Nanotechnology

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ISM101
What's going on on the nanoscale?

- Simple molecules (<1nm)
- DNA proteins (nm)
- Bacteria (~1μm)
- Red blood cell (~5μm SEM)
- Diatom (30μm)
- Semiconductor nanocrystal (CdSe) 5nm
- Nanometer memory element (Lieber) $10^{12}$ bits/cm² (1Tbit/cm²)
- SOI transistor width 0.12μm
- Circuit design Copper wiring width 0.2μm
- IBM PowerPC 750™ Microprocessor 7.56mm×8.799mm 6.35×10⁶ transistors

(courtesy R. Ram, MIT)
What is Nanotechnology?

Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to understand and create materials, devices and systems with fundamentally new properties and functions because of their small structure.

**NNI definition encourages new contributions that were not possible before.**

- novel phenomena, properties and functions at nanoscale, which are nonscalable outside of the nm domain
- the ability to measure / control / manipulate matter at the nanoscale in order to change those properties and functions
- integration along length scales, and fields of application

MC. Roco, 9/29/03
Why Nanotechnology?

• Miniaturization
  – less space, faster, less material, less energy

• Novel Properties/ Phenomena/ Processes
  – Low dimensional structures, Quantum phenomena
  – Enhanced surface effects (increased surface/volume ratio)

• Unity and Generality
  – Building blocks of natural/artificial things

• Interdisciplinary (Science & Technology, bio/nano)

• Most efficient length scale for manufacturing
  – Less energy than for subatomic or macroscopic
Reaching nano-world and system creation

Size of structure

Top down
- Biology, mechanics, top-down tools
- Robotics
- Biomimetics
- Guided assembling
- Evolutionary

Bottom up
- Physics, chemistry, simulations
- Utilization of nanoscale laws
- Biological principles
- Information technology
- Knowledge of integration

System creation

Converging S&E

Reaching nano-world

Diverging architectures

PASSIVE NANO-STRUCTURES (in production)
ACTIVE NANO-STRUCTURES (to prototypes)
SYSTEMS OF NANOSYSTEMS (in research)
MOLECULAR NANO-SYSTEMS (in concept)

Successive developments

2000 2010 2020
Timeline for nanotechnology commercialization

1st: Passive nanostructures
   - (1st generation products)
   - Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics
   - ~ 2000

2nd: Active nanostructures
   - Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures
   - ~ 2005

3rd: Systems of nanosystems
   - Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary
   - ~ 2010

4th: Molecular nanosystems
   - Ex: molecular devices ‘by design’, atomic design, emerging functions
   - ~ 2015-2020

R&D

**Context – Nanotechnology in the World**

**Past government investments 1997-2005** (est. NSF)

![Graph showing government investments in nanotechnology](image)

- **Seed funding (1991 -)**
- **NNI Preparation (vision / benchmark)**
- **1st Strategic Plan (passive nanostructures)**
- **2nd Strategic Plan (active nanostruct. & systems)**

Total government expenditure in FY 2005 – about $4.1 billion

MC. Rose, 7/12/05
Size Scales Accessible to Nanofabrication Approach

Characteristic Size (Meters)

- 1 micrometer
- 1 nanometer

Dimensions

Fabrication Technologies

- Photolithography
- Microcontact Printing
- Electron Beam Lithography
- Scanned Probes

New Materials
<table>
<thead>
<tr>
<th>SENSE</th>
<th>PROBE</th>
<th>MICROSCOPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIGHT</td>
<td>ELECTROMAGNETIC RADIATION</td>
<td>LIGHT, ELECTRON, ION MICROSCOPES, STM</td>
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<tr>
<td>SOUND</td>
<td>ACOUSTICAL RADIATION</td>
<td>ACOUSTICAL MICROSCOPE</td>
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<tr>
<td>TOUCH</td>
<td>MECHANICAL, ATOMIC FORCES</td>
<td>STYLUS, AFM, STM</td>
</tr>
<tr>
<td>SMELL</td>
<td>CHEMICAL</td>
<td>?</td>
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</tbody>
</table>
Surface of the Moon viewed by the Apollo 11 Lander
Field Emission Scanning Gun Microscope, 1968

M. Isaacson, D. Johnson and A. V. Crewe
Surface of Moon Rock from Apollo 11 Mission
Using Field Emission SEM, (SE image)

M. Isaacson, D. Johnson and A.V. Crewe, 1969
Nanodevices Require Atomic Characterization

Scanning Transmission Electron Microscope
Nanodevices require Atomic Characterization

Scanning Transmission Electron Microscope

Uranium atoms on carbon

20 nanometers
Uranium atoms on carbon

20 nanometers
Fabrication I: Top-down
Tobacco Mosaic Virus
Nanorulers formed by electron beam sublimation

STEM bright field images, 100keV

a) sodium chloride  b) lithium fluoride  c) aluminum fluoride  d) calcium fluoride

M. Isaacson and E. Kratschmer
Self-Supporting Silicon Nanowires

M. Isaacson and K. Lin
A Model Device

Stimulating the Neural Tissue Immune Response

Backside Processing - DRIE to Remove Bulk Silicon

Frontside Processing - Hard mask deposition, patterning, and DRIE

Silicon
Silicon Dioxide
Photo Resist
Cortical Microprosthetic Device

Optical Section of Rat Cortex

Microdevice in Silicon Wafer
Local Drug Delivery

Development of Prostheses with Fluidic Channels

20 µm

20 µm
U Channel Fluidic Probes

The U-Channel device will allow fluid to be passively cycled through the implanted section of the microfluidic channels. Diluted fluid will evaporate out of the exit port as higher concentration fluid is drawn through the inlet. Material in the implanted region of the channel will remain at a relatively high concentrations resulting in a constant diffusion source.
Local Drug Delivery

Device Characterization

500 µm
Local Drug Delivery

Device Characterization
Local Drug Delivery

Device Characterization

500 µm
Microfabricated Electrode Arrays Used In Vivo

- Microfabricated electrode arrays record the activity of simple insect neural networks.
- Fruit flies with just 14 large motion sensitive neurons navigate their surroundings at 1 m/s, land on surfaces, avoid obstacles.
Cricket cercal system and ventral nerve cord across a bridge electrode array
Cybercricket response to directional airflow

*posterior*

*Neural response*

*Spence, Hoy and Isaacson*
Cybercricket response to directional airflow

*posterior*  
*Neural response*

*Spence, Hoy and Isaacson*
**Vision:** light, compact biosensors with single molecule sensitivity

- planar platform
- fiber-optic coupling
- single molecule control
- single molecule sensitivity

- compact
- light
- fast
- inexpensive

**Will impact both basic science and diagnostic applications**

*H. Schmidt et. al.*
Fig. 1. SEM cross section of hollow ARROWs made using (a) reflowed photoresist sacrificial core and (b) SU8 sacrificial core. Silicon dioxide and silicon nitride are indicated by alternating light and dark layers.
Biology on the nanoscale

ARROW: AntiResonant Reflecting Optical Waveguides

• first hollow-core ARROW
• Si-based fabrication
• other substrates possible
• $\mu$m cross sections, cm lengths
• picoliter volumes
• light guiding

Biology on the nanoscale

- intersecting waveguide arrays
- excitation volume ~100 fl
- fluorescence detection with fully planar beam geometry
- single molecule sensitivity

(H. Schmidt et al., JSTQE 11, 519 (2005)
D. Yin et al., submitted)
Fabrication II: Bottom-up
Possible Applications

- Electric power generator with no moving part
- Waste heat recovery
- Microscale power sources

Goal: Efficiency >20%, Power>1W/cm², $T_{\text{hot}} = 300-650^\circ \text{C}$

Terry J. Hendricks, et al., 21st International Conference On Thermoelectrics, Long Beach, CA, 28 August 2002
Si/SiGeC Superlattice Structures for Heterostructure Thermionic Filtering

Funded by ONR and DARPA/ARMY HERETIC

150x SiGeC/Si Superlattice (10nm/10nm) Barrier

Si Cathode

Hot Electron

Cold Electron

Si (001) Substrate Anode

Si$_{0.89}$Ge$_{0.1}$C$_{0.01}$

• MBE Grown 5” Substrate

• Material and Processing Compatible with SiGe HBTs.


Novel Materials for Thermoelectric Conversion

FIG. 2. High-resolution cross-sectional transmission electron micrograph of randomly distributed particles (structure B). The micrograph confirms the formation of nanometer sized particles. The spatial distribution of the particles appears to be essentially random. For clarity, several particles are highlighted with arrows.

A. Shakouri et. al.
Surface Chemical Patterning by Microcontact Printing

Requires no harsh solvents or bases
Rapid and low cost
Can be used to stamp multiple components

Stamp cast from photolith master

Stamp onto substrate using “ink”

Peel stamp from surface

From Kumar and Whitesides
Microcontact Stamp

a. SEM micrograph of a microcontact stamp
b. Optical micrograph of a stamped poly-L-lysine pattern stamped on a gold electrode array

Scale bars are 50micrometers

C.James, et.al.
1. Microelectrode array

2. Alignment tool

3. Stamp in contact with the array surface

4. Protein pattern

Aligned µCP
Control of Neuronal Growth by Microcontact Printing

unpatterned

patterned
Multiwalled Carbon Nanotubes

Backscattered imaging/2keV
Multiwalled CNT Electrodes
For Neural Recording

W.K. Wong, et.al., 2006
Primary Hippocampal Neurons (rat)
And corresponding spontaneous firing
Recorded on SOG, MWCNT arrays

A. Seger, et. al.
Biological self assembly

1. Cell level

bilayer membrane

bilayer membrane is the framework of cell membranes
Lipid imprinting and Self-Assembly Protein Arrays

Top view
Side view

STEM image

TEM image

Trent, Macmillan, Pavola, Isaacson
Chaperonin Molecules, uranyl acetate stained

Bright Field STEM Images

J.Trent, C.Pavola, M.Isaacson
Fig. 1. Optical micrograph of stamped lipid pattern  

Fig 2. Chaperonin rings covering surface of lipid tube.
Stamped lipid pattern
Texas red stained

Chaperonin attached to lipid stamped pattern
Oregon green stained
So what should ‘nano’ mean to us?

Sessions in IEEE Nano-Conference, July 2005, Nagoya, Japan

• Molecular Electronics
• Spintronics and Nanomagnetics
• Nanoelectronics
• Nano (quantum) wires and dots
• Nanorobotics
• Carbon Nanotubes
• Nano-optics, Nanophotonics
• Nanosensors and Nanoactuators
• Nanobiotechnology
• Nanofabrication
Motivation I: Microprocessor Evolution

Source: Intel
Soon, all microchips will be nanoscale devices

M. Dresselhaus, Integrated Nanosystems 2002
Howard Banks, "Life at 100 billion bits per second", Forbes Magazine, Oct. 6, 1997
How far exponential growth in electronic and optics will continue?

Airplanes - Past, Present, Future (2002 perspective)

Fig. 6 Absolute airplane speed record (Refs. 10 and 11).

Fig. 7 Evolution in the productivity of commercial aircraft (Ref. 12).

McMasters & Cummings, Journal of Aircraft, Jan-Feb 2002
## Science and Technology Trends

<table>
<thead>
<tr>
<th>Year</th>
<th>Science (understanding &amp; measurement)</th>
<th>Technology (real life applications)</th>
<th>Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800’s</td>
<td>Electromagnetism</td>
<td>Engines</td>
<td>Machine automation</td>
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<td></td>
<td>Thermodynamics</td>
<td>Electricity</td>
<td>Lighting</td>
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<td>Periodic table</td>
<td>Telegraph</td>
<td>Telecommunication</td>
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<tr>
<td>1900</td>
<td>Quantum mechanics (Nano Phys. understanding)</td>
<td>Automobile</td>
<td>Transport (inter city)</td>
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<td>Relativity</td>
<td>Radio</td>
<td>Information Broadcast</td>
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<tr>
<td>1950</td>
<td>Quantum electrodynamics, Laser, Transistor, Bonding, DNA (Nano Chem &amp; Bio understanding)</td>
<td>Aviation</td>
<td>Transport (inter continent)</td>
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<td>TV, Telephone</td>
<td>Communication</td>
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<td>Electronic ICs, Computers</td>
<td>Calculations/ Smart systems</td>
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<td></td>
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<td>Nuclear (solar) energy</td>
<td>Energy consumption</td>
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<tr>
<td>2000</td>
<td>String theory, BEC, HiT&lt;sub&gt;C&lt;/sub&gt; superconductors, SPM (Nano measurement), Human Genome Project</td>
<td>Satellites, space shuttle</td>
<td>Comm., Space exploration</td>
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<td>Fiber optics, RF Electronics</td>
<td>Comm./ Comput. (Internet)</td>
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<td>SPM, Laser</td>
<td>Charact./Fab. Micro-nanoscale</td>
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<td>Batch processed MEMS</td>
<td>Micro sensors/ novel devices</td>
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<tr>
<td>Short term 2010</td>
<td>Nanotechnology (sensors)</td>
<td>Lab on a chip</td>
<td></td>
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<tr>
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<td>0.05um 10GHz ICs, Cellular</td>
<td>Internet/PC everywhere</td>
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<tr>
<td></td>
<td></td>
<td>DWDM photonics (THz), OEICs</td>
<td>Internet/PC everywhere</td>
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<tr>
<td>long term 2050</td>
<td>Nanotechnology (self assembly)</td>
<td>More information/communication</td>
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<td>Single spin/charge/photon electronics &amp; photonics</td>
<td>More computation for simulations</td>
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<td></td>
<td>Bio/Opto/Electro/MEMS VLSIs</td>
<td>Genomics (drug design, testing)</td>
</tr>
</tbody>
</table>

A. Shakouri, ASME Nanoscale Transport Panel, 11/13/2001
A Decade of Discovery and Impact in Science and Technology

- High temperature superconductivity
- Fractional quantum Hall effect
- Bose-Einstein condensation in gases
- Buckyballs/tubes
- Atomic-scale manipulation and single molecule mechanisms
- Fast algorithms for computational physics
- 4-5 orders of magnitude in synchrotron x-ray brilliance
- 2 orders of magnitude in computing power and information storage ($150 billion industry)
- 2 orders of magnitude in optical fiber data rates (network is being installed at 2000 km/hr)
- Transition metal catalysts for polymer synthesis (100 billion lbs./yr)

V. Narayanamurti, Harvard University
Broad societal implications
(examples of societal implications; worldwide estimations made in 2000, NSF)

✪ Knowledge base: better comprehension of nature, life

✪ New technologies and products: ~ $1 trillion/year by 2015
(With input from industry US, Japan, Europe 1997-2000, access to leading experts)

- Materials beyond chemistry: $340B/y
- Pharmaceuticals: $180 B/y
- Aerospace about $70B/y
- Electronics: over $300B/y
- Chemicals (catalysts): $100B/y
- Tools ~ $22 B/y

Est. in 2000 (NSF): about $40B for catalysts, GMR, materials, etc.; + 25%/yr
Est. in 2002 (DB): about $116B for materials, pharmaceuticals and chemicals

Would require worldwide ~ 2 million nanotech workers

✪ Improved healthcare: extend life-span, its quality, physical capabilities

✪ Sustainability: agriculture, food, water, energy, materials, environment; ex:
- lighting energy reduction ~ 10% or $100B/y

NanoBusiness Alliance www.nanobusiness.org/

MC. Roco, 11/07/03
Collaborators

Keith Neeves, Cornell (chem. eng)
Scott Retterer (ORNL)
Andrew Spence (University of London)
Devon Murphy (Nanofluidics)
Gary Banker (OHSU)
Conrad James (Sandia)
Andrea Turner, Cornell NBTC
Ron Hoy, Cornell (neuroscience and behavior)
James Turner, Wadsworth Center
William Shain, Wadsworth Center
Karen Smith, Wadsworth Center
Jonathan Trent (NASA-Ames)
Karen Kagoo (LSI Logic)

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