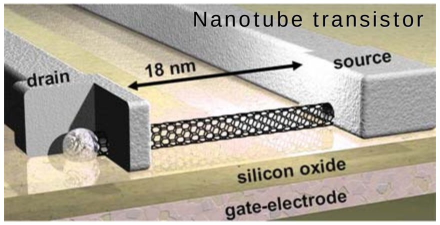
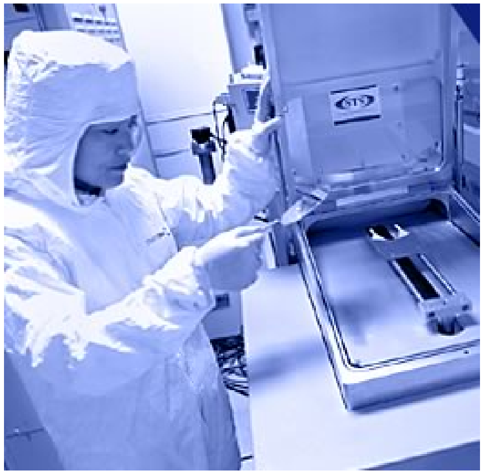
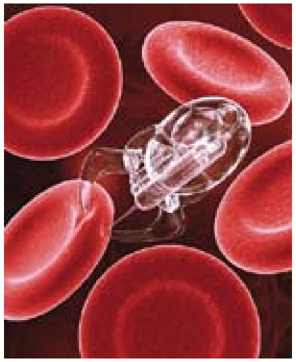
Nanotechnology







"**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.

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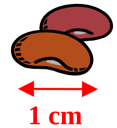
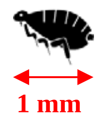
How small is a nanometer? (and other small sizes)

Start with a centimeter.



A **centimeter** is about the size of a **bean**.

Now divide it into 10 equal parts.

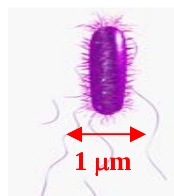


Each part is a **millimeter** long. About the size of a **flea**.

Now divide that into 10 equal parts.

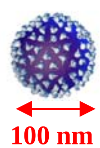
Each part is **100 micrometers** long. About the size (width) of a **human hair**.

Now divide that into 100 equal parts.



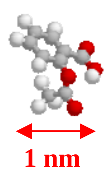
Each part is a **micrometer** long. About the size of a **bacterium**.

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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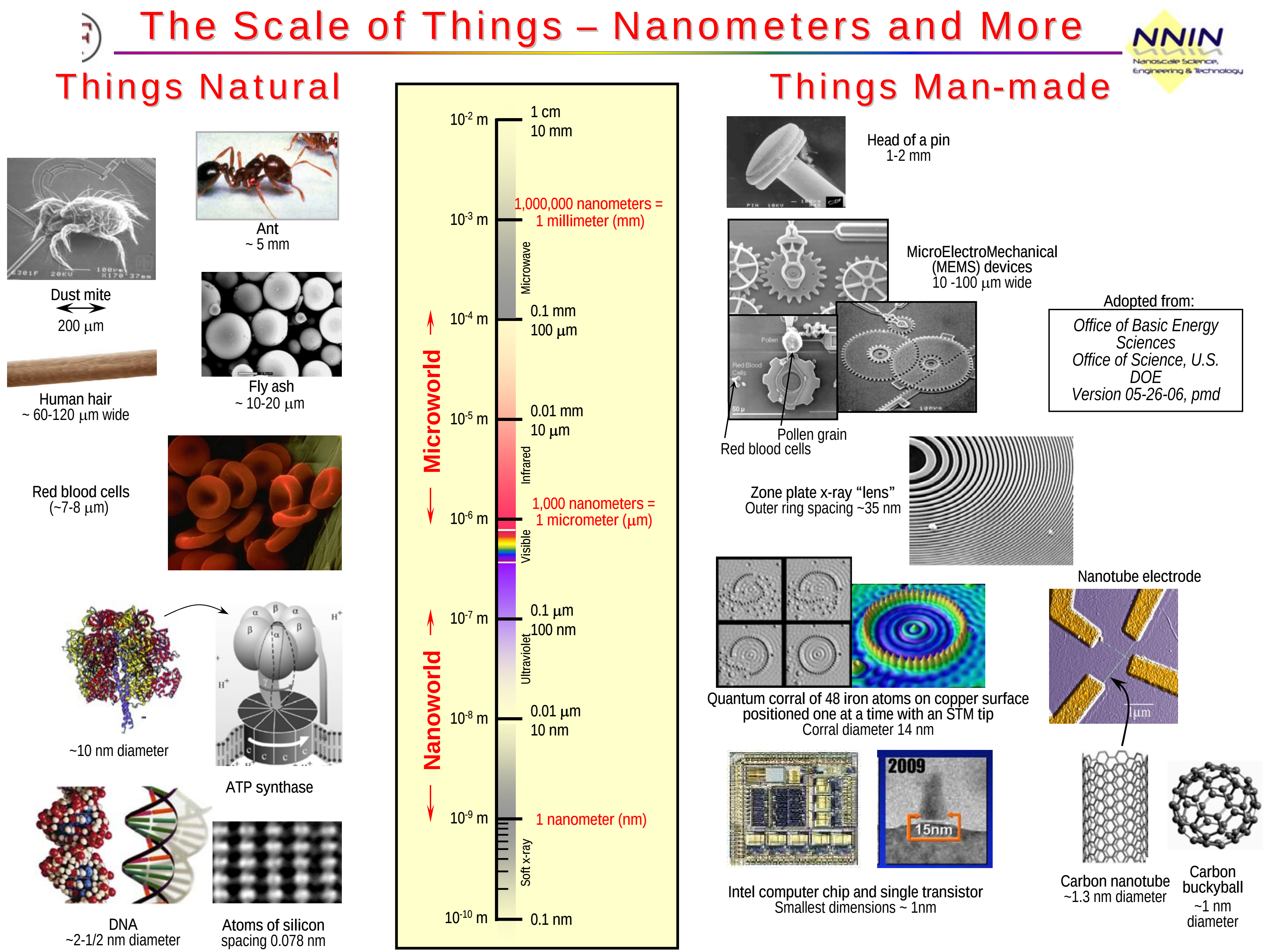

The Scale of Things – Nanometers and More
NNIN
Nanoscale Science, Engineering & Technology
Things Natural
Things Man-made
Dust mite
200 µm
Ant
~ 5 mm
Human hair
~ 60-120 µm wide
Fly ash
~ 10-20 µm
Red blood cells
(~7-8 µm)
~10 nm diameter
ATP synthase
DNA
~2-1/2 nm diameter
Atoms of silicon
spacing 0.078 nm
10^{-2} m
1 cm
10 mm
10^{-3} m
1,000,000 nanometers =
1 millimeter (mm)
Microwave
10^{-4} m
0.1 mm
100 µm
Microworld
10^{-5} m
0.01 mm
10 µm
Infrared
10^{-6} m
1,000 nanometers =
1 micrometer (µm)
Visible
10^{-7} m
0.1 µm
100 nm
Ultraviolet
Nanoworld
10^{-8} m
0.01 µm
10 nm
10^{-9} m
1 nanometer (nm)
Soft x-ray
10^{-10} m
0.1 nm
Head of a pin
1-2 mm
MicroElectroMechanical
(MEMS) devices
10 -100 µm wide
Pollen
Red Blood Cells
Pollen grain
Red blood cells
Adopted from:
Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 05-26-06, pmd
Zone plate x-ray "lens"
Outer ring spacing ~35 nm
Nanotube electrode
Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm
1 µm
2009
15nm
Intel computer chip and single transistor
Smallest dimensions ~ 1nm
Carbon nanotube
~1.3 nm diameter
Carbon buckyball
~1 nm diameter

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

• Exact definition of nanotechnology is not clear.

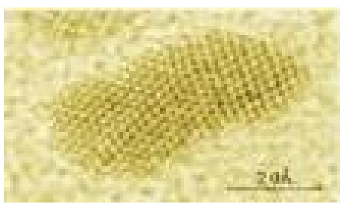
• At SNF, we provide tools to do work at nanometer, micron, and up to mm scales.

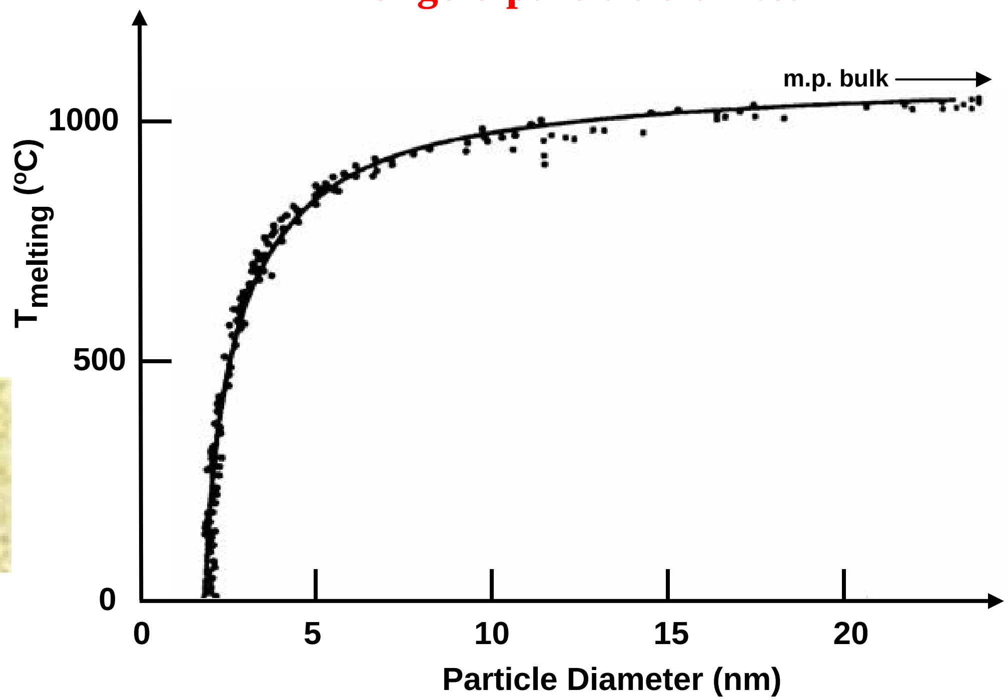
Why is Small Good?

- **Faster**
- **Lighter**
- **Can get into small spaces**
- **Cheaper**
- **More energy efficient**
- **Different properties for very small structures**

- The melting point of gold decreases rapidly as the particle dimension reaches the nanometer scale.

Melting point of gold as a function of gold particle diameter





Reference: Buffat and Borel, Phys. Rev. A, vol. 13, p. 2287,1976.

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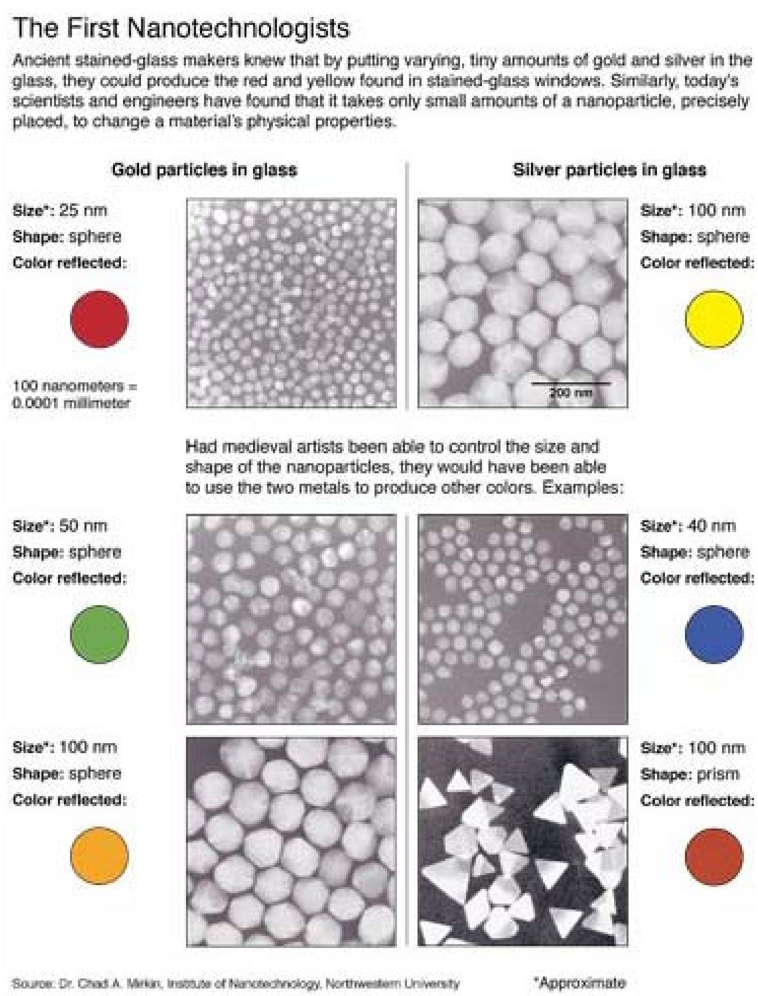
The color of gold changes as the particle size changes at the nanometer scale.



Chad Mirkin, Northwestern University, in NYTimes article by K. Chang - 2005

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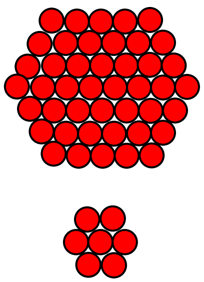
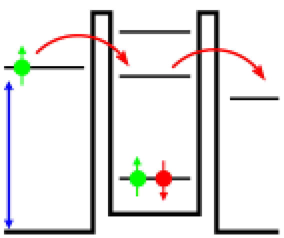
Why might properties of materials/structures be different at the nanoscale?

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)

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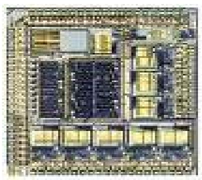
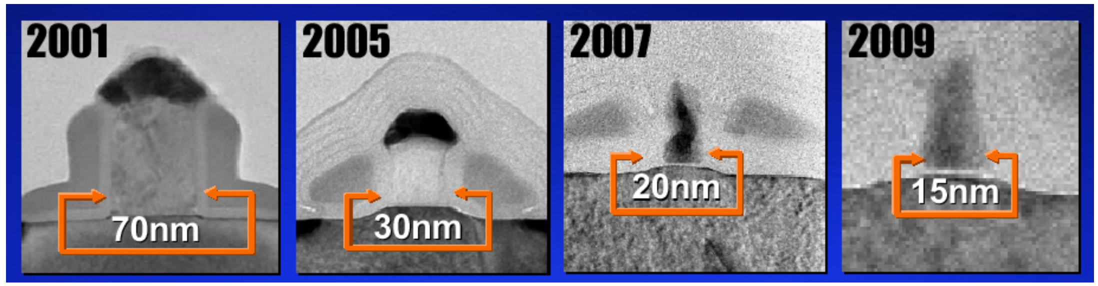
Much of the motivating force and technology for nanotechnology came from the integrated circuit industry





Intel's transistors

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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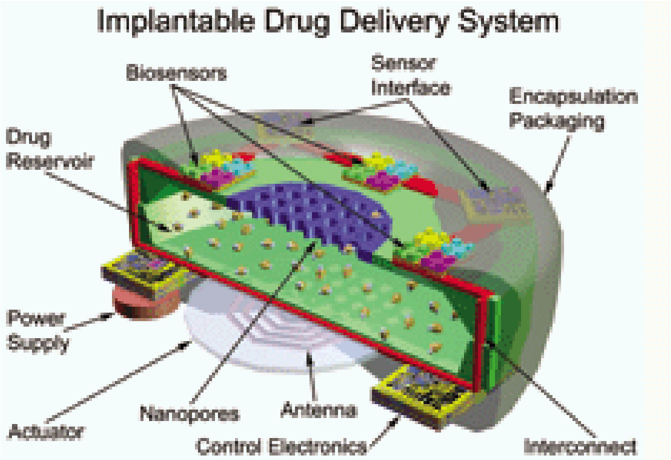
Examples of Nanotechnology Applications

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

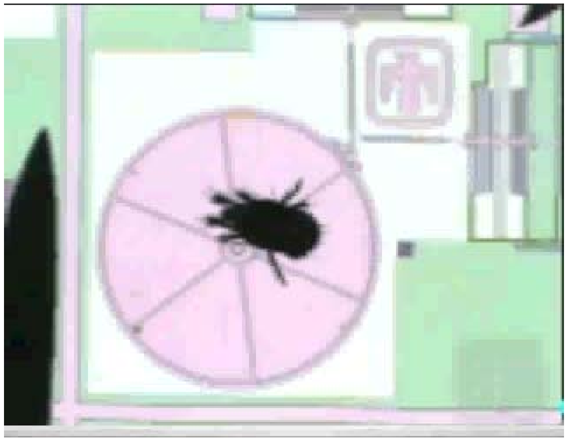
- Very tiny motors, pumps, gyroscopes, and accelerometers; helicopters the size of flies or smaller

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



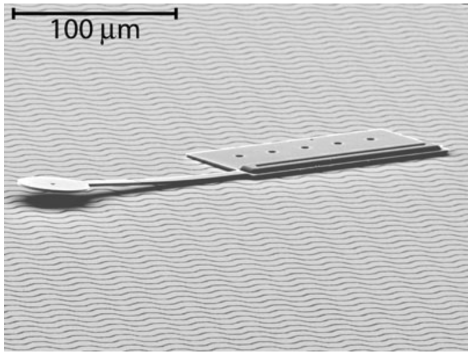
- Energy storage (batteries) and conversion (solar cells) using nanowires and nanotubes

- 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



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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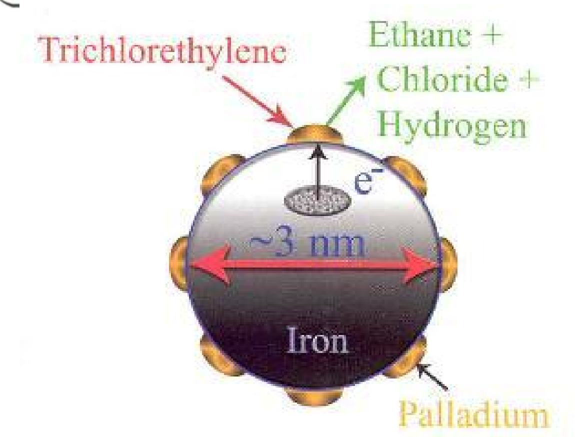
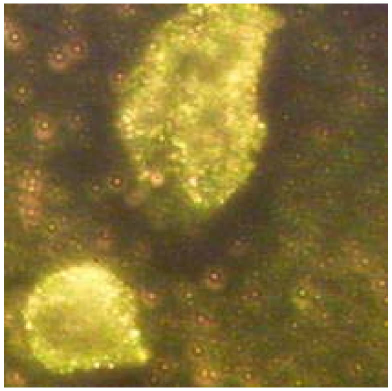
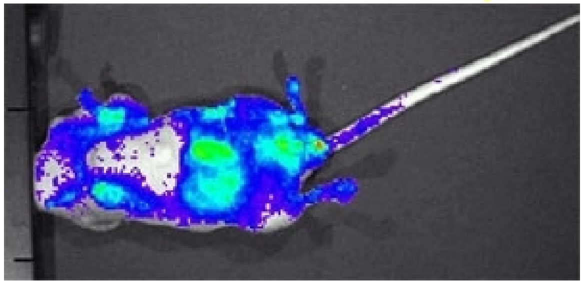
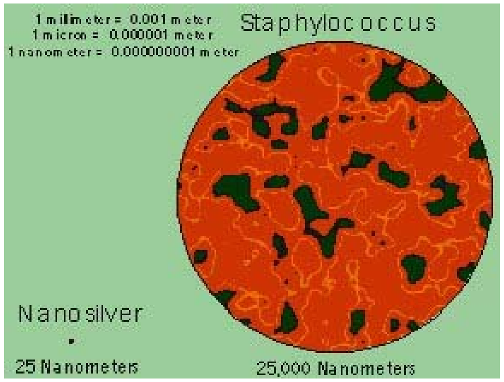


Iron nanoparticles to clean poisons from water. Can also clean heavy metals from soil. (Lehigh University)





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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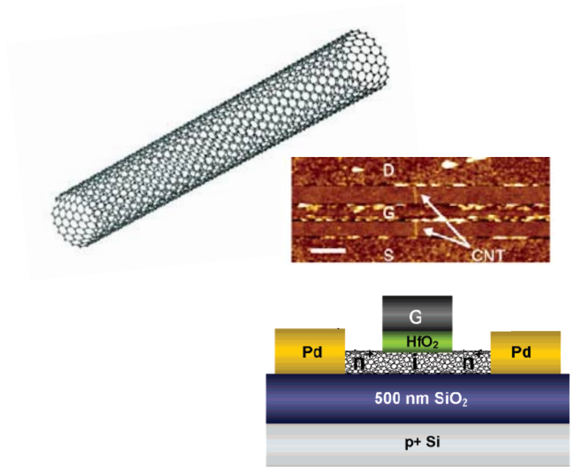
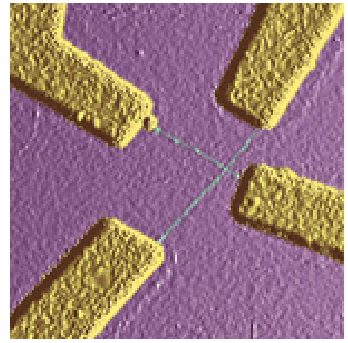
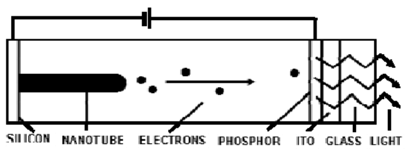
NNIN
Nanoscale Science, Engineering & Technology

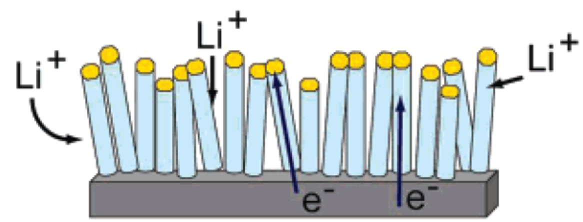




Carbon nanotube (CNT) transistor for future computer chips (Stanford, UC Berkeley)



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



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

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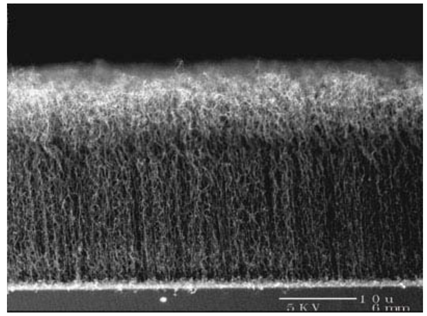
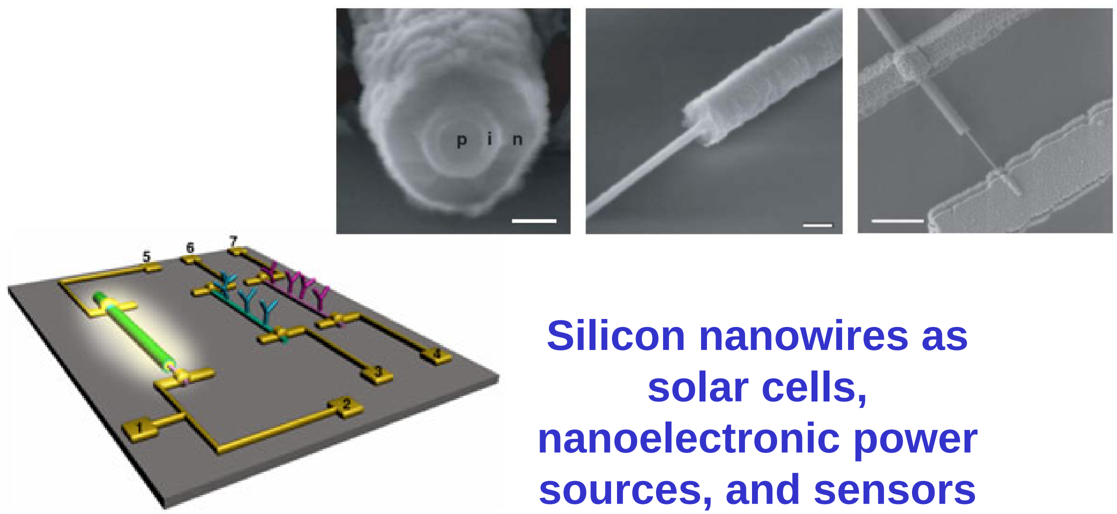


Carbon nanotube “shag electrode” in ultra-capacitors for energy storage (MIT)



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

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Easton CNT (carbon nanotube) baseball bat

ArcticShield “stink-proof” socks with silver nanoparticles

Nano Wear sunblock with TiO_2/ZnO_2 nanoparticles

IPOD Nano with 50nm features in memory chip

LacVert Nano hydrating cream

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

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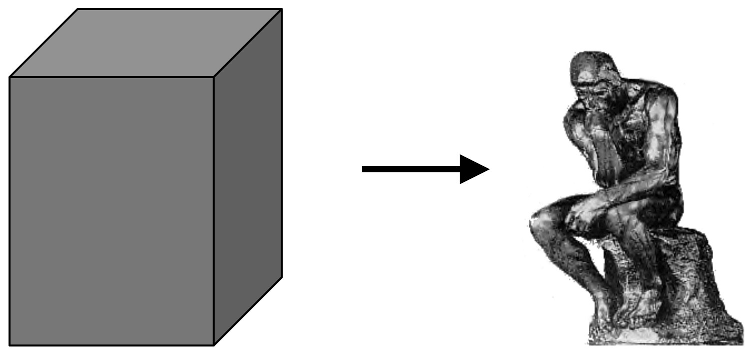
How do you build something so small?

“**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).

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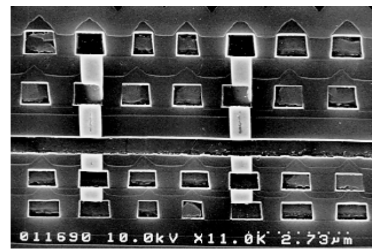
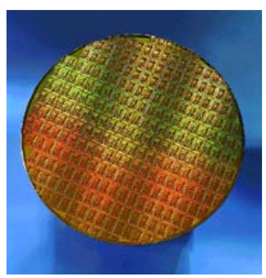
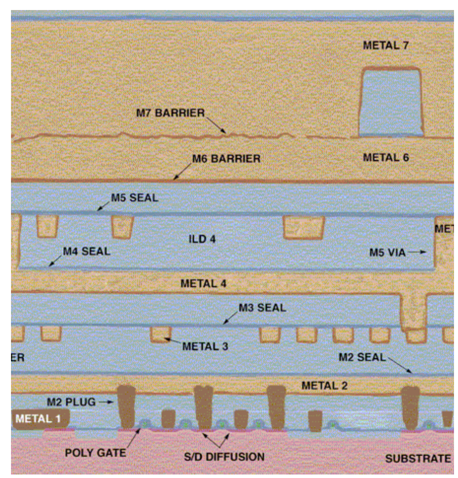
Top-down fabrication

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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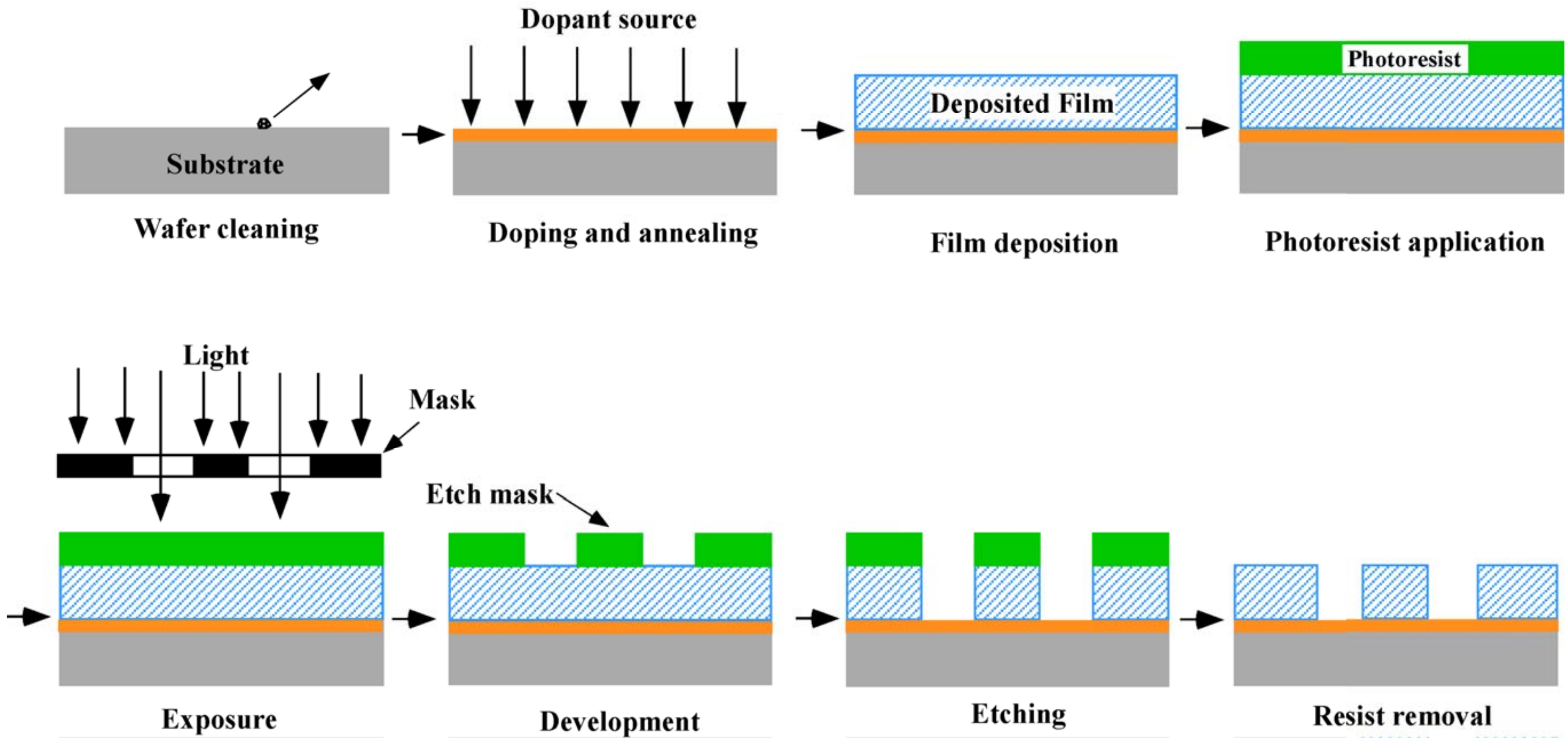
Top-down fabrication



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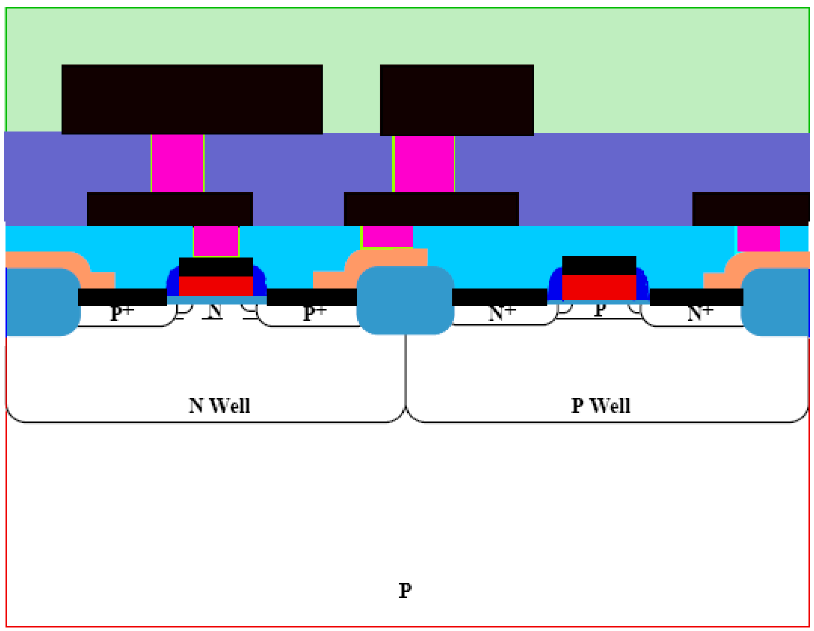
Repeat process with different thin films and different patterns (each aligned to lower layer) to produce desired structure.

Use scanning electron beam to produce masks with very small feature sizes.



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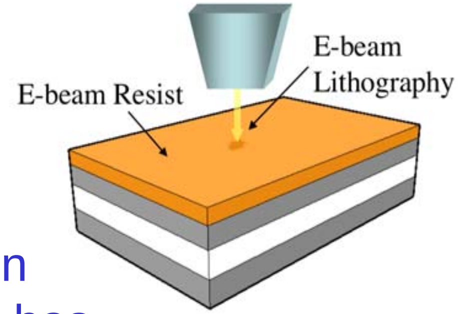
Limitations of top-down fabrication

• 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.

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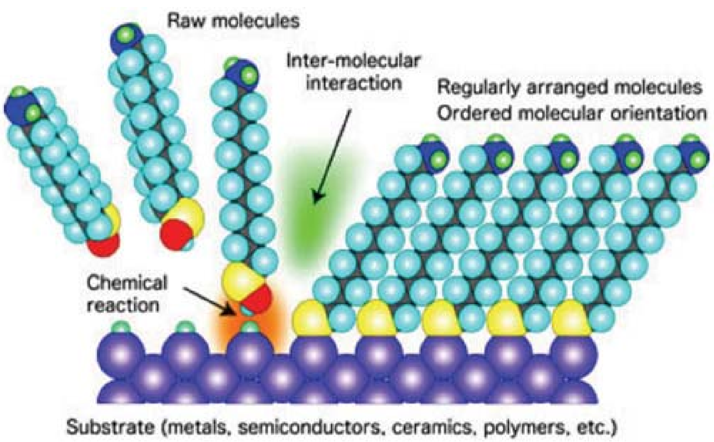
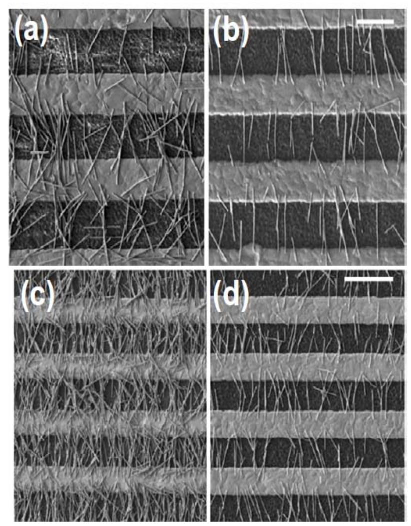
Bottom-up fabrication

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

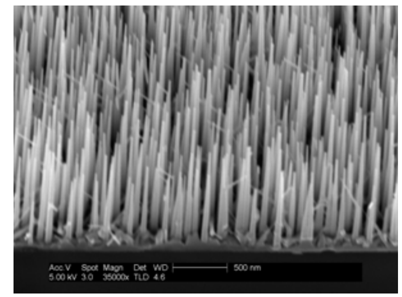
Current day examples:



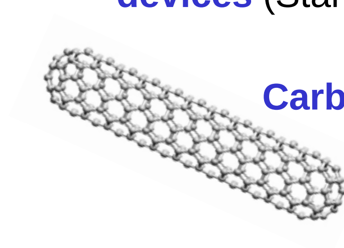
Self-assemble of organic monolayers for molecular transistors, etc. (Florida)



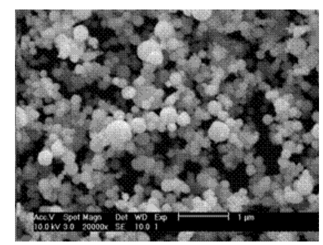
Electric field aligning of nanowires (U. Mass)



Vertical growth of nanowires for electronic devices (Stanford)



Carbon nanotube growth



Nanoparticles by flame pyrolysis (Princeton)

More extreme example: Self-replicating robots.

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Challenges of bottom-up fabrication

• Getting the structures to always grow or be placed exactly how and where you want them to

• Making complicated patterns

• Fabricating robust structures

Some common strategies:

• Use catalysts, stress fields, electric fields, capillary forces, diffraction gratings, etc. to achieve selective growth or placement in specific locations

• Use top-down processes in conjunction with bottom-up processes, and build on silicon substrates

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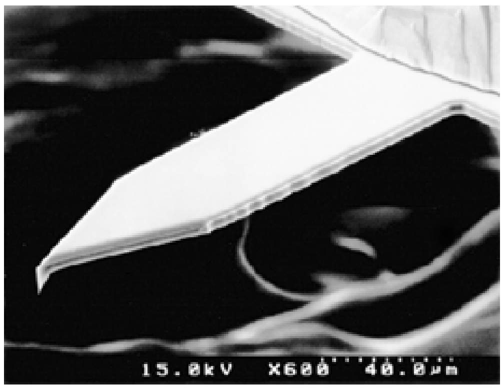
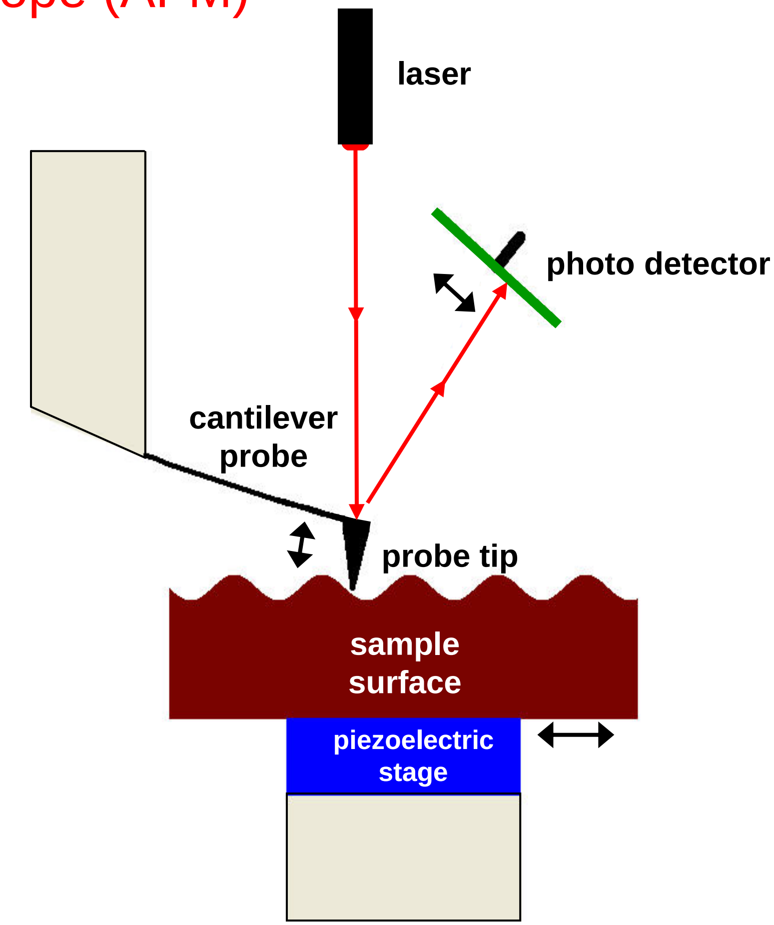
How do you build something so small?

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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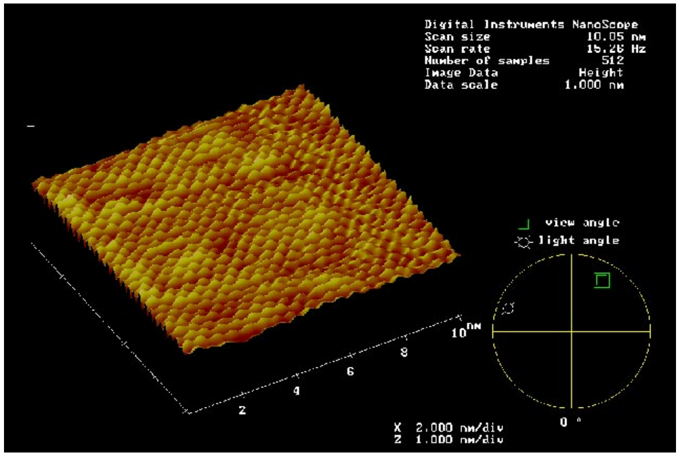
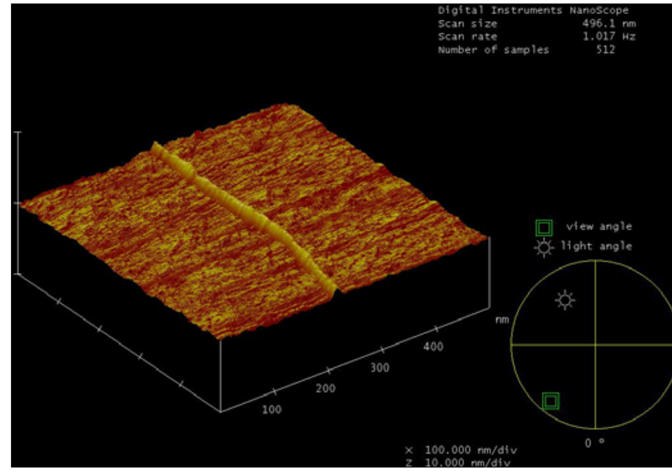
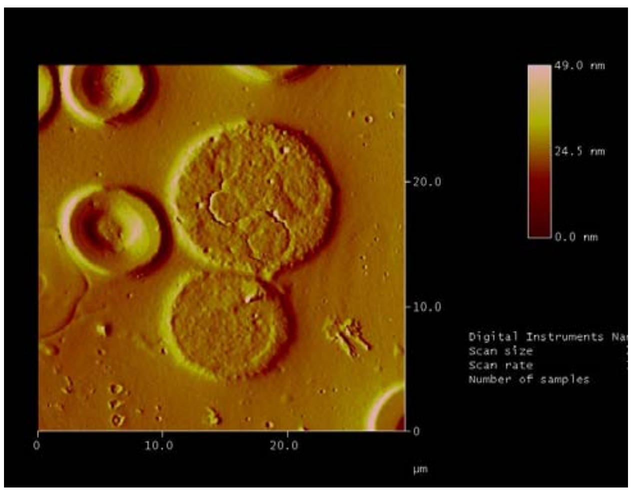


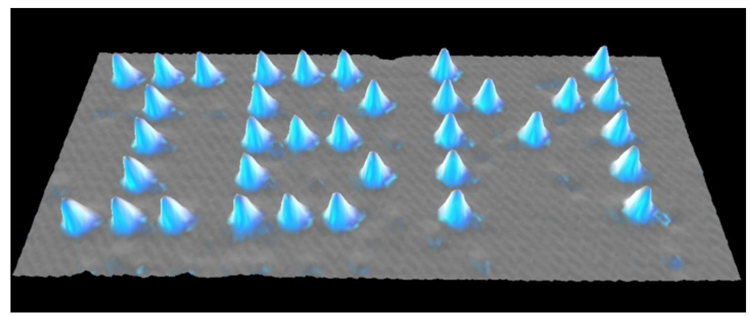
AFM image of mineral surface showing atomic structure.



AFM image of carbon nanotube



AFM image of human blood cells



Positioning single atoms with scanning tunneling microscope (Xe on Ni). Eigler, IBM, 1990.

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

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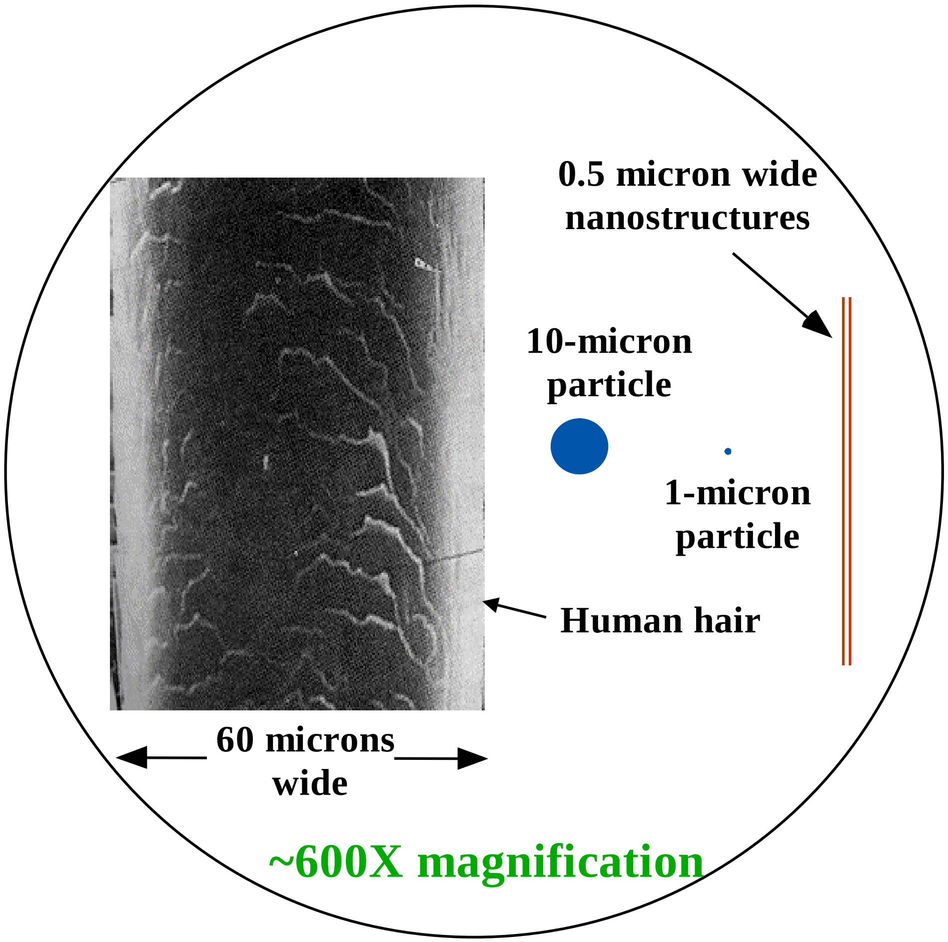
How do you build something so small?

-Requires very clean environment: “clean room”



Relative size of clean room contaminants

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"**

A lab user "gowning-up" in SNF

- **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**

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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 soon-to-be-built nanoscience building

Stanford Nanofabrication Facility (SNF)

- 10,000 sq.ft. clean room, available to any researcher in the world.

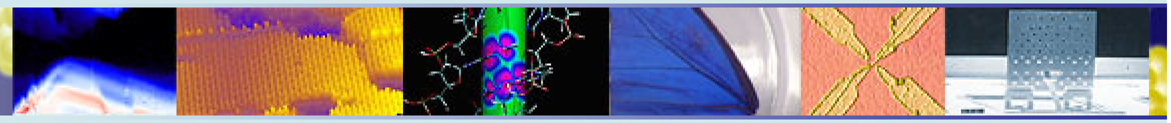
- Includes state-of-the-art equipment for nano- and micro-fabrication and research.

- 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).

Stanford Nanofabrication Facility (SNF)

HOW TO START A PROJECT ■ REU ■ FAQs: GENERAL · TECHNICAL ■ MULTIMEDIA ■ EVENTS ■ ANNOUNCEMENTS ■ CONTACT



ABOUT NNIN NNIN SITES SERVICES RESEARCH SOCIETY & ETHICS EDUCATION & TRAINING

NNIN Sites

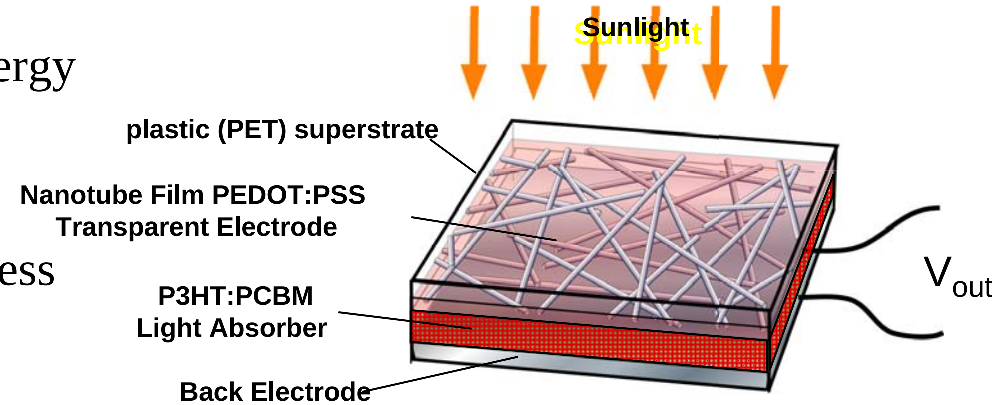
- The Cornell NanoScale Science & Technology Facility at Cornell University
- The Stanford Nanofabrication Facility at Stanford University
- The Lurie Nanofabrication Facility at the University of Michigan
- The Nanotechnology Research Center at the Georgia Institute of Technology
- The Center for Nanotechnology 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

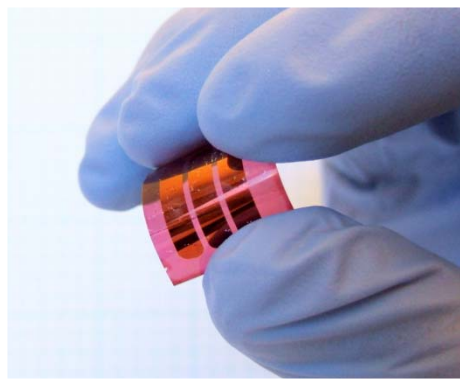
A few examples of research at the Stanford Nanofabrication Facility (SNF)

M. Deal, Stanford

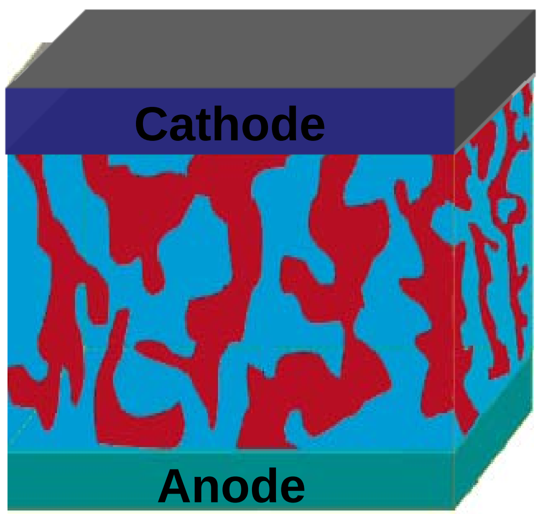
Advanced Molecular Photovoltaics

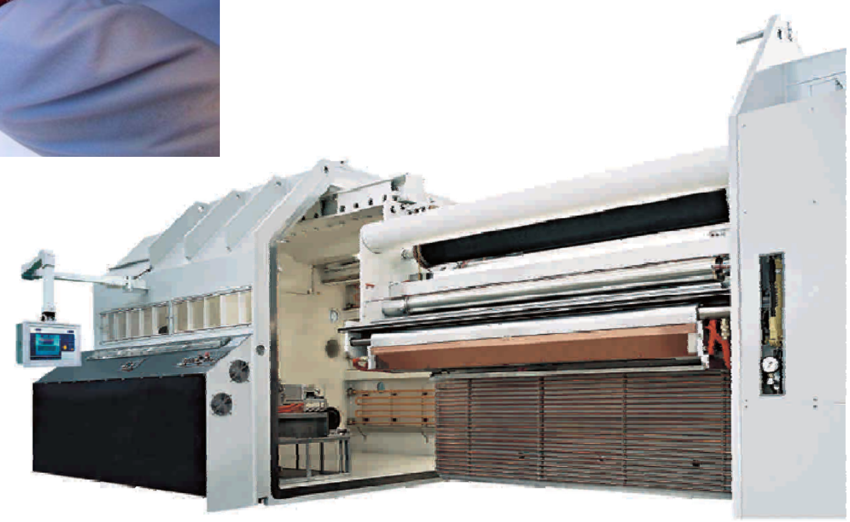
- Motivation
  - Meet current and future clean energy needs
- Desired properties
  - Cheaper ($30 m2) which is 10x less than Si
  - Efficient (> 15 %)
  - Durable (> 20 years)
  - Flexible





Organic donor-acceptor network



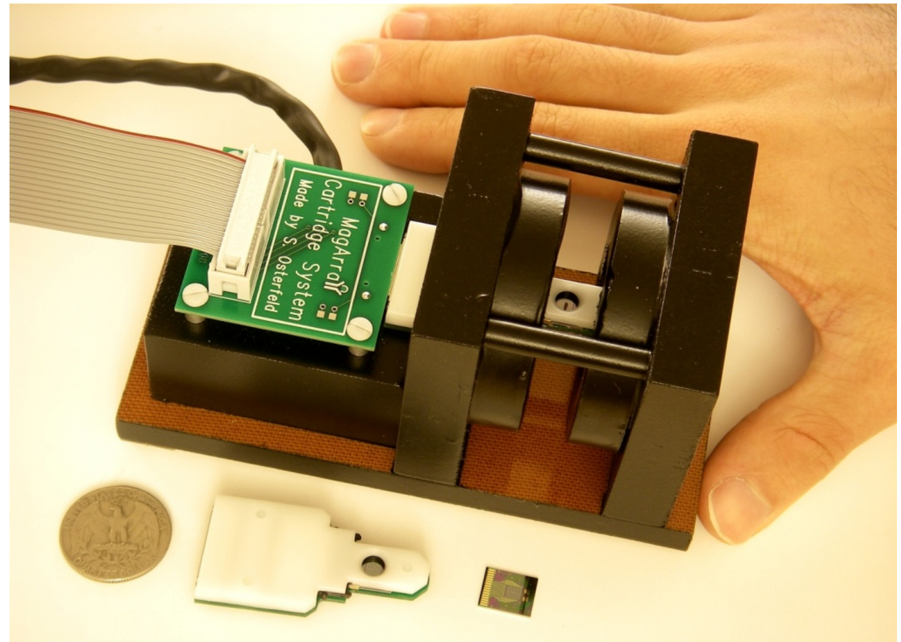


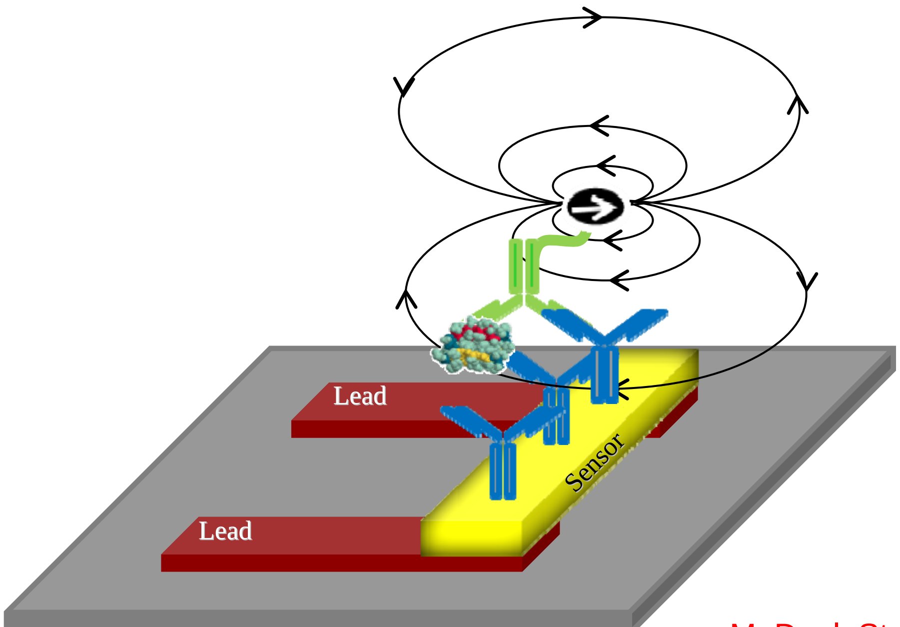
Prof. M. McGehee

M. Deal, Stanford

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

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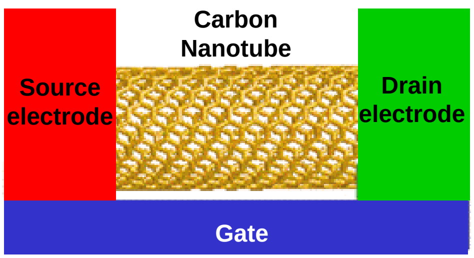
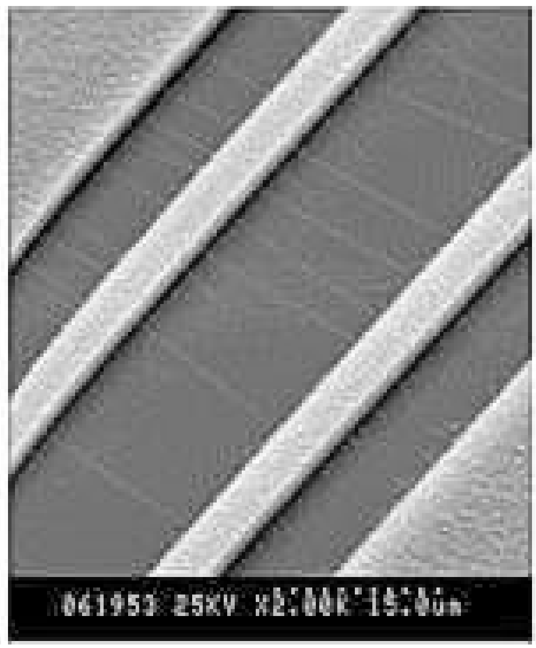
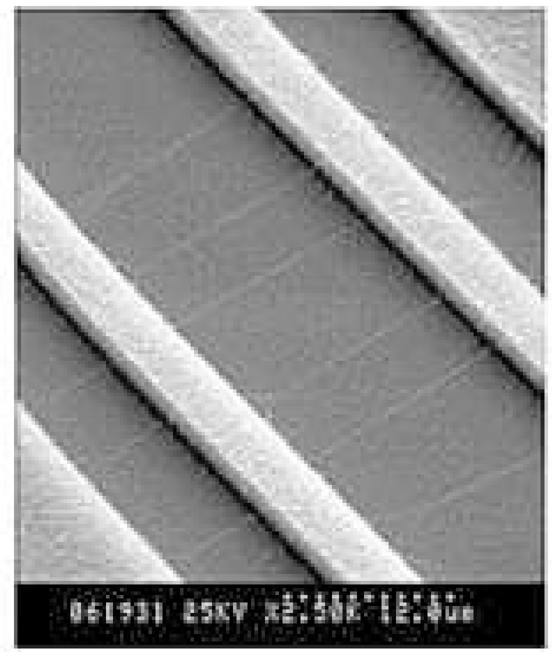
Prof. S. Wang Group

Electric-Field-Directed Suspended Carbon Nanotubes

Ant Ural, Yiming Li, and Professor Hongjie Dai, Stanford



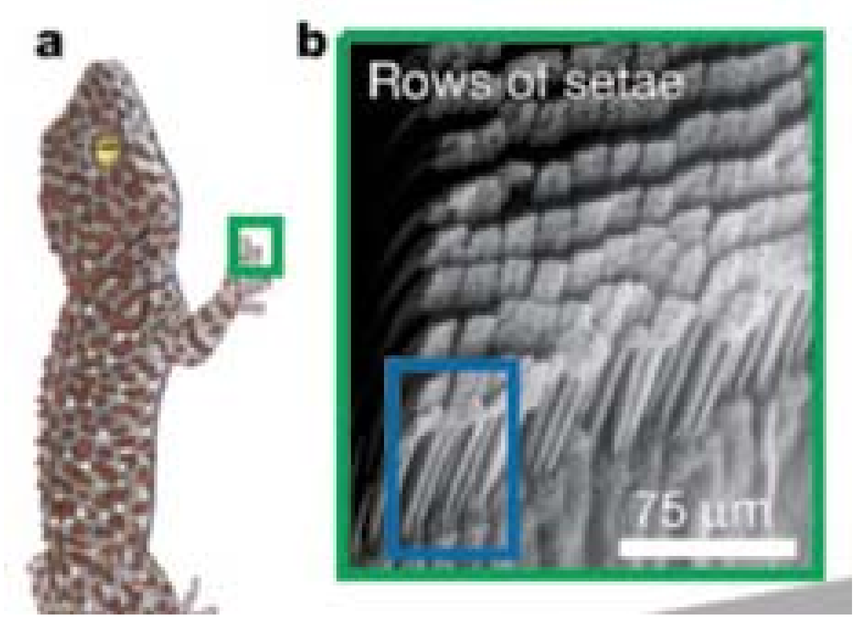


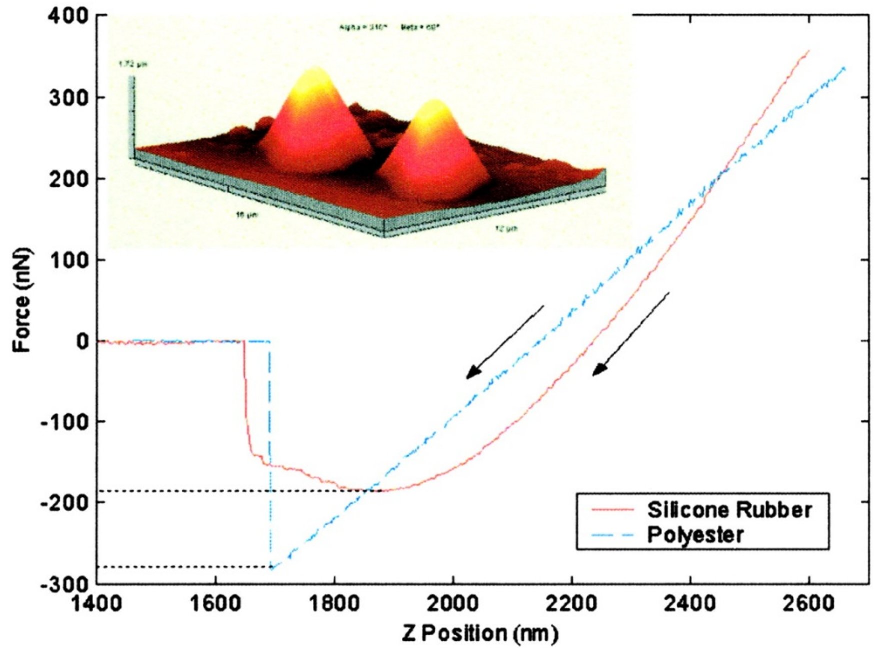


- Iron catalyst was patterned on top of molybdenum electrodes.
- Nanotubes nucleate from the iron islands and extend to the opposite electrode in the direction of the applied field and are suspended over the space in between.
- This method could be used in fabrication of complex organized nanotube structures for molecular electronics applications.

Adhesive Force of Gecko Toes

Ben Chui, Yiching Liang and Professor Thomas Kenny, Stanford





- 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.

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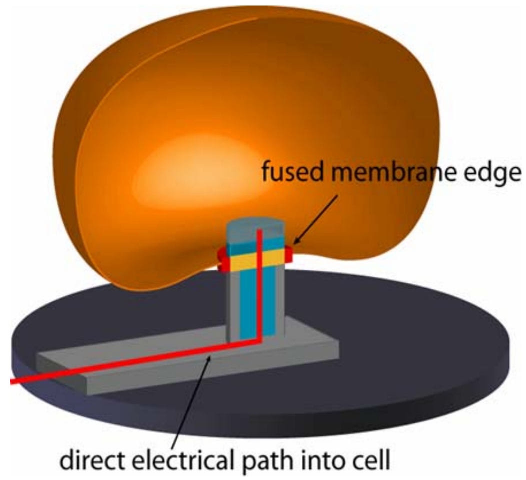
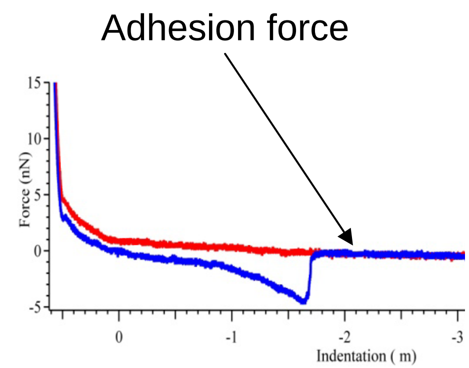
Integration of Electronics into Cells

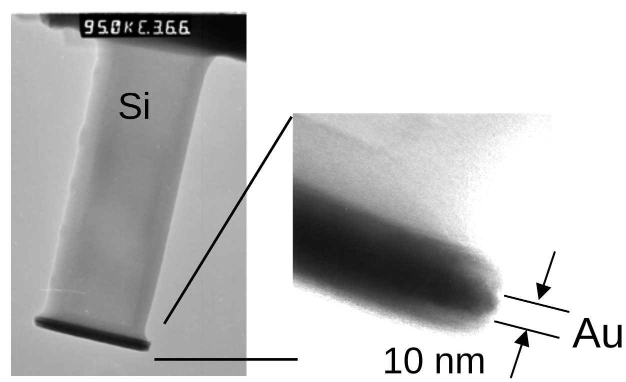
Professor Nicholas Melosh, Stanford University

- Nanoscale-functionalized probes at the end of AFM cantilever tips that can directly integrate into a cell membrane.
- “Stealth electrodes” do not cause membrane damage, and specifically attach to the core of the lipid bilayer.
- To be used for on-chip electrophysiological measurements.





AFM force measurements of the tip interaction with the bilayer.



A nanoprobe tip.

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Nanotechnology – Social and Ethical Issues

• Along with many potential benefits of nanotechnology, there comes some possible adverse consequences

- Environmental and health dangers
- Privacy and personal freedom issues
- Intellectual property and information concerns
- Work force and sociology effects
- 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.