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Carbon Nanotubes for Space Applications

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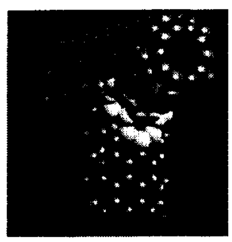

http://www.ipt.arc.nasa.gov

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Ames Nanotechnology Research Focus

NASA Ames' nanotechnology program started about five years ago, and the carbon nanotube research is the largest in any federal government lab and one of the largest in the world. The broad focus includes experimental work with complementary theoretical and simulation work. The group has won two Feynmann prizes awarded by the Foresight Institute. A list of journal publications can be found at www.ipt.arc.nasa.gov.

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Ames Nanotechnology Research Focus

Nanotubes

- Controlled, patterned growth of CNT
- Large scale production of CNT
- CNT-based biosensor for cancer diagnostics
- Functionalization of nanotubes
- AFM study of Mars dust
- AFM study of Mars meteorite
- CNT-based sensors for astrobiology
- Hydrogen storage in nanotubes
- 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 Ultra-small semiconductor devices
- Development of semi-classical methods with quantum correction terms
- Investigation of device technologies suitable for petaflop computers
- Modeling of optoelectronics devices, VCSEL, THz modulation
- Optical interconnect modeling

Why Nanotechnology at NASA?

As a result of the National Nanotechnology Initiative currently being implemented by all federal agencies, NASA is earnestly evaluating the potential of nanotechnology for the agency's missions. The pay-off to NASA, particularly for investment in nanotube based nanotechnology, appears to be significant.

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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
- In vivo and noninvasive astronaut health diagnosis and prognosis, in vivo therapy

Carbon Nanotube

Carbon nanotube (CNT), a tubular form of carbon, is an extraordinary material in terms of its mechanical and electronic properties. The remarkable figures-of-merit of CNT have caused much excitement among researchers about the future of this technology. The anticipated investment is expected to accelerate the speed of innovation in the field.

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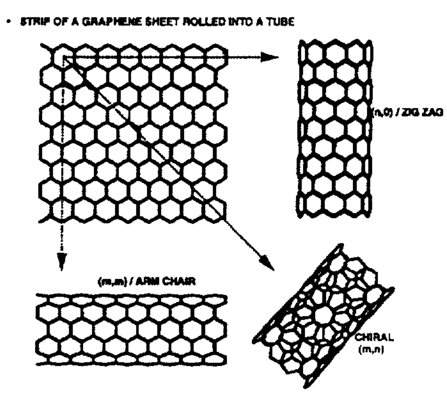
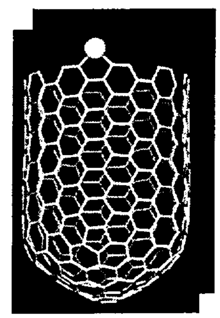
Carbon Nanotube

CNT is a tubular form of carbon with a 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.

CNT Properties

Comparison with materials such as aluminum, titanium, and steel, shows that CNT has much superior strength-to-weight ratio. CNT's thermal conductivity is second only to CVD-grown diamond. Thermal conductivity appears to be a function of temperature, chirality, etc. Also, the remarkable combination of properties enables CNT to be a multifunctional material in structural applications.

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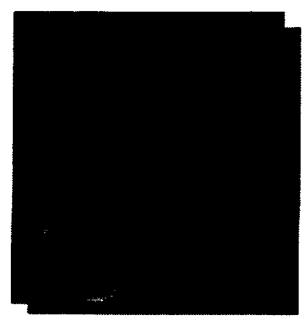
CNT Properties

- 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 10-30% much higher than any material
- Thermal conductivity ~ 3000 W/mK in the axial direction with small values in the radial direction



CNT Properties (Cont'd.)

CNT's electrical properties are unique. Depending in chirality, the nanotube can be metallic or semiconducting. Creative functionalization can also lead to insulating nanotubes. All of this allows us to dream of building an entire architecture predominantly based on this one material. The excellent field emission properties have led Japanese and Korean companies to make serious investments on exploiting for display technology.

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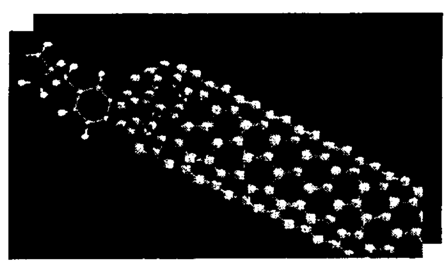
CNT Properties (cont.)

- 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 ratio of curvature are ideal for field emission
- Can be functionalized



CNT Applications: Structural, Mechanical

The applications mentioned herein are based on what we know about the properties. No serious demonstrations of any kind have been made yet.

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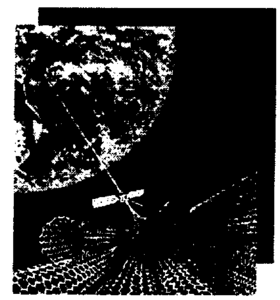
CNT Applications: Structural, Mechanical

- High strength composites
- Cables, tethers, beams
- Multifunctional materials
- Functionalize and use as polymer back bone
  - Plastics with enhanced properties like "blow molded steel"
- Heat exchanges, 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: Electronics

Nanotube based molecular computing is a couple of decades away. A key to the development is to focus on novel circuits and architectures at an early stage (now), and not to try to create field effect transistors to fit into the existing CMOS-like scheme.

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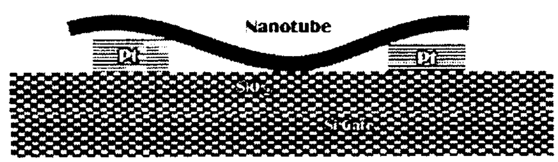
CNT Applications: Electronics

- 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

CNT Applications: Sensors, NEMS, Bio

Applications in the fields of sensors and nanodevices are amazingly numerous. In a few years, when research becomes successful in control of nanotube diameter and chirality, characterization, and development of nano-fabrication and nano-manipulation techniques, some of these dream applications will become reality.

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CNT Applications: Sensors, NEMS, Bio

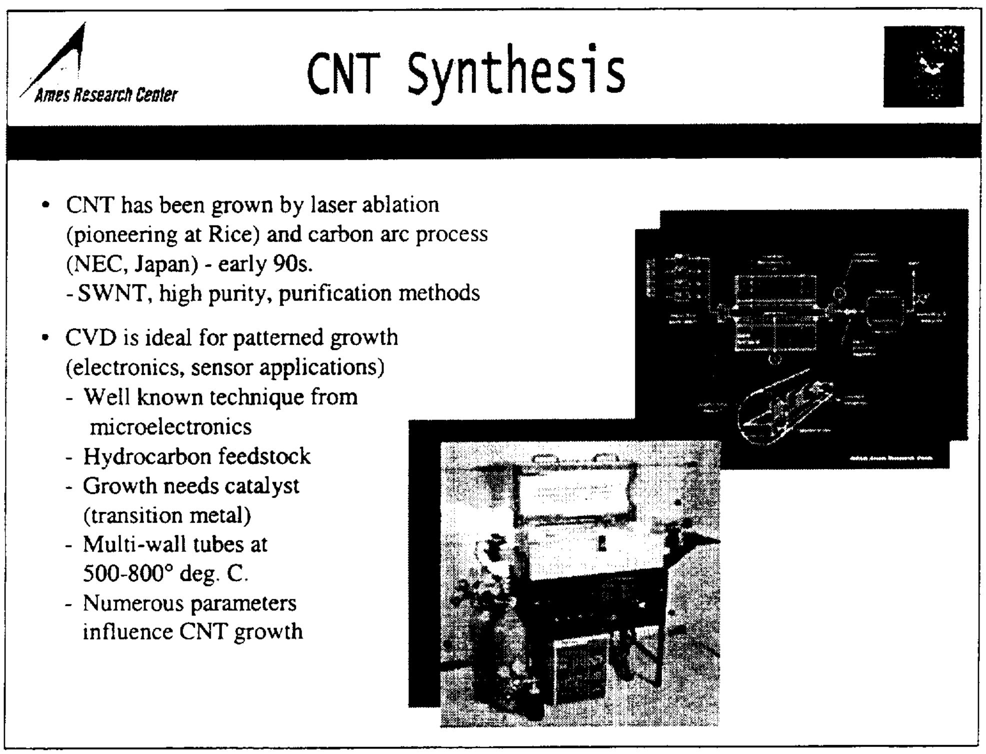
- CNT based microscopy: AFM, STM...
- Nanotube sensors: force, pressure, chemical...
- Biosensors for astrobiology
- Molecular gears, motors, actuators
- Batteries, Fuel Cells: H_2, Li storage
- Nanoscale reactors, ion channels
- Biomedical
  - in vivo real time crew health monitoring
  - Lab on a chip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

Challenges

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

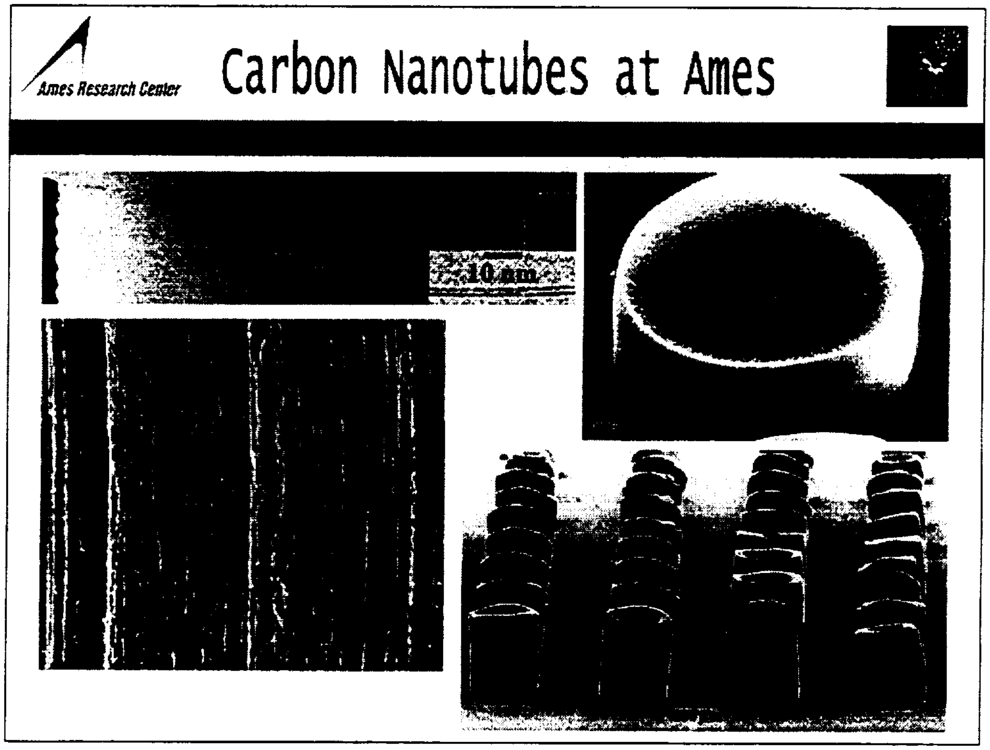
CNT Synthesis

Laser ablation provides ~ 70% purity single wall nanotubes. It is not a suitable process for mass production. Universities and companies across the country are investigating new approaches to producing nanotubes in large quantities. CVD on the other hand enables controlled growth on patterned substrates. NASA Ames runs three CVD reactors to grow nanotubes on substrates. Parameters controlling the outcome are numerous: feed gas composition, temperature, choice of catalyst material, catalyst preparation technique, resulting catalyst particle size, substrate preparation.... Ames' work includes a combinatorial chemistry analysis to speed up this investigation.



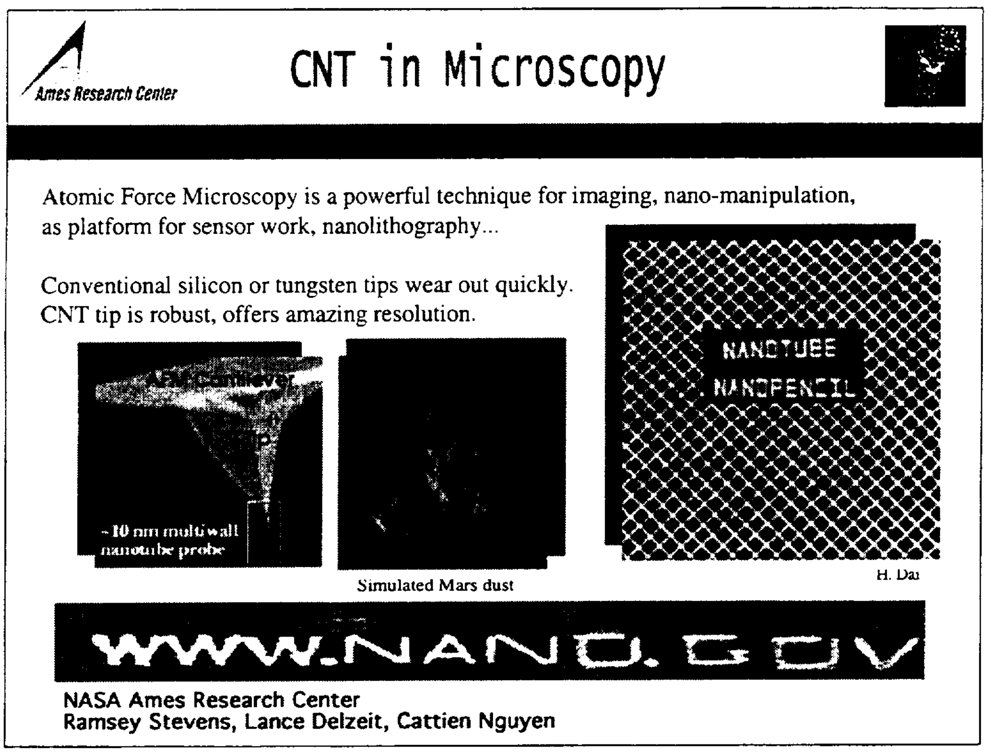
Carbon Nanotubes at Ames

The top left picture shows a single wall nanotube between two contacts. The top right shows a multi-wall nanotube pillar. A close examination of this pillar is shown in the bottom left picture. When the catalyst is arranged in a ring-like pattern on the substrate, then structures resembling a nano-trash can emerge as shown on the bottom right. All of this CVD work was done by Alan Cassell of the Ames team.



CNT in Microscopy

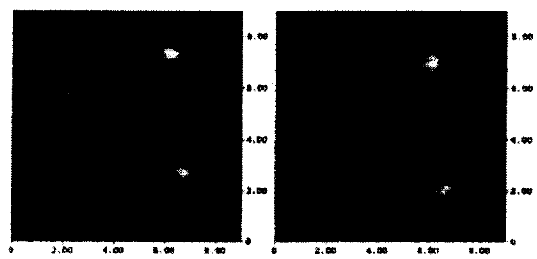
Using CNT as a tip in AFM is well known. However, most groups attach the CNT to the cantilever manually using epoxy or glue. This is tedious. Stevens and Nguyen of Ames are able to attach nanotubes directly to the cantilever by CVD. At Ames, an AFM with a nanotube tip is used to study simulated Mars dust as well as ALH 84001. The image on the right extreme is from H. Dai of Stanford University and Jie Han of NASA Ames which shows a 10nm line lithographic pattern on silicon. The bottom image is nano-lithography as well as nano-calligraphy where the White House nano-website address was written out as 10nm size letters using nanotube tip in an AFM at Ames.



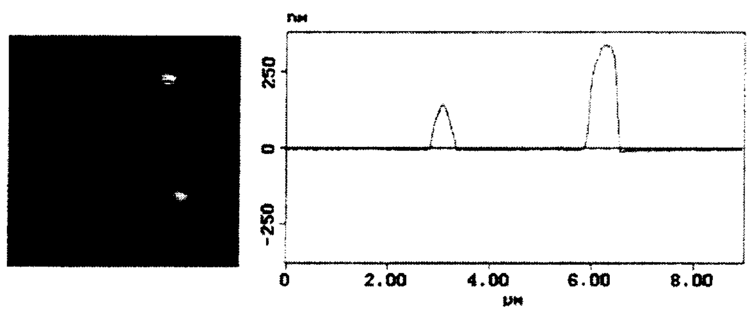
Tapping Mode AFM Images of Simulated Mars Dust on Mica Using Different Tips

Srin Manne of the University of Arizona did a comparison of nanotube tips and silicon tips in an AFM. When the particle size is small, the silicon tip cannot capture the shape correctly; all particles appear to be triangular on one side. In contrast, the nanotube tip captures the shape very well. The tip is also very robust and long lasting.

Tapping mode AFM images of simulated Mars dust on mica using different tips



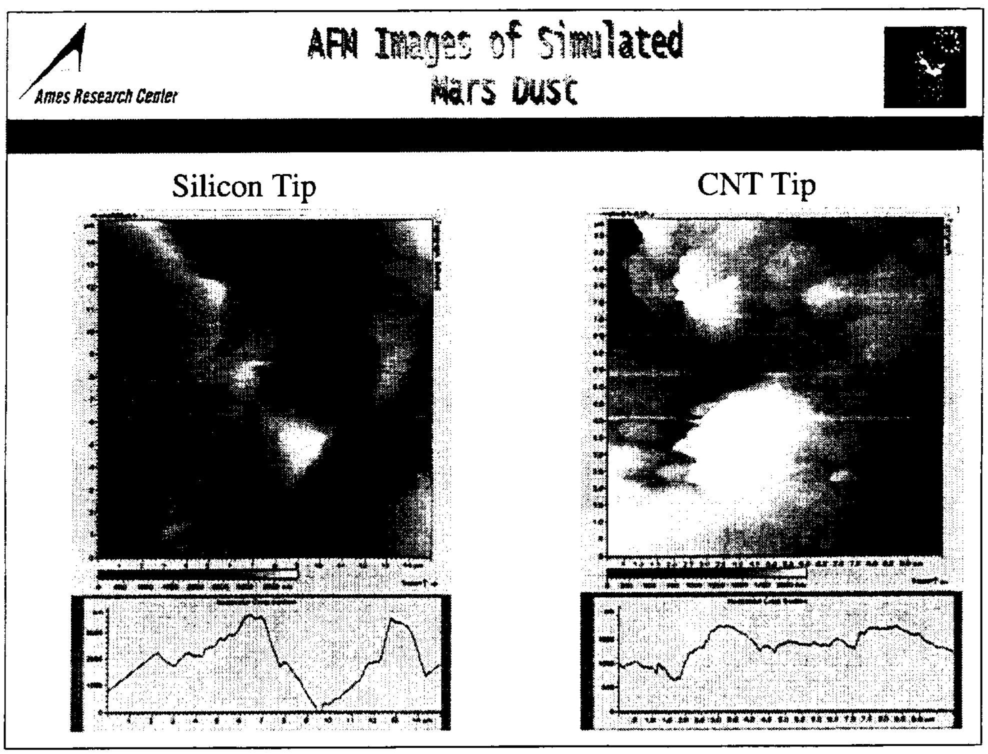
Mars dust imaged with standard silicon tip (left) and a single wall carbon nanotube tip (right). The nanotube tip was reported to be 50-70 nm long and 2-3 nm diameter. original images: simars4.017(left) and tmars4.014



Above: Cross section of simulated mars dust particle imaged with a silicon tip

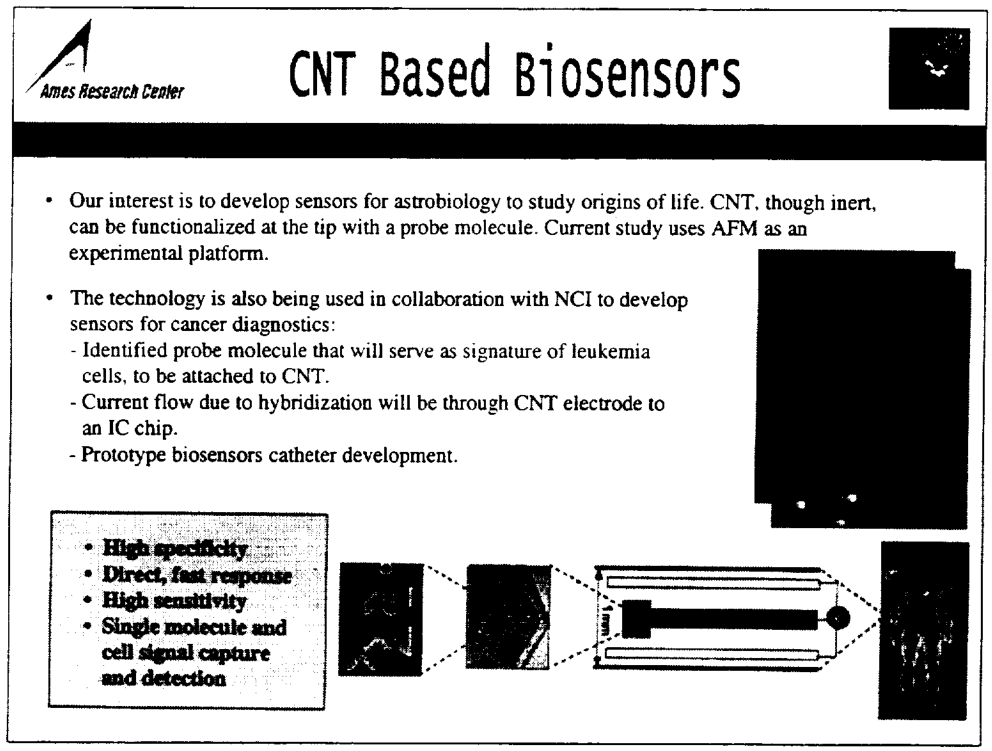
AFM Images of Simulated Mars Dust

This comparison, done by Ramsey Stevens of Ames, shows the image of 20 μm simulated Mars dust. The image using silicon tip, though topologically smooth, is a false image and is an artifact due to the pyramidal tip of the cantilever making contact with a tall feature before the apex of the tip reaches the surface. In contrast, the image using the nanotube tip shows a complex topography. The cross section at the bottom shows that the tip is tracking the surface even into deep valleys and over sharp peaks. It does, however, exhibit a 'record skipping' type artifact because the tip is reaching so deep past tall features that sometimes the side of the pyramid bumps into a tall feature as the tip scans past. This artifact has been overcome by altering tip size.



CNT Based Biosensors

The National Cancer Institute (NCI) is funding NASA Ames to develop a nanotube based cancer sensor. The focus is on developing a sensor for Leukemia. David Loftus, Ames medical officer, is a hematologist working on this project along with the Ames nanotube team. The experience gained in aligned nanotube growth and functionalization for this project would be directly beneficial to the sensor efforts in astrobiology.



Computational Nanotechnology

Computational modeling and simulation have been valuable in the nanotube field. Numerous papers in the literature have been devoted to evaluation of properties and transport in nanotubes. The Ames team has made significant contributions to the field of computational nanotechnology. The CNT networks shown here, as modeled by Srivastava, appear to have the potential for revolutionary electronics. The nanogear designed by Han and Srivastava has captured the imagination of nano-enthusiasts across the world and represents one of the most widely used images in nanotechnology.

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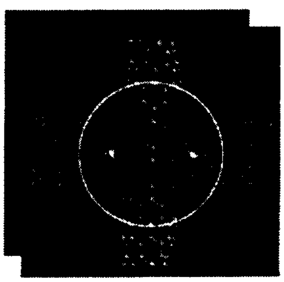
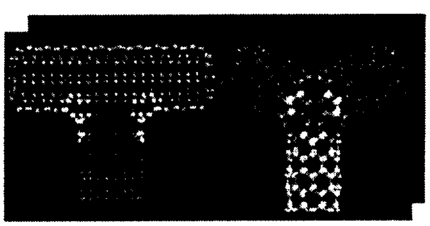
Computational Nanotechnology

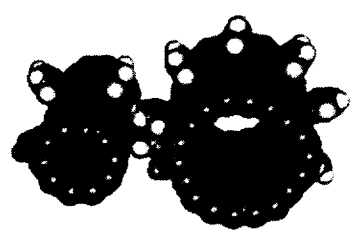


CNT Molecular Network

- 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)

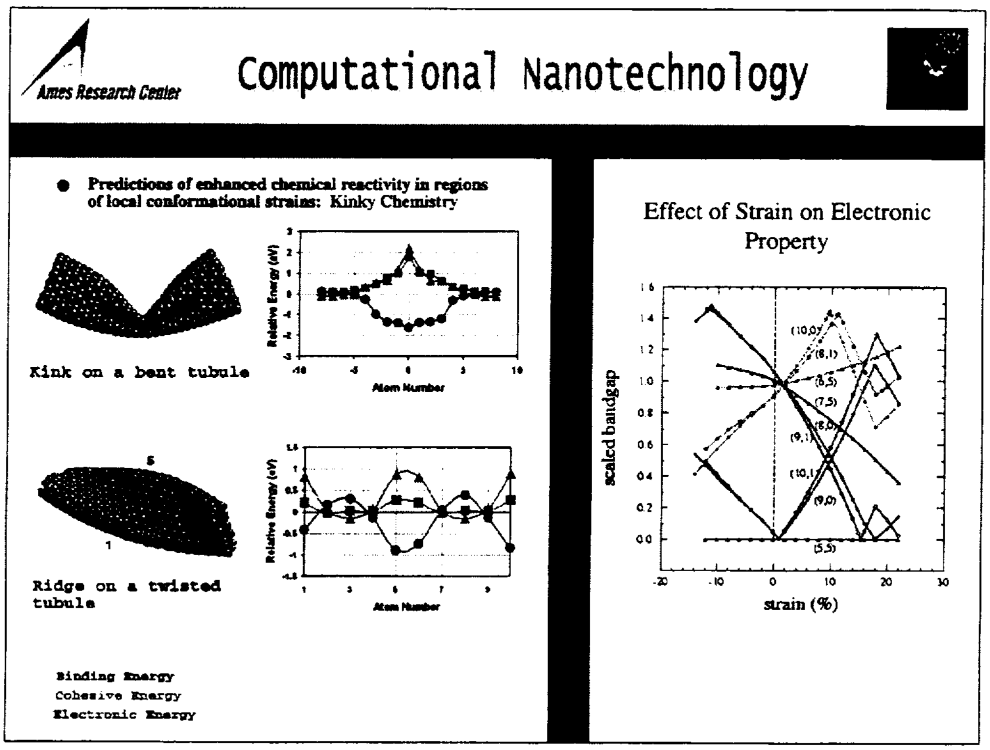


CNT "T" and "Y" Junctions



Computational Nanotechnology

CNT itself is chemically inert. Srivastava's simulations show enhanced chemical reactivity at locations of conformational strain. This prediction has been experimentally verified by Rodney Ruoff's group at Washington University. The electronic properties of CNT are tightly coupled to the mechanical properties. Liu Yang of Ames has computed the bandgap as a function of elongational and torsional strain. In addition, several papers by Anantram focus on transport in nanotubes and metal-nanotube contact characteristics. See www.ipt.arc.nasa.gov for a bibliography.



Protein Nanotubes

The study of extremophiles is an area of interest to Ames Astrobiology scientists. Jonathan Trent at Ames has been able to assemble HSP 60 into nanotubes. These protein tubes are about 12-15nm in diameter and a few microns long. The image on the left shows a self-assembly pattern of the protein nanotubes.

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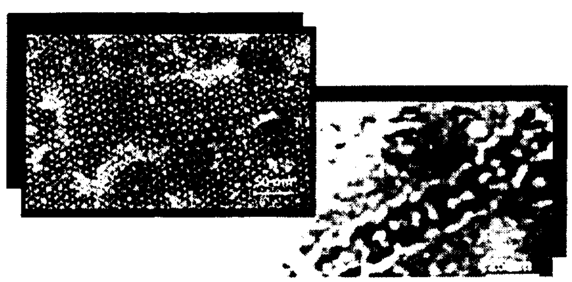
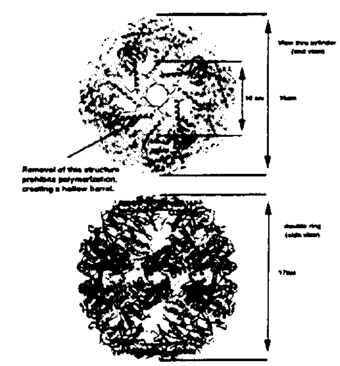
Protein Nanotubes

- 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.





Summary

The potential of nanotube technology for NASA missions is significant and is properly recognized by NASA management. Ames has done much pioneering research in the last five years on carbon nanotube growth, characterization, atomic force microscopy, sensor development and computational nanotechnology. NASA Johnson Space Center has focused on laser ablation production of nanotubes and composites development. These in-house efforts, along with strategic collaboration with academia and industry, are geared towards meeting the agency's mission requirements.

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Summary

- Nanoscale science and technology will have significant impact on the future of NASA missions by enabling cheaper, more capable and reliable, and more frequent missions.
- Given the tremendous potential, there is a need for investment from all enterprises.
- Given the breadth of nanotechnology subfields, there is significant overlap with DoD, DOE missions and opportunity to share fundamental research sponsored by NSF.
- Nano-revolution has just begun; there is a long way to go before significant system level payoff. It is time to focus on:
  - Fundamental research
  - Material development, characterization
  - Novel instrumentation
  - Cost effective manufacturing routes
  - Identification of most promising applications
  - System level concepts