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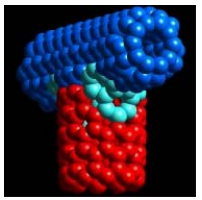
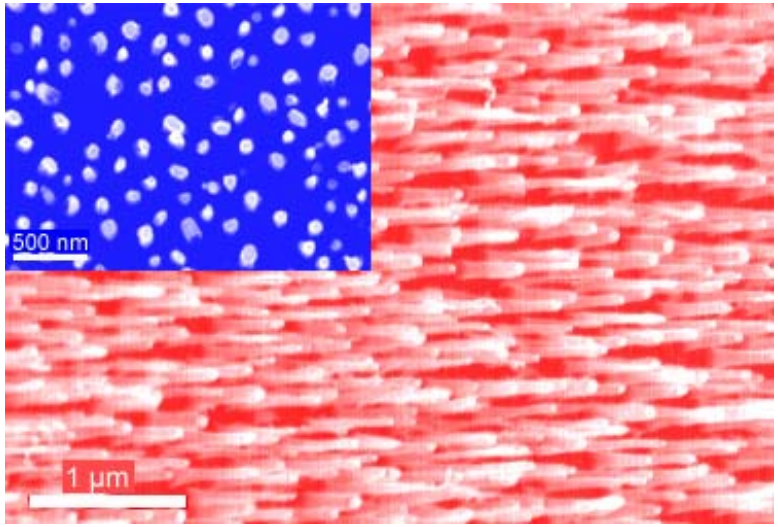
Nanotechnology: Opportunities and Challenges





M. Meyyappan
Director, Center for Nanotechnology
NASA Ames Research Center
Moffett Field, CA 94035

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

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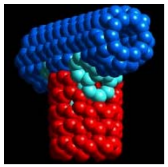
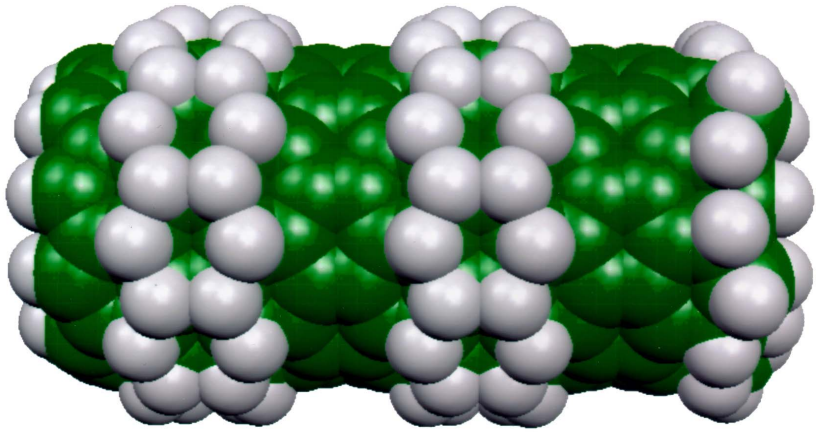
What is Nanotechnology?



Nanotechnology is the creation of **USEFUL/FUNCTIONAL** materials, devices and systems through control of matter on the nanometer length scale and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale



Charles Bauschlicher

"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."

-Neal Lane
Former Assistant to the President for Science And Technology

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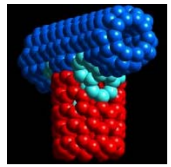
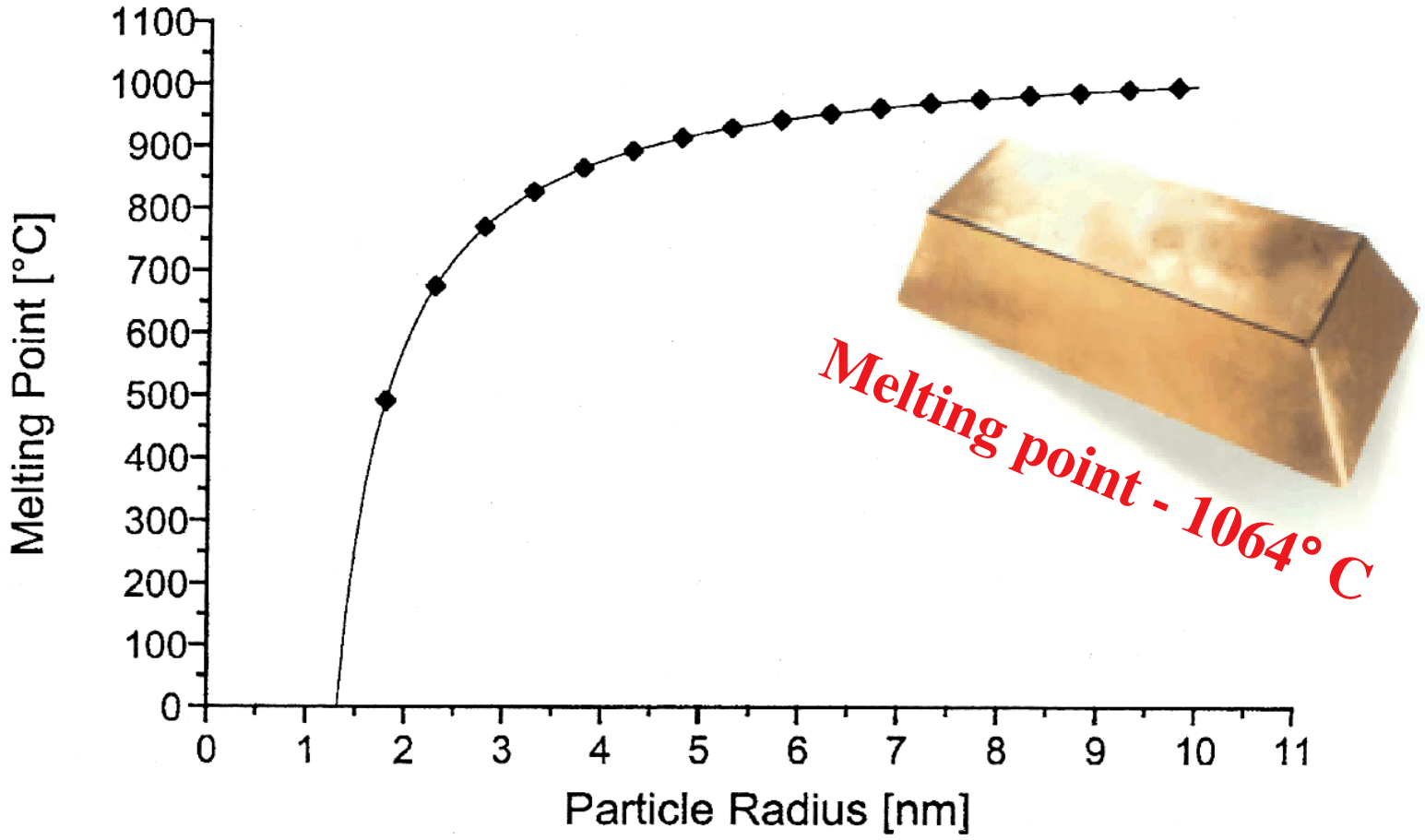
Melting Point of Gold





Melting point - 1064° C

Source: K.J. Klabunde, 2001

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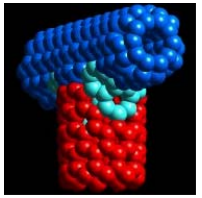
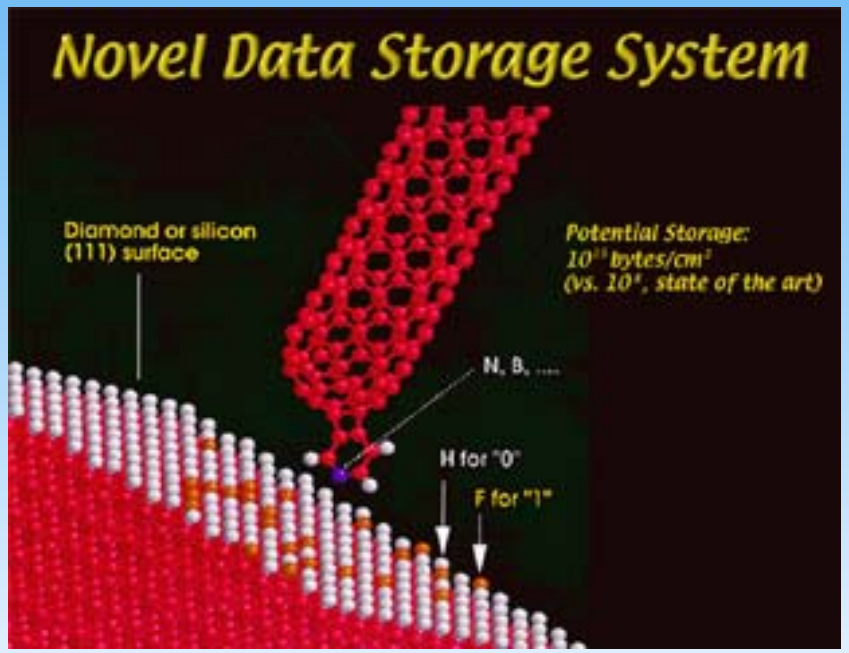
Impact of Nanotechnology





Nanotechnology is an enabling technology

- Computing and Data Storage
- Materials and Manufacturing
- Health and Medicine
- Energy and Environment
- Transportation
- National Security
- Space exploration
-
-

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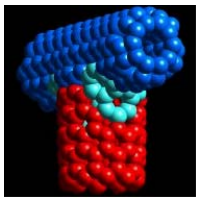
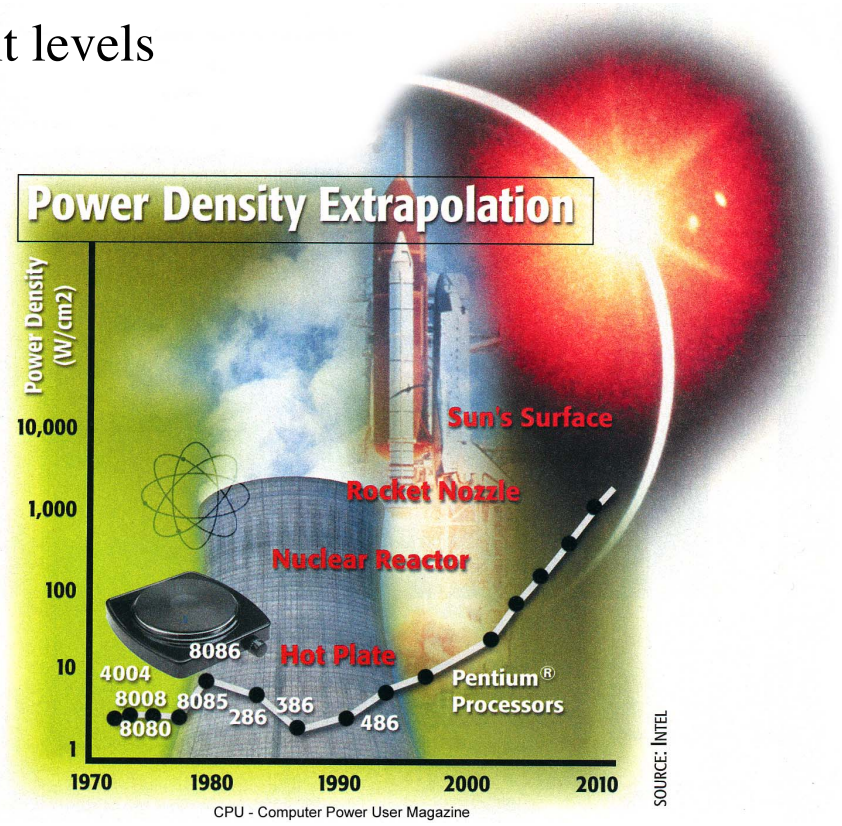
Expected Nanotechnology Benefits in Electronics and Computing



- Processors with declining energy use and cost per gate, thus increasing efficiency of computer by 10^6
- Small mass storage devices: multi-tera bit levels
- Integrated nanosensors: collecting, processing and communicating massive amounts of data with minimal size, weight, and power consumption
- Higher transmission frequencies and more efficient utilization of optical spectrum to provide at least 10 times the bandwidth now
- Display technologies
- Quantum computing



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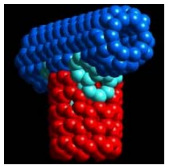
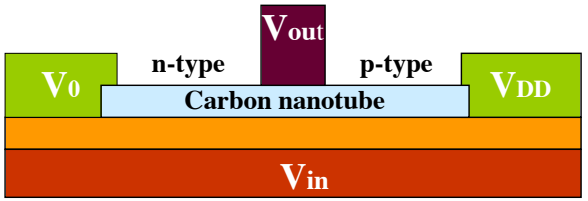
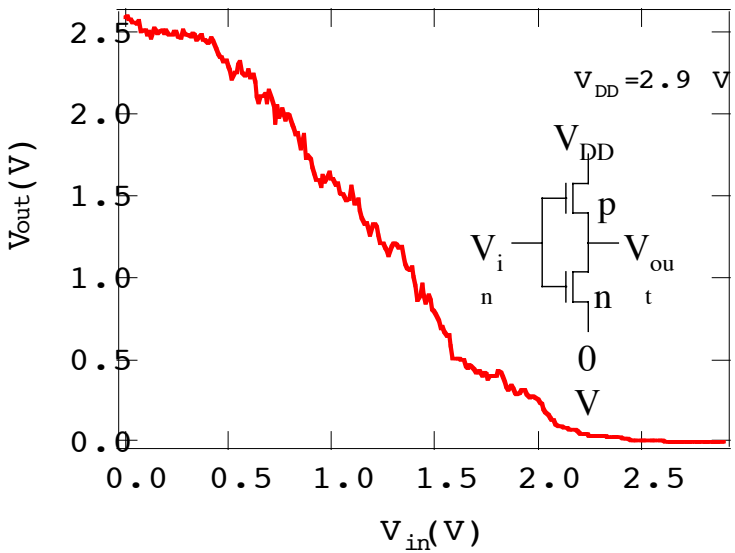
CNT-based Logic and Memory Devices

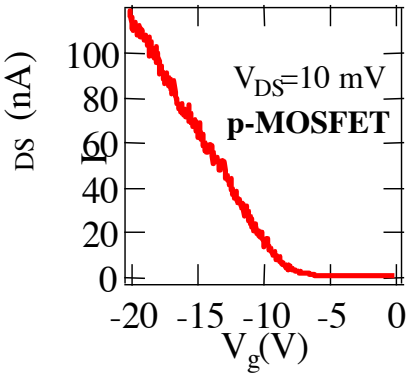


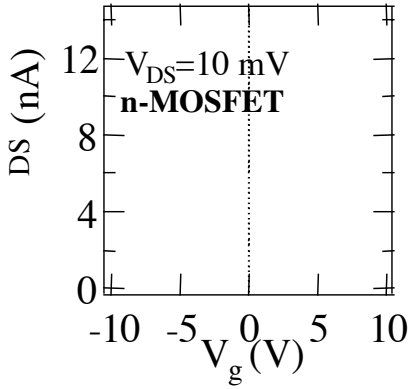
*First single nanotube logic device – Inverter demonstration (Appl. Phys. Lett., Nov. 2001)

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









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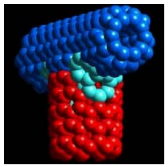
Nanoelectronics: What is Expected from Alternative Technologies?

(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….

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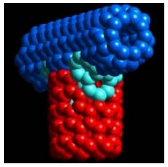
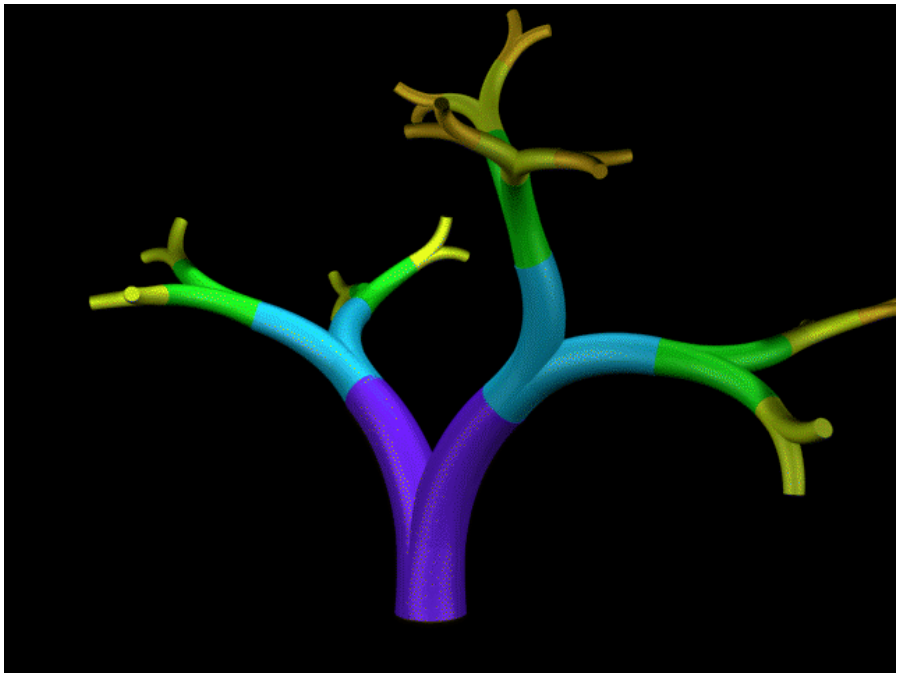
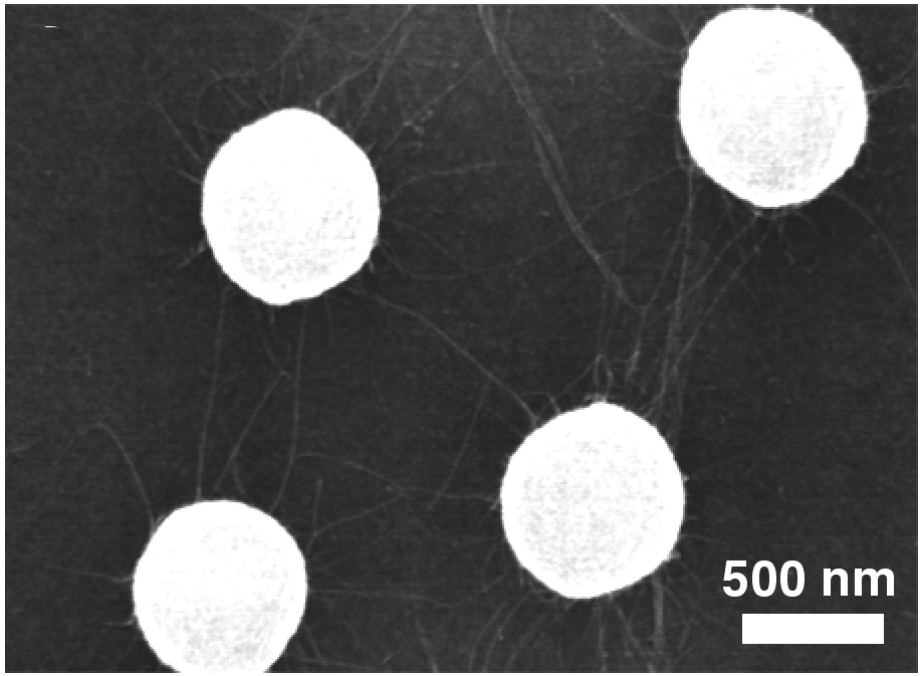
Four-level CNT Dentritic Neural Tree



- 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





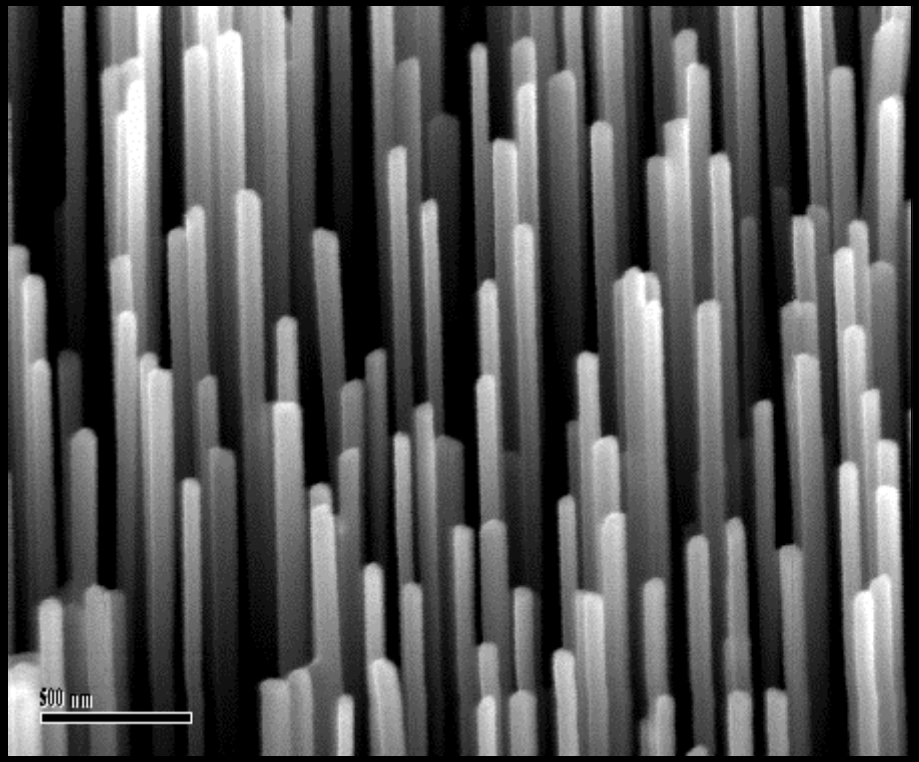
Motivations for selecting Single Crystalline Nanowires & Nanowalls (in Nano-scale Electronics)

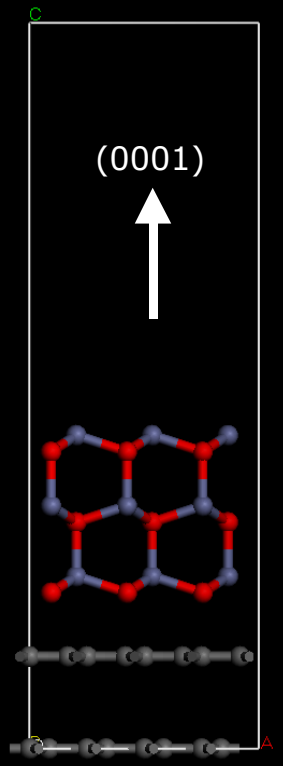
- ❖ High single crystallinity ⇒ Low defect density, grain boundary free
- ϖ Well-defined surface structural properties ⇒ Enhanced interfacial engineering
- ❖ Predictable electron transport properties ⇒ Predictable device performance
- ❖ Unique physical properties due to quantum confinement effects ⇒ 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

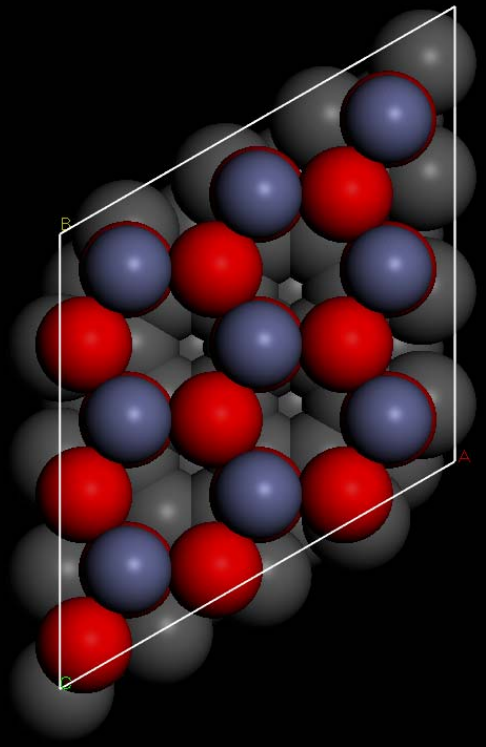
Challenges in Nanowire Growth

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

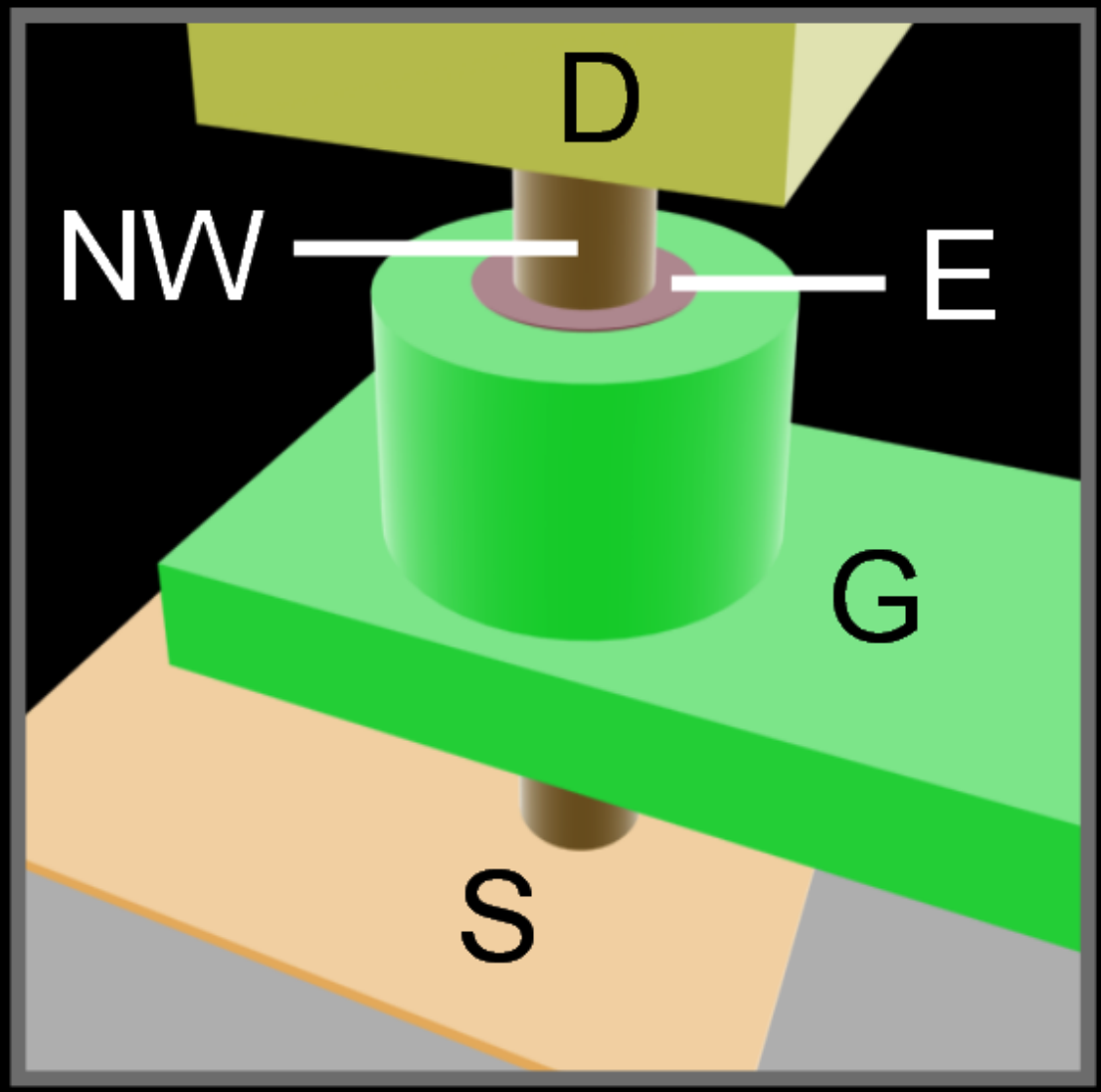
Understanding of the interfacial epitaxial relationship between potential substrates and nanowire structures ⇔ modeling and simulations ⇔ experiments ⇔ combinatorial approach



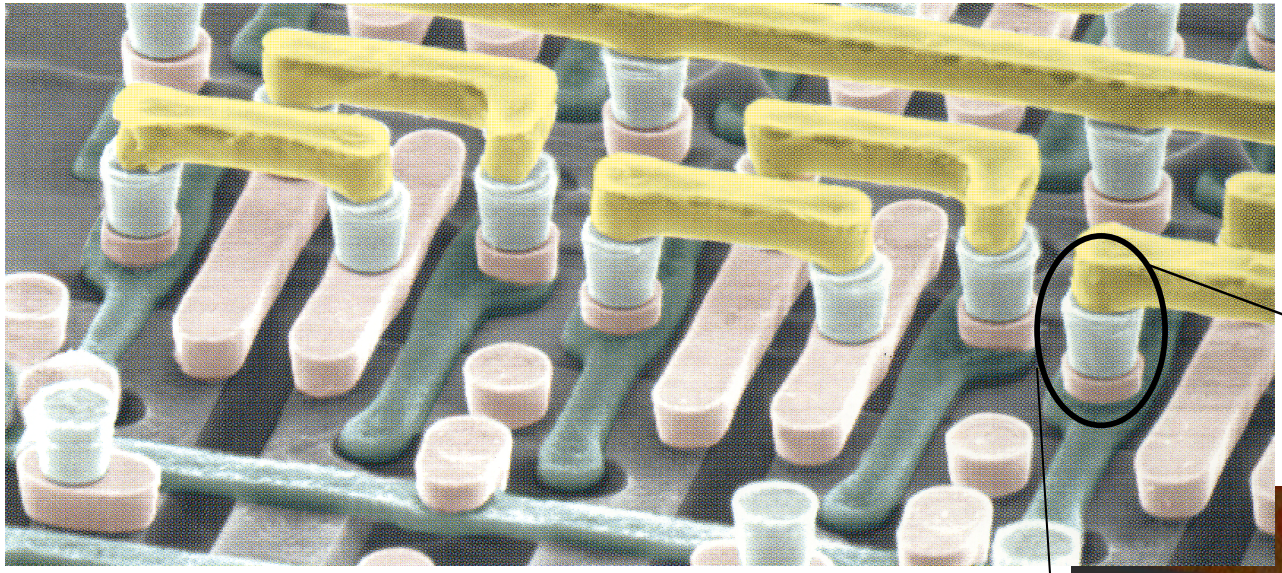


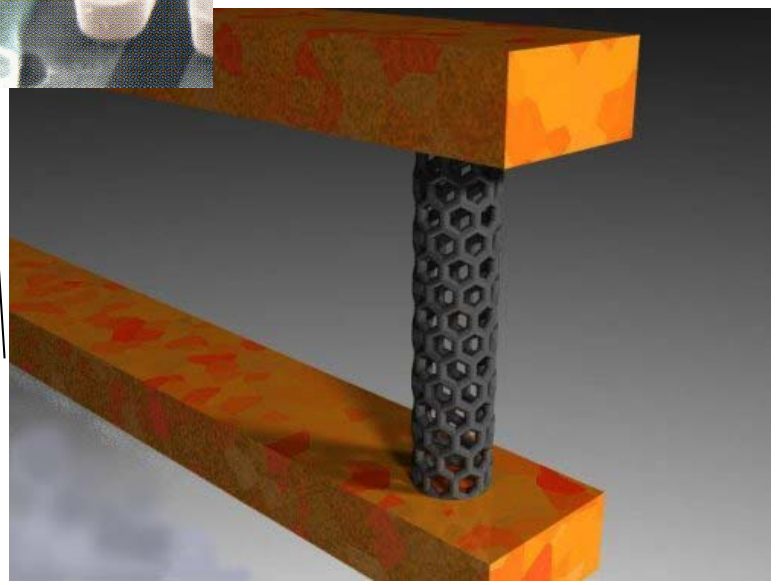


Nanowire-based Vertical Surround Gate FET



MWNT Interconnects ?





CNT advantages:

(1) Small diameter

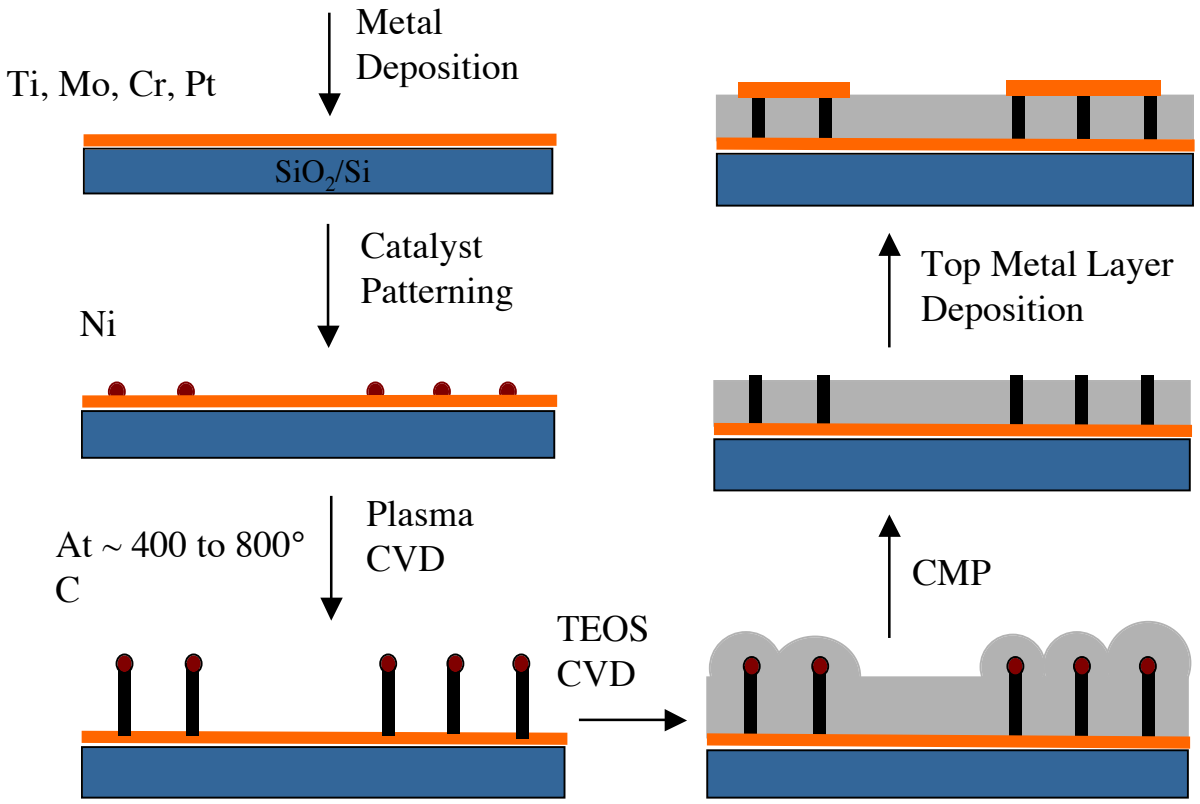
(2) High aspect ratio

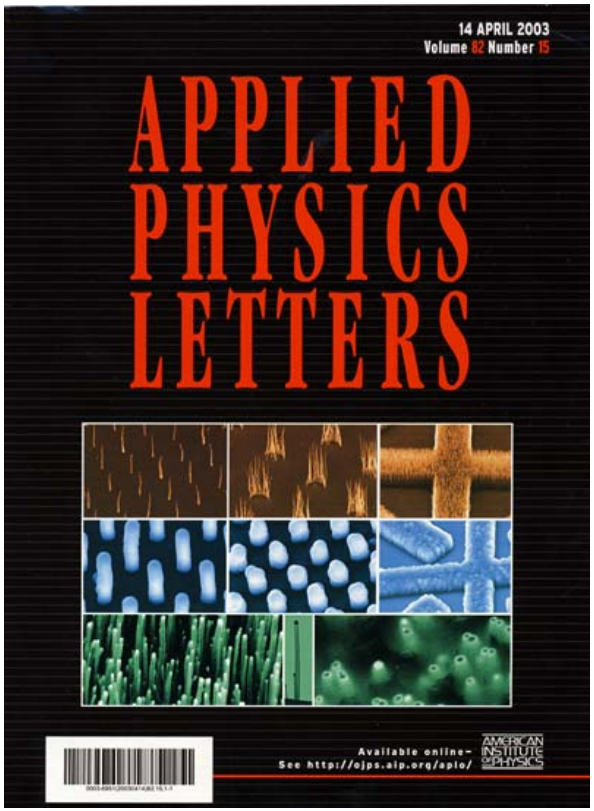
(3) Highly conductive along the axis

(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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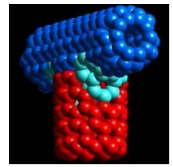
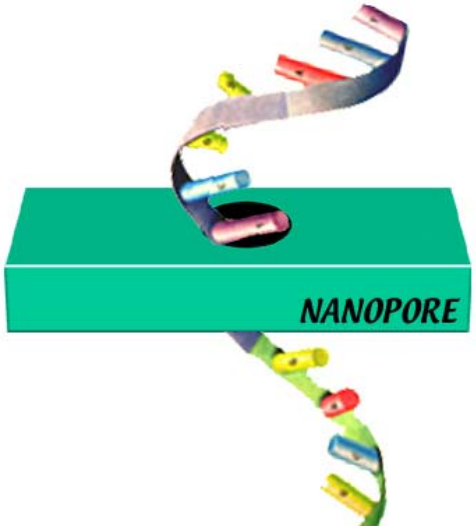
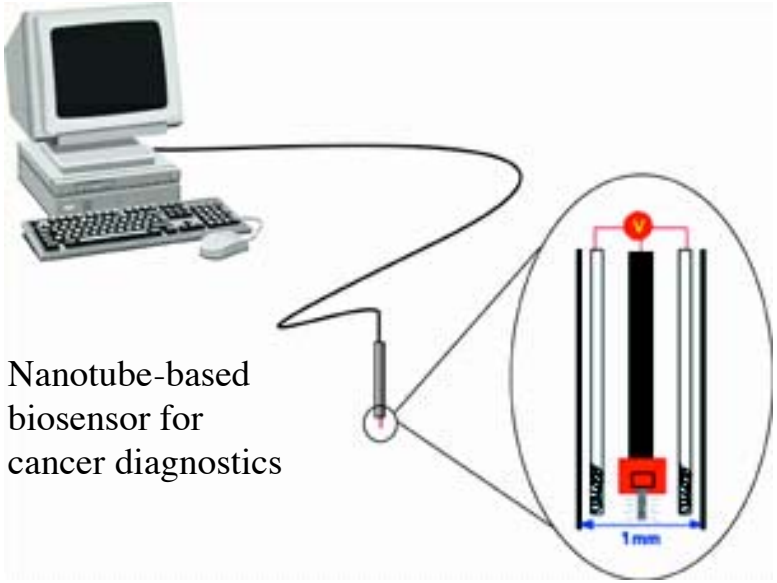
Health and Medicine



- Expanding ability to characterize genetic makeup will revolutionize the specificity of diagnostics and therapeutics
  - Nanodevices can make gene sequencing more efficient



- Effective and less expensive health care using remote and in-vivo devices



Nanotube-based biosensor for cancer diagnostics

- New formulations and routes for drug delivery, optimal drug usage
- More durable, rejection-resistant artificial tissues and organs
- Sensors for early detection and prevention

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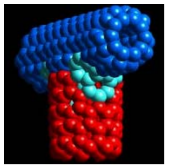
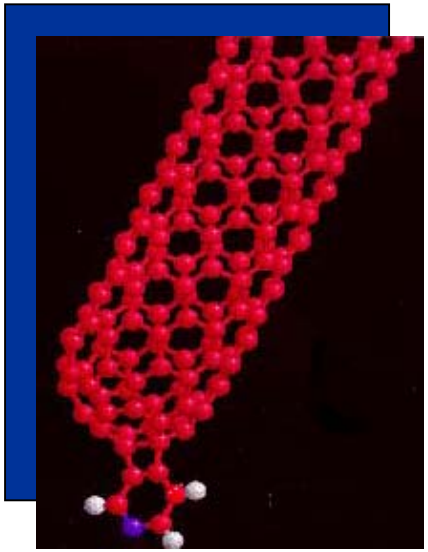
CNT Based Biosensors

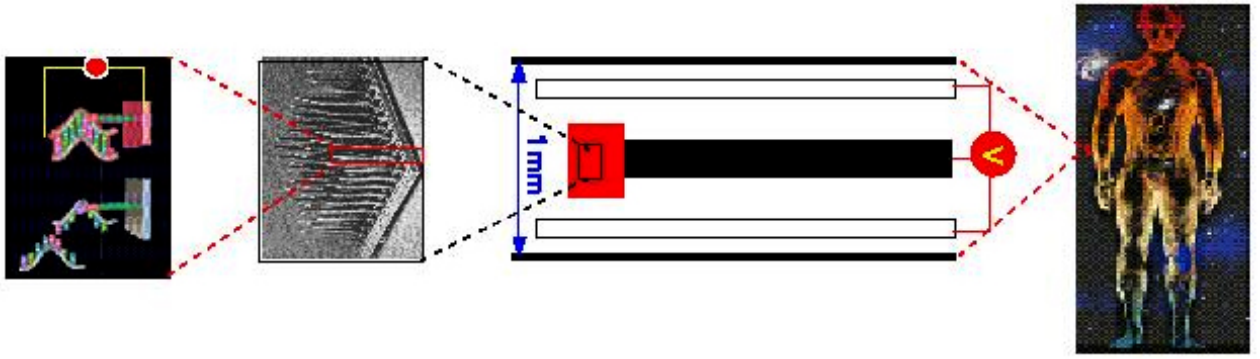


- Our interest is to develop sensors for astrobiology to study origins of life. CNT, though inert, can be functionalized at the tip with a probe molecule. Current study uses AFM as an experimental platform.



- 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**



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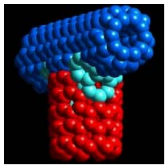
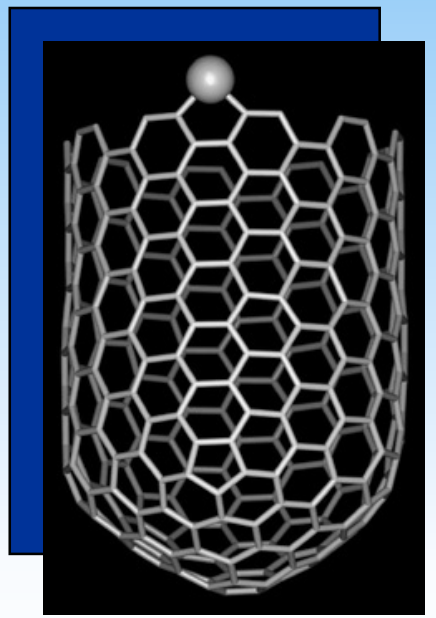
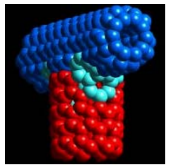
Materials and Manufacturing



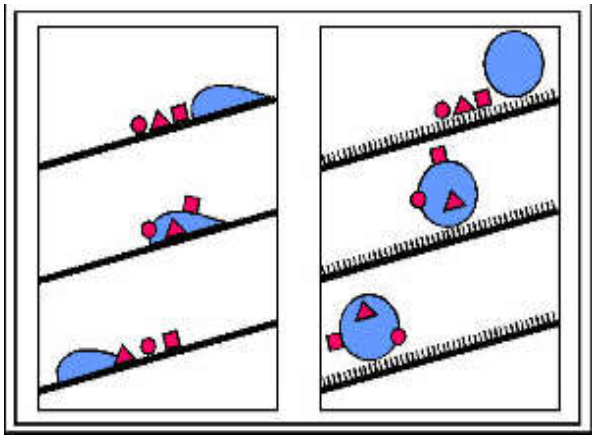
- Ability to synthesize nanoscale building blocks with control on size, composition etc. ⟹ further assembling into larger structures with designed properties will revolutionize materials manufacturing
  - Manufacturing metals, ceramics, polymers, etc. at exact shapes without machining
  - Lighter, stronger and programmable materials
  - Lower failure rates and reduced life-cycle costs
  - Bio-inspired materials
  - Multifunctional, adaptive materials
  - Self-healing materials



Self-Cleaning Surfaces: Lotus Effect

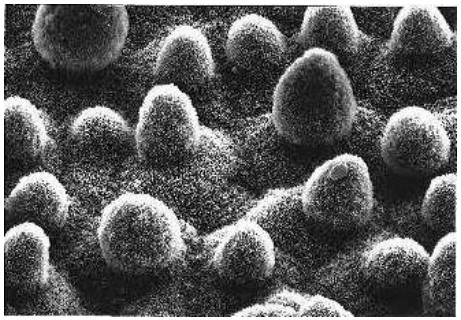


10 mm

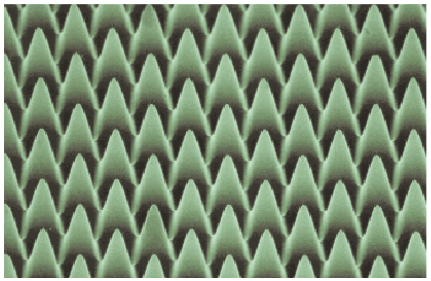


W. Barthlott, Univ. of Hamburg

On a smooth surface the contaminating particles are only moved by the water droplet (left). In contrast to that, on a rough surface they stick to the droplet rolling off the leaf thus being washed off (right).



Epicuticular wax



REM recording of a holographically produced self-cleaning surface.
© Fraunhofer ISE

(Source: Metin Sitti, CMU)

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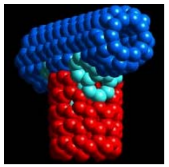
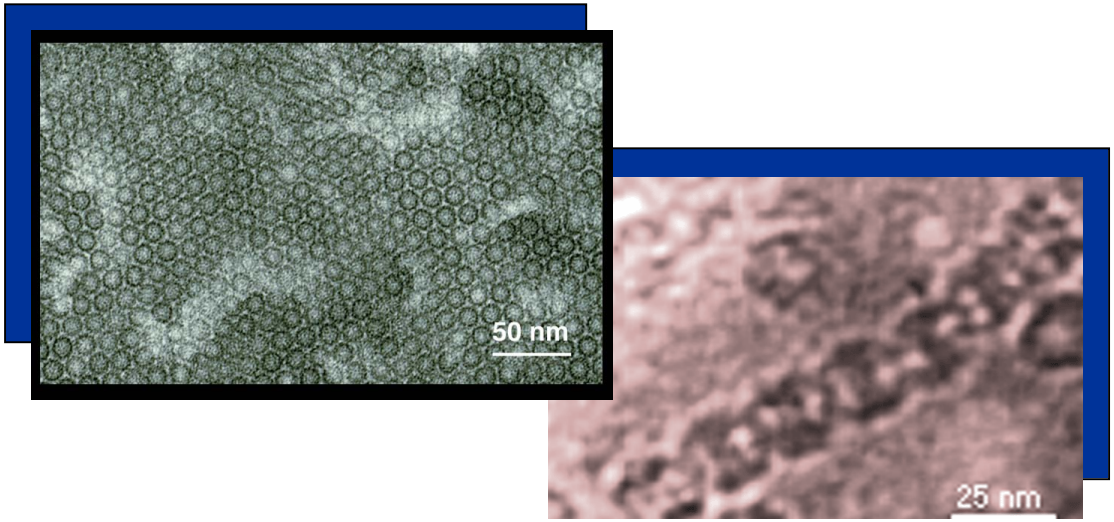
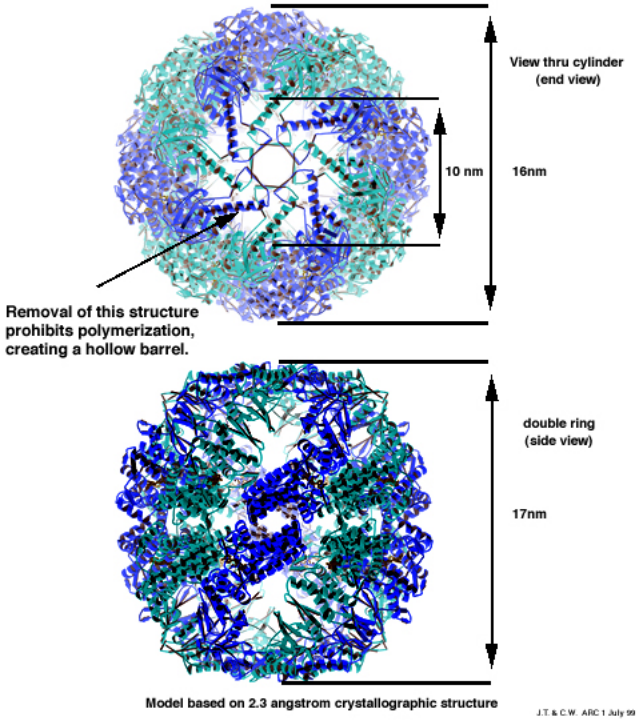
Protein Nanotubes



- 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.





Extremophile Proteins for Nano-scale Substrate Patterning

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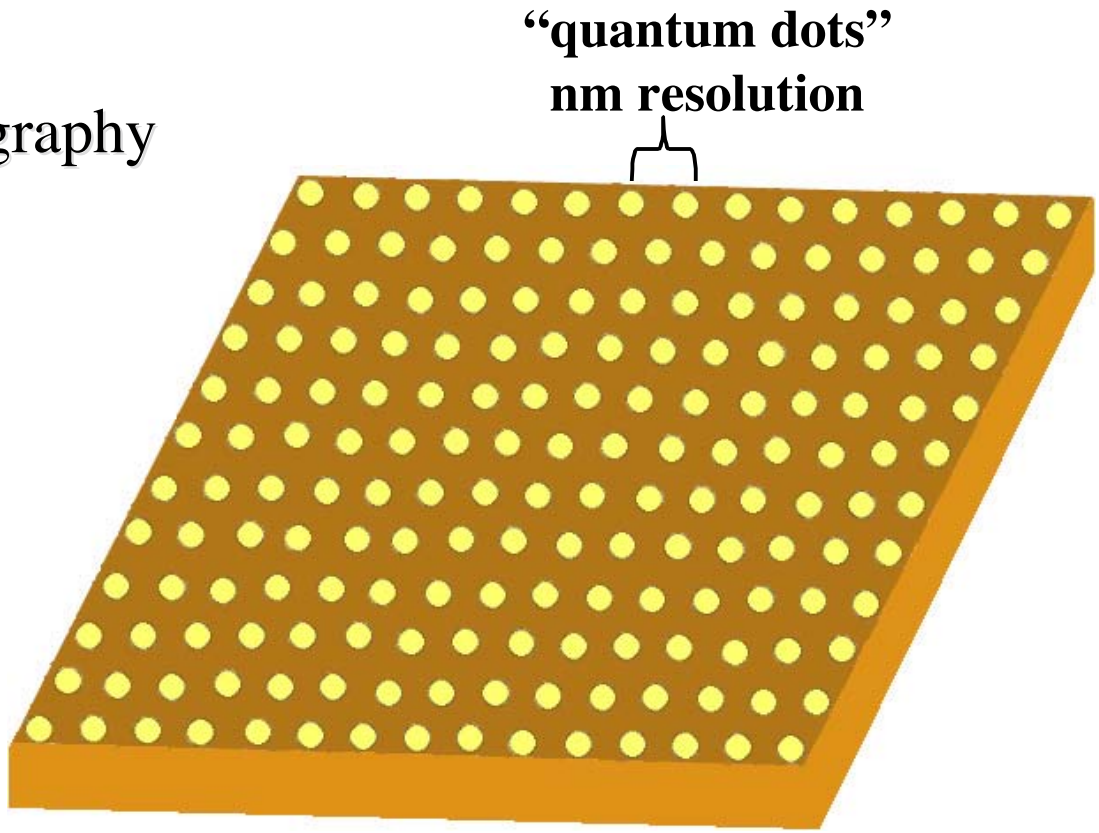
Nano-scale engineering for high resolution lithography

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



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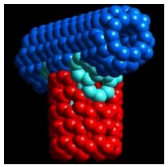
Energy and Environment



- Energy Production
  - Clean, less expensive sources enabled by novel nanomaterials and processes
- Energy Utilization
  - High efficiency and durable home and industrial lighting
  - Solid state lighting can reduce total electricity consumption by 10% and cut carbon emission by the equivalent of 28 million tons/year (Source: Al Romig, Sandia Lab)

- Materials of construction sensing changing conditions and in response, altering their inner structure

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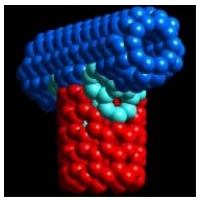
Benefits of Nanotechnology in Transportation



- Thermal barrier and wear resistant coatings
- High strength, light weight composites for increasing fuel efficiency
- High temperature sensors for ‘under the hood’
- Improved displays
- Battery technology
- Wear-resistant tires
- Automated highways

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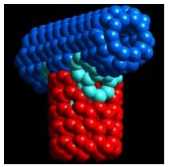
National Security



- Very high sensitivity, low power sensors for detecting chem/bio/nuclear threats

- Light weight military platforms, without sacrificing functionality, safety and soldier security
  - Reduce fuel needs and logistical requirements

- Reduce carry-on weight of soldier gear
  - Increased functionality per unit weight

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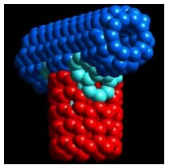
Why Nanotechnology at NASA?



- 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

Europa Submarine

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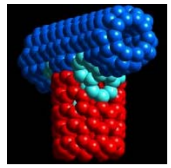
Assessment of Opportunities



- **Short term (< 5 years)**
  - Nanoparticles
    - * Automotive industry (body moldings,timing belts, engine covers…)
    - * Packaging industry
    - * Cosmetics
  - Flat panel displays
  - Coatings
  - CNT-based probes in semiconductor metrology
  - Tools
  - Catalysts (extension of existing market)

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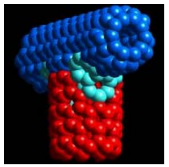
Assessment of Opportunities (Cont.)



- **Medium term (5-10 years)**
  - Memory devices
  - Fuel cells, batteries
  - Biosensors (CNT, molecular, qD based)
  - Biomedical devices
  - Advances in gene sequencing
  - Advances in lighting
- **Long term (> 15 years)**
  - Nanoelectronics (CNT)
  - Molecular electronics
  - Routine use of new composites in Aerospace, automotive (risk-averse industries)
  - Many other things we haven't even thought of yet

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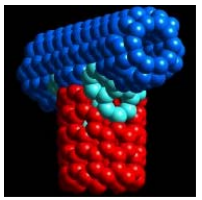
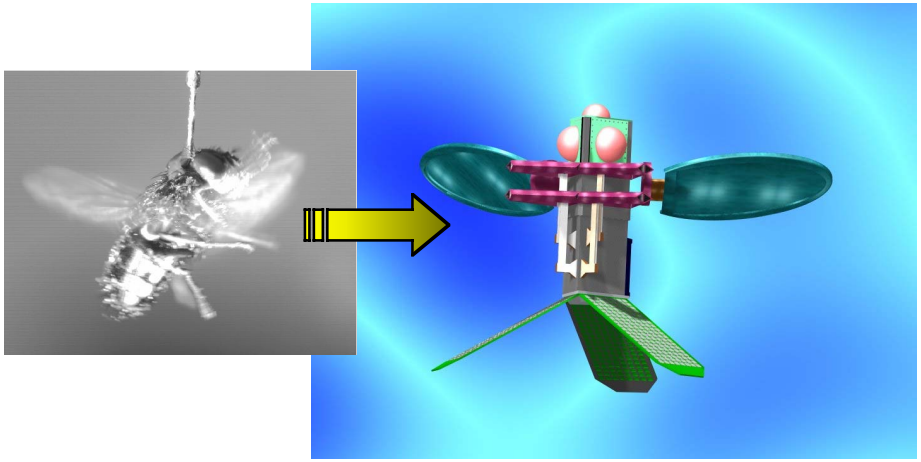
Challenges facing Nanotechnology



- Lots of nanoscience now, some nice nanotechnology; more emphasis on technology development and participation from engineering communities are needed
- People do not buy technology; they buy products
  - Robust product development is critical to realize the potential
  - Early and periodic wins, a must to keep investor confidence high
- Recognition of nano-micro-macro hierarchy in product development

Source: UC Berkeley



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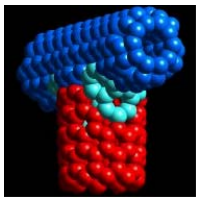
Challenges facing Nanotechnology (Continued)



- Need some sanity in issuing patents
- Given the long term nature of the technology and payoffs in terms of job creation and economic returns,
  - Lack of patience from Federal Government will kill the field
  - But history indicates, Federal agencies have been responsible for numerous technology wins in the last 50 years
  - So, ignore the hype and stay the course for the long run
- Venture community behavior will determine the fate
  - Lack of patience will hurt the startup activities
  - Indiscriminate investment like in the dotcom days will seal the field
- Educating future generation scientists and engineers

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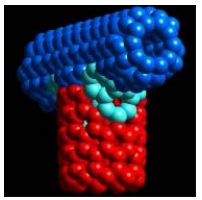
Summary



- 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