

## Nanotechnology and energy

One application of “nano” that we haven’t discussed is the possibility of using nanostructured materials to address the energy crunch.

- What is the energy problem?

Realistic niches for nano here:

- Solid state lighting
- Nanostructured materials
- Solar energy - photovoltaics
- Photocatalysis and the “hydrogen economy”

*Caveat emptor*: this is a limited view of this issue - others have been spending way more time thinking about this.

## The coming energy problem

Report#:DOE/EIA-0484(2002)

Annual energy consumption is predicted to continue to grow at a large rate for the foreseeable future.

One major issue: developing world has large, rapidly growing population that will eventually want “first-world” standard of living.

We consume, per person, vastly more energy than, say, citizens of Afghanistan.

**Figure 2. World Energy Consumption, 1970-2020**  
Quadrillion Btu



Sources: **History**: Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, February 2001). **Projections**: EIA, World Energy Projection System (2002).

1 BTU ~ 1.06 kJ

1 quad ~  $1.06 \times 10^{18}$  J = 33 GW-yr

## The coming energy problem

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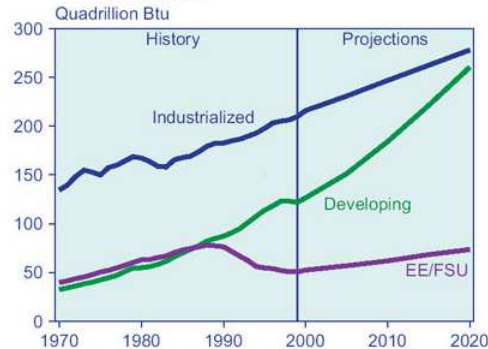
Carbon emissions are another issue....

Do we really want India and China to be building huge fossil fuel based power facilities?

Alternately, do we really want to be putting large numbers of nuclear reactors in places like Somalia or Afghanistan?

No silver bullet - we need to address this problem or pay the price later.

**Figure 3. World Energy Consumption by Region, 1970-2020**



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, February 2001). **Projections:** EIA, World Energy Projection System (2002).

## The role of nanostructures and nanotechnology

Nanostructures and nanotechnology can realistically contribute in several distinct ways:

- Increased technology efficiency to decrease energy demands of developed world.
- Enabling technologies such as light/strong materials to make power generation and distribution cheaper and more efficient.
- Direct contributions to power generation.
- Improved waste remediation to lessen environmental impacts of energy use.

## Increased efficiency: solid state lighting

Incandescent lights are terribly inefficient - only a very small fraction of the power consumed comes out in useful light.

Figure of merit:  $\sim 20$  lm/W (can be  $\sim 60$  lm/W for fluorescent)

Nanostructured materials pave the way for alternatives: LEDs and electroluminescent devices.

These systems can have efficiencies approaching 50% (!).

Projected figure of merit for white LEDs:  $\sim 200$  lm/W

Current consumption:  $2000$  TW-hr =  $7.2 \times 10^{18}$  J = 21% of world electricity demand (!).

Imagine being able to cut that by a factor of, say, 8.

## Increased efficiency: solid state lighting

“White” LEDs could result in savings of (2000-2025) just in US:

- Elim. of 258 MT of carbon emissions
- Financial savings  $> \$100$ B
- Alleviate need for 133 new 1 GW power stations.

Estimated demand:  $\$50$ B / year (!).

Basic ideas:

UV LED encapsulated by phosphor material

RGB LEDs

Structure tailored to allow maximum light escape from material.

## Enabling technologies: nanomaterials

This, too, is fairly obvious when you think about it.

Nanostructured light/strong materials with improved performance can lead to, for example:

- engines that burn hotter and more efficiently
- cars / planes that weigh less and consume less fuel
- improved thermal properties for housing

More exotic possibilities:

- better materials for nuclear power
- superconductors for power distribution
- cheaper routes to orbit for solar power satellites

## Solar energy basics

Solar flux at Earth orbit  $\sim 1.3 \text{ kW/m}^2$ .

Useful solar flux reaching the ground:  $\sim 340 \text{ W/m}^2$ .

Projected annual energy demands of the world in 2020: 700 quads  
 $= 7.42 \times 10^{20} \text{ J} = \text{rate of } 24 \text{ TW}$ .

Therefore, at a generous 10% overall efficiency, would need  $7 \times 10^{10} \text{ m}^2$  of solar cells

That's a square 263 km on a side.

Not absurd....

## Photovoltaics

Most current solar cells are photovoltaic:

Typically made from silicon or amorphous silicon.

Typical efficiency ~ 12%.

Best efficiency ever in laboratory: ~30%.

**Theoretical maximum**, including concentrating light: 43%

Generic design: doped *pn* junction.

Photons come in and photoionize donors.

Built-in electric field at junction causes carriers to flow, building up a potential (voltage) btw the *p* and *n* sides.

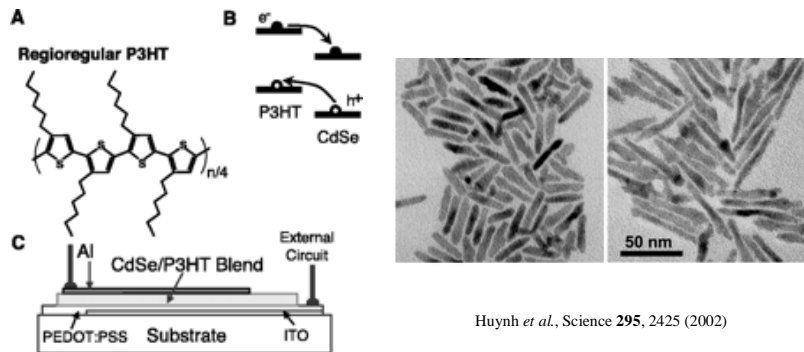
Clearly one can play with different band gap systems to arrive at materials with different absorption spectra.

Also, good mobility of charge essential for this to work well - trapping of charge or poor mobility will kill efficiency.

## Nanostructured solar cell materials

Big possibilities for improvement based on composite nanomaterials:

- Designer absorption via confinement effects
- Ability to use cheaper, flexible semiconductors (polymers), despite their worse charge transport properties.
- Less energy cost to make them! Si panels = 5 GJ/m<sup>2</sup>....



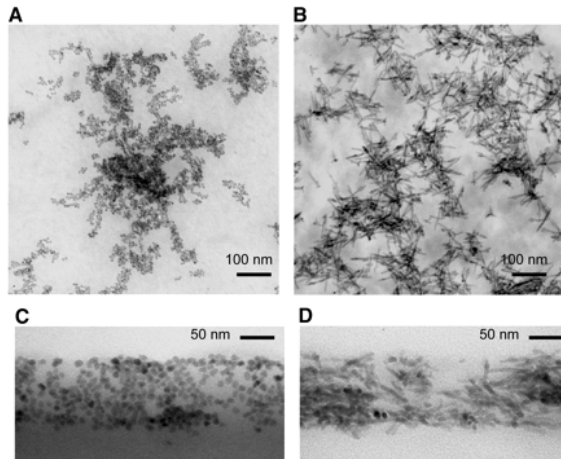
Huynh *et al.*, Science **295**, 2425 (2002)

## Nanostructured solar cell materials

Huynh *et al.*, Science **295**, 2425 (2002)

By blending absorbing nanoparticles into absorbing / decent mobility organic semiconductor, can produce films with equivalent quantum efficiencies of ~ 50%.

Power conversion efficiency ~ 7%, with room for improvement.



## Nanostructured solar cell materials

Nanostructuring also makes possible alternative approaches beyond traditional semiconductor-based ones:

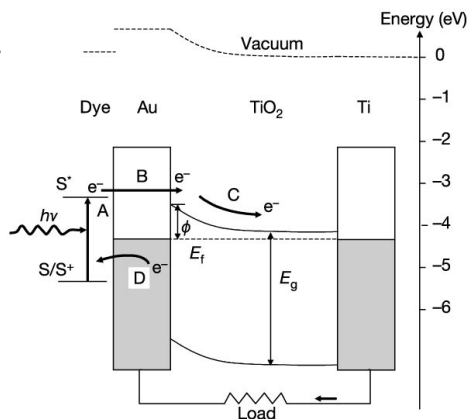
McFarland *et al.*, Nature **421**, 616 (2003)

Here authors use dye molecules designed to absorb well over the visible.

Electrons liberated in absorption are of right energies to fly ballistically (!) through ~ 50 nm Au film on top of TiO<sub>2</sub>.

Theoretical efficiency maxes out at ~ 25%.

Still, could be cheap, flexible.



## Nanostructured solar cell materials

Can we beat the maximum theoretical efficiency of 43%?

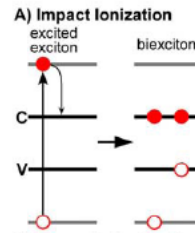
That number assumes that each photon produces a single electron-hole pair, and that any excess energy is dissipated into the phonons.

What if each photon could produce more than 1 pair?

**Impact ionization:**

Schaller and Klimov, PRL (2004) in press.

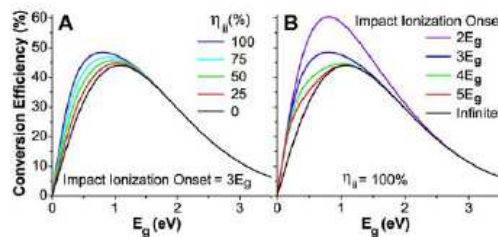
- Photon with energy  $> 2 E_G$  produces *two* excitons.
- Process is enhanced in nanocrystals b/c of easing of conservation of crystal momentum.
- Can be achieved 100% of the time under the right conditions, for photons relevant to solar energy!



## Nanostructured solar cell materials

How far can you go with Impact Ionization?

Schaller and Klimov, PRL (2004) in press.

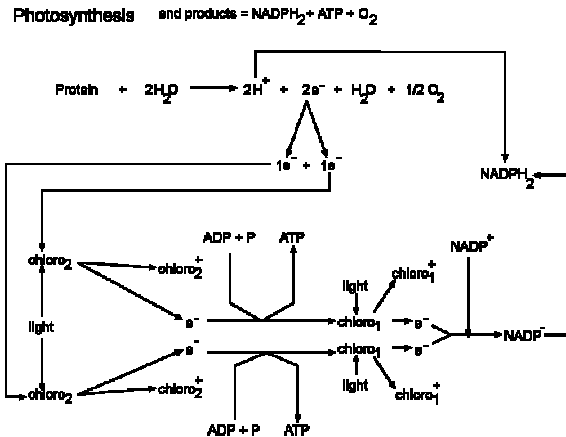


- Band gaps can be tuned by nanocrystal size (confinement).
- Effective masses are also important in determining the onset of impact ionization as a fn. of incident photon energy.
- With right choices, they predict maximum possible efficiencies of  $\sim 60\%$  using concentrated sunlight....

## Photoelectrochemical cells

Can also try to mimic certain aspects of photosynthesis.

Essentially use photogenerated electrons to perform some sort of electrochemical reaction (in this case, converting ADP+P into ATP).



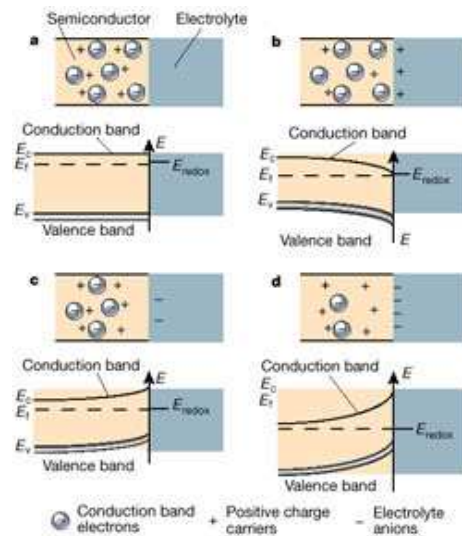
## Photoelectrochemical cells

Gratzel, Nature 414, 338 (2001)

One sensible approach is to use (possible nanostructured) semiconductor as the source of photogenerated carriers.

Must then worry about interactions and charge transfer at semiconductor-electrolyte interface.

Not very different from other heterointerfaces....





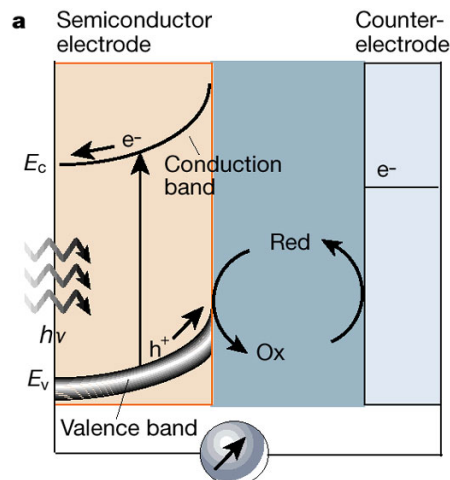
## Photoelectrochemical cells

Gratzel, Nature **414**, 338 (2001)

Here's one basic scheme.

The trick is then finding a semiconductor that adsorbs in the right part of the spectrum to maximize solar efficiency, and a compatible electrolyte for the redox side.

Best efficiencies done so far ~ 20%.



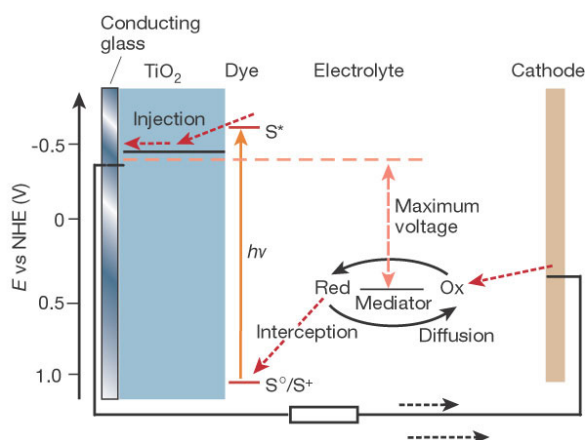
## Photoelectrochemical cells

Gratzel, Nature **414**, 338 (2001)

Alternative:

Use a dye that's a better absorber.

Now, as in the thin metal film device we'd discussed above, use the semiconductor largely as a convenient way to move charge away from the dye.



## How is this nano?

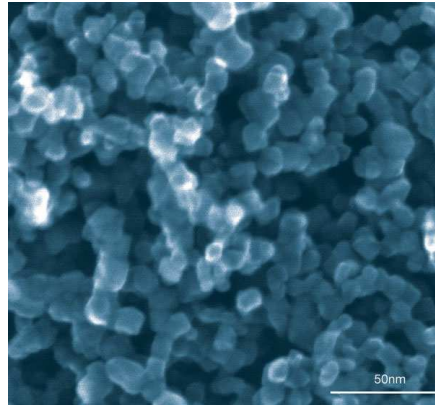
Can use nanoscale semiconductor to try to tune adsorption.

Nanoscale semiconductor also allows large surface area interface with the electrolyte and/or dye.

One popular choice: titania

Adsorbs in the UV

Easily prepared in nanostructured form.



Gratzel, Nature **414**, 338 (2001)

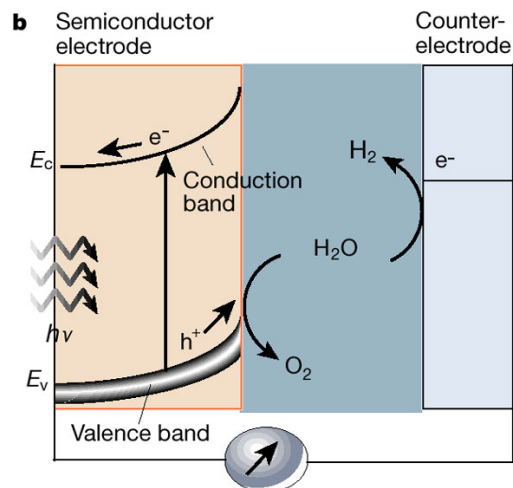
## Photocatalysis

Another very serious way that such materials could be useful:

Designer photocatalysis.

For energy production:  
Imagine efficient production of hydrogen from water via photochemistry.

“The hydrogen economy”.



## Nanocatalysis

Other applications of nanostructured catalysts could be in waste remediation.

For example:

- Photocatalysts to take CO<sub>2</sub> out of the atmosphere and sequester it elsewhere.
- Photocatalysts to treat ground water pollution.
- Special nanocatalysts to improve existing remediation technologies (catalytic converters).

## Summary

Several roles for nanostructured materials and technology in addressing the very serious looming energy needs of the world's population.

- Enabling technologies
- Improved efficiency
- Improved energy generation
- Improved waste remediation

This is a very important problem!!

## Personal opinions

- “Hydrogen” is not a solution to the energy problem, and it’s not even a terribly good fuel.
- Nuclear power has to play an important role.
- Improved energy *storage* can have at least as big an impact as improved power generation – batteries, supercapacitors.
- Improved energy *transmission* is also important – room temperature superconductors with high critical currents and fields?
- China and India will burn lots of fossil fuels.

## Nanostructures and nanotechnology: wrap-up

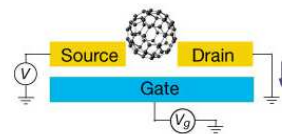
- The highlights
- A realistic assessment of the future of nanotechnology
- “Molecular nanotechnology”?
- Dangers, sensible and otherwise

## The highlights

- Electronic, structural, and thermodynamic properties can differ greatly from bulk when the materials are structured on the nanometer scale!
- This means that the physics underlying current technologies may no longer work after further miniaturization.
- However, new properties of nanoscale systems can be useful, and permit new or improved technologies.

### Electronic properties:

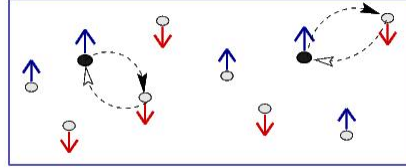
- New physics relevant at nanometer scale: quantum coherence, quantum confinement, tunneling, electron-electron interactions.
- Possible new technologies: single electron transistors, molecular electronics, optoelectronic devices



## The highlights (con't)

### Magnetic materials:

- Newly relevant physics: superparamagnetism, single domain reversal, coherent spin manipulation
- Possible new technologies: new magnetic media, spintronics, quantum computation



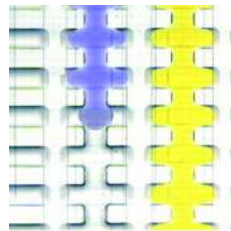
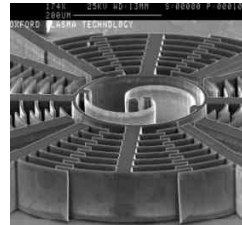
### Photonics:

- Newly relevant physics: confinement effects on carriers in optoelectronic devices, photonic band gaps, negative index metamaterials, near field.
- Possible new technologies: optical switching and computation, sub-diffraction optical probes, new spectroscopies.

## The highlights (con't)

### Micro- and nanomechanical systems:

- Newly relevant physics: quantum effects in mechanical systems, fundamental origins of dissipation and friction
- Possible new technologies: new sensors and transducers, new coatings and materials



### Micro/nanofluidics and bionanotechnology:

- Newly relevant physics: limits of fluid mechanics, role of surfaces in solutions
- Possible new technologies: new enabling technologies for biology, chemistry, materials science

## Realistic assessment

Where is nanoscale science and technology going?

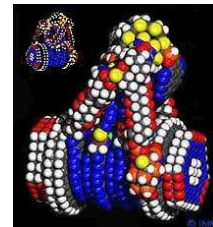
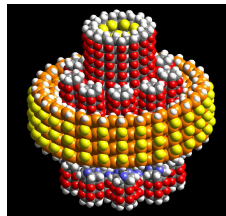
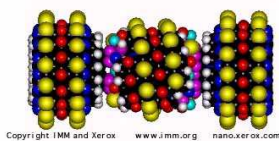
Is it really going to change the world in a revolutionary way, or is it going to be an evolutionary effect?

That is, is nanotechnology a “disruptive technology” (like the wheel, the printing press, the transistor)?

My personal bet: there is a significant chance (30%) that our recently developed capabilities for controllably modifying matter on the molecular scale will be a disruptive technology on the timescale of 100 years.

However, there are huge economic barriers at work here to commercialization!

## Is **molecular nanotechnology** even possible?



Molecular nanotechnology: idea that we'll be able to assemble structures an atom or molecule at a time using nanoscale machines, possible self-reproducing (von Neumann) devices.

Examples of this vision: K. Eric Drexler's *Engines of Creation*; Neil Stephenson's *The Diamond Age*.

My personal view: no, not as such. The route to self-reproducing engineered systems is biology. Also, just because a structure may be stable does not imply that it can be made....

## Dangers lurking at the nanoscale

There are groups (*e.g.* the ETC group) who want a complete moratorium on nanoscale research while risks are assessed, because they fear major dangers (unintended consequences) of nanotechnology.

Two hazards:

- Environmental toxicity

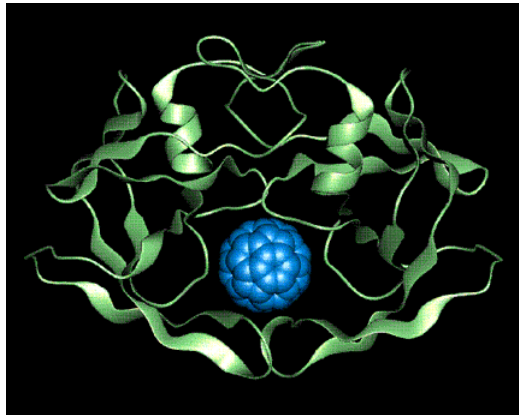
The example: asbestos.

Nanoscale particles can interact very differently with biological systems than larger particles.

Can slip through cell pores and capillaries; can interact in complicated ways with biological molecules.

## Biological interactions

Univ. of Wisconsin



C60 molecule is right size and shape to interfere with functioning of HIV-I protease - an enzyme necessary for the spread of HIV.



## Biological interactions

Is this a realistic concern? Sure, within reason:

- We're already exposed, every day, to particles on these scales at some concentration.
- Some work needs to be done, doubtless, to assess the hazards of nanostructured materials while research and development proceeds.
- It is certain that some nanomaterials will be harmful. It is also certain that some nanomaterials will be beneficial.
- We now know much more about testing and toxicology than ever before - we should be able to avoid first order mistakes (like black lung disease or exposing pregnant women to large concentrations of semiconductor solvents).
- Many materials that you use every day are processed with hazardous chemicals and techniques.

## Biological interactions

Concerns of scientists:

- Wild, unsupported overreaction (GM foods example)
- Crushing regulation that would stifle totally reasonable research, put forward without real facts to back it.

Note that CBEN is already doing research to determine the environmental impacts of nanotechnology....

## The “gray goo” problem

Worry that self-reproducing nanomachines will run amok, eating raw materials around them and reducing the entire world to “gray goo”.

Is this a realistic concern?

In my opinion, no, though with a qualification.

- Self-reproducing nanomachines are not going to happen any time soon.
- Much more likely would be some sort of plague due to modified virii or bacteria.
- Of course, gray goo has already been demonstrated to be a threat to global ecology - us.

## The “gray goo” problem

Researchers seek to create a living cell

SHARON BEGLEY, The Wall Street Journal

Friday, April 2, 2004

That approach doesn't raise any eyebrows when applied to gizmos and gadgets, but now a loosely organized band of scientists is extending it in an audacious way. In hopes of answering the age-old question "what is life?" they are trying to assemble -- from off-the-shelf, nonliving molecules -- a living cell.

"Creating a cell from scratch is probably at least 10 years away, but it is going to happen," says Mark Bedau of Reed College, Portland, Ore. "We're in for some very interesting, very profound new ways of thinking about what life is, and about where you draw the boundary between life and nonlife."

## Molecular nanotechnology

In short, never say “never”, but I’m not losing any sleep over it.

On the other hand, the electron was only discovered in 1897.

The neutron was only discovered in 1932.

DNA was only (sort of) understood in 1953.

People are exceedingly creative, and nature is even moreso....