter structure



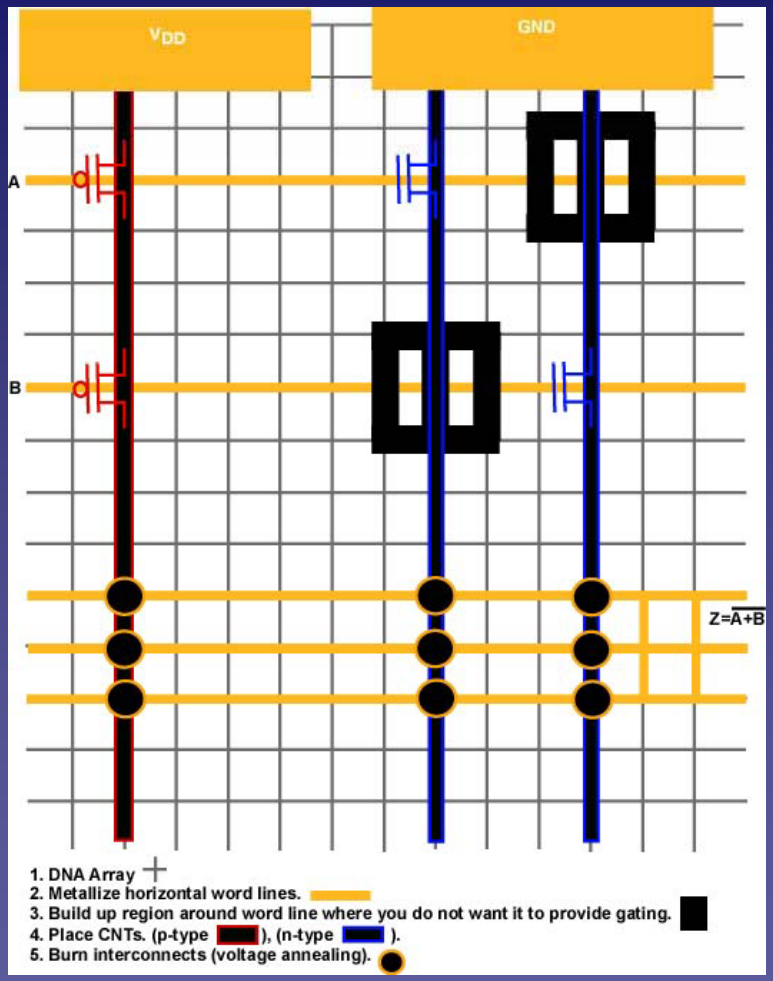
2-terminal device: Resonant tunneling diode

Nano Letters (2003)
Carbon (2004)
Carbon (2006)
PSS (2006)
JNO (2006)
Small (2006)
nature nanotechnology (2006)
JNO (2007)
JNO (2008)

Our vision

Cross-bar logic circuit on a DNA array

- **Map bio-assembly onto a cross-bar architecture**
- **Gray grid represents DNA array.**
- **Gold is metallized DNA providing gating and contacts**
- **2D topology**



Layout of cross-bar NOR gate bio-assembled on DNA tile array

JNO (2006)

Other recent work…

A. Dehon, *ACM J. on Emerging Technologies in Computing Systems*, **1**, 109 (2005)

G. Snider, P. Kuekes, and R. S. Williams, *Nanotechnology*, **15**, 881 (2004)

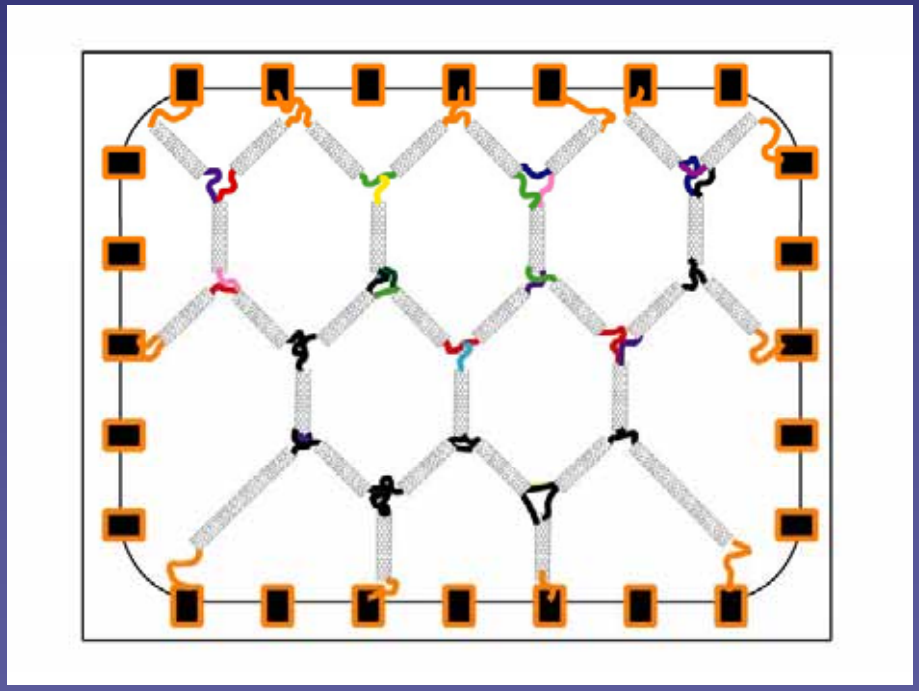
R. Beckman, E. Johnston-Halperin, Y. Luo, J. E. Green, and J. R. Heath, *Science*, **310**, 465 (2005)

C. Dwyer, V. Johri, M. Cheung, J. Patwardhan, A. Lebeck, and D. Sorin, *Nanotechnology*, **15**, 1240 (2004)

Our vision

CNT-Mol RTD Array

- **Cellular automata type architecture.**
- **2D array of non-linear elements**



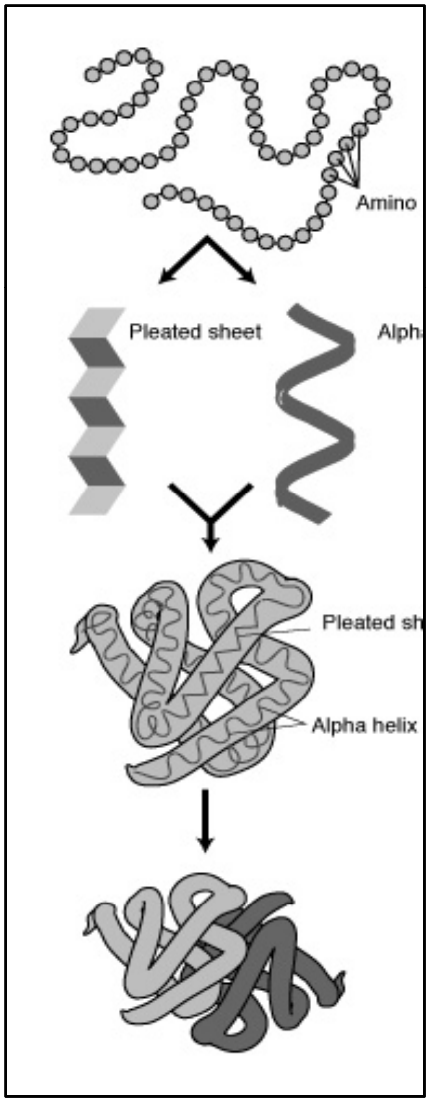
2D CNT-Mol RTD network to implement a cellular automata-type architecture

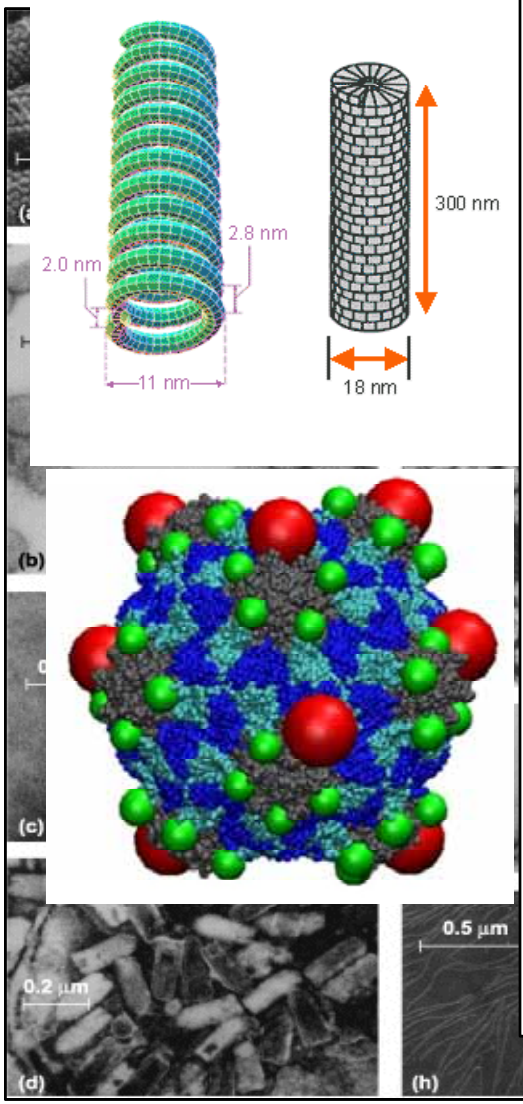
Design Considerations

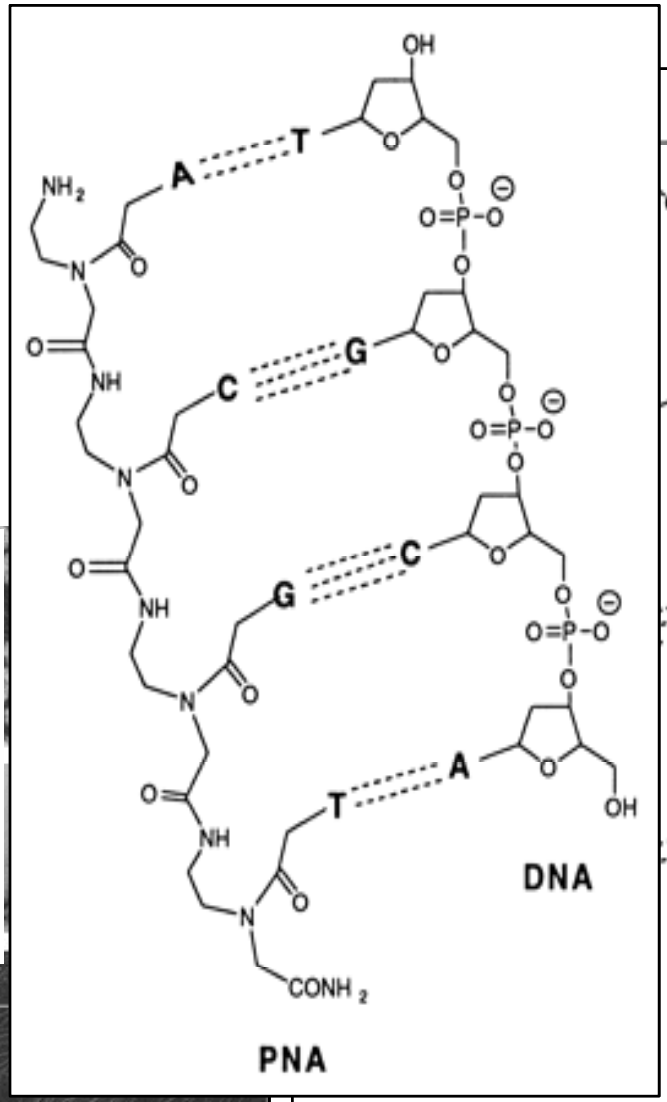
- What linkers to be used?
- How and where to start assembly process?
- What templates to use?
- How to solve poor conductivity between the components within the assembly?
- How to integrate to existing device platforms?

What linkers to use: Biological Linker Archive

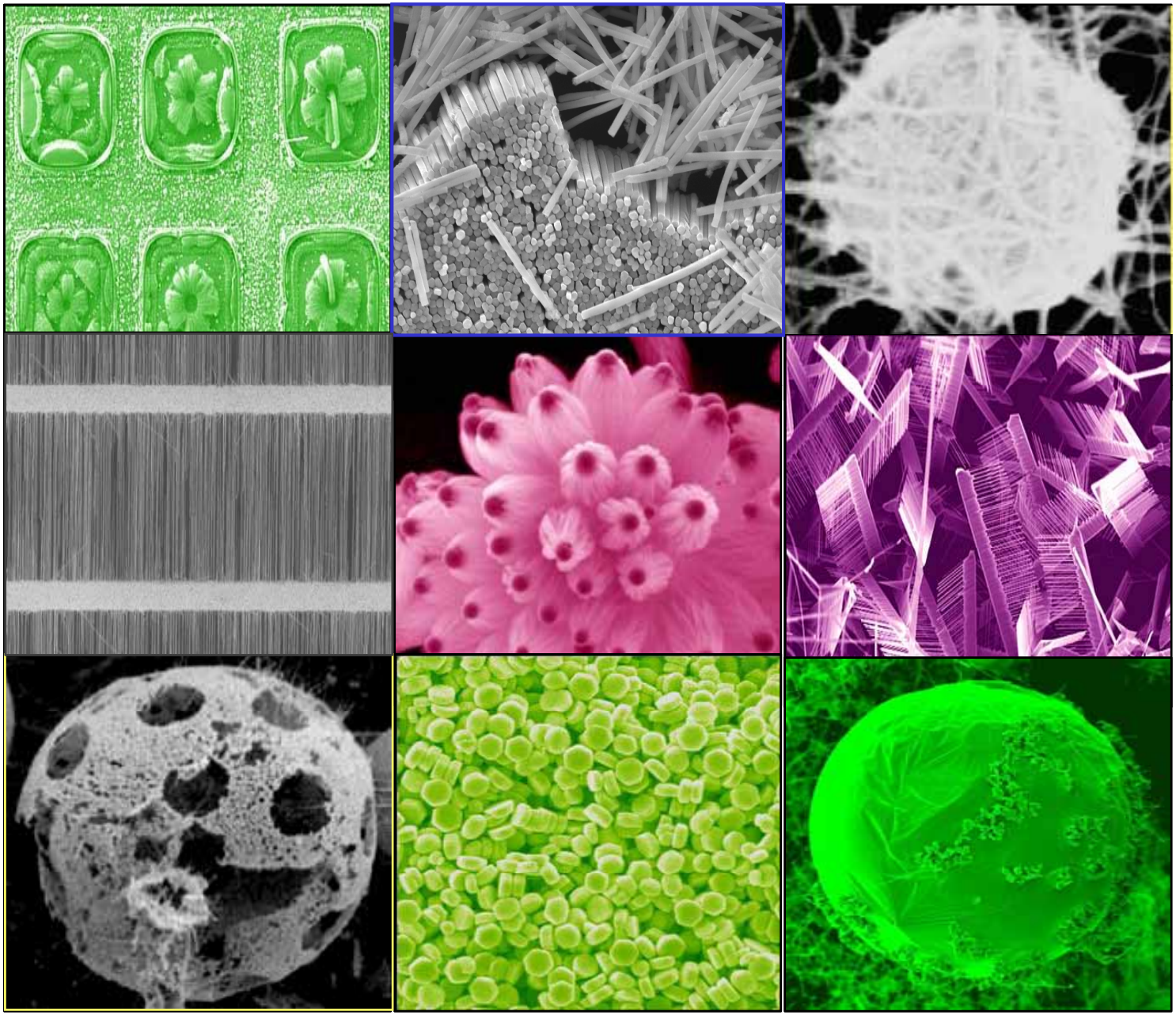
- Protein: amino acids
- Virus: (a) Adenovirus (b) Rotavirus (c) Influenza virus (d) Vesicular stomatitis virus (e) Tobacco mosaic virus (f) Alfalfa mosaic virus (g) T4 bacteriophage (h) M13 bacteriophage
- Nucleic Acid: DNA, RNA, PNA*







Nanowires, Nanotubes, Combs, Spheres….

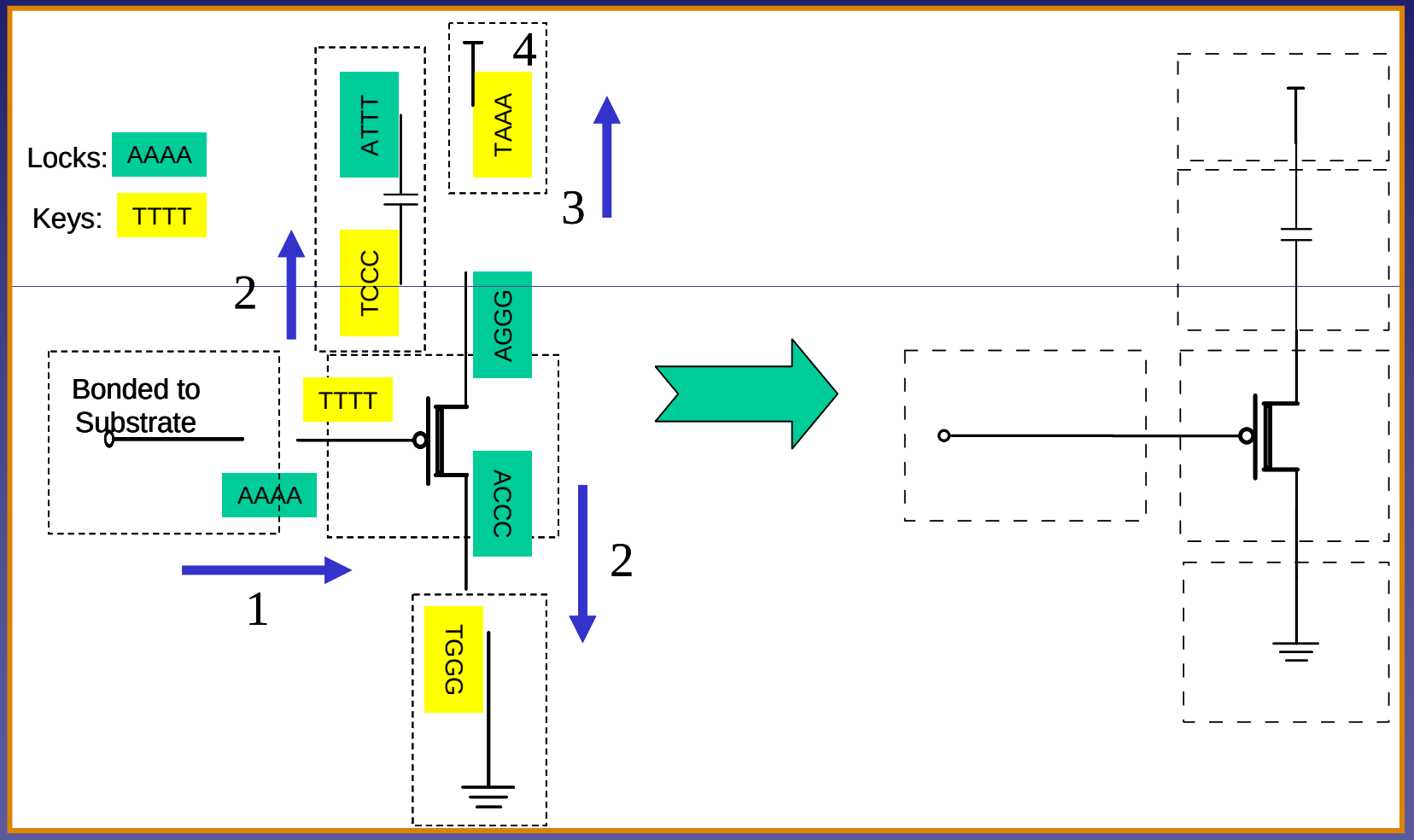


Biological self assembly of carbon nanotubes

- **Biological Linkers (e.g. DNA, PNA, Streptavidin)**
  - **Specificity – unique labeling of CNTs for assembly on conventional substrates**
  - **Insulators for engineering purposes**
  - **Metallization for conducting interconnects**
    - **Demonstrated with Pd, Pt, Ni, Cu, Au, Ag**

Nanotechnology 2006, Small 2006, Carbon 2007

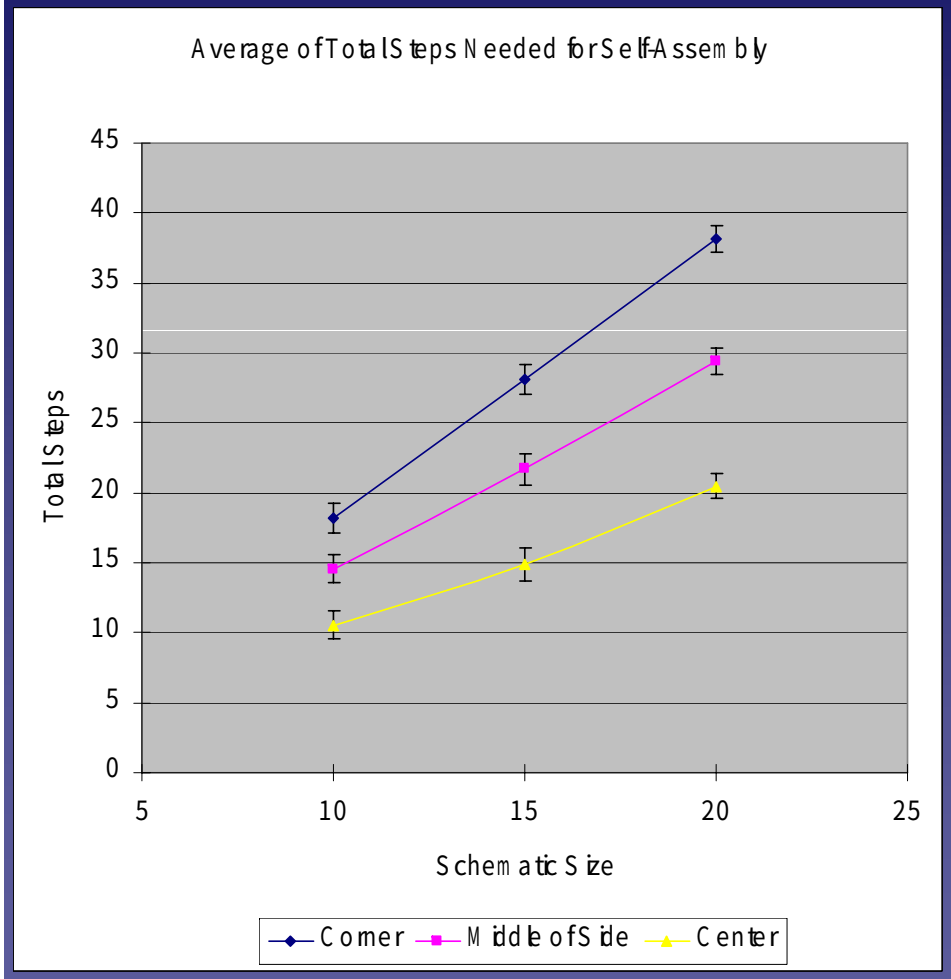
Where and How to Start Assembly: Lock and Key Lithography™ assembly of nanostructures

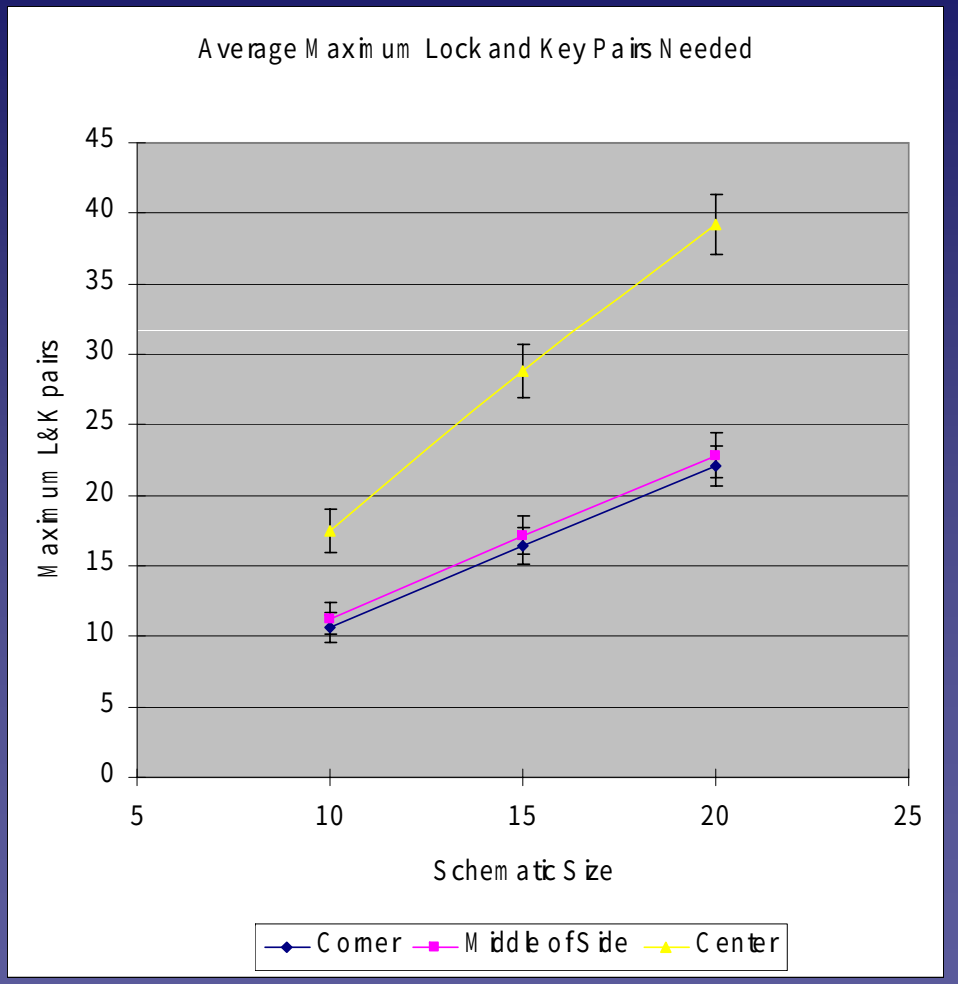


Collaboration with J. Hartley (University of Albany) and M. Ozkan (UCR)

TECHCON, 2007 Austin, TX
NIST, 2007, Gaithersburg, Maryland

Where and How to Start Assembly: Lock and Key Lithography™ assembly of nanostructures





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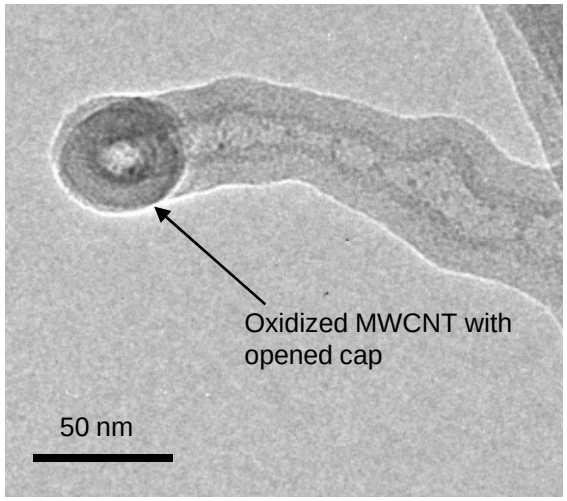
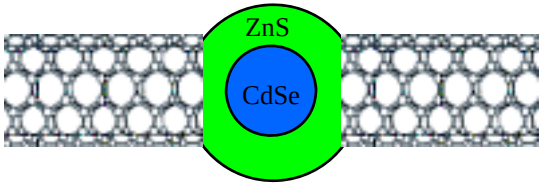
TECHCON, 2007 Austin, TX
NIST, 2007, Gaithersburg, Maryland
Nature Nanotechnology (in preparation)

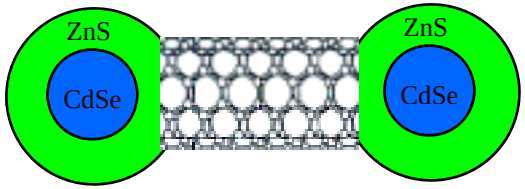
Carbon Nanotubes and Quantum Dots FOR SELF ASSEMBLY



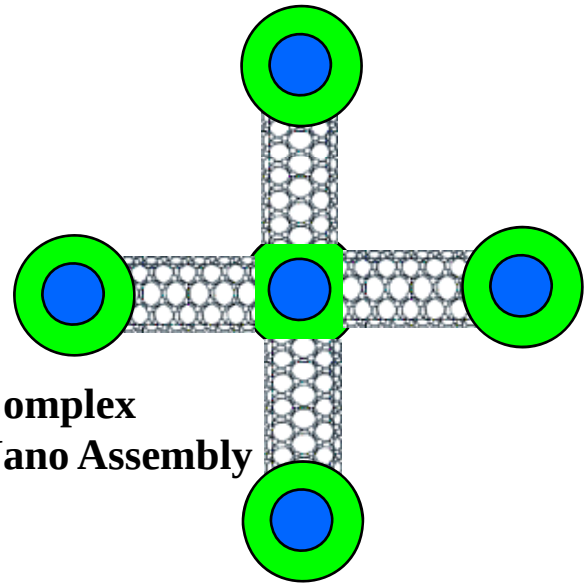
Ravindran et al, Nano Letters, 3, 4, 447 (2003)



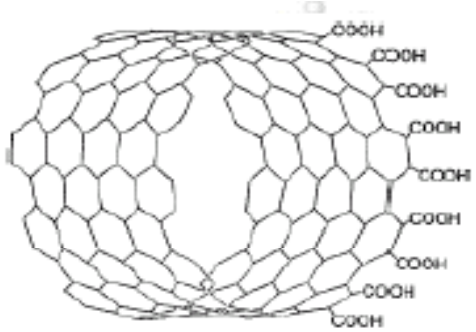
CNT-QD-CNT



QD-CNT-QD



Complex Nano Assembly

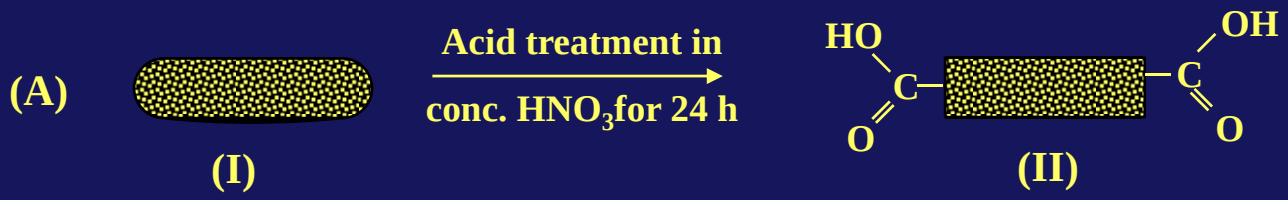


Purification and shortening of nanotubes is achieved via strong acid axidation

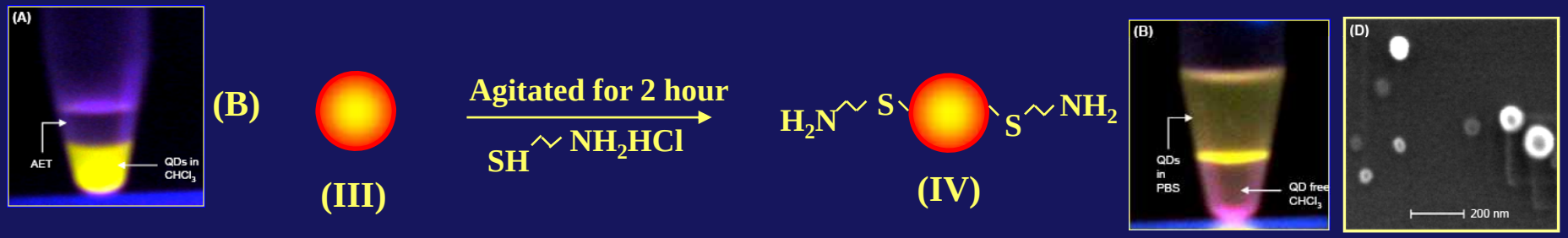
Liu et al, Science, 280, 1253 (1998)
Rinzler et al, Appl. Phys. A, 67, 29 (1998)
Rao et al, Phys. Rev. Lett., 86, 3895 (2001)

Ends of carbon nanotubes can be functionalized with a variety of groups, -COOH, -NH_2, etc. which provides flexibility for their utilization in assembly with other organic and inorganic materials.

Chemical Self Assemby of CNT-QD Hybrids



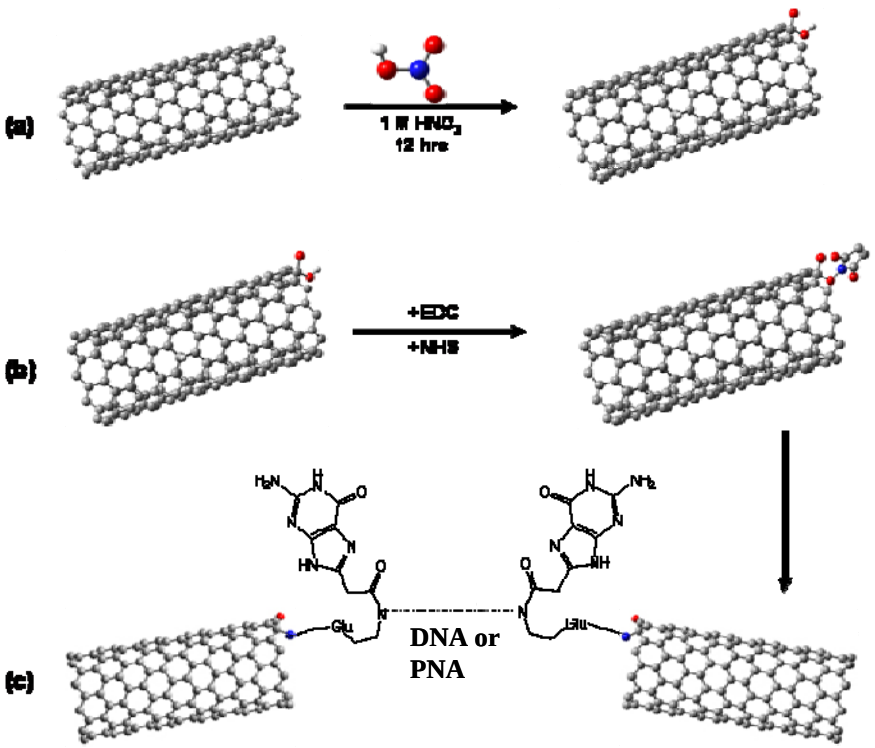
Introduction of carboxyl-terminal groups via acid treatment (Oxidation)



Water stabilization of CdSe/ZnS QDs via aminoethane thiol treatment

Heterojunction formation via Ethylene carbodiimide reaction

Biological Assembly of Carbon Nanotubes



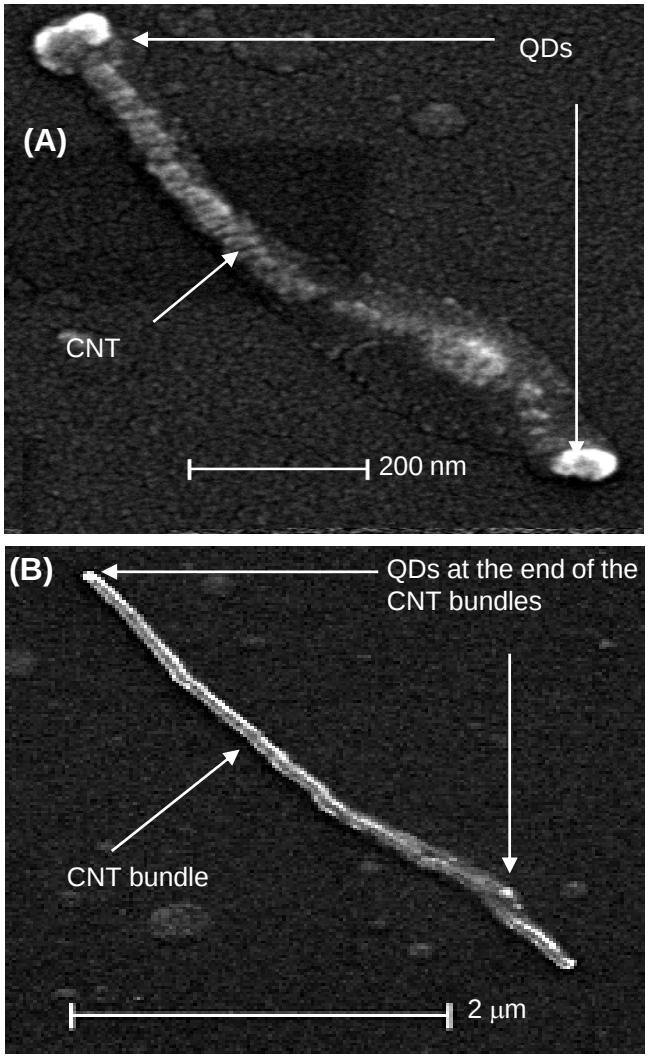
- **deoxyribonucleic and peptide nucleic acid fragments are used as linkers**
- **EDC coupling is used to connect SWCNTs through DNA and PNA**

•SWCNT-DNA-SWCNT
•SWCNT-PNA-SWCNT

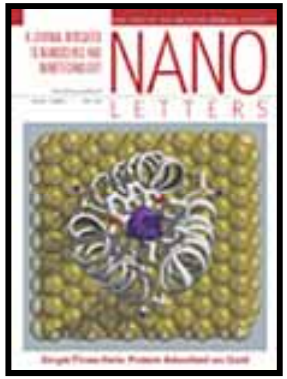
- Conjugation with DNA and PNA linkers have been demonstrated
- Electrical characterization of bioconjugates have been carried out
- Three terminal device fabrication is the next step...

Carbon (2007)
Small (2006)
Nanotechnology (2006)

QD end-conjugation for short and long CNTs

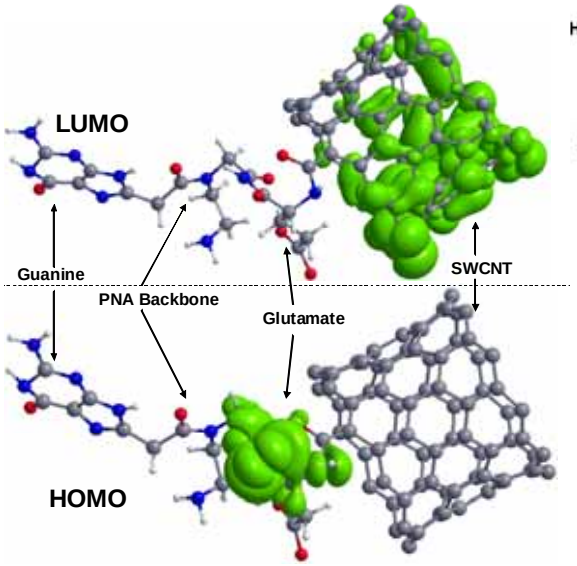


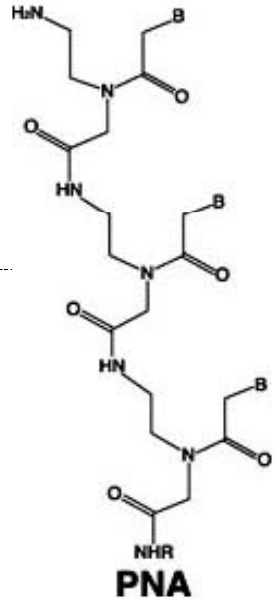
(A) CNT ~500 nm in length with QD conjugation at both the ends. (B) QD conjugation only at CNT ends for overall length larger than 4μm

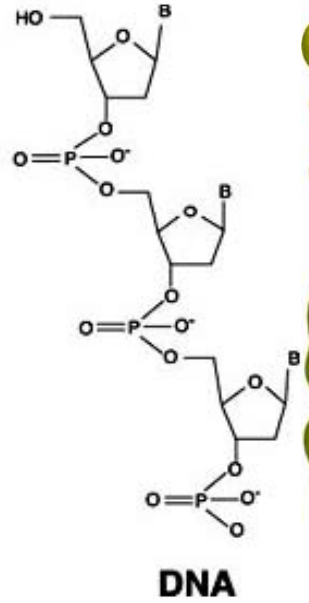


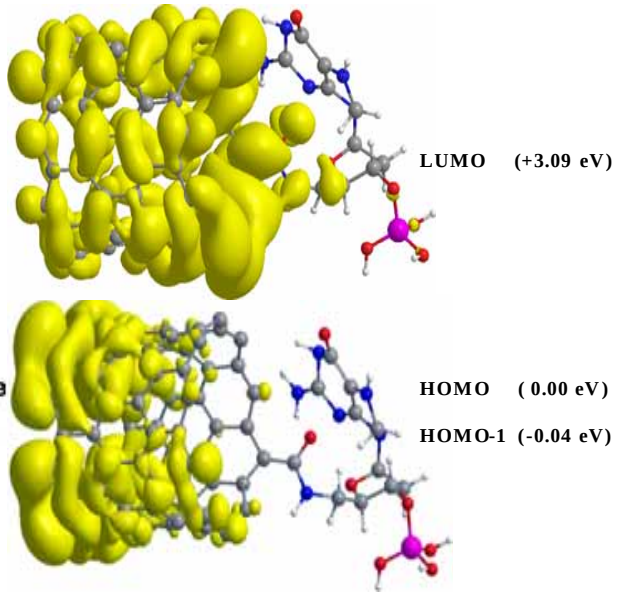
Nano Letters (2003)

Molecular Linkers: DNA and PNA



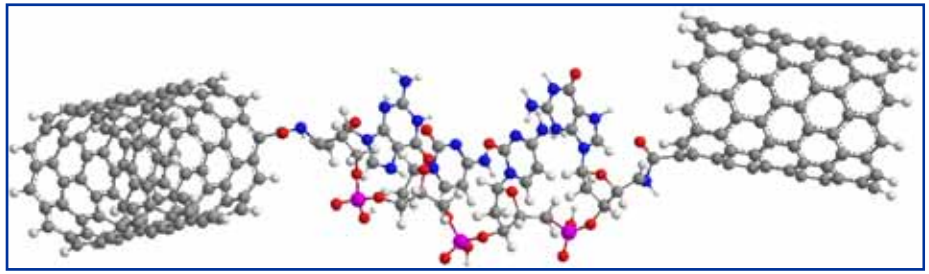






Hole conducting

Electron conducting

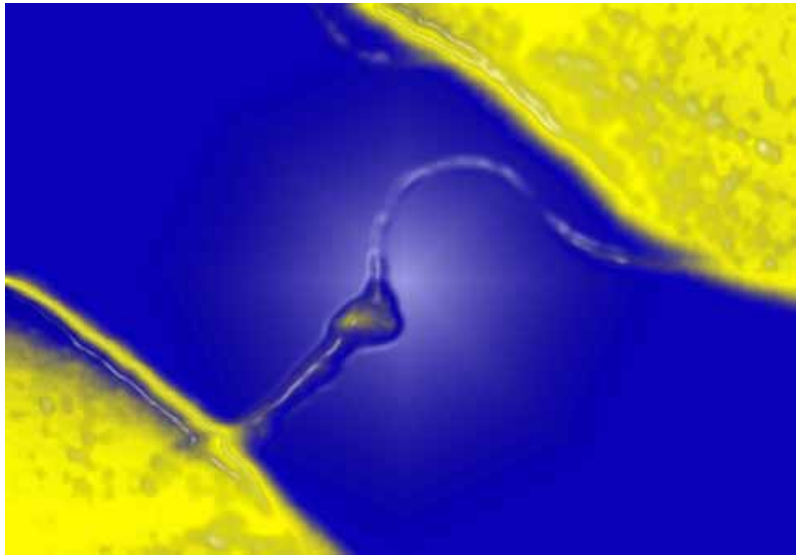


CNT-DNA-CNT Resonant tunneling diode

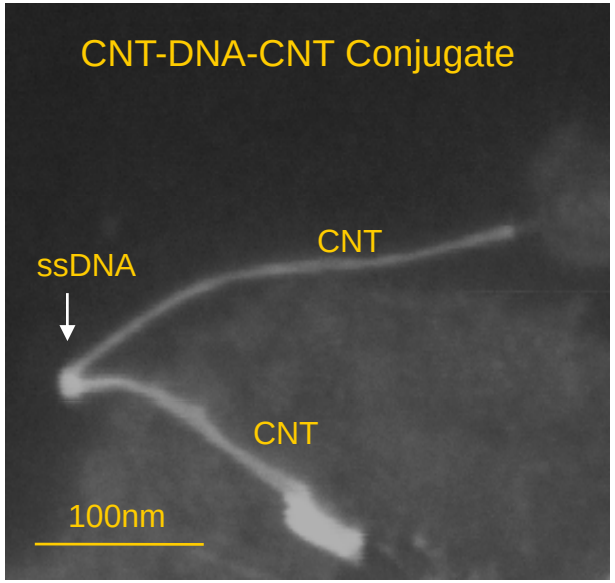
The comparison between DNA and PNA:

- **The bases (G,C,A,T) in DNA and PNA are the same. DNA has sugar phosphate backbone, while PNA has a synthetic peptide backbone usually formed N-(2-amino-ethyl)-glycine units.**

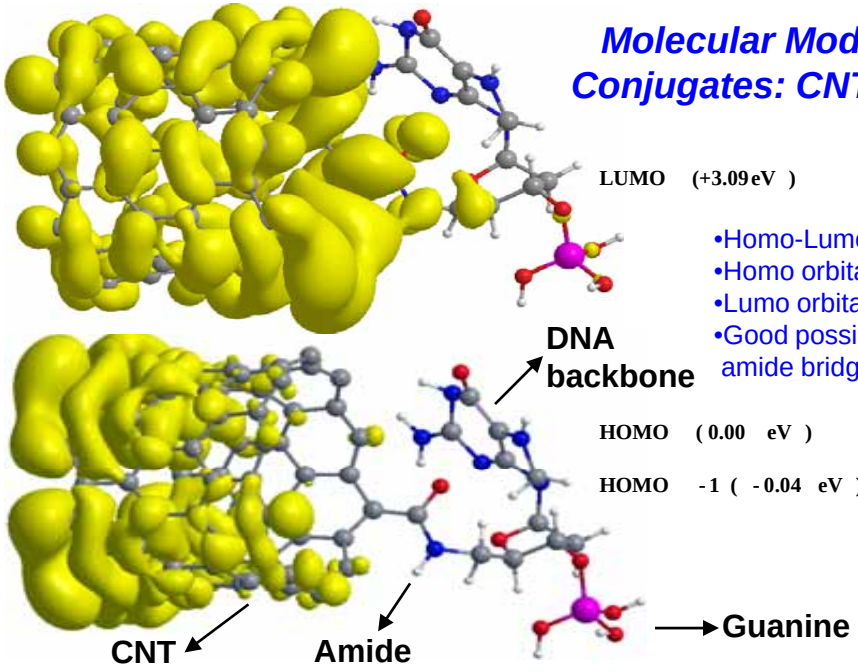
Biological Self Assembly of Nanostructures



- **ssDNA used as the linker**
- **EDC coupling is used to connect SWCNTs**
- **SWCNT-DNA-SWCNT bioconjugates are formed**
- **Conjugation confirmed with FTIR**

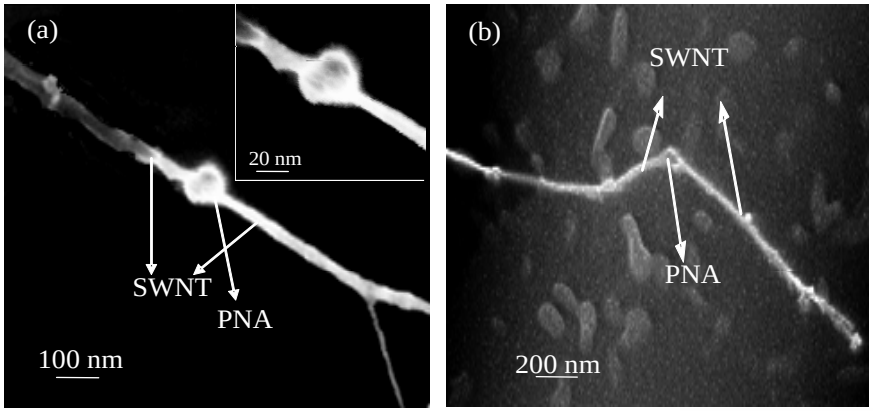


Molecular Modeling of the Conjugates: CNT-Amide-DNA

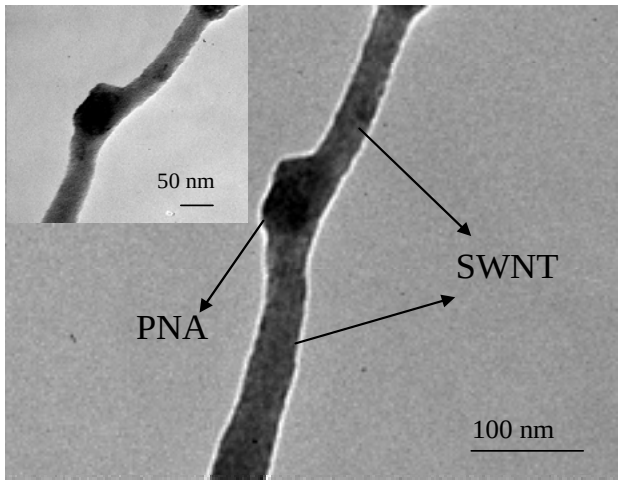


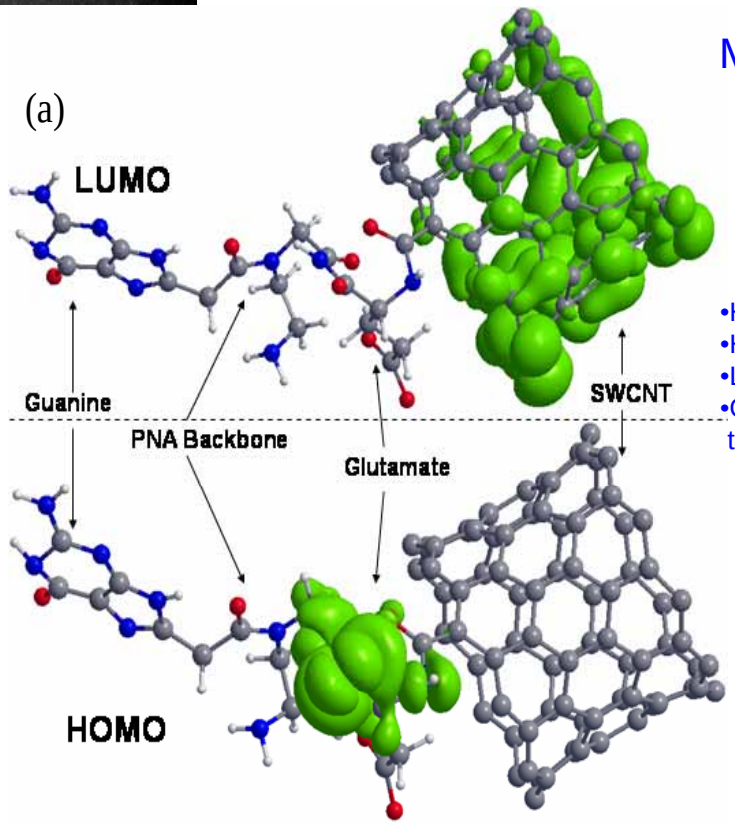
- Homo-Lumo gap: ~3.1 eV
- Homo orbital is confined on bare CNT
- Lumo orbital extends across amide bridge
- Good possibility for electron transport across amide bridge for n-type CNT

Biological Self Assembly of Nanostructures



- **ssPNA used as the linker (neutral backbone)**
- **EDC coupling is used to connect SWCNTs**
- **SWCNT-PNA-SWCNT bioconjugates are formed**
- **Conjugation confirmed with FTIR**





Molecular Modeling of the Conjugates

(b)

3.6 eV — LUMO / CNT

- Homo-Lumo gap: ~3.6 eV
- Homo orbital is confined on glutamate
- Lumo orbital is located on the CNT
- Good possibility for hole transport across the conjugate

0 eV — HOMO / glu

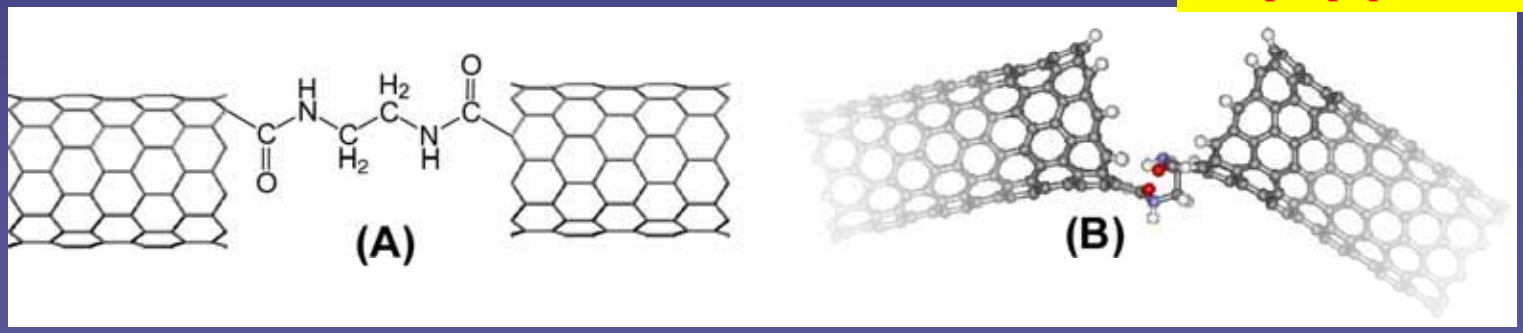
-1.1 eV — HOMO-1 / glu

-1.7 eV — HOMO-2, HOMO-3 / CNT, HOMO-4

Amide Linker

- **CNT end functionalization completed with EDC reaction results in an amide group (-CONH-) linking to molecule of interest**
- **Simulated 2 CNTs terminated with an amide group linked to C_2H_4 using FIREBALL and NEGF codes**

Simple peptide bond

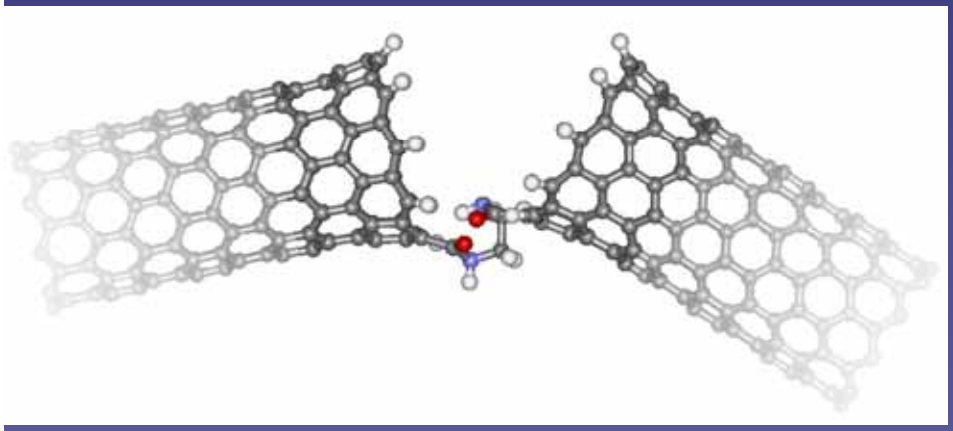


(A) Schematic of CNT-amide-C_2H_4-amide-CNT. (B) Relaxed structure with H passivation

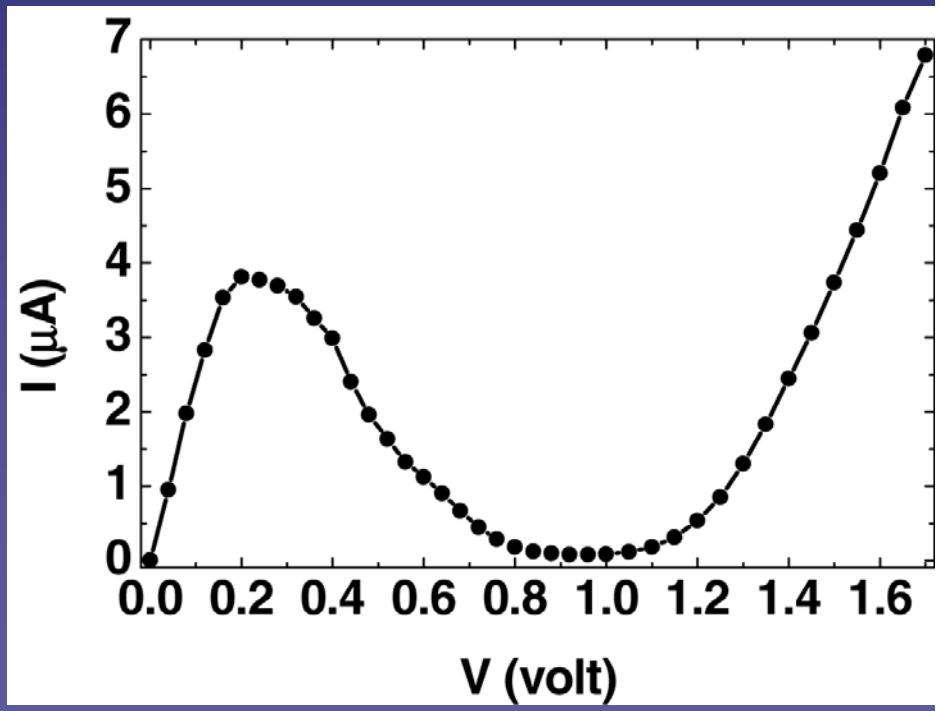
R. Pandey, N. Bruque, K. Alam, and R. Lake, *Phys. Stat. Sol. (a)*, **203**, R5 (2006)

CNT-Molecule-CNT RTD

- **Molecular linkers can act as functional electronic elements, not just mechanical linkers**



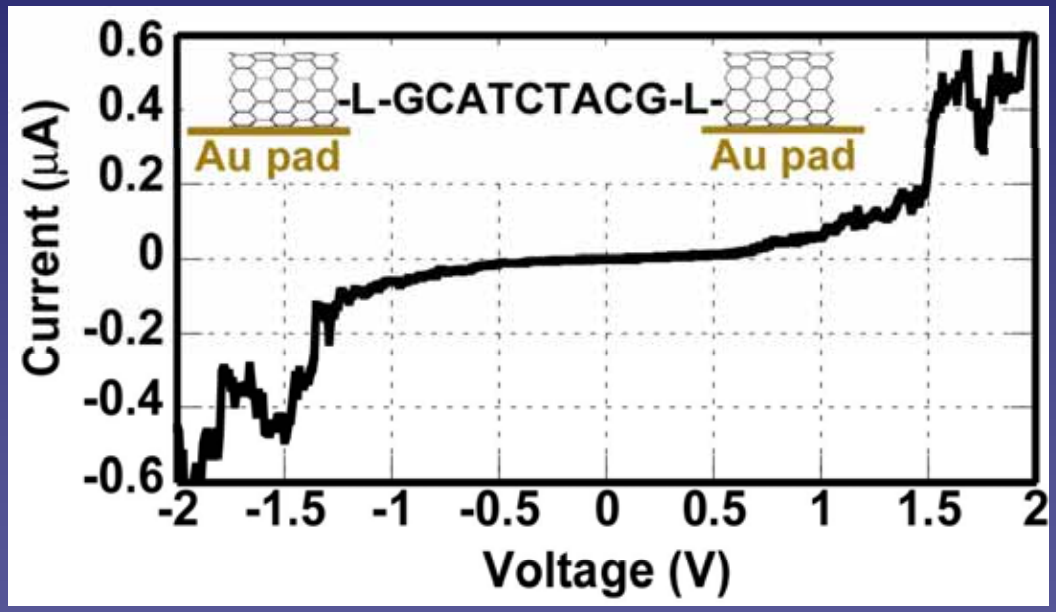
Relaxed CNT-amide-C_2H_4-amide-CNT structure



Current – voltage characteristic of CNT-amide-C_2H_4-amide-CNT

Experimental Demonstration

- **CNT-amide-DNA-amide-CNT**

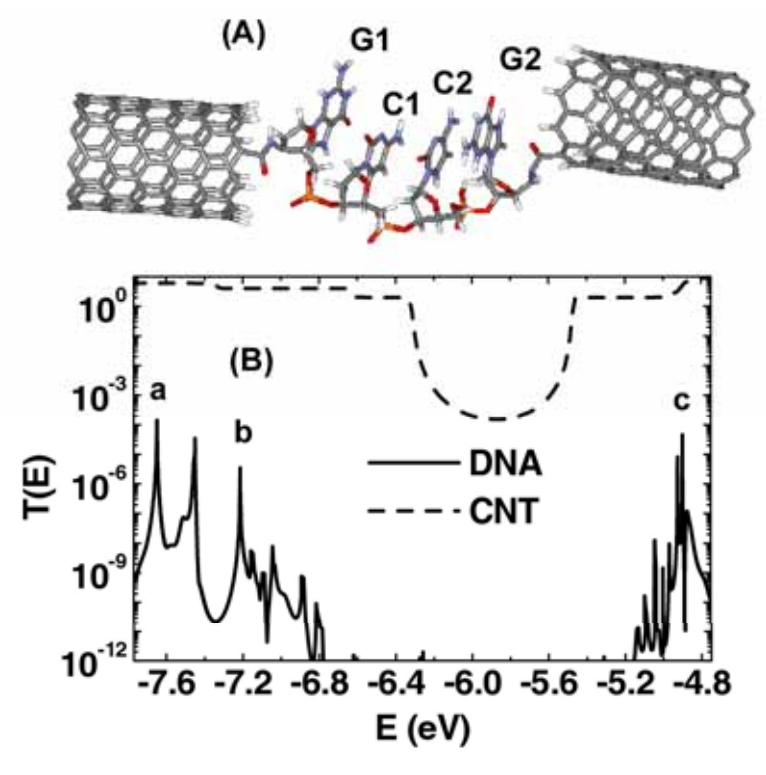


Measured current-voltage response of a Au-CNT-ssDNA-CNT-Au nanostructure

PSS (2006)
JNO (2006)
Small (2006)

Simulation CNT-ssDNA-CNT

- **CNT-amide-GCCG-amide-CNT**



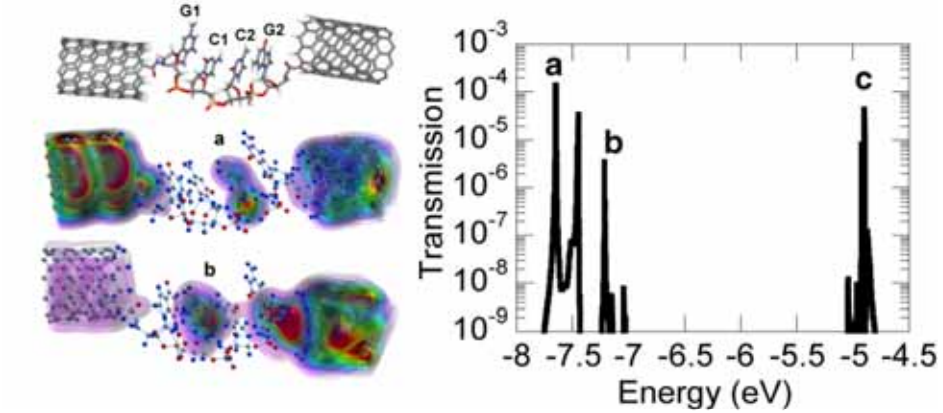
(A) Symmetric ss-DNA connected to 2 (10,0) CNTs with amide linkers. (B) Transmission of CNT-ssDNA-CNT superimposed on transmission of ideal (10,0) CNT (dashed).

Simulate electronic transmission function

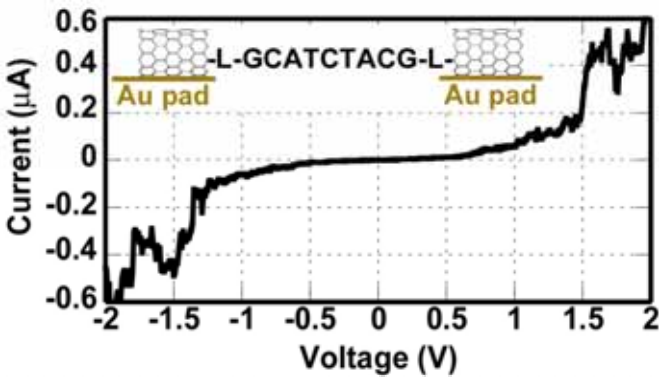
- 3 major resonances in valence band
- 1 double resonance in conduction band.
- Major peaks lie 0.5 – 1.0 eV above and below the E_c and E_v.
- Consistent with experimentally observed plateau in I-V around 0-bias.

Self-Synthesized Functional Devices

- Bio-assembled CNTFETs – DNA assembly
  - First simulations of the CNT-ssDNA-CNT system.



FIREBALL / NEGF calculations of transmission and spectral functions at transmission peaks a and b.

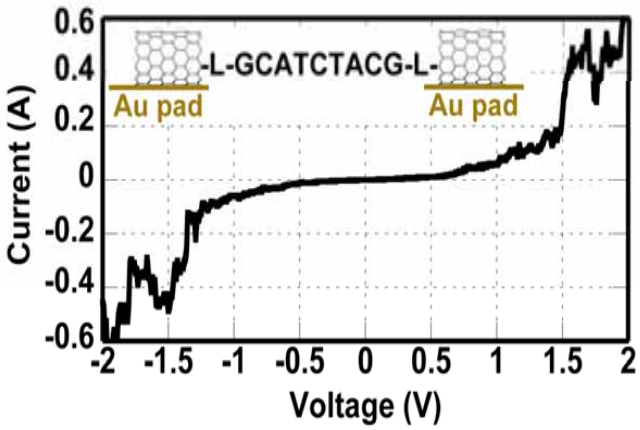


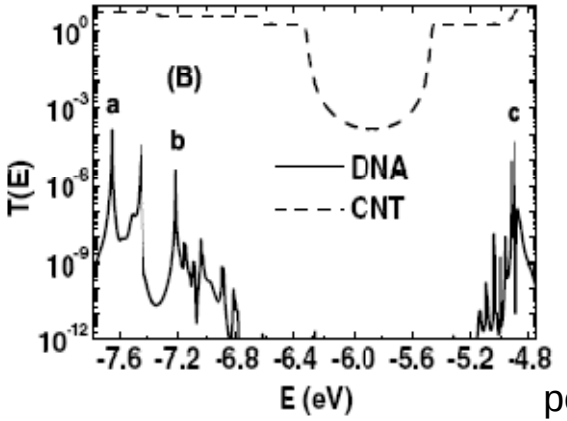
Experimentally measured I-V of CNT-ssDNA-CNT

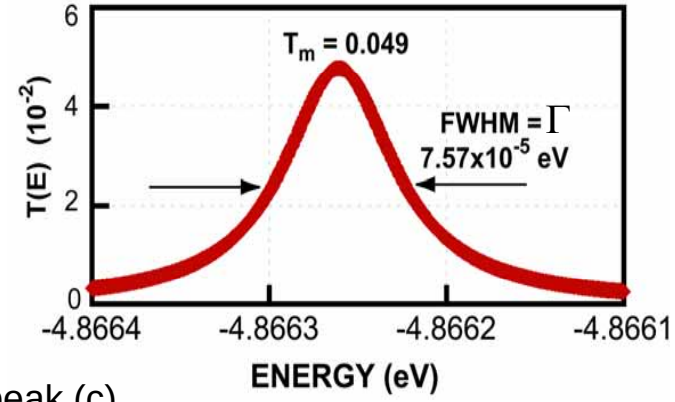
- The spacing of the major transmission peaks is consistent with the experimentally observed plateau around zero bias.
- The base pair types dictate the voltage of the resonant peaks in the I-V
- Spectral function indicates the spatial extent of energy states of charge carriers for a given system

C. Ozkan et al, Small (2006)

SWNT-ssDNA-SWNT Resonant Tunneling Diode







peak (c)

Calculate the maximum current carried by the resonance (integrate the peak area)

$$I_m = \frac{2e}{\hbar}\int \frac{dE}{2\pi} T(E) = \frac{2e}{\hbar}\frac{\Gamma_L \Gamma_R}{\Gamma_L + \Gamma_R} \cong 2e\frac{T_m}{4}\frac{\Gamma}{\hbar}$$

→ I_m = 0.4 nA current tunneling through a 4-base linker (–G-C-C-G-)

Experimental system is more complex: may have 10-100 SWNTs in a bundle, and each SWNT is functionalized with n>1 oligomers

Assume n=2 with 20 SWNTs → Max. current of 0.4 μA

In the 9-base and 24-base configurations → plateau region in I-V curves is also 2 eV wide...

Assume on-current for 9-base device 0.4 μA → divide by 20 (or 100) → 20 (or 4) nA per SWNT

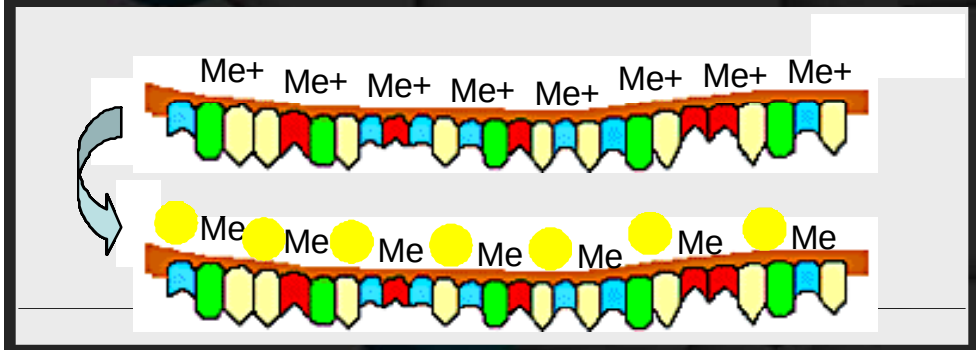
If n=4 → roughly 1-5 nA per DNA strand, so similar order of magnitude

C. Ozkan et al, Small (2006)

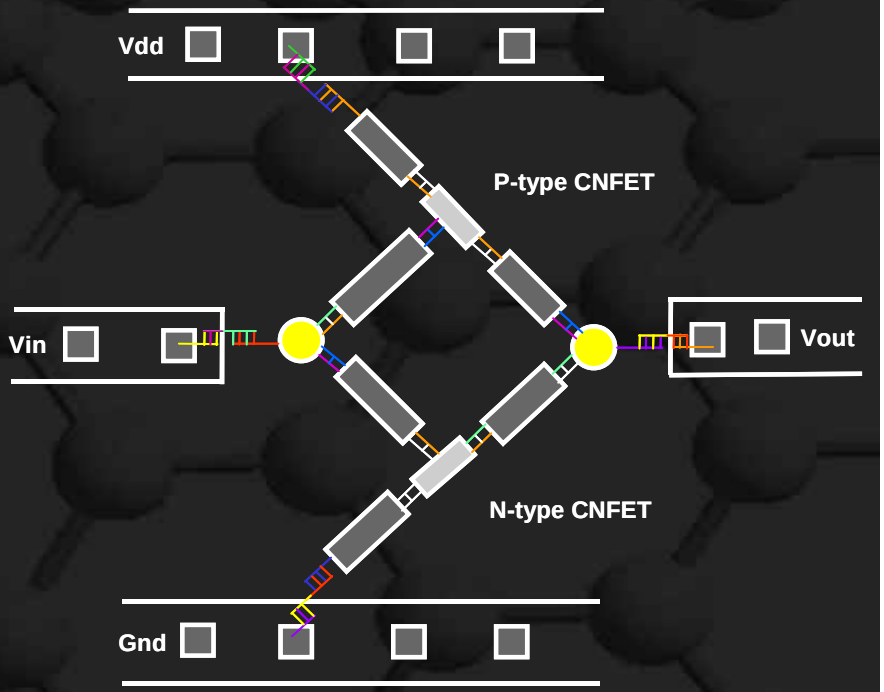
INTEGRATION APPROACH

Example

- Code unique nodes with DNA linkers
- Metallized DNA backbone as conducting linkers



Ag, Au, Cu, Pt, **Pd**



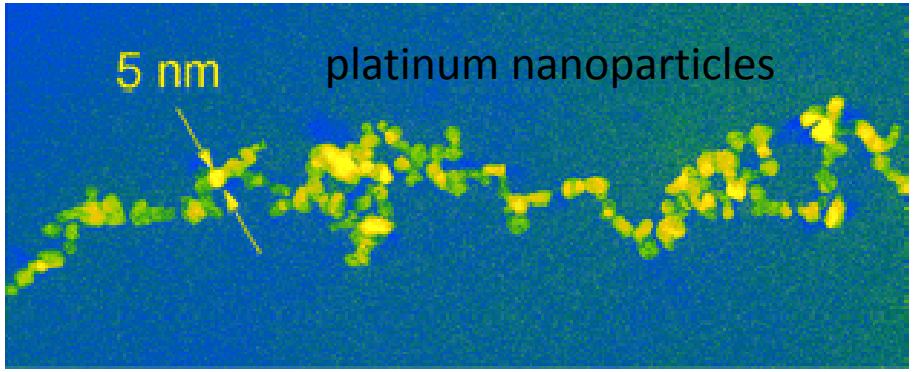
Self-synthesized inverter

DNA conductivity improvement via metallization

1.The adsorption of metal (II) complexes prior to their reduction to the metal

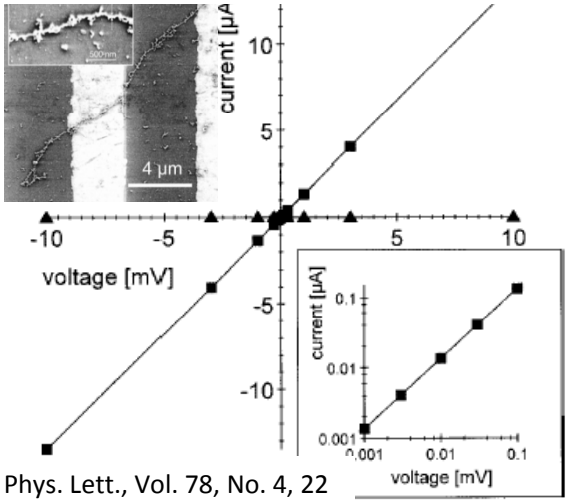
2.Electrostatic interaction of the negatively charged DNA with positively charged particles

Pt nanowire templated by DNA



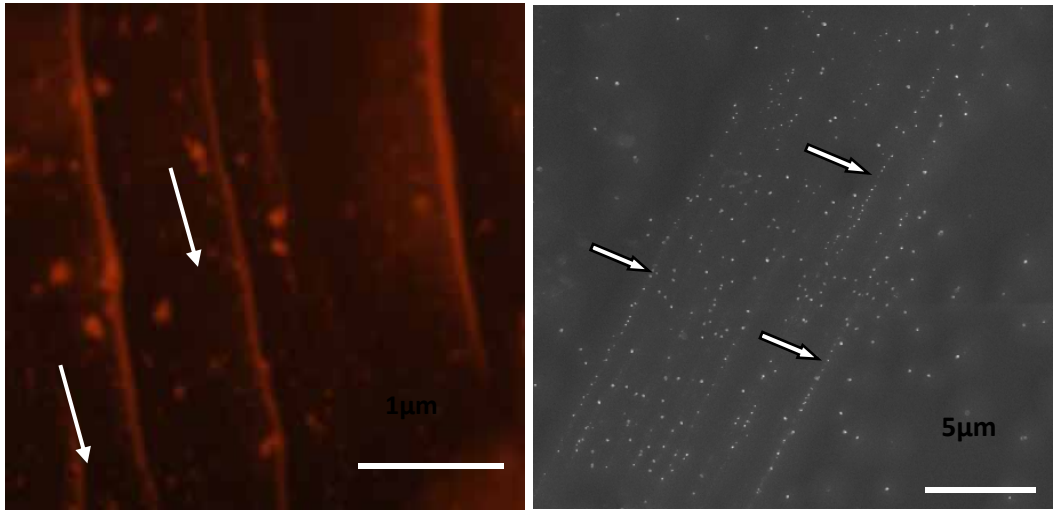
Michael Mertig, et al, *Nano Lett., Vol. 2, No. 8, 2002*

Pd metallized DNA by chemical reduction



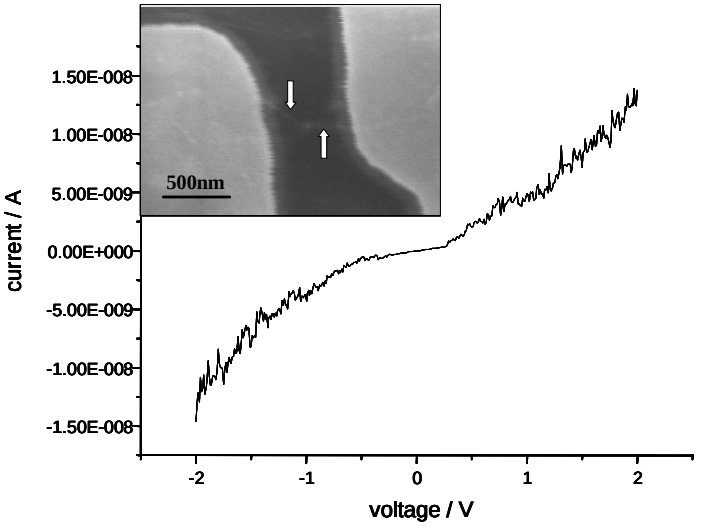
Richter et al, Appl. Phys. Lett., Vol. 78, No. 4, 22

Au nanowire templated by DNA

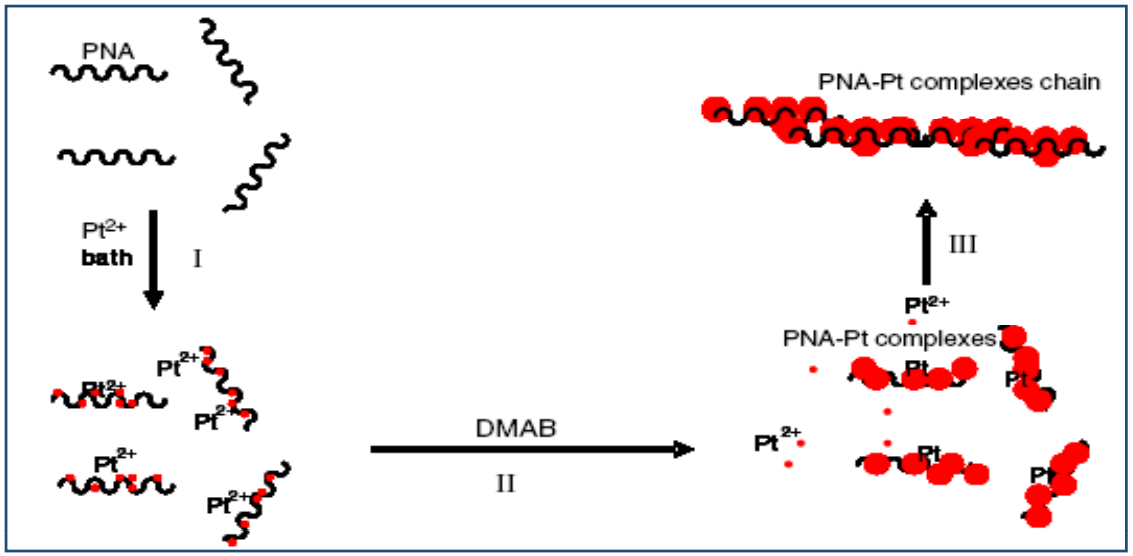


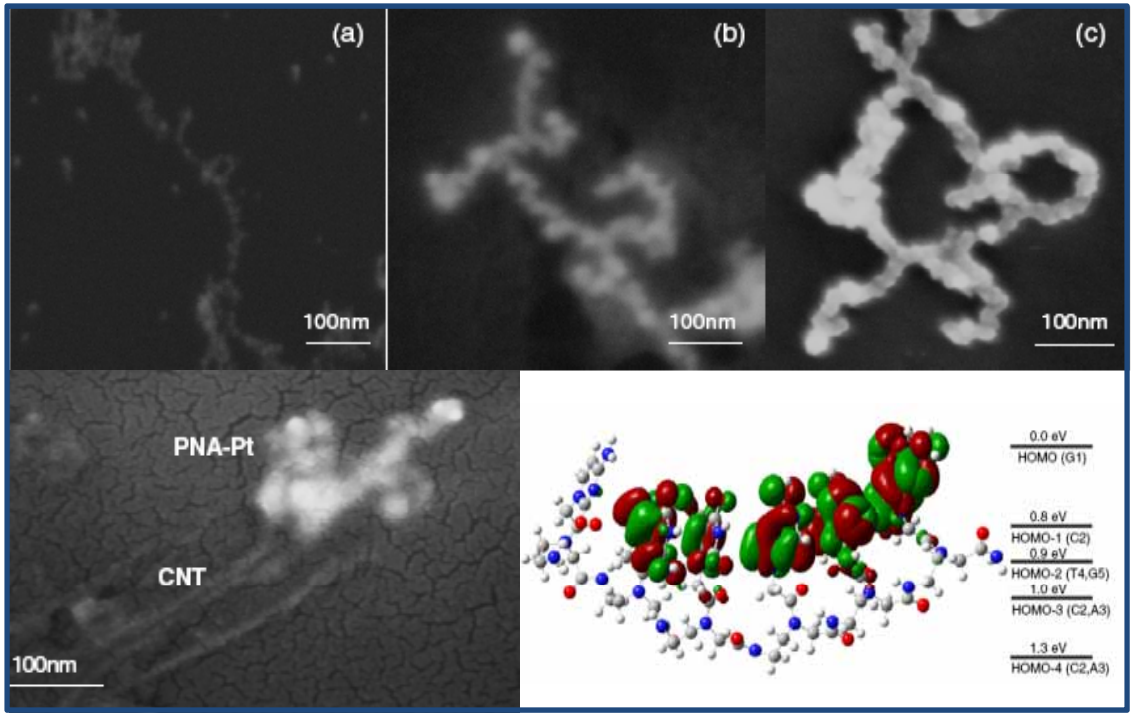
C. Ozkan et al, Nanotechnology (2005), *JNO* (2006)

Au NP bound to DNA electrostatically

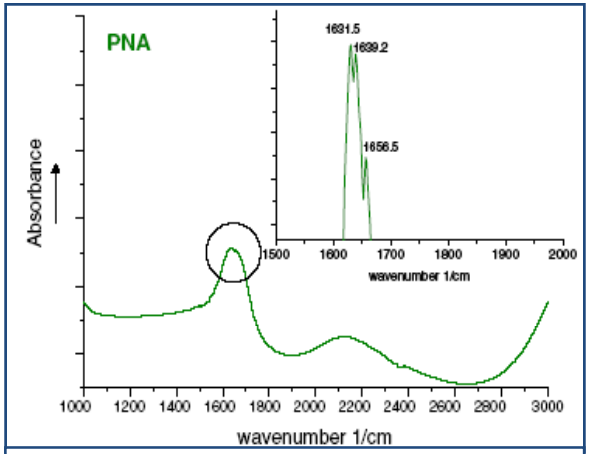


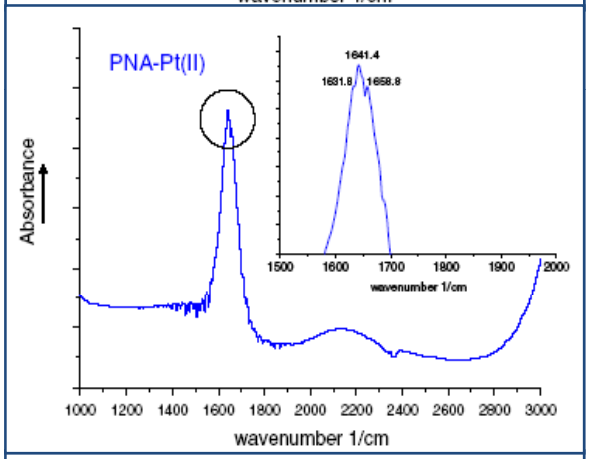
Metallization of PNA fragments

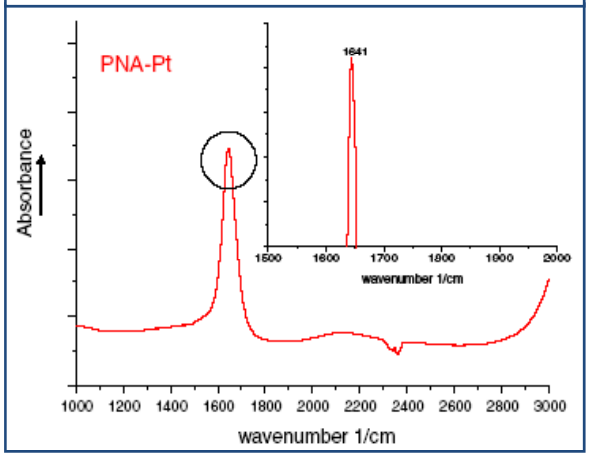




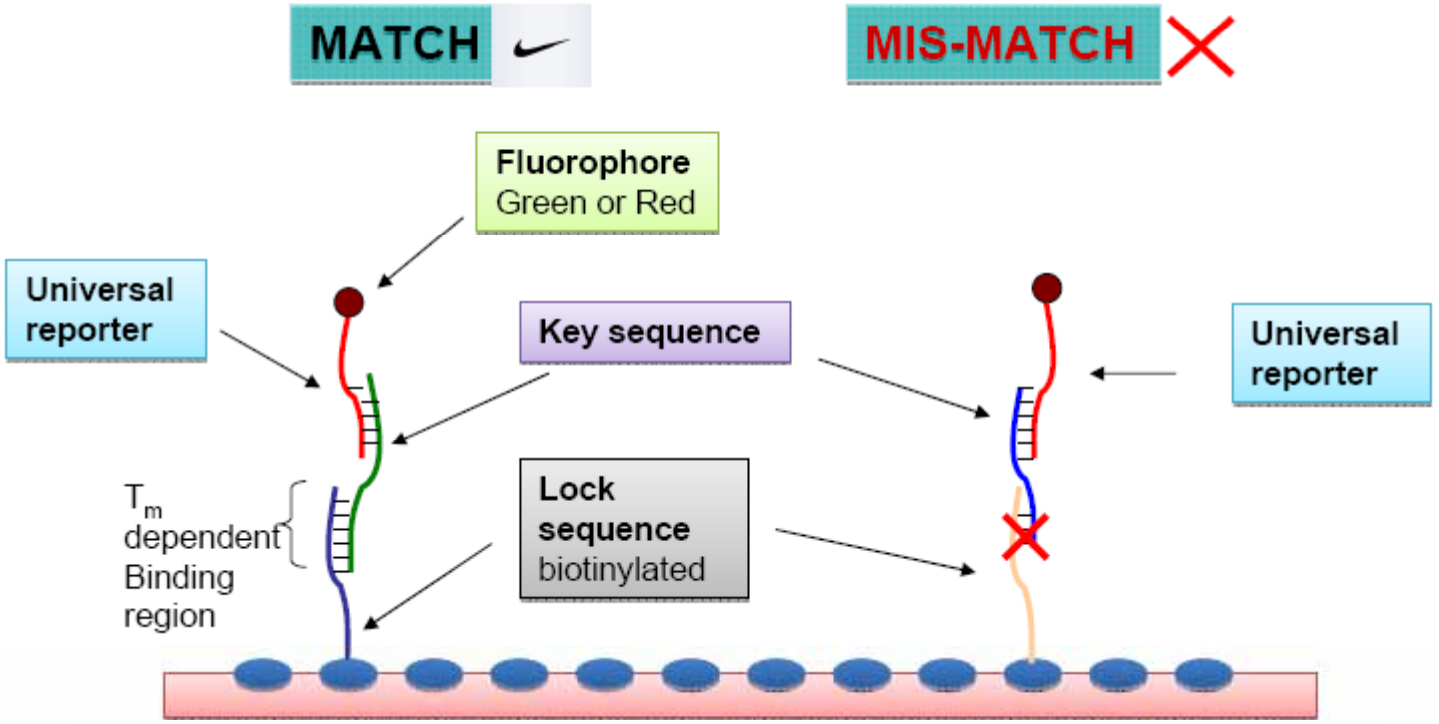
Ozkan et al, *Nanotechnology* (2006)







Initial Lock and Key Lithography™ Tests



1-Immobili
2-Hybridiz
3-Fluoresc
in the sam

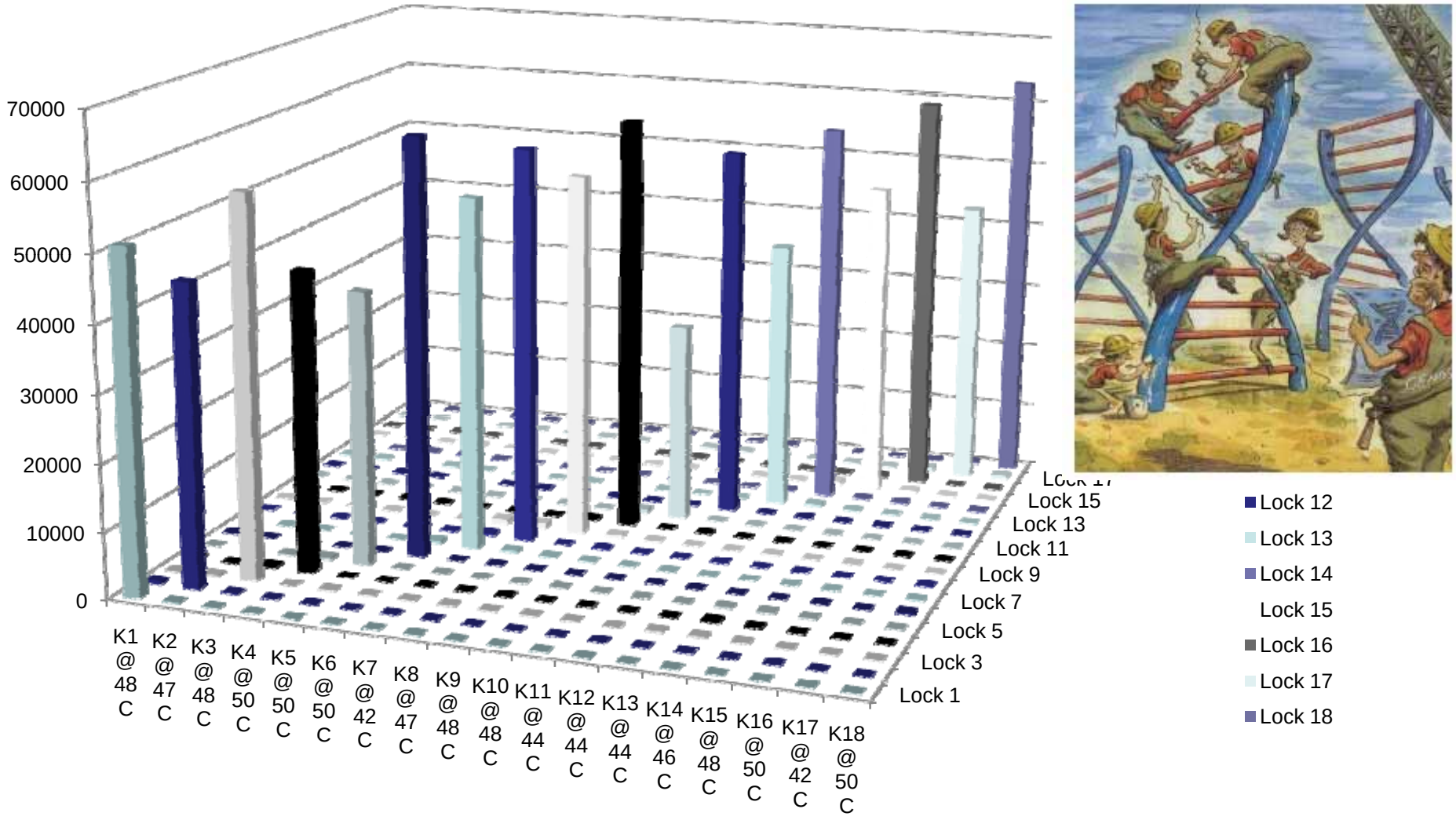
- On Silicon (Si-CMOS compatible)
- Error correction integrated through thermal cycling
- Metrology integrated through fluorescent Reporter
- Specificity provided by engineered DNA tethers

cular gene

Collaboration with J. Hartley (University of Albany) and M. Ozkan (UCR)

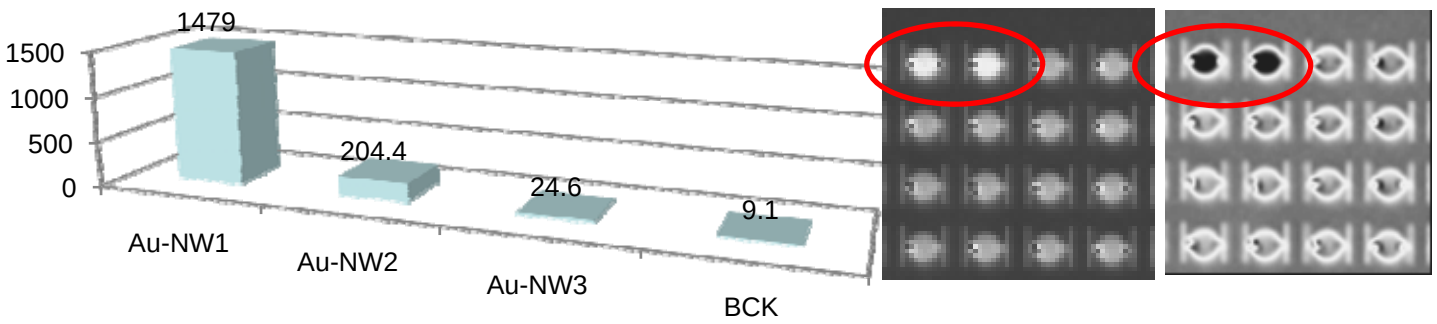
Engineered Tethers

Signal Detection from 18 Engineered DNA Sequence

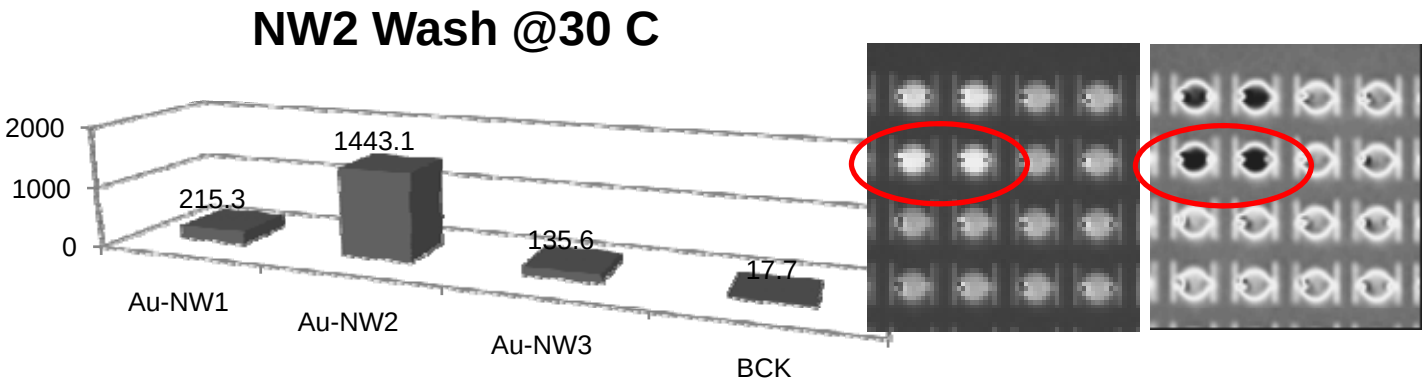


Collaboration with J. Hartley (University of Albany) and M. Ozkan (UCR)

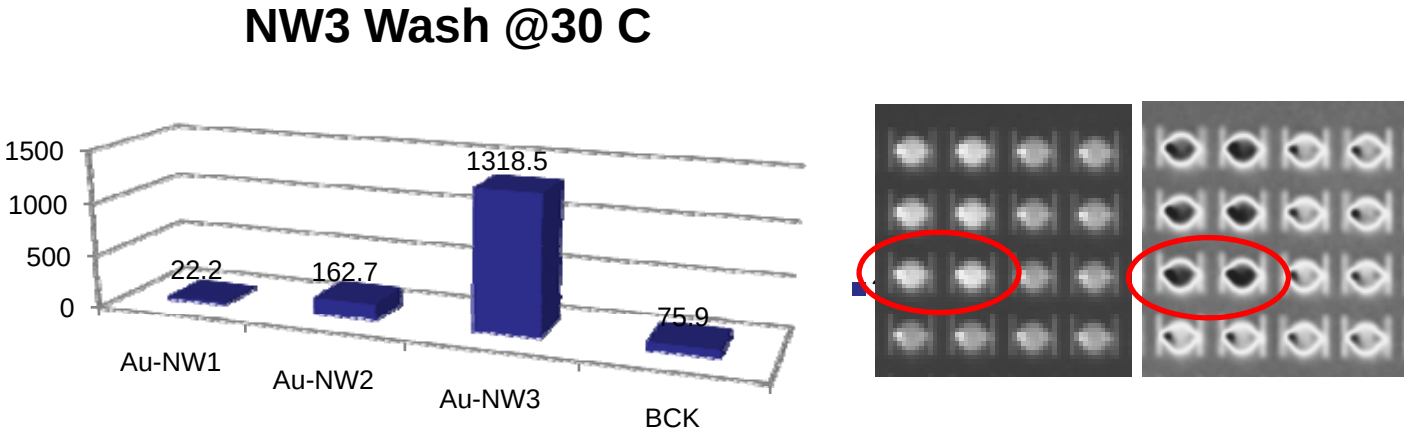
Experimental Results



Au Nanowires functionalized with key1 sequence are addressed to the pads.



Au Nanowires functionalized with key2 sequence are addressed to the pads.



Au Nanowires functionalized with key3 sequence are addressed to the pads.

Collaboration with J. Hartley (University of Albany) and M. Ozkan (UCR)

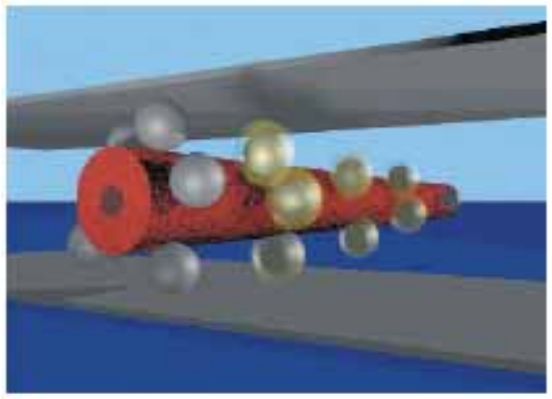
Virus-based memory device

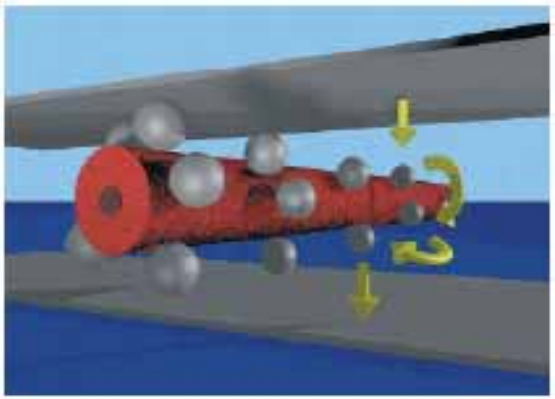
• *Tobacco Mosaic Viruses* (TMV) functionalized with platinum nanoparticles attached to their outer surfaces could be used as nanoscale memory devices that can be switched on and off electronically.

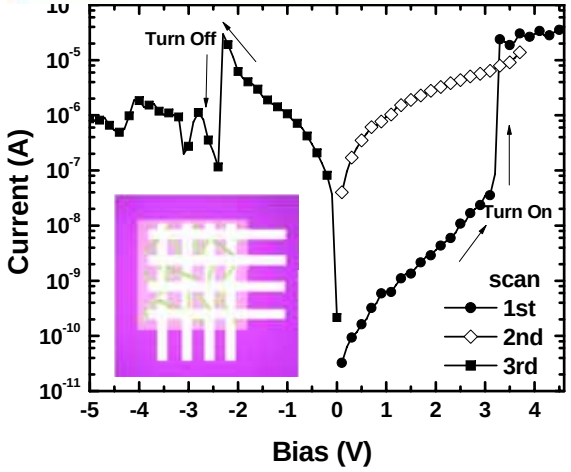
•The hybrids are embedded in a conductive polymer, and sandwiched between two metallic electrodes.

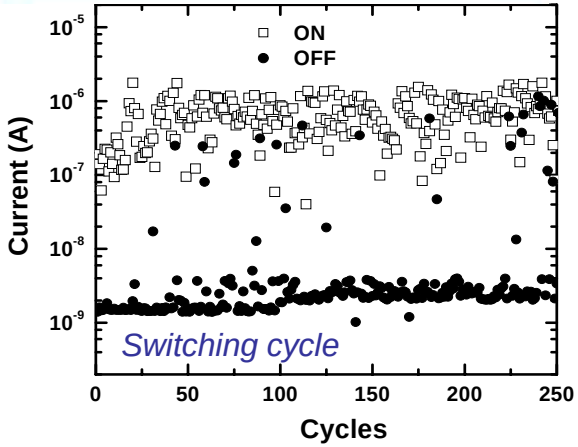
•By applying an electrical potential between the two electrodes, a marked increase in current is observed at 3 volts. In this 'on' state, electrons were able to tunnel through a seemingly impenetrable barrier because of their quantum nature.

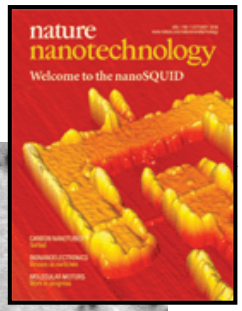
•The 'on' state remained stable unless the voltage went below –2.4 volts, when it switches off.

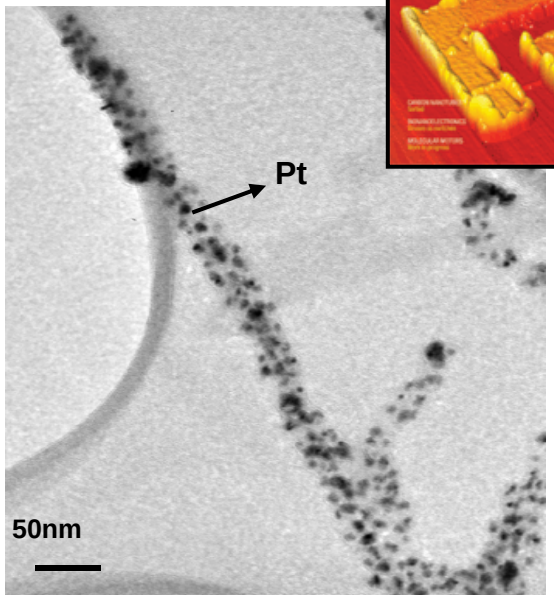








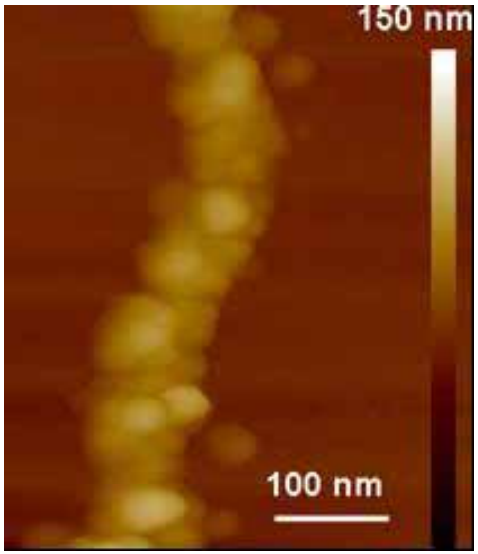


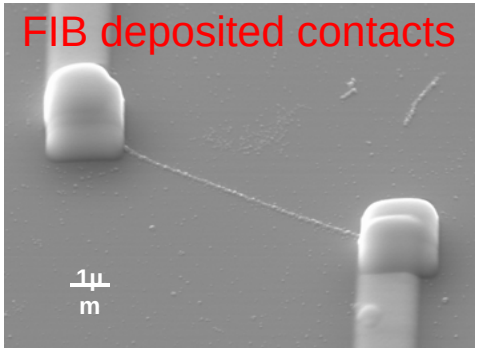


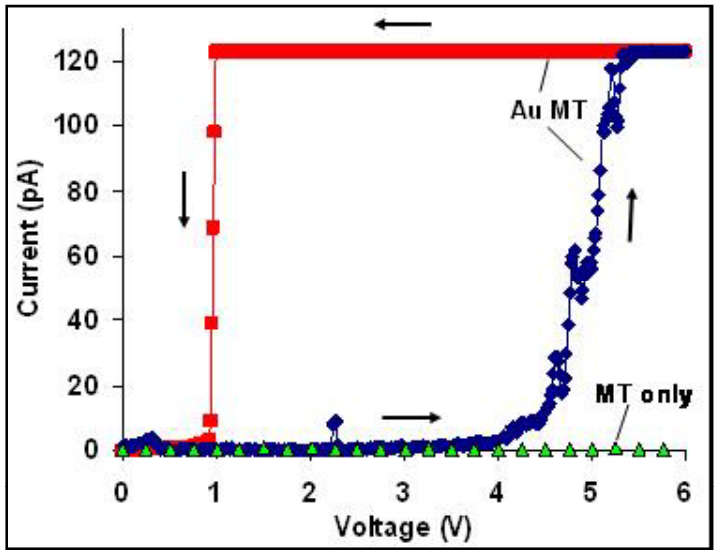
***nature nanotechnology*, 2006**

Collaboration with Y. yang (UCLA)

Microtubules as 1-D templates for Au nanowires







- Long filamentous proteins that are found in eukaryotic cells
- Play a crucial role in positioning organelles and guiding intracellular movement
- Rigid hollow cylindrical tubes 25 nm in diameter and several microns in length
- Self-assembled from noncovalently associated heterodimer proteins called αβ-tubulins
- Covalently linked with colloidal Au through surface primary amine groups, followed by photochemical reduction of a gold ions from $HAUCl_4$ (Tetrachloroauric Acid)

- Tunneling AFM (TUNA): a Pt/Ir coated Si tip is placed on a single MT-Au nanowire. I-V measurements were taken transversely across the nanowire
- Bistable behavior: A low conductivity state (OFF state) is present until an applied voltage surpasses a ~ 4.5 V threshold → material switches to a high conductivity, current increases by two orders of magnitude (ON state)
- By applying a reverse bias: MT-Au nanowires return to their original low conductivity state (erasing process)

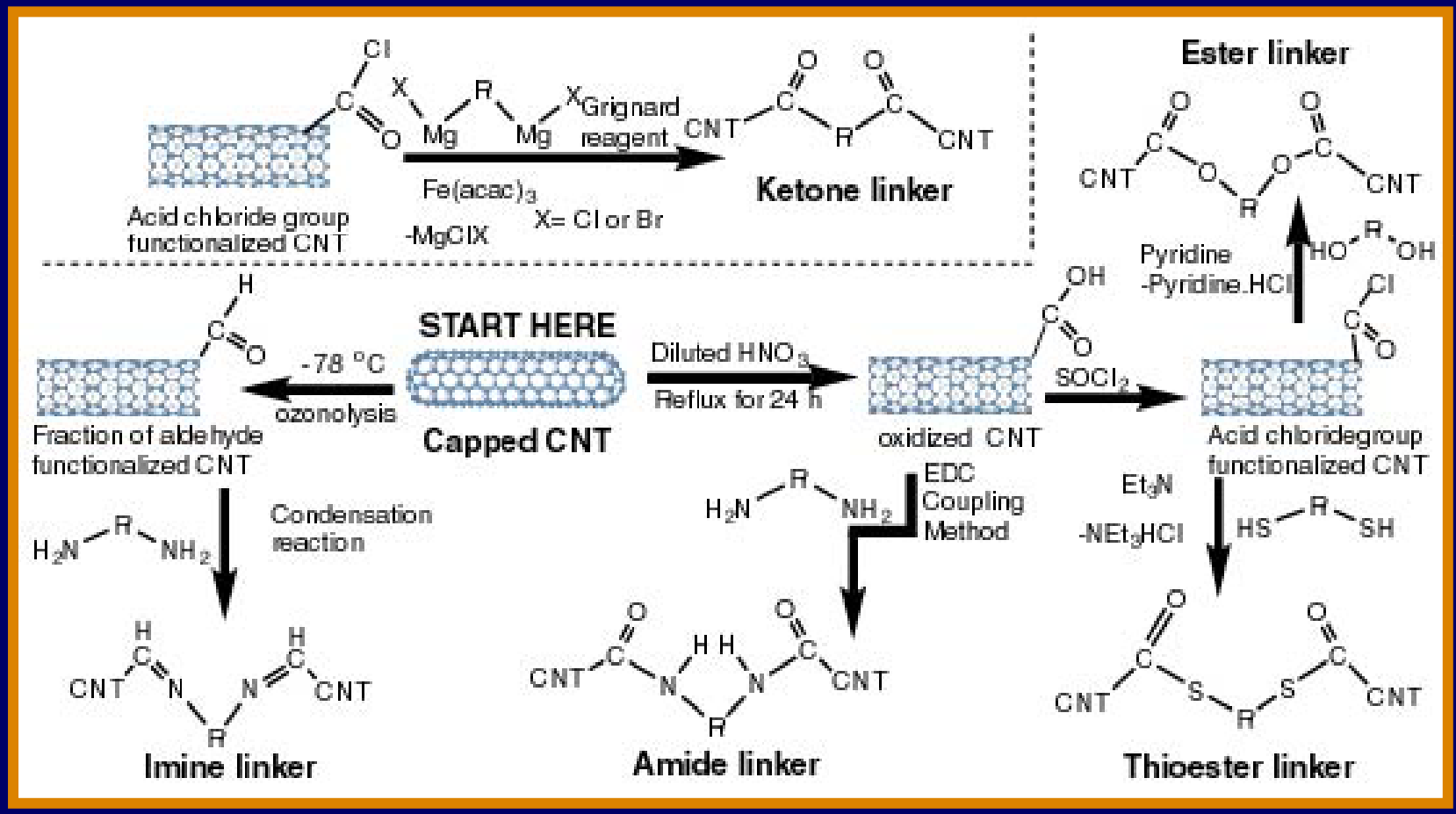
Collaboration with Bruce Dunn (UCLA)

In Press, Small (2008)

Other Research Areas

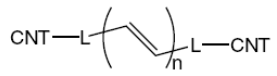
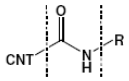
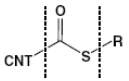
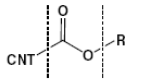
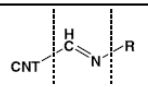
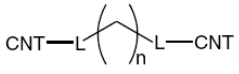
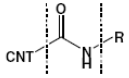
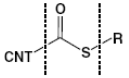
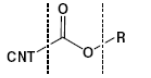
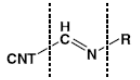
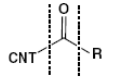
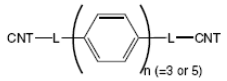
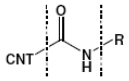
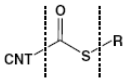
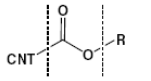
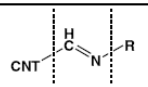
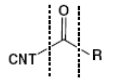
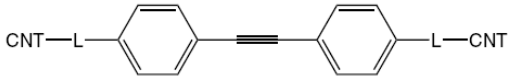
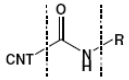
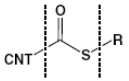
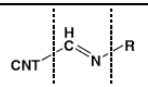
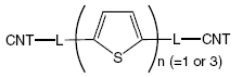
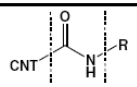
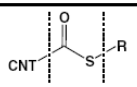
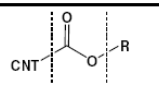
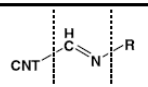
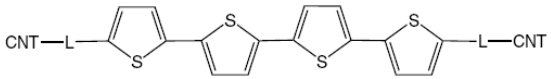
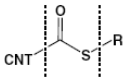
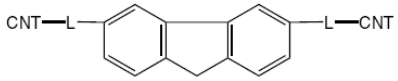
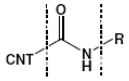
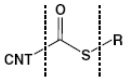
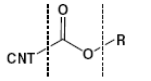
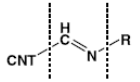
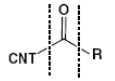
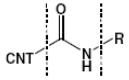
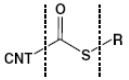
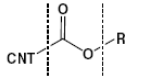
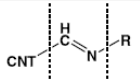
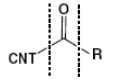
- Electron transport through molecular-nanotube and bio-inorganic interfaces and nano architectures
- Virus templates for hierarchical nanoengineering
  - Hybrid memory Device
  - Therapeutics/Imaging Probe
- Electrochemical nanoengineering of structures
  - Nanowire solar cell and battery applications
  - Nanopatterning (vertical and lateral arrays)
  - Multisegment nanowires for sensors
- Imaging for cell biology (live cell imaging and micro/nano bubble imaging in the NSOM and the AFM)
- Integration of block-co-polymer patterning with DNA assembly

Electron Transport through Molecular-Carbon Nanotube Interfaces: Alternative Routes for End-Functionalization of Carbon Nanotubes

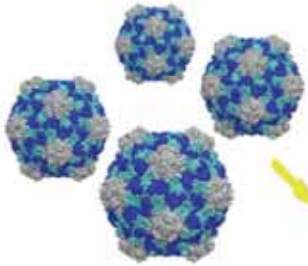


Reaction pathways for different linkers

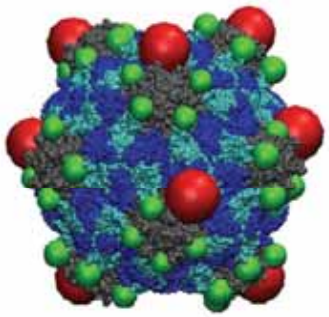
SWNT-L-R-L-SWNT Nano Architectures

No	Molecule (R)	Linker (L)				
		Amide	Thioester	Ester	Imino	Ketone
I	 disubstituted oligomeric olefine					–
II	 disubstituted oligomeric alkane					
III	 polyaromatic					
IV	 Dimercaptodiphenylacetylene			–		–
V	 2,5-disubstituted oligothiophene					–
VI	 Terthiophene-dithioester	–		–	–	–
VII	 3,7-disubstituted Flourene					
VIII	 1,1́-disubstituted Ferrocene					

Virus based nanoassembly -novel devices and therapuetics

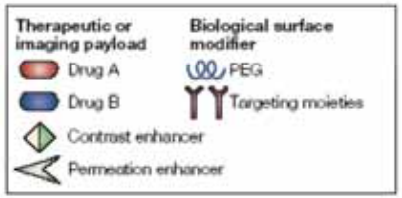


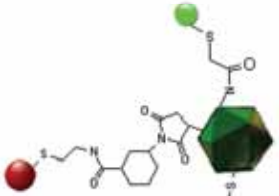
Icosahedral virus templates



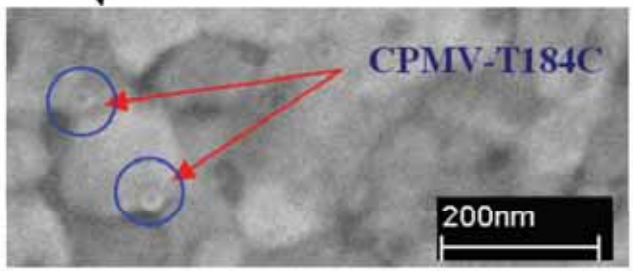
Nanoparticles (FeO, Qdots, etc.)

- Targeting peptide
- Iron oxide
- PEG coating



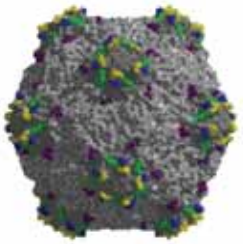


- No cross products
- Imaging platform
- Deposition control



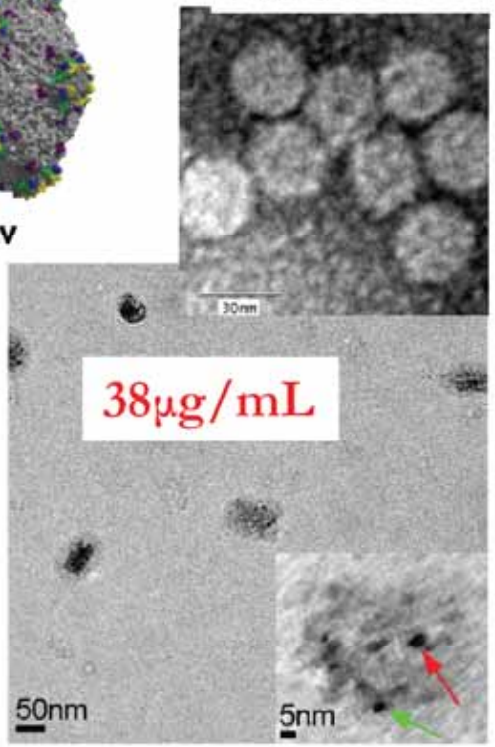
CPMV-T184C SEM, 10kV

Stepwise substrate

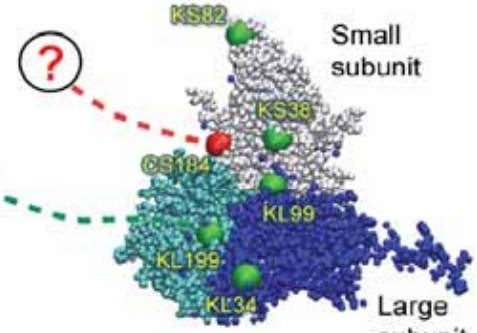


CPMV

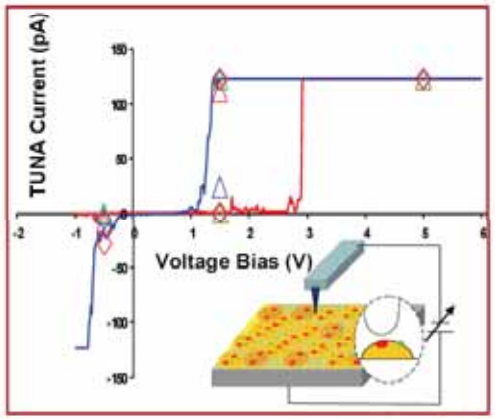
CPMV-WT

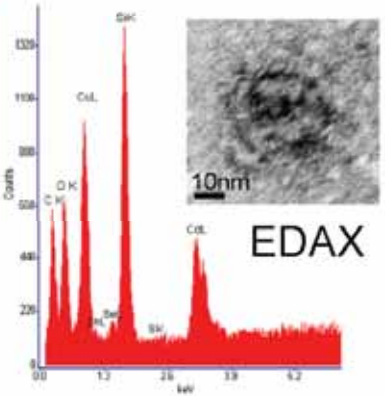


TEM CPMV-T184C-QD(1,2)

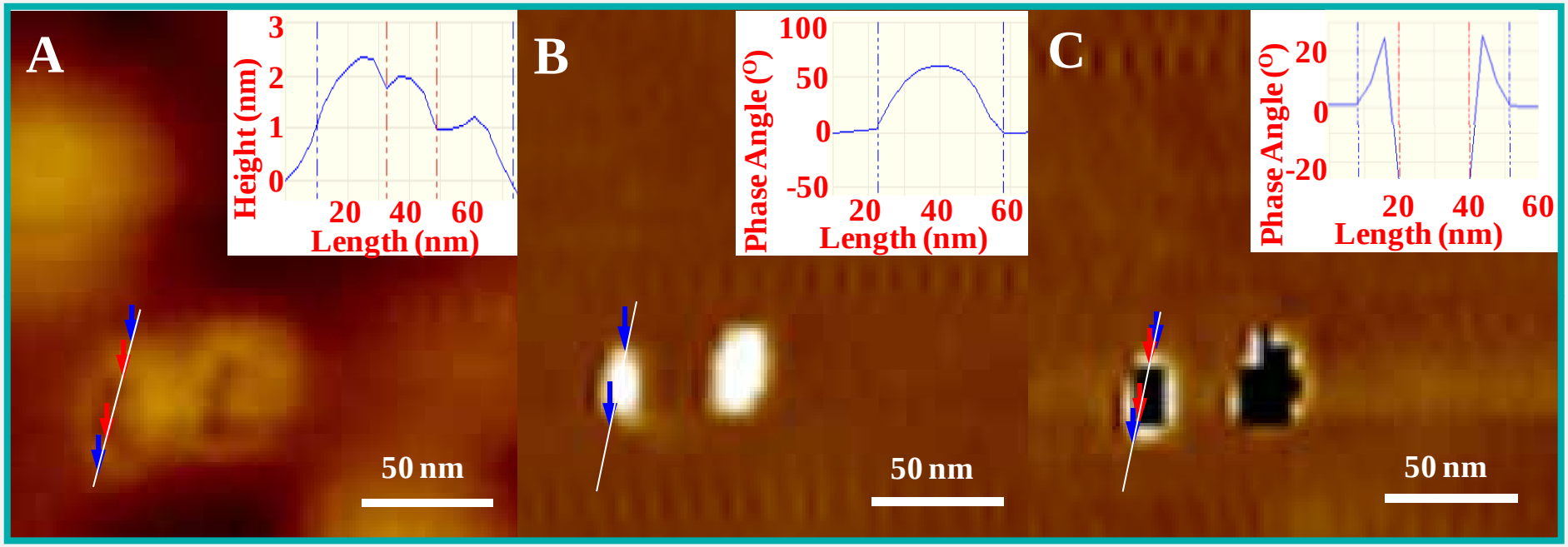


QD_{green}





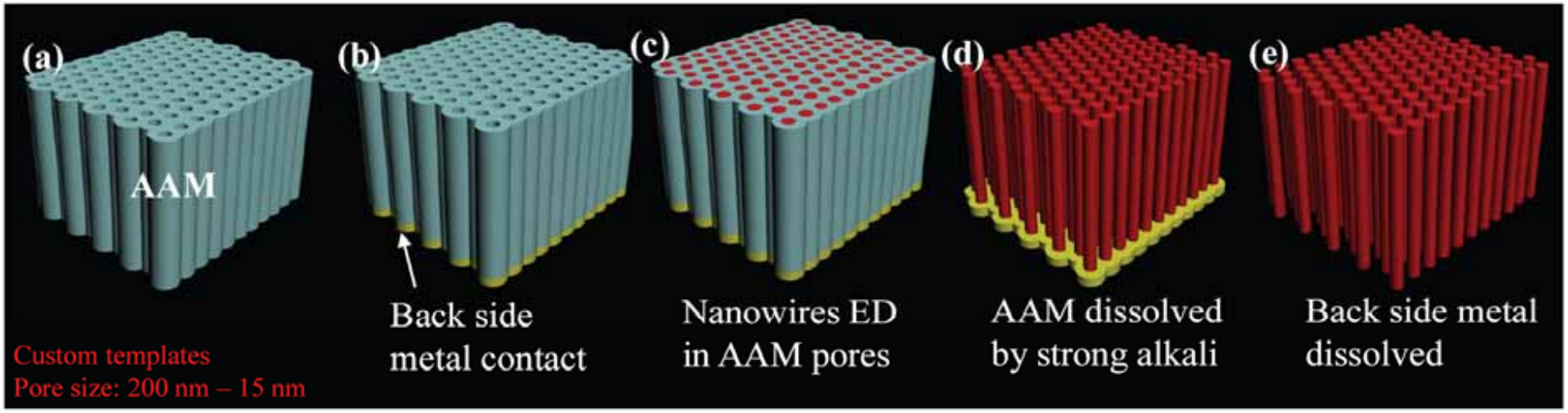
CPMV-Fe_2O_3 NP hybrids



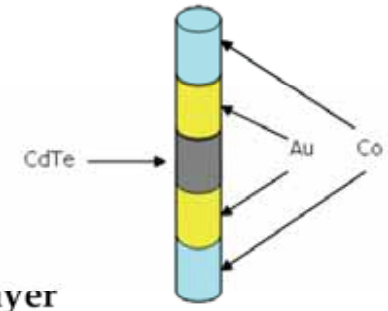
TAFM and MFM imaging of single CPMV-IO hybrids. (A) TAFM topography. (B) TAFM phase detection and (C) MFM phase detection of two adjacent CPMV-IO hybrids and their corresponding cross-sections (insets). Nominal size for nanoparticles and nanoclusters are ~ 12 nm and 30 nm respectively.

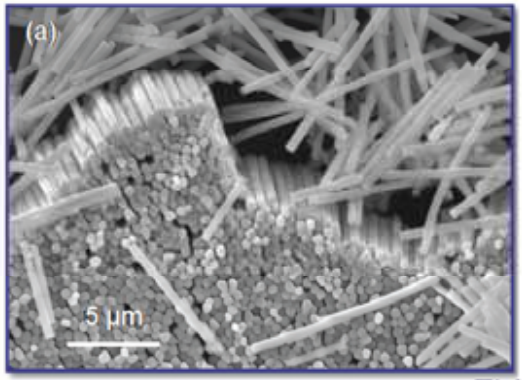
In collaboration with M. Ozkan (UCR), G. Budak (GU, Turkey), E. Ozbay (Bilkent, Turkey)

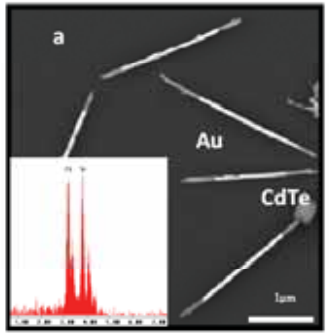
Electrochemical nanoengineering of structures for nanoelectronics, sensing and solar cell applications

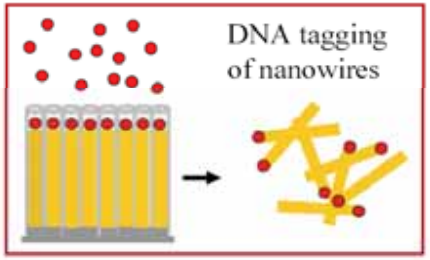


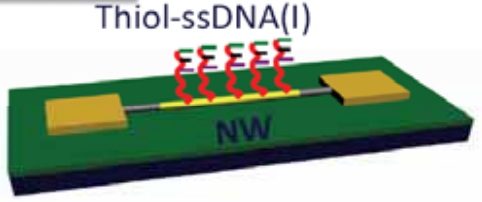
- Introducing the seed layer
  - Sputtering
  - Evaporation
  - Electrodeposition
- Dissolving Alumina and seed layer
  - NaOH, KOH
  - Acids
- Template integration to Si substrates
- Multisegment nanowire structures
- Vertically aligned and laterally aligned nanowires











Ozkan et al., Nano Letters, 2008

Imaging Methods for Cell Biology (NANOTUMOR Center, NCI-NIH)

Light microscopy
- Resolution of several hundreds of nanometers
- Non invasive

Electron/x-ray microscopy
- Resolution of several nanometers
- Not possible live cell imaging

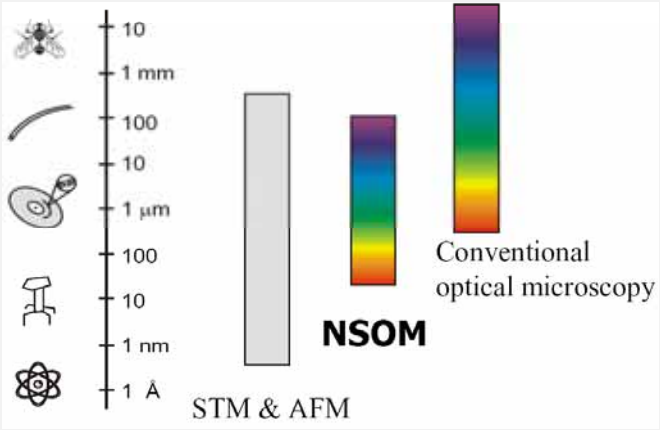
AFM/NSOM
- Resolution of several tens of nanometers

Veeco Multimode V AFM / MFM / TUNA system

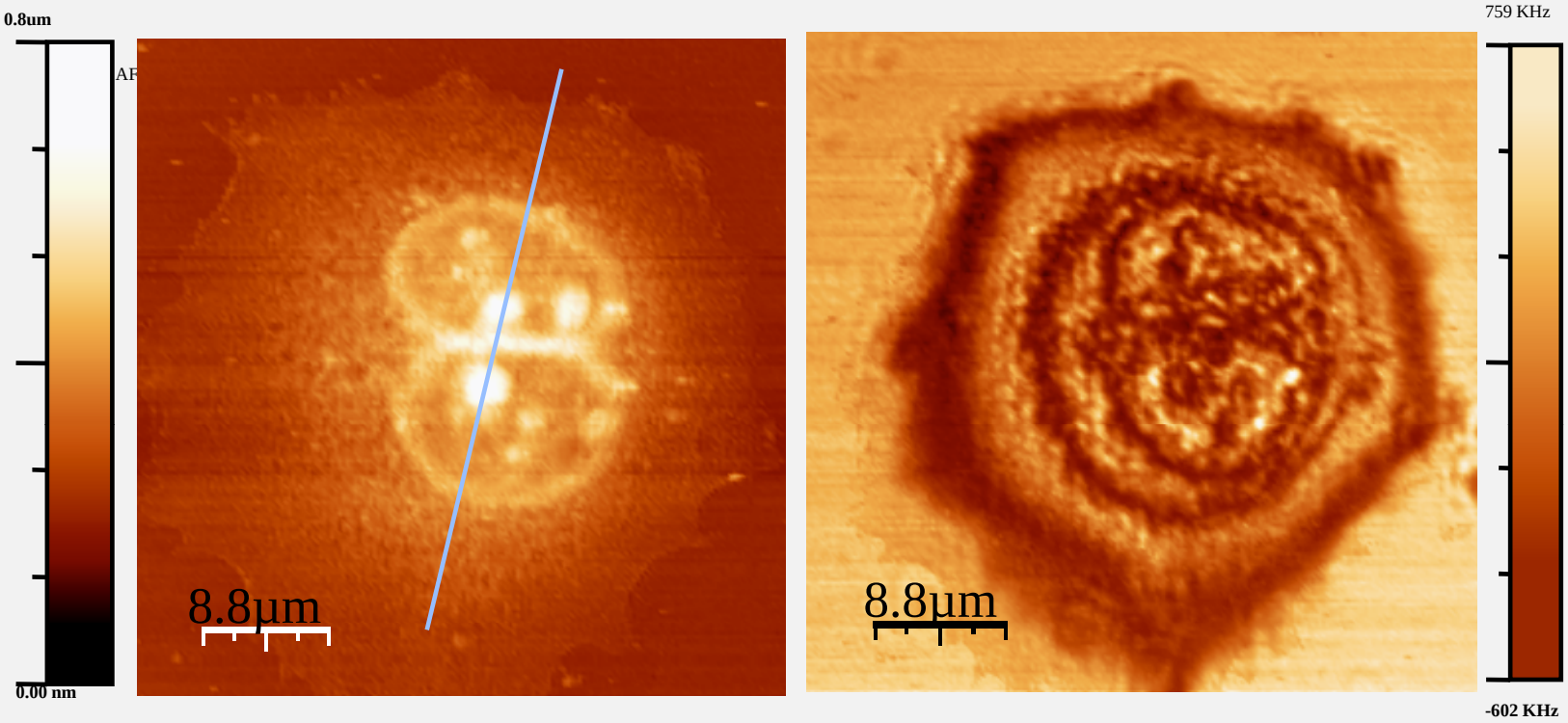
The Nanonics Multiview 1000 AFM/NSOMsystem

Advantanges of AFM:
- Surface morphologies
- Accurate size measurements
- Higher forces can be used to probe mechanical response of cell

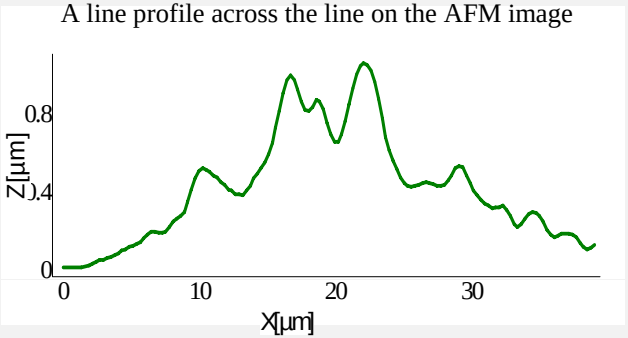
Advantages of NSOM:
- Can see inner details of cells
- Increase resolution of optical microscope from ~200nm far-field to ~30nm near-field
- Can use fluorescence to mark specific parts of cell
- Simple sample preparation: No need to coat or extract a thin slice. Live cells can be used.

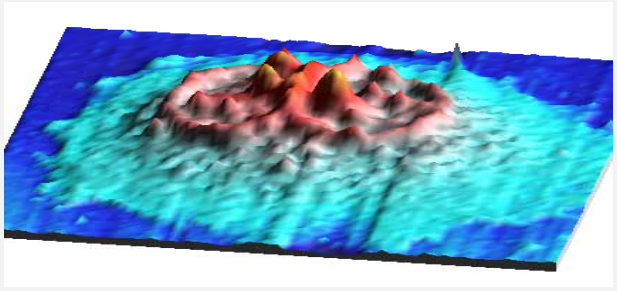


AFM and NSOM Image for a MCF10A cell Experiencing Telophase of Mitosis



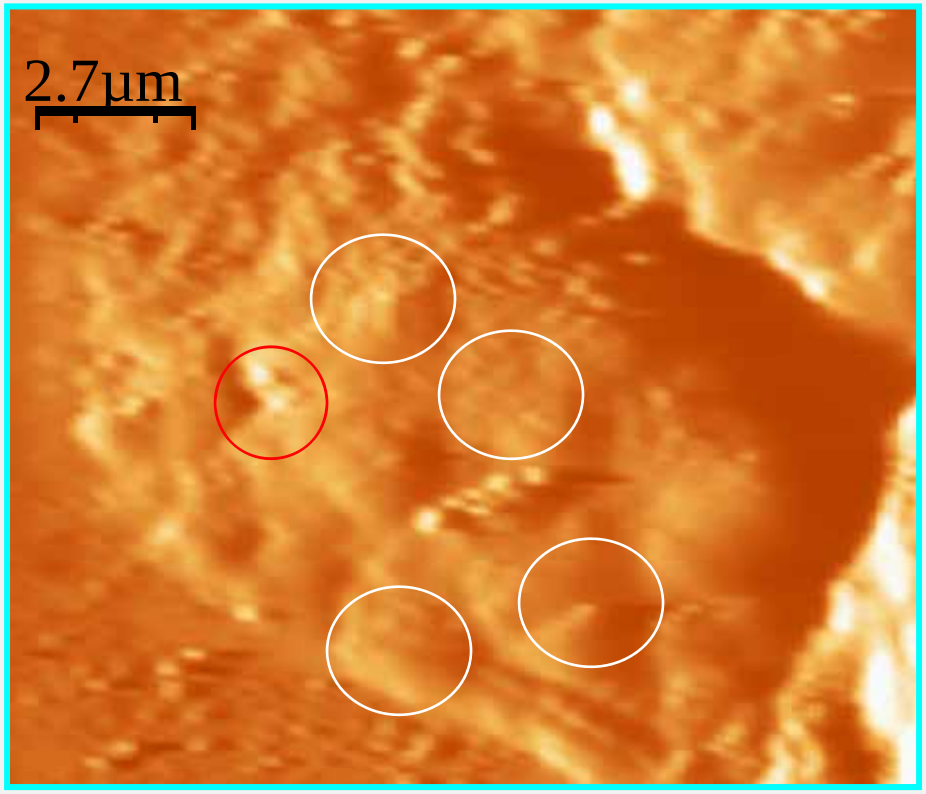
A line profile across the line on the AFM image



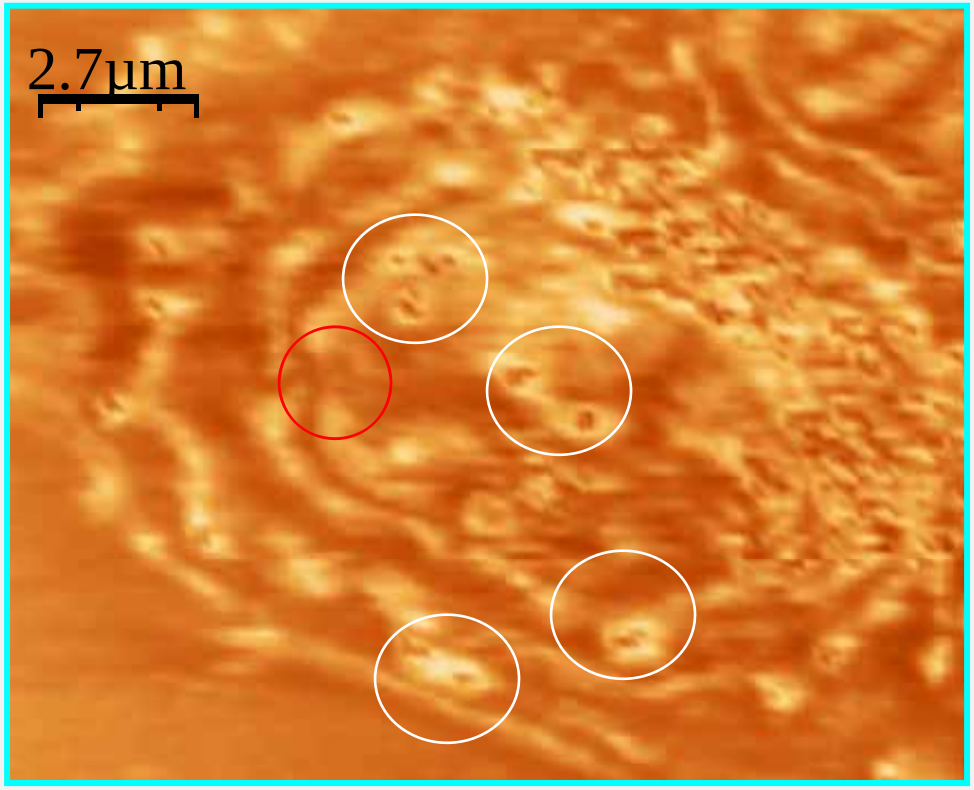


MCF10A Normal Cell Incubated for 24 hours
8 nm Iron Oxide Nanoparticles

AFM Image



NSOM Image



We can see iron oxide nanoparticles inside the cell by NSOM

AFM can give complementary information to decide the particles' position.

AFM/NSOM hybrid technique together provide more detailed information for nanoparticles and cells

We observed endocytosis of iron oxide nanopartles

Recent Addition

MOCVD system start up in December 2008

-Massively parallel array of nanowires
-Multi-segment nanowires
-Core-shell nanowires

Summary

- Functionalized carbon nanotubes serve as 1-D building blocks for self-assembled electronic architectures
- Bio-molecular linkers can provide both binding and electrical functionality
- Virus and microtubule 1-D templates are also promising for device applications
- Electrochemical nanostructures for a variety of applications
- Massively parallel arrays of 1D templates are needed for large scale nanopatterning

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