

Nanotubes and Nanowires - One-dimensional Materials

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100 nm

Si/SiGe nanowires grown by the vapor-liquid-solid mechanism - Y. Wu et. al., Nano Lett 2:83 2002

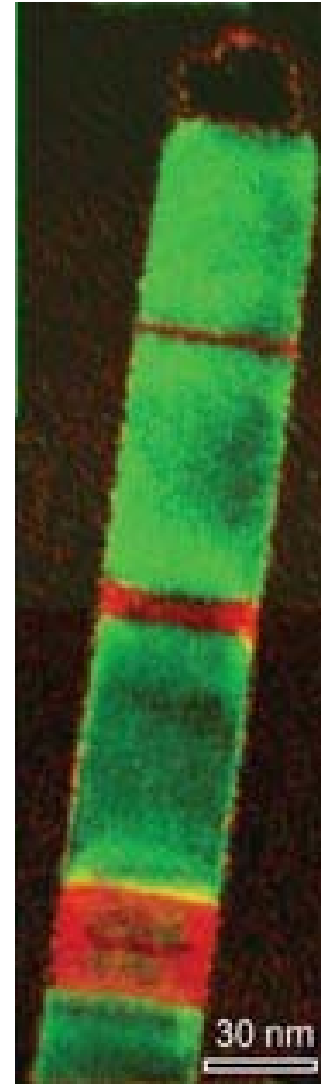
Note: The diameter of these relatively large nanowires is 1/1,000th the diameter of a human hair!

Questions...

- What is a nanowire? What is a nanotube?
- Why are they (scientifically) interesting?
- What are their potential applications?
- How are they made?
- ???

Q: What is a nanowire?

- A: Any solid material in the form of wire with diameter smaller than about 100 nm

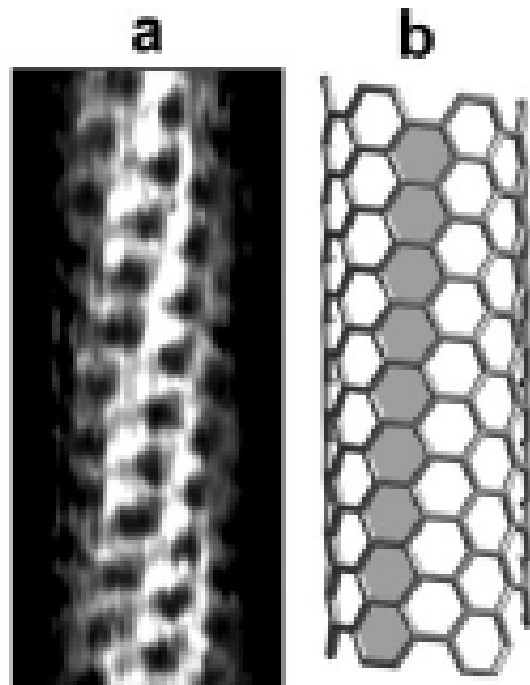


Transmission electron micrograph of an InP/InAs **nanowire**

(M.T. Bjork et. al., Nanoletters, 2:2 2002)

Q: What is a nanotube?

- A: A hollow nanowire, typically with a wall thickness on the order of molecular dimensions
- The smallest (and most interesting) nanotube is the single-walled carbon nanotube (SWNT) consisting of a single graphene sheet rolled up into a tube



Scanning
Tunneling
Micrograph of a
single-walled
carbon **nanotube**
and corresponding
model (Dekker)

Q: How big is a nanometer?

PolySi image: C. Song, NCEM

- 1 billionth of a meter
- 1/50,000 the diameter of a human hair
- 40% of the diameter of a DNA molecule
- 5 times the interatomic spacing in a silicon

crystal



1 nm

Things Natural



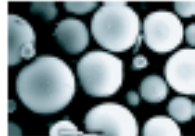
Dust mite
~500 μm



Human hair
10-50 μm dia.

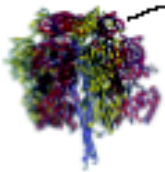
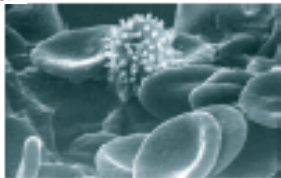


Ant
~5 mm



Fly ash
~10-20 μm dia.

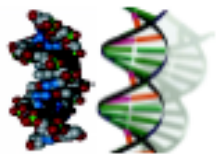
Red blood cells
with white cell
2-5 μm dia.



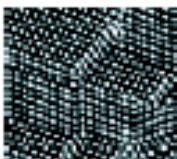
~10 nm dia.



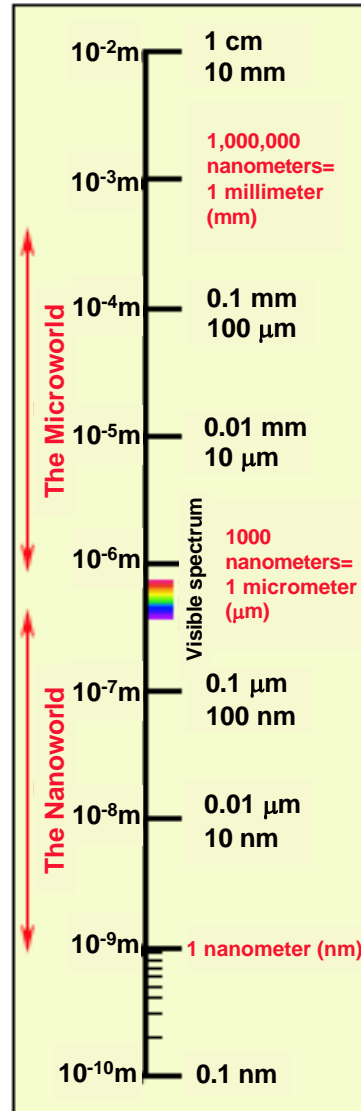
ATP synthesis



DNA
2.5 nm dia.



Atoms in silicon
0.2 nm spacing



Things Man-made

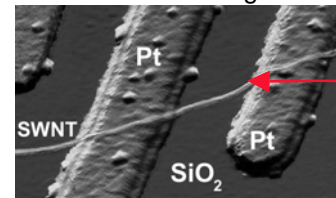


Head of a pin
1-2 mm

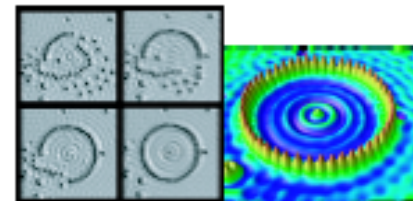
Microelectromechanical devices
10-100 μm wide



Red blood cells
Pollen grain



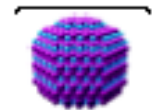
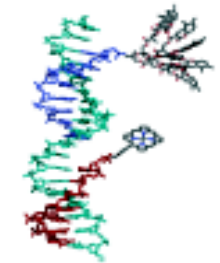
Nanotube devices (C. Dekker)



Quantum corral of 48 iron atoms on copper surface positioned one at a time with an STM tip - Corral diameter 14 nm

Carbon nanotube
~2 nm diameter

21st Century Challenge



Assemble nanoscale building blocks to make functional devices, e.g., a photosynthetic reaction center with integral semiconductor storage

FIGURE 1.1 The size of nanoscale objects and phenomena compared with the size of small everyday objects. Courtesy of Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy.

Adapted from: NRC Report: Small Wonders, Endless Frontiers: Review of the National Nanotechnology Initiative (National Research Council, July 2002)

Q: What makes nanowires and nanotubes (scientifically) interesting?

- **Electronic & optical properties**
 - Nanowires and nanotubes are the most confining electrical conductors - puts the squeeze on electrons
 - Can be defect free - electrons move “ballistically”
 - Quantum confinement - tunable optical properties
- **Mechanical properties**
 - Small enough to be defect-free, thus exhibiting ideal strength
- **Thermal properties**
 - Can be designed to conduct heat substantially better (or much worse) than nearly every bulk material
- **Chemical properties**
 - Dominated by large surface-to-volume ratio

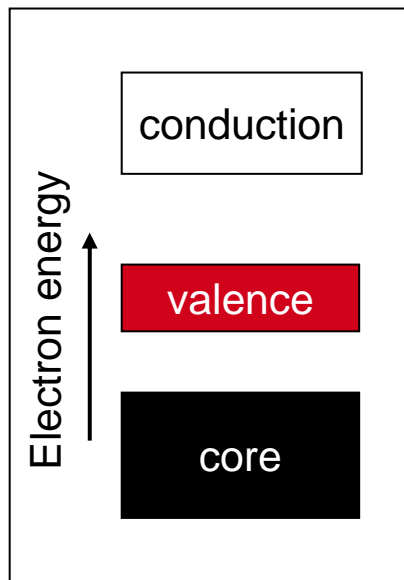
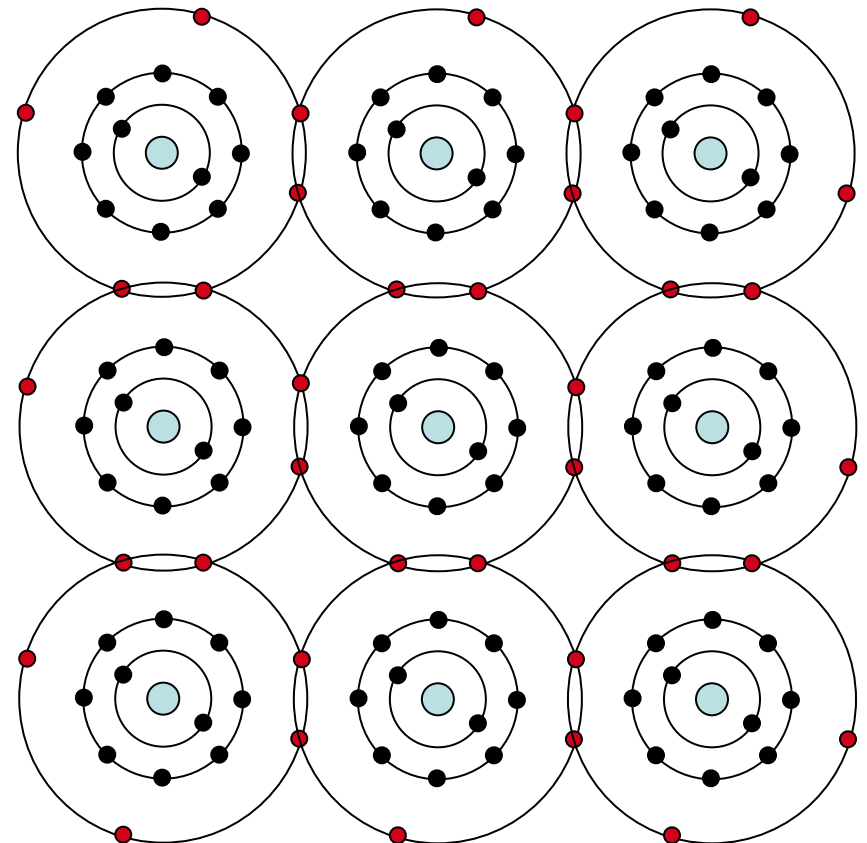
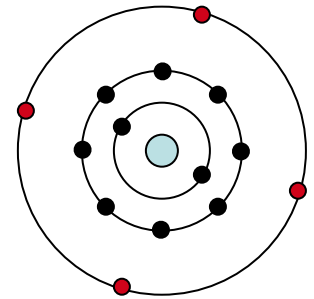
Nanowires and Nanotubes are New Materials!

Electronic and Optical Properties

Quantum Confinement

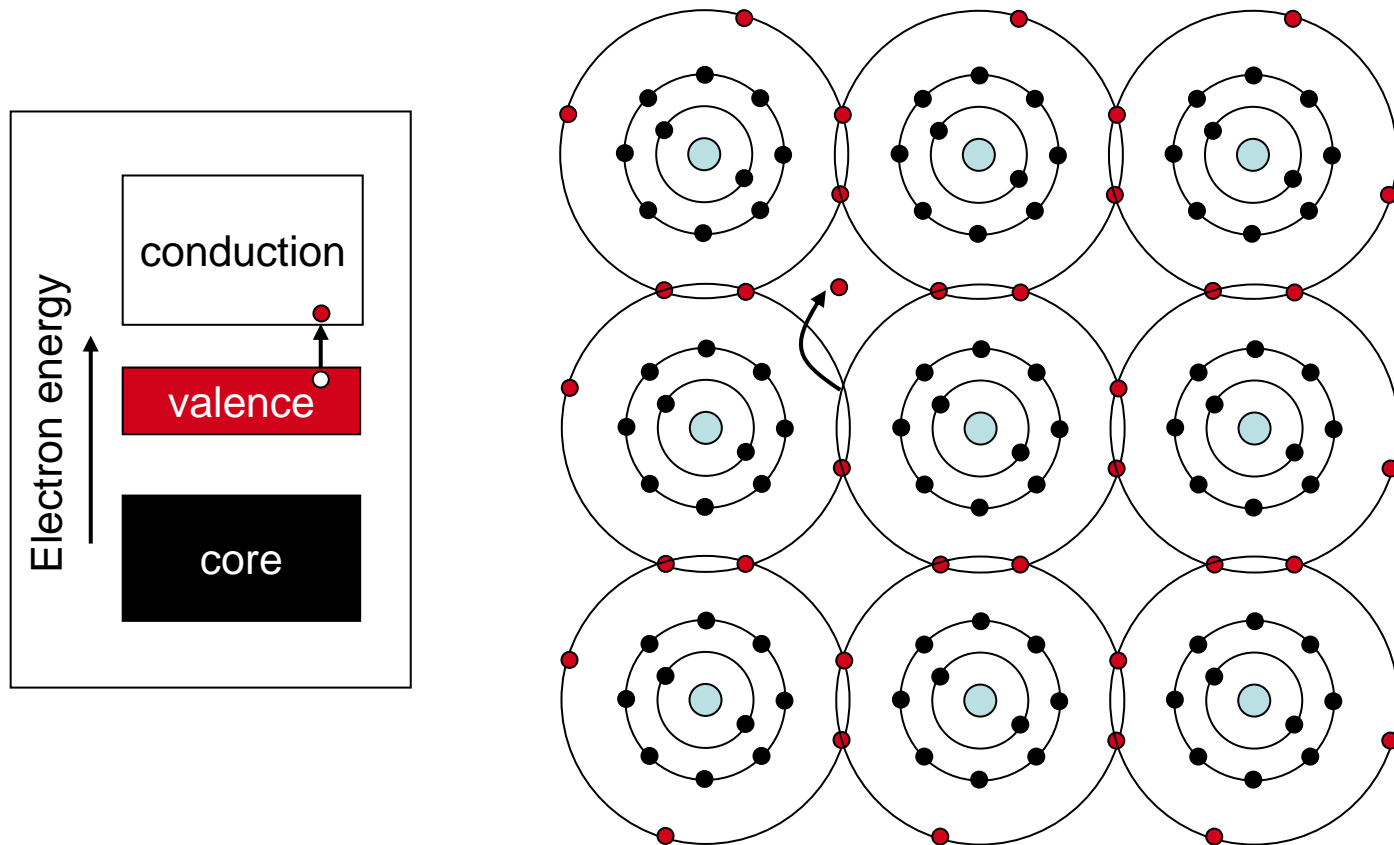
Electrons in solids

- Core shell electrons are tightly bound to atoms, and do not interact strongly with electrons in other atoms
- Valence shell electrons are the outer electrons that contribute to bonds between atoms
- If all of the bonds are “satisfied” by valence electrons, and if these bonds are strong, then the material does not conduct electricity - an **insulator**



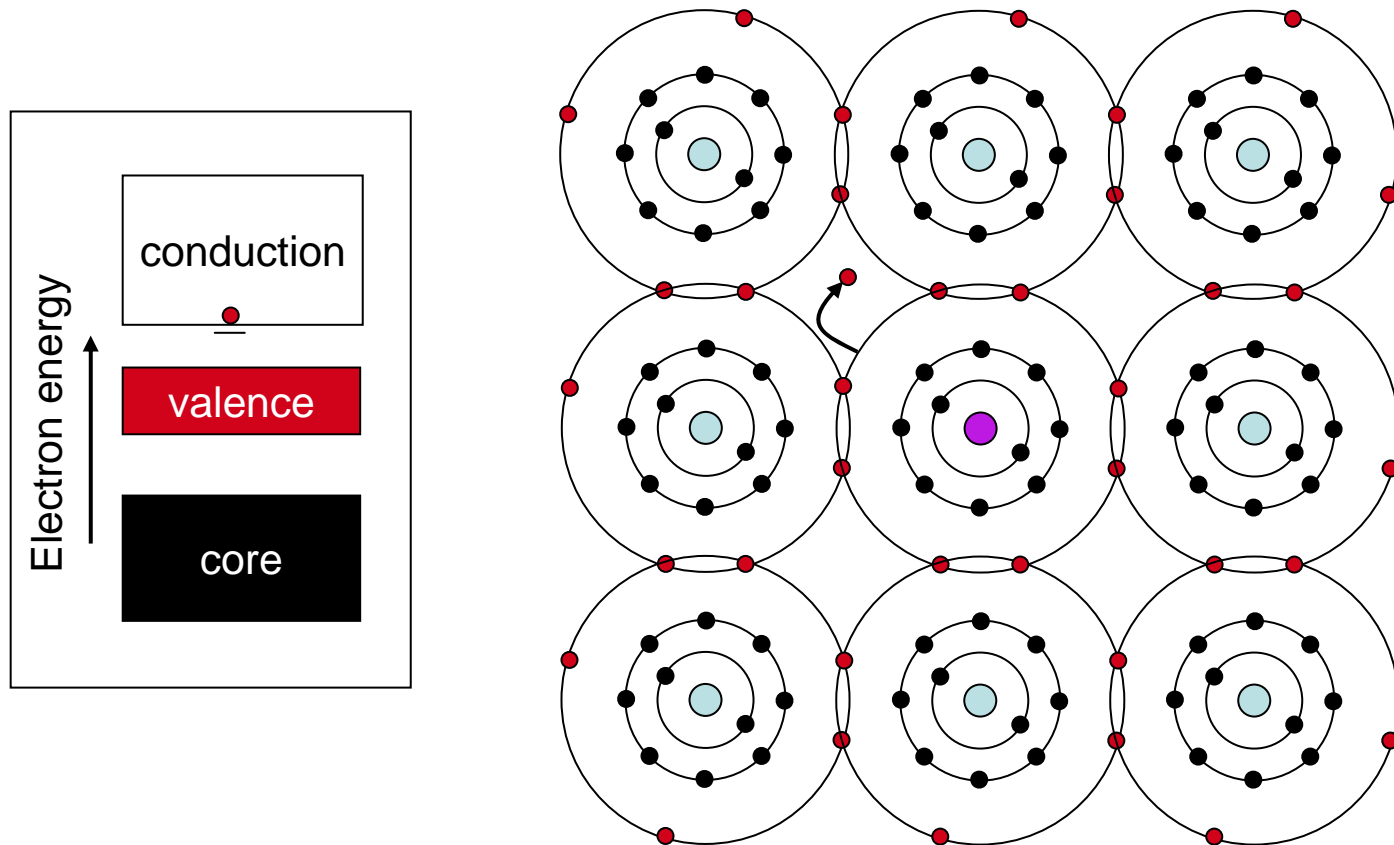
Electrons in solids

- If all the bonds are “satisfied”, but the bonds are relatively weak, then the material is an **intrinsic semiconductor**, and thermal energy can break a small number of bonds, releasing the electrons to conduct electricity



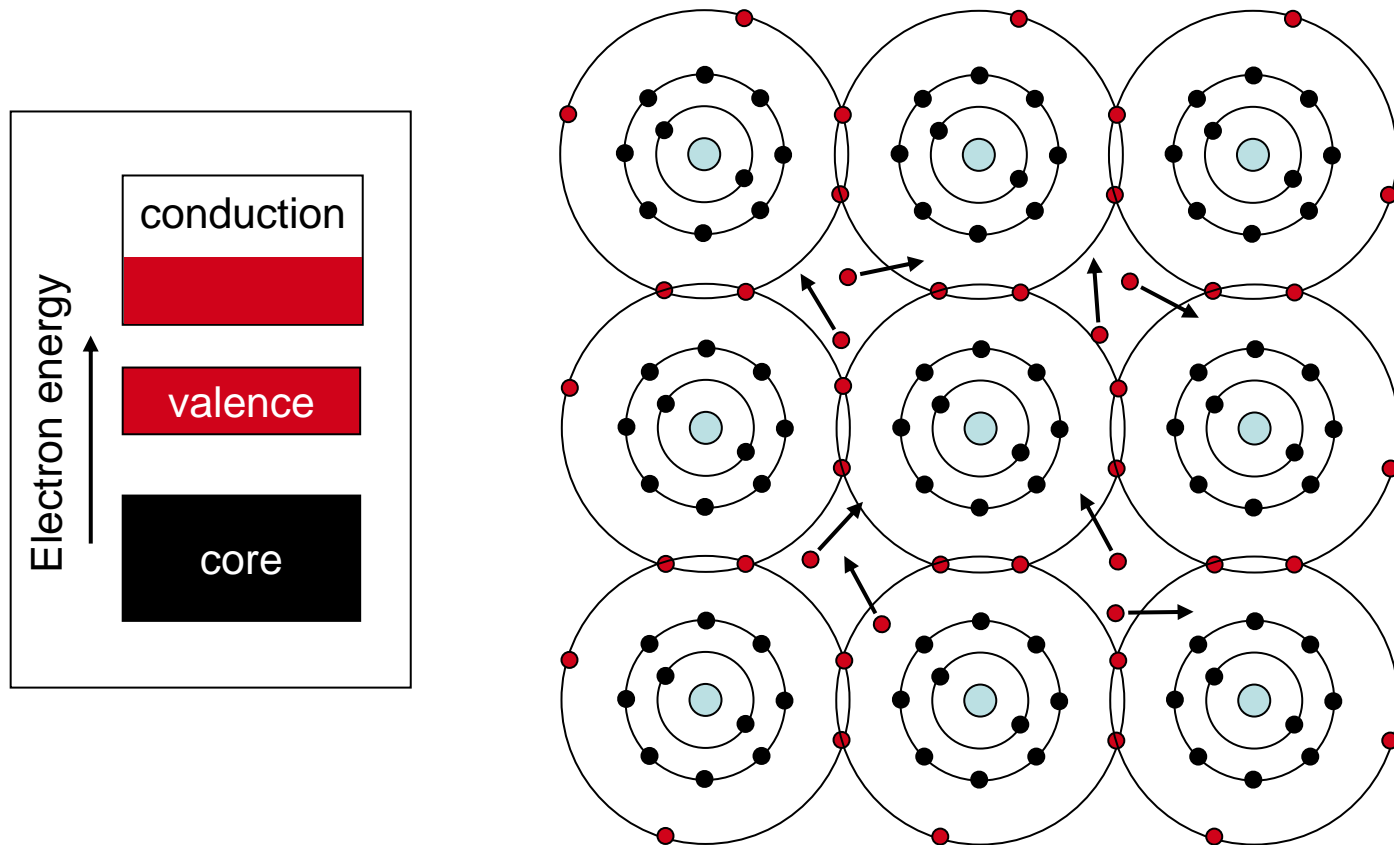
Electrons in solids

- If impurities with one more or one fewer electrons than a host atom are substituted for host atoms in a semiconductor, then the material becomes conductive - an **extrinsic semiconductor**



Electrons in solids

- If only a fraction of the bonds are satisfied (or alternatively, if there are many more electrons than are needed for bonding) then there is a high density of electrons that contribute to conduction, and the solid is a **metal**

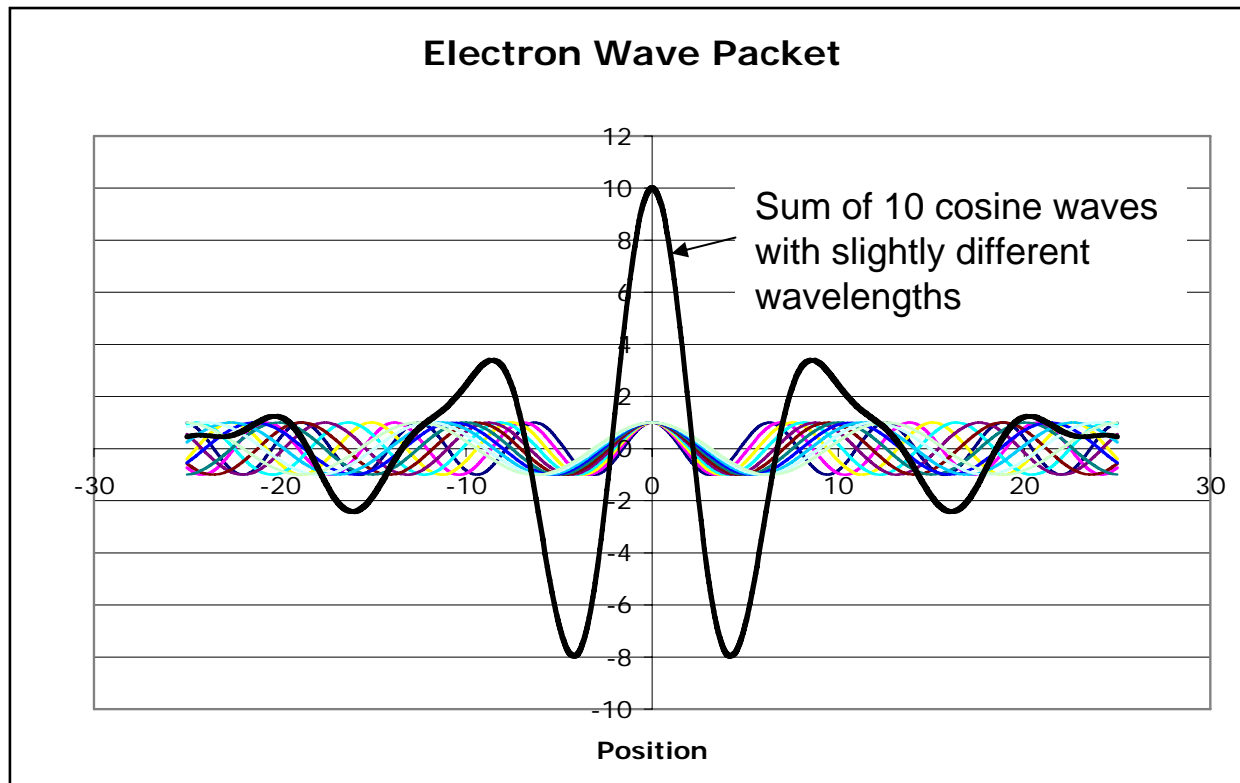


Electrons in nanostructured materials

- Electrons can be considered to be both waves and particles
- **Particle:** momentum = mass x velocity ($p = mv$)
- **Wave:** momentum = Planck's constant/wavelength ($p = h/\lambda$)
- **Particle or wave:** kinetic energy = $p^2/2m$

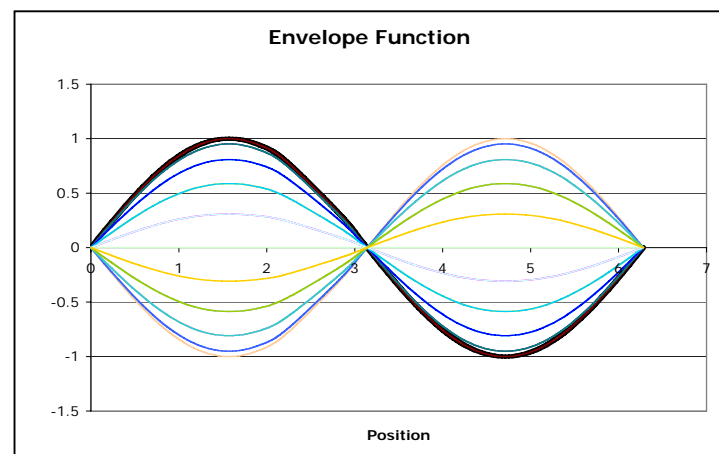
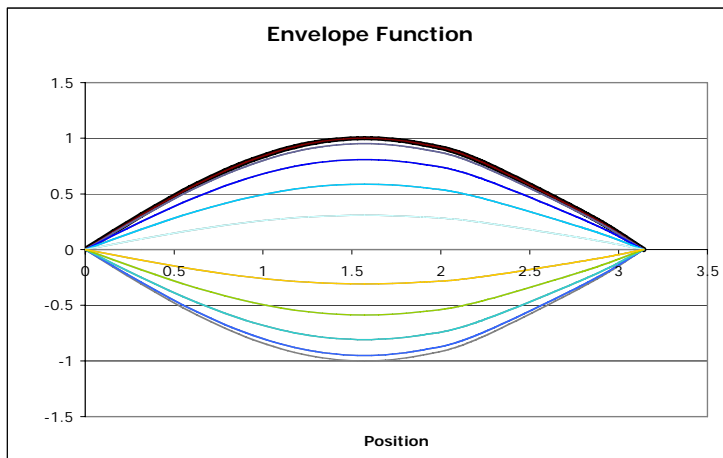
Electrons in nanostructured materials

- An electron (particle) can be described as a wave packet, i.e. the sum of sinusoidal waves, each with a slightly different wavelength



Electrons in nanostructured materials

- Each wave (“wavefunction”) is analogous to the shape of a vibrating string (or jump rope).
- If we hold two ends of the string, we constrain the string to vibrate within an “envelope” that contains an integer number of half wavelengths...a “standing wave”.
- Each half-wavelength exists between two “nodes” - points that do not move
- The shorter the wavelength (shorter string or more nodes), the more energy it takes to vibrate the string



From vibrating strings to electrons

- An electron's wavefunction is just like the vibrating string
- If we move the nodes closer together, the electron's energy increases.
- If we put an electron in a "box", the walls of the box become nodes - so the smaller the box, the higher the energy of the electron

Confining the electrons fundamentally changes their electronic structure...

Quantum confining materials are *NEW* materials with properties that are tunable with size

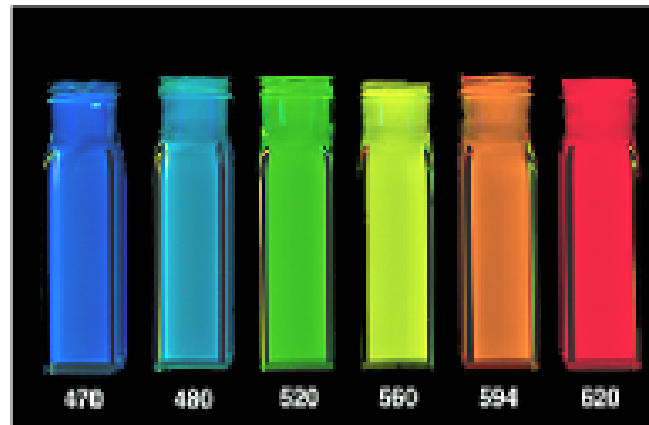
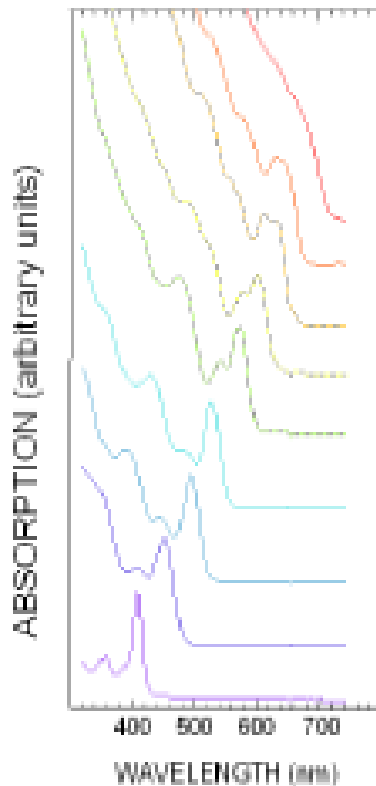
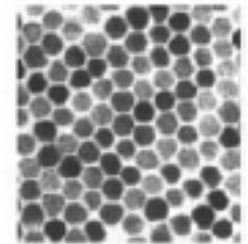
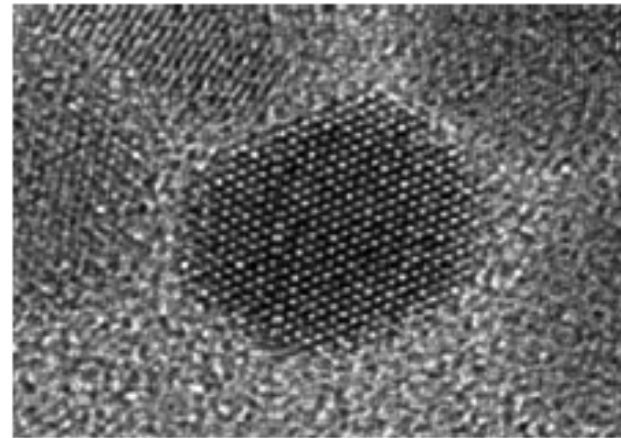
Optical properties

- Decreasing the size of a nanostructured material increases the energy difference, ΔE , between allowed electron energy levels
- When an electron drops from a higher energy state to a lower energy state, a quantum of light (“photon”) with wavelength, $\lambda = hc/\Delta E$ may be emitted
- Larger ΔE implies shorter wavelength (“blue shifted”)

h is Planck’s constant; c is the speed of light

Example: Quantum Dots

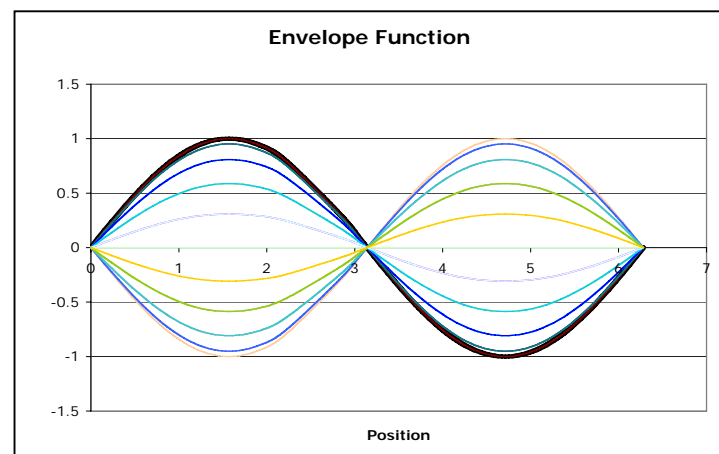
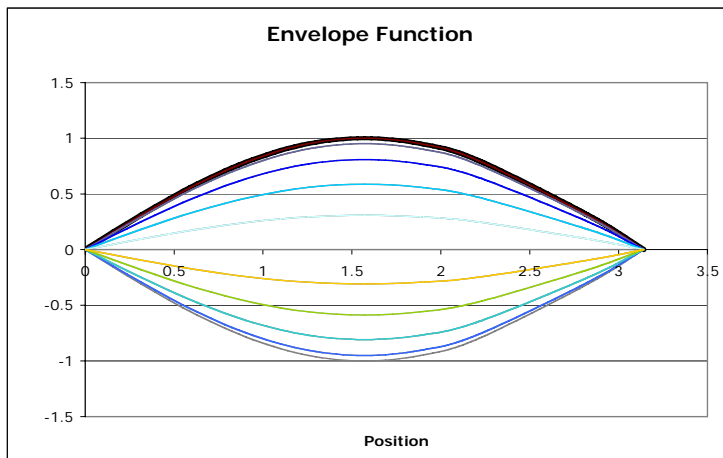
CdSe nanocrystals; Manna, Scher and Alivisatos, J. Cluster Sci. 13 (2002)521



Left- absorption spectra of semiconductor nanoparticles of different diameter (Murray, MIT). Right- nanoparticles suspended in solution (Frankel, MIT) - National Science Foundation Report, "Societal Implications of Nanotechnology" March 2001

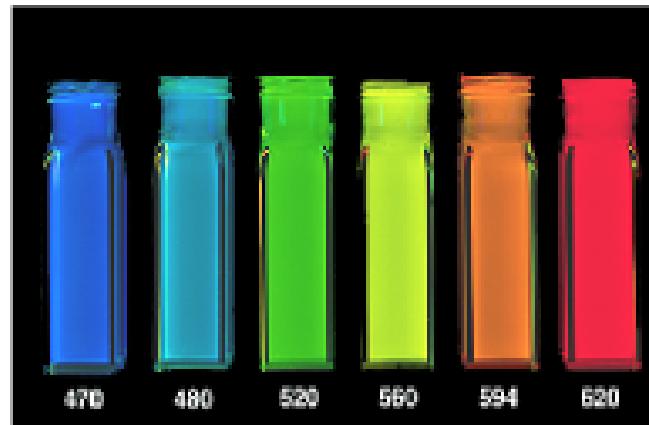
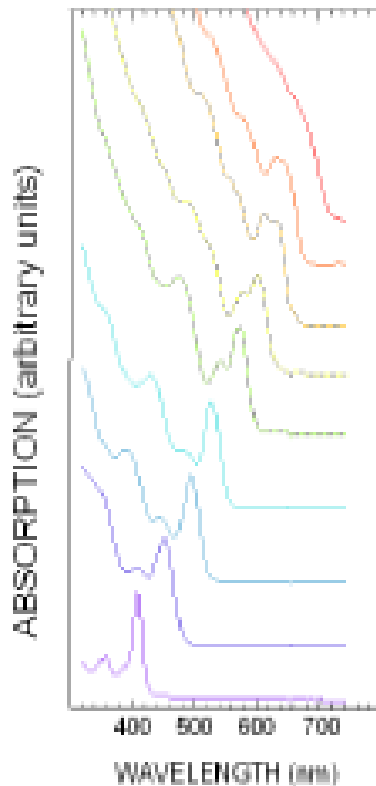
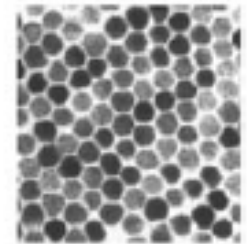
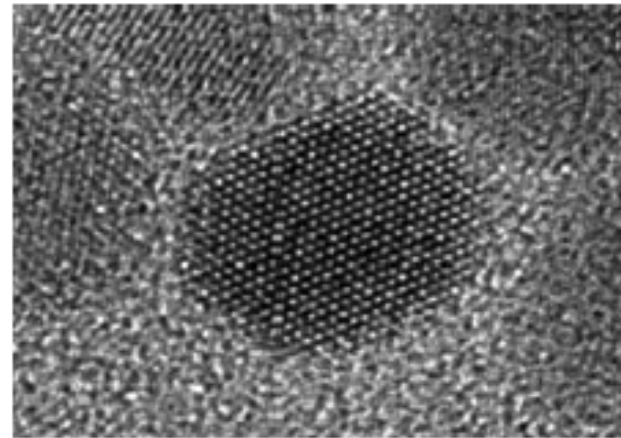
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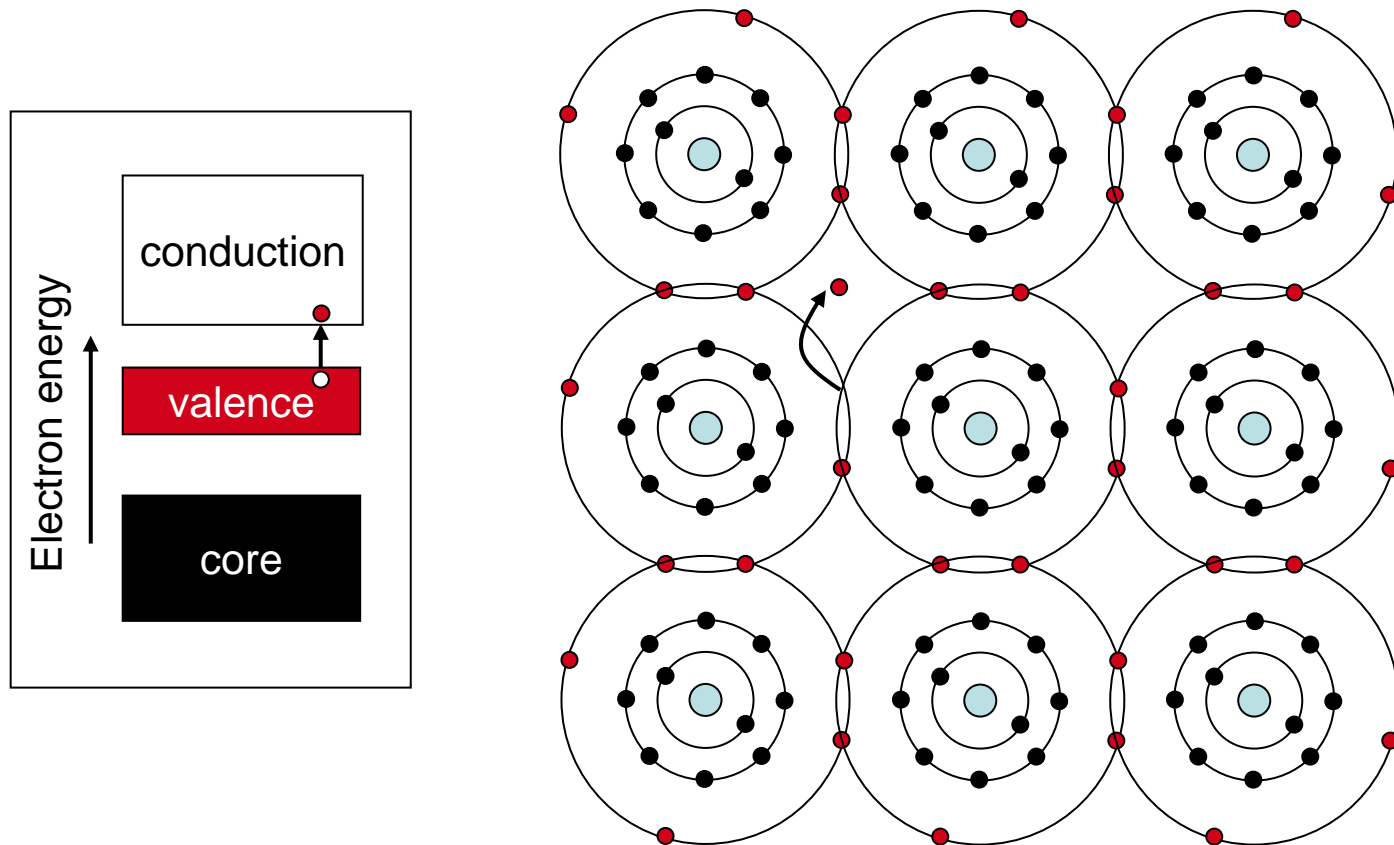
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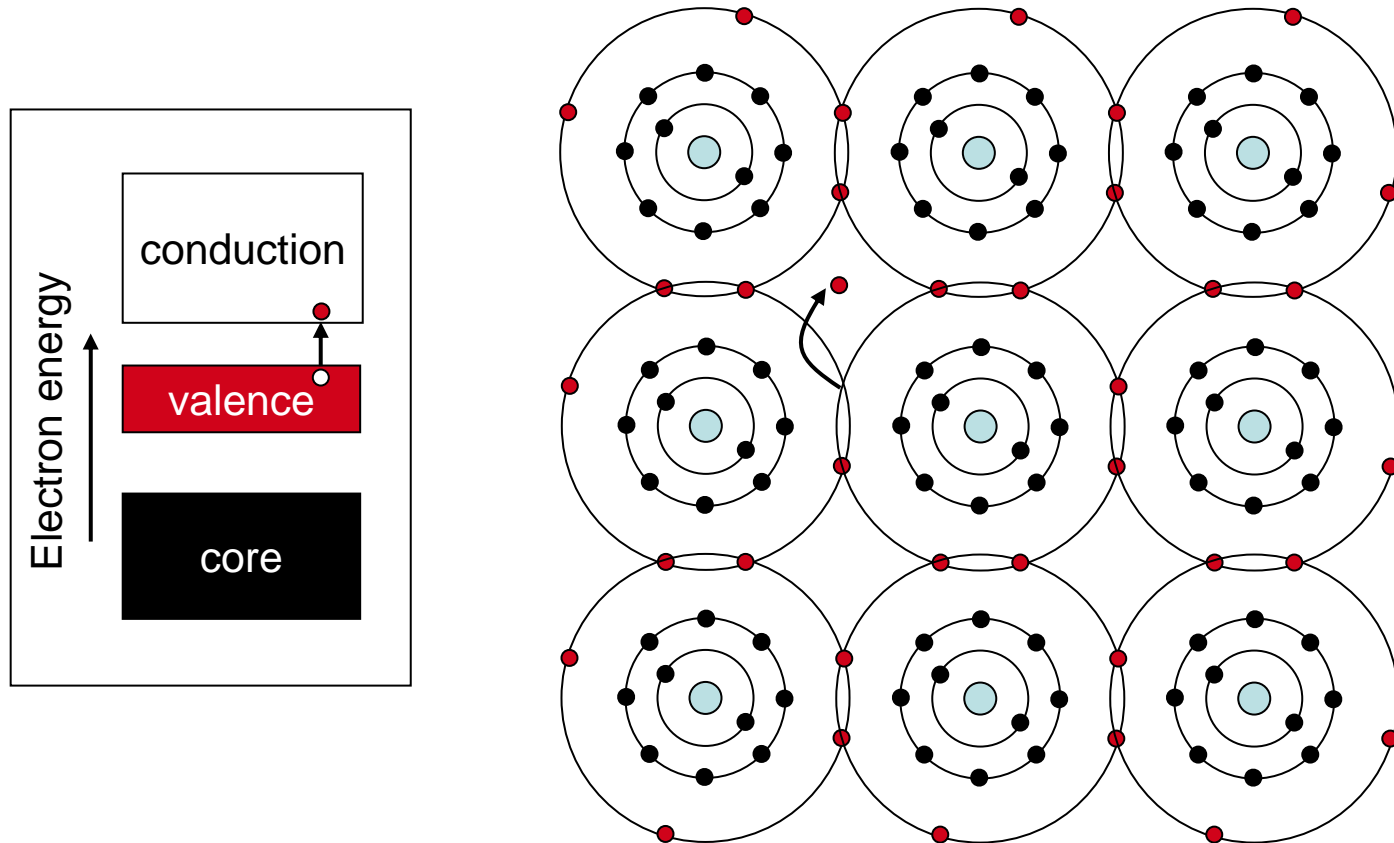
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Questions and Answers

Electrons in solids

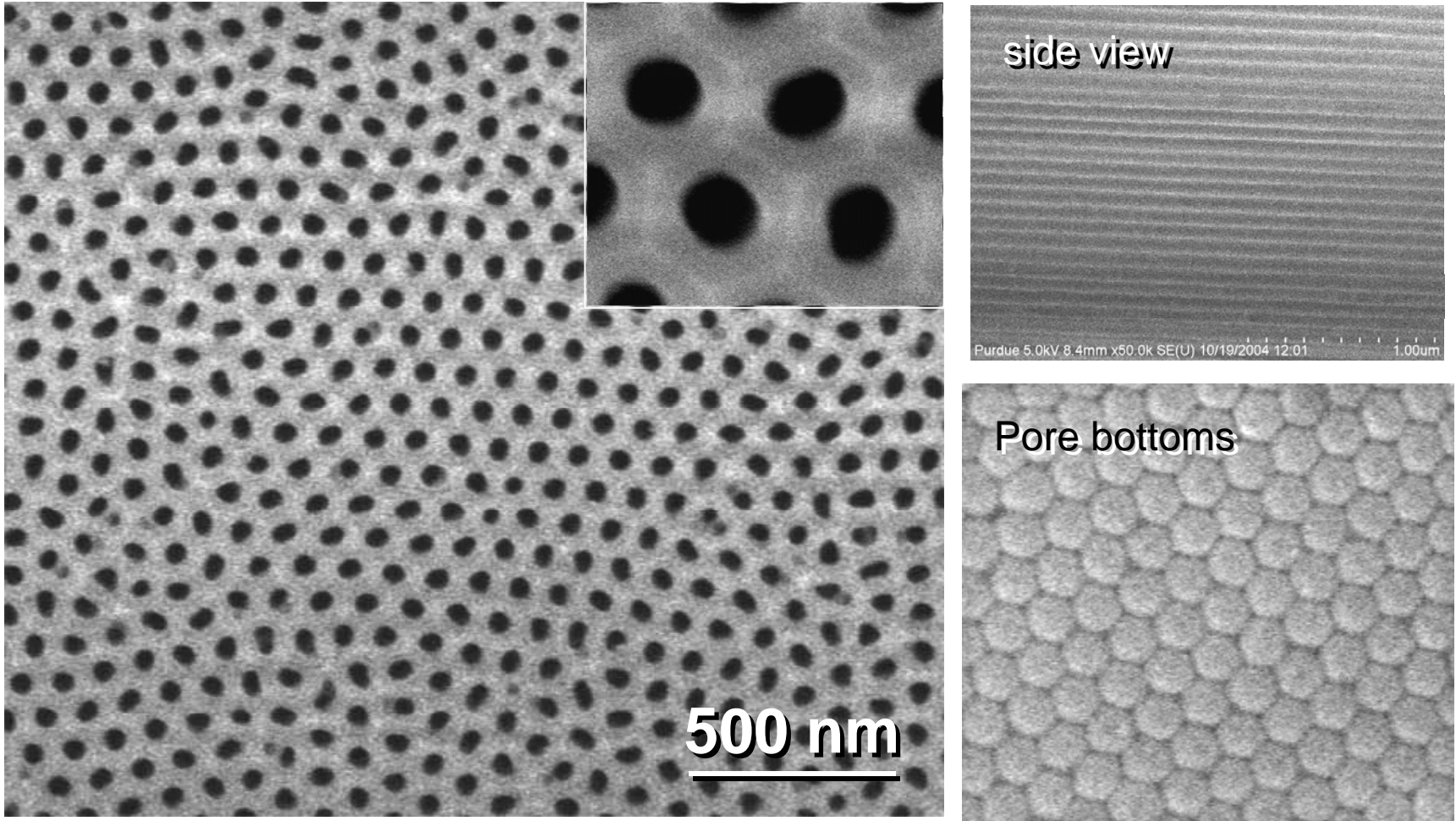
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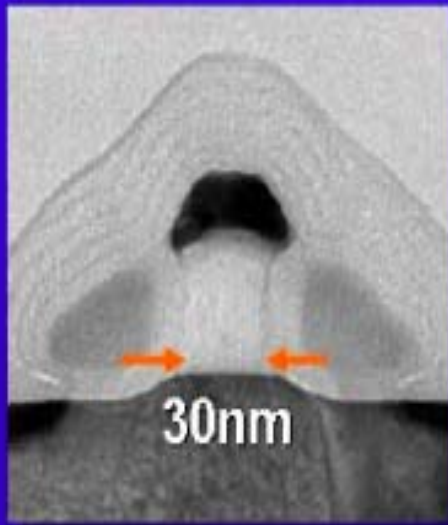
Another approach: nanoporous templates



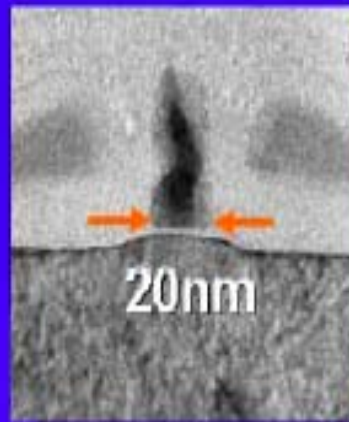
Porous anodic alumina (PAA) with 50 nm diameter pores on 100 nm centers produced by anodizing Al foil at 40V at 4°C in oxalic acid

How far can we go with silicon?

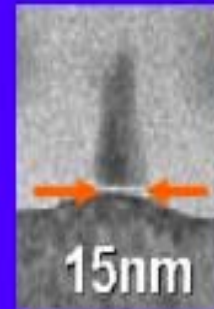
Experimental transistors for future process generations



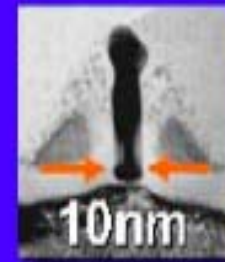
65nm process
2005 production



45nm process
2007 production



32nm process
2009 production



22nm process
2011 production

...or nano-tennis racquets...

Free Babolat Tee Shirt AND a \$20 Instant rebate on any Nanotechnology racket for a limited time only!

New high Modulus Carbon Graphite Carbon Nanotube

Headsizes:118 sq. in. * Length:28 in. * Weight (strung):9.3 oz.
* Stiffness (Babolat RDC):73 * Balance:14.63 in. Head Heavy *
Cross Section: 28mm Head/26mm Throat * Swingweight: 326 kg*sq.
cm * "This year, Babolat introduced two Nano Carbon Technology,
or NCT, racquets, the Tour and the Power. The Tour, above is
geared toward high-level intermediates while the Power (below) is
for those with short strokes. Both models are *reinforced in the throat
and the bottom half of the head with carbon nanotubes, strings of
carbon molecules constructed at the nano level, which are five times
stiffer than graphite.* Net result: Babolat is able to increase the
stiffness and power of the racquets without adding weight."—
Racquet Sports Industry.



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