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Why Nanotechnology at NASA?
- 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-movers that drive, hop, fly, and burrow
  - Collection of microspacecraft making a variety of measurements

NASA Ames Nanotechnology Program
- Started in FY 97, currently about 25 FTEs on site working on nanotechnology research: additional 15 FTEs involved in simulation, process modeling, and computational chemistry
- Research focus ranges from carbon and protein nanotubes, quantum device physics, quantum computing, data storage to optoelectronics, DNA electronics.
- Bio-Sensors, Bacteriorhodopsin based Data-Storage
- Largest carbon nanotube effort in the Federal government and also one of the largest in the world
  - About ~60 refereed publications in the field
  - Over 100 talks in National/International Meetings
  - Two Feynmann Awards

What is Expected from Alternative Electronic Technologies?
- 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 (10^7 transistors/chip)
- High reproducibility (better than ± 5%)
- Reliability (operating time > 30 years)
- Very low cost (< 1 cent/transistor)
- Everything about the new technology must be compelling and simultaneously CMOS scaling should fail. If these two together do not happen, the enormous infrastructure built around silicon will make it difficult for alternatives to emerge

Carbon Nanotube
CNT is a tubular form of carbon with diameter as small as 1 nm. Length: few mm to microns.
- 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.
- Chemical Synthesis of Data
- Atomic Chain Devices
- Nanoarchitectonics based topographic data storage
- Computational Electronics
- Computational Spintronics
- Development of novel functional and quantum materials for device
design
- Ultrasmall nanoelectronic devices
- Development of quantum methods with quantum simulation
- Investigation of device technologies usable for portable computers
- Modeling of space electronics devices
- NIST: High resolution modeling
Potential CNT Applications and Challenges

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<td>CNT for drug delivery in plants</td>
<td>Transferability is needed</td>
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<td>CNTs can be used to detect pollutants</td>
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<td>CNT for energy storage</td>
<td>High energy density</td>
<td>CNTs must be rechargeable and scalable</td>
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<td>CNT for electronic devices</td>
<td>High current density</td>
<td>CNTs must be compatible with conventional electronics</td>
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CNT Synthesis

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

Carbon Nanotubes at Ames

- Atomic Force Microscopy is a powerful technique for imaging, nanomanipulation, as a platform for sensor work, nanolithography...
- Conventional silicon or tungsten tips wear out quickly, CNT tip is robust, offers amazing resolution

CNT in Microscopy

- CNT Based Biosensors
  - One interest is in development for astronomy to study origins of life. CNT, though laser, can be finely resolved as thin tips with a probe molecule. Current study uses AFM as an experimental platform.
  - The technology is also being used to develop sensors for cancer diagnostics
    - Identified probe molecule that will serve as signature of tumor cell, to be attached to CNT
    - Current flow due to hybridization will be through CNT electrode to an R F chip
    - Prototype biosensor culture development

- Computational Nanotechnology
  - Large scale computer simulations based on ab initio methods enable understanding nanotube characteristics and serve as design tool
    - Evaluation of mechanical properties
    - Evaluation of electronic properties
    - Electron transport in CNT devices
    - Functionalization of the nanotubes
    - Design of electrical and mechanical devices
    - Evaluation of storage potential (H2, Li)

www.rms.nasa.gov/deepsub/home.html
Protein Nanotubes

- Heat shock protein (HSP 60) in organisms living at high temperatures ("extremophiles") is of interest in astrophysics.
- 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.
Experiments: Nanotube based Devices

Nanotube as Quantum Molecular Wire  (Nature 1997)

Nanotube Field Effect Transistor  (Nature 1998)

Nanotube Hetero-Junctions  (Nature 1999)
Electronic Transport in Y-Junction Carbon Nanotubes

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(Received 22 February 2000)

1st experimental Step to a Three-Terminal Nanoscale Transistor.
Atomic Force Microscopy is a powerful technique for imaging, manipulation, or platform for diverse work, nanolithography.

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

AFM Imaging with Single Wall Nanotube Tips

280 nm Line/Space Array of Polymeric Resist on silicon Substrate

Silicon Tip

Multi-Walled Carbon Nanotube Tip
Based on Phosphate bridges acting as tunnel junctions and H acting as capacitive element.

DNA coated with metals can act as interconnects.

DNA has self-assembly properties.
Example: (NYU)

Topologically Connected DNA Segments

Cube

Truncated Octahedron

DAE  DAO  DPE  DPON  DPOW

Double Cross-Over Molecules

DNA Nano-mechanical Device
DNA as Electronics Elements:

Conflicting Claims about DNA as metal or semiconductor?

Indirect measurements in the beginning led to this controversy?

Transport measurements on single DNA molecules C. Dekker (Delft)
Nature, 2000

A 10.4 nm long, double-stranded poly(G)–poly(C) DNA molecule
Metal nanoelectrodes that are separated by 8 nm
Small gap semiconductor

Metal coated DNA serve as conductor.
Bacteriorhodopsin for Optical Data Storage
Ann Hermone and Richard Jaffe
ahermone@mail.arc.nasa.gov

- Bacteriorhodopsin (BR) contains the chromophore retinal in an all-trans conformation.

- on photoexcitation retinal isomerizes from all-trans to mainly 13-cis.

- Changes in BR’s optical properties in the excited state, such as refractive index, make it a candidate for optical data storage.
All-trans Retinal
• The lifetime of 13-cis retinal is short and when retinal returns to the all-trans form any data stored is lost.

• Mutant BR molecules have been prepared, in which retinal isomerizes to the 9-cis form with a long lifetime, making long-term data storage possible.

• Therefore, we are trying to characterize the 9-cis isomerization pathway.
- Various experimental and simulation aspects of Nanoelectronics are currently in progress
- Individual devices and characteristics need to be incorporated in NASA specific applications
- Biosensors and nanotubes for interconnects are preliminary step in that direction
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AFM Imaging with Single Wall Nanotube Tips

2 nm thick Au on Mica

5 nm thick Ir on Mica

Si$_3$N$_4$ on Silicon substrate
280 nm Line/Space Array of Polymeric Resist on silicon Substrate

Silicon Tip

Multi-Walled Carbon Nanotube Tip
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  - Identified probe molecule that will serve as signature of leukemia cells, to be attached to CNT
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  - Prototype biosensors catheter development

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

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- 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.
- Conductivity of DNA has been controversial for decades.

- Electron transfer experiments (biochemistry) / Possible connection to cancer

- Transport experiments (physics)

- DNA Electronics (Device / Lithography)
ELECTRON TRANSFER EXPERIMENTS

- Oxidative damage of DNA has been linked to cancer.

- How effective is long range electron transfer in causing oxidative damage?

  ![Diagram of electron transfer](image)
  * Fluorescent analog of a base pair
  * Intercalator

- Estimates of electron transfer rates span two orders of magnitude.

  ![Diagram of electron transfer](image)
  Intrastrand & Interstrand
  Significant dependence on base pair mismatches.
  Significant dependence on intervening sequence
TRANSPORT EXPERIMENTS


- Current ~ 1 nA
- Voltage ~ 1 V

Fink et al., Science (1999)

- Current ~ 10 nA
- Voltage ~ 20 mV

NO GAP!
Based on Phosphate bridges acting as tunnel junctions and H acting as capacitive element.

DNA coated with metals can act as interconnects

DNA has self-assembly properties
DNA as Electronics Elements:

about DNA as metal or semiconductor?

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www.nasa.nasa.gov/~deepak/home.html
Carbon Nanotube Electronics Band Structure (basics)

Hexagonal Lattice of a Graphene Sheet – (2xunit cell)

First Brillouin zone for an armchair tube.

Ch = n \vec{a} + m \vec{a}_2 (chiral vector)
3-terminal CNT Heterojunctions

FIG. 1(color). (a) Fully relaxed (5,5)-(10,0)-(5,5) tube (T1). The turquoise colored balls denote the atoms forming the heptagons. The structure contains six heptagons and no pentagons. (b) Fully relaxed (9,0)-(10,0)-(9,0) tube (T2). The turquoise colored balls denote the atoms forming the heptagons. Pentagons are denoted by white balls. The structure contains eight heptagons and two pentagons.

FIG. 3. LDOS for the relaxed (9,0)-(10,0)-(9,0) structure (T2) at various cross sections indicated in Fig. 1(b). The larger contribution in the gap is due to the presence of two extra pairs of heptagon-pentagon defects at the junctions.

LDOS of (10,0)-(9,0) "T-junction"

3-terminal "T-tunnel" CNT Heterojunctions for Molecular Electronics Applications

Mol Elect 2000 – D. Srivastava
Computational Nanotechnology
Multi-wall Y-junction Carbon Nanotubes
Semiconducting Y-junction Nanotubes with Different Angles
D. Srivastava, J. D. Schall, D. W. Brenner, K. D. Ausman, M. Feng
Bio-mimetic Dendritic Neurons: Carbon Nanotube

Model of 4-level dendritic neural tree that could be made of branched carbon nanotubes

D. Srivastava et. al., Comp. in Science and Engineering, IEEE, APS (2001)