Nanotechnology

“Nano” – From the Greek word for “dwarf” and means $10^{-9}$, or one-billionth. Here it refers to one-billionth of a meter, or 1 nanometer (nm).

1 nanometer is about 3 atoms long.

“Nanotechnology” – Building and using materials, devices and machines at the nanometer (atomic/molecular) scale, making use of unique properties that occur for structures at those small dimensions.

Most consider nanotechnology to be technology at the sub-micron scale: 1-100’s of nanometers.

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How small is a nanometer? (and other small sizes)

Start with a centimeter. A centimeter is about the size of a bean.

Now divide it into 10 equal parts. Each part is a millimeter long. About the size of a flea.

Now divide that into 10 equal parts. Each part is 100 micrometers long. About the size (width) of a human hair.

Now divide that into 10 equal parts. Each part is a micrometer long. About the size of a bacterium.

Now divide that into 10 equal parts. Each part is a 100 nanometers long. About the size of a virus.

Finally divide that into 100 equal parts. Each part is a nanometer. About the size of a few atoms or a small molecule.

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**The Scale of Things – Nanometers and More**

### Things Natural

- **Dust mite**
  - 200 µm
- **Human hair**
  - ~60-120 µm wide
- **Red blood cells**
  - (~7-8 µm)
- **Ant**
  - ~5 mm
- **Fly ash**
  - ~10-20 µm
- **Human hair**
  - ~60-120 µm wide
- **DNA**
  - ~2-1/2 nm diameter
- **Atoms of silicon**
  - spacing 0.078 nm
- **ATP synthase**
  - ~10 nm diameter

### Things Man-made

- **Fly ash**
  - ~10-20 µm
- **Head of a pin**
  - 1-2 mm
- **MicroElectroMechanical (MEMS) devices**
  - 10-100 µm wide
- **Pollen grain**
- **Red blood cells**
- **Zone plate x-ray “lens”**
  - Outer ring spacing ~35 nm
- **Quantum corral of 48 iron atoms on copper surface**
  - Positioned one at a time with an STM tip
  - Corral diameter 14 nm
- **Intel computer chip and single transistor**
  - Smallest dimensions ~1 nm
- **Carbon nanotube**
  - ~1.3 nm diameter
- **Carbon buckyball**
  - ~1 nm diameter

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Why is Small Good?

- Faster
- Lighter
- Can get into small spaces
- Cheaper
- More energy efficient
- Less waste products, and uses less energy and materials to produce
- Different properties at very small scale
- The melting point of gold decreases rapidly as the particle dimension reaches the nanometer scale.


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The color of gold changes as the particle size changes at the nanometer scale.

Chad Mirkin, Northwestern University, in NYTimes article by K. Chang - 2005
Why might properties of materials/structures be different at the nanoscale?

Two of the reasons:

1. Ratio of surface area-to-volume of structure increases
   (most atoms are at or near the surface, which make them more weakly bonded and more reactive)

2. Quantum mechanical effects are important
   (size of structure is on same scale as the wavelengths of electrons, and quantum confinement occurs resulting in changes in electronic and optical properties)
Much of the motivating force and technology for nanotechnology came from the integrated circuit industry.

As with the fabrication of integrated circuits (IC’s), nanotechnology is based on building structures and systems at very small sizes.

Done to enhance performance (like IC’s) and as well as result in new properties and applications.

Can involve combinations of many types of systems (mechanical, biological, chemical, optical, as well as electronic).

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Examples of Nanotechnology Applications

- **Supercomputer in your palm**, perhaps made from silicon nanowires, carbon nanotubes, or organic materials such as DNA

- Very tiny **motors, pumps, gyroscopes, and accelerometers**; helicopters the size of flies or smaller

- Tiny **bio- and chemical-sensors**; nanoparticles that **track and destroy cancer cells**; artificial body parts and implantable **drug delivery systems**

- **Energy storage (batteries) and conversion (solar cells)** using nanowires and nanotubes

- **Enhanced consumer products** using nano-whiskers, nanoparticles, and nanotubes for: stain and wrinkle resistant clothes, transparent zinc oxide sunscreen, fast-absorbing drugs and nutrients, extra-strong tennis racquets, and scratch-resistant paint

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Mite spinning on micromotor (Sandia National Labs)
“MEMS” and “NEMS” – micro/nano electro-mechanical systems

“Bugbot” for traveling and taking photos in human digestive system (Carnegie Mellon University)

World’s smallest mobile robot, with no wheels, gears or hinged joints (Dartmouth College)

Ant’s leg strength and motion measured on microsensor, for robot development (Stanford)

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Iron nanoparticles to clean poisons from water. Can also clean heavy metals from soil. (Lehigh University)

Gold nanoparticles, coated with antibodies, and which fluoresce and heat up, can track and destroy cancer cells (University of Illinois, Georgia Tech, Rice, U. Texas, and UCSF)

Using “Nano-silver” (solutions of silver nanoparticles) to coat medical tools, and in burn and surgical dressings, which protects against bacteria and fungus by inhibiting cellular metabolism and growth (Nanotech)

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Carbon nanotube (CNT) transistor for future computer chips (Stanford, UC Berkeley)

Si or Ge nanowire batteries holding 10 times the charge of existing lithium-ion batteries (Stanford)

Flat panel displays using carbon nanotubes as mini electron emitters instead of CRT’s (Motorola, Samsung)


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Silicon nanowires as solar cells, nanoelectronic power sources, and sensors
(Stanford)

Carbon nanotube “shag electrode” in ultra-capacitors for energy storage (MIT)
Some Currently Available Nanotechnology Products

- **Easton CNT (carbon nanotube) baseball bat**
- **ArcticShield “stink-proof” socks with silver nanoparticles**
- **Nano Wear sunblock with TiO₂/ZnO₂ nanoparticles**
- **Nanopants that repel liquids by nanowhiskers attached to cloth fibers**
- **Zelens Fullerene C-60 (buckyball) Face Cream to “attract and neutralise the damaging free radicals”**

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How do you build something so small?

“Top-down” – building something by starting with a larger component and carving away material (like a sculpture).

In nanotechnology: patterning (using photolithography) and etching away material, as in building integrated circuits.

“Bottom-up” – building something by assembling smaller components (like building a car engine).

In nanotechnology: self-assembly of atoms and molecules, as in chemical and biological systems.

M. Deal, Stanford
How do you build something so small?

“Top-down” – building something by starting with a larger piece and carving away material (like a sculpture).

“Bottom-up” – building something by putting together smaller pieces (like building a car engine).
Top-down fabrication

Method used by integrated circuit industry to fabricate computer chips down to ~ 15 nm size

- Makes use of depositing thin films, then “photolithography” and plasma etching to make films into desired patterns on a silicon wafer.

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Top-down fabrication

1. Substrate preparation
   - Wafer cleaning

2. Dopant source introduction
   - Doping and annealing

3. Film deposition

4. Photoresist application

5. Exposure
   - Light exposure
   - Mask

6. Development
   - Etch mask

7. Etching

8. Resist removal

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Repeat process with different thin films and different patterns (each aligned to lower layer) to produce desired structure.

Use scanning electron beam to produce masks with very small feature sizes.
Limitations of top-down fabrication

• Due to diffraction effects, the practical limit for optical lithography is around 100 nm. Can use lithography and processing “tricks” to get feature sizes even smaller (as in Intel devices).

• To define much smaller features, electron beams, or “e-beams,” (which have smaller wavelengths) can be used. Feature sizes smaller than 15 nm can be patterned.

• But e-beam projection systems using masks have not been fully developed – instead, “direct-write” e-beam lithography has been used.

• While optical lithography works in parallel over the wafer (with high throughput), direct-write e-beam lithography works as a series process (with very low throughput).

• An alternate method is “bottom-up” fabrication.
Bottom-up fabrication

- Adding atoms to atoms, molecules to molecules
- “Self-assembly” of atoms and molecules
- Use of chemical and biological processes

Current day examples:

Self-assemble of organic monolayers for molecular transistors, etc. (Florida)

Electric field aligning of nanowires (U. Mass)

More extreme example: Self-replicating robots.

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Bottom-up fabrication

• A way to make nanometer size features, and lots of them, letting “nature” work for you.

• But some challenges:
  • Getting the structures to always grow exactly how and where you want them to
  • Making complicated patterns

Some common strategies:

• Use catalysts, stress fields, electric/magnetic fields, capillary forces, etc. to achieve selective growth or placement

• Use top-down processes in conjunction with bottom-up processes, and build on silicon substrates
How do you build something so small?

Tools are needed to image, analyze, and manipulate very small features - Scanning Probe Microscopy, including the Atomic Force Microscope (AFM).

AFM tip, used to manipulate, image and measure atomic scale features.

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AFM image of mineral surface showing atomic structure.

AFM image of carbon nanotube

AFM image of human blood cells


Other scanning probe microscopes measure other properties, such as electrical and magnetic.

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How do you build something so small?
- Requires very clean environment: “clean room”

Relative size of clean room contaminants

~600X magnification

60 microns wide

10-micron particle

0.5 micron wide nanostructures

Magnified image of contaminant on wafer surface, which can cause defects and failures in nanostructures

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How do you build something so small?

- Requires very clean environment: “clean room”

- People wear clean room suits (also called “gowns” or “bunny-suits”)

- Huge fans circulate filtered air throughout the facility

- Wafers are cleaned in liquid solutions between every processing step

A lab user “gowning-up” in SNF
SNF provides tools where researchers can do research in all areas of nanotechnology

- Mostly top-down in this facility
- Some bottom-up (generally done on thin film substrates like silicon wafers and usually together with some sort of top-down technique)
- Bottom-up done in perimeter labs, and in new nanoscience building
Stanford Nanofabrication Facility (SNF)

- 10,000 sq.ft. clean room, available to any researcher in the world.
- Includes state-of-the-art equipment for nano- and micro-fabrication and research.
- Over 600 users last year, working in all areas of nano (and larger) fabrication.
- Funded by user fees and by NSF grant. Part of National Nanotechnology Infrastructure Network (NNIN).

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Stanford Nanofabrication Facility (SNF)

NNIN Sites

- The Cornell NanoScale Science & Technology Facility at Cornell University
- The Stanford Nanofabrication Facility at Stanford University
- The Lurie Nanofabrication Facility at the University of Michigan
- The Nanotechnology Research Center at the Georgia Institute of Technology
- The Center for Nanotechnology at the University of Washington
- The Penn State Nanofabrication Facility at the Pennsylvania State University
- Nanotech at the University of California at Santa Barbara
- The Nanofabrication Center at the University of Minnesota
- The Microelectronics Research Center at University of Texas at Austin
- The Center for Nanoscale Systems at Harvard University
- The Howard Nanoscale Science and Engineering Facility at Howard University
- The Colorado Nanofabrication Lab at University of Colorado
- Nanofab at the Arizona State University
- The Nano Research Facility at Washington University in St. Louis

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A few examples of research at the Stanford Nanofabrication Facility (SNF)
Retinal degeneration leads to blindness due to loss of photoreceptors. Sight can be restored by patterned electrical stimulation of the surviving inner retinal neurons. Photovoltaic subretinal prosthesis directly converts pulsed light into pulsed electric current in each pixel, stimulating nearby neurons. Visual information is projected onto retina by video goggles using pulsed NIR (~900 nm) light. Photovoltaic arrays including 3 diodes in each pixel were fabricated in SNF.

Video goggles projecting captured image onto subretinal photovoltaic array using pulsed near-IR light (~900 nm).

Photovoltaic array implanted under the retina in a blind rat. Higher magnification view shows the array itself, and a single pixel of the implant.

Daniel Palanker’s group (Ophthalmology and HEPL) and James Harris’s group (EE) at Stanford U., Alexander Sher’s group at UCSC. Fabrication performed at Stanford Nanofabrication Facility.

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Nanomagnetics for Cancer Detection

• Motivation
  – Earlier cancer detection

• Development of nanomagnetic sensor chip
  – Use same principles employed in magnetic storage industry
  – Use magnetic nanoparticles to ‘tag’ proteins indicative of cancer

• Sensitivity:
  – 1 picogram/ml or femto-molar level
  – Much higher sensitivity than previously available
  – Enabling earlier cancer detection

Prof. S. Wang Group, Stanford

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The objective of this project is to design a hybrid inorganic/organic solar cell with low-cost processing. Si nanocones fabricated by colloidal lithography were covered with a conductive polymer, which formed a Schottky junction between the Si and polymer. The power conversion efficiency of the hybrid Si/polymer device was more than 11%, which is the world-record among the hybrid devices.

S. Jeong, et al., Stanford University
work performed at Stanford Nanofabrication Facility

M. Deal, Stanford
Carbon Nanotube Computer

Max M. Shulaker\textsuperscript{1}, Gage Hills\textsuperscript{2}, Nishant Patil\textsuperscript{3}, Hai Wei\textsuperscript{4}, Hong-Yu Chen\textsuperscript{5}, H.-S. Philip Wong\textsuperscript{6} & Subhasish Mitra\textsuperscript{7}

Stanford University

\textbf{Figure 3 | Characterization of CNFET subcomponents.} \textit{a}, Top: Final 4-inch wafer after all fabrication. Middle: scanning electron microscope (SEM) image of a CNFET, showing source, drain and CNTs extending into the channel region. Bottom: measured characterization (current–voltage) curves of a typical CNFET. The yellow highlighted region of the \textit{I}_D–\textit{V}_DS curve shows the biasing region that the CNFET operates in for the CNT computer. \textit{b}, Top: transistor-level schematic of an arithmetic unit. Numbers are width of transistors (in micrometres). Middle: SEM of an arithmetic unit. Bottom: measured outputs from 40 different arithmetic units, all overlaid. \textit{c}, Top: transistor-level schematic of 4 D-latches. Numbers are width of transistors (in micrometres). Middle: SEM of a bank of 4 D-latches. Bottom: measured outputs from 200 different D-latches, all overlaid.
• A dual-axis piezoresistive cantilever was used to characterize the adhesive properties of a single gecko seta.

• Studies of adhesive force under both hydrophobic and hydrophilic conditions indicate the gecko’s ability to stick to and climb smooth surfaces is due to (relatively weak) van der Waals intermolecular interactions.

• Nanofabricated, synthetic setae show similar adhesive forces.
Nanotechnology – Social and Ethical Issues

• Along with many potential benefits of nanotechnology, there come some possible adverse consequences and other important issues

  • Environmental and health dangers
  • Privacy and personal freedom issues
  • Intellectual property and information concerns
  • Work force and sociology effects
  • Misleading claims, and even falsified data
  • Others…….
Nanotechnology

• Nanotechnology holds a lot of promise in terms of potential applications and products.

Whatever the exact definition, key features in this field are:
  • combining different sciences and technologies
  • enhanced or new properties
  • new applications
  • all at very small dimensions.

• And we now have sophisticated tools to build, characterize and utilize structures at the nanoscale, across a breadth of disciplines.

• But we must also be aware of possible consequences.