Nanoscale Probing and Imaging

Big Things from the small World

1 inch = 25,400,000 nanometer
1 human hair = 150,000 nanometer
Nano-scale: *how small is 1 nanometer?*
## Size Matters for both morphology and composition

The table below illustrates the relationship between morphology size and composition:

<table>
<thead>
<tr>
<th>Bulk</th>
<th>Powders</th>
<th>Microns</th>
<th>Nanometers</th>
<th>Angstroms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cluster</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Molecules</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Atoms</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
**Nanoscience:** shaping science at nanometer. Examples? Chemical reactions, bonding formation, ...

**Nanotechnology:** improve technology through nanometer scale manipulation, optimization. Examples? Nanoparticles, Single-molecule transistor, single-cell imaging/operation, ...

1 nm ~ a few atoms $\rightarrow$ molecule $\leftrightarrow$ building-blocks of materials

$\rightarrow$ Nanoscale research leads to atomic/molecular scale optimization of materials (e.g. single-crystals) --- bottom up approach, for which the central, and most critical technique is nanoscale imaging and probing, thus developed for characterizing the size, structure, morphology of nanomaterials and their relationship with the optical, electrical and magnetic properties.

One such example is the structure manipulation of carbon materials. See next slide.
Atomic Manipulation of Carbons

Three major allotropes of carbon: graphite, diamond, and amorphous carbon.

- **Amorphous carbon:** glassy materials
- **Graphite:** Black, conductor or semimetal
- **Diamond:** transparent, insulator

Timeline of Nanotechnology:
- 1985: zero-dimension
- 1991: one-dimension
- 2004: two-dimension

Nobel Prize, 1996
Nobel Prize, 2010
Nano-Quote:

- $32 billion in nanotechnology sale, 2008.
- $2.6 trillion, by 2014.
Materials Science and Engineering

- Structure, Property, Function
- Technology
  - Manipulation
  - Manufacturing products

Size Scale

- Atom, Molecule level
  - nanometer (nm) scale
- Nanotechnology
- Nanostructure
- Microstructure
- Bulk phase materials
  - large area arrays, chips, panels, devices, etc.
- Macroscopic

relationship
improvement
All kinds of ‘Nano’

- Nanosphere
- Nanoparticle
- Quantumdot
- Nanorod
- Nanowire
- Nanochain
- Nanobelt
- Nanoribbon
- Nanotube
- Nanokids
Nanocar Rolls Into Action

World's first molecular car zips about on fullerene wheels

A single-molecule car was developed by Kelly, Tour, and coworkers.

Nano Lett. 2005, 5, 2330
Playing at Nanoscale

Nanoalignment

Nanocross

Nanowriting

As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on the market they tell me, by which you can write the Lord’s Prayer on the head of a pin. But that’s nothing; that’s the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

Richard P. Feynman, 1959
Nano-Research: not just emerging, but expanding

Few terms in the chemical and physical sciences have seen more use (and abuse) in recent years than “nanoscience” or even worse “nanotechnology”

--- James Heath

Big Boost in Nano Research

Number of Papers (thousands)

Years

US Yearly Budget on National Nanotechnology Initiative (NNI)

Yearly Publications in Nanoscience (SCI)

Billion Dollars
The National Nanotechnology Initiative (NNI)

--- a program established in fiscal year 2001 to coordinate Federal nanotechnology research and development. The NNI provides a vision of the long-term opportunities and benefits of nanotechnology.

http://www.nano.gov/

other website for updated nanotech news:
http://pubs.acs.org/cen/nanofocus/
Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight -- shrinking all the information housed at the Library of Congress into a device the size of a sugar cube --- detecting cancerous tumors when they are only a few cells in size.

President William J. Clinton
January 21, 2000
California Institute of Technology
Where was Nanotechnology originated?

By Richard Feynman, Nobel Prize in Physics in 1965

in a 1959 talk on top-down nanotechnology called “There's Plenty of Room at the Bottom”.
--- American Physical Society meeting at Caltech on December 29, 1959

Feynman considered a number of interesting ramifications of a general ability to manipulate matter on an atomic scale. He was particularly interested in the possibilities of denser computer circuitry, and microscopes which could see things much smaller than is possible with electron microscopes. These ideas were later realized by the use of the scanning tunneling microscope (STM), the atomic force microscope (AFM) and other examples of scanning probe microscopy (SPM).
What is **Nanotechnology**?

*Traditional bio-med research with proteins or other nanosized biological units is not considered as nanotechnology.*

**Making**
- Synthesis of Nano-sized molecules (Tour, Muellen)
- Nanowires, nanotubes (Yang, Lieber, Wang, Dai)
- Nanocrystals (Alivisatos, Bawendi)

**Measuring**
- Nanoscale imaging/probing (Weiss, Brus)
- Single-molecule measurement (Moener, Nie, Xie, Chu, Barbara)
- AFM, STM (Weiss, Bawendi)
- Molecule I/V measurement (Reed)

**Manipulating**
- Surface nanopatterning (Whitesides, Chou)
- Fabrication of nanowires (Lieber, Heath)
- DNA assembly (Mirkin, Seeman)
- Nano-electronic device (Reed, Heath)
Why at Nanoscale?

- Nanoscale
- Materials
  - Quantum size effect
  - Complexity
  - Heterogeneity
- Electronics
  - Miniaturization
- Biology
  - Proteins, enzymes, DNAs, all nanometer size
- Nanoscience
  - Chemistry, physics, medical
  - Chemistry, physics, engineering

Nano-photochemistry
Molecular Nanotechnology: an interdisciplinary field of research
Broad interests in Nano-Research
NANOTECHNOLOGY: THE NEXT BIG THING

U.S. National Nanotechnology Initiative aims to create another Industrial Revolution

William Schulz
C&EN, Washington

By anyone's measure, nanotechnology is the next big thing. In fact, according to government R&D planners, nanotechnology is nothing short of the next Industrial Revolution.

But to keep the ball rolling, government planners will also have to keep alive the drumbeat of promise about the fruits of nanotechnology research. By their own estimate, government R&D analysts say, payoffs from significant investments in nanotechnology are at least 20 years away.

"We are constantly faced with the question of how do we keep this going through the system?" says Dart C. Moore, the Administration's point man for nanotechnology in the White House Office of Science & Technology Policy (OSTP). As with any cross-agency government program, he says, the President's recently announced National Nanotechnology Initiative (NNI) will likely face many challenges over the next decade that it is scheduled to be in operation.

"A lot of the old barriers between [R&D agencies] have been broken down," Moore says, to jump-start the nanotechnology initiative. Six of the nation's largest R&D agencies—the National Science Foundation; the Commerce Department's National Institute of Standards & Technology (NIST); the National Institutes of Health; the Department of Defense; the Department of Energy; and the National Aeronautics & Space Administration—will have significant involvement in the initiative, he says. What's more, the Administration has requested an extra $435 million in funding for those agencies' NNI programs in fiscal 2001. Details of how much money will go out of the initiative can be found at http://www.nano.gov.

The initiative got its official start in August 1999 when the National Science & Technology Council's (NSTC) Interagency Working Group on Nanoscience, Engineering & Technology released its first report, "Nanostructure Science & Technology." It is, he says, a blueprint for the federal government to assess how to make strategic R&D investments in nanotechnology.

One of the immediate challenges, Moore points out, is dealing with Congress. Because the initiative is spread out across federal agencies, the Administration must "sell" NNI to different appropriations committees—each with a different set of priorities. But Moore and others feel confident that lawmakers will support the initiative. With varying degrees of success, he says, OSTP took the same approach with its cross-agency initiative for information technology research.

When NNI was officially unveiled last year by NSTC—a subunit of OSTP that coordinates cross-agency research initiatives—It was accompanied by a strategic public relations plan. NSTC, for example, hired science writer Irwin Amato to pen a glossy brochure entitled "Nanotechnology: Shaping the World Atom by Atom."

In the brochure, Amato sets forth a basic definition of nanotechnology—generally, the world as it works on the nanometer or "billionths" scale—and he lays out the following vision: "What could we humans do if we could assemble the basic ingredients of the material world with even a glint of nature's virtuosity? What if we could build things the way nature does—atom by atom and molecule by molecule?"

Because nanotechnology involves the control of matter at the atomic or molecular level where quantum effects must be taken into account, it is often a difficult subject even for fellow scientists to grasp, Moore says. The brochure and other outreach methods, he continues, are "much like NIH saying, 'This is basic research, and it is to be applied to X, Y, and Z disease categories.' And that's an easier thing to sell to my neighbor."

That strategy has garnered outside support, and it appears to be having an impact. The initiative, for example, was the focus of an American Chemical Society "Science and the Congress" luncheon briefing on Capitol Hill to help acquaint members and congressional staff with the field of nanotechnology and its promise.

Entitled "Tiny Dynamite: The Nanotechnology Revolution," the briefing reviewed some of the scientific issues concerning nanotechnology and the ways that nanotechnology will affect R&D efforts in everything from drug delivery to aerospace materials. Speakers included Harvard University chemistry professor George Whitesides and Motorola's...
Nanoscale Research is beyond Academia

- IBM
- Lucent, Bell Labs
- Intel
- GE
- Numerous Nano-companies: beyond your imagination
  (Zyvex, Nanosys, Nanoproducts, Nanologic, Nano Ink, Nanolayers, NanoGram, Nanodevices, Nanomaterials, Nanosphere, …)
- National Labs:
  Argonne, Brookhaven, Oak Ridge…
Moore's law describes a long-term trend in the history of computing hardware. The number of transistors that can be placed inexpensively on an integrated circuit doubles approximately every two years.
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Ryan E. Clarke : Department of Electrical, Computer and Systems Engineering, RPI
THE EVOLUTION OF A REVOLUTION
EXPLORING THE INTEL TECHNOLOGY INNOVATIONS THAT HAVE CHANGED THE WORLD.

The Revolution Begins
The first microprocessor was introduced in 1971. This marked the beginning of the computer revolution. The microprocessor allowed computers to become smaller, faster, and more powerful. This led to the development of personal computers, which revolutionized the way people work and communicate.

1969

1972

1976

1983

1992

2002

2006

The Revolution Continues
Intel continues to deliver on the promise of Moore's Law with the introduction of powerful multi-core technologies, transforming the way we live, work, and play once again.

Intel continues to deliver on the promise of Moore's Law with the introduction of powerful multi-core technologies, transforming the way we live, work, and play once again.

1992

2002

2006

The Revolution Continues
Intel continues to deliver on the promise of Moore's Law with the introduction of powerful multi-core technologies, transforming the way we live, work, and play once again.
Expanding Moore’s Law

50nm Prototype (IEDM2002)
15nm Prototype (IEDM2001)
10nm Prototype (DRC 2003)

Nano

From Intel
Expanding Moore’s Law

Intel R&D PIPELINE

2011

22 nm

IN PRODUCTION

2013

14 nm

IN DEVELOPMENT

2015+

10 nm 7 nm 5 nm

IN RESEARCH

Lithography • Materials • Interconnect ...

Innovating for the Next Decade of Computing

From Intel
# Highly Conductive Molecular Wires

<table>
<thead>
<tr>
<th></th>
<th>Cross-section size (nm²)</th>
<th>Current Density (electrons/nm² sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm copper wire</td>
<td>~ 3x10^{12}</td>
<td>~ 2x10^6</td>
</tr>
<tr>
<td><img src="image" alt="Molecular Structure" /></td>
<td>~ 0.05</td>
<td>~ 4x10^{12}</td>
</tr>
<tr>
<td>Carbon nanotube</td>
<td>~ 3</td>
<td>~ 2x10^{11}</td>
</tr>
</tbody>
</table>
Fabrication of a molecular device

- **Nano-gap Electrodes:** very low successful yield for fabrication.
- **Large molecules:** to fit in the nano-gap.
Molecules used for electronic devices

wire

diode

switch

Fabrication and evaluation of molecular devices:

- **Surface deposited electrode systems:** *distance fixed.*

- **Piezo controlled electrode system:** *distance adjustable.*

- **AFM/STM based measurement:** *flexible for various kinds of samples.*
The Biggest Challenge in Molecular Electronics

Ultimate goal --- Interconnecting and integrating billions of molecular units into a functional chip.

Challenge --- How to organize billions of molecules within a 1X1 inch area. An Intel Dual-core Xenon CPU has 820,000,000 transistors!

Self-assembly --- Seems to be the most promising approach, since photolithography method (top-down approach) does not work for molecules.

Prerequisites --- high recognition or selectivity.
Quad-Core Intel® Xeon® processor (Penryn)
Dual-Core Intel® Xeon® processor (Penryn)
Quad-Core Intel® Core™2 Extreme processor (Penryn)
Introduced 2007
Initial clock speed

> 3 GHz

Number of transistors
820,000,000

Manufacturing technology
45nm
DNA
--- an Perfect Self-assembler by Nature

- Extremely high selectivity;
- Strong binding via H-bonds;
- Highly flexible for modification;
- Good physicochemical stability;
- Good mechanical rigidity.
Self-organized nanostructure of DNA

Single-Molecule Probing of Protein Systems

Single-molecule blinking; movie of protein dynamics in living cells.