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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-rovers that drive, hop, fly, and burrow
  - Collection of microspacecraft making a variety of measurements

Nanotechnology at NASA Ames

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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
- Largest carbon nanotube effort in the Federal government and also one of the largest in the world
  - International reputation, program well known in scientific community
  - About ~60 refereed publications in the field
  - Over 100 talks in National/International Meetings
  - Two Feynmann Awards

Ames Research Center

Research Focus

Nanotechnology

Nanotubes

- Controlled, patterned growth of CNT
- Large scale production of CNT
- Hydrogen storage in nanotubes
- CNT-based biosensor for cancer diagnostics
- Functionalization of nanotubes
- AFM study of Mars dust
- AFM study of Mars meteorite
- CNT-based sensors for astrobiology
- Protein nanotubes: growth and applications
- Reactor/Process Modeling of CNT growth
- Computational investigation of electronic, mechanical and other properties of CNT
- Transport in CNT, Nanoelectronics
- BN nanotubes, structure and properties
- Design of CNT-based mechanical components

- Chemical Storage of Data
- Atomic Chain Electronics
- Bacteriorhodapsin based holographic data storage

Computational Electronics,
Computational Optoelectronics

Development of multidimensional quantum simulators to design ultrasmall semiconductor devices
Development of semiclassical methods with quantum correction terms
Investigation of device technologies suitable for petaflop computers
Modeling of optoelectronics devices, VCSEL, THz modulation
Optical interconnect modeling

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What is Expected from Alternative 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 (10^9 transistors/circuit)
- High reproducibility (better than ± 5%)
- Reliability (operating time > 10 years)
- Very low cost (< 1 μcent/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.

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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.

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.

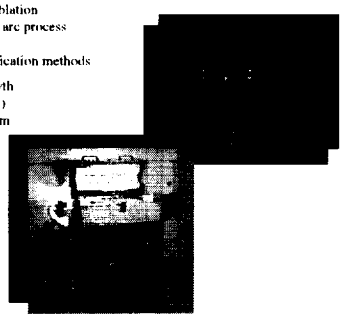
Potential CNT Applications and Challenges

Source: Workshop Report - SRC/NASA Ames Workshop on Emerging Opportunities and Issues in Nanotubes and Nanoelectronics

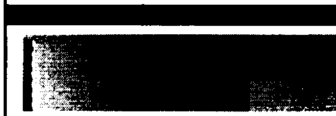
Application	Property	Challenge
CNT for active electronic devices	Possibilities to control electronic properties by structural characteristics	The current standards should be met: low cost (1 pcent/transistor), high level of integration (10^8 transistors/circuit), high reproducibility (+/- 5%), reliability(operating time >10years)
CNT as interconnects	Low resistivity	Manipulation/attachment of individual CNT
Passive devices: capacitors and inductors	Geometrical characteristics	Is it possible to grow helical conducting nano tubes?
Field emitters	High aspect ratio, thermal conductivity	Performance of CNT field emitters?
CNT-film as a low-K insulator	Inherent low density of the CNT-films	The CNT film would need to be deposited, planarized, patterned and etched with techniques compatible with the underlying silicon devices
Probes for metrology	High aspect ratio of tips	Attachment of a single CNT to the cantilever
Manufacturing with Micro- or Nano-Tools	High aspect ratio of tips	Micro-tool arrays must be "fast, flexible, and inexpensive"

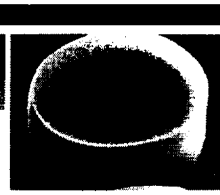
CNT Synthesis

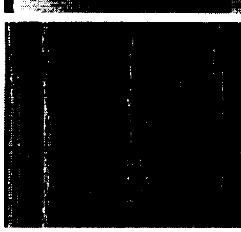
- CNT has been grown by laser ablation (pioneering at Rice) and carbon arc process (NEC, Japan) - early 90s
  - SWNT, high purity, purification methods
- CVD is ideal for patterned growth (electronics, sensor applications)
  - Well known technique from microelectronics
  - Hydrocarbon feedstock
  - Growth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



Carbon Nanotubes at Ames



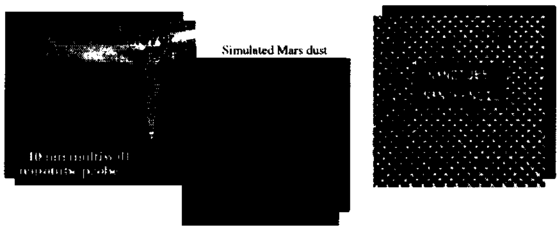




CNT in Microscopy

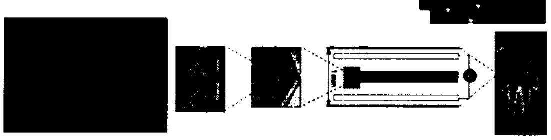
Atomic Force Microscopy is a powerful technique for imaging, nanomanipulation, as platform for sensor work, nanolithography...

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



CNT Based Biosensors

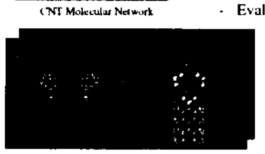
- Our interest is to develop sensors for astrobiology to study origins of life. CNT, though inert, can be functionalized at the tip with a probe molecule. Current study uses AFM as an experimental platform
- The technology is also being used in collaboration with NCI to develop sensors for cancer diagnostics
  - 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



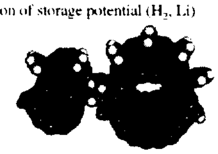
Computational Nanotechnology

CNT Molecular Network

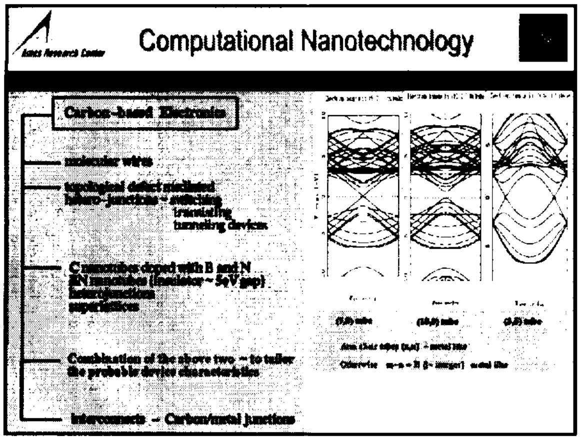
- Large scale computer simulations based on ab initio methods enable understanding nanotube characteristics and serve as design tool
  - Evaluation of mechanical properties
  - Evaluation of electronic properties
  - Electron transport in CNT devices
  - Functionalization of the nanotubes
  - Design of electrical and mechanical devices
  - Evaluation of storage potential (H_2, Li)

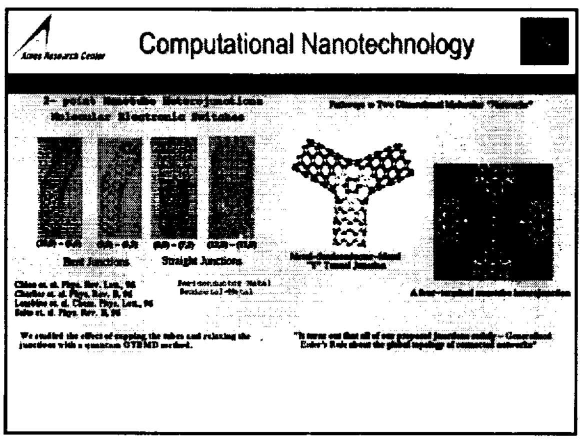


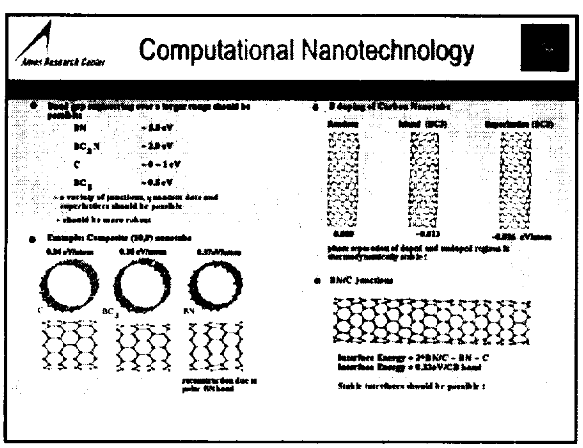
CNT "T" and "Y" Junctions



www.nas.nasa.gov/~deepak/home.html

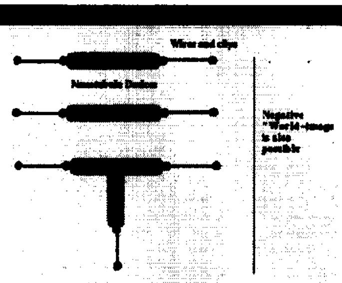

Computational Nanotechnology


Computational Nanotechnology
Bent Junctions
Straight Junctions


Computational Nanotechnology

Computational Nanotechnology

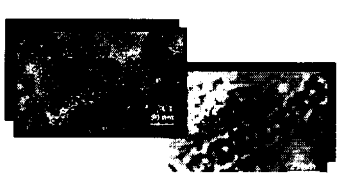
Computational Nanotechnology

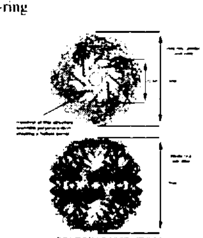


- Amenable to self-assembly through shape and color interactions
- Provision for molecular interconnects to the outside metallic contacts

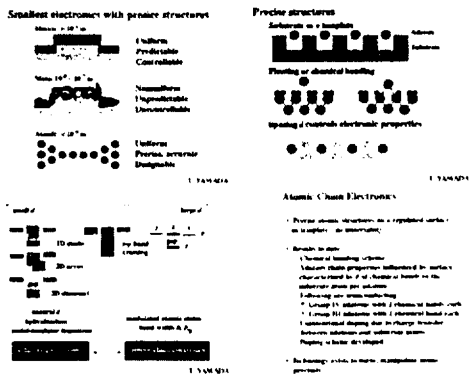
Protein Nanotubes

- 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.





Atomic Chain Electronics



Nanotechnology: Comments

- Various experimental and simulation aspects of Nanotechnology 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