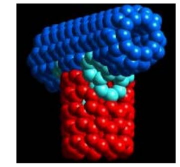
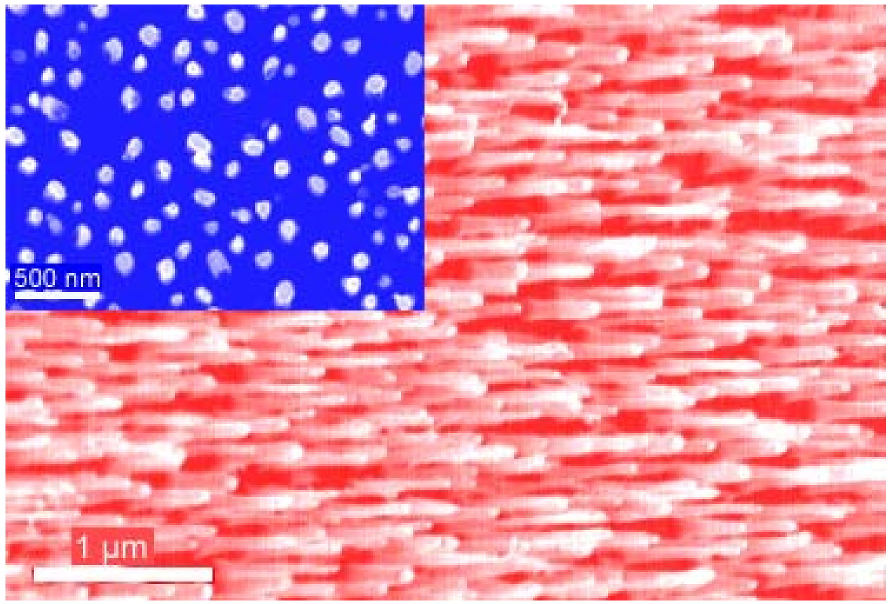
An Overview of Recent Developments in Nanotechnology





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Why Nanotechnology at NASA?

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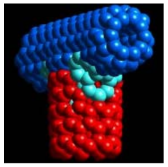


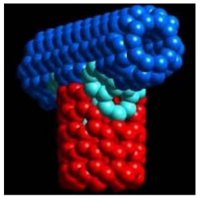
- Advanced miniaturization, a key thrust area to enable new science and exploration missions
  - Ultrasmall sensors, power sources, communication, navigation, and propulsion systems with very low mass, volume and power consumption are needed

- Revolutions in electronics and computing will allow reconfigurable, autonomous, "thinking" spacecraft

- Nanotechnology presents a whole new spectrum of opportunities to build device components and systems for entirely new space architectures
  - Networks of ultrasmall probes on planetary surfaces
  - Micro-rovers that drive, hop, fly, and burrow
  - Collection of microspacecraft making a variety of measurements

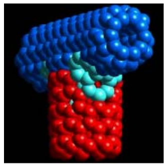
Europa Submarine

NASA Ames Nanotechnology Research Focus



* **Carbon Nanotubes**
  - Growth (CVD, PECVD)
  - Characterization
  - AFM tips
    - Metrology
    - Imaging of Mars Analog
    - Imaging Bio samples
  - Electrode development
  - Biosensor (cancer diagnostics)
  - Chemical sensor
  - Logic Circuits
  - Chemical functionalization
  - Gas Absorption
  - Device Fabrication
* **Molecular Electronics**
  - Synthesis of organic molecules
  - Characterization
  - Device fabrication
* **Inorganic Nanowires**
* **Protein Nanotubes**
  - Synthesis
  - Purification
  - Application Development
* **Genomics**
  - Nanopores in gene sequencing
  - Genechips development
* **Computational Nanotechnology**
  - CNT - Mechanical, thermal properties
  - CNT - Electronic properties
  - CNT based devices: physics, design
  - CNT based composites, BN nanotubes
  - CNT based sensors
  - DNA transport
  - Transport in nanopores
  - Nanowires: transport, thermoelectric effect
  - Transport: molecular electronics
  - Protein nanotube chemistry
* **Quantum Computing**
* **Computational Quantum Electronics**
  - Noneq. Green's Function based Device Simulator
* **Computational Optoelectronics**
* **Computational Process Modeling**

Nanotechnology Research of Interest to IEEE Community



- Nanoelectronics (CNTs, molecular electronics)
- Non-CMOS circuits and architectures, reconfigurable systems
- Spintronics, quantum computing, nanomagnetics
- Nanophotonics, nano-optics, nanoscale lasers….
- Chemical and biological sensors
- Novel materials for all applications (CNTs, quantum dots, inorganic nanowires…
- Integration of nano-micro-macro
- Bio-nano fusion

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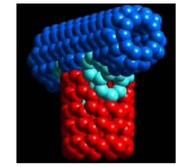
Agenda



- Carbon Nanotubes
  - CNT - growth and characterization
  - CNT based nanoelectronics
  - CNT based microscopy
  - CNT interconnects
  - CNT based biosensors
  - CNT chemical sensors
- Some other Nano examples
  - Inorganic nanowires
  - Protein nanotubes
  - Nano in gene sequencing

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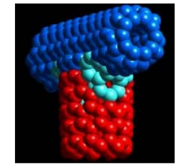
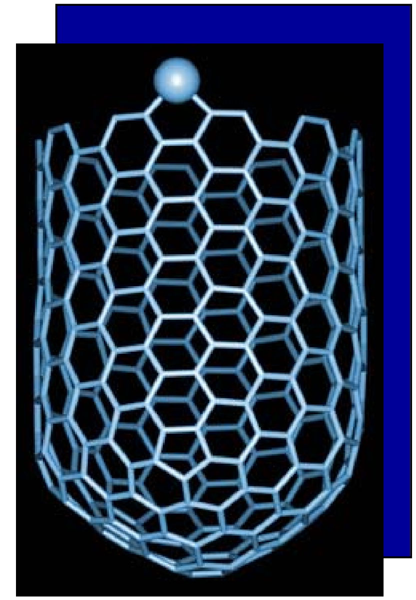
Carbon Nanotube

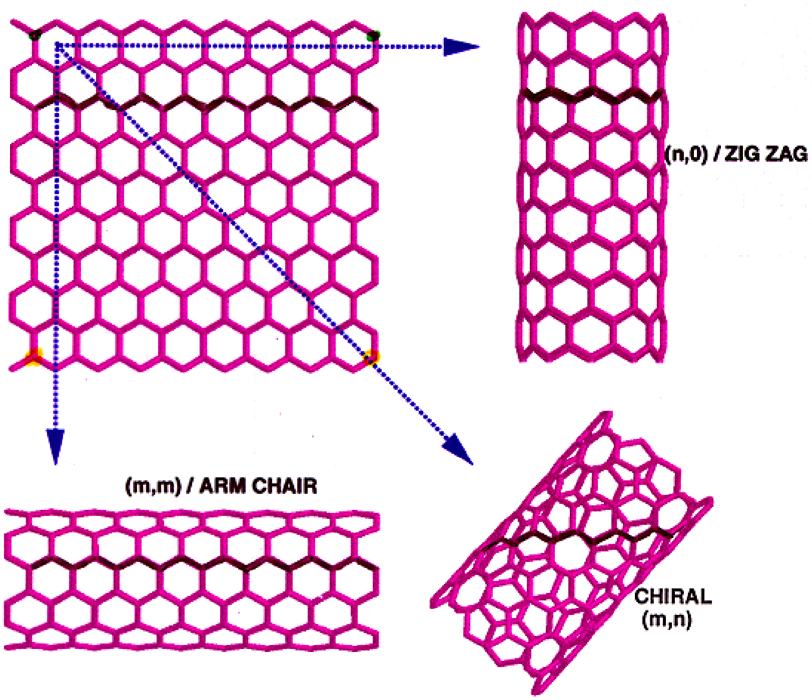


CNT is a tubular form of carbon with diameter as small as 1 nm.
Length: few nm to microns.

CNT is configurationally equivalent to a two dimensional graphene sheet rolled into a tube.



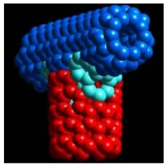
- STRIP OF A GRAPHENE SHEET ROLLED INTO A TUBE

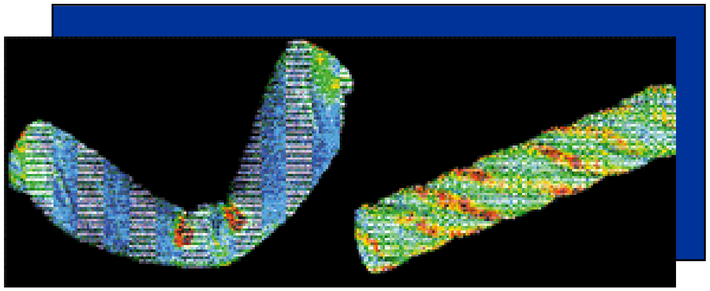


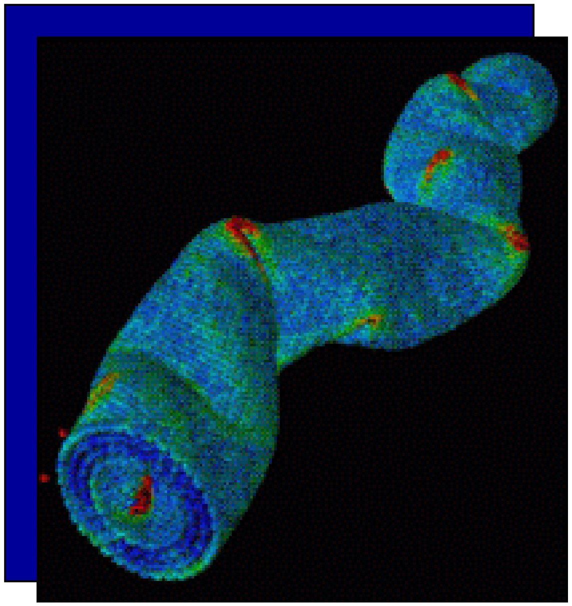
CNT exhibits extraordinary mechanical properties: Young's modulus over 1 Tera Pascal, as stiff as diamond, and tensile strength ~ 200 GPa.

CNT can be metallic or semiconducting, depending on chirality.

CNT Properties







- The strongest and most flexible molecular material because of C-C covalent bonding and seamless hexagonal network architecture

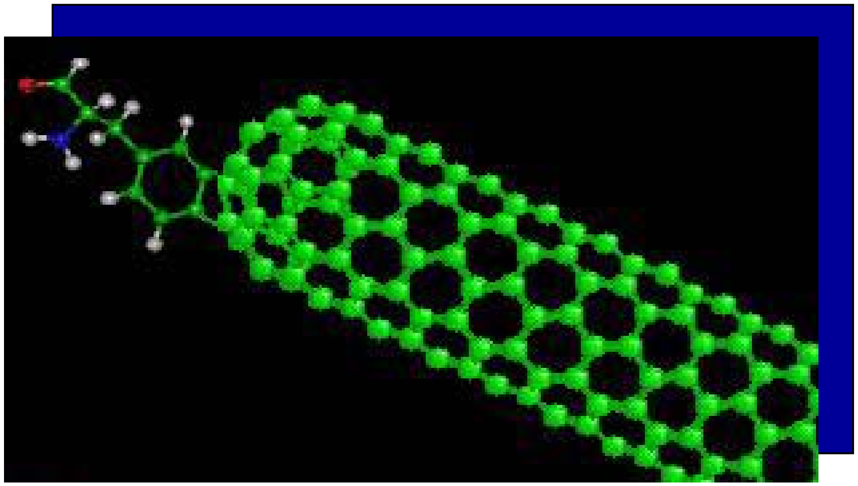
- Young's modulus of over 1 TPa vs 70 GPa for Aluminum, 700 GPA for C-fiber
  - strength to weight ratio 500 time > for Al; similar improvements over steel and titanium; one order of magnitude improvement over graphite/epoxy

- Maximum strain ~10% much higher than any material

- Thermal conductivity ~ 3000 W/mK in the axial direction with small values in the radial direction

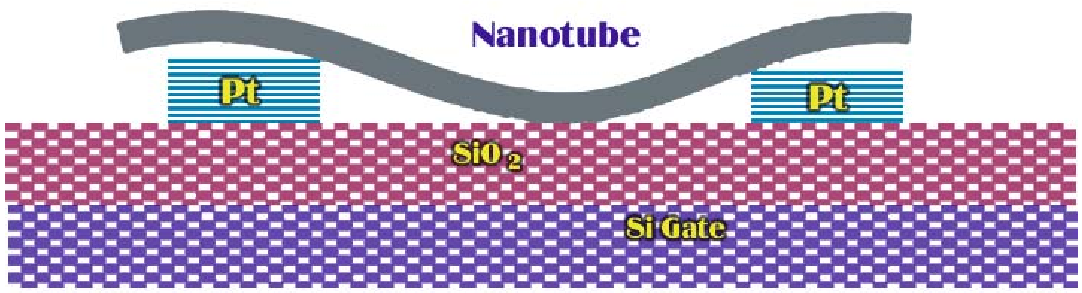
CNT Properties (cont.)

- Electrical conductivity six orders of magnitude higher than copper
- Can be metallic or semiconducting depending on chirality
  - ‘tunable’ bandgap
  - electronic properties can be tailored through application of external magnetic field, application of mechanical deformation…
- Very high current carrying capacity
- Excellent field emitter; high aspect ratio and small tip radius of curvature are ideal for field emission
- Can be functionalized



CNT Applications: Electronics

- CNT quantum wire interconnects
- Diodes and transistors for computing
- Capacitors
- Data Storage
- Field emitters for instrumentation
- Flat panel displays
- THz oscillators



Challenges

- Control of diameter, chirality
- Doping, contacts
- Novel architectures (not CMOS based!)
- Development of inexpensive manufacturing processes

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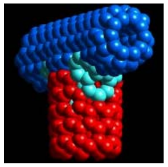
CNT Applications: Structural, Mechanical

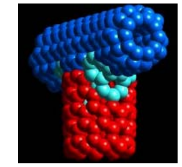


- High strength composites
- Cables, tethers, beams
- Multifunctional materials
- Functionalize and use as polymer back bone
  - plastics with enhanced properties like "blow molded steel"
- Heat exchangers, radiators, thermal barriers, cryotanks
- Radiation shielding
- Filter membranes, supports
- Body armor, space suits

Challenges

- Control of properties, characterization
- Dispersion of CNT homogeneously in host materials
- Large scale production
- Application development

CNT Applications: Sensors, NEMS, Bio



- CNT based microscopy: AFM, STM…
- Nanotube sensors: force, pressure, chemical…
- Biosensors
- Molecular gears, motors, actuators
- Batteries, Fuel Cells: H_2, Li storage
- Nanoscale reactors, ion channels
- Biomedical
  - in vivo real time crew health monitoring
  - Lab on a chip
  - Drug delivery
  - DNA sequencing
  - Artificial muscles, bone replacement, bionic eye, ear...

Challenges

- Controlled growth
- Functionalization with probe molecules, robustness
- Integration, signal processing
- Fabrication techniques

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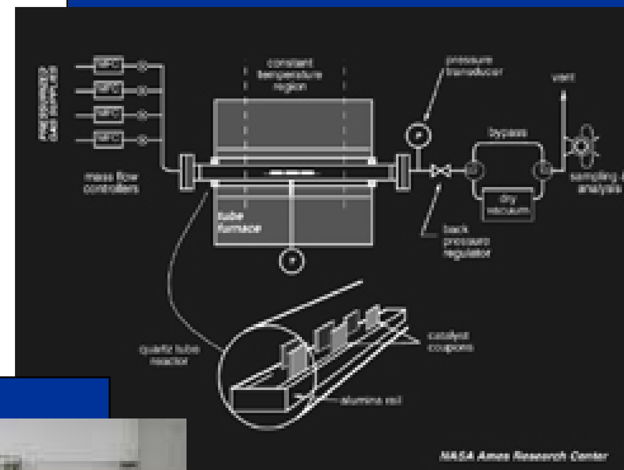
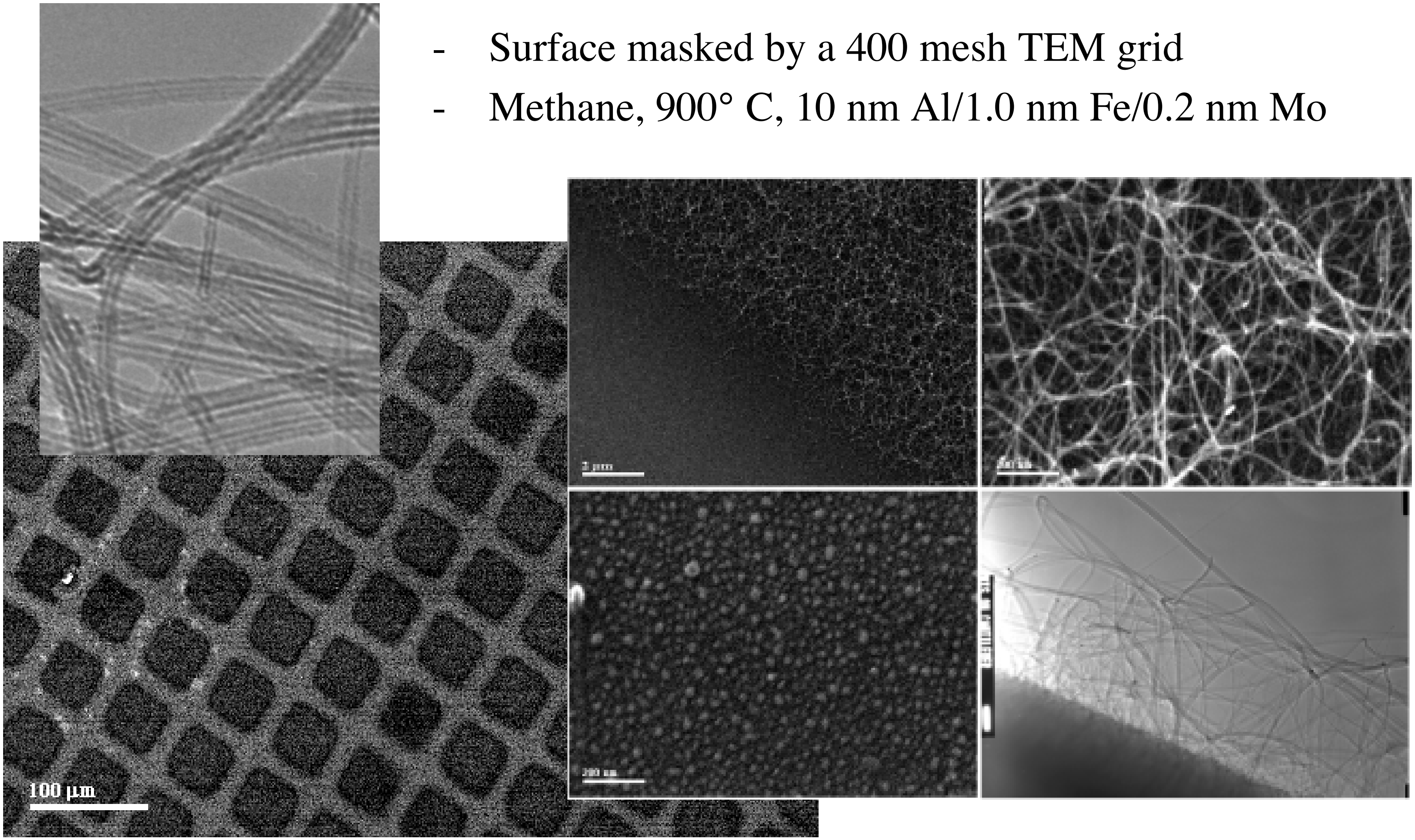
CNT Synthesis

- CNT has been grown by laser ablation (pioneering at Rice) and carbon arc process (NEC, Japan) - early 90s.
  - SWNT, high purity, purification methods
- CVD is ideal for patterned growth (electronics, sensor applications)
  - Well known technique from microelectronics
  - Hydrocarbon feedstock
  - Growth needs catalyst (transition metal)
  - Multiwall tubes at 500-800° deg. C.
  - Numerous parameters influence CNT growth



SWNTs on Patterned Substrates

- Surface masked by a 400 mesh TEM grid
- Methane, 900° C, 10 nm Al/1.0 nm Fe/0.2 nm Mo



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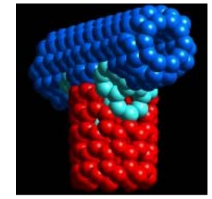
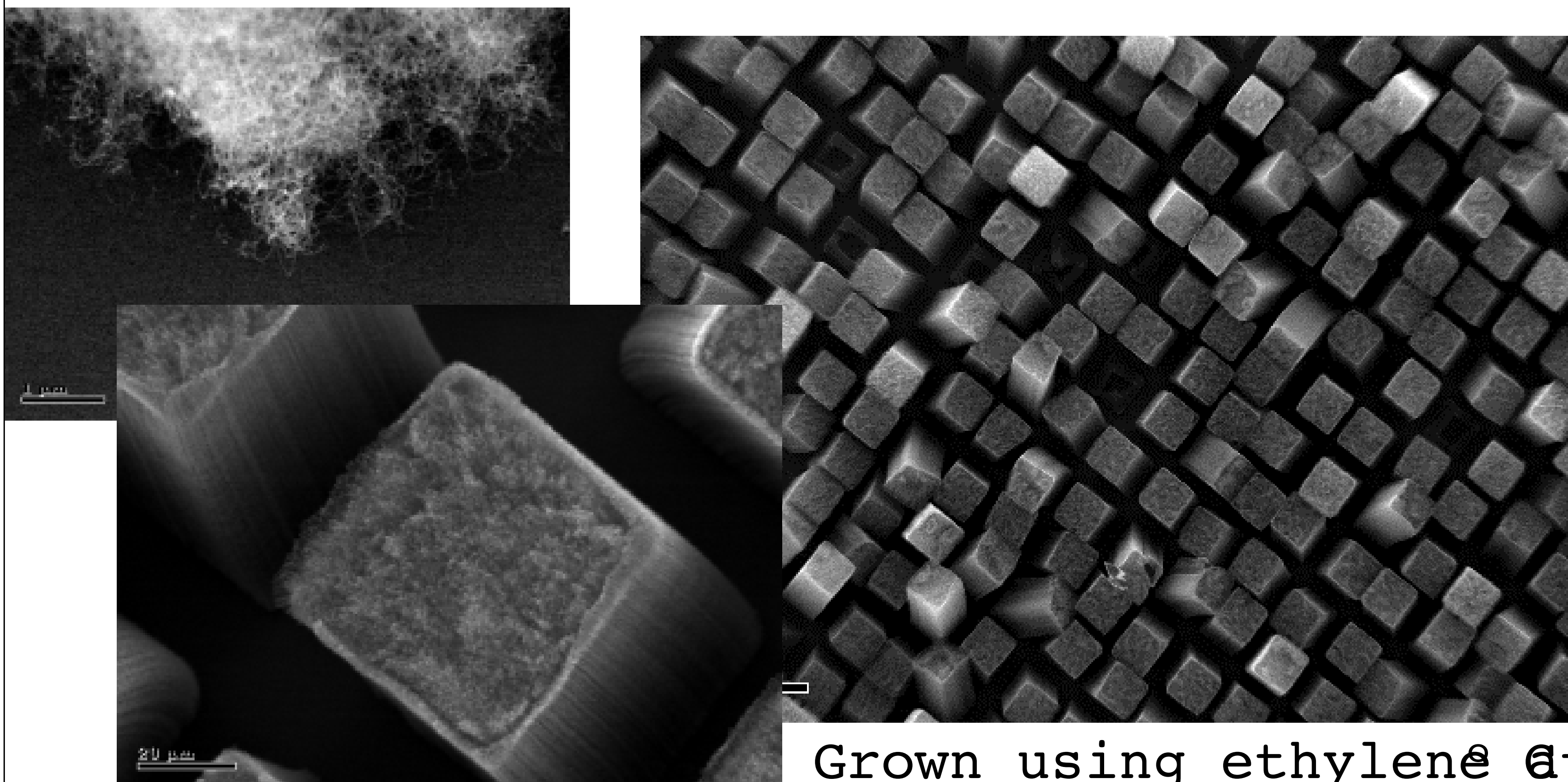
Multiwall Nanotube Towers



- Surface masked by a 400 mesh TEM grid; 20 nm Al/ 10 nm Fe; nanotubes grown for 10 minutes



Grown using ethylene at 75

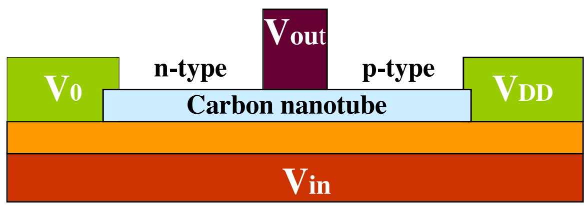
ICP Reactor for CNT Growth

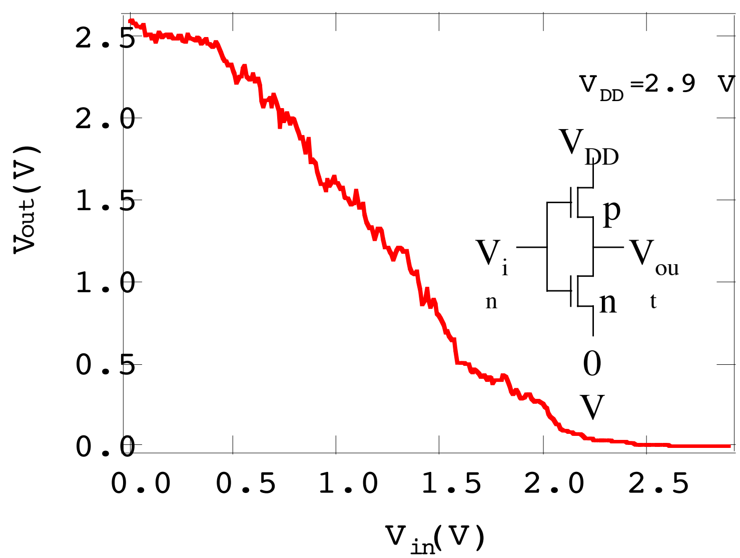
- Inductively coupled plasmas are the simplest type of plasmas; very efficient in sustaining the plasma; reactor easy to build and simple to operate
- Quartz chamber 10 cm in diameter with a window for sample introduction
- Inductive coil on the upper electrode
- 13.56 MHz independent capacitive power on the bottom electrode
- Heating stage for the bottom electrode
- Operating conditions
  CH_4/H_2 : 5 - 20%
  Total flow : 100 sccm
  Pressure : 1 - 20 Torr
  Inductive power : 100-200 W
  Bottom electrode power : 0 - 100 W

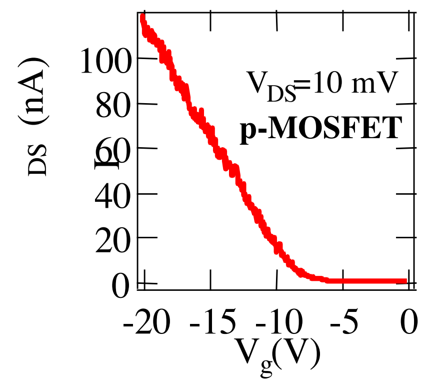
CNT-based Logic and Memory Devices

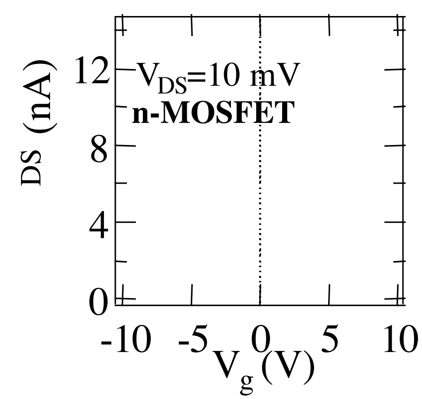
*First single nanotube logic Inverter device demonstration Appl. Phys. Lett., Nov. 200

by Chongwu Zhou (USC) and Jie Han (NASA Ames)

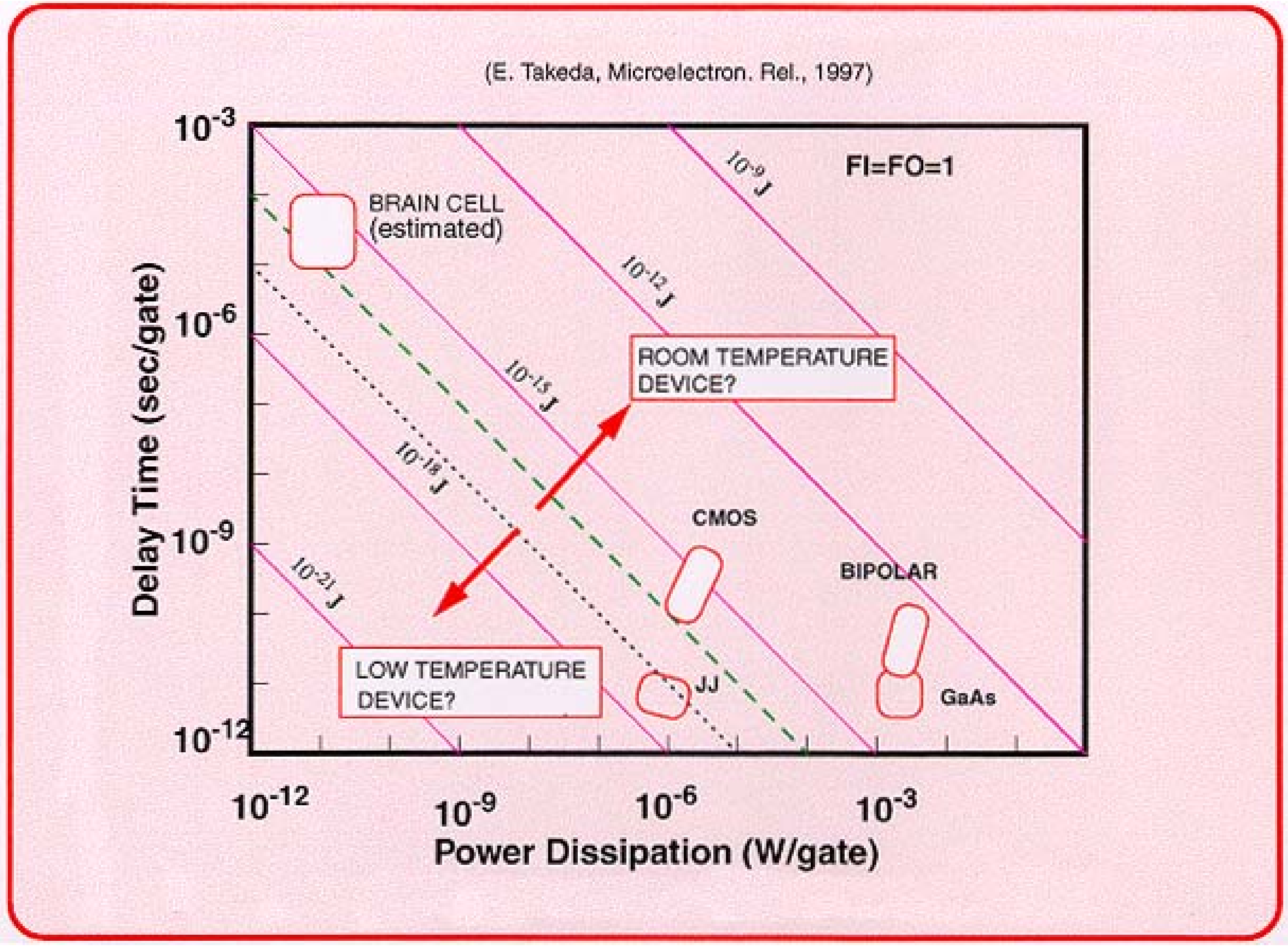






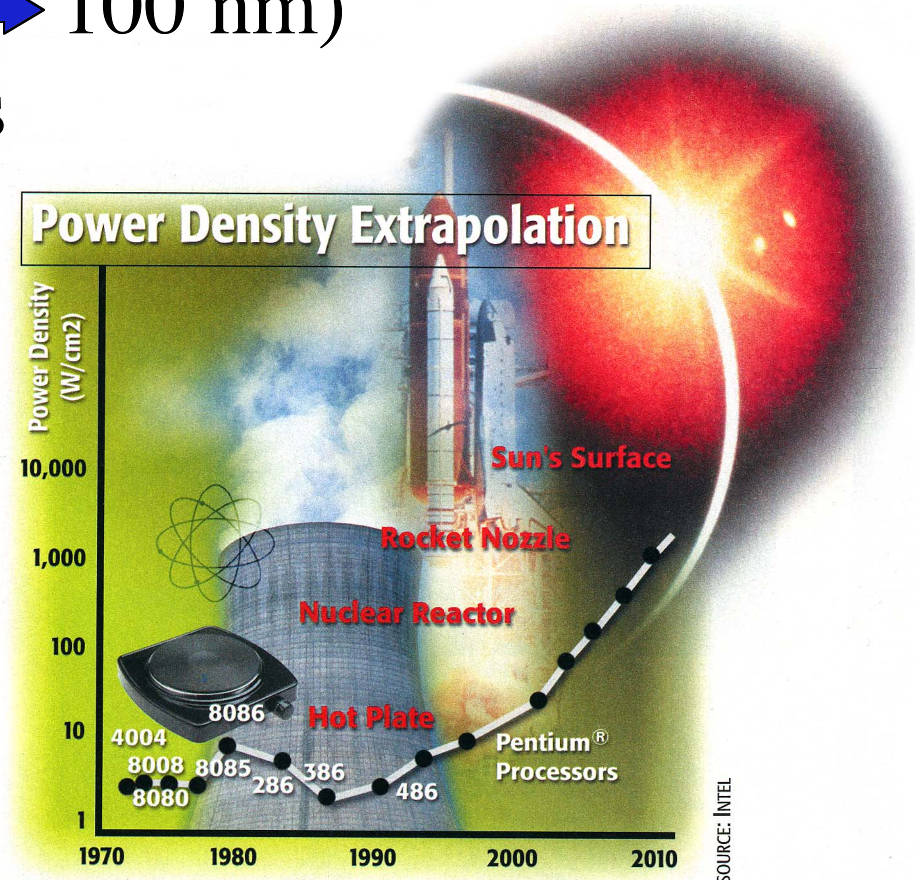


Switching Energy of Electron Devices and Brain Cells



Too Hot to Handle

As device feature size continues to shrink (180 nm → 130 nm → 100 nm) and chip density continues to increase, heat dissipation from the chip is becoming a huge challenge.



CPU - Computer Power User Magazine

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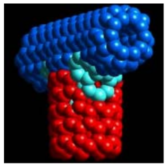
Nanoelectronics: What is Expected from Alternative Technologies?

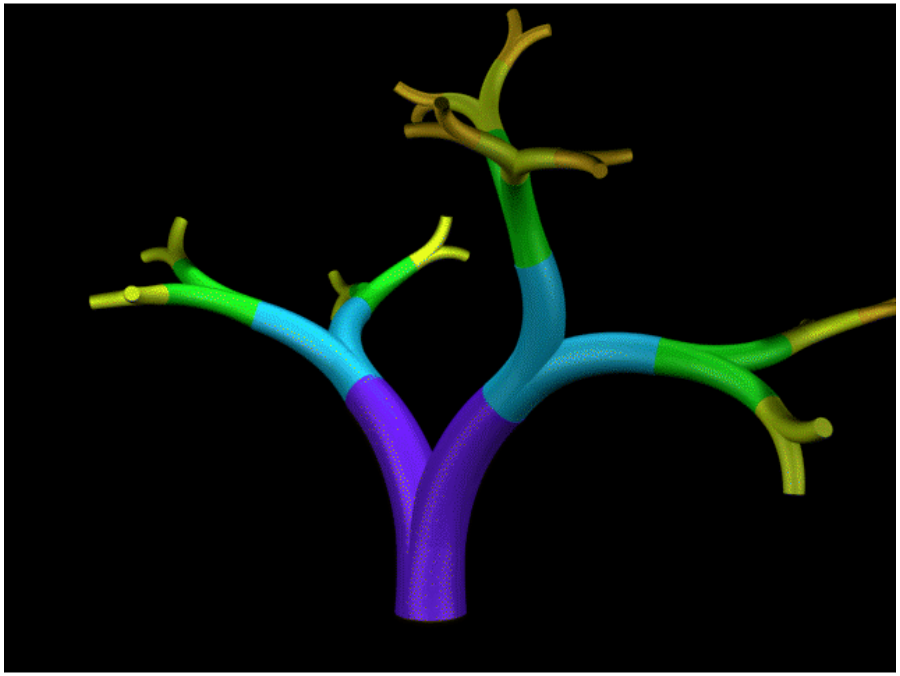
(Beyond the SIA Roadmap for Silicon)

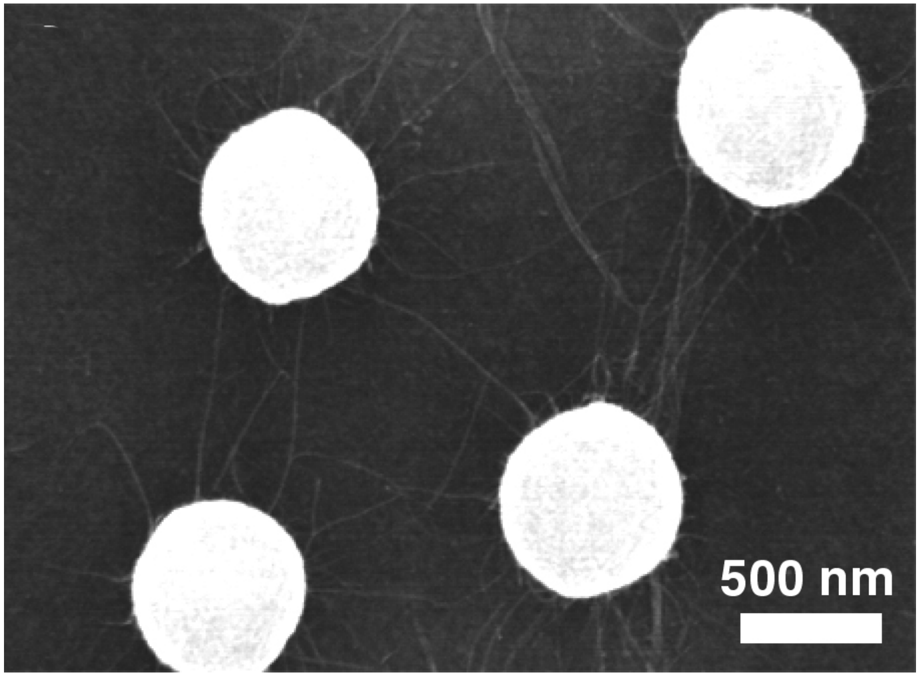


- Must be easier and cheaper to manufacture than CMOS
- Need high current drive; should be able to drive capacitances of interconnects of any length
- High level of integration (>10^{10} transistors/circuit)
- High reproducibility (better than ± 5%)
- Reliability (operating time > 10 years)
- Very low cost (< 1 μcent/transistor)
- Better heat dissipation characteristics and amenable solutions
- Everything about the new technology must be compelling and simultaneously further CMOS scaling must become difficult and not cost-effective. Until these two happen together, the enormous infrastructure built around silicon will keep the silicon engine humming….

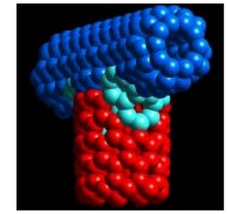
Four-level CNT Dentritic Neural Tree

- Neural tree with 14 symmetric Y-junctions
- Branching and switching of signals at each junction similar to what happens in biological neural network
- Neural tree can be trained to perform complex switching and computing functions
- Not restricted to only electronic signals; possible to use acoustic, chemical or thermal signals



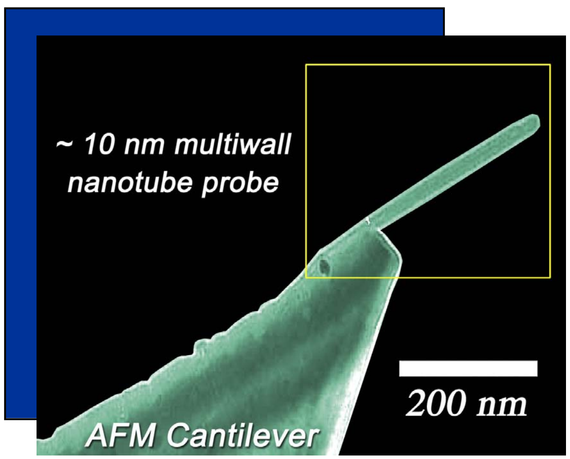


CNT in Microscopy

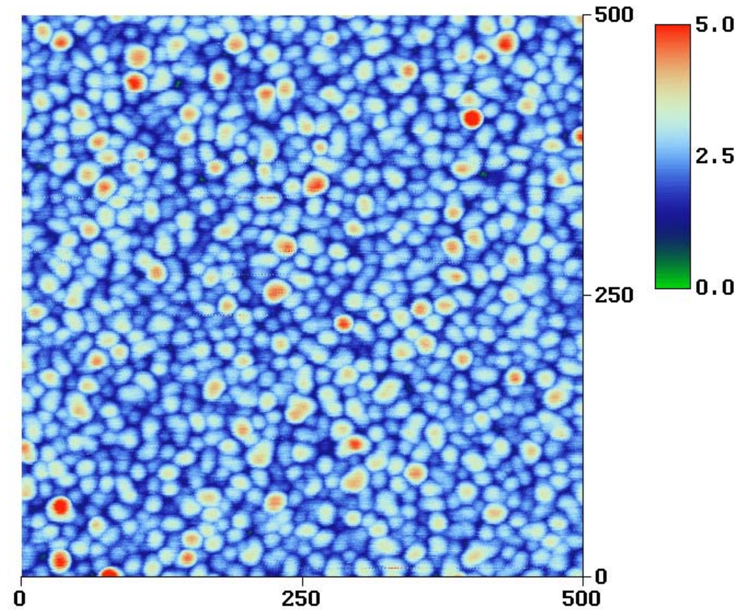


Atomic Force Microscopy is a powerful technique for imaging, nanomanipulation, as platform for sensor work, nanolithography...

Conventional silicon or tungsten tips wear out quickly. CNT tip is robust, offers amazing resolution.



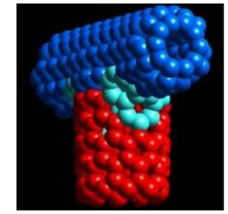
Simulated Mars dust

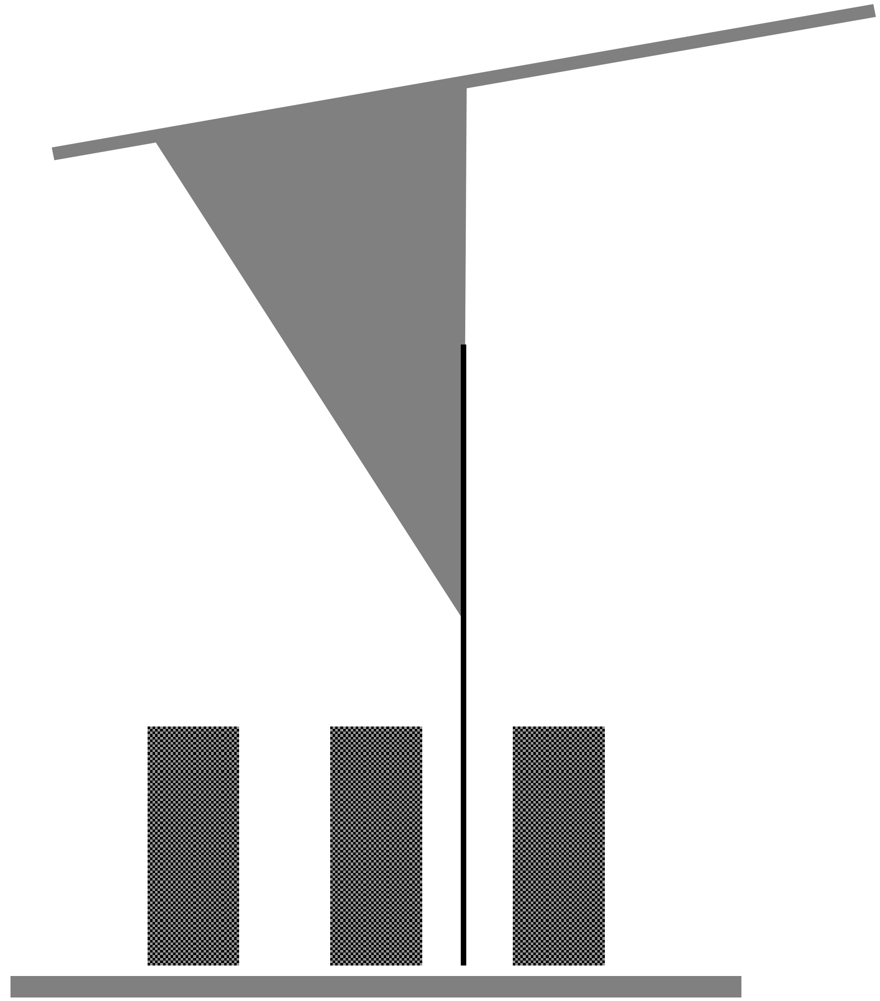


2 nm thick Au on Mica

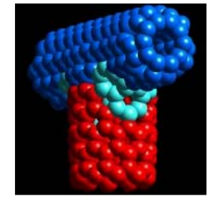
NASA Ames Research Center
Ramsey Stevens, Lance Delzeit, Cattien Nguyen

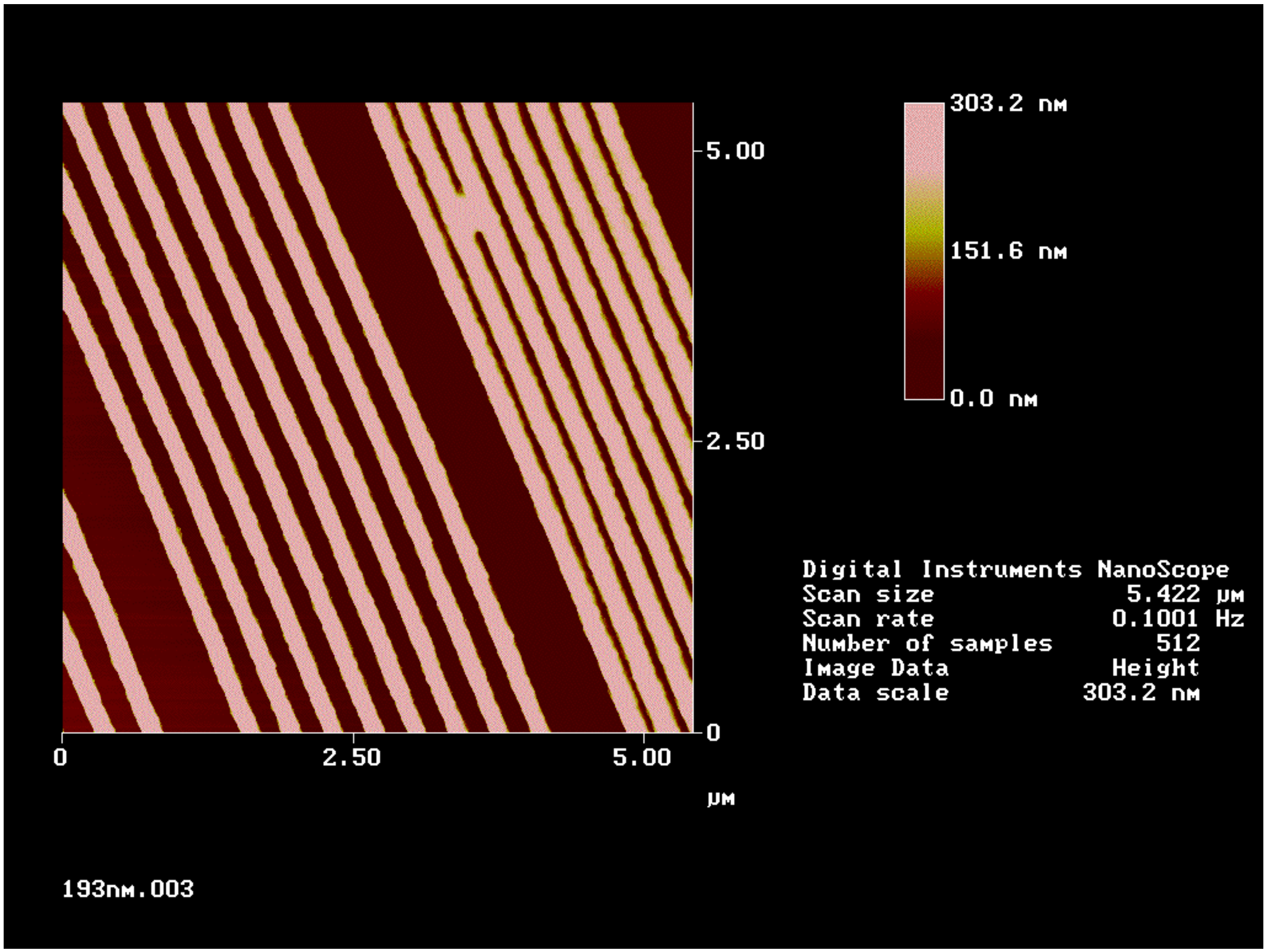
MWNT Scanning Probe





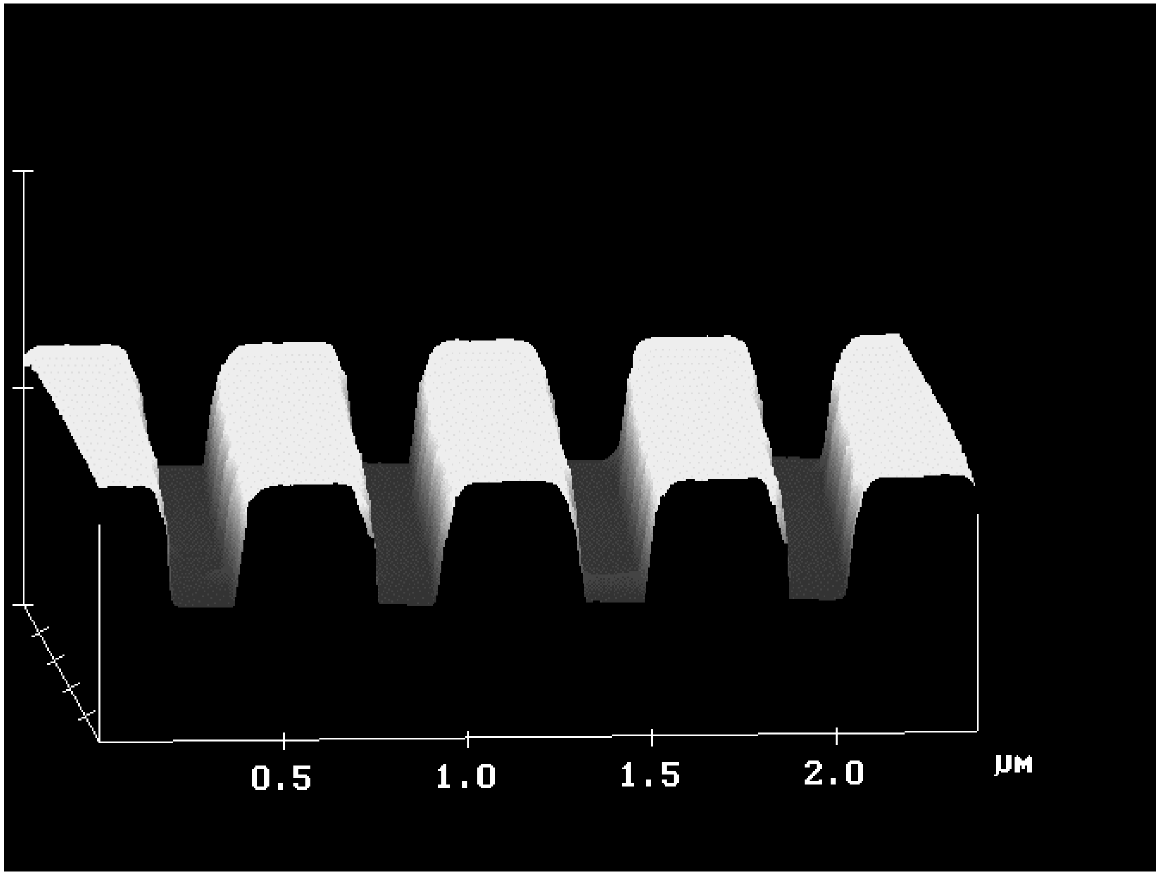
AFM Image with a MWNT Tip
193 nm IBM Version 2 Resist





AFM Image with MWNT Tip

DUV Photoresist Patterns Generated by Interferometric Lithography

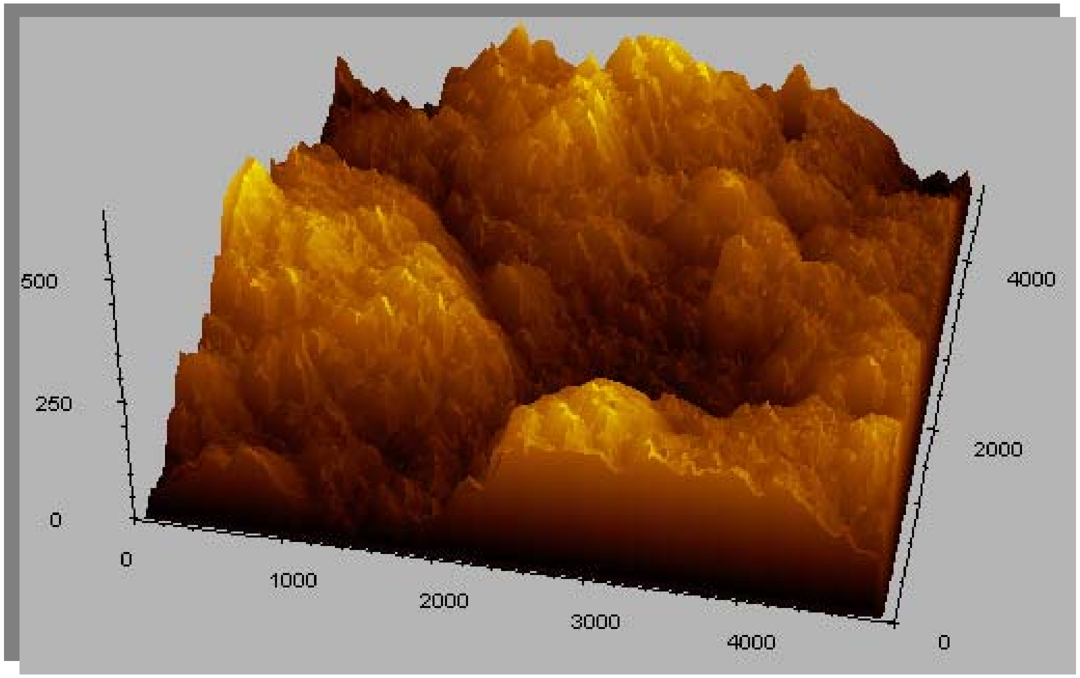


Nguyen et al., App. Phys. Lett., 81, 5, p. 901 (2002).

Imaging of Mars Analogs

Red Dune Sand (Mars Analog)

Optical image



AFM image using
carbon nanotube tip

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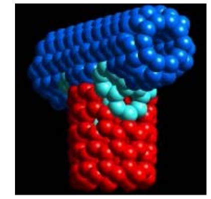
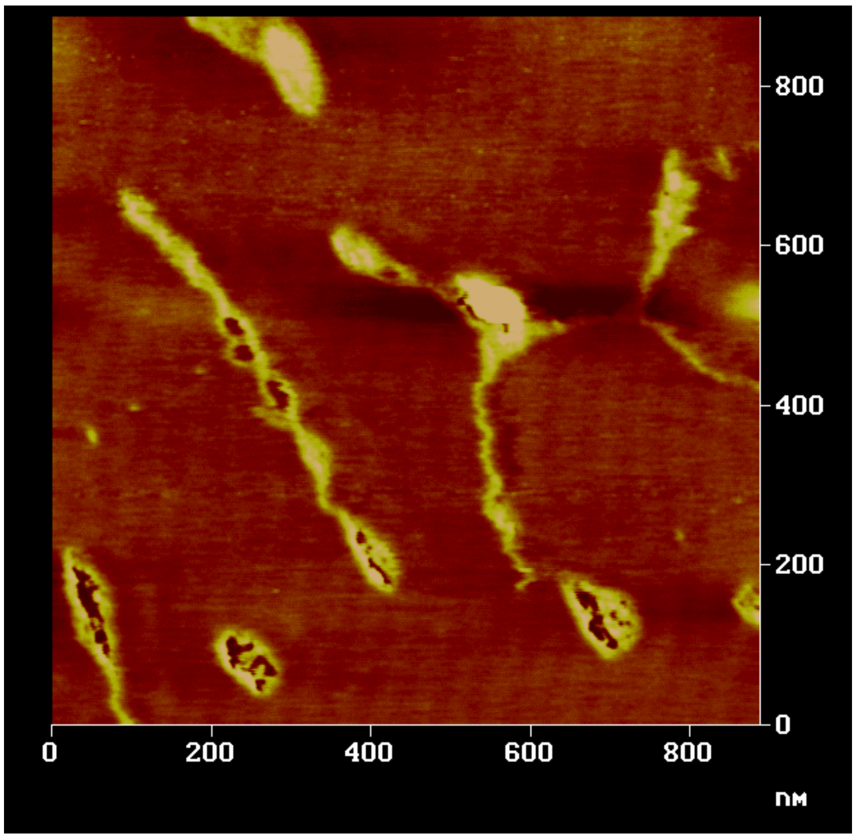
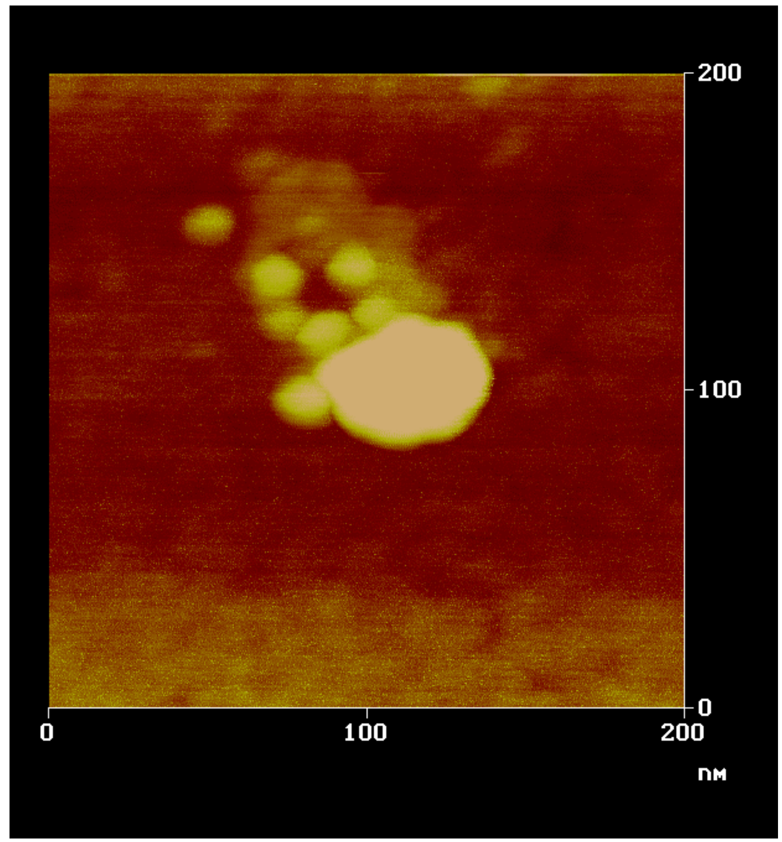
High Resolution Imaging of Biological Materials



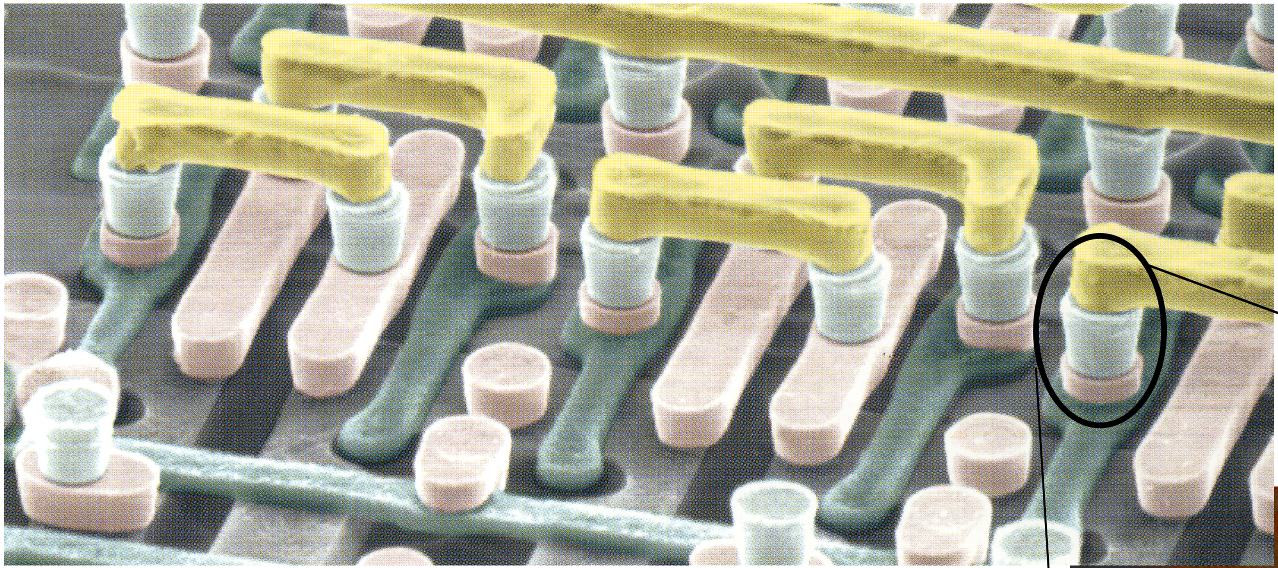


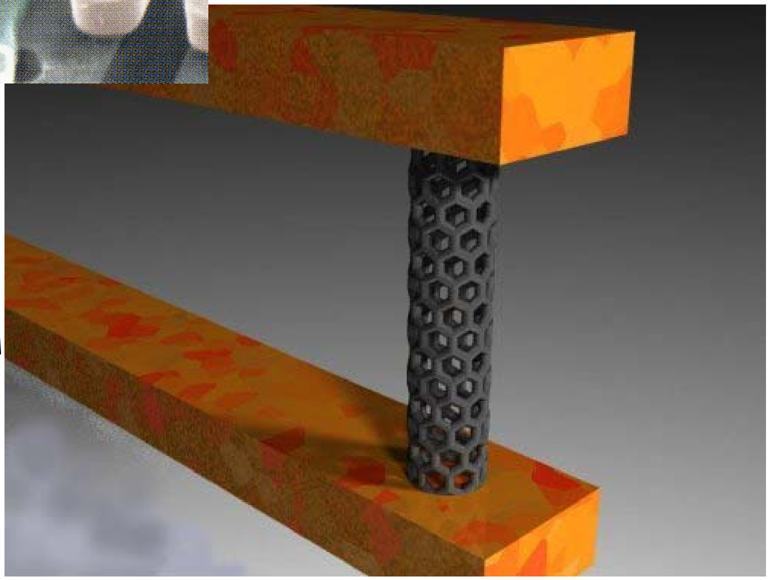
DNA



PROTEIN

MWNT Interconnects ?

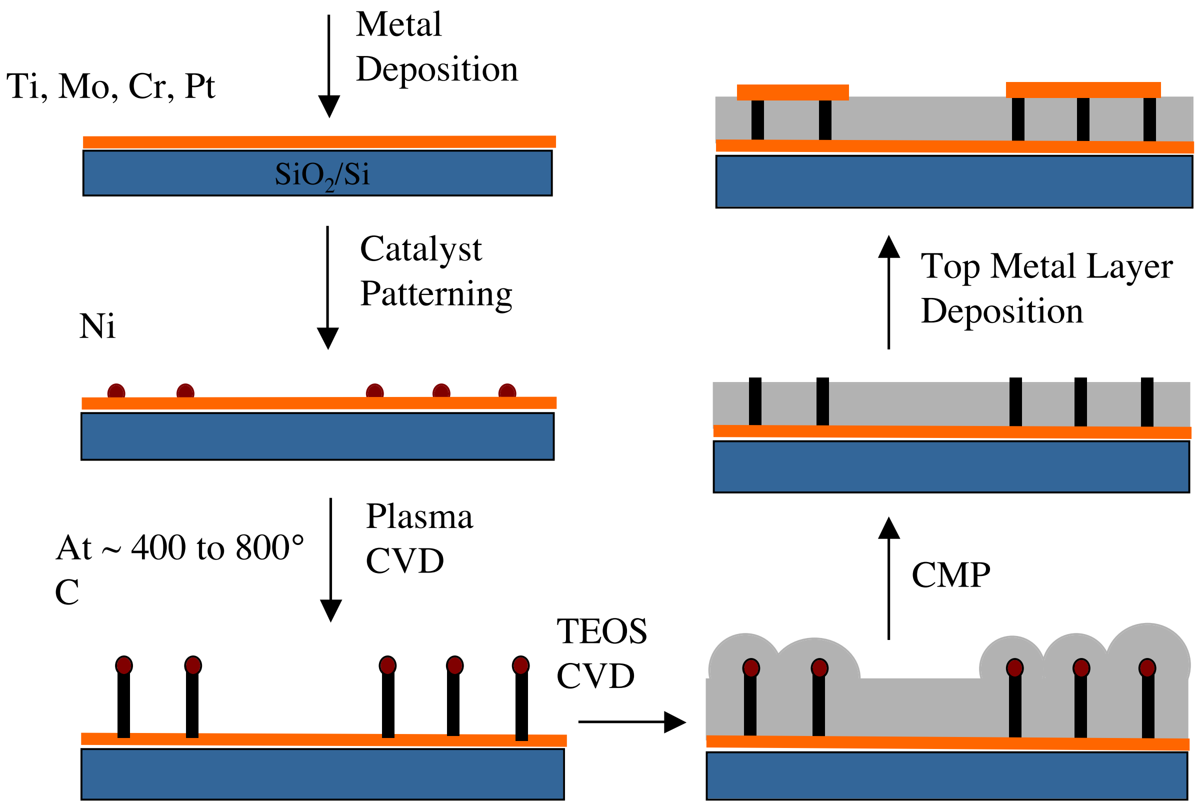


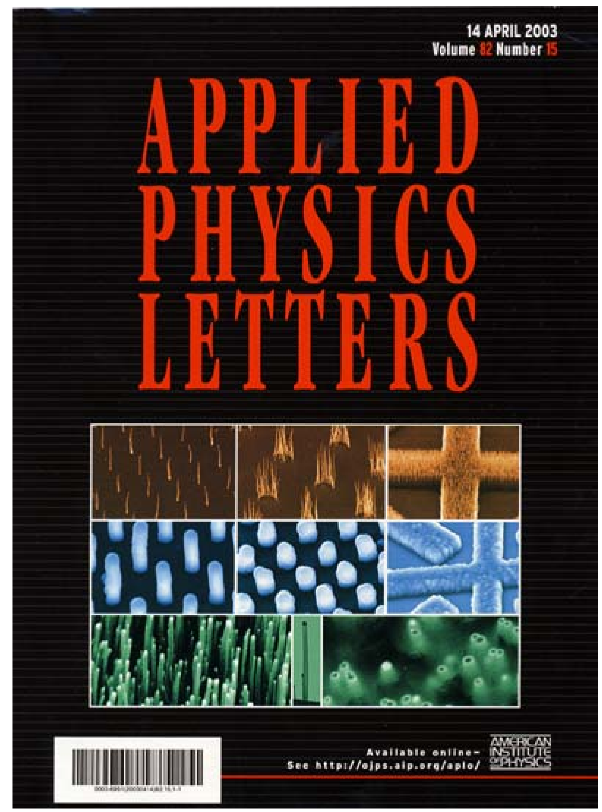


CNT advantages:
(1) Small diameter
(2) High aspect ratio
(3) Highly conductive along the axis
(4) High mechanical strength

Question: How to do this ?

Bottom-up Approach for CNT Interconnects





J. Li, Q. Ye, A. Cassell, H. T. Ng, R. Stevens, J. Han, M. Meyyappan, *Appl*. *Phys*. *Lett*., **82**(15), 2491 (2003)

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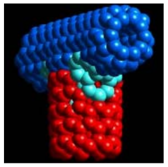
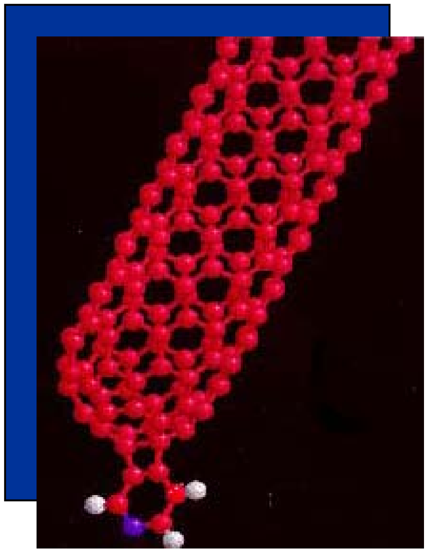
CNT Based Biosensors

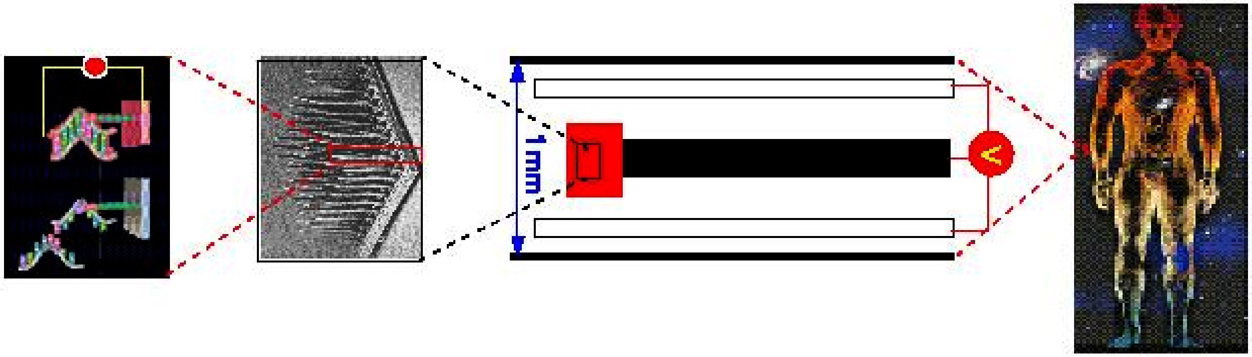


- Our interest is to develop sensors for astrobiology to study origins of life. CNT, though inert, can be functionalized at the tip with a probe molecule. Current study uses AFM as an experimental platform.

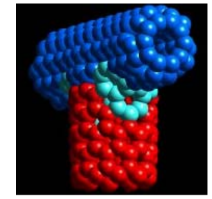


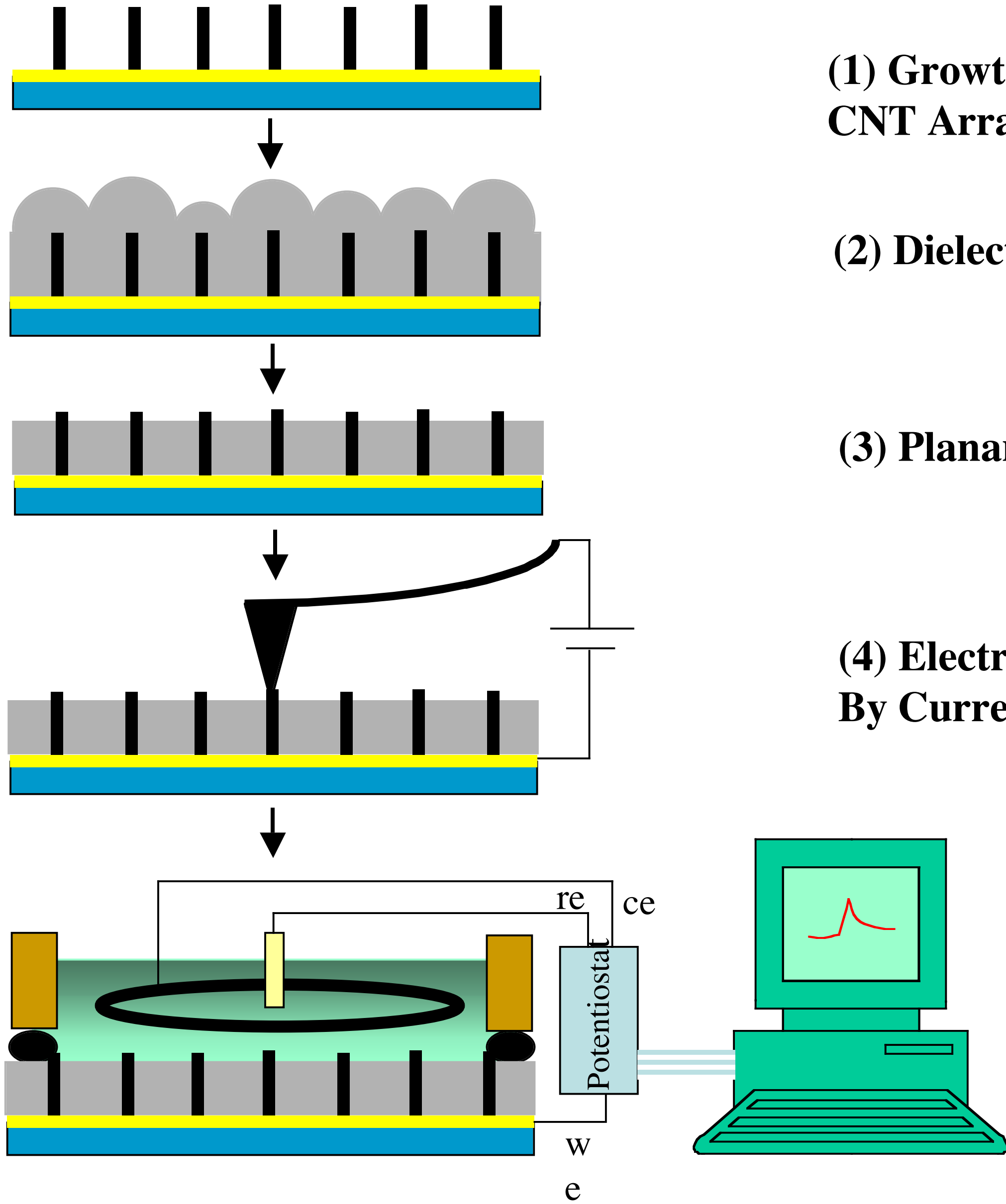
- The technology is also being used in collaboration with NCI to develop sensors for cancer diagnostics
  - Identified probe molecule that will serve as signature of leukemia cells, to be attached to CNT
  - Current flow due to hybridization will be through CNT electrode to an IC chip.
  - Prototype biosensors catheter development

- **High specificity**
- **Direct, fast response**
- **High sensitivity**
- **Single molecule and cell signal capture and detection**



The Fabrication of CNT Nanoelectrode Array





(1) Growth of Vertically Aligned CNT Array

(2) Dielectric Encapsulation

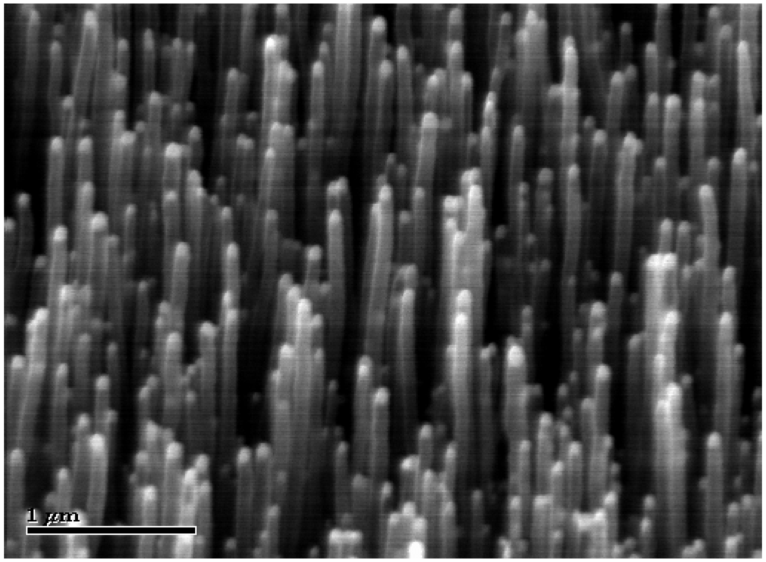
(3) Planarization

(4) Electrical Property Characterization By Current-sensing AFM

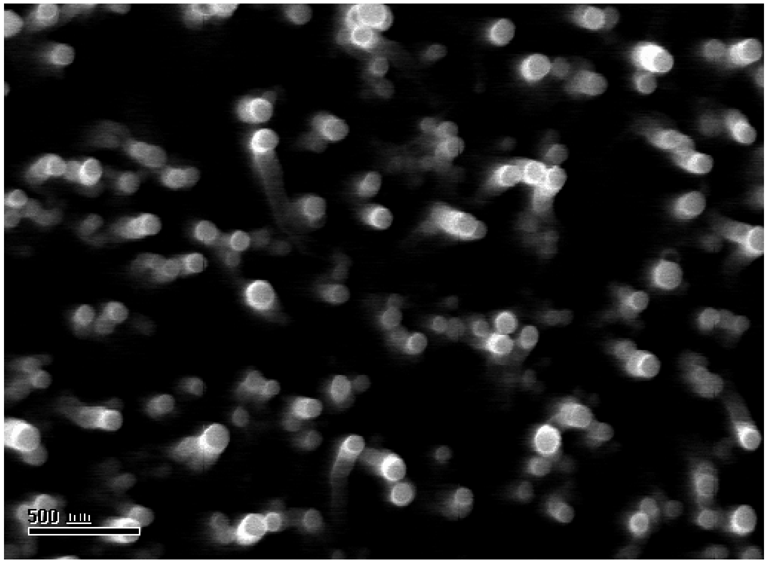
(5) Electrochemical Characterization

Fabrication of CNT Nanoelectrodes

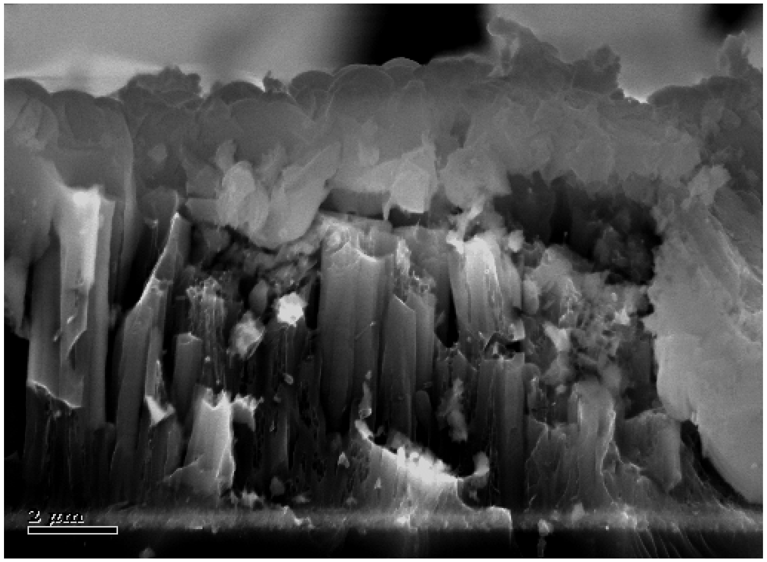
J. Li et al, *Appl. Phys. Lett.*, **81**(5), 910 (2002)



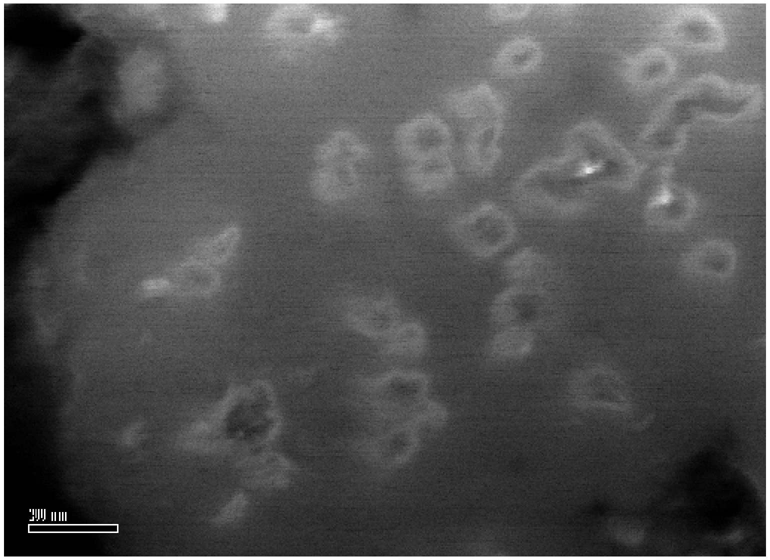
45 degree perspective view



Top view

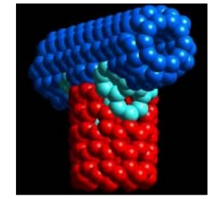


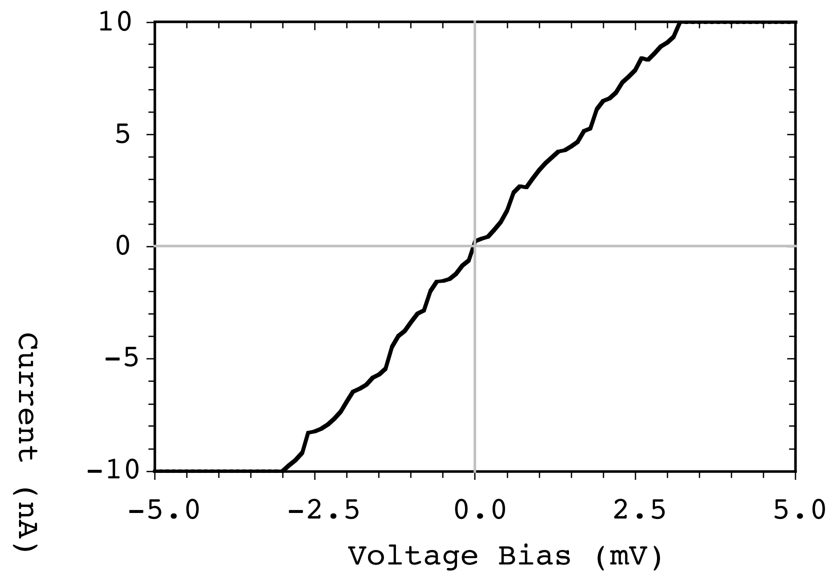
Side view after encapsulation

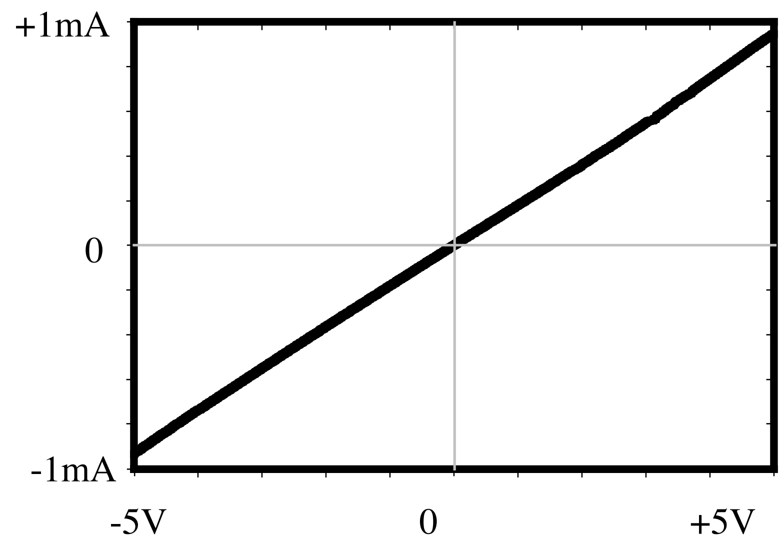


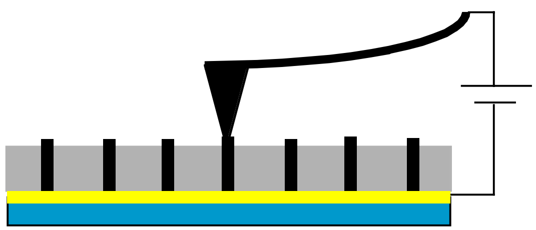
Top view after planarization

Electrical Properties of CNTs

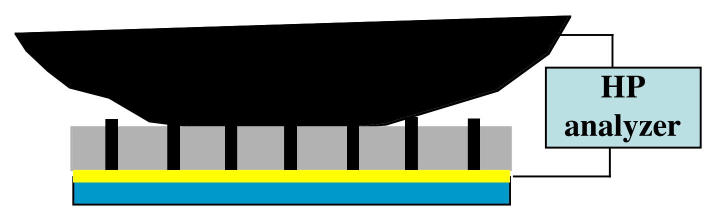






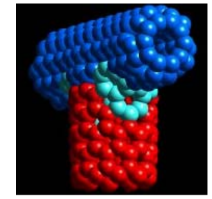


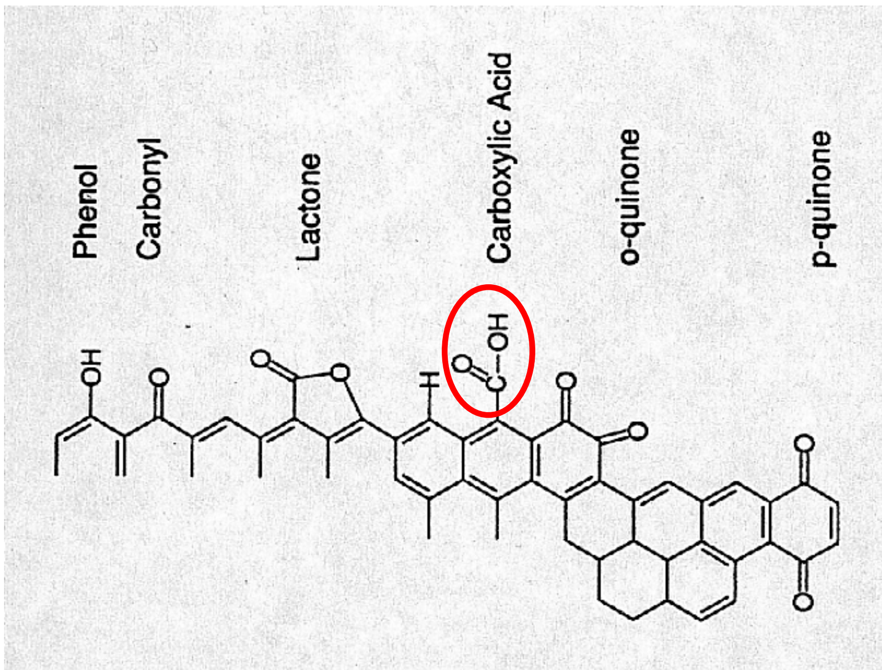
Current Sensing AFM

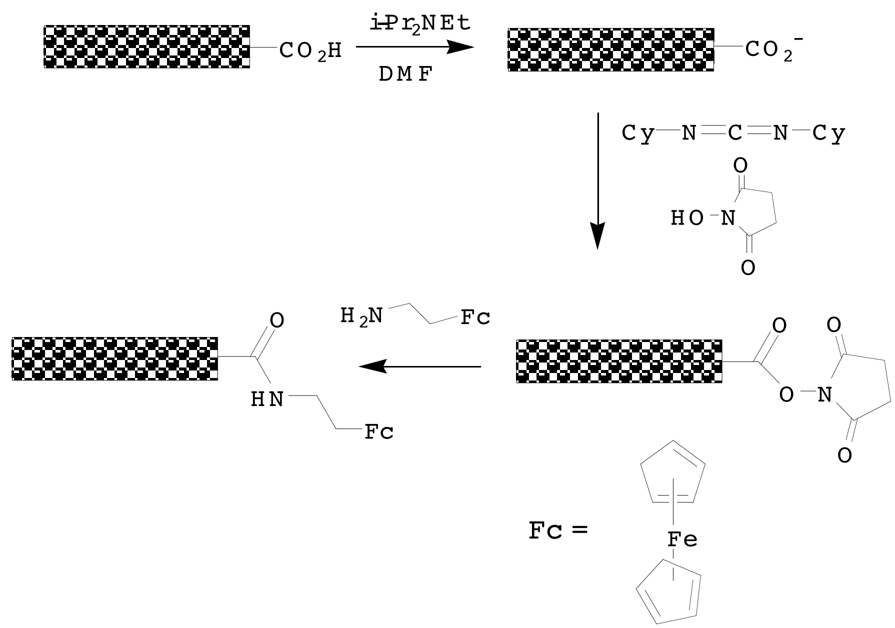


Four-probe station
And HP parameter analyzer

Chemical Functionalization

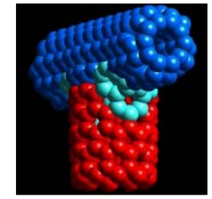


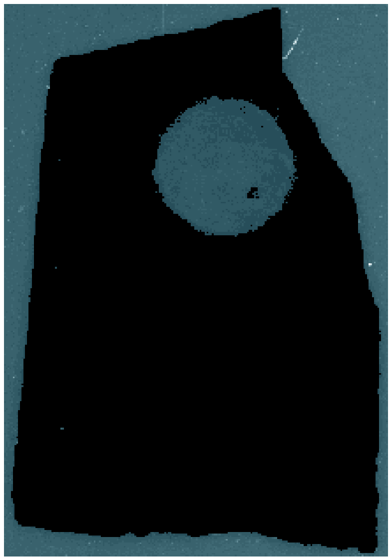




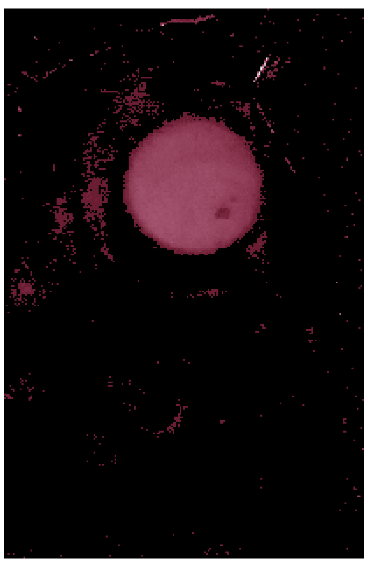
Highly selective reaction of primary amine with surface –COOH group

Functionalization of DNA

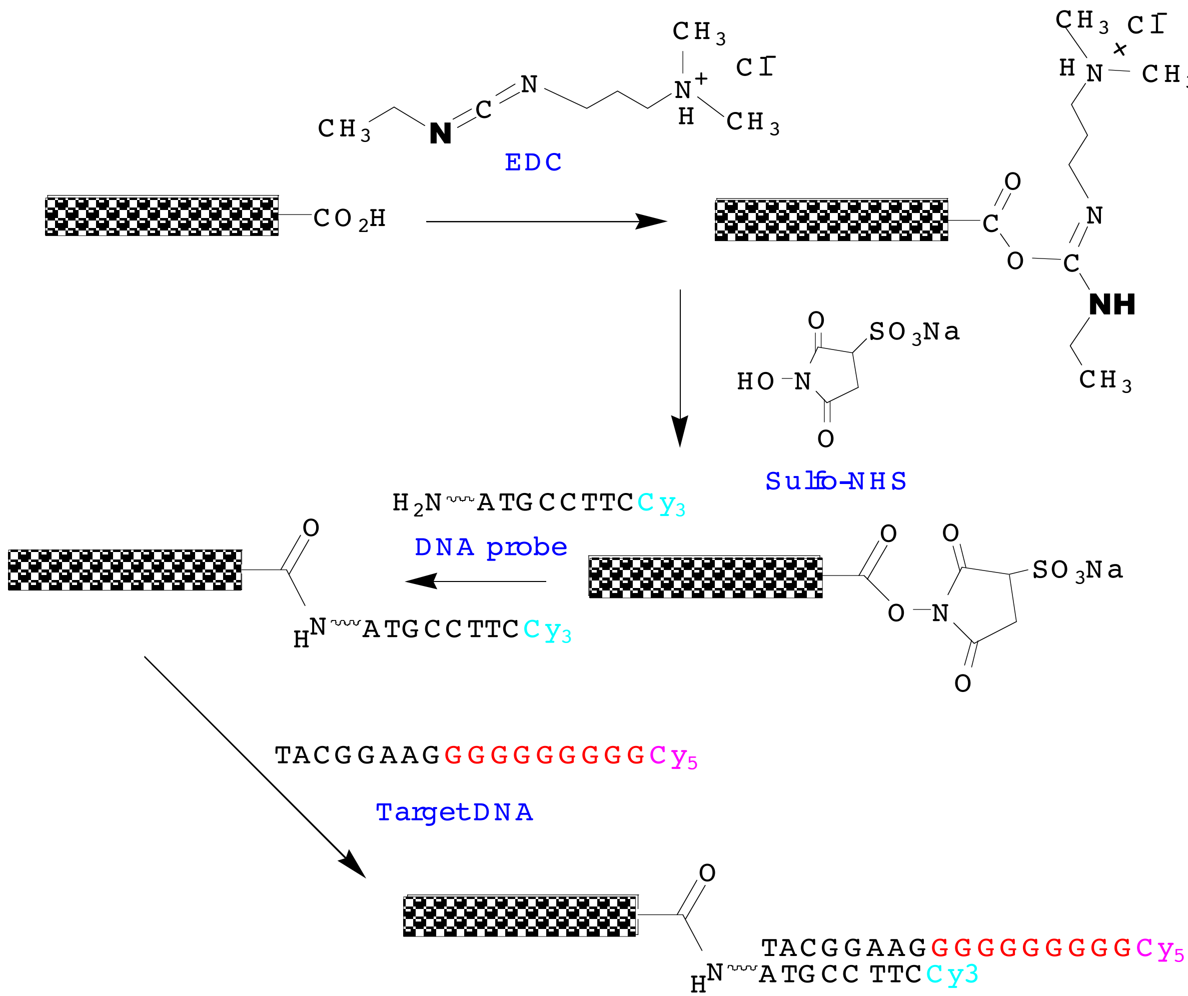




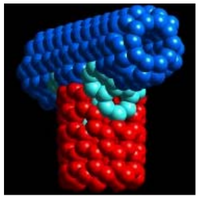
Cy3 image

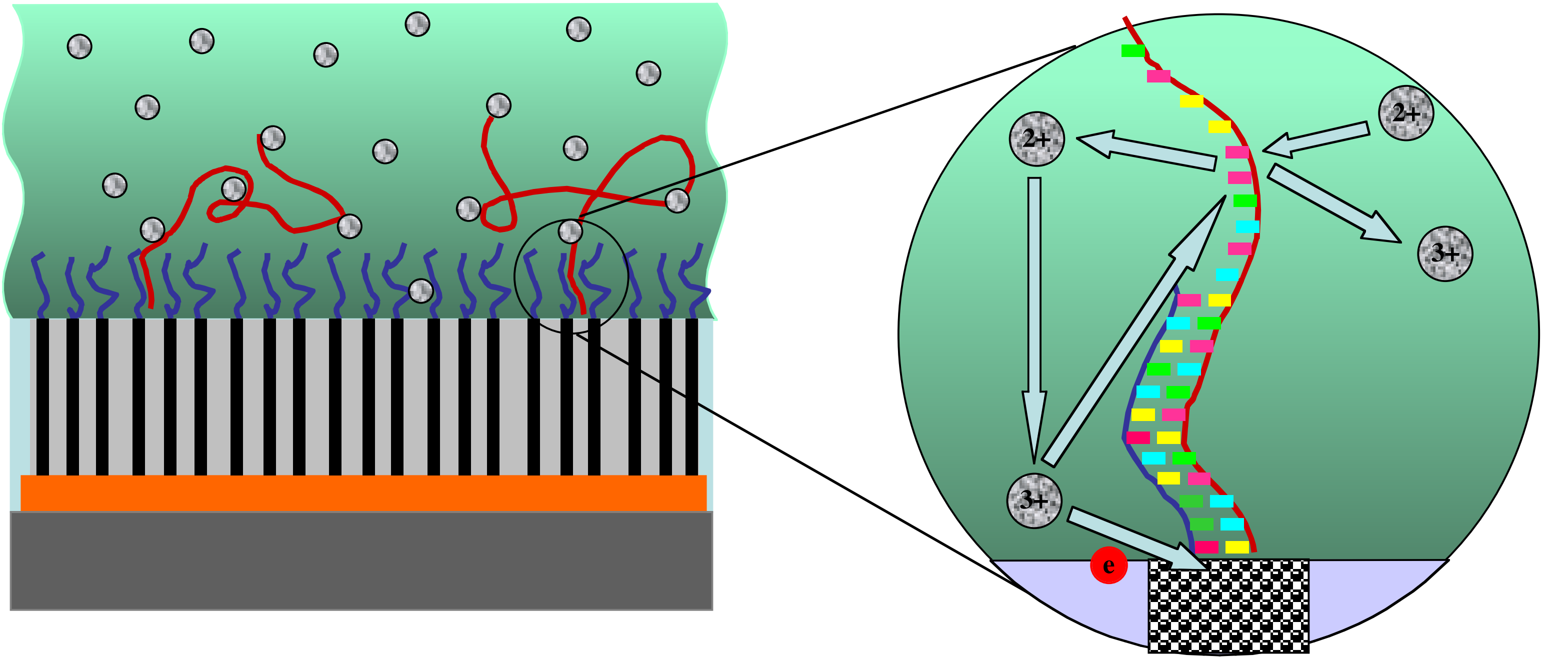


Cy5 image

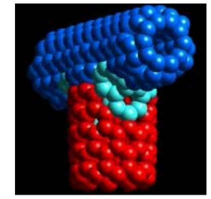


CNT DNA Sensor Using Electrochemical Detection

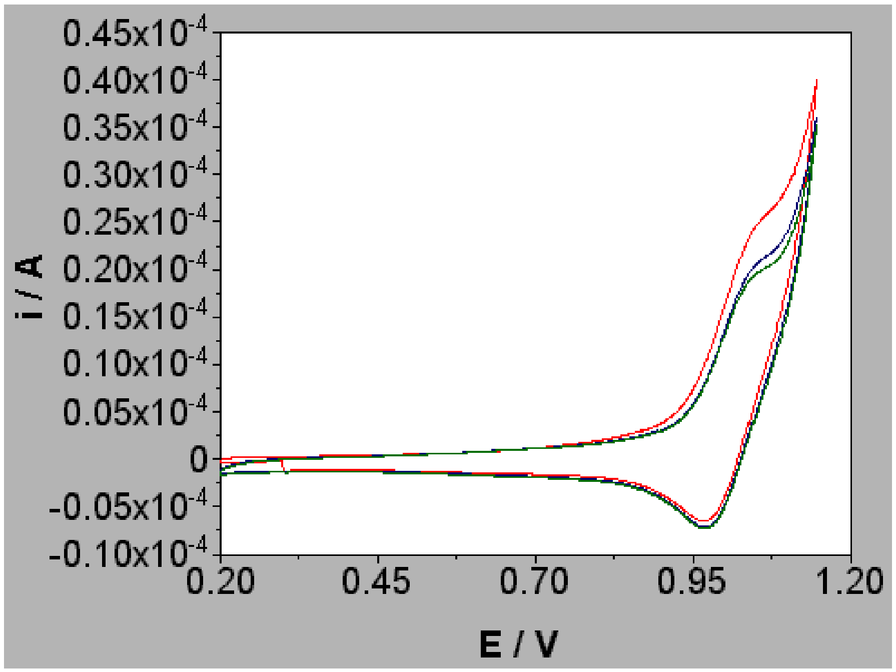


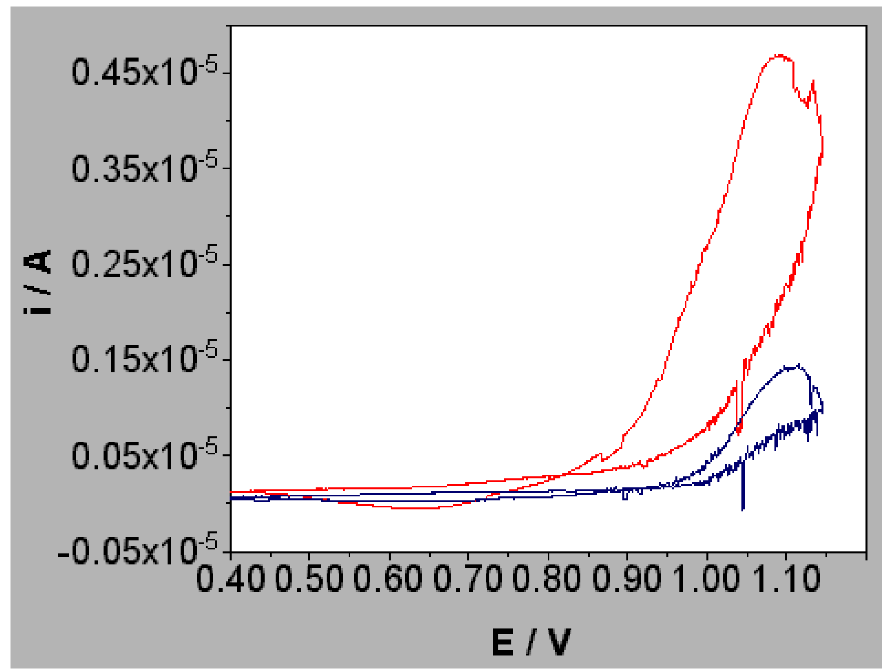


- MWNT array electrode functionalized with DNA/PNA probe as an ultrasensitive sensor for detecting the hybridization of target DNA/RNA from the sample.
  - Signal from redox bases in the excess DNA single strands
- The signal can be amplified with metal ion mediator $\left[Ru(bPy)_3^{2+}\right]$ oxidation catalyzed by Guanine.



Electrochemical Detection of DNA Hybridization



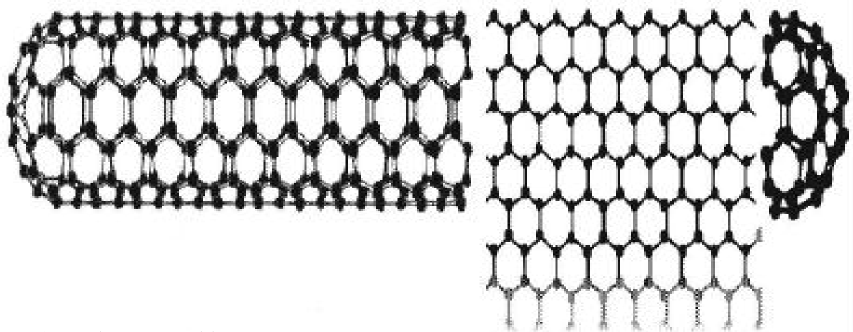


1st, 2nd, and 3rd cycle in cyclic voltammetry

1st – 2nd scan: mainly DNA signal

2nd – 3rd scan: Background

Single-Walled Carbon Nanotubes For Chemical Sensors



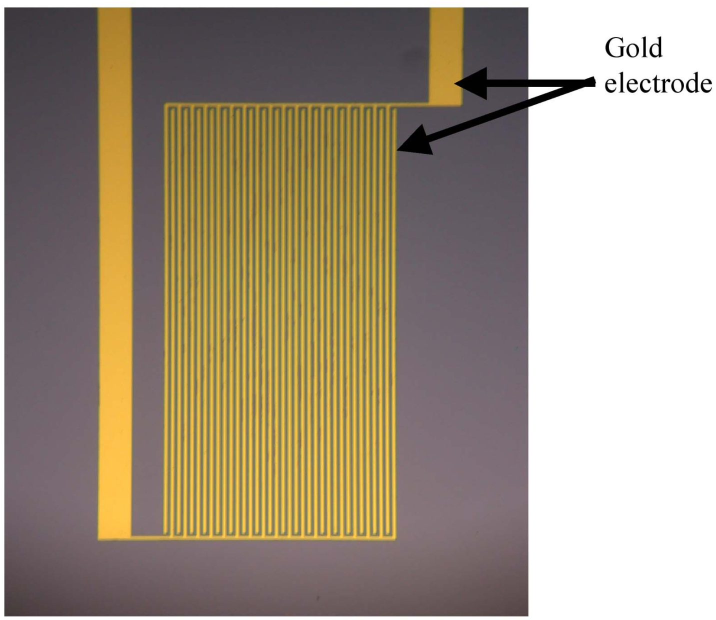
Single Wall Carbon Nanotube

- Every atom in a single-walled nanotube (SWNT) is on the surface and exposed to environment
- Charge transfer or small changes in the charge-environment of a nanotube can cause drastic changes to its electrical properties

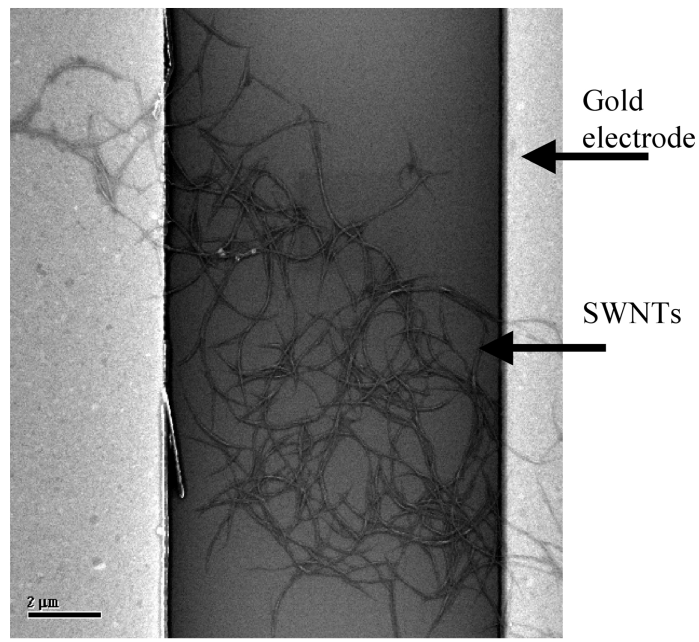
SWNT Sensor Assembly

- Purified SWNTs in DMF solution
- Cast the SWNT/DMF onto IDE

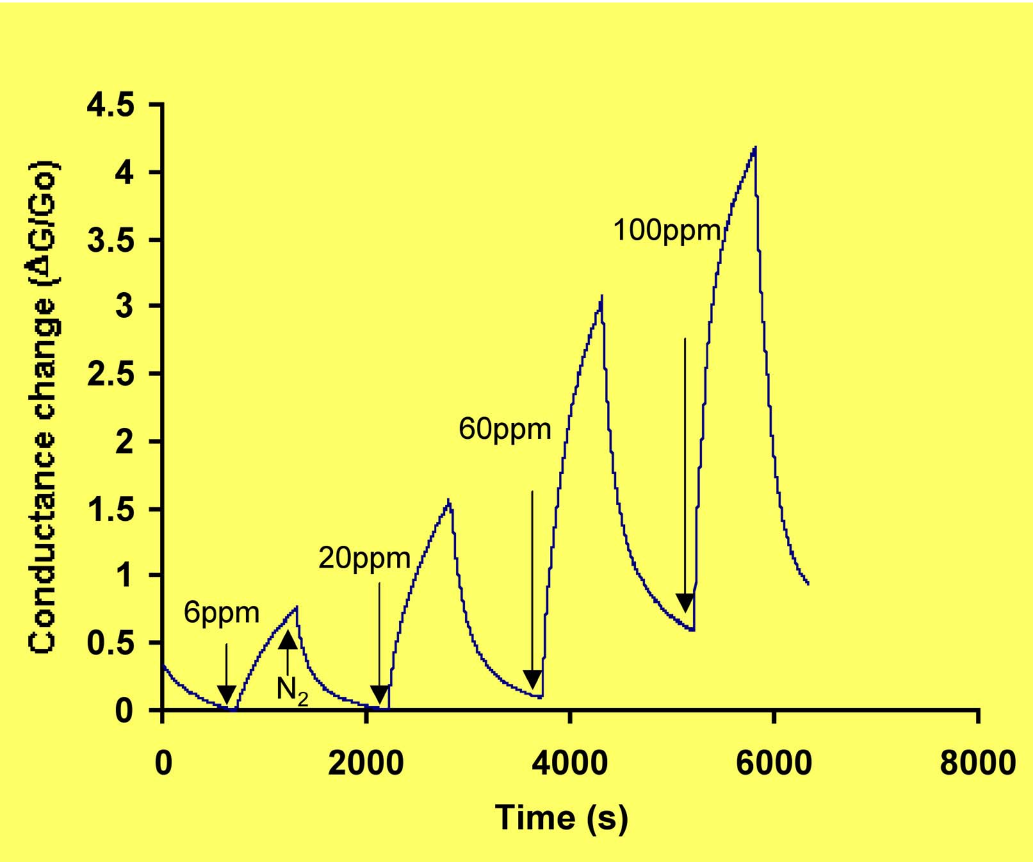
a

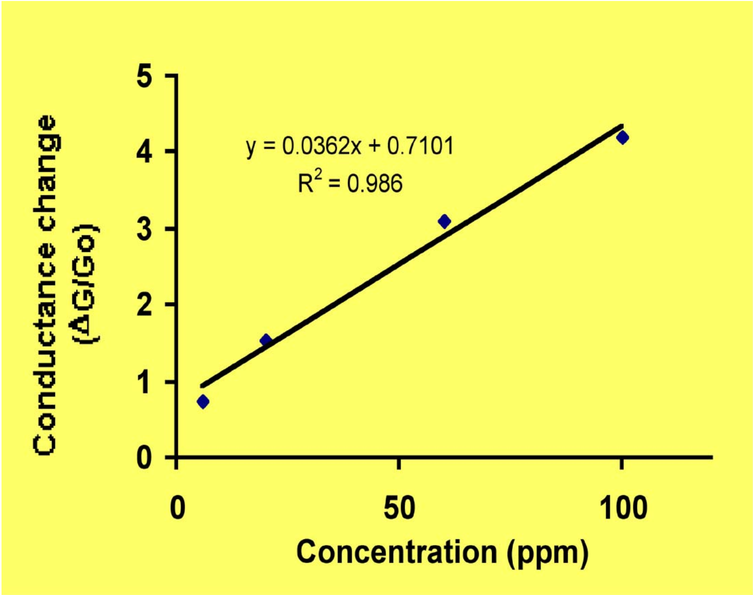


b



SWNT Sensor Response to NO_2 with UV Light Aiding Recovery





Detection limit to NO2 is 44 ppb.

Motivations for selecting Single Crystalline Nanowires & Nanowalls (in Nano-scale Electronics)

- ❖ High single crystallinity ⇒ Low defect density, grain boundary free
- ϖ Well-defined surface structural properties ⇒ Enhanced interfacial engineering
- ❖ Predictable electron transport properties ⇒ Predictable device performance
- ❖ Unique physical properties due to quantum confinement effects ⇒ Enhancement in device characteristics
- ❖ Tunable electronic properties by doping ⇒ Enhancement in device characteristics
- ❖ Truly bottom-up integration approach ⇒ Innovative fabrication schemes
- ❖ Potential to revolutionize nano-scale science and technology

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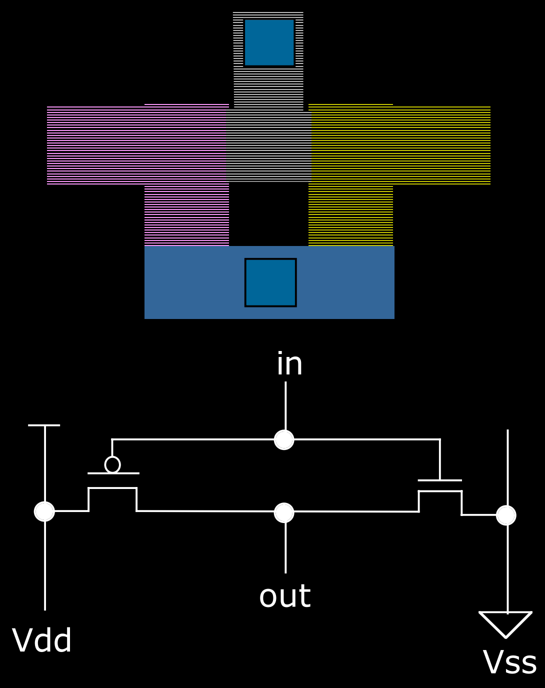
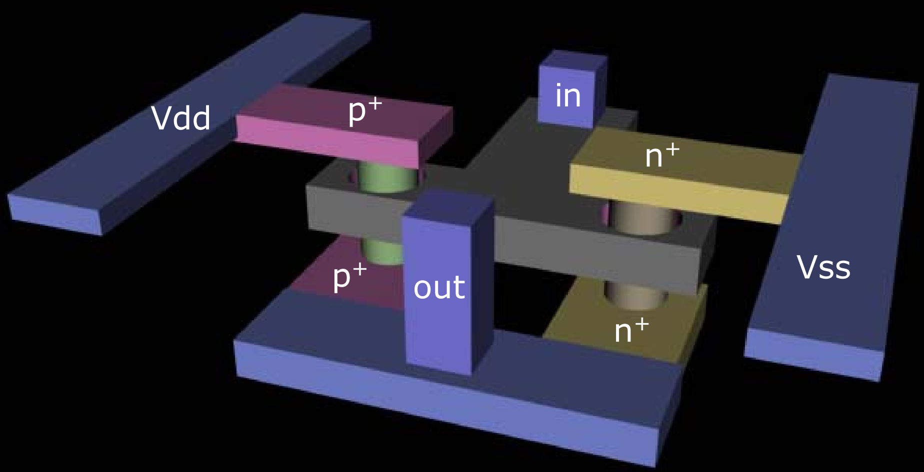
Challenges in Nanowire Growth

• Uni-directional nanowire growth;	⇔	substrate engineering
vertical or horizontal	⇔	electric field directed
• Uniform nanowire diameter	⇔	soft template control
• Acceptable uniform height (± 10%)	⇔	reactor optimization
• Localized single nanowire growth	⇔	substrate patterning
• High structural integrity	⇔	materials characterization



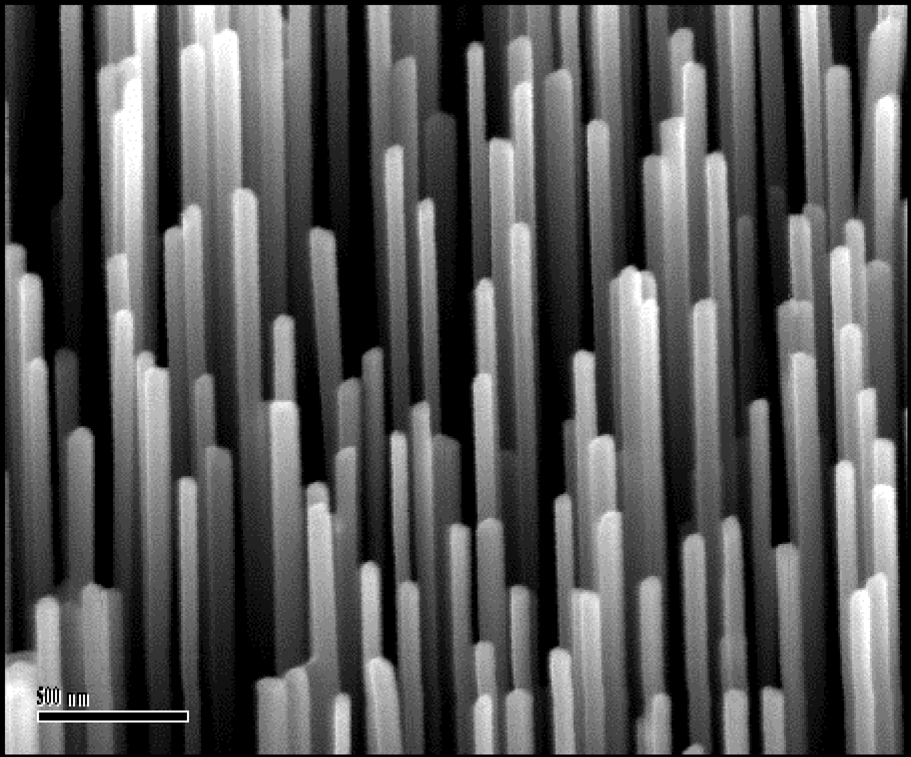


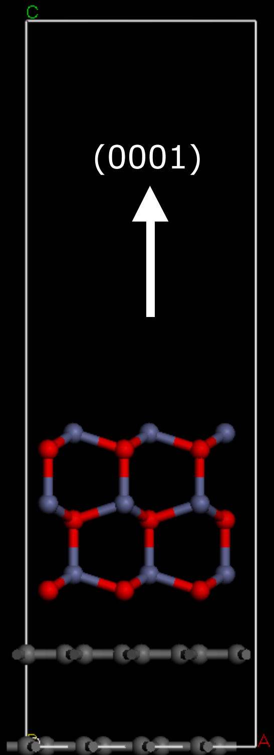
3D view of NW-based CMOS inverter

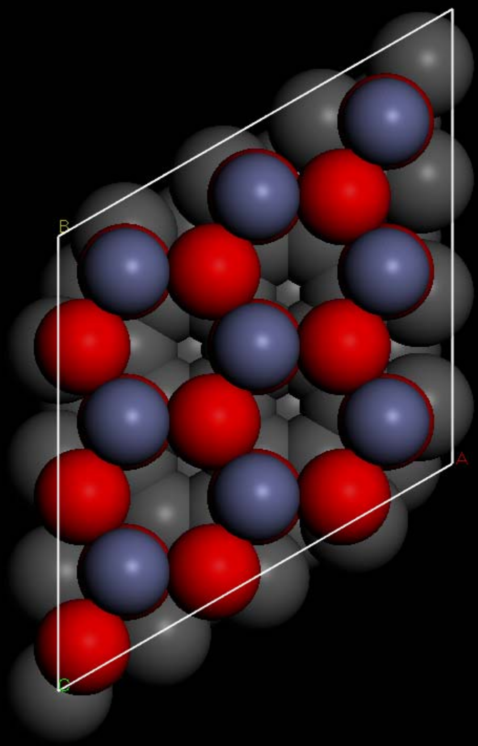
Challenges in Nanowire Growth

- Uni-directional nanowire growth; ⇔ substrate engineering
  vertical or horizontal ⇔ electric field directed

Understanding of the interfacial epitaxial relationship between potential substrates and nanowire structures ⇔ modeling and simulations ⇔ experiments ⇔ combinatorial approach







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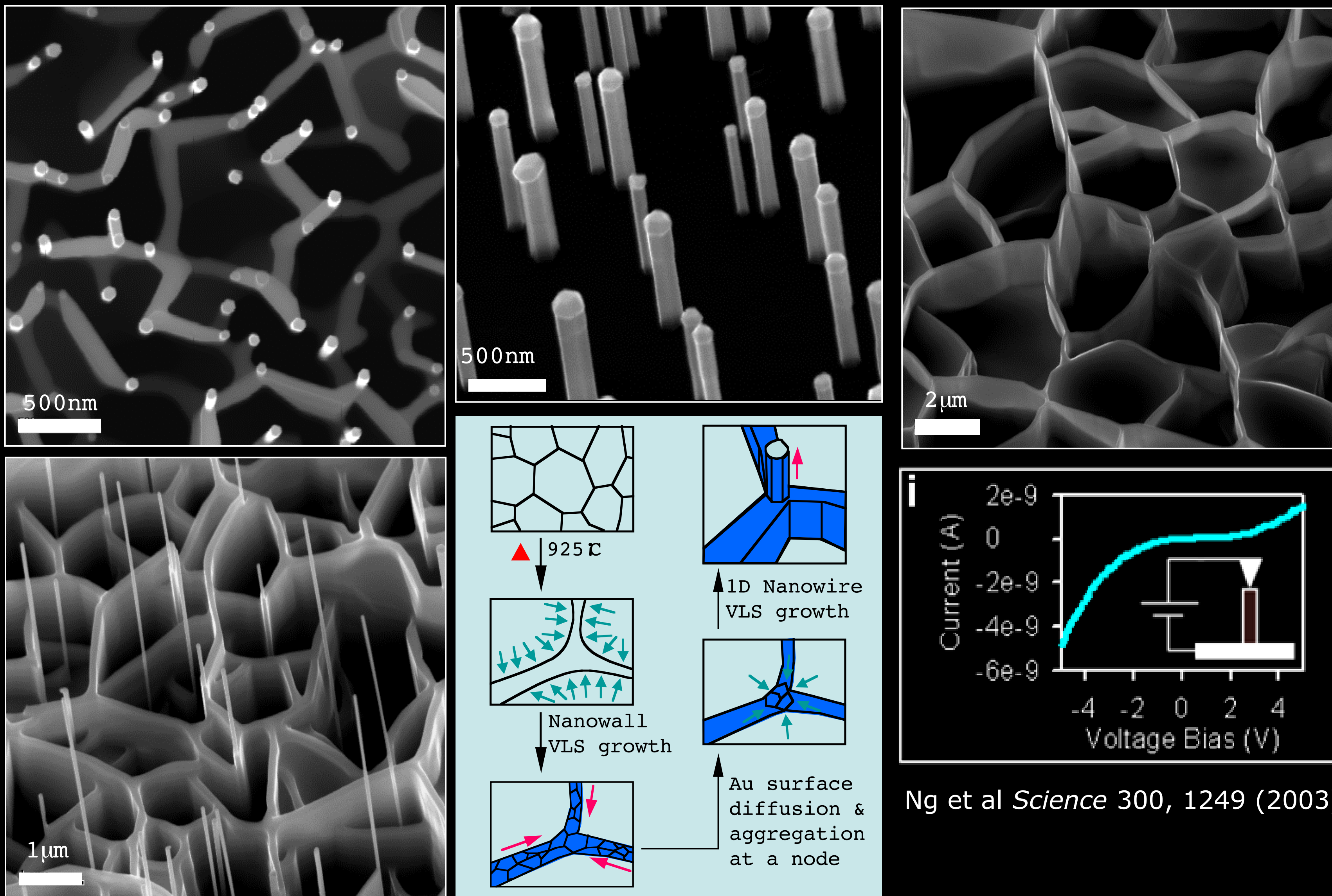
Directional Metal Oxide Nanowires & Nanowalls Growth (Cont')



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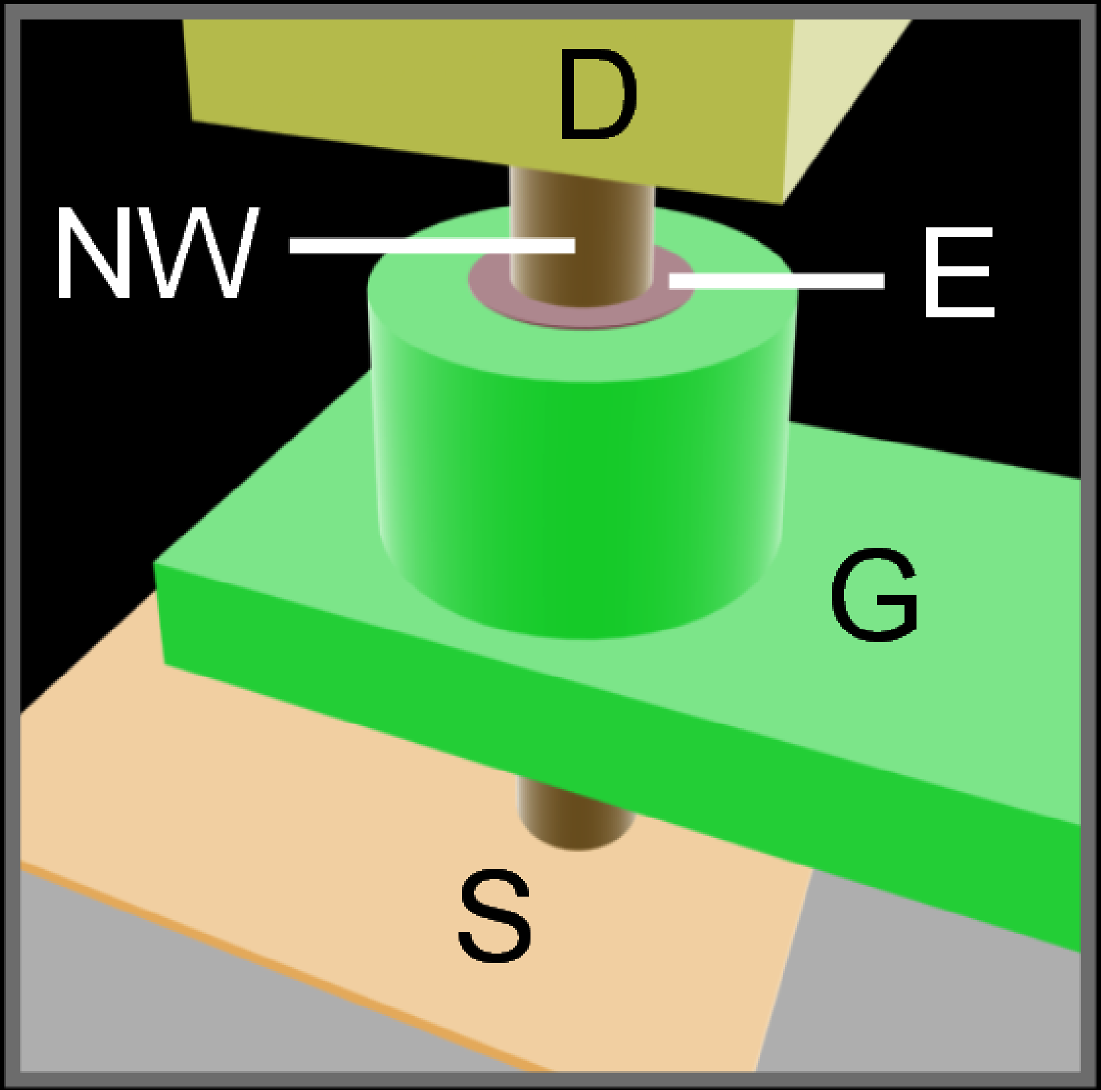
Nanowire-based Vertical Surround Gate FET



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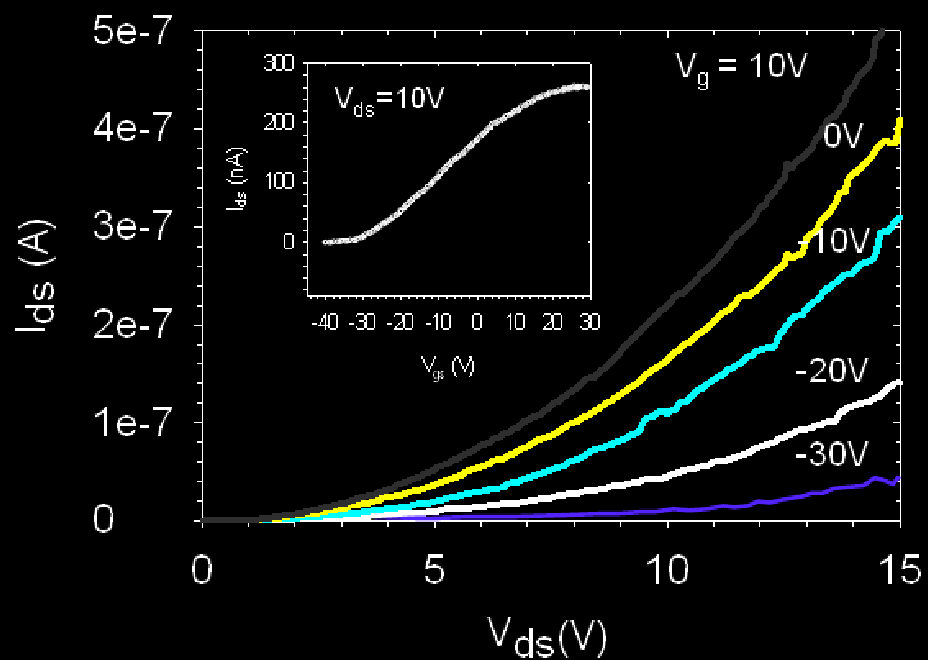
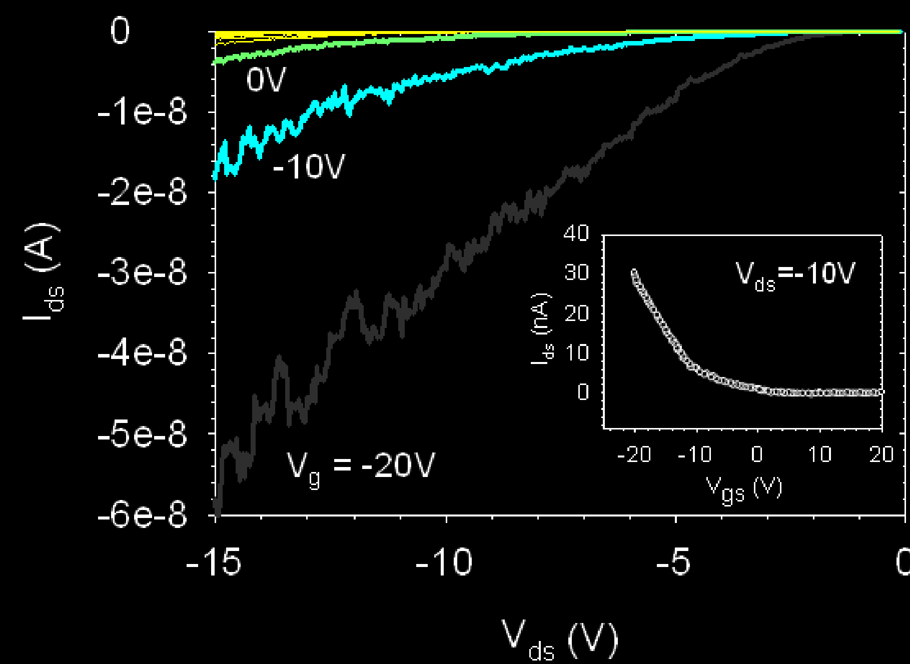
Nanowire-based Vertical Surround Gate FET

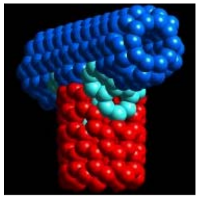
n-NWVFET

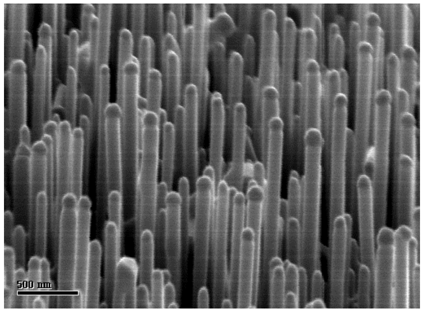


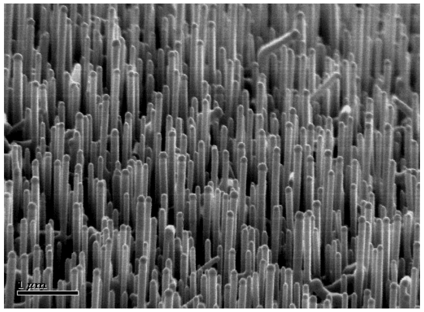
p-NWVFET

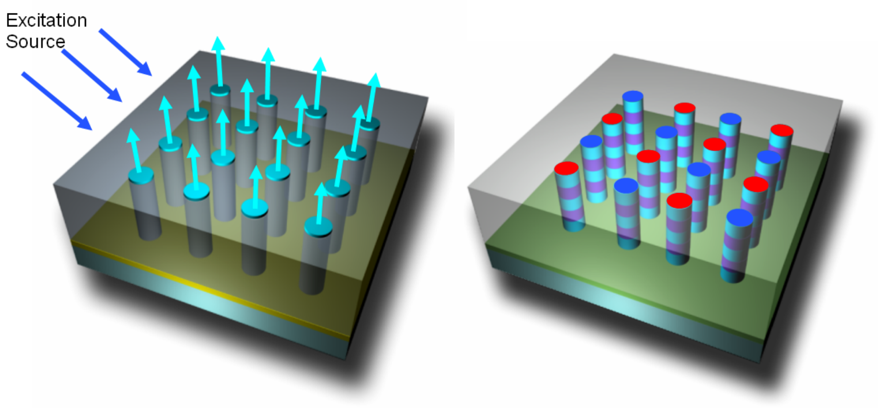


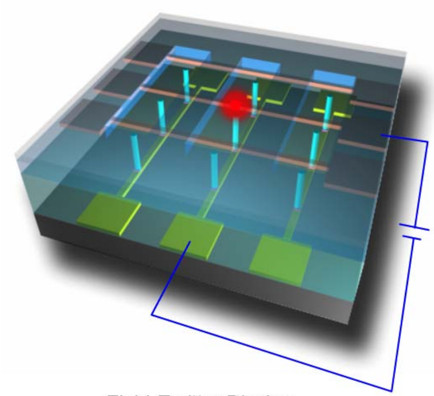
Zinc Oxide Nanowires



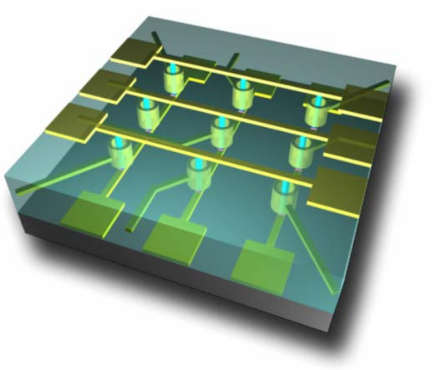




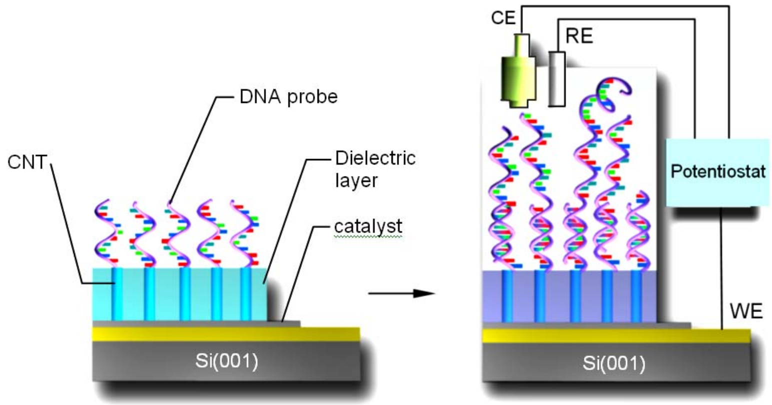




Field-Emitter Display



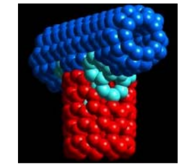
Vertical Transistor Arrays



Functionalization

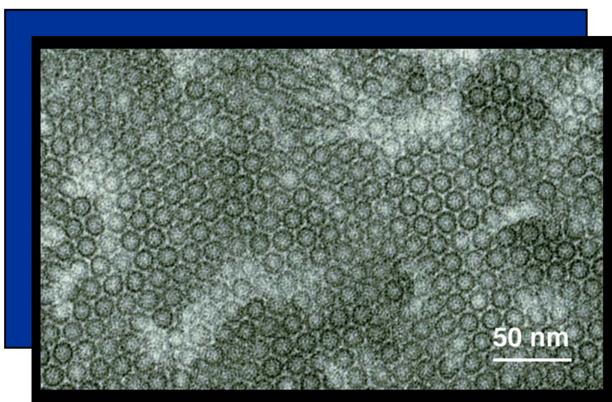
Detection

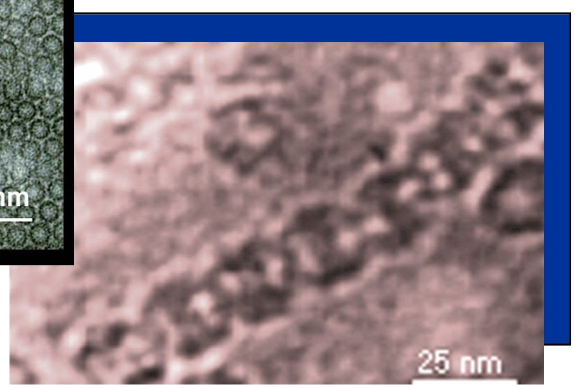
Protein Nanotubes

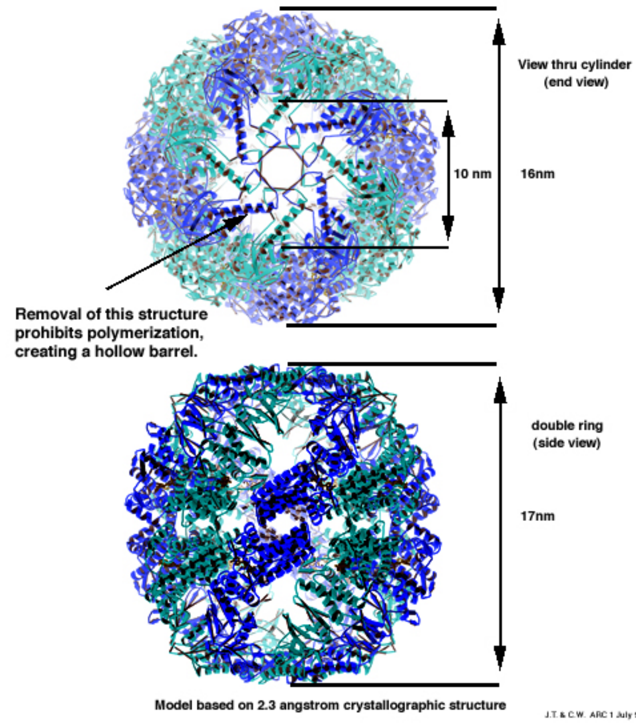


- Heat shock protein (HSP 60) in organisms living at high temperatures ("extremophiles") is of interest in astrobiology

- HSP 60 can be purified from cells as a double-ring structure consisting of 16-18 subunits. The double rings can be induced to self-assemble into nanotubes.



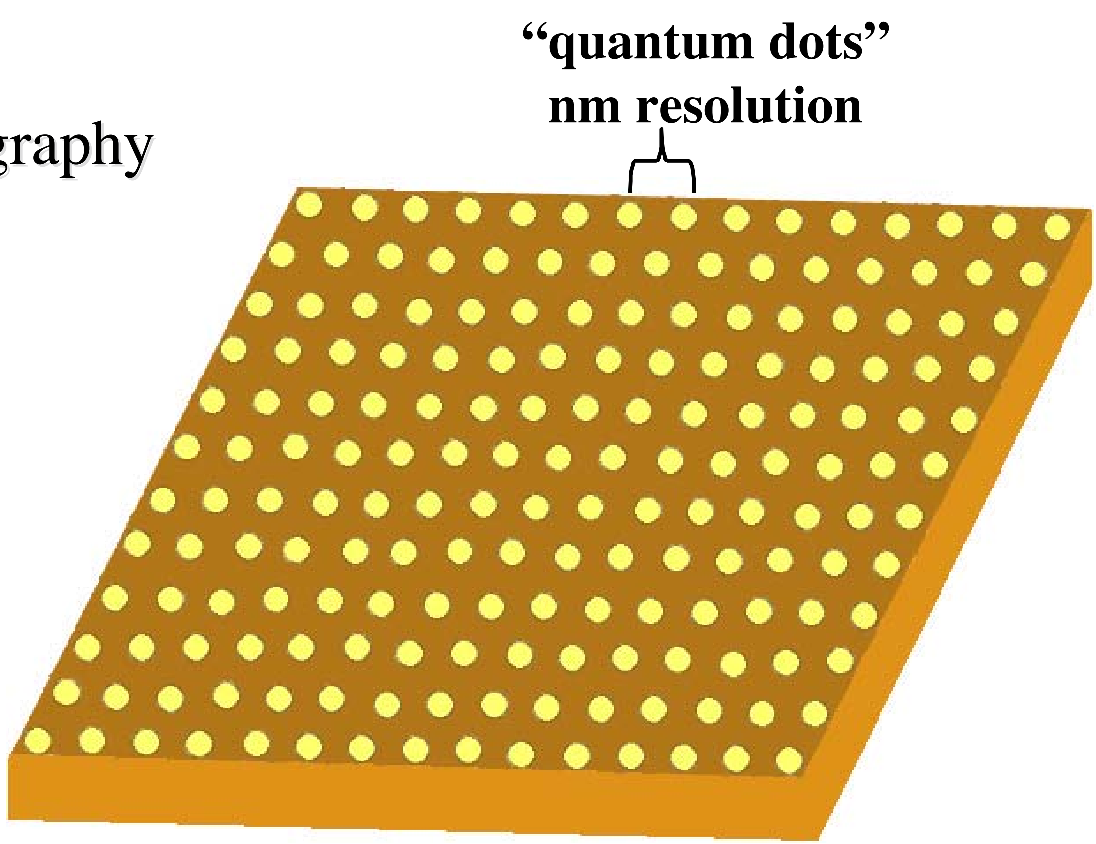




Extremophile Proteins for Nano-scale Substrate Patterning

Nano-scale engineering for high resolution lithography

Future: Bio-based lithography
- Batch self-assembly
- Evolving
- Inexpensive



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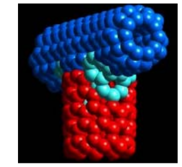
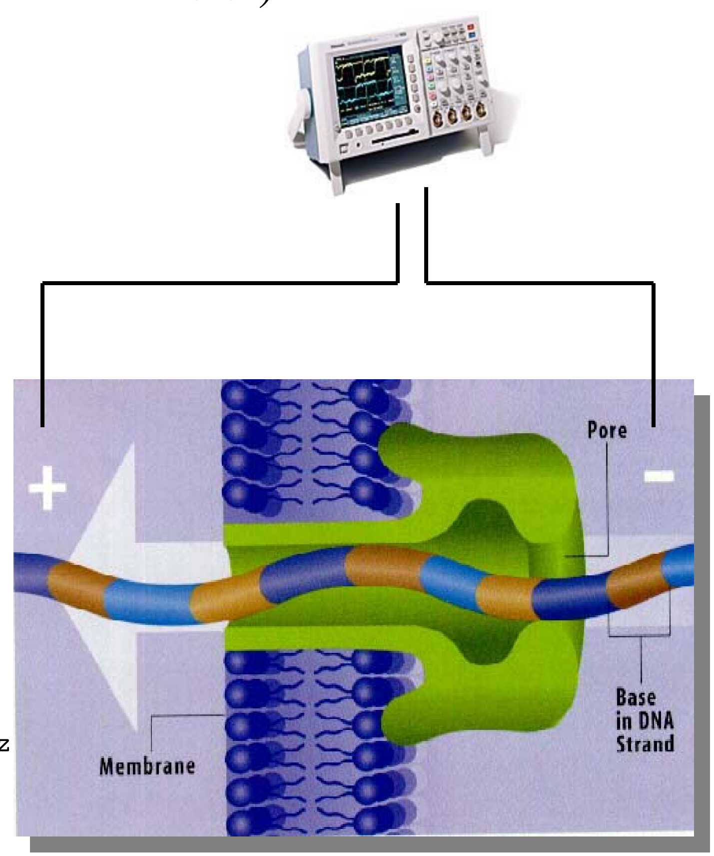
DNA Sequencing with Nanopores

The Concept



- Nanopore in membrane (~2nm diameter)
- DNA in buffer
- Voltage clamp
- Measure current



G. Church, D. Branton, J. Golovchenko, Harvard
D.Deamer, UC Santa Cruz

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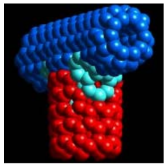
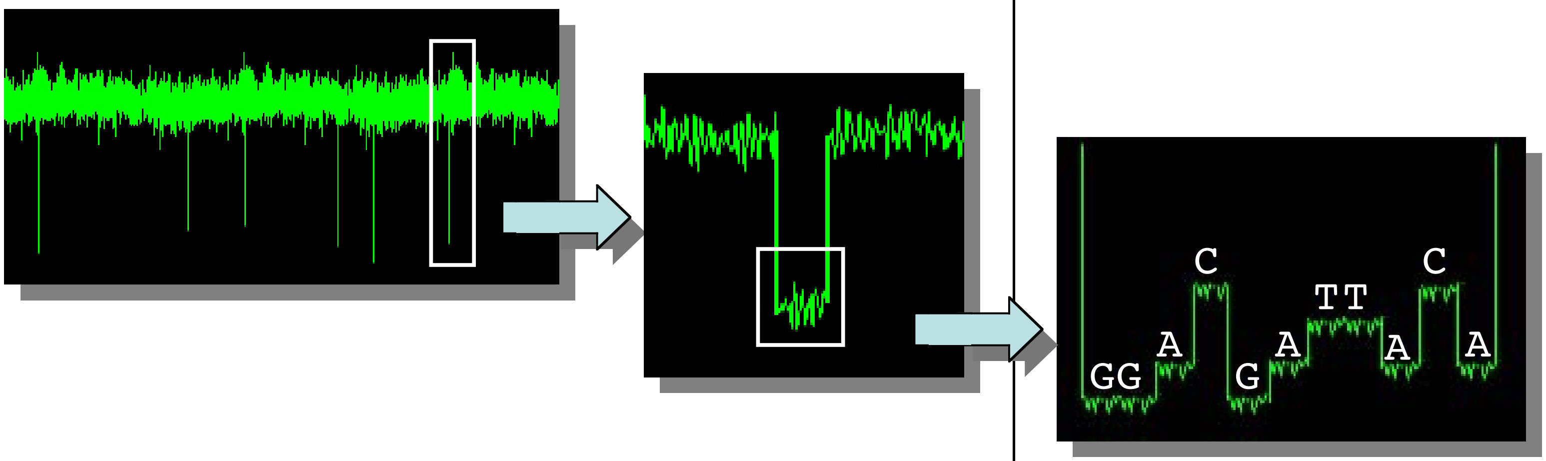
The Sequencing Concept





Present

Future

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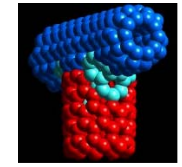
Summary



- Nanotechnology is an enabling technology that will impact electronics and computing, materials and manufacturing, energy, transportation….
- The field is interdisciplinary but everything starts with material science. Challenges include:
  - Novel synthesis techniques
  - Characterization of nanoscale properties
  - Large scale production of materials
  - Application development
- Opportunities and rewards are great and hence, tremendous worldwide interest
- Integration of this emerging field into engineering and science curriculum is important to prepare the future generation of scientists and engineers