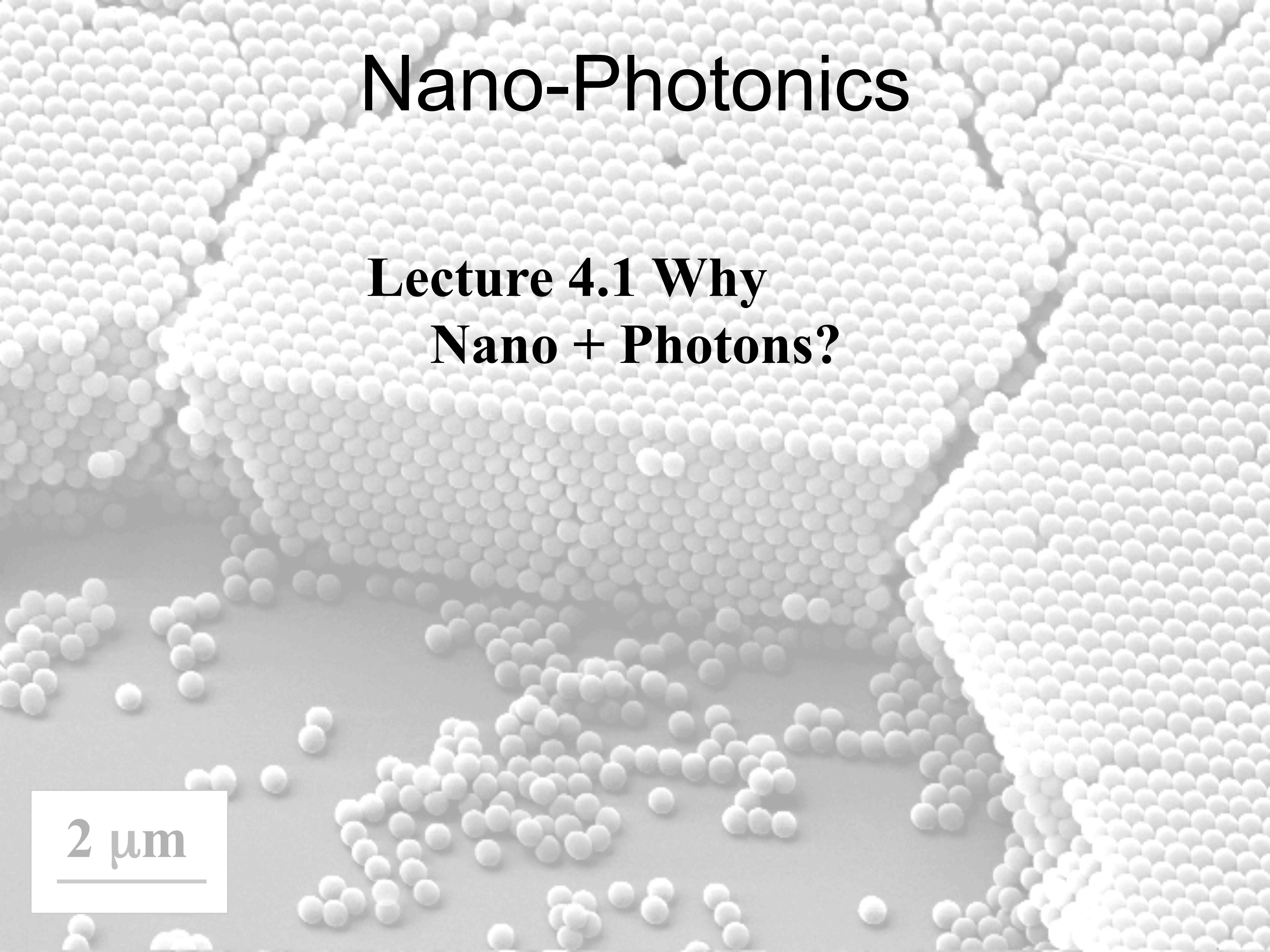
Nano-Photonics

Lecture 4.1 Why Nano + Photons?



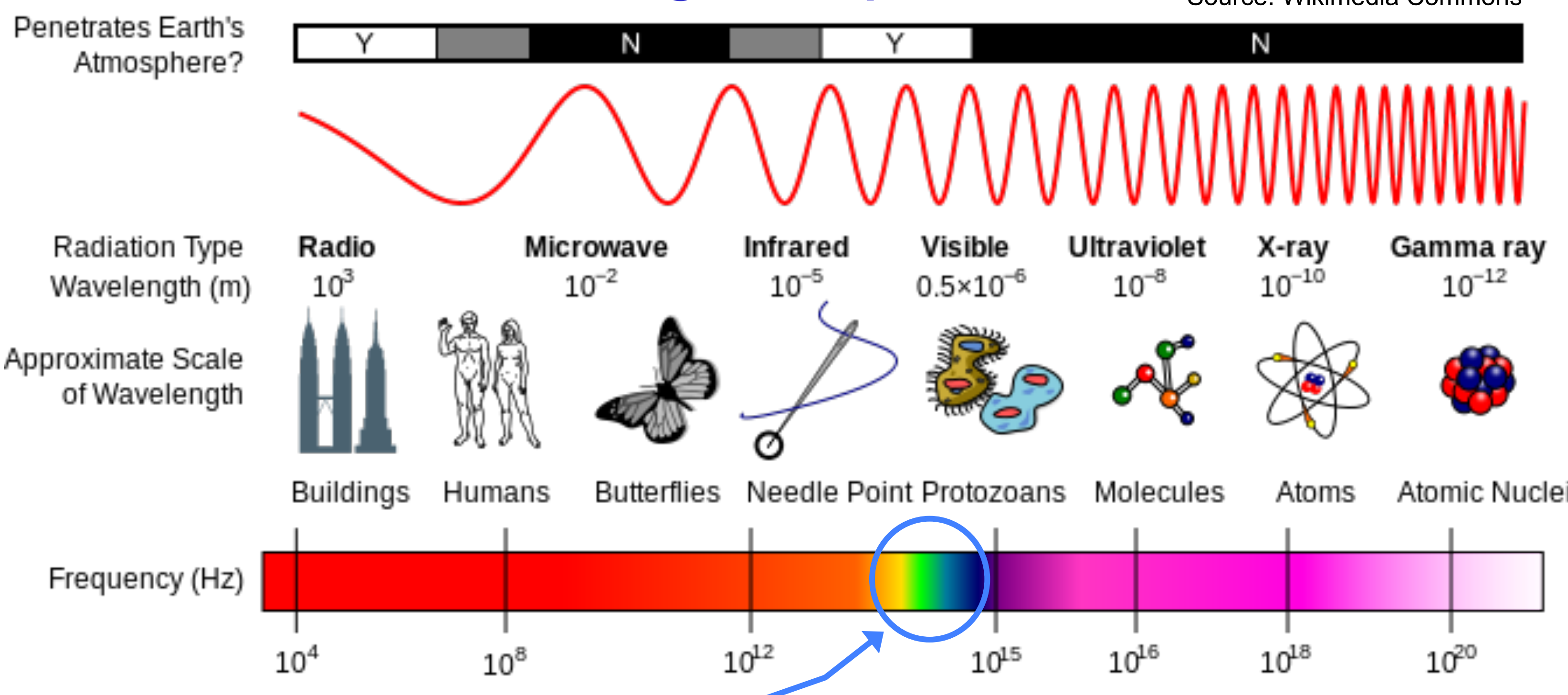
Start with a good question

What does light have to do with nano-objects?

Light is characterized by its **wavelength** - a fundamental length scale

The Electromagnetic Spectrum

Source: Wikimedia Commons



Visible light is here. Its wavelength is between 400 and 700 nm.

λ is small, but nanomaterials are smaller

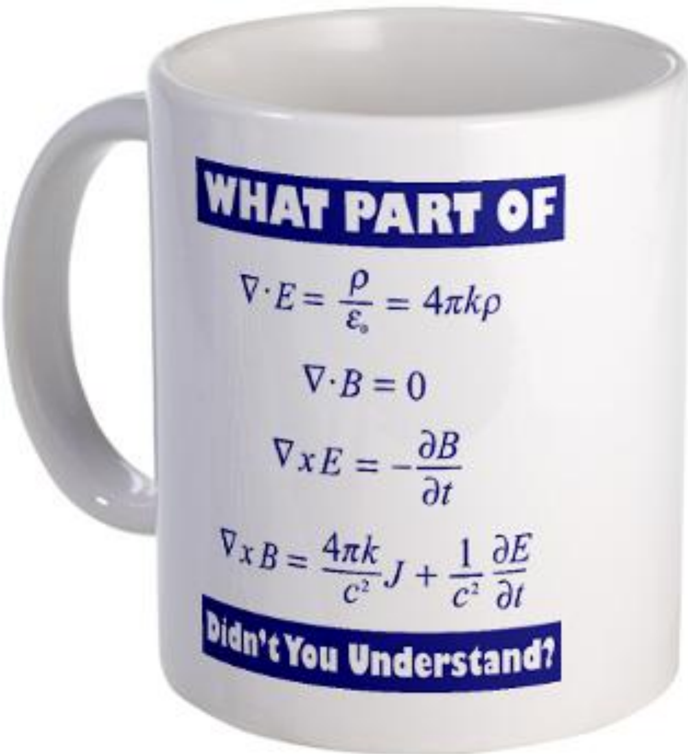
the size of a one-nanometer object, in comparison to the wavelength of visible light:

1 nm

500 nm

This big size mismatch seems to suggest that light might be irrelevant for nanoscience…

The properties of light are governed by Maxwell's equations

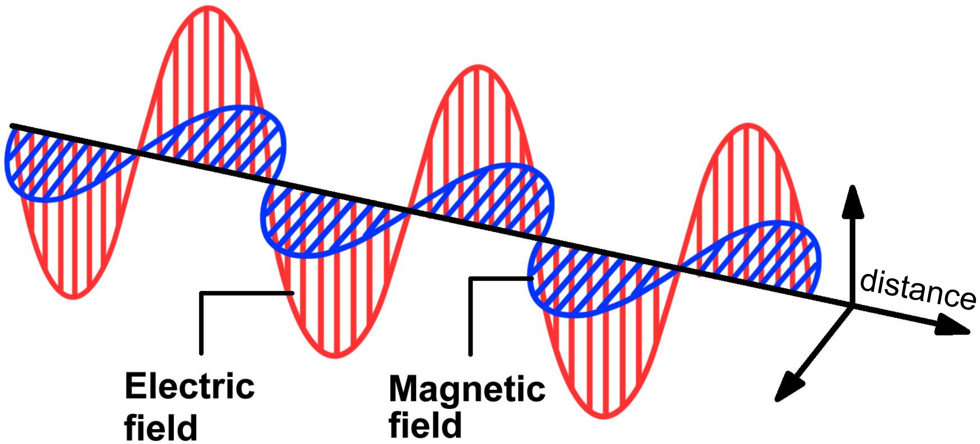


Fortunately, we won't have to deal with them.

http://www.cafepress.com
Image used with permission

Some definitions: how do we talk about light?

Light: electromagnetic radiation. Light is a wave. Actually, two waves propagating together:



University of Denver, www.du.edu

wavelength = λ (lambda)

400 nm - 700 nm for visible light

infrared: larger λ

ultraviolet: smaller λ

frequency = ν (nu)

$\lambda \times \nu = c$, which is the speed of the wave

Light waves in empty space: $c \approx 3 \times 10^8$ m/sec

No object or signal can ever travel faster than that.

Some definitions: how do we talk about light?

Source: Wikimedia Commons

The energy in a light wave:

The energy of a single photon (the smallest indivisible quanta of a light wave): $E_{photon} = h\nu$

h = Planck's constant, a fundamental constant

larger frequency ν = smaller wavelength λ = higher photon energy

The intensity* of a light wave:

Intensity is total energy per unit area per second.

Units: joules / sec m^2 = Watts / m^2

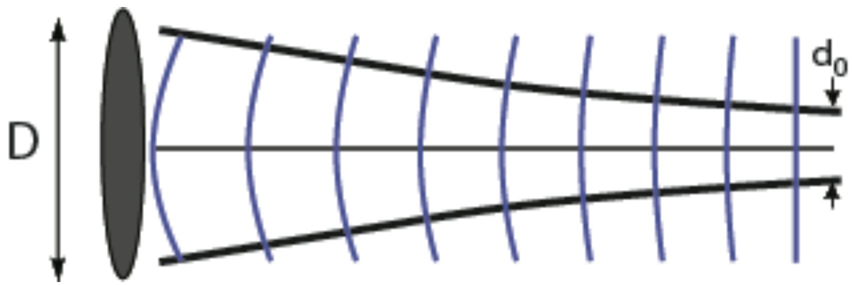
Examples:

- a laser pointer: 1 kW/m^2
- direct sunlight (at zenith): 1 kW/m^2, about half of which is visible light
- most powerful lasers: ~10^{20} W/m^2

*more properly called the "irradiance"

What about focusing light?

Can we focus light down to a nano-spot?



Focus a laser beam with a lens of diameter D and focal length f.

$$d_0 = \frac{2 f \lambda}{D} = 2(f\#)\lambda$$

How big is the focal spot?

This is the diffraction limit. Practically speaking, $f\# < ½$ is very difficult, so d_0 is never much smaller than the wavelength!

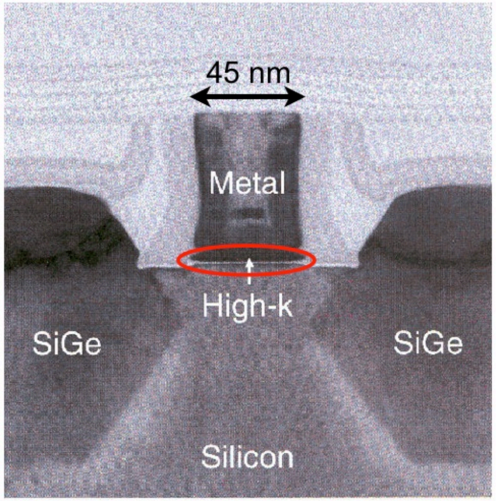
Diffraction is a general property of any wave, including light waves.

This limit is why you can use an optical microscope to look at cells (which are larger than λ) but you can't use one to see nano-objects (which are smaller).

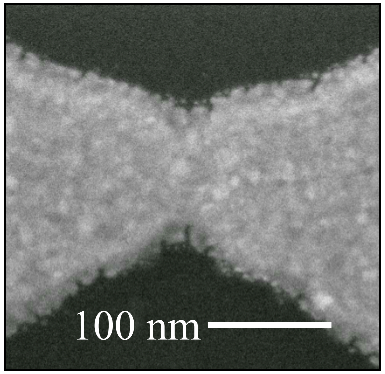
An aside: images you've seen

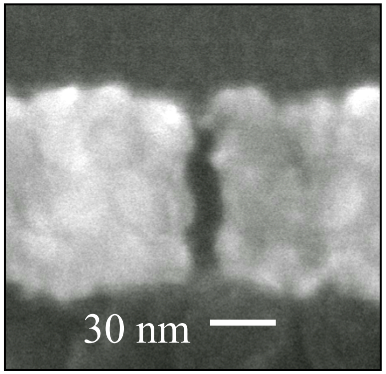
These images, and others like them from Week 2 lectures, were <u>not</u> made in an optical microscope. Now you know why.

Doug Natelson, Rice University
http://www.ruf.rice.edu/~natelson/group.html

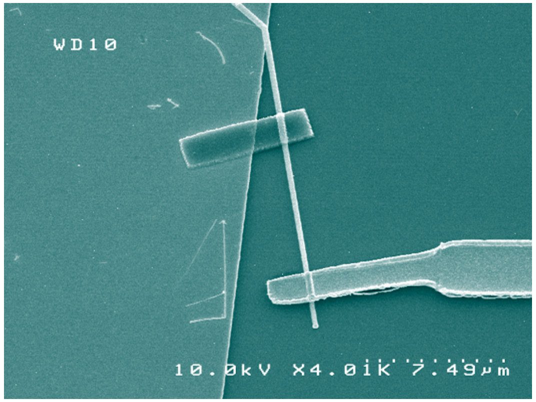


Sohrab Ismail-Beigi, Yale University
http://volga.eng.yale.edu





$$d_0 = \frac{2f\lambda}{D} = 2(f\#)\lambda$$

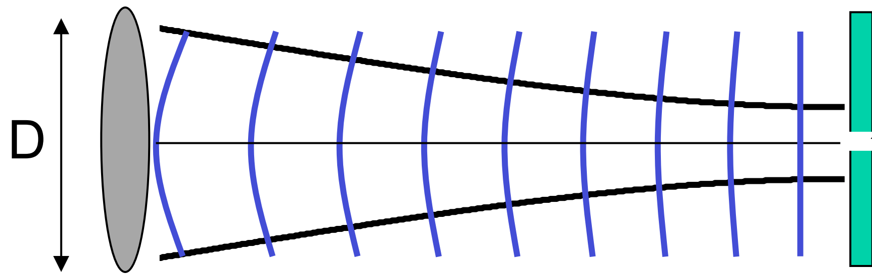


Pengyu Fan, Stanford University
http://www.stanford.edu/~fanpy839/publication.html

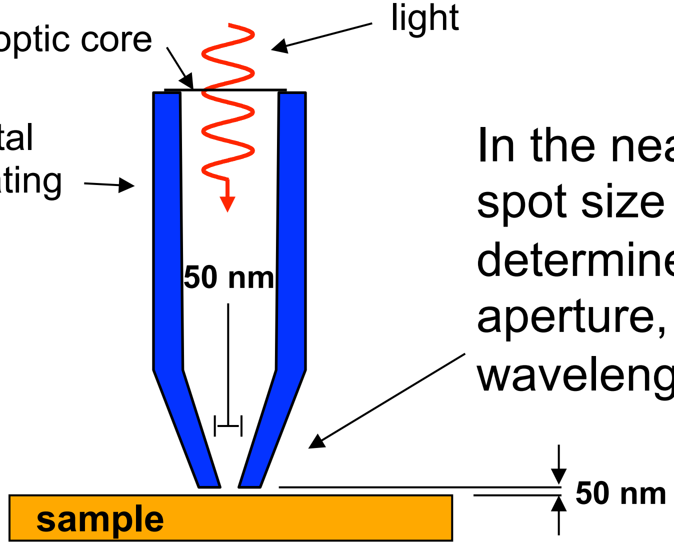
Electron microscopes use electrons instead of photons to create images. The effective wavelength of an electron wave can be *much* smaller than the wavelength of visible light.

What if we use a small hole?

Light doesn't transmit well through sub-wavelength-sized holes, but some things are still possible.

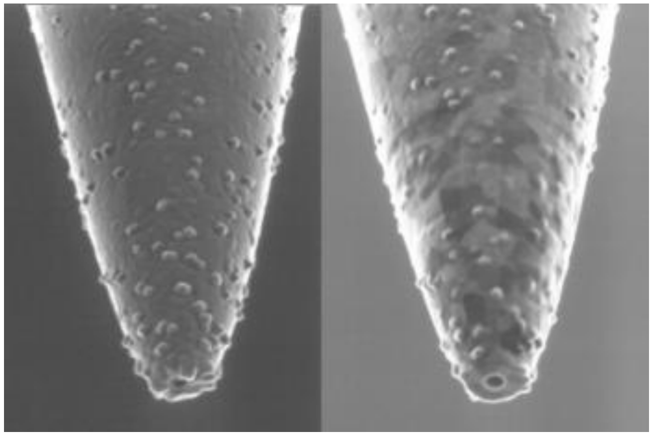


More often, the input light is delivered via a tapered fiber:



In the near field, the spot size is determined by the aperture, not the wavelength!

tapered fibers:

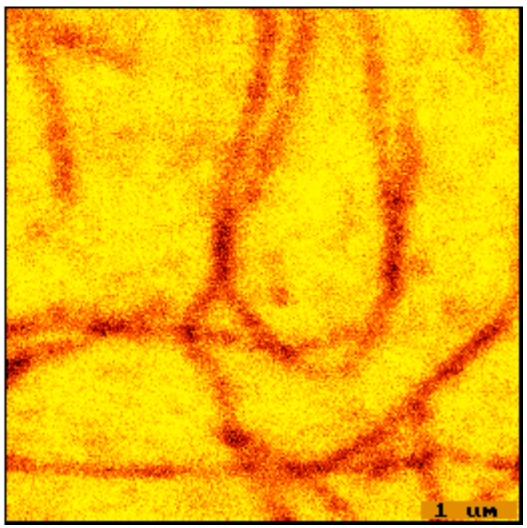


Robert Dunn, University of Kansas, http://www2.chem.ku.edu/rdunngroup/

NSOM

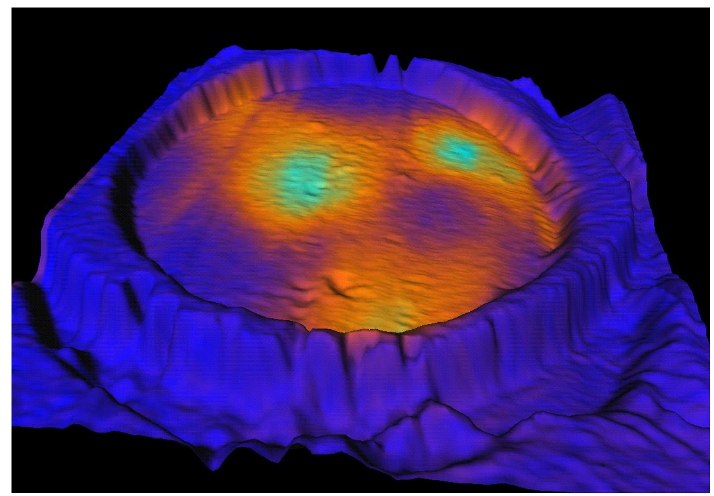
This technique is known as NSOM:
"near field scanning optical microscopy"

Fluorescence from individual actin molecules. Resolution is about 200 nm.



University of Michigan,
http://www.umich.edu/~protein/NSOM/Spectroscopy.html

A combination topographic and NSOM image of laser emission from a vertical-cavity laser. Resolution: about 100 nm.



Bennett Goldberg, Boston University,
http://ultra.bu.edu/

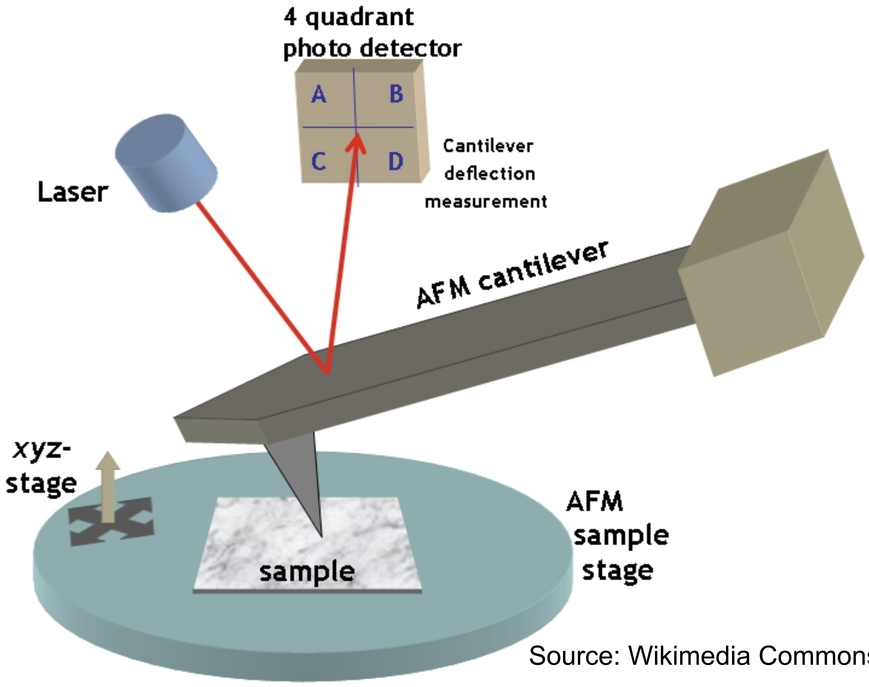
Best NSOM resolution reported: about $\lambda/30$

So what else is interesting about nano + photons?

Idea #1: sensing using light to transduce the signals.

We have seen one example of this already:

The motion of a nanostructured object can be detected using a laser, plus a position-sensitive detector. This can be done with nanometer precision.



Source: Wikimedia Commons

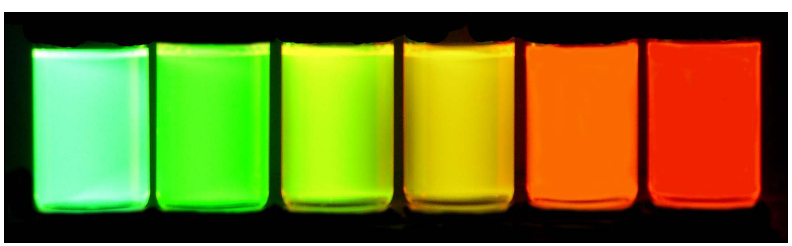
Idea #2: Optical properties of nanomaterials

The important idea: when you make a material small, its optical properties can change.

We've seen an example of this before, too:

3 nm CdSe nanoparticles

6 nm CdSe nanoparticles



Quantum confinement: the squeezing of electrons in a semiconductor causes their energy to go up, like shortening a violin string.

Idea #3: Optical properties of nanostructured materials

The important idea: when you structure a material on the nanoscale, it can interact with light in different ways, *even if the intrinsic material properties are completely unchanged*.

Thought experiment: Imagine looking through a window pane.

Now, imagine that we replace the window glass with a piece of glass that is thinner.

Does the view out the window change?

What if the glass is only 200 nanometers thick?

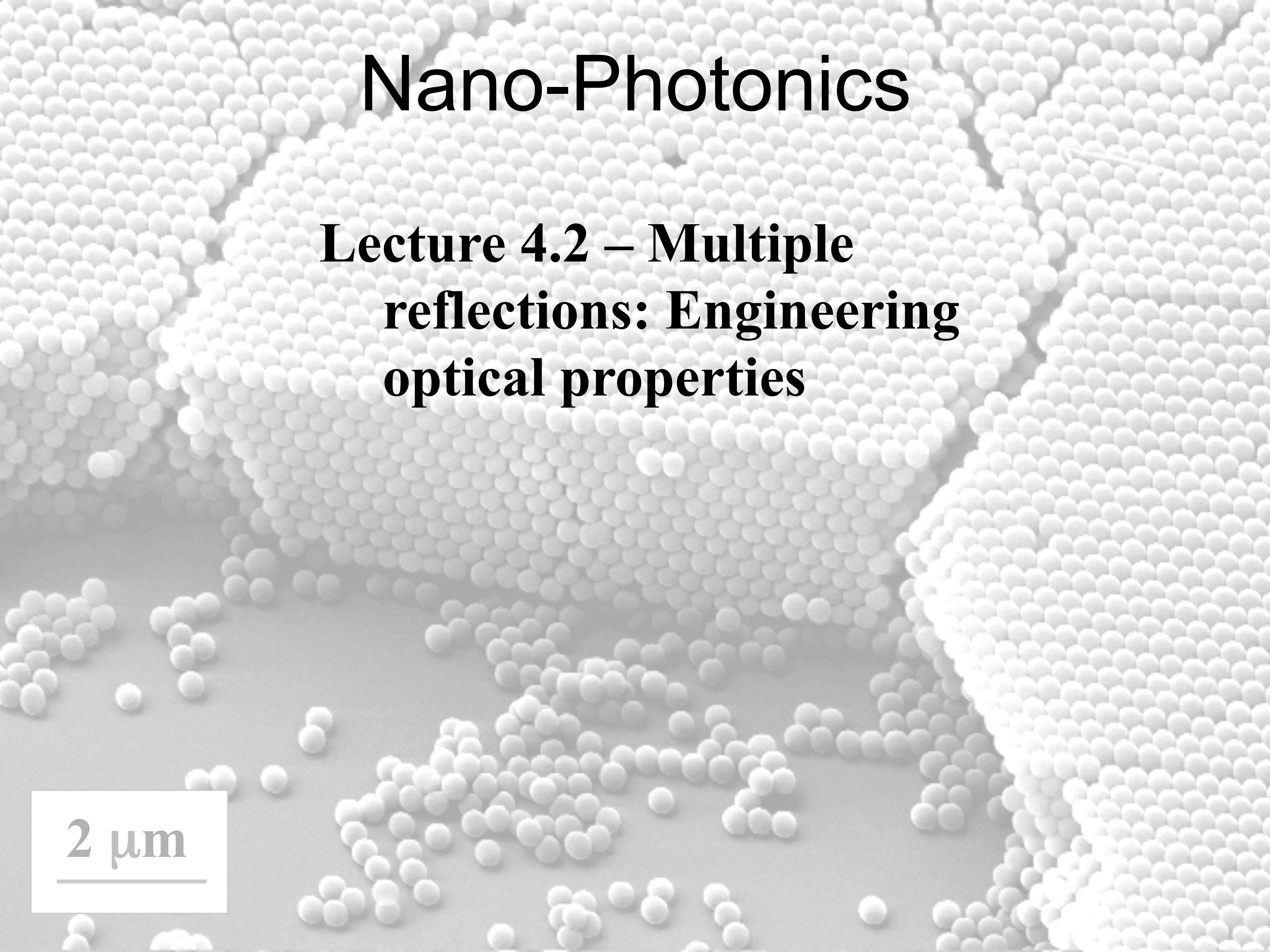
the view out of my office window, which is not nano-glass.

The ideas

- Light waves have a characteristic length scale, λ, which is much larger than a nanometer.
- But the interaction of light with nano is still important:
  - nano-enabled sensing is often transduced with light
  - nanomaterials have unique and size-dependent optical properties
  - nanostructured materials have unique and structure-dependent optical properties

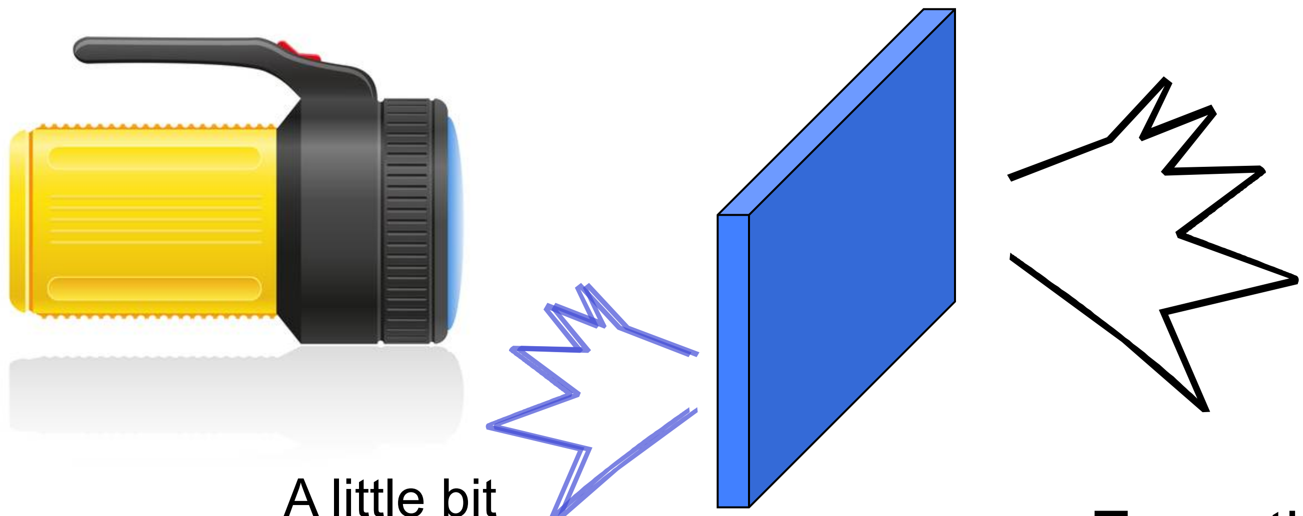
Nano-Photonics

Lecture 4.2 – Multiple reflections: Engineering optical properties



Here's a thought experiment

Suppose we shine white light on a slab of window glass:



Most of the light transmits through.

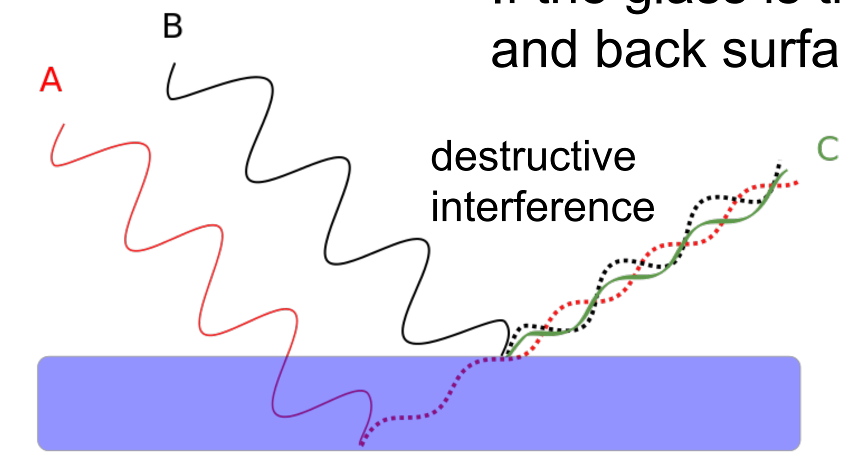
A little bit reflects back.

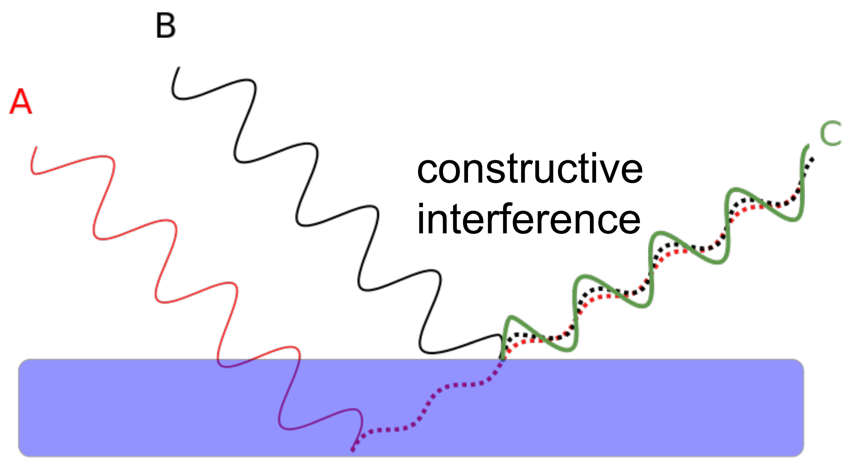
This is really two reflections, one from the front surface and one from the back.

→ Essentially the same behavior for all visible wavelengths.

If the glass is thin, how do things change?

If the glass is thin, then the reflections from the front and back surfaces can interfere with each other.





This is different for different wavelengths and angles. It is why soap bubbles have shimmering rainbow colors.

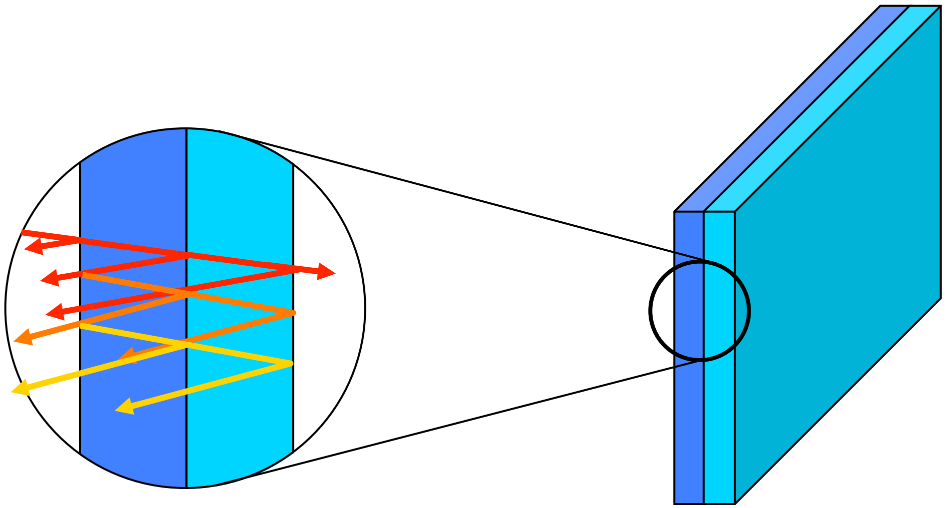
Source: Wikimedia Commons

Add a second layer

Now, let's add a 2^{nd} layer, of a different type of glass.

Now, three different reflected rays

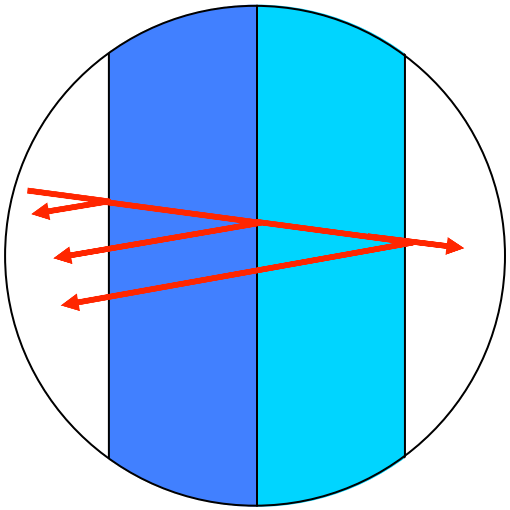
…or more…

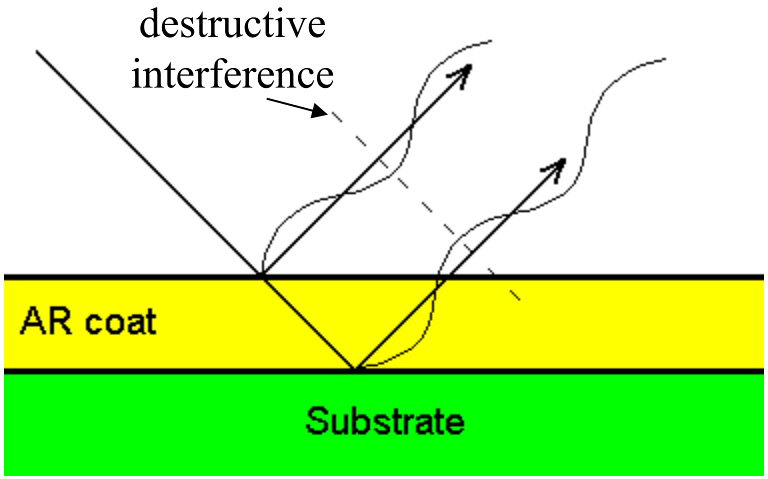


There is actually an infinite number of reflections which add up (superpose) to give the total.

Anti-reflection coatings

If we choose the layer thicknesses correctly, we might find that each reflection destructively interferes with the next one.

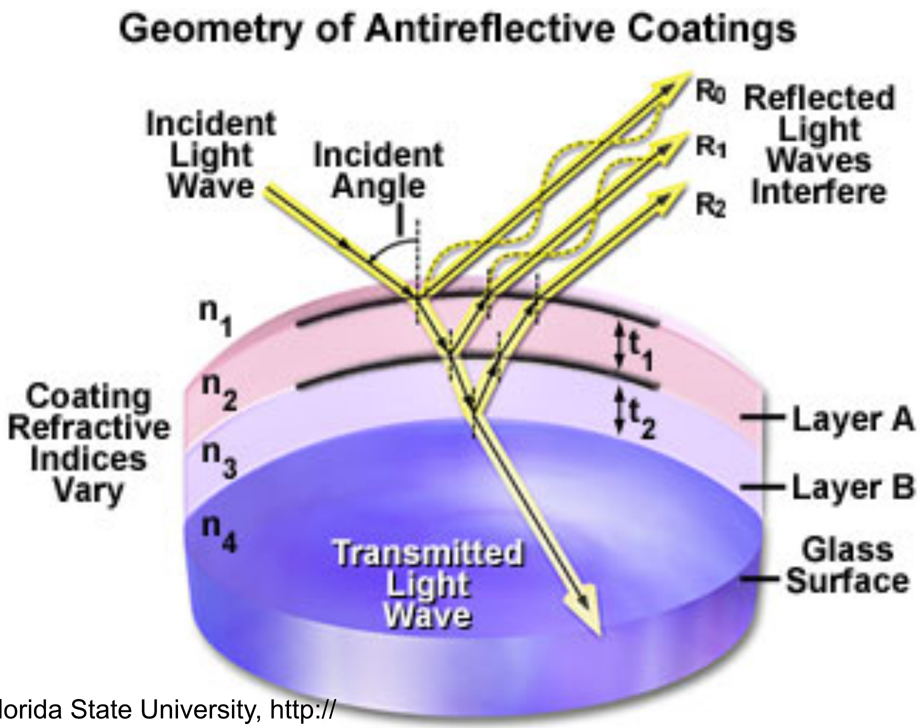




This requires that the top layer have a thickness of $\lambda/4$.

Of course, it only works for one particular value of λ.

Anti-reflection for many wavelengths



Florida State University, http://micro.magnet.fsu.edu

To extend the performance over a range of wavelengths, multiple layers are required.

The key parameters are the thickness and 'refractive index' n of each layer.

The refractive index of a material is: $\dfrac{\text{speed of light in empty space}}{\text{speed of light in the material}}$

In real materials, it is always greater than 1.

These coatings are widely used

no coating coating

http://research.che.tamu.edu

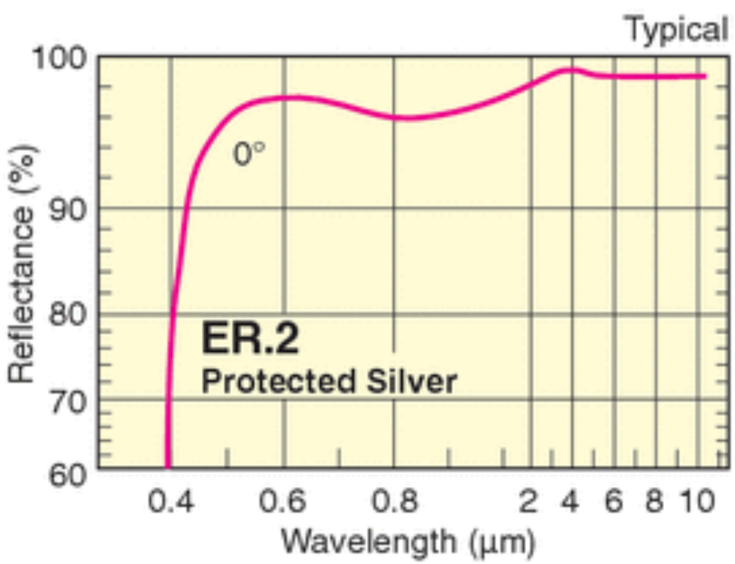
coating no coating

http://www.phys.uconn.edu/~gibson/Notes/Section5_3/Sec5_3.htm

Multilayers are the world's best mirrors

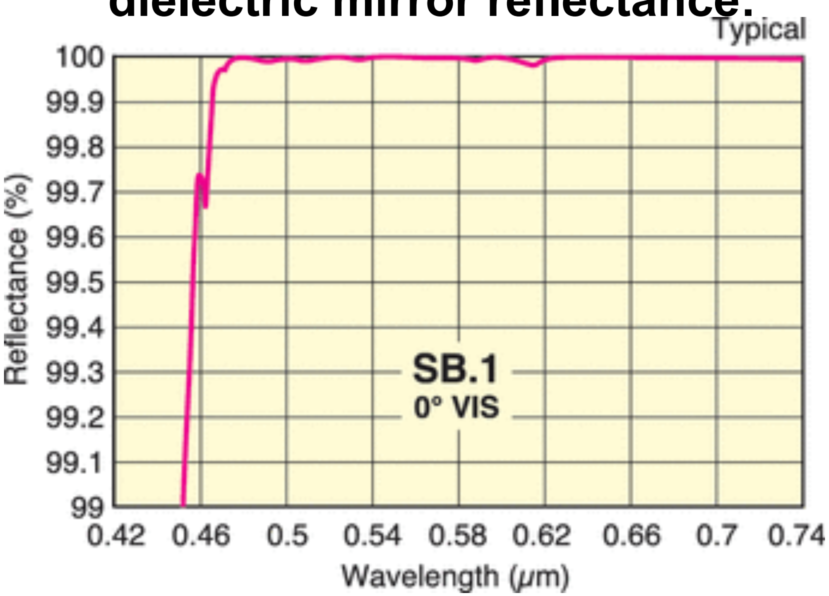
Multiple layers can be used to make dielectric mirrors that are better than the best polished metal surface. But they usually work over a smaller range of wavelengths.

metal mirror reflectance:



1 inch mirror: $140

dielectric mirror reflectance:



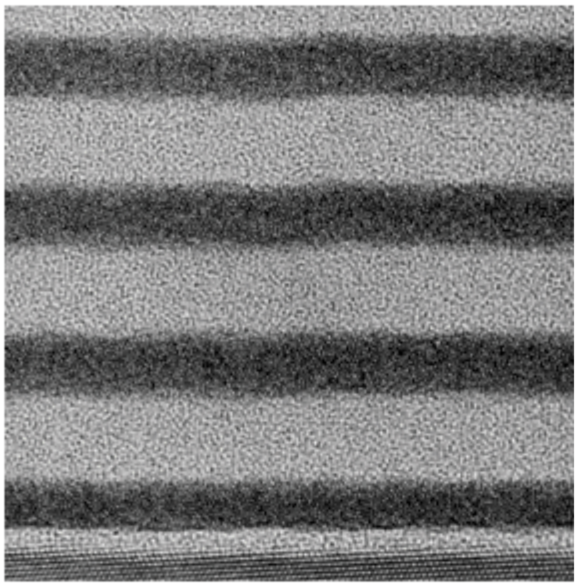
1 inch mirror: $545

This is the only way to make mirrors for x-rays

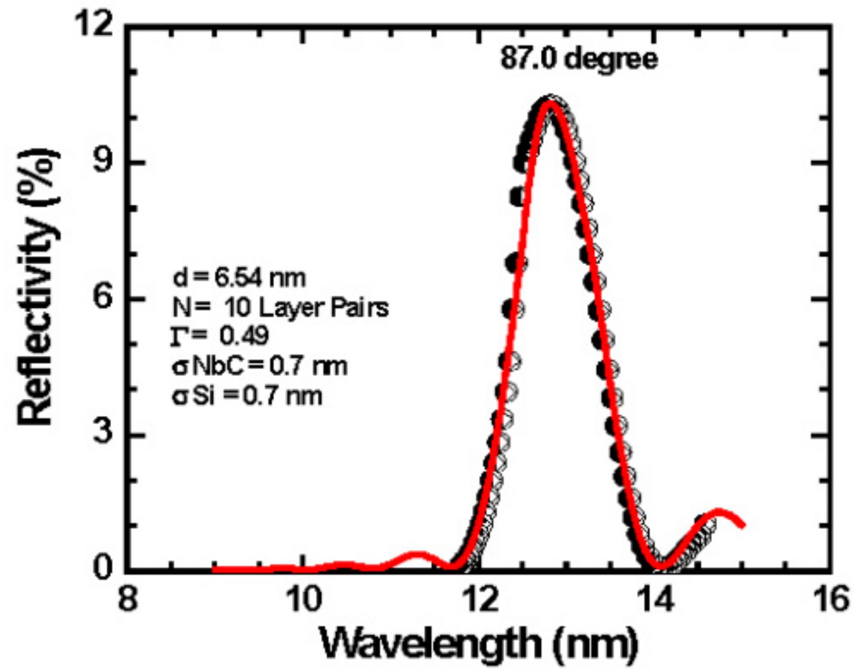
In the x-ray region of the spectrum, multilayer coatings are the only option.

https://www.llnl.gov/str/Troy.html

about 10 nm



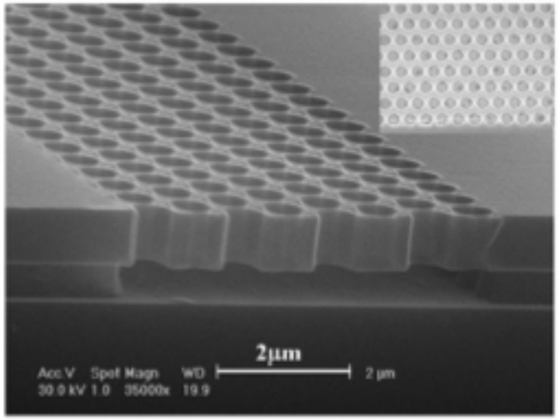
Transmission electron micrograph of a cross-section of a multilayer mirror for x-ray optics. The layers are silicon (lighter stripes) and molybdenum carbide (darker stripes).

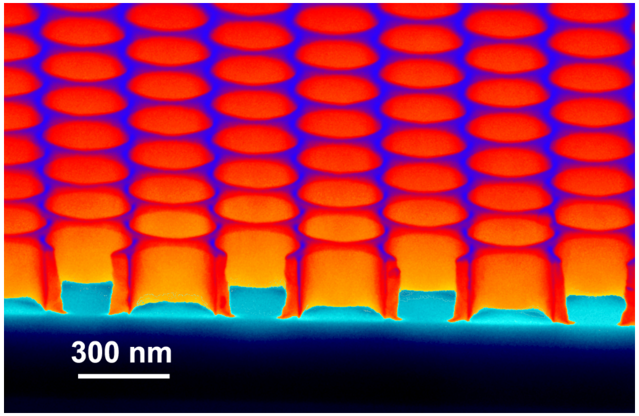


M. Modi, S. Rai, M. Idir, F. Schaefers, and G. Lodha, "NbC/Si multilayer mirror for next generation EUV light sources," Opt. Express 20, 15114-15120 (2012)

If 1D structuring is good, how about 2D structuring?

We can make a material that has a two-dimensional variation in the refractive index, by (for example) drilling an array of holes in a slab:



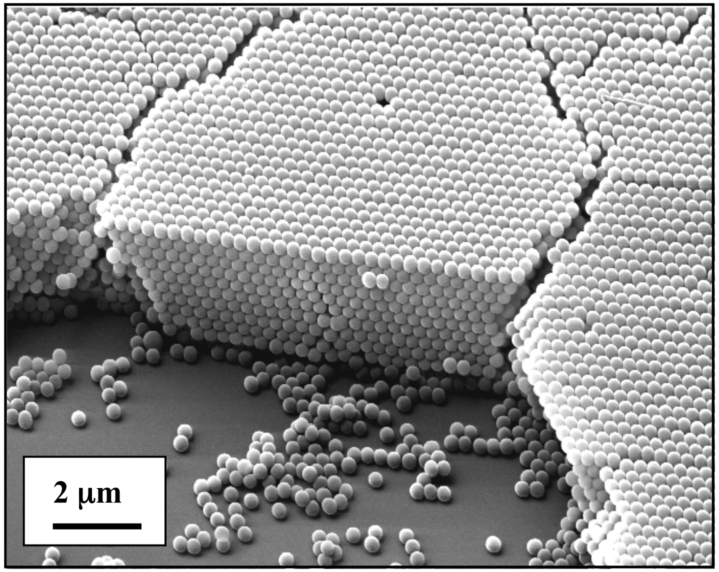


http://phys.org/news7839.html

Any light ray propagating in the plane of the slab sees a periodic spatial variation of the refractive index. This can give rise to perfect reflection in the plane.

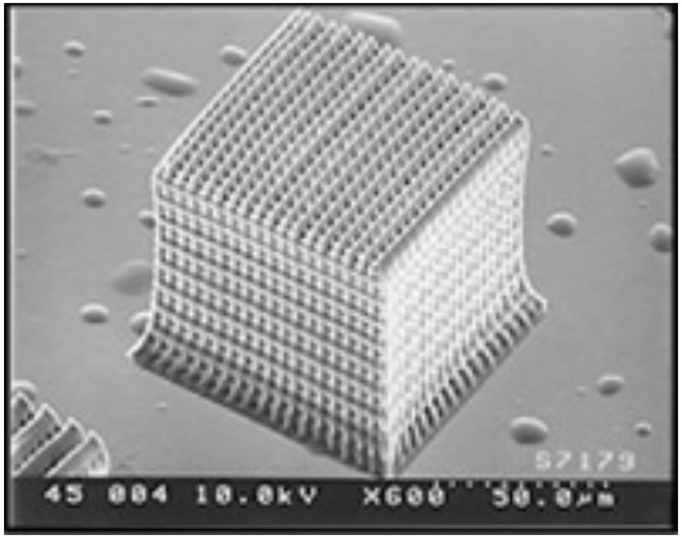
Or how about 3D?

Periodic arrangements in 3D are also possible, although harder to fabricate.



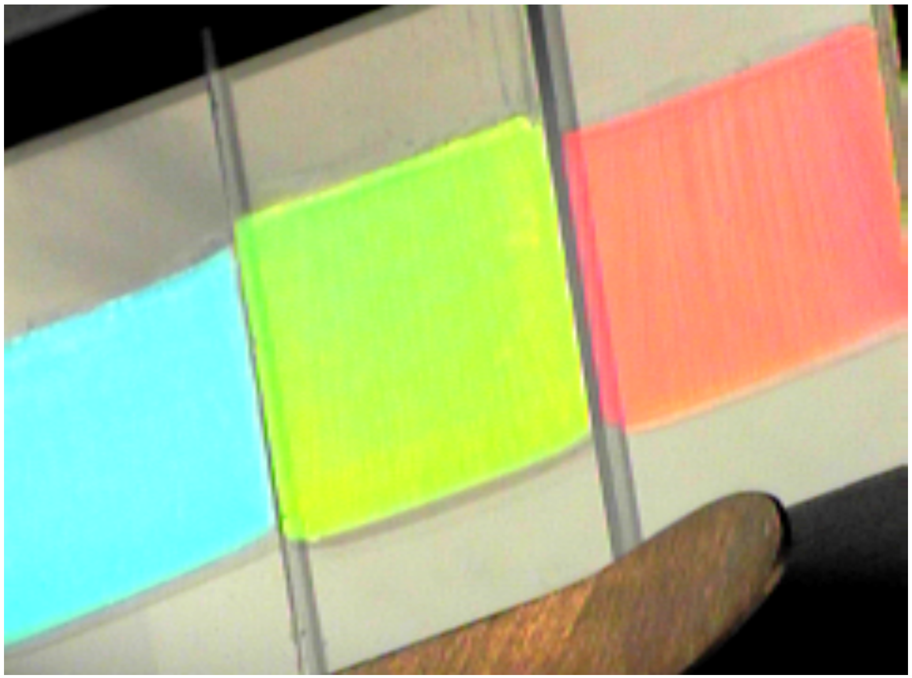
Colvin group, Rice University

These are known as “photonic crystals”.



http://www.cope.gatech.edu/research/

Dramatic reflection effect



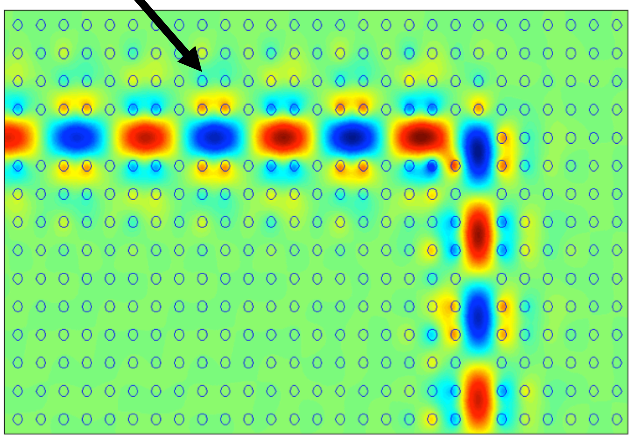
Colvin group, Rice University

Distinct colors arise because of the size of the spheres used to assemble the photonic crystal.

This is also why butterflies are colorful.

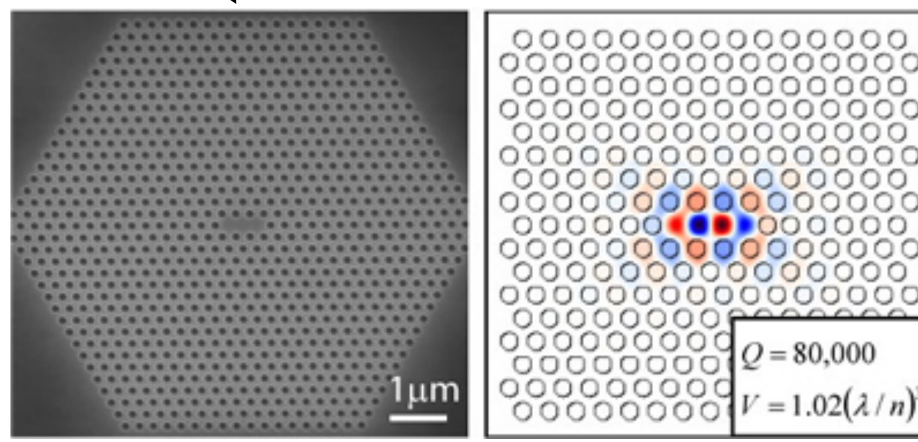
These ideas enable many new photonic devices

a waveguide with a sharp bend



Jaime Peraire & Joel Saa-Seoane,
Massachusetts Institute of Technology
http://web.mit.edu/jsaa/www/research.html

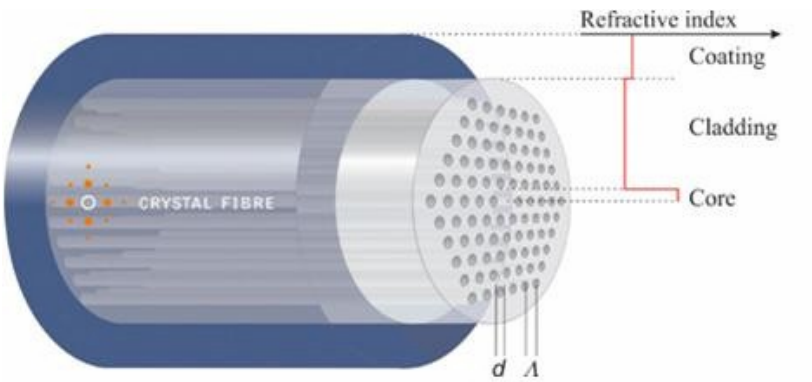
a resonant microcavity



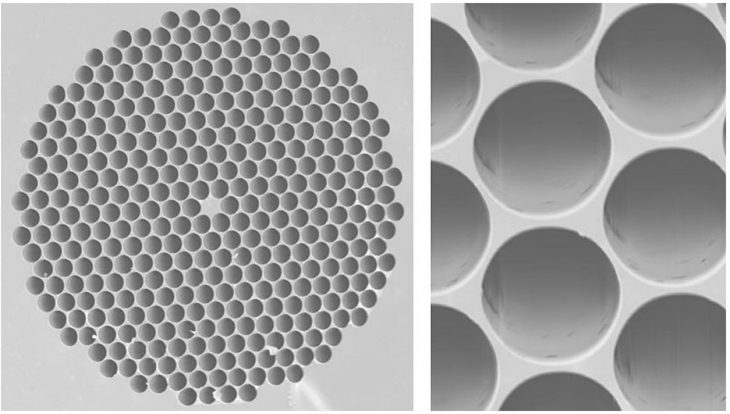
Edo Waks, University of Maryland
http://www.ireap.umd.edu/NanoPhotonics/PCdevices.html

Another important application: holey fibers

Optical fiber with holes running along the length – a whole new way of guiding light.



Azer Yalin, Colorado State University
http://www.engr.colostate.edu/lpdl/research/fiber/fiber.html



Source: Wikimedia Commons

Such fibers can have many advantages:

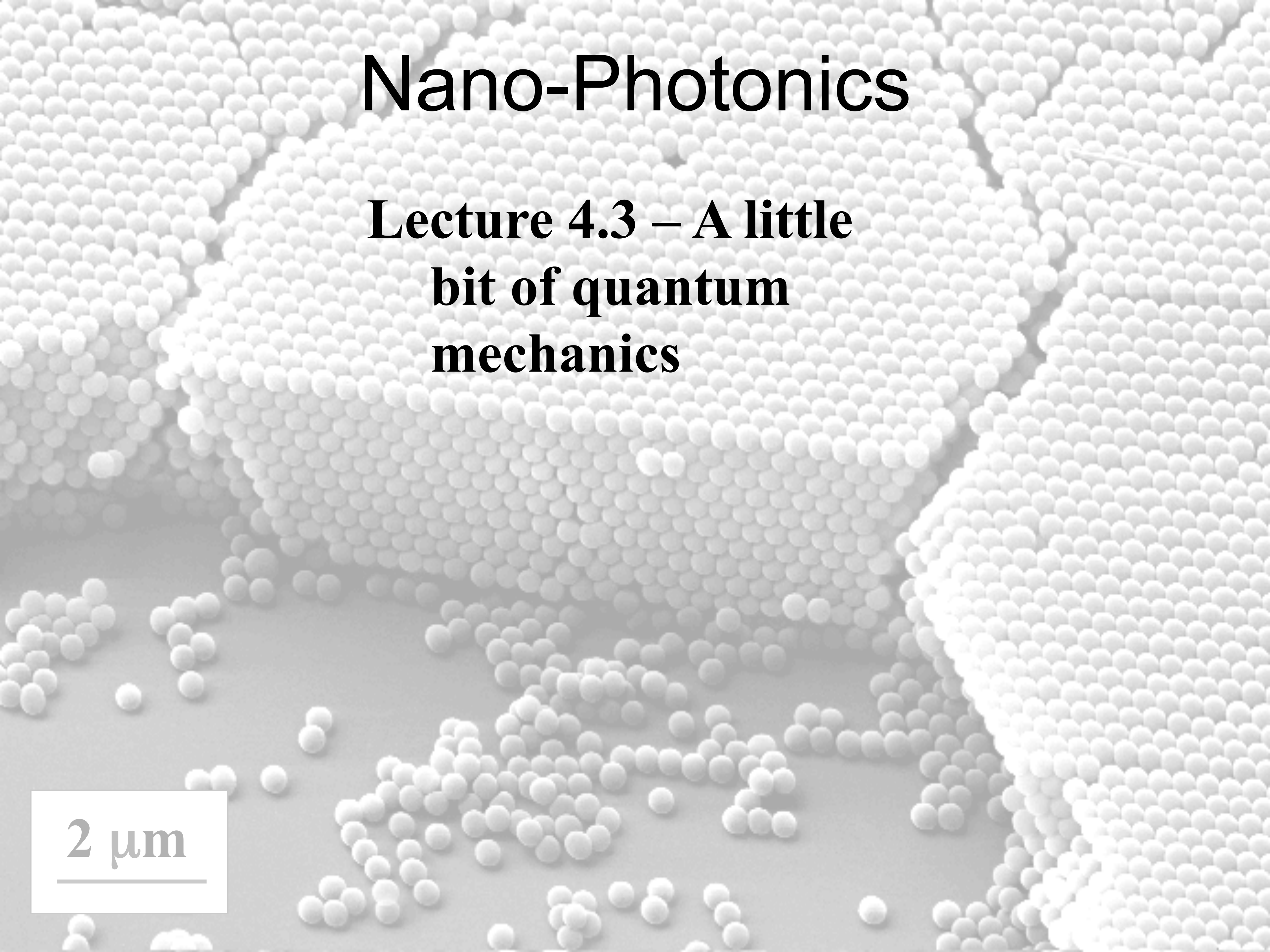
- low bend loss
- high power handling
- controllable dispersion
- controllable nonlinearity
- endlessly single mode
- air guiding
- air cladding

The ideas

- Light waves reflect off of interfaces.
- By structuring the shape, size, and materials appropriately, we can engineer reflections so that they vanish, or so that they are perfect.
- This can be done in 1D, 2D, or 3D: “photonic crystals”
- Nature does it too!

Nano-Photonics

Lecture 4.3 – A little bit of quantum mechanics

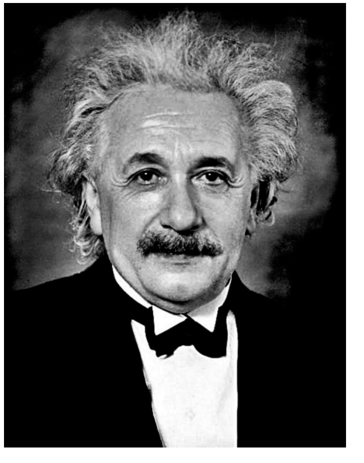


Nanotechnology: quantum confinement

We have seen that the color of the light emitted by semiconductor nanoparticles depends on their size. This idea, called quantum confinement, has profound implications.

In order to discuss this, we need to know something about quantum mechanics.

But not too much.

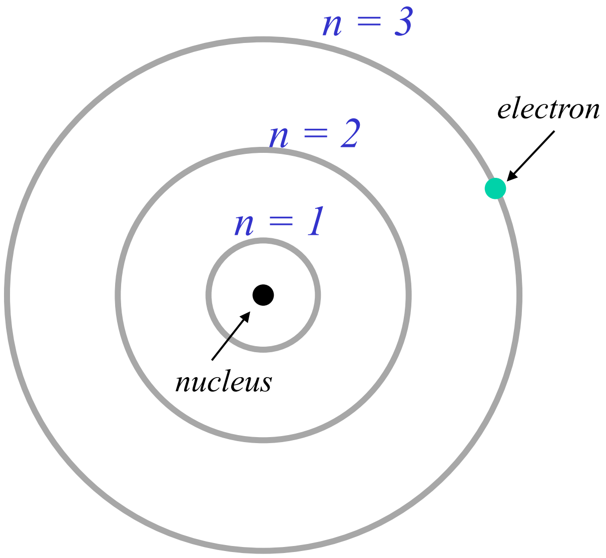


Energy states are discrete

Electrons all have a certain energy. In most cases, the allowed energies are discrete, not continuous.

This is the origin of the familiar cartoon picture of an electron in a circular orbit around the nucleus of an atom.

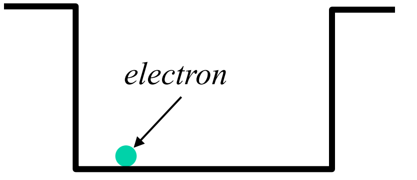
That picture isn't quite right, but it is good enough for today's discussion



This seems like a pretty crazy idea, but it works.

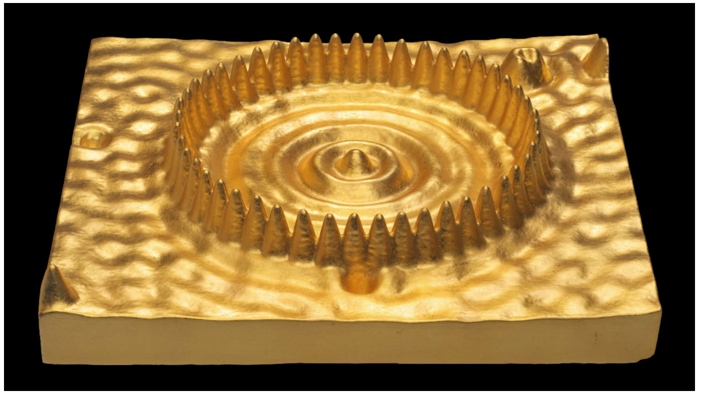
An electron in a box

Atoms are complicated, so let's consider something simpler: an electron in a box.



By "box", we mean: anything that confines the electron to a region of space, like a spatially varying voltage or the Coulomb attraction that binds the electron to the nucleus of an atom.

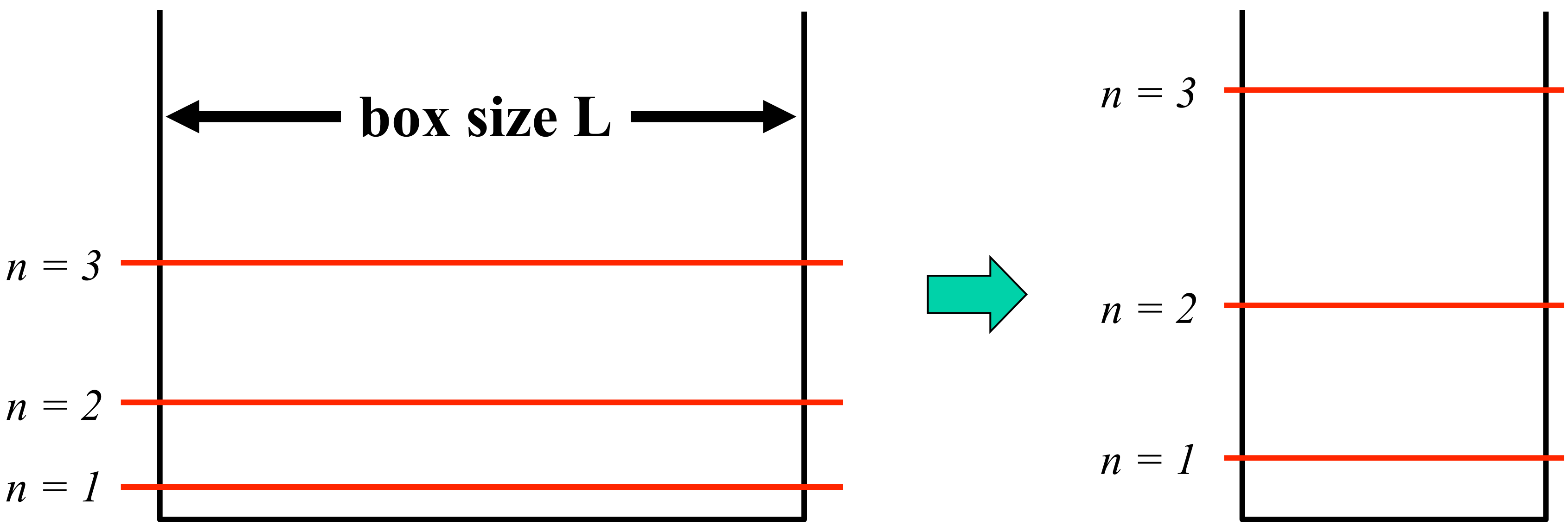
Inside the box, the electron behaves as a wave, and exists in one of a discrete set of possible energies.



Source: Wikimedia Commons

The energies of the discrete states

If we make the box smaller, the energies of all of the states go up.

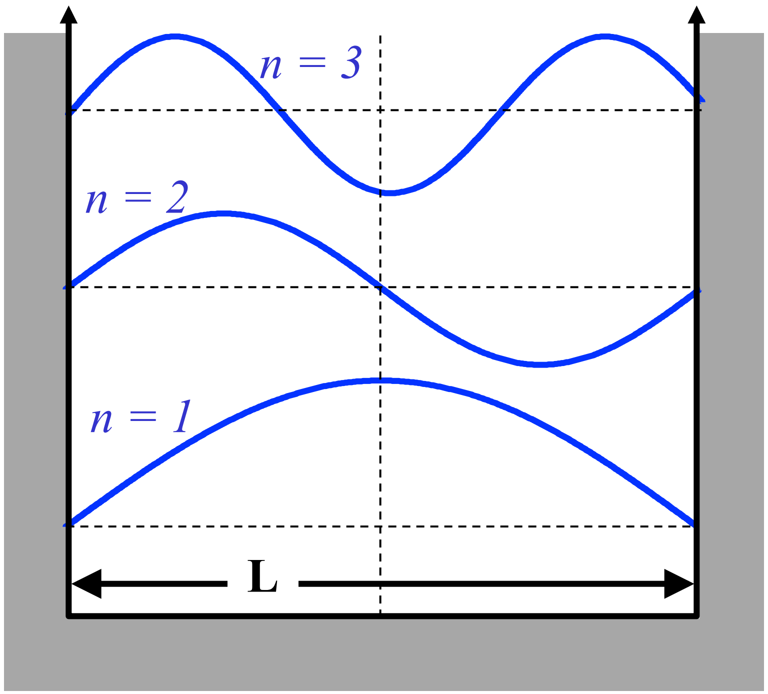


Energy ~ $1/L^2$

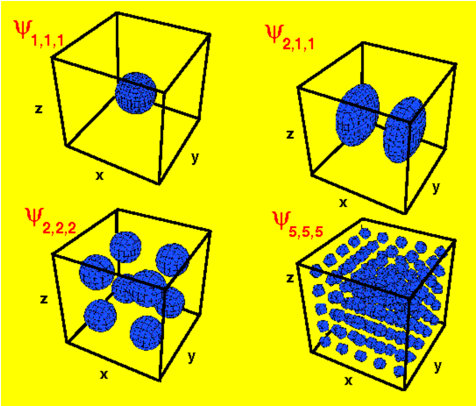
You may have heard of this effect: Heisenberg!

The wave functions of the electron in the box

How do we determine these energies? By finding the "wave function" of the electron.



These functions tell us about the probability of where the electron is located within the box.

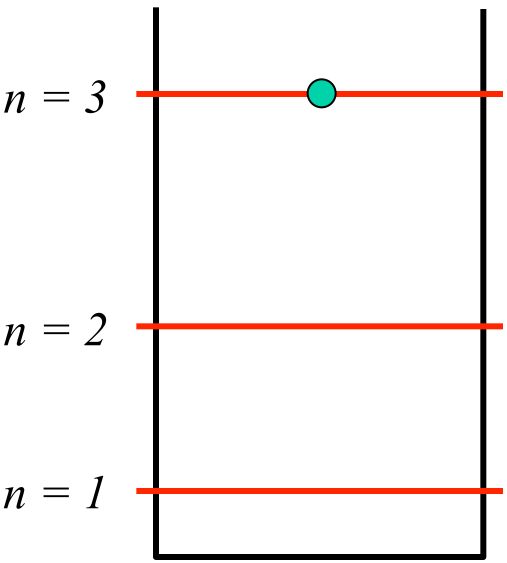


For a three-dimensional box, the results are somewhat more complicated.

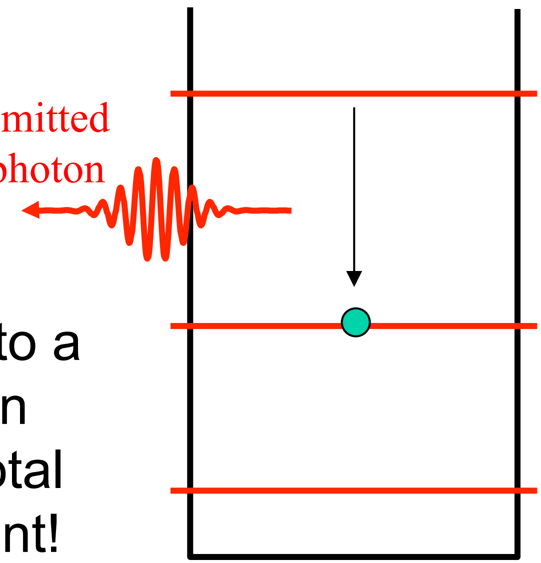
Source: University of Florida, chem.ufl.edu

Electrons can emit photons

Suppose our electron happens to start in the $n = 3$ state.



When it decays to a lower state, it can emit light - the total energy is constant!



So, by changing the dimensions of the box, we change the color of the emitted light.

Semiconductor nanoparticles: one way to make a box for electrons

As you have seen earlier, this quantum confinement effect is the basis of the changing light emission from chemically synthesized semiconductor nanoparticles.

3 nm Nanoparticles

6 nm Nanoparticles

light emission:

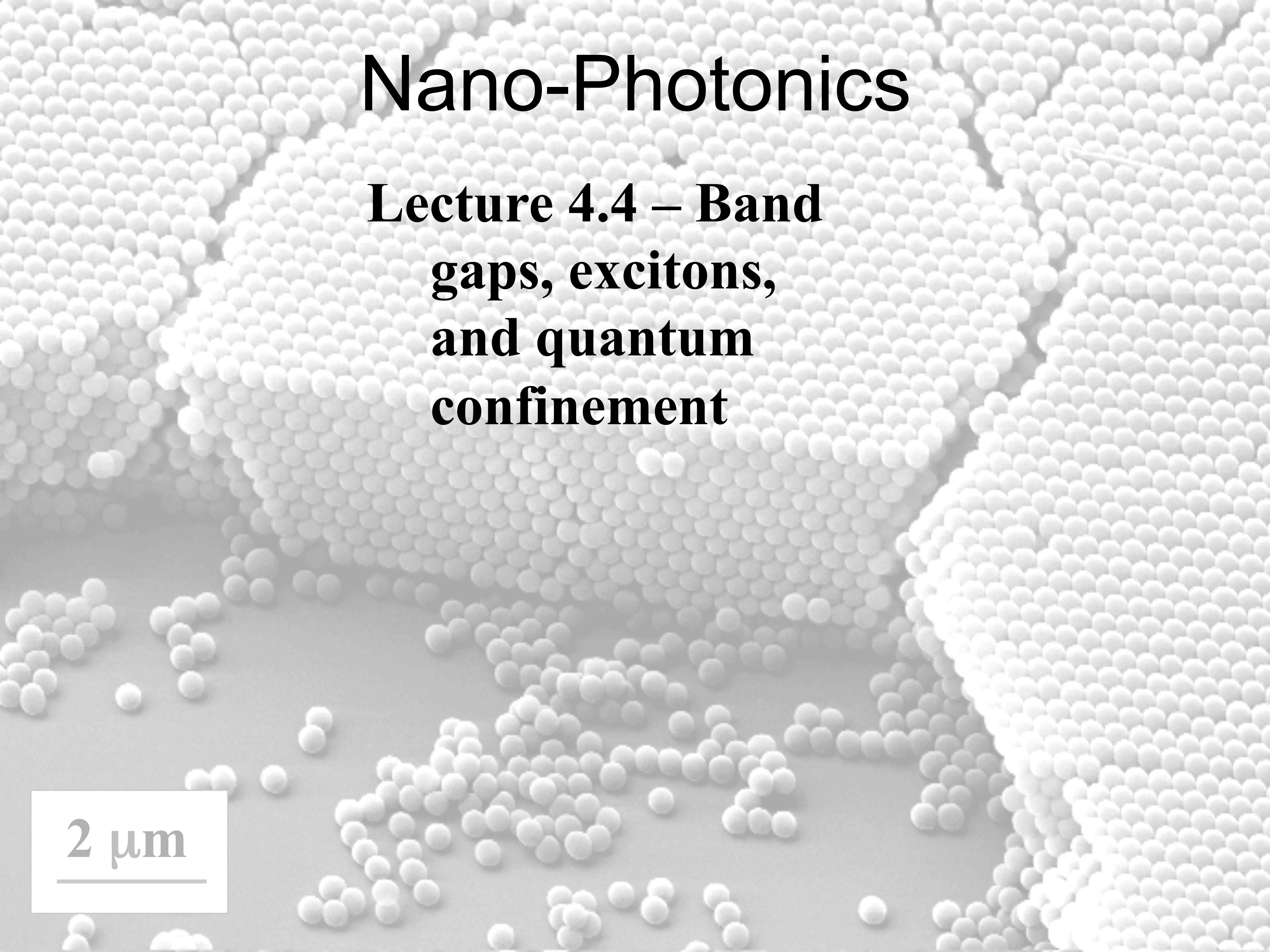
These colors can be predicted using a particle-in-a-3D-box model!

The ideas

- In the quantum world, energy levels are discrete. This is very different from what we are used to.
- Confining particles on a small scale causes their energy to go up: Heisenberg Uncertainty Principle
- This has *dramatic* implications for the interaction of light with nano-semiconductors.

Nano-Photonics

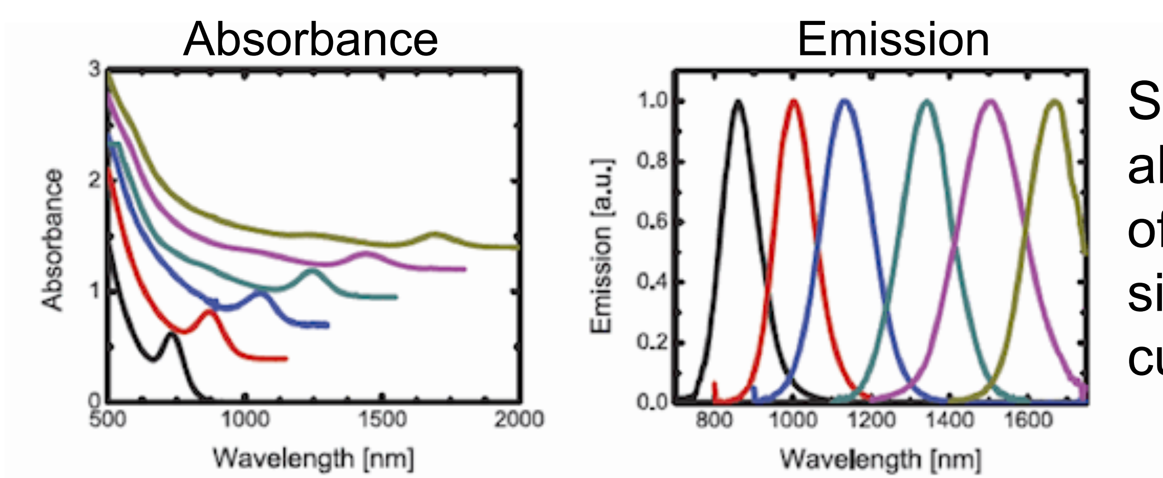
Lecture 4.4 – Band gaps, excitons, and quantum confinement



Quantum dots: 3D boxes for electrons

We have seen that quantum confinement in a 3D box (a spherical quantum dot, for example) leads to a change in the color of emitted light.

We might also expect a change in the color of light that the particle absorbs.



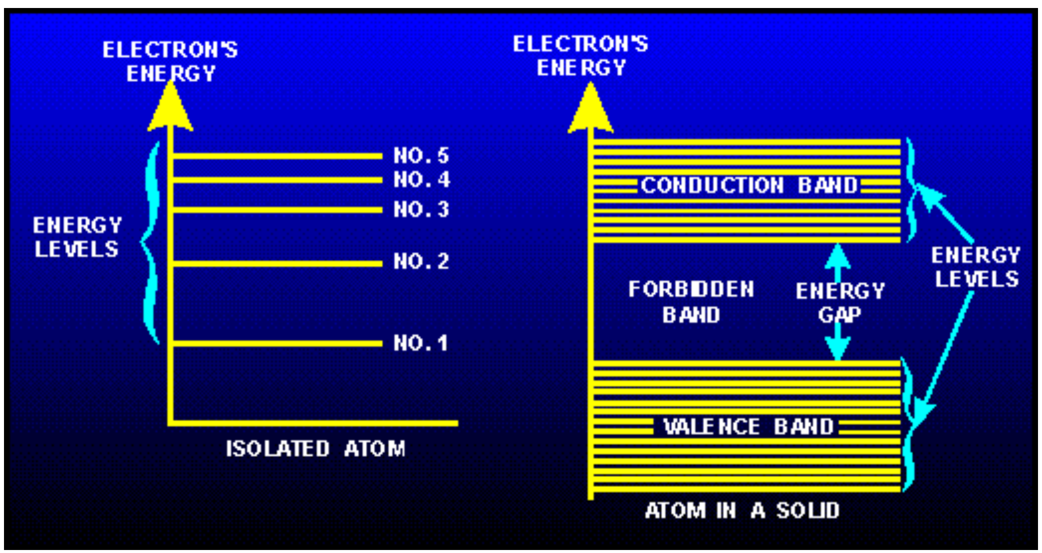
Size-dependent absorbance and emission of PbS quantum dots. The size range is 3 nm (black curves) to 7 nm (olive).

Source: Cornell University, wise.research.engineering.cornell.edu

Semiconductors: band gaps

In order to understand how this works, we need to know how the energy levels are arranged in semiconductors.

All semiconductors have a "band gap" - a range of energies with no states. This is different from the case of isolated atoms.



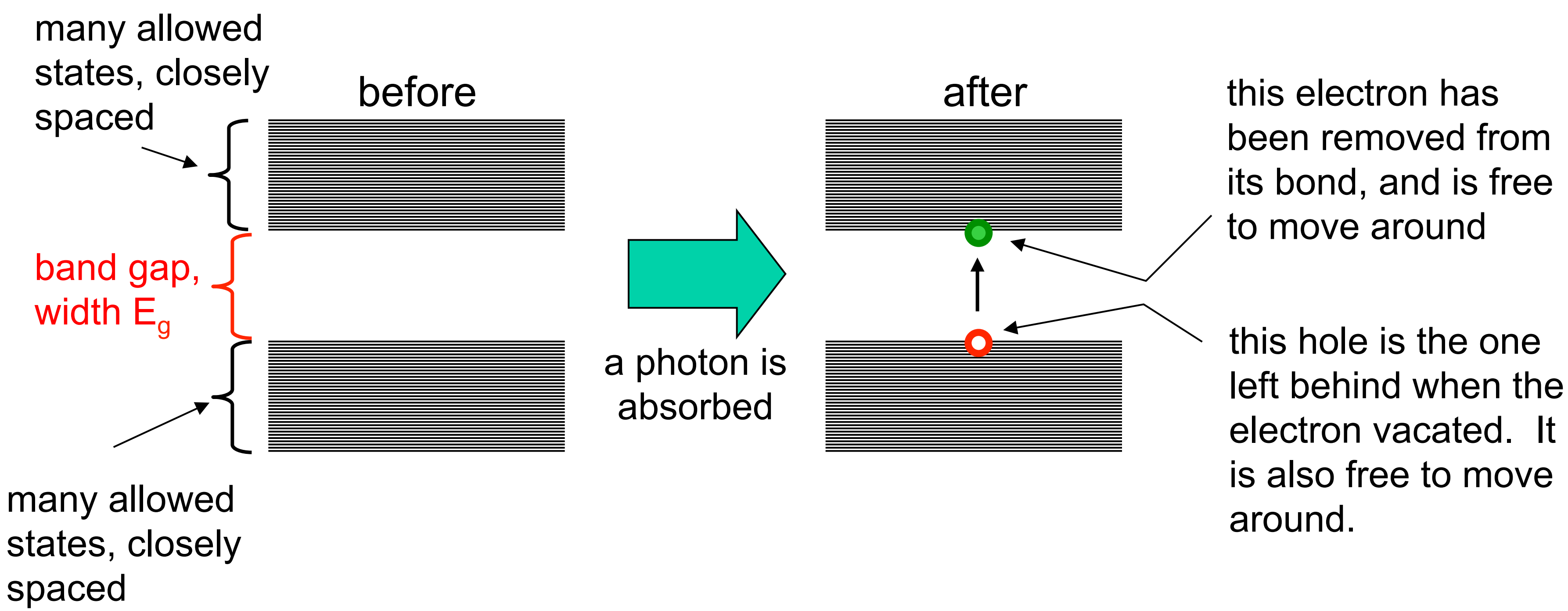
Harvard University, http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/energy_gap/energy_gap.html

Different materials have different values for the band gap energy E_g.

The energy E_g is simply the amount of energy it takes to remove an electron from its bond and set it free (see Week 2 supplemental lectures).

Semiconductors and light absorption

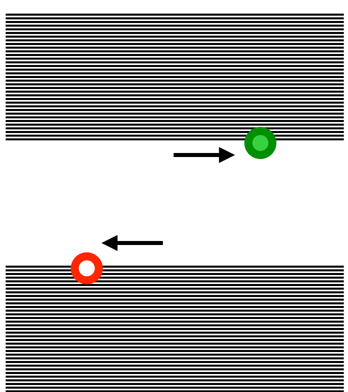
When a semiconductor absorbs a photon with energy equal to E_g, this removes an electron from the lower set of states, leaving a hole behind. The electron acquires the energy of the photon, and thus is moved up in energy to the upper set of states.



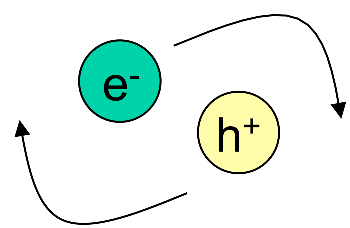
Semiconductors and light absorption II

What happens next?

One possibility is that the electron and hole just drift off, leaving each other.



Another possibility is that the electron and hole become bound to each other!

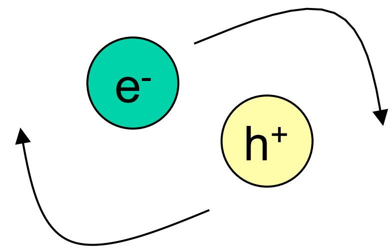


They orbit each other, just like an electron orbiting a proton in a hydrogen atom.

This composite object is called an "exciton".

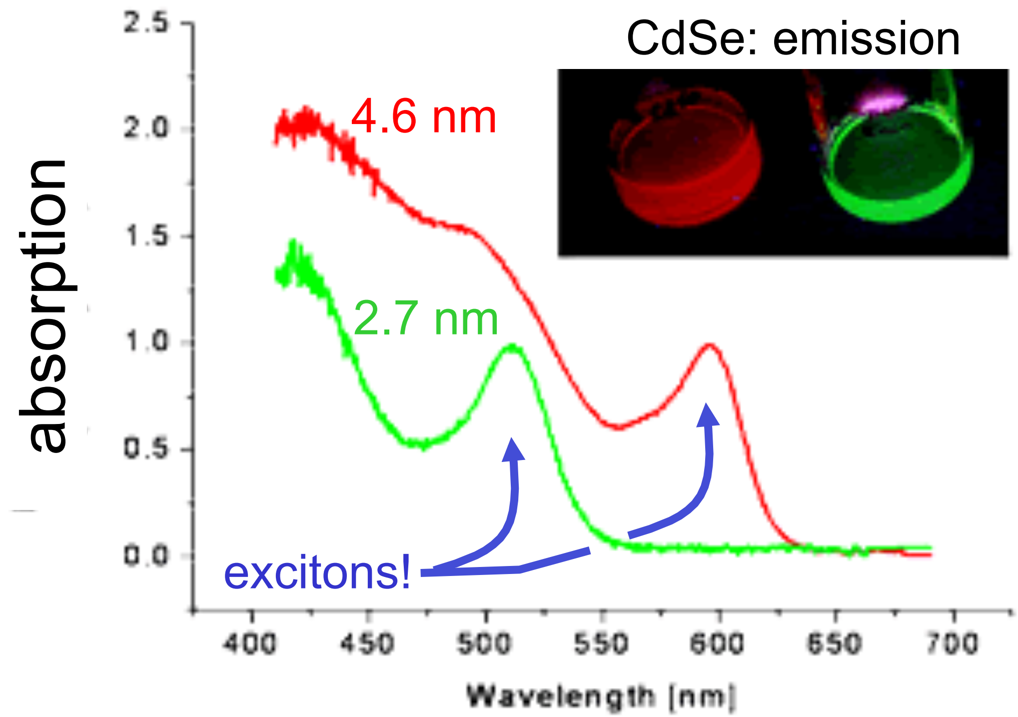
How big is an exciton?

Just like a hydrogen atom, the size of an exciton is well defined.



Material	Exciton radius
ZnO	2.3 nm
silicon	4.5 nm
CdTe	6.8 nm
GaAs	11.6 nm
PbSe	46 nm

Quantum dots exhibit confinement effects when they are close to (or smaller than) the natural size of the exciton.

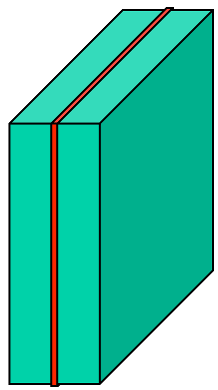


Michael Bartl, University of Utah,
http://www.chem.utah.edu/faculty/bartl/webpage/research.html

Ways to squeeze an exciton

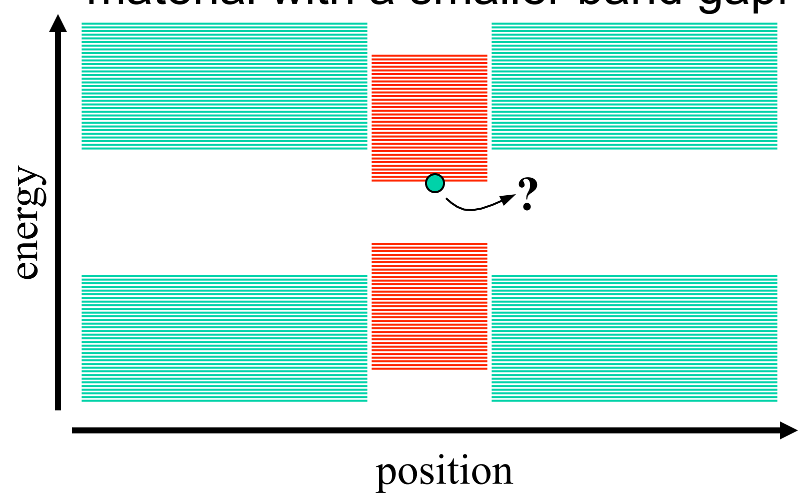
How else can we squeeze an exciton?

Picture a sandwich of different types of semiconductor material, like this:



two different semiconductor materials, in a sandwich

The middle slab is made of a material with a smaller band gap.

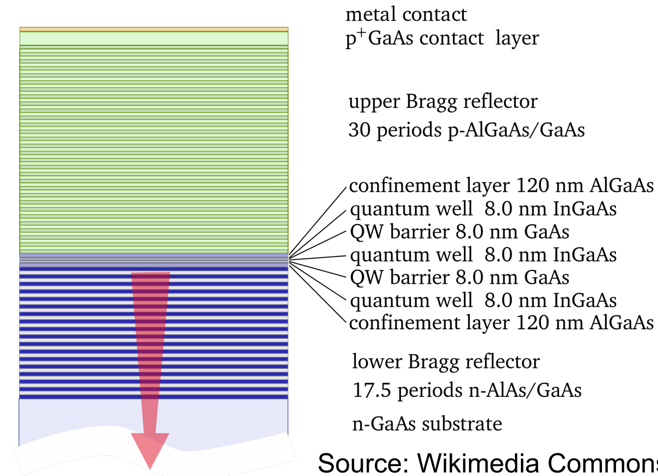


"quantum well": a thin layer of semiconductor material which traps excitons in a two-dimensional space

Quantum wells

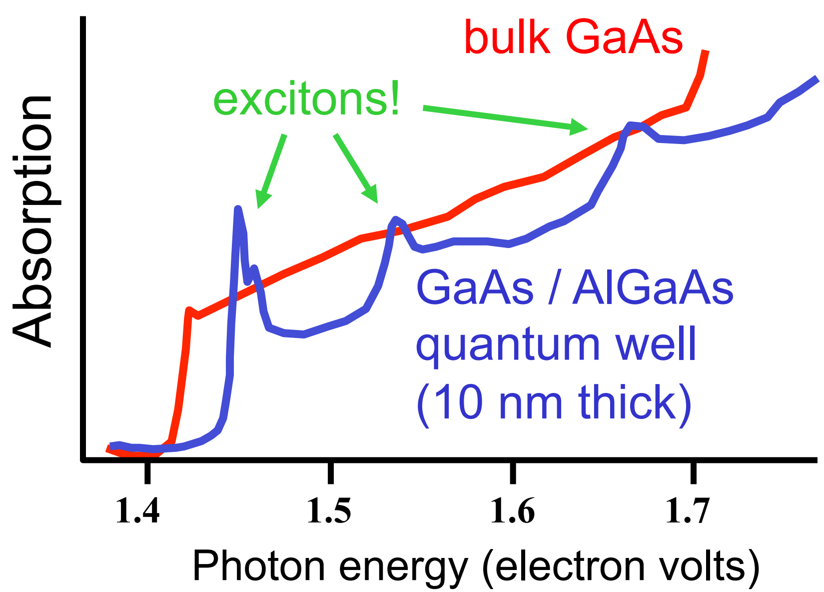
First of all, how do we make these?

Reminder: lecture 2.6 (depositing thin layers)



Source: Wikimedia Commons

A quantum well laser: cross-sectional structure



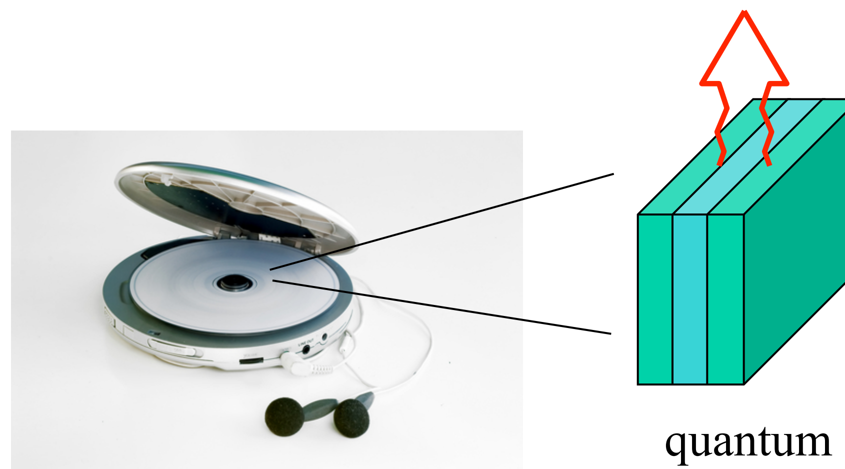
What does this do to the optical properties?

Similar to what we saw in the case of quantum dots.

So why is this useful?

We can control the properties of the electron states by changing the thickness and composition of the quantum well. In this way, we can engineer the color of the emission. Quantum wells make great lasers!

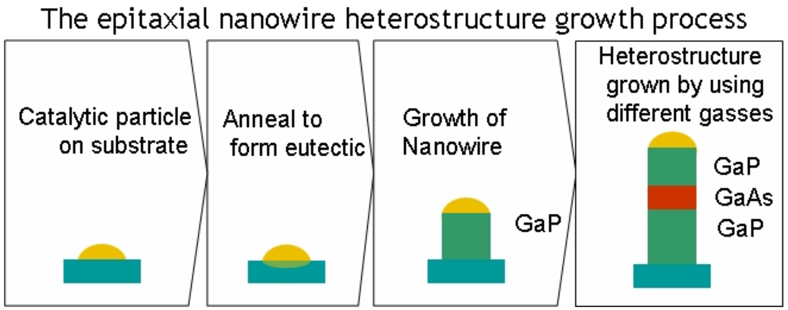
- most red laser pointers
- the laser in your CD or DVD player
- the lasers in bar code scanners



quantum
well laser

Dots, wells, … anything else?

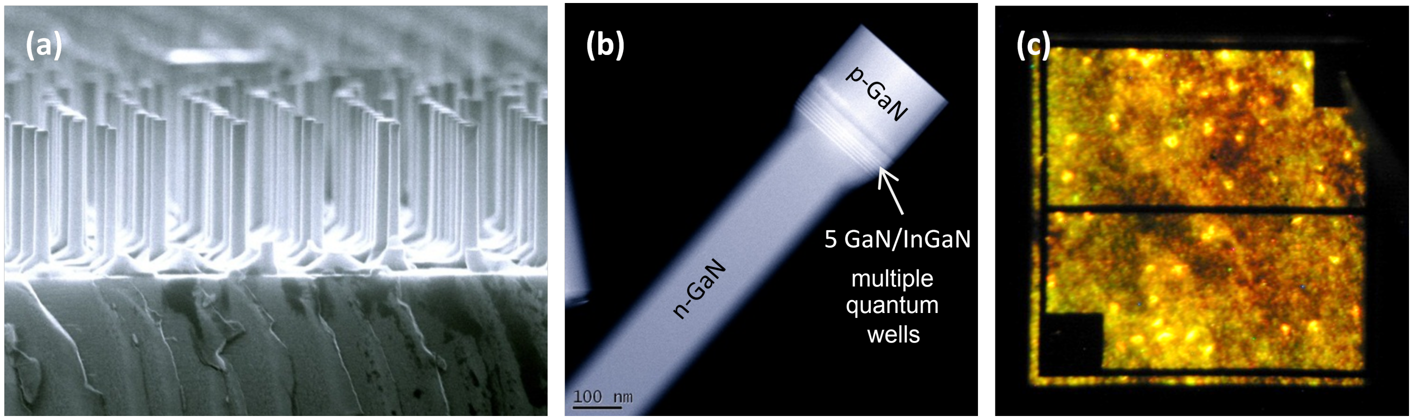
Sure! How about nanowires?



Open Source Handbook of Nanoscience and Nanotechnology, Molhave

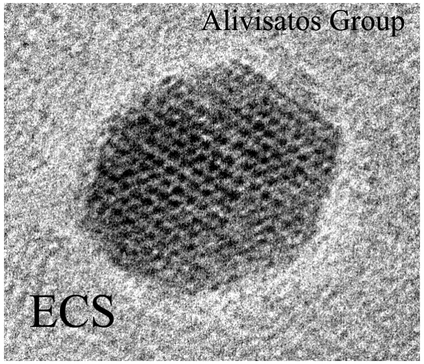
Remember this? (Lecture 2.3)

GaN nanowires, with quantum wells built in, as yellow light-emitting diodes.



Sandia National Laboratories, http://energy.sandia.gov/?page_id=8229

The degrees of quantum confinement

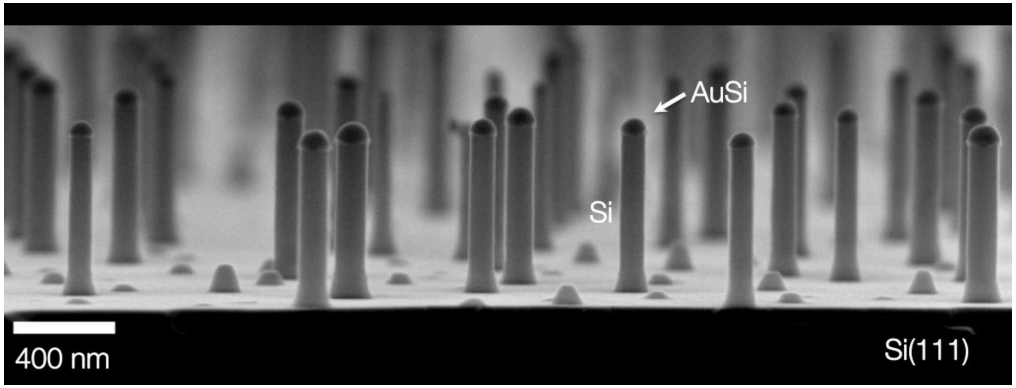


iron oxide nanocrystal
Paul Alivisatos, UC Berkeley,
http://www.cchem.berkeley.edu/pagrp/gallery.html

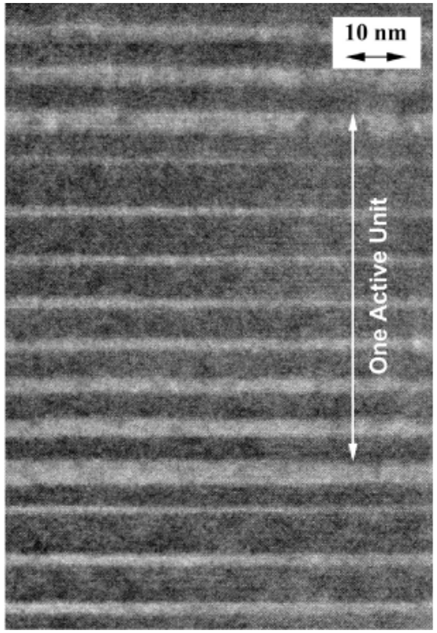
Quantum dots: excitons confined in all three dimensions

Quantum wires: excitons confined in two dimensions

Quantum wells: excitons confined in one dimension



Silicon nano-wires
Michael Filler, Georgia Tech, http://fillergroup.gatech.edu/research/



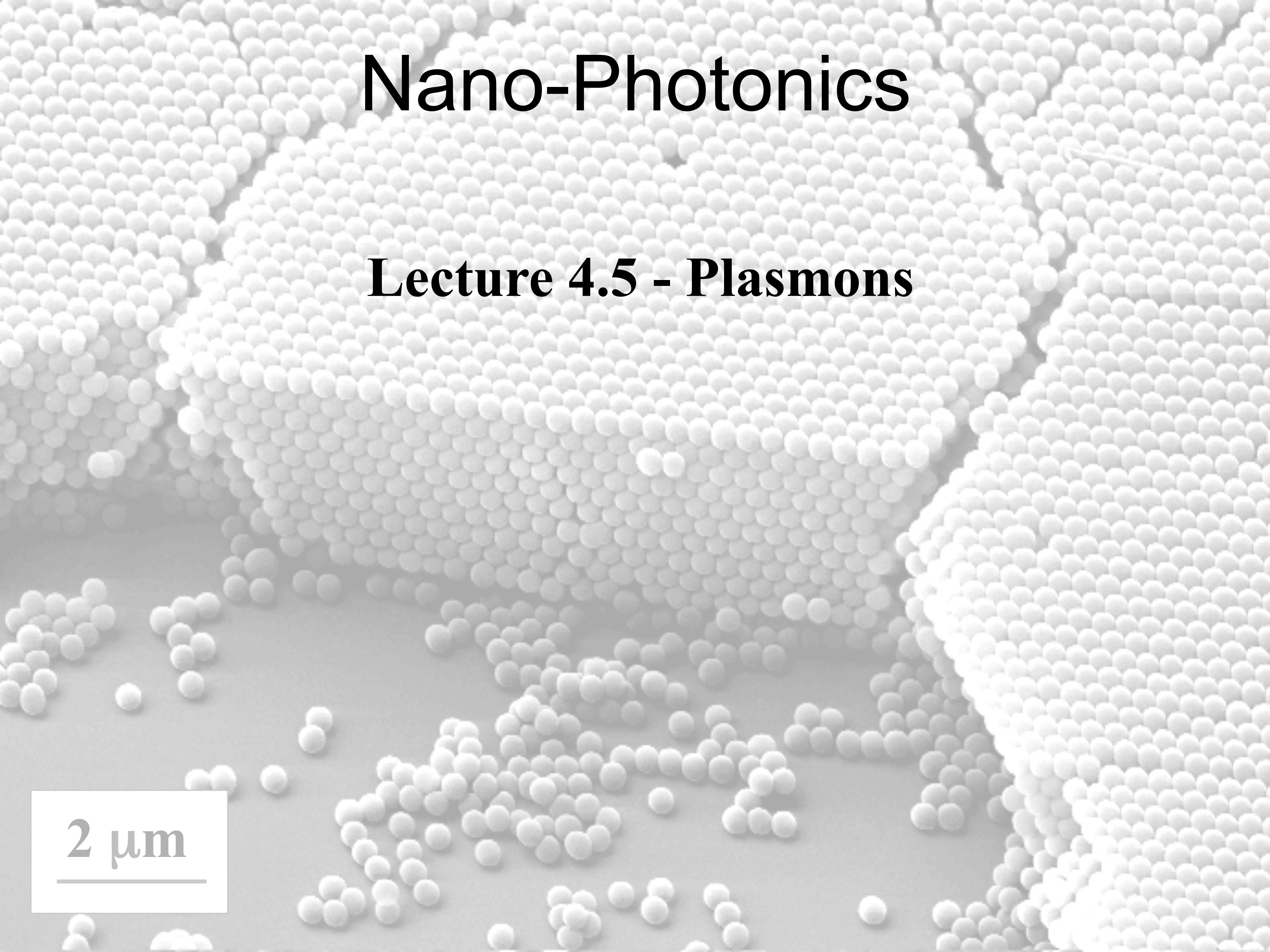
Si / SiGe quantum wells
Douglas Paul, University of Glasgow
http://userweb.eng.gla.ac.uk/douglas.paul/QCL.html

The ideas

- Semiconductors have energy bands and energy gaps.
- Excitons are bound states of an electron and a hole, similar to a hydrogen atom.
- Band gap engineering: another way to implement quantum confinement.
- This is what makes CD and DVD players possible!

Nano-Photonics

Lecture 4.5 - Plasmons

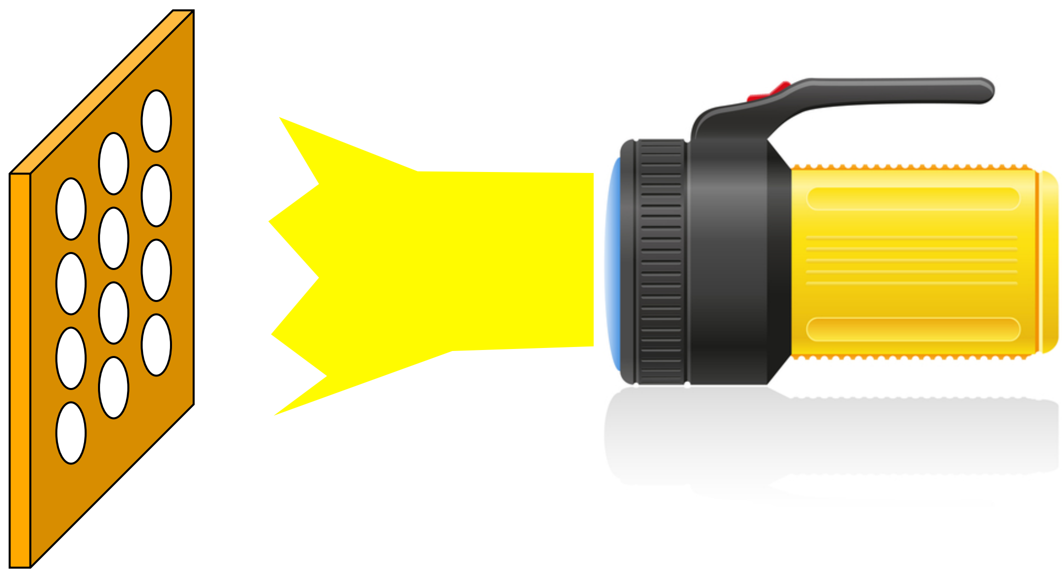


Let's start with a thought experiment

Suppose we have a sheet of metal, with some holes in it. Let's illuminate the sheet from one side, and ask the question:

"What fraction of the light makes it to the other side?"

Each hole has a radius of R. And there are N holes in the sheet.



To make it easy, we will assume that the entire face of the metal sheet is uniformly illuminated.

Let's start with a thought experiment

This seems easy, so far:

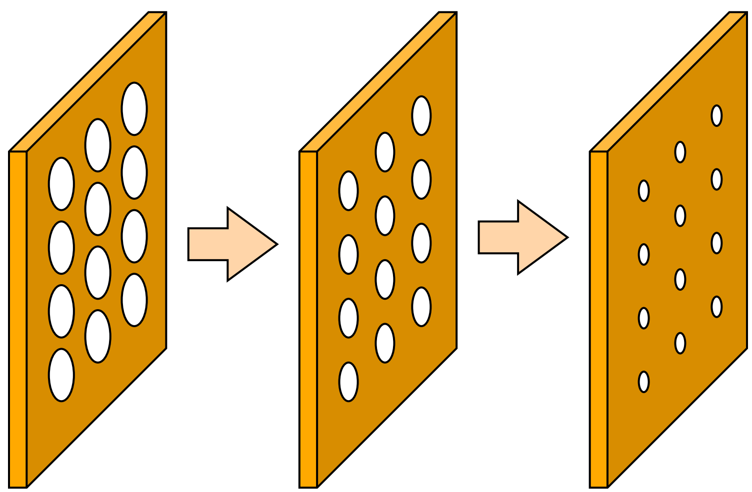
total area of the metal sheet (including the holes) = A_s

total area covered by just the holes = $A_h = N\pi R^2$

Thus, the fraction transmitted is simply $\frac{N\pi R^2}{A_s}$. Obviously, this fraction is always less than 1.

It would be very strange if we ever observed a fraction transmitted that was greater than this ratio…

Now, what if we start making the holes smaller?



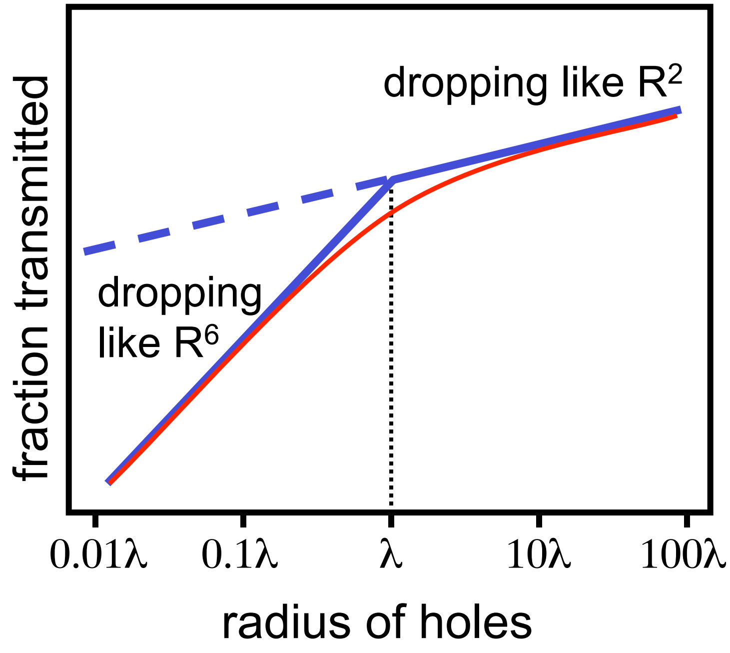
Clearly, the transmitted fraction decreases in proportion to R^2.

Ok… then what?

Two interesting things happen.

1. When the size of the holes reaches close to the wavelength of the light, the transmitted fraction decreases even faster.

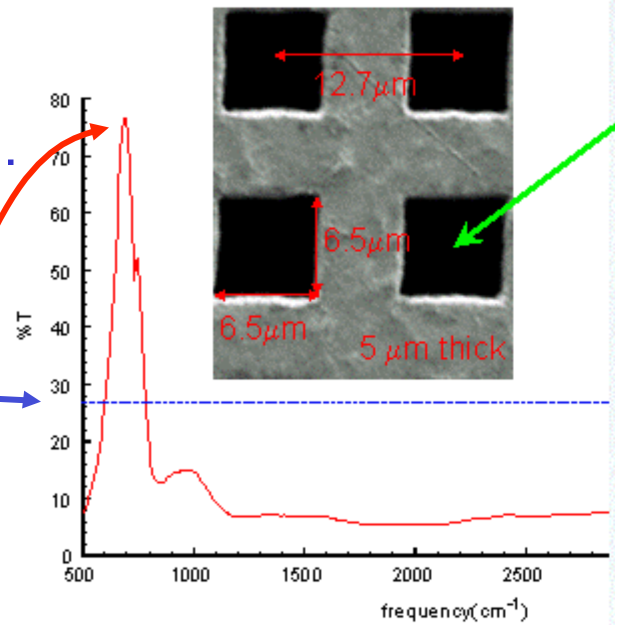
This effect has been understood for many decades. Holes that are smaller than λ transmit <u>very</u> little light.



Ok… what else?

2. Under certain special circumstances, the transmission can become huge!

The holes cover this percentage of the area...



…but the transmitted percentage is way up here!

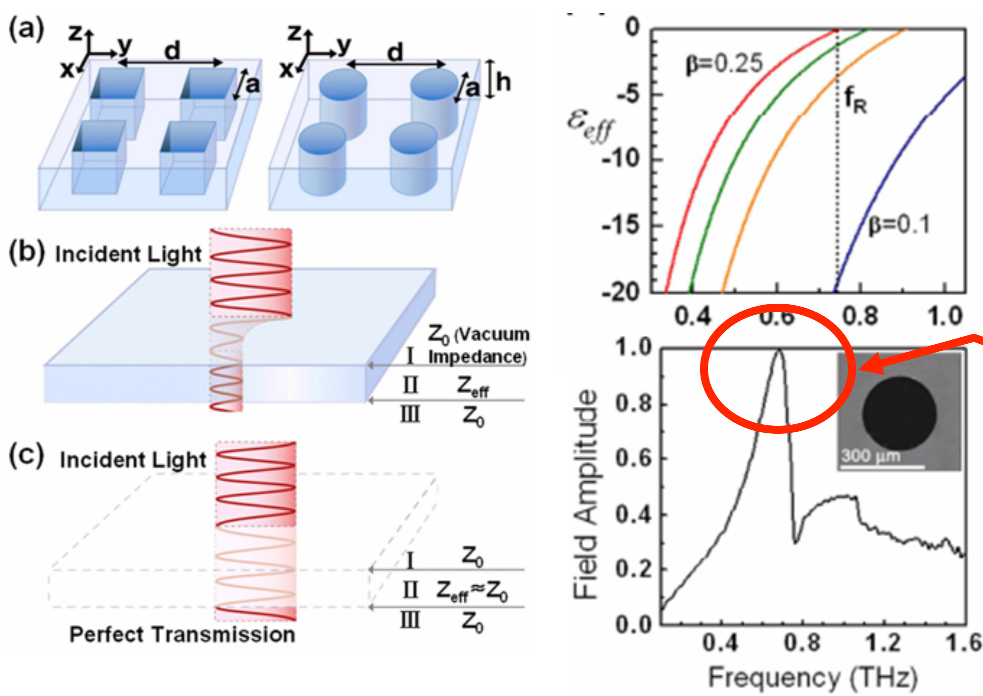
In this example, the holes are about λ/2 in size.

James Coe, The Ohio State University,
http://kb.osu.edu/dspace/handle/1811/30578

Wait… what??

The holes cover about 28% of the area of the metal surface.

But about 78% of the incident light is transmitted through the metal sheet.



Dai-Sik Kim, Seoul National University, http://nanooptics.snu.ac.kr/

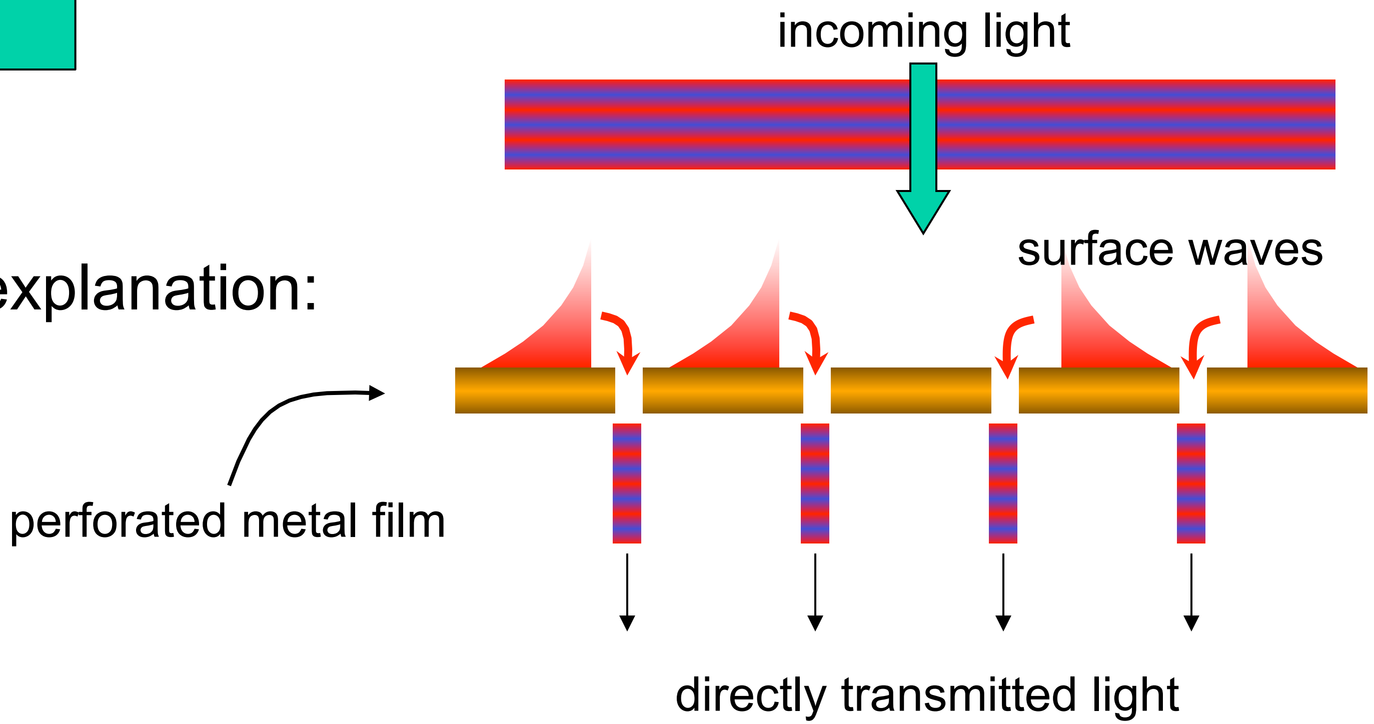
In other words, the fraction transmitted is greater than the area ratio! It is equal to about 78/28 ~ 2.8

In some cases, the transmitted fraction can approach 100%!

In this example, the holes cover about 30% of the area, but 100% of the light gets through them (at a specific frequency).

Plasmons: the key to it all

The cartoon explanation:

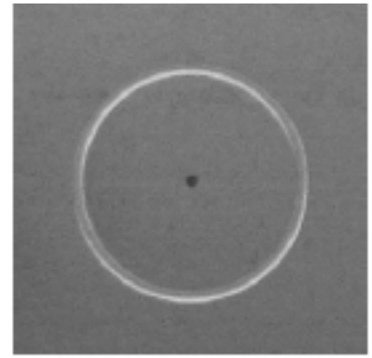


The incoming light wave excites surface waves on the film, which then propagate along the surface and funnel through the apertures.

These surface waves are known as “surface plasmons”.

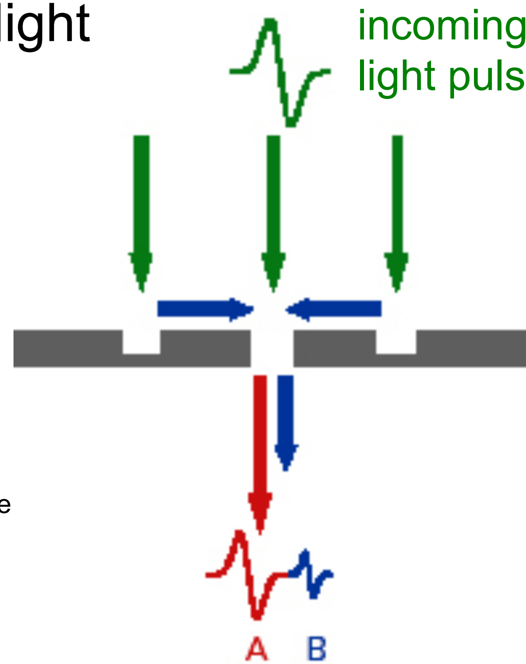
Extraordinary transmission

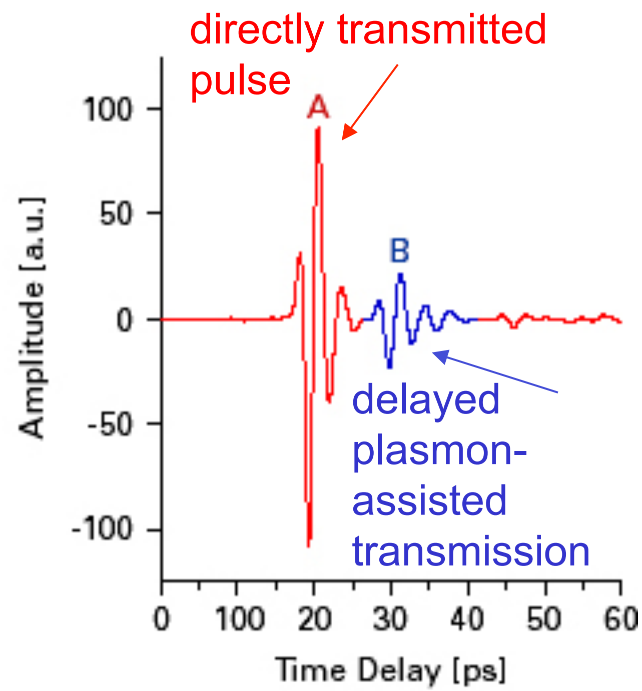
- It also works with a single hole!
- …if you appropriately structure the surface
- this can be observed as a <u>delayed</u> transmission of light



(a)

A single small hole with a concentric groove





Amit Agrawal et al., Excitation and scattering of surface plasmon-polaritons on structured metal films and their application to pulse shaping and enhanced transmission, *New J. Phys.* **7** 249 (2005) doi: 10.1088/1367-2630/7/1/249

An aside: kilo-nano-optics

In the example on the previous slide, the "nano-hole" was actually 490 microns in diameter (that's a frequency in the terahertz range)

So is this really nano-optics?

Well, sort of. The wavelength of the radiation was more than 1 millimeter.

In many cases, the physics of plasmons and light confinement depends only on the ratio:

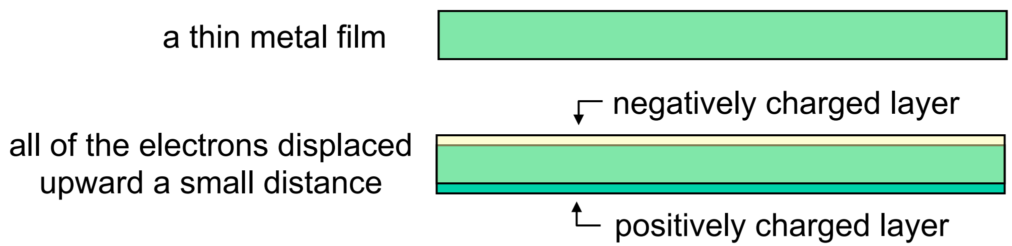
$$\lambda / d$$

wavelength   confinement size

It is often much easier to study these effects using longer wavelengths.

What's a plasmon?

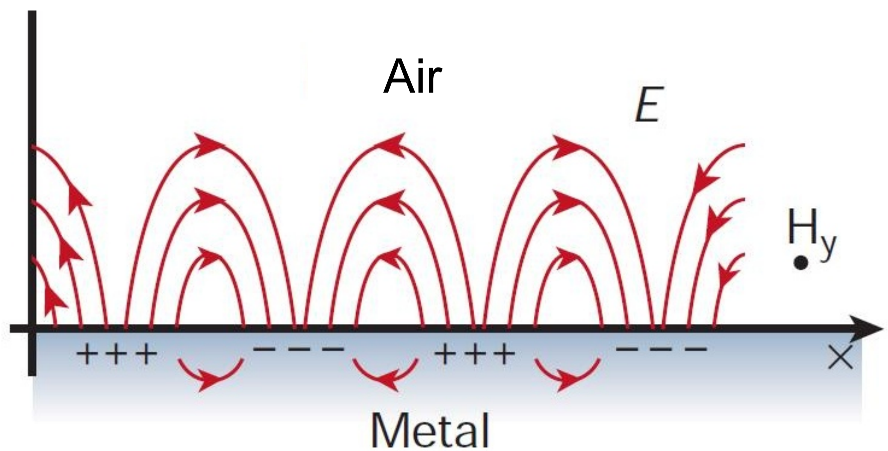
Plasmon: a collective oscillation of a large number of electrons



The sloshing electrons behave like an incompressible fluid – e.g., water (except don't forget that they' re carrying a charge)

This can take different forms, depending on the geometry of the metal.

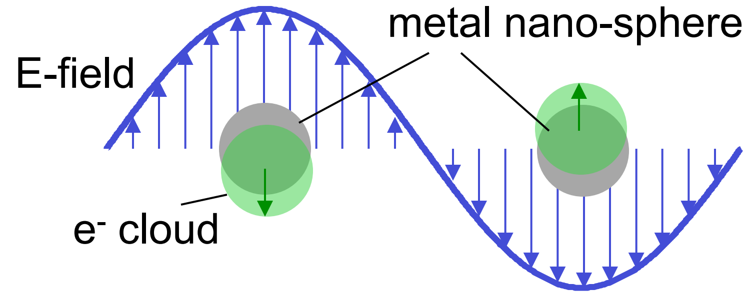
A plasmon can form a wave on a metal surface, where the electron density oscillates periodically. There is also an associated oscillation of the light wave.

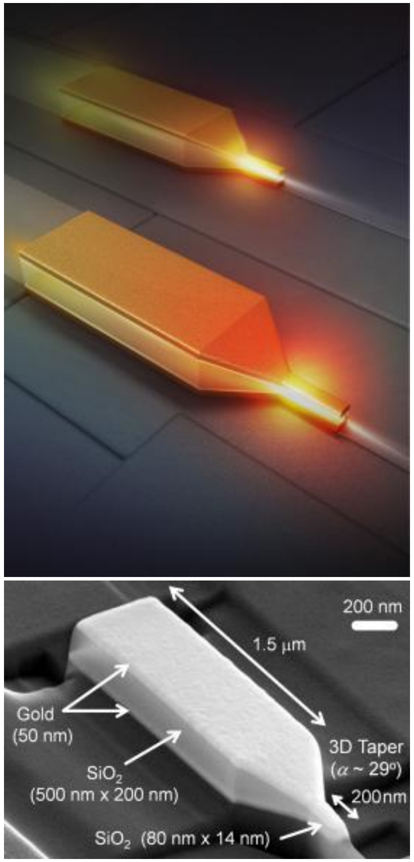


In this case, the plasmon propagates across the metal surface.

Miriam Deutsch, University of Oregon, http://mo.uoregon.edu

Special things about plasmons





Focusing light into a nanometer-sized region

Hyuck Choo and Myung-Ki Kim, CalTech

http://www.caltech.edu/content/point-light

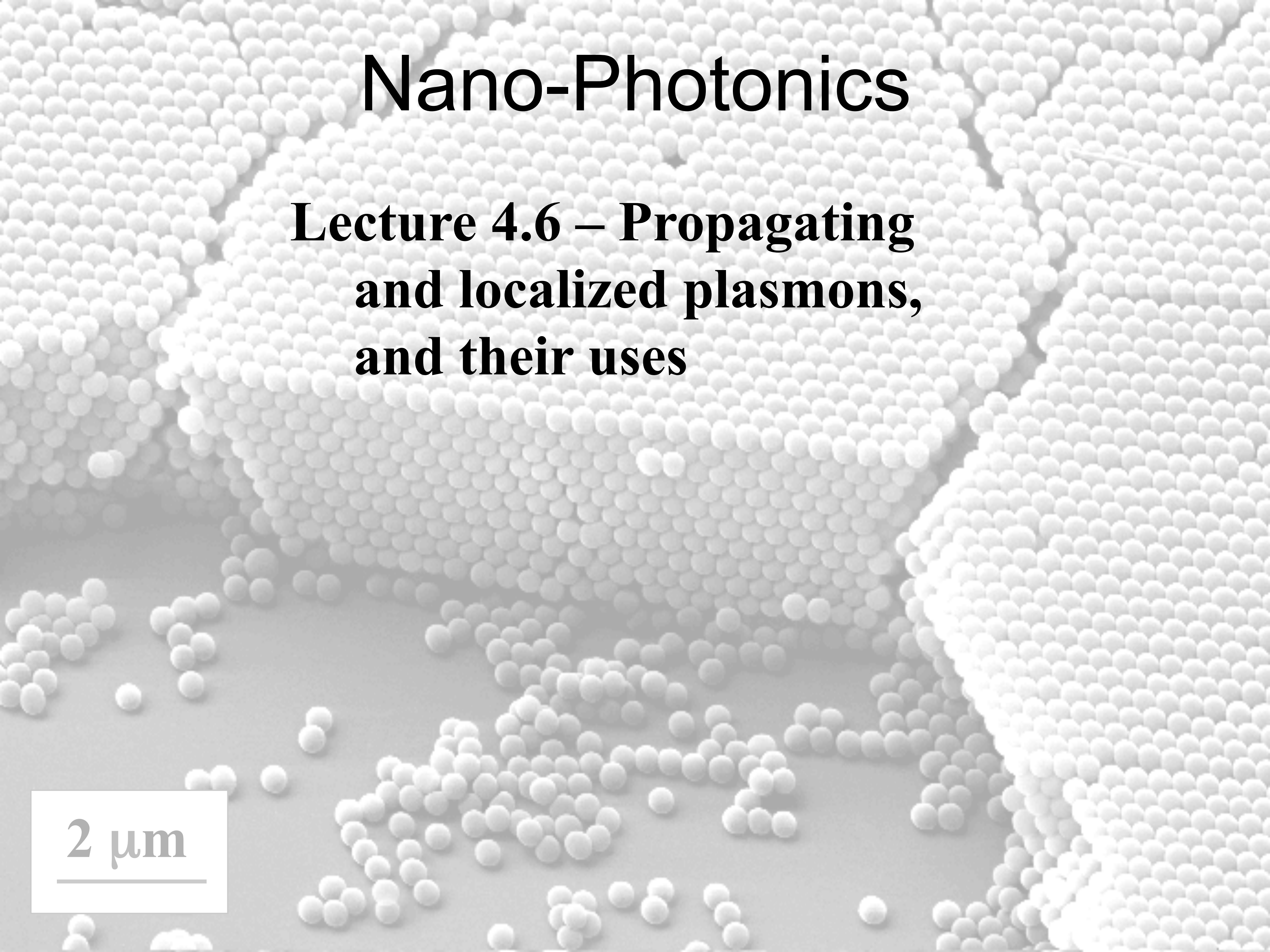
1. They are a coupled excitation: not just sloshing electrons, but also an oscillating electromagnetic field.
2. They are not limited by the ‘diffraction limit’ of focused light, discussed earlier (Lecture 4.1). They can be much smaller than λ!
3. They live very close to metal surfaces, which means:
   - the electromagnetic field strength near the surface can be HUGE
   - they are very sensitive to things happening at the surface of the metal

The ideas

- Plasmon: an oscillation of the ‘fluid’ of electrons in a metal
- Plasmons are *both* an oscillation of electrons *and* an oscillating electromagnetic field – a coupling between the two
- One surprising consequence: efficient funneling of light through small holes

Nano-Photonics

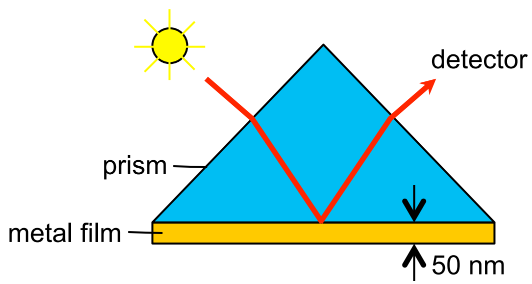
Lecture 4.6 – Propagating and localized plasmons, and their uses



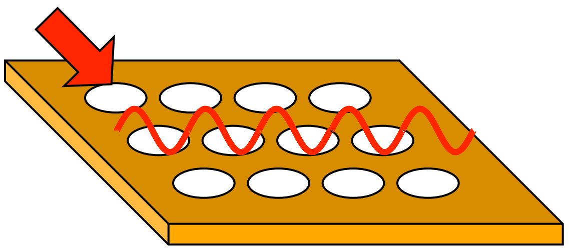
Excitation of plasmons

In a macroscopic metal, excitation of a plasmon is not trivial, due to the fact that the plasma wave generally propagates at a different velocity from the light wave.

Kretschmann configuration:

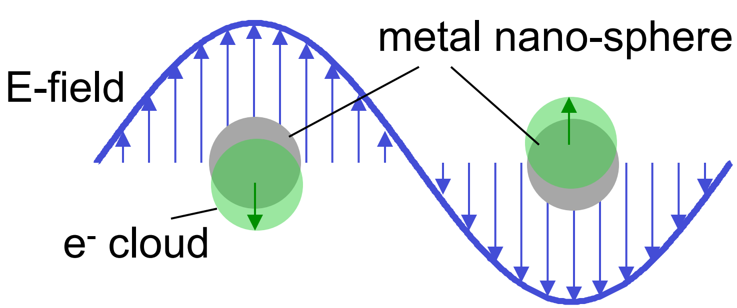


Prism coupling is one popular strategy.



Surface patterning is another.

In a nanometer-sized metal particle, the problem simplifies because the plasmon is smaller than the wavelength of the radiation - plasmon propagation is irrelevant!



Surface plasmons for sensing

Because plasmons reside near metal surfaces, they are very sensitive to molecules at the surface. This makes them excellent bio-sensors.

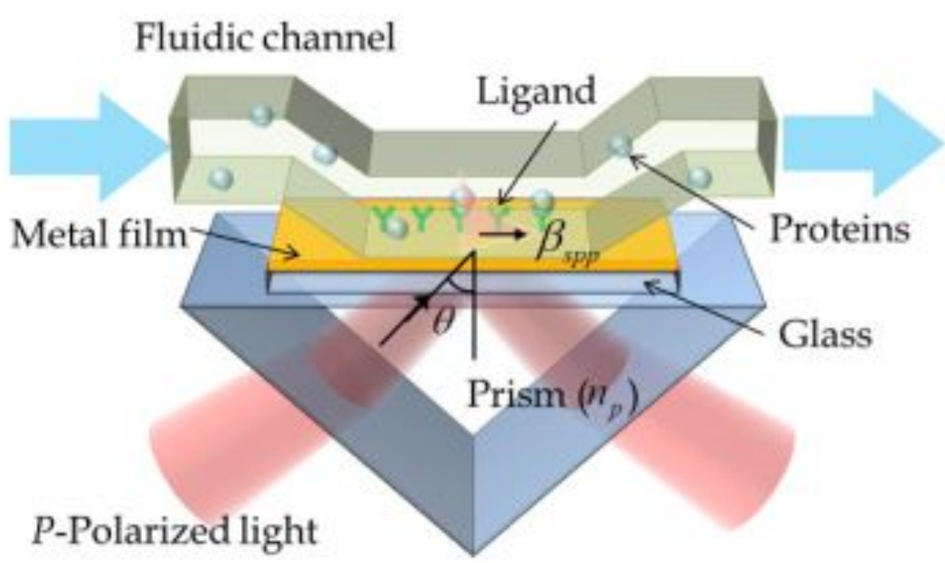
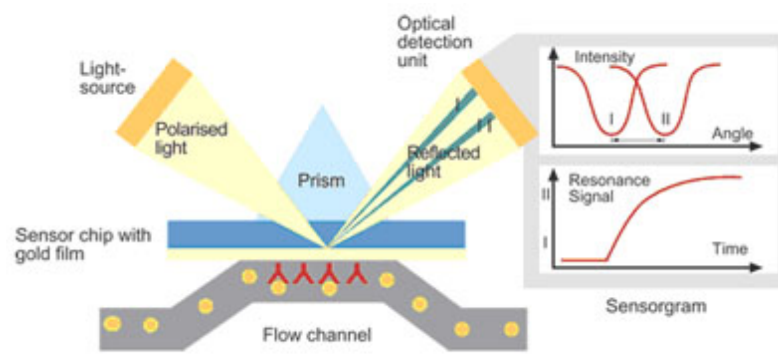


Diagram from: C. Roh, T. Chung, B. Lee
Sensors **11**, 1565 (2011).
Image credit: www.mdpi.com

Detecting the change in angle or spectrum of the light reaching the detector provides a sensitive measurement of stuff at the surface where the plasmon resides.

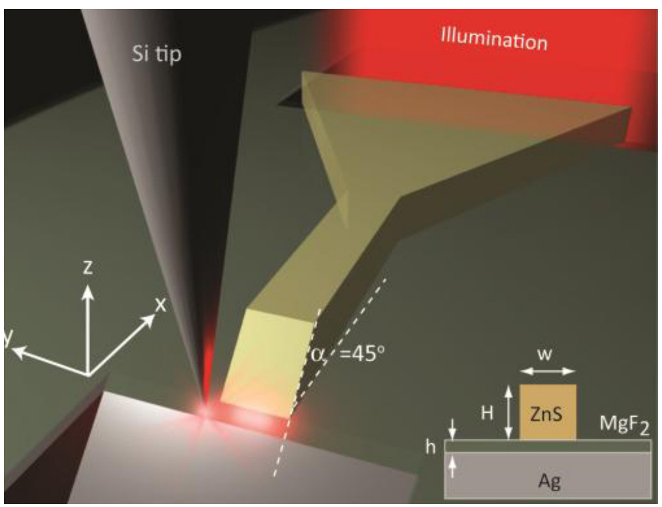


University of Oklahoma,
http://microgen.ouhsc.edu/biacore.htm

Plasmons can be small

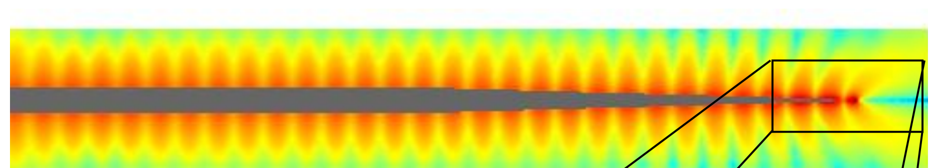
Because plasmons are not restricted to be larger than λ, a tapered structure can guide them down to a *much* smaller size: deep subwavelength confinement of light!

Input light is converted to a plasmon, which then funnels down to a ~50 nm output aperture.

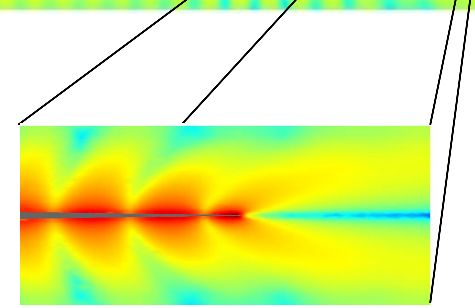


Xiang Zhang, UC Berkeley,
http://xlab.me.berkeley.edu/

Scaling to longer wavelengths: the same idea works for λ_{input} = 6 mm too.



Output spot size: about λ_{input} / 100

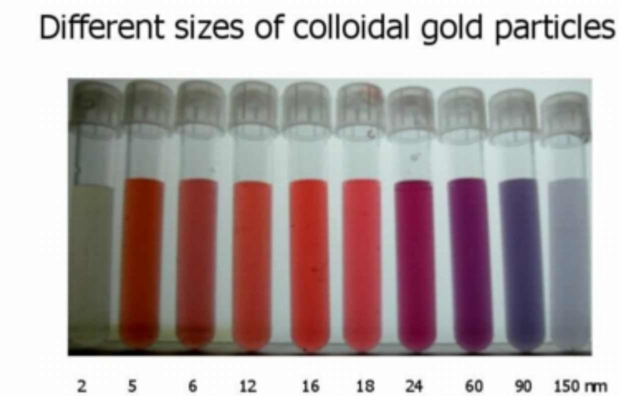


Note: much smaller than NSOM (in proportion to λ)

Plasmons are why nano-gold is red

The sloshing electrons interact with light most strongly at the resonant frequency of their oscillation.

Solid gold is gold-colored.



Gold nanospheres are red.

Image by Irawati Kandela, Dept. Pharmaceutical Sciences, Sch. of Pharmacy, & Ralph Albrecht lab, Dept. Animal Sciences, University of Wisconsin http://www.ansci.wisc.edu/facstaff/faculty/pages/albrecht/albrecht_web/programs/microscopy/home.html

The Lycurgus cup (4th century AD) is made of 'ruby glass', which contains gold nanoparticles.

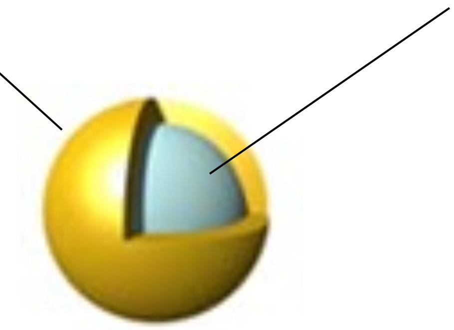
in reflected light in transmitted light

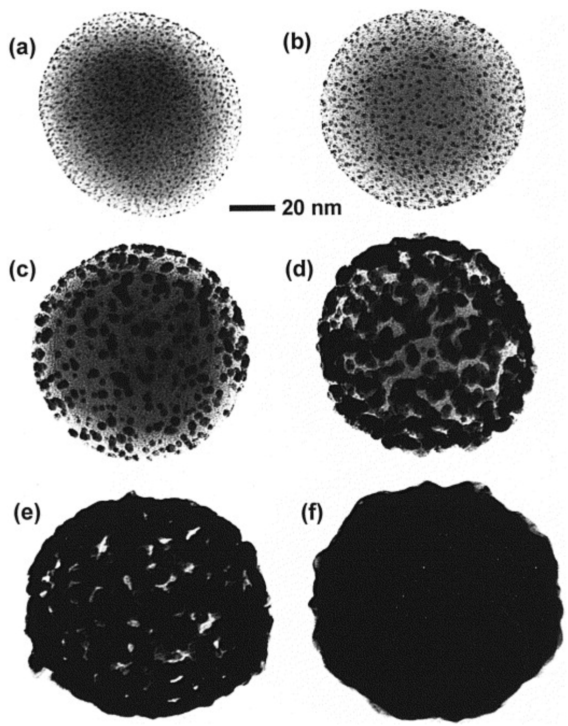
Ancient technologists used nanoparticles as pigments, although they didn't know it was nanotechnology.

Geometry matters

The size, shape, and geometry of the metal nanoparticle have a huge influence on the wavelength of the plasmon resonance.

A good example: a gold shell surrounding a glass core

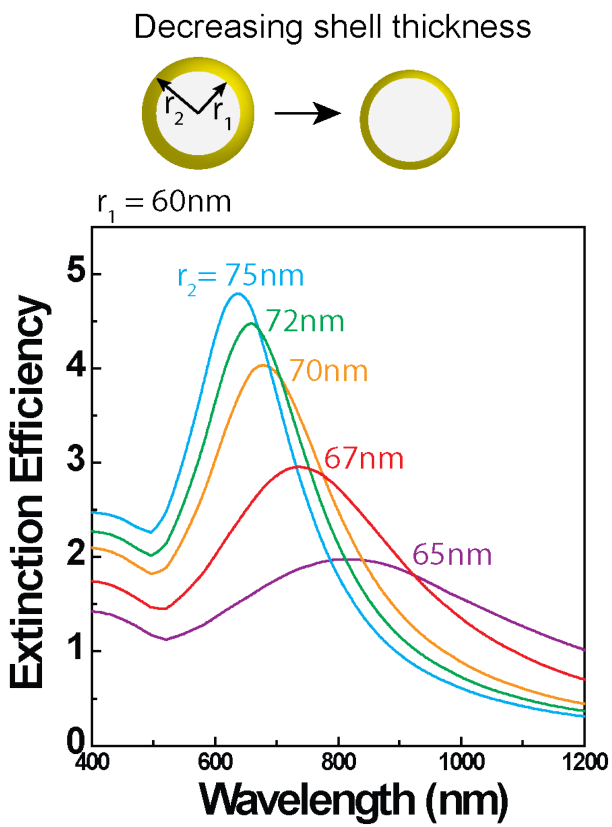




growth of a gold nanoshell on a glass core by aggregation of gold nanoparticles

Halas group, Rice University
http://halas.rice.edu
image used with permission

Tuning the optical properties



absorption spectrum changes
with gold shell thickness

solid
gold
spheres

gold nanoshells of
decreasing shell thickness

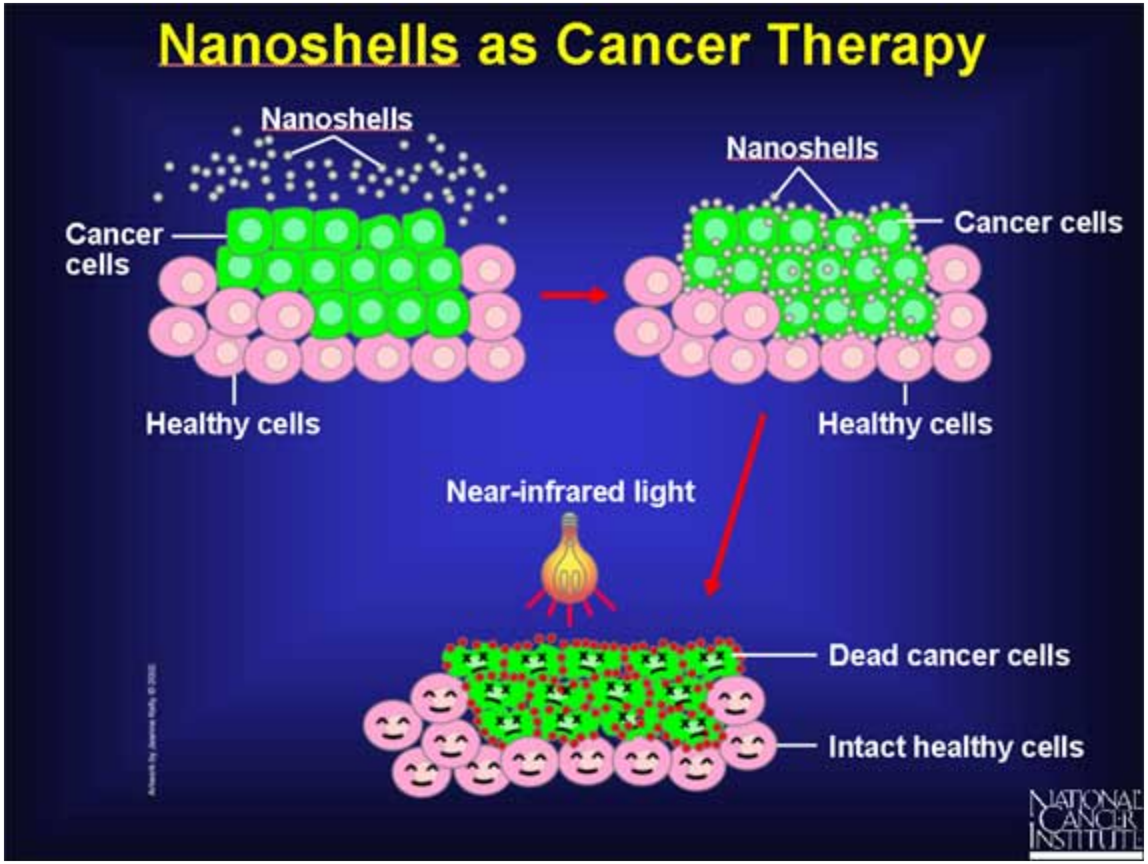
Why does this vial
look almost colorless?

Halas group, Rice University
http://halas.rice.edu
images supplied by Dr. Surbhi Lal,
used with permission

Why is this useful?

One can move the absorption resonance to a wavelength where your body is (more) transparent – in the near infrared.

Then, these particles become useful for treatment of diseases, like cancer.



www.cancer.gov

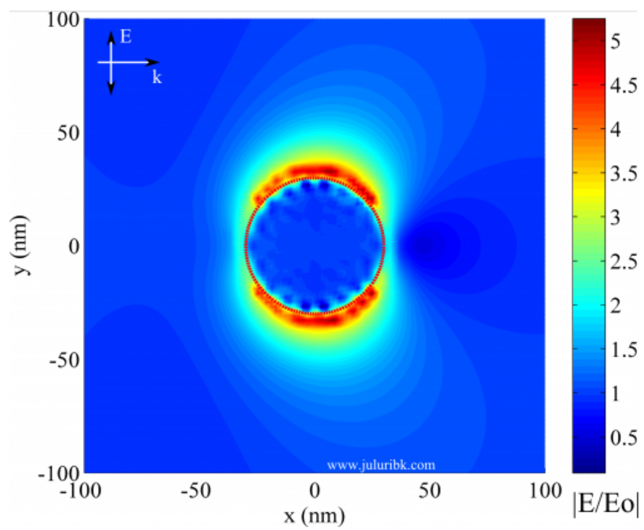
Nano-plasmons: antennas for light

When irradiated with light at the frequency of the oscillating plasmon, the nanoparticle behaves like an antenna for light.

The sloshing electrons produce a local field which can be much more intense than the incident wave.

A calculation of the field near the surface of a metal nanosphere.

The local field is greatly enhanced.

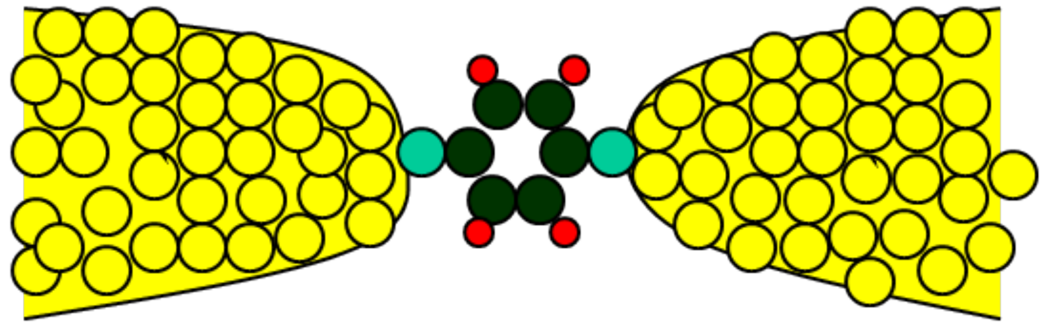


http://juluribk.com/

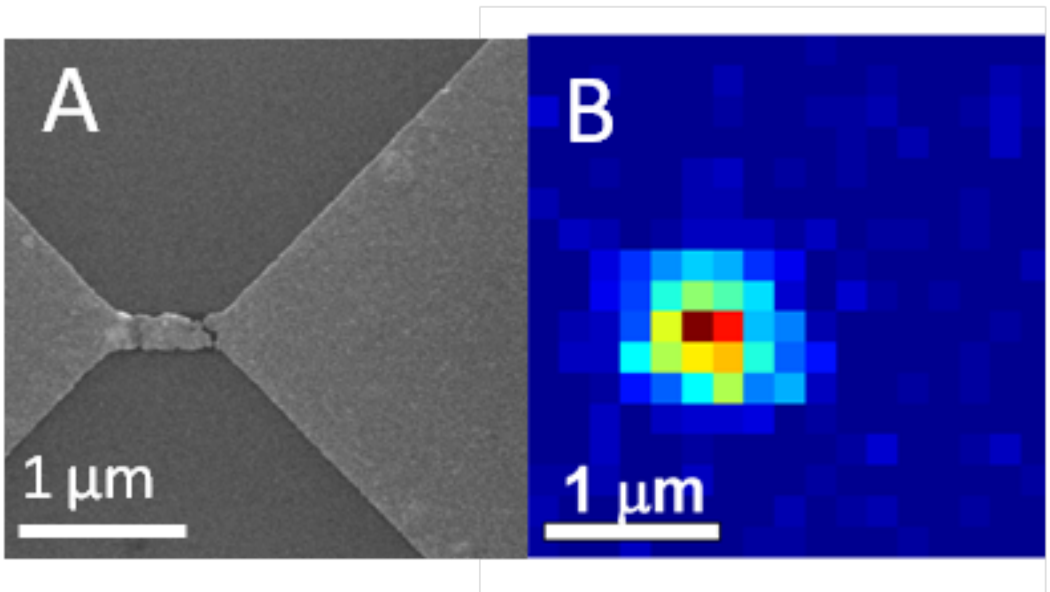
This is the basis of sensitive optical sensing techniques, even at the single-molecule level.

Single-molecule sensing using plasmons

A single molecule stuck between two tiny metal leads – the molecule couples to the plasmon oscillations in the metal.



Natelson group, Rice University



Light emitted from a single molecule!

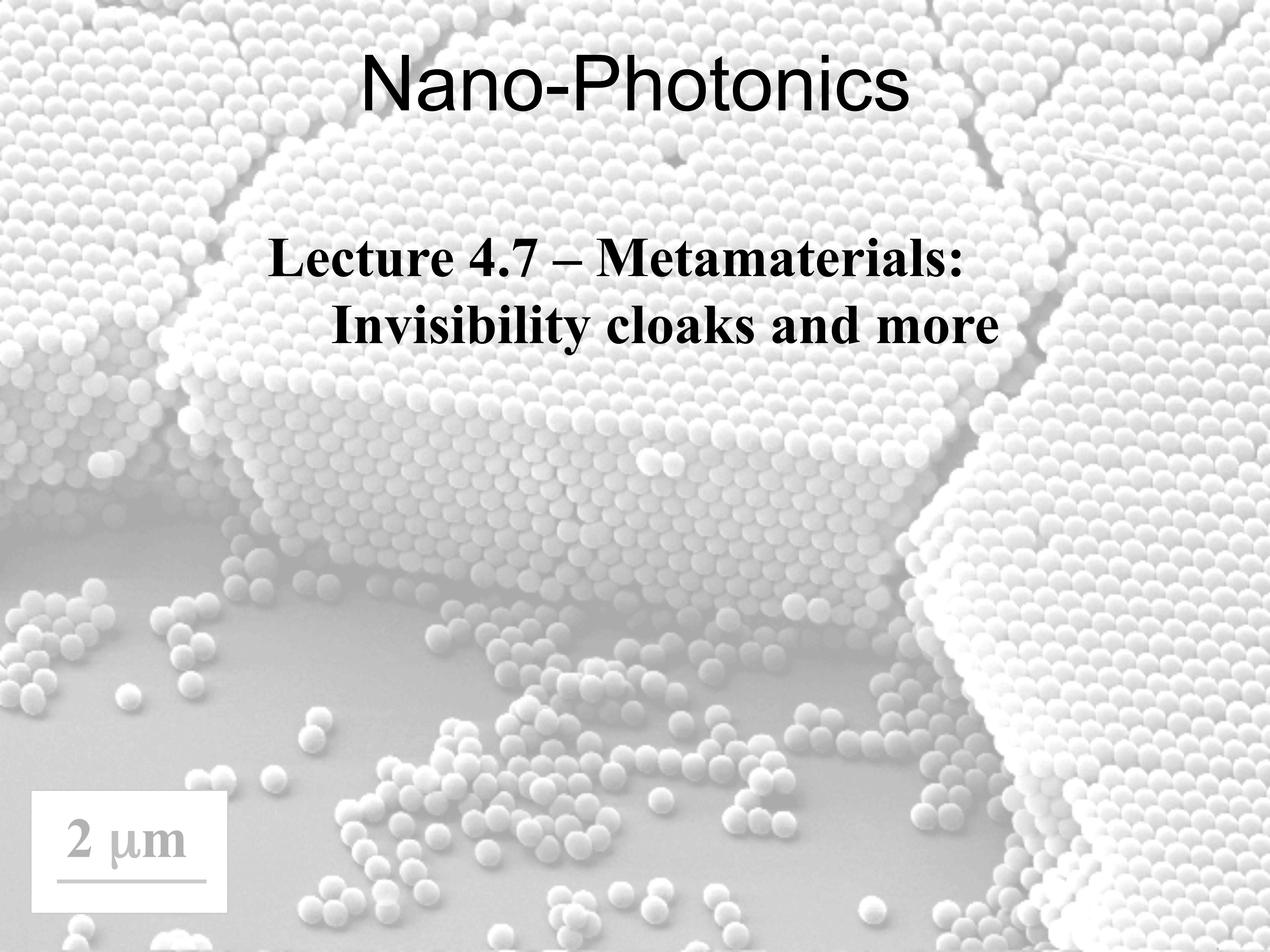
D. R. Ward, N. J. Halas, J. W. Ciszek, J. M. Tour, Y. Wu, P. Nordlander, and D. Natelson, "Simultaneous measurements of electronic conduction and Raman response in molecular junctions", Nano Lett. 8, 919-924 (2008).

The ideas

- Propagating plasmons vs. localized plasmons
- Plasmons for sensing (single molecule!)
- Plasmons for nano-focusing (λ/100 or better!)
- Plasmons: *antennas* for light

Nano-Photonics

Lecture 4.7 – Metamaterials: Invisibility cloaks and more



Antennas for light

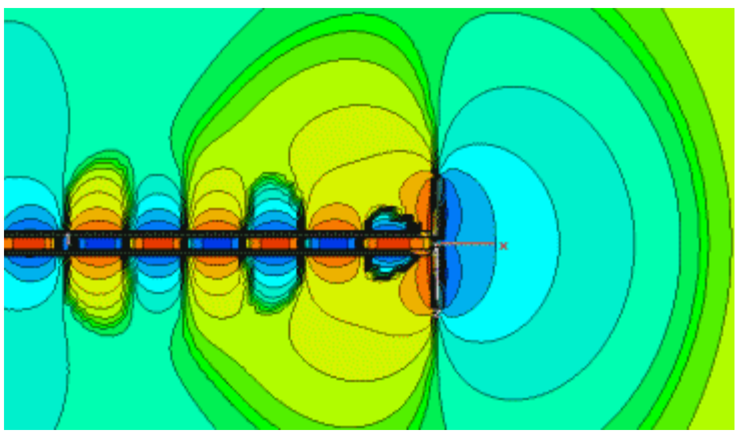
We normally don't think about antennas in the world of optics. That's a concept that is usually associated with radio frequencies and microwaves.

But, what's an antenna?

A device that collects electromagnetic energy and converts it into current (i.e., oscillating electrons), or visa versa.

Nano-metals act like antennas

a silver nanoantenna, attached to a feed line. The animation shows an electrical signal propagating along the feed line to the antenna, and then radiating.



Andrea Alu, University of Texas at Austin
http://users.ece.utexas.edu/~aalu/research.html

Can we make other electrical elements for optics?

What would this enable?

Permittivity and permeability

We have seen that the refractive index of a material is an important number to determine how light propagates inside the material.

Refractive index is composed of two fundamental quantities, the *dielectric permittivity* and the *magnetic permeability*:

$$n = \sqrt{\varepsilon\mu}$$

permittivity permeability

For transparent materials, $\varepsilon > 0$ and $\mu > 0$.

For metals, $\varepsilon < 0$ for visible and lower frequencies.
Thus $n = \sqrt{\text{a negative number}}$. That's why metals are opaque.

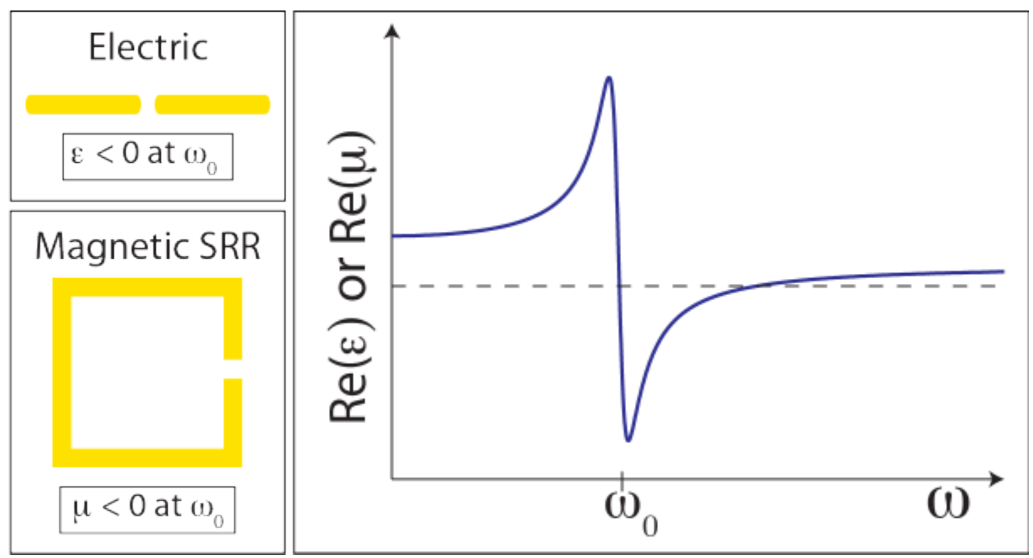
Negative permeability

If we could find a material with $\varepsilon < 0$ and $\mu < 0$, then we would recover a real-valued refractive index, and light could propagate, but with a *negative refractive index*!

In real materials, μ is never negative.
So this never happens in nature.

But in a composite material with appropriately structured sub-wavelength elements, we can engineer a material with a magnetic response.

A negative μ!

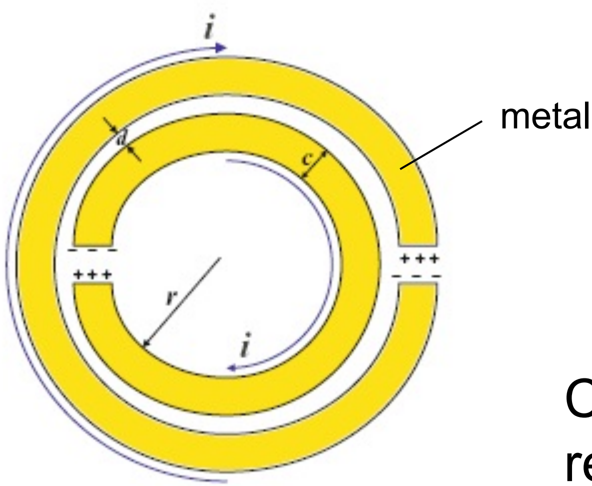


Keith Nelson, Massachusetts Institute of Technology
http://nelson.mit.edu/blog/terahertz-polaritonics

Nanostructures make this possible

In many ways, the analogy to circuit elements can be extended to the optical regime, using metal structures with size d < λ.

a “split ring resonator” can act effectively like an LC circuit.



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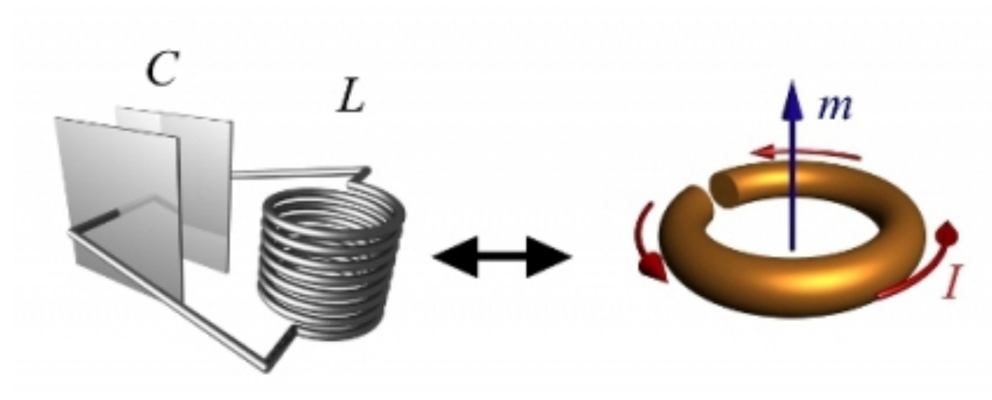


Martin Wegener, Karlsruhe Institute of Technology
http://www.aph.kit.edu/wegener/english/264.php

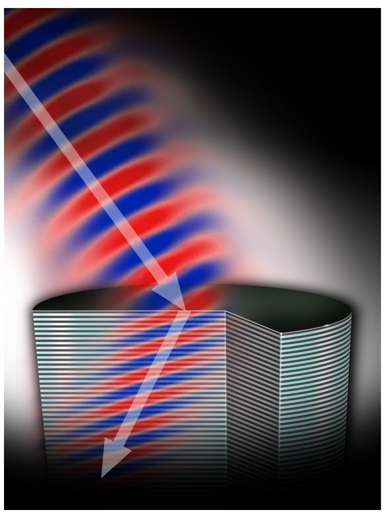
Circuit elements like this can have the kind of resonant response (with a negative μ) shown on the previous slide.

Metamaterials

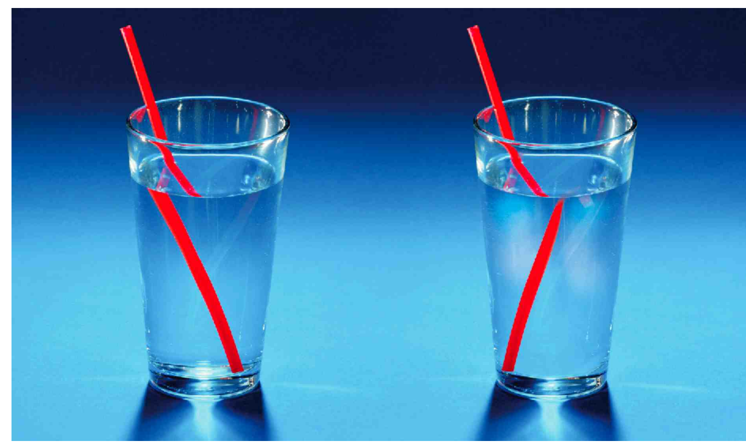
- a material which is composed of a large number of sub-wavelength-sized elements, with properties not found in any natural material.

The most famous example: a negative index of refraction!

Wikimedia Commons



An artist's rendition of light entering a negative-index material. It bends the wrong way!

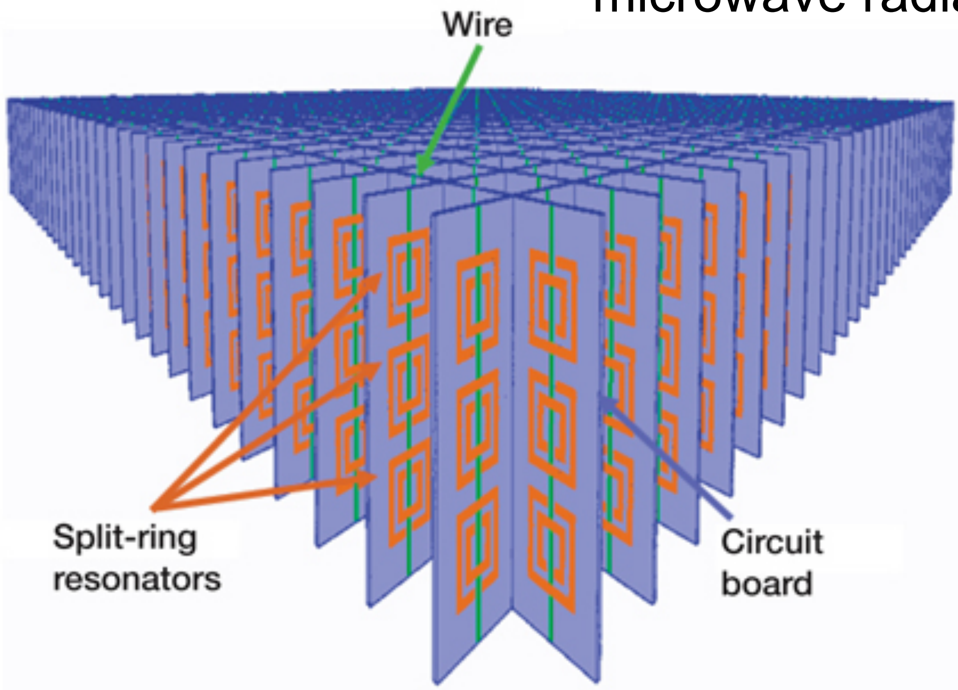


These simulated images show what a glass of ordinary water looks like (left), and what it would look like if the refractive index was negative (right).

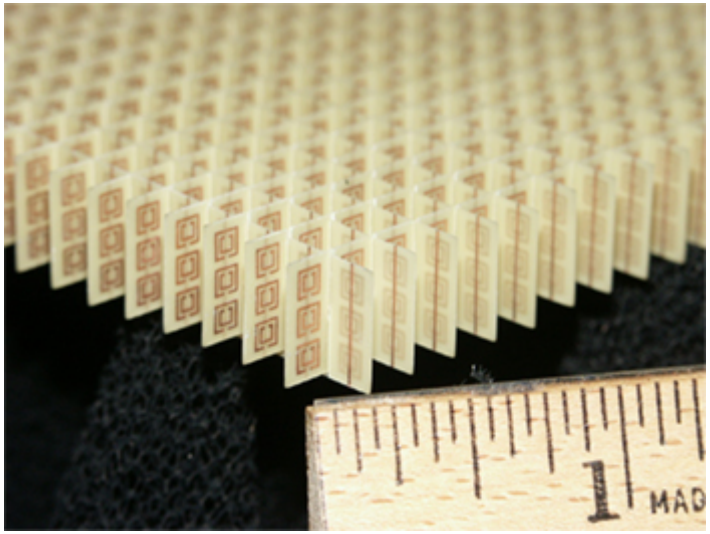
http://www.mat.ucsb.edu/~g.legrady/academic/courses/10f200a/md/metamaterials.htm

Metamaterials: the first experiment

Here, an array of split ring resonators and short wires acts as a two-dimensional medium for microwave radiation.



The wires give the negative ε.
The split rings give the negative μ.



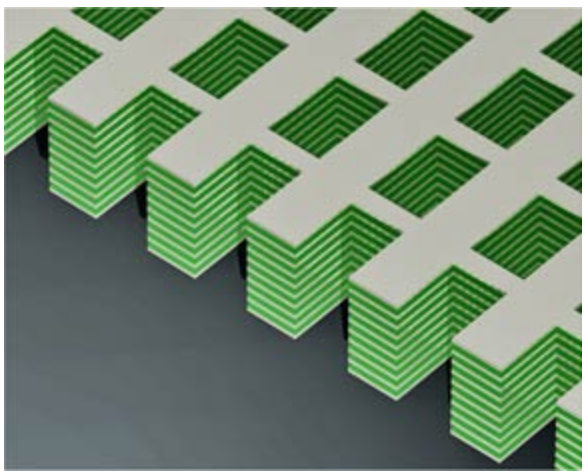
At a certain frequency (10.5 GHz), this metamaterial has a negative refractive index.

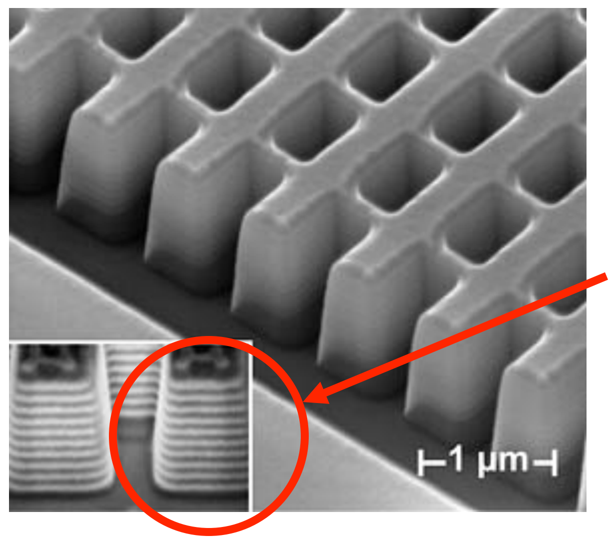
Images: Wikimedia Commons

Is it possible to make structures that do this for visible light?

Yes, but it's much harder than for microwaves, because the length scale ($\sim\lambda/10$) is small.

Xiang Zhang, UC Berkeley,
http://xlab.me.berkeley.edu/



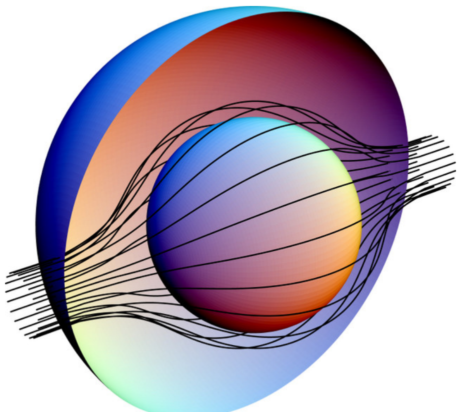


Alternating nano-layers of silver and magnesium fluoride

A first step: a nanostructured "fishnet" material that exhibits negative refractive index for near-infrared light

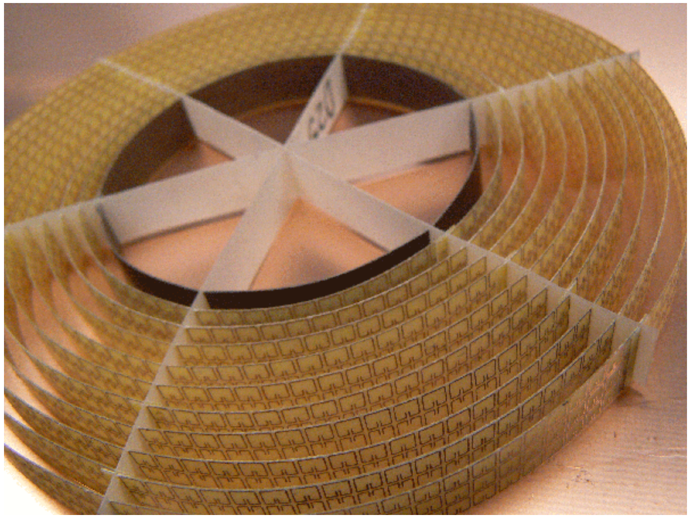
A negative index material would enable many new things

Example: the invisibility cloak



David Smith, Duke University
http://www.pratt.duke.edu/news/david-smith-creating-new-materials-go-beyond-nature

David Smith, Duke University
http://people.ee.duke.edu/~drsmith/gallery.htm

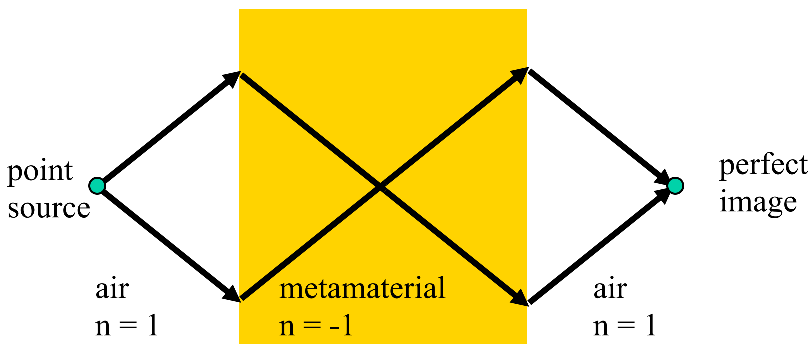


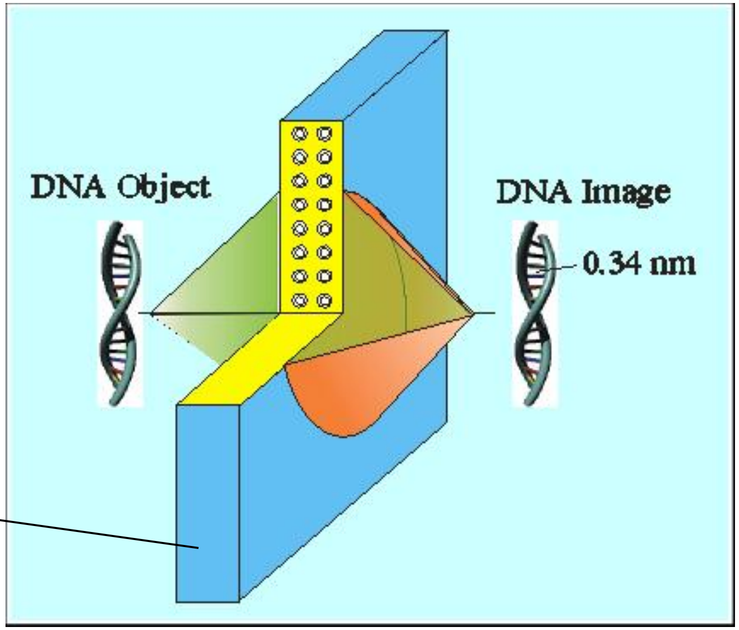
The first demonstration of invisibility cloaking, using microwave radiation

Because this was done for long wavelength radiation (λ ~ cm), nothing here is nano-sized.

Other uses for metamaterials

Another example: a negative refractive index would enable perfect lenses and therefore perfect imaging.



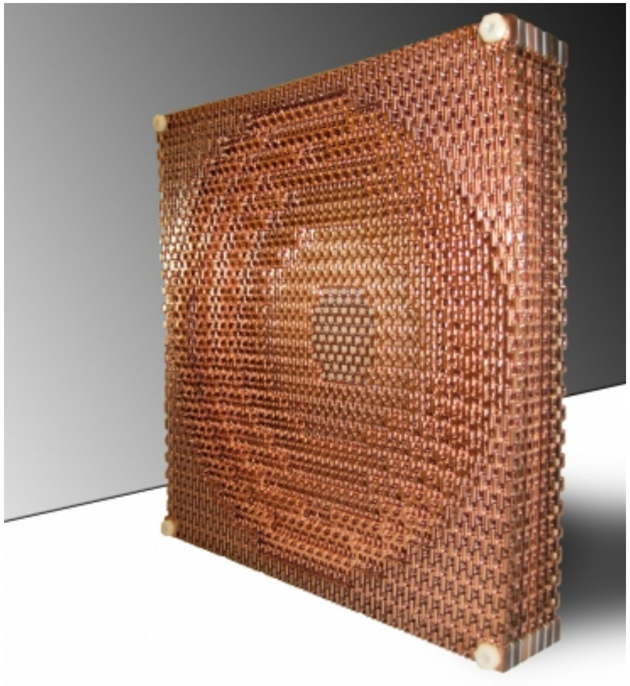


a slab of material
with negative index

Xiang Zhang, UC Berkeley,
http://xlab.me.berkeley.edu/

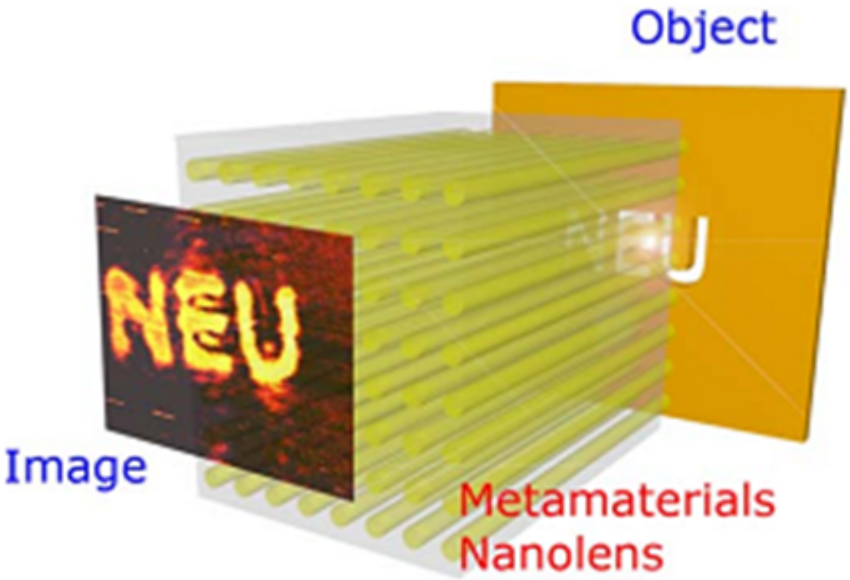
Superlenses: demonstrations

A demonstration using radio waves (λ = 3 cm) of focusing to a spot size of $\lambda/4$ by a negative index lens.



Sanjay Sarma, Massachusetts Institute of Technology,
http://web.mit.edu/newsoffice/2012/new-metamaterial-lens-focuses-radio-waves-1114.html

An image of letters using λ = 1500 nm, with ~500 nm resolution.



Srinivas Sridar, Northeastern University
http://sagar.physics.neu.edu/nanooptics.htm

Much remains to be done.

The ideas

- Metamaterials: artificial composite materials that exhibit properties not found in nature (e.g., negative refraction)
- Works from microwaves (easier) to visible (much harder!)
- Perfect lenses, invisibility cloaks