



Excitons and Plasmons

- light manipulation on the nanoscale -



Roman Krahne
Erice - August 2012





ISTITUTO ITALIANO
DI TECNOLOGIA

Nanostructures Department – Director Enzo Di Fabrizio





ISTITUTO ITALIANO
DI TECNOLOGIA

Nanostructures Department

Research Themes

- Delivering energy at the nanoscale
- Novel devices for single molecule detection
- Metal-semiconductor hybrid nanosystems

Approaches and tools

- Plasmonic nanostructures
- Raman spectroscopy
- Clean room device fabrication
- Electrical and optical experiments



Nanostructures group @ IIT



CdSe
nanocrystals

Excitons and Plasmons - light manipulation on the nanoscale -



Lycurgus cup

Notre Dame
Paris

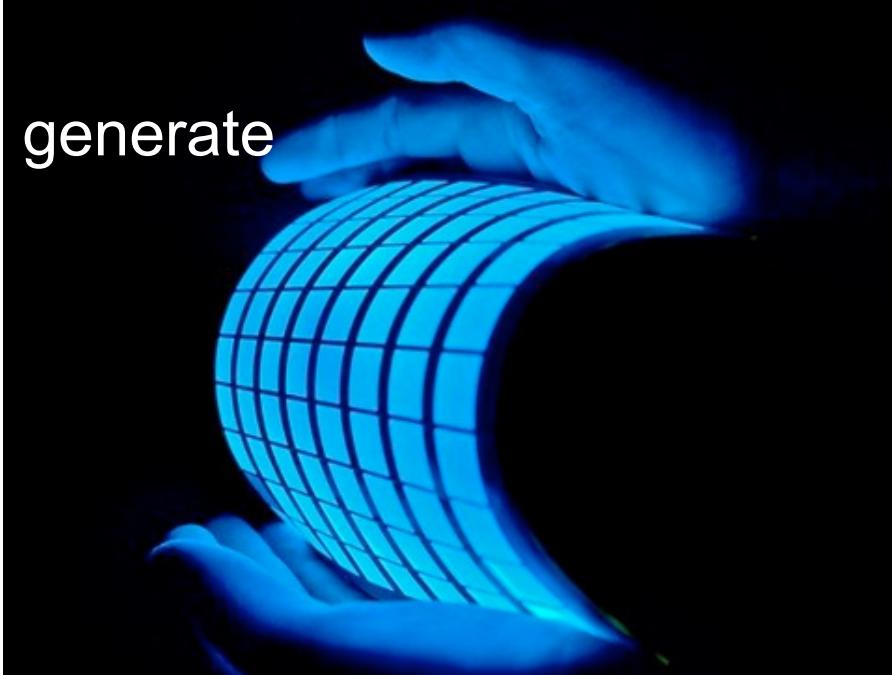




This talk is on light

What we want to do

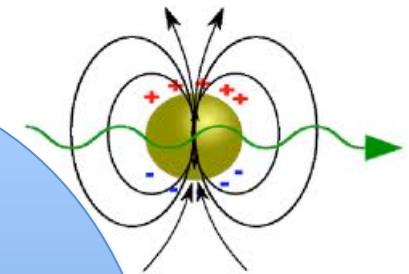
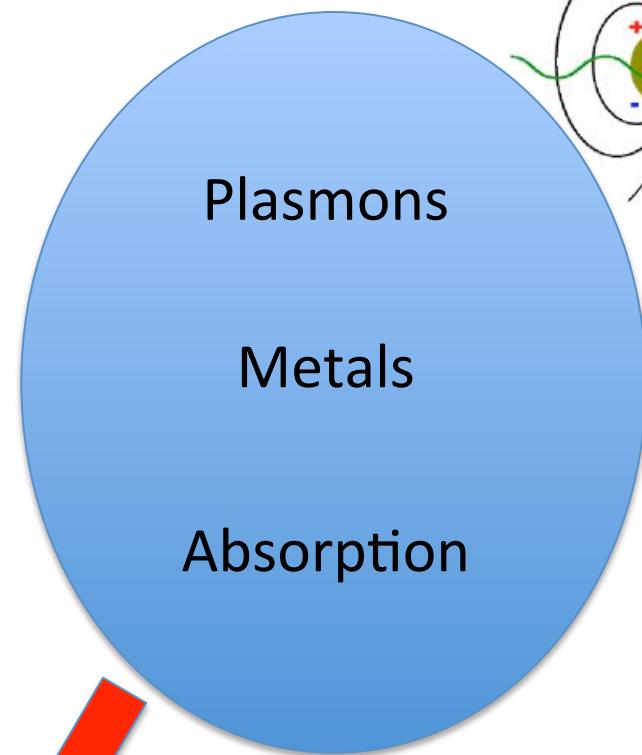
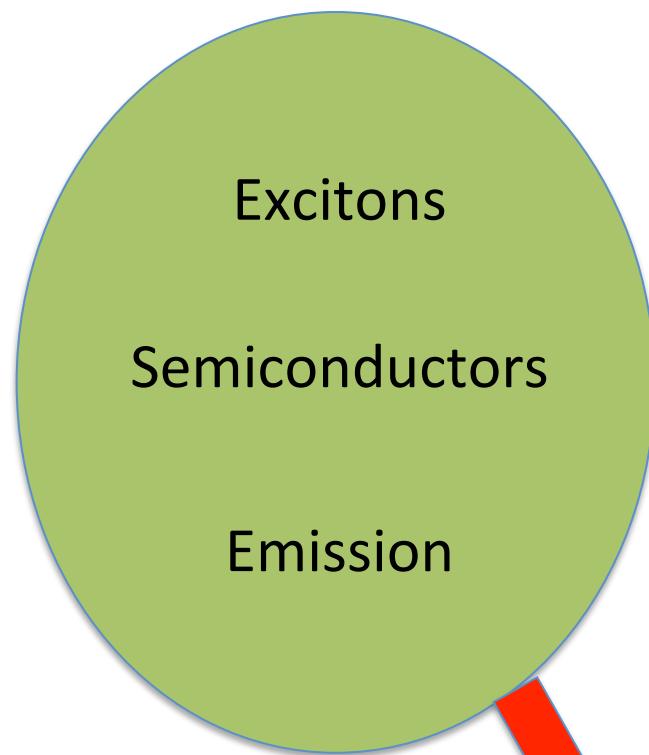
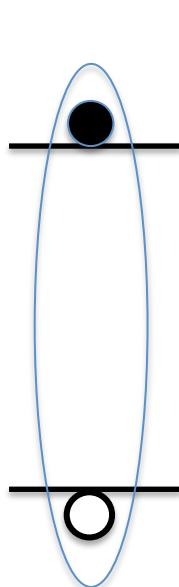
filter



generate



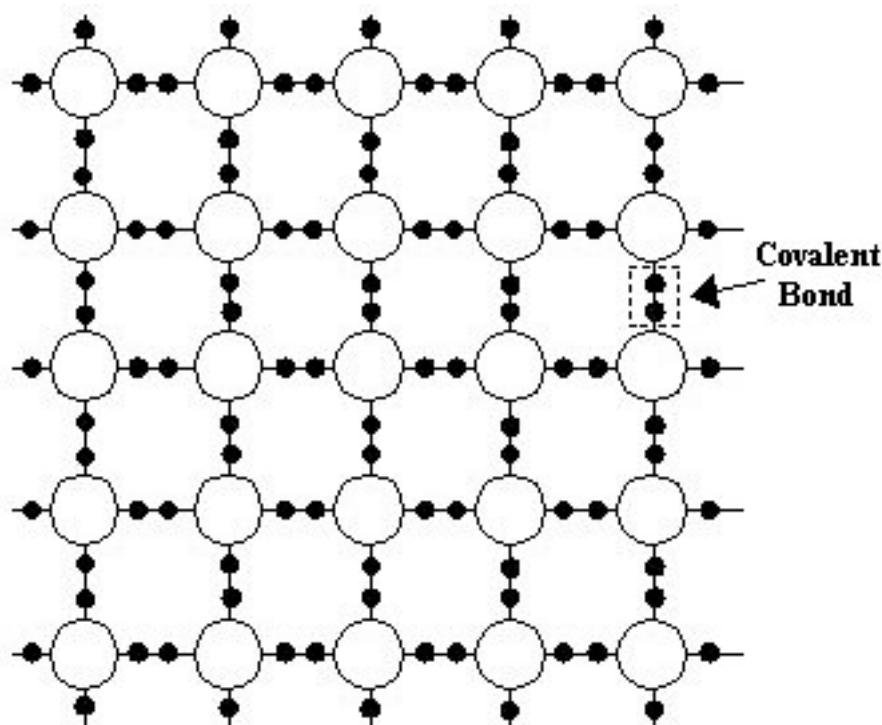
Understand the basics



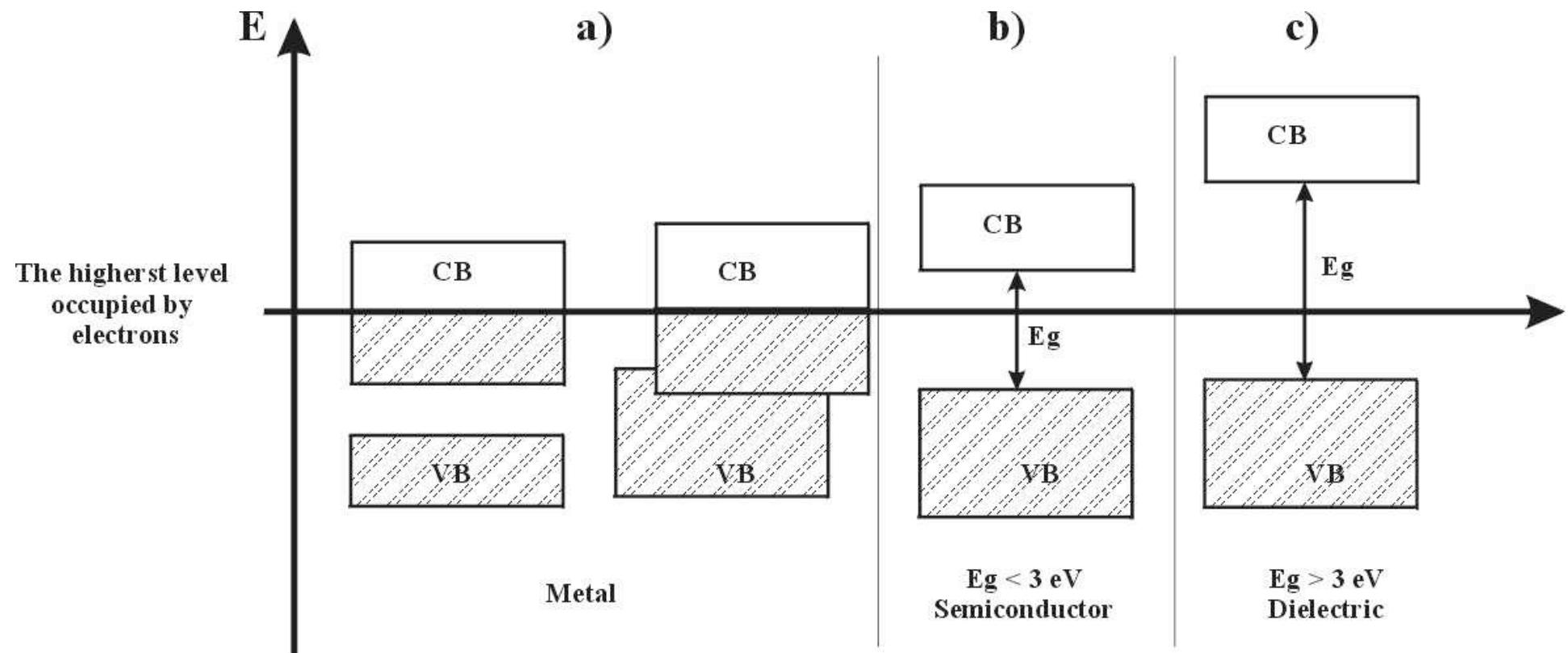
-> Solid State Physics

Solid State Physics

Crystals: regular lattice of atoms

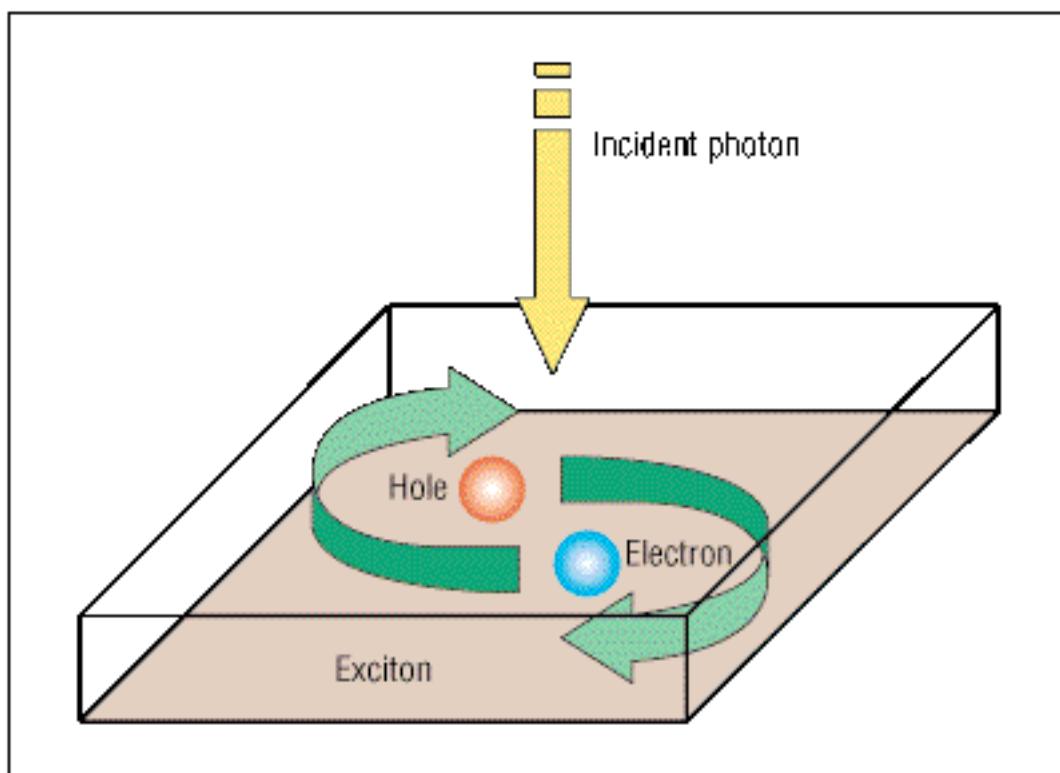


Band structure

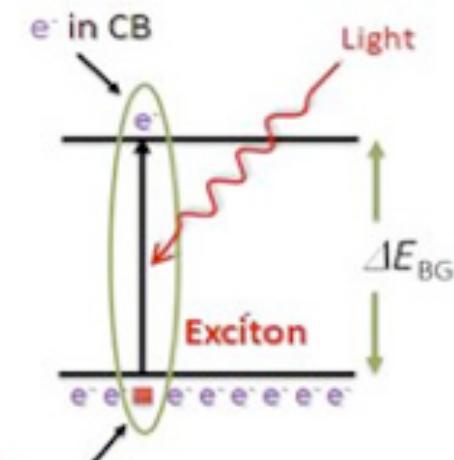
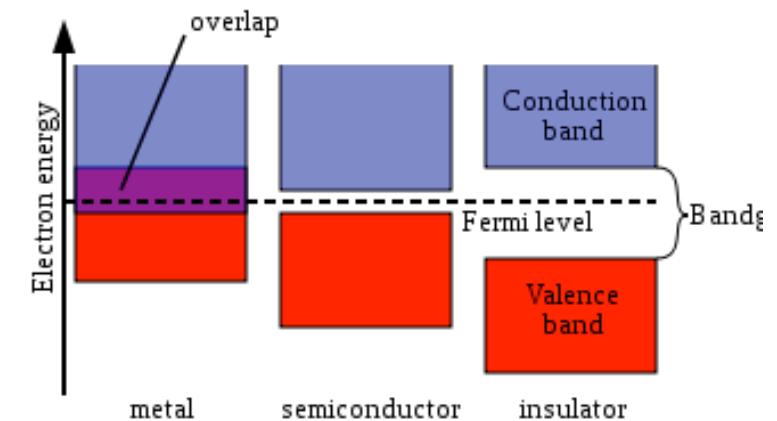


Band gap determines the amount of energy needed to excite an electron!

Semiconductors: excitons

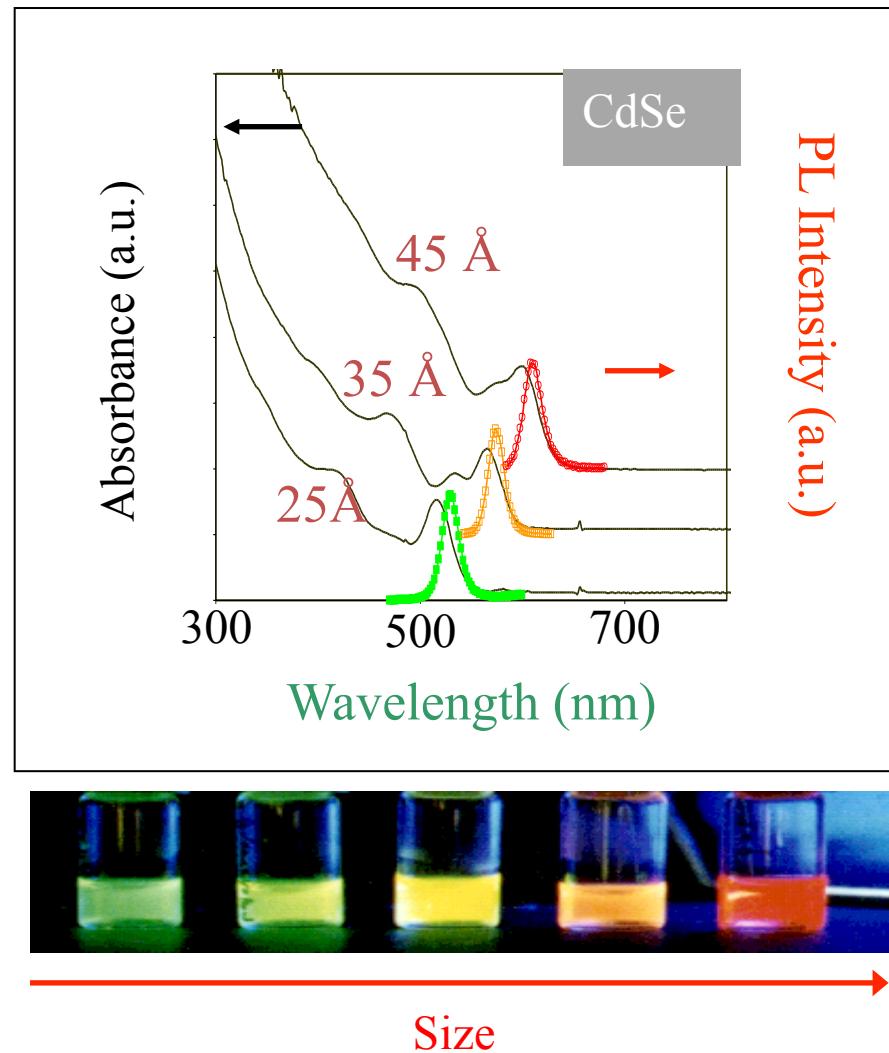
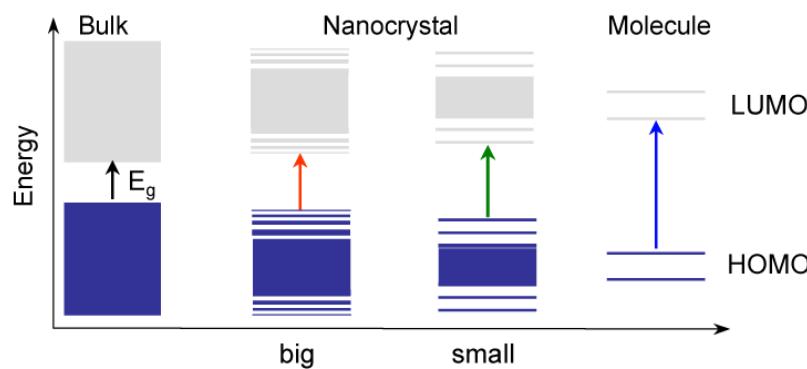
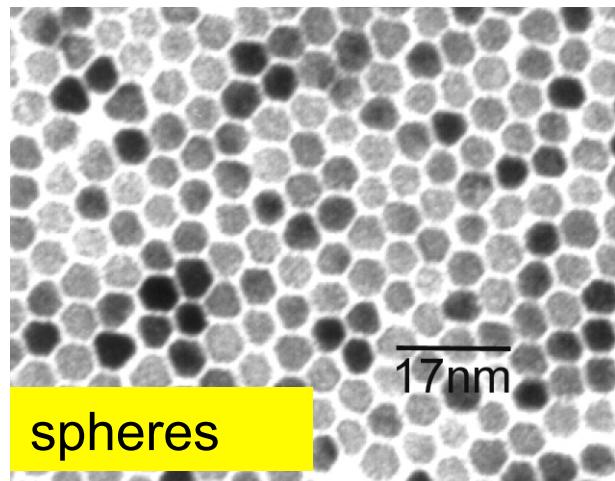


Real space



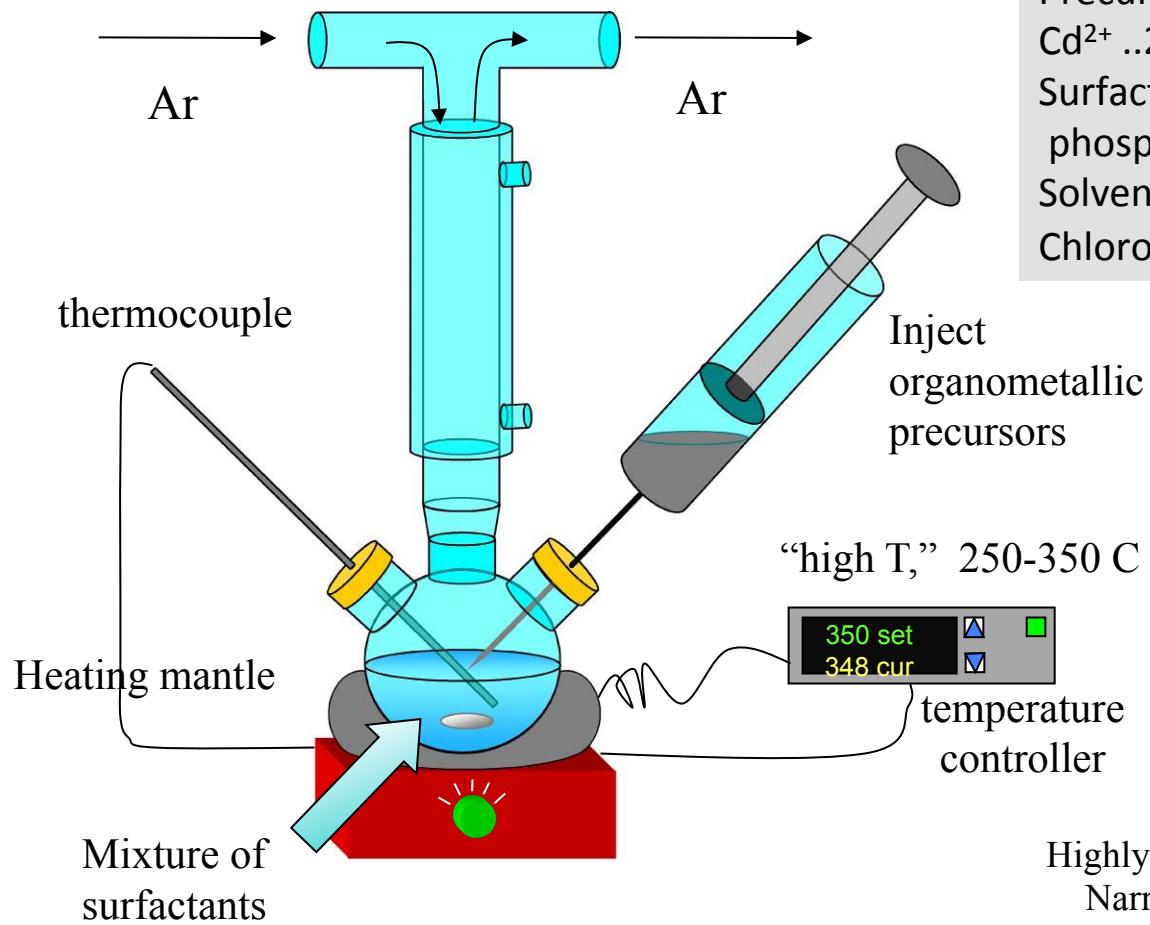
Energy diagram

Size-Dependent Optical Properties of Semiconductor Nanocrystals



- 1) the positions of both the exciton and the PL peaks are related to the mean NC size
- 2) the width of the peaks reflects the size-distribution

Synthesis of colloidal nanocrystals in hot surfactants



Precursors:

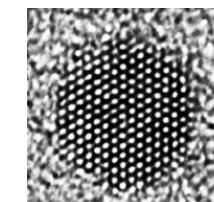
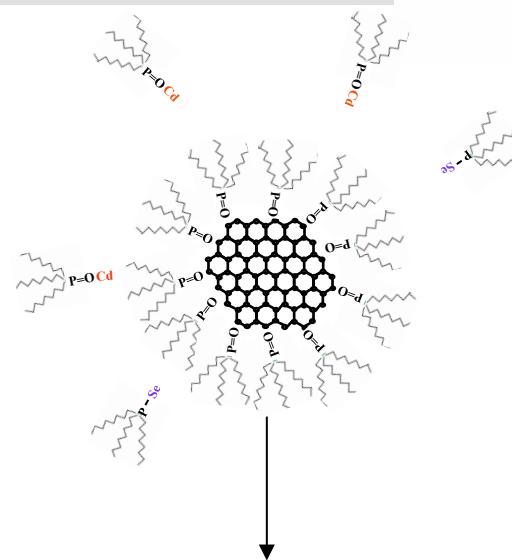
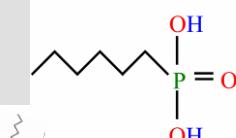
$\text{Cd}^{2+} \dots 2(\text{ODPA})$ and $\text{Te}:(\text{C}_8\text{H}_{17})_3\text{P} \rightarrow \text{CdTe}$

Surfactants:

phosphonic acids, phosphine, phosphine oxide

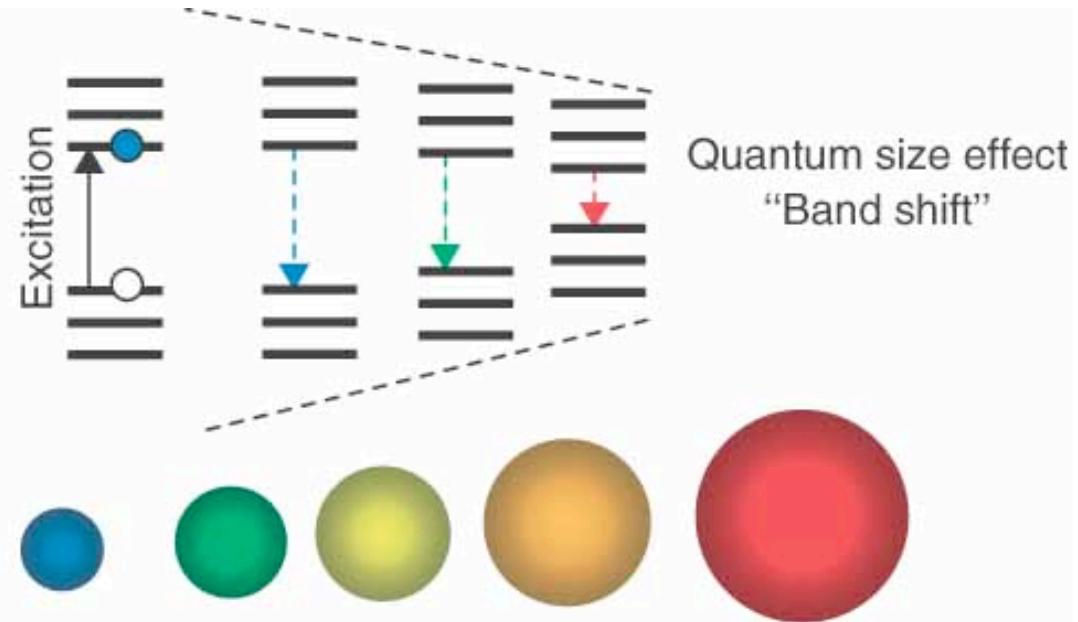
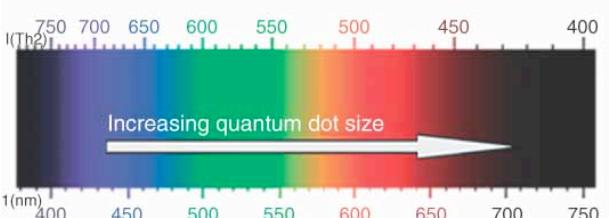
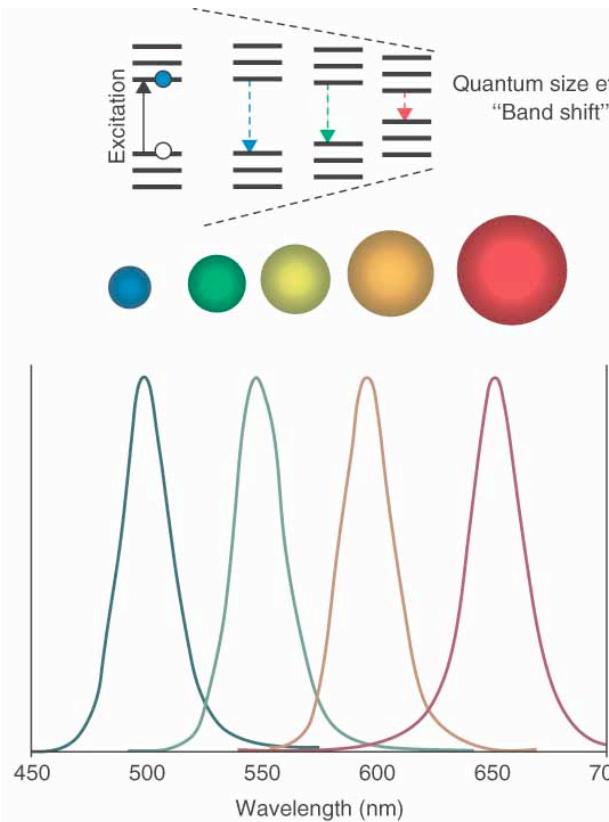
Solvents:

Chloroform, toluene,



After injection:

- Nucleation
- Reaction limited regime (high monomer concentration)
- Diffusion limited regime

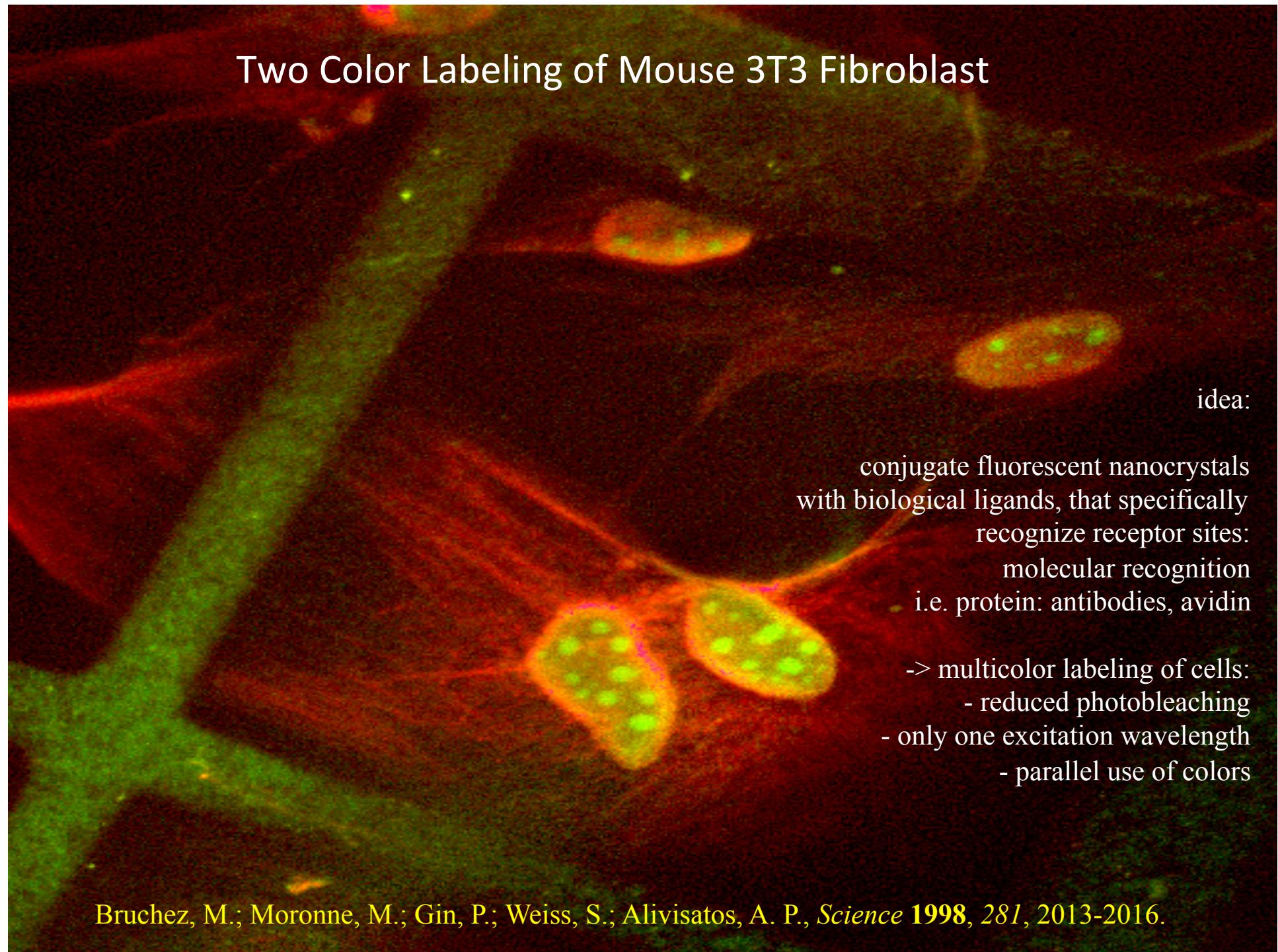


Example CdSe:

Nanocrystal size: 2-6nm

Emission wavelength: 450-650 nm

Application examples



Two Color Labeling of Mouse 3T3 Fibroblast

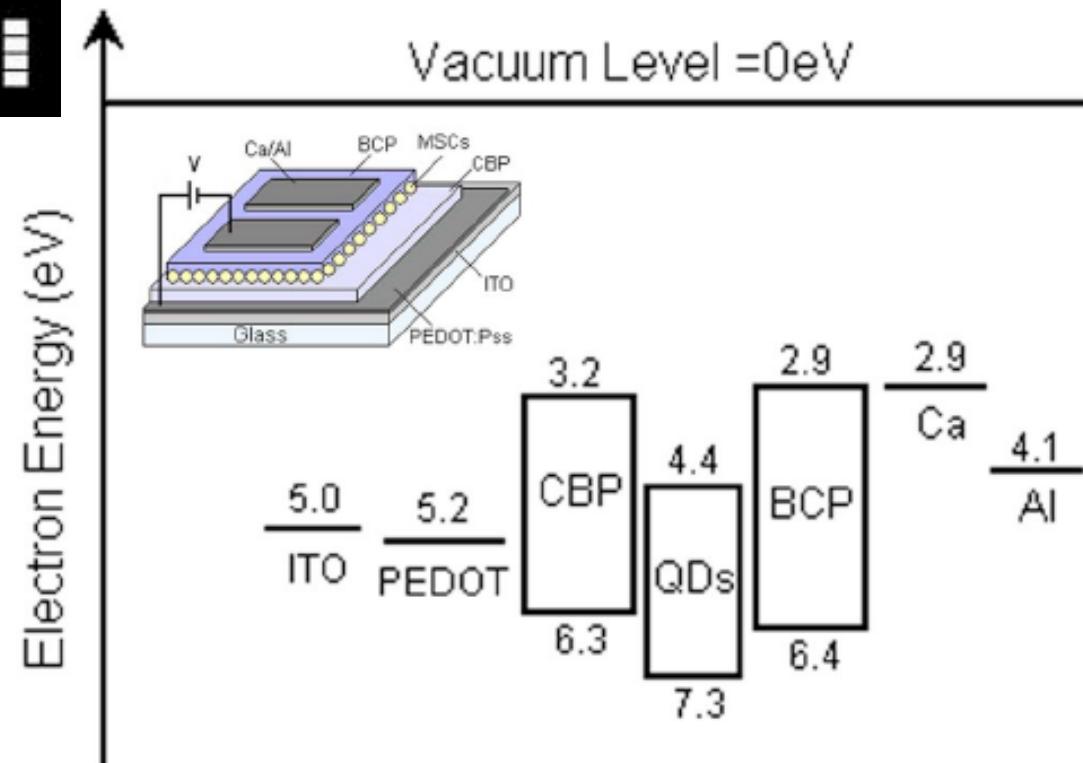
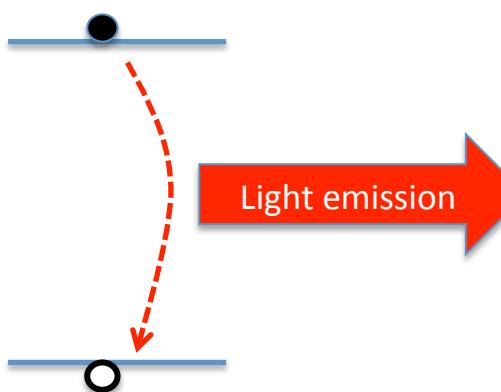
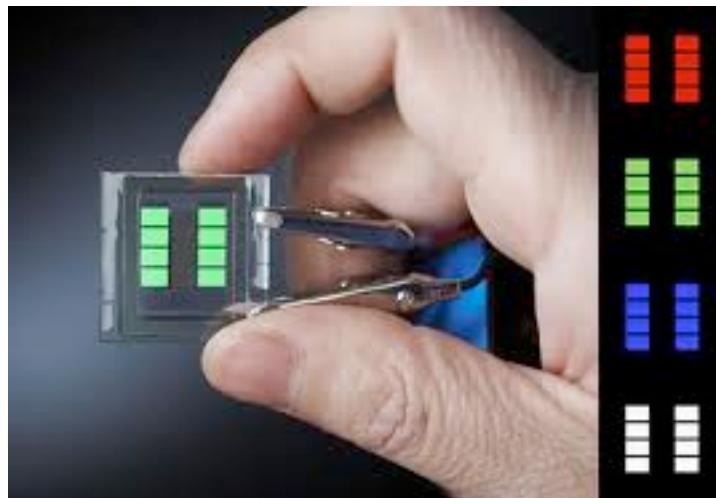
idea:

conjugate fluorescent nanocrystals
with biological ligands, that specifically
recognize receptor sites:
molecular recognition
i.e. protein: antibodies, avidin

- > multicolor labeling of cells:
 - reduced photobleaching
 - only one excitation wavelength
 - parallel use of colors

Bruchez, M.; Moronne, M.; Gin, P.; Weiss, S.; Alivisatos, A. P., *Science* **1998**, *281*, 2013-2016.

Light emitting diodes



A. Rizzo et al. APL 90, 51106 (2007)

Color-selective semiconductor nanocrystal laser

Hans-Jürgen Eisler,^{a)} Vikram C. Sundar,^{a)} and Moungi G. Bawendi^{b)}

Department of Chemistry and Center for Materials Science and Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge Massachusetts 02139

Michael Walsh and Henry I. Smith

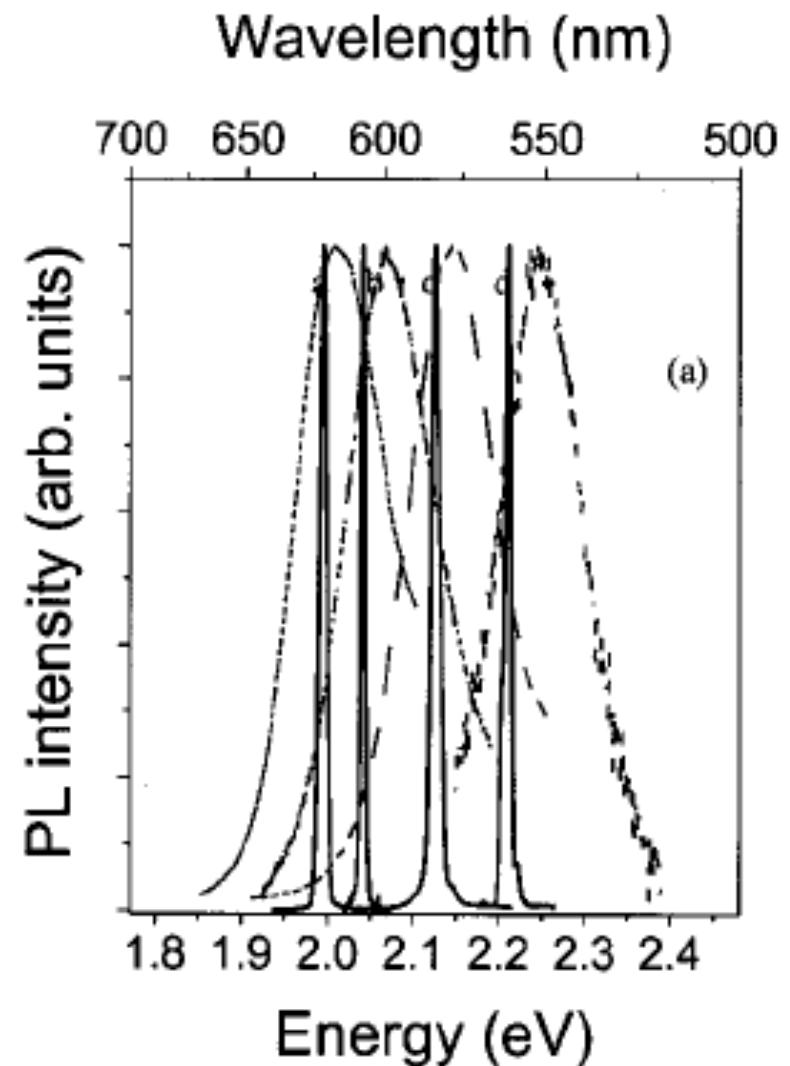
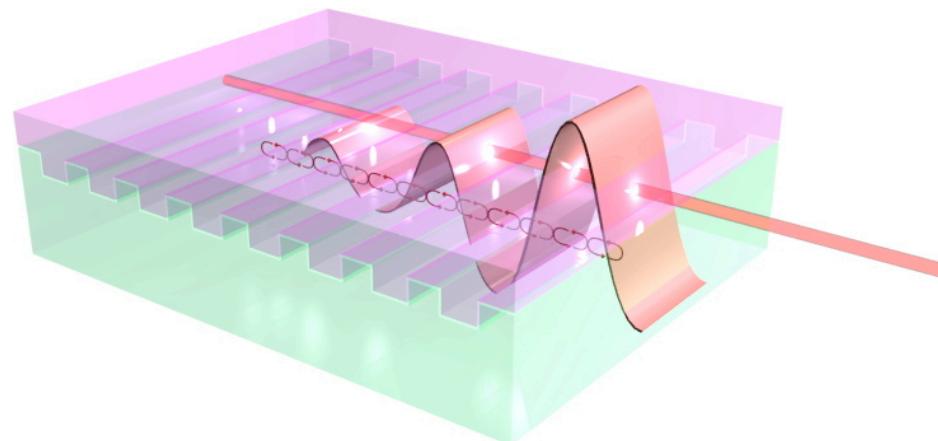
Nanostructures Laboratory, Department of Electrical Engineering at Institute of Technology, 77 Massachusetts Avenue, Cambridge Massa

Victor Klimov

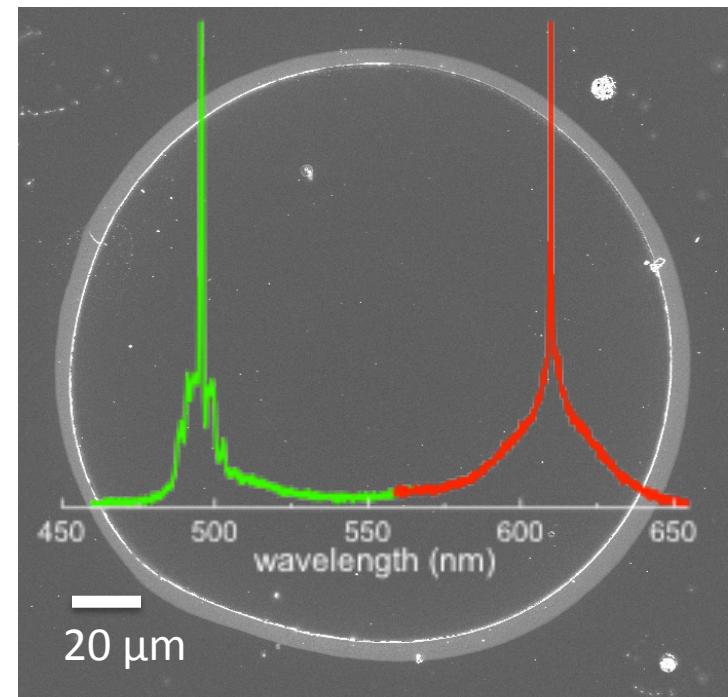
Chemistry Division, C-PCS, Los Alamos National Laboratories, Los

(Received 14 February 2002; accepted for publication 22 Apr

Gain material: nanocrystals
Resonator: Distributed Feedback



Coffee stain microlasers

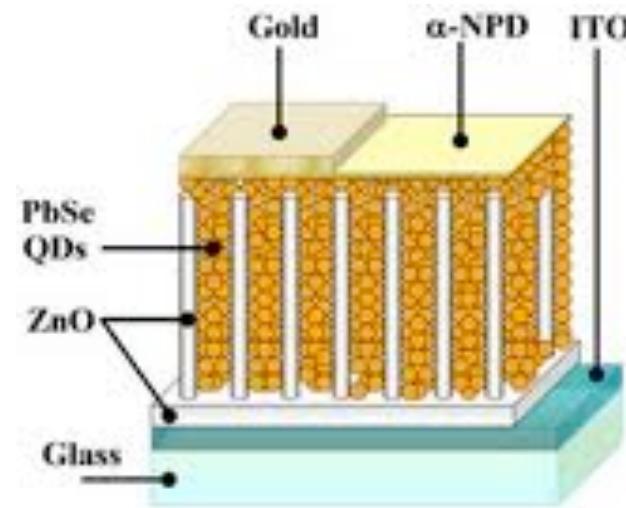
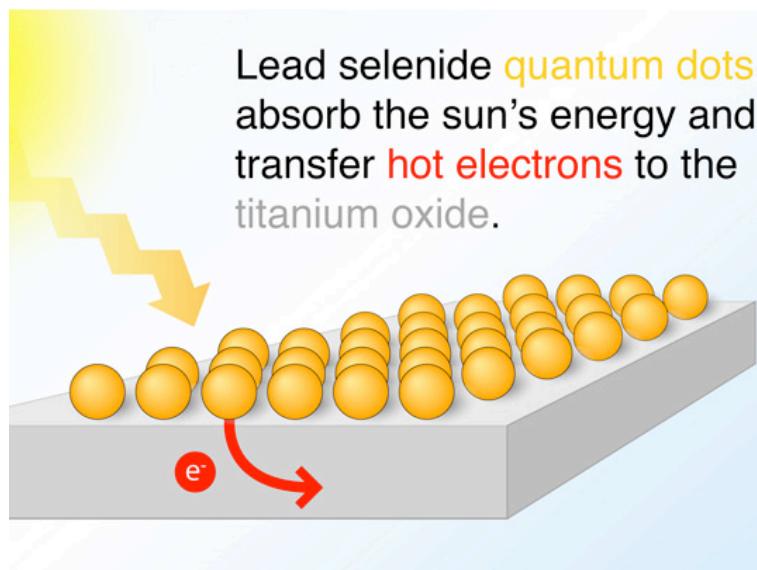


R. Krahne et al., US patent application n. 13/021.221 (04-02-2011)

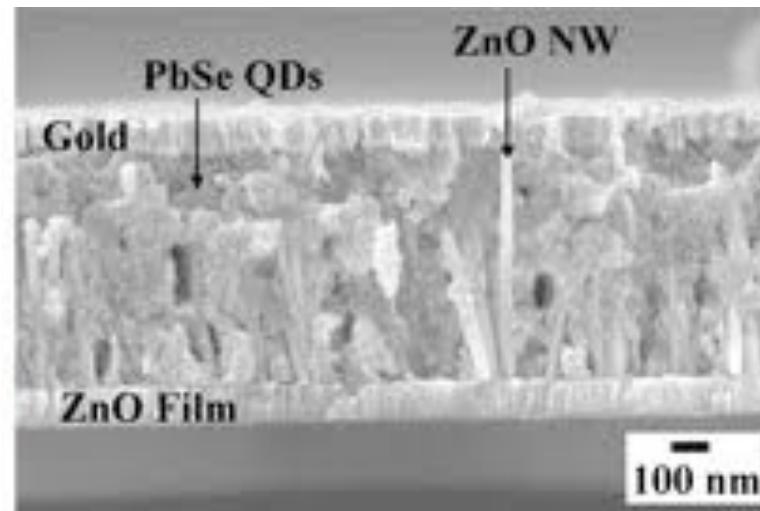
M. Zavelani et al., "Self-assembled CdSe/CdS nanorod micro-lasers fabricated from solution by capillary jet deposition", Laser&Photonics Reviews 2012

Lasing in self-assembled microcavities

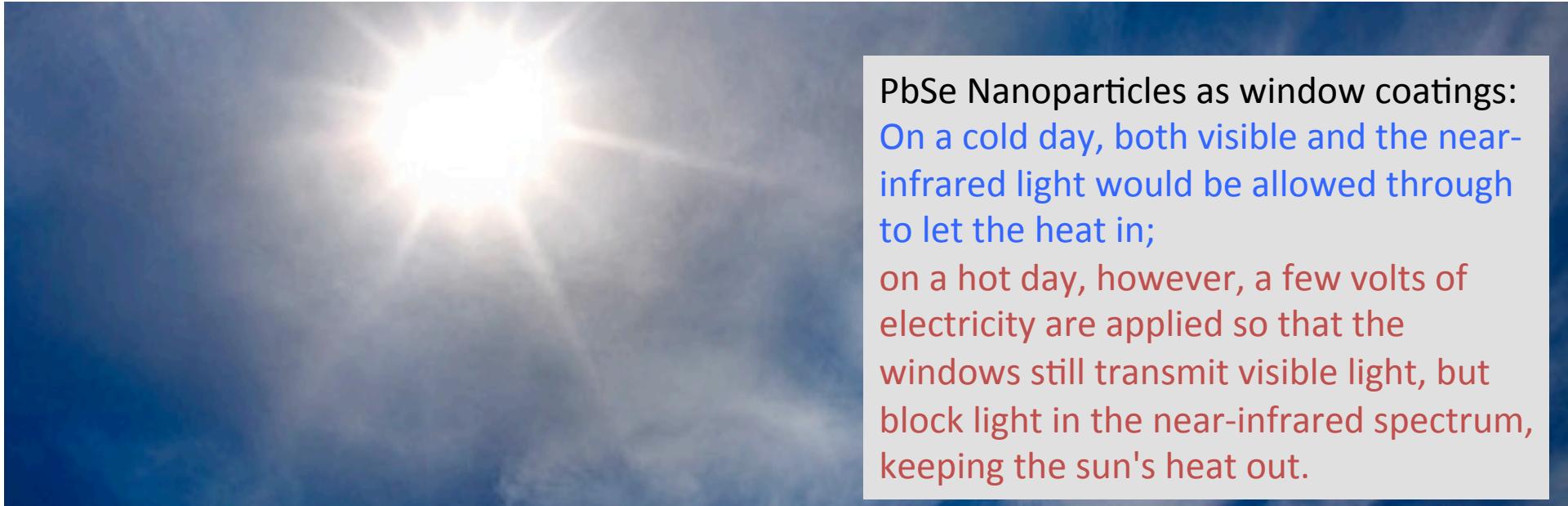




Quantum dots for photovoltaics

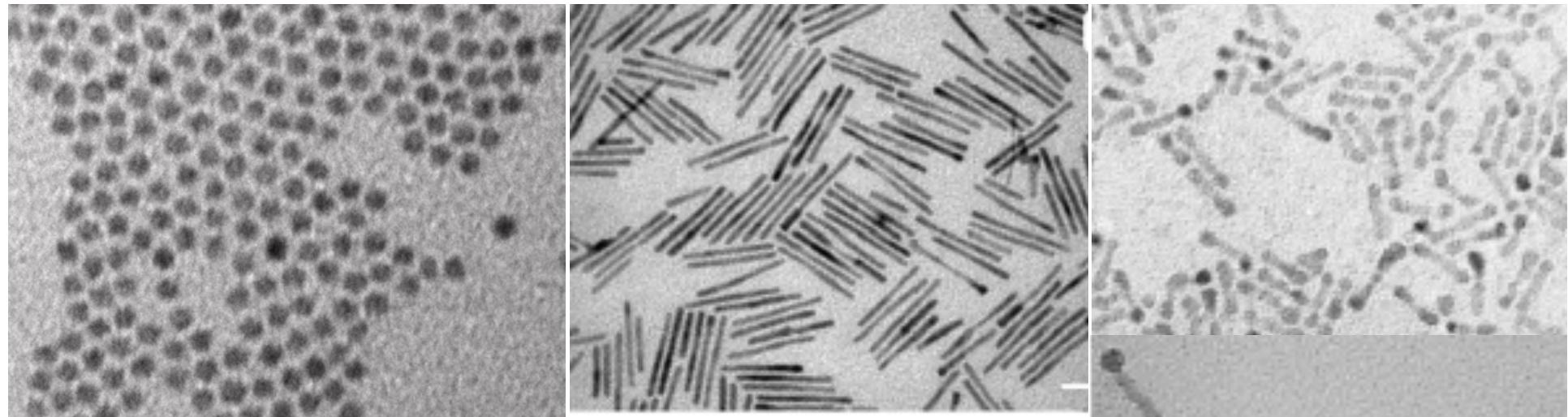


["Hot Electron Transfer from Semiconductor Nanocrystals"](#), W. A. Tisdale, K. J. Williams, B. C. Timp, D. J. Norris, E. S. Aydil, and X.-Y. Zhu; *Science* **328**, 1543 (2010).

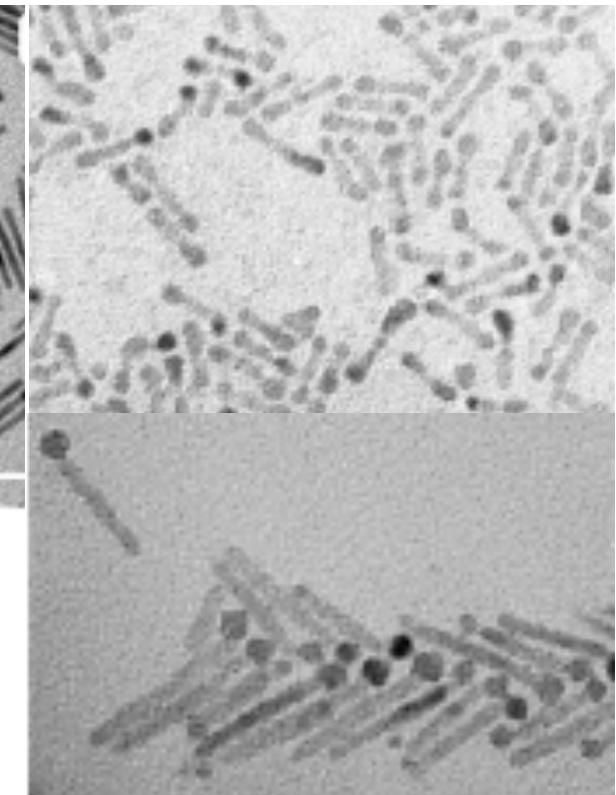
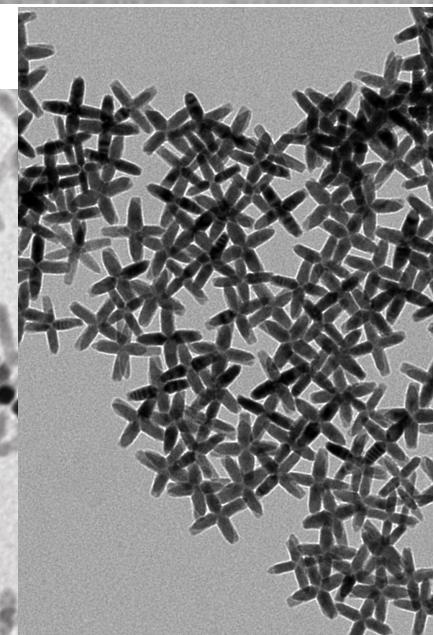
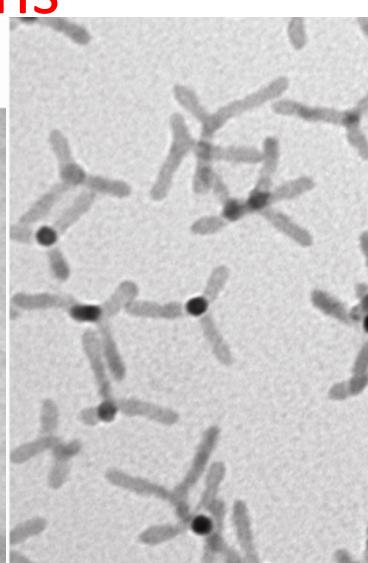
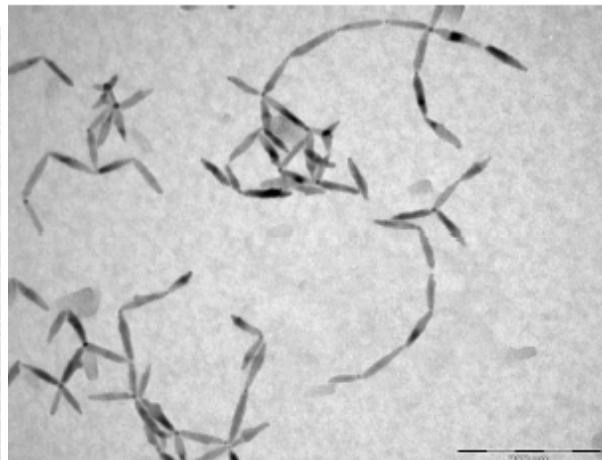
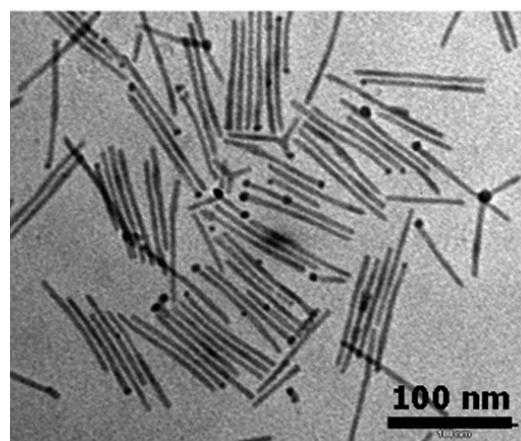
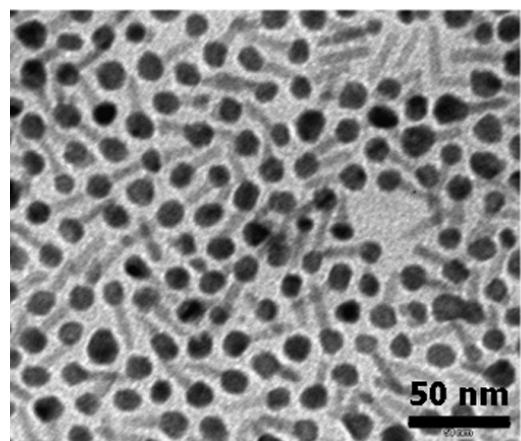


PbSe Nanoparticles as window coatings:
On a cold day, both visible and the near-infrared light would be allowed through to let the heat in;
on a hot day, however, a few volts of electricity are applied so that the windows still transmit visible light, but block light in the near-infrared spectrum, keeping the sun's heat out.





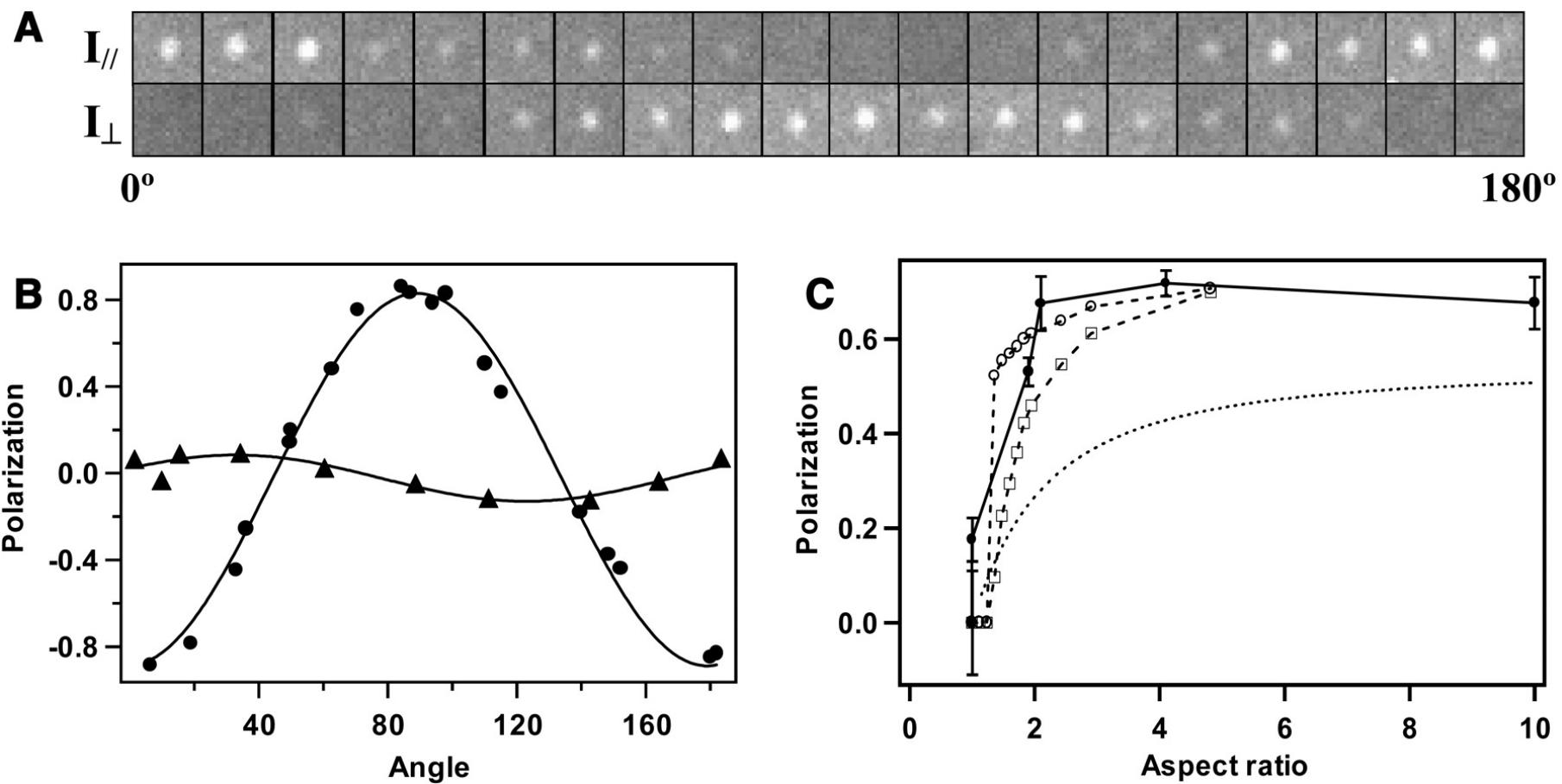
Colloidal semiconductor nanocrystals: Various shapes and compositions



Shape control: nanorods

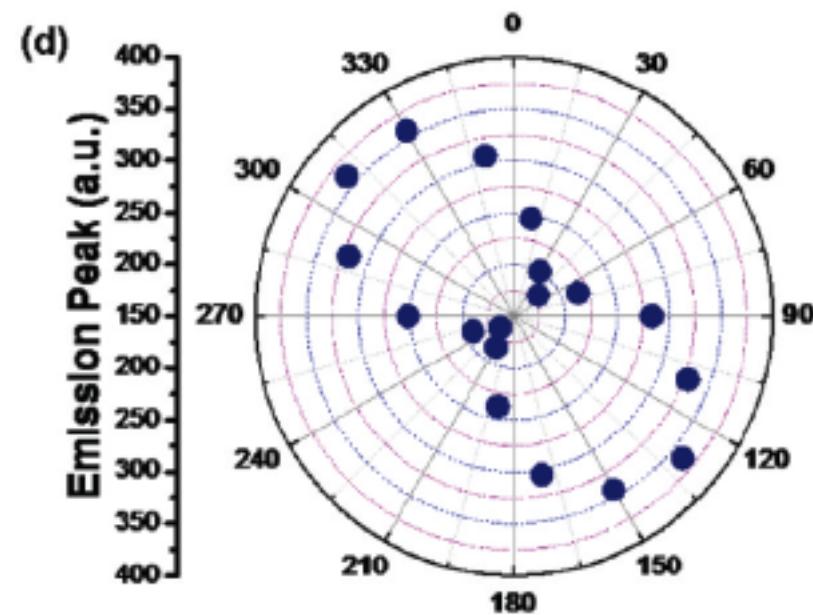
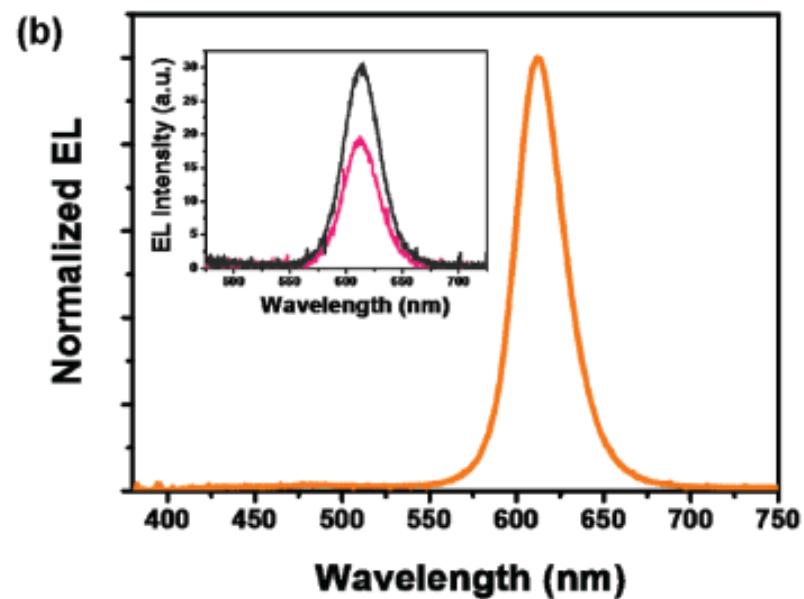
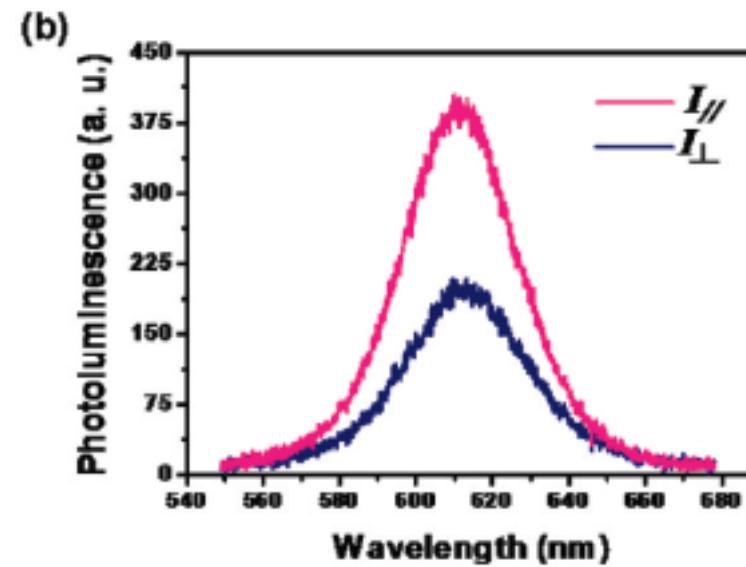
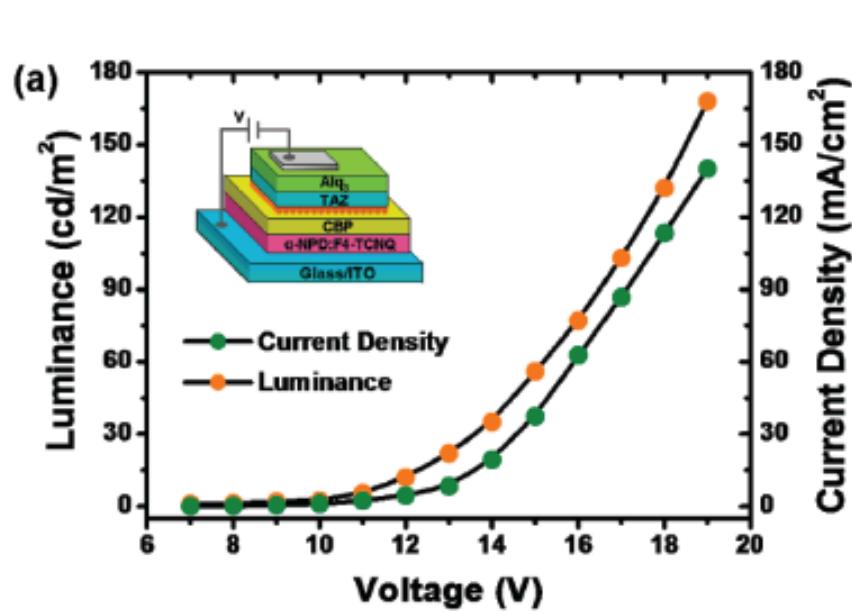


Polarized emission

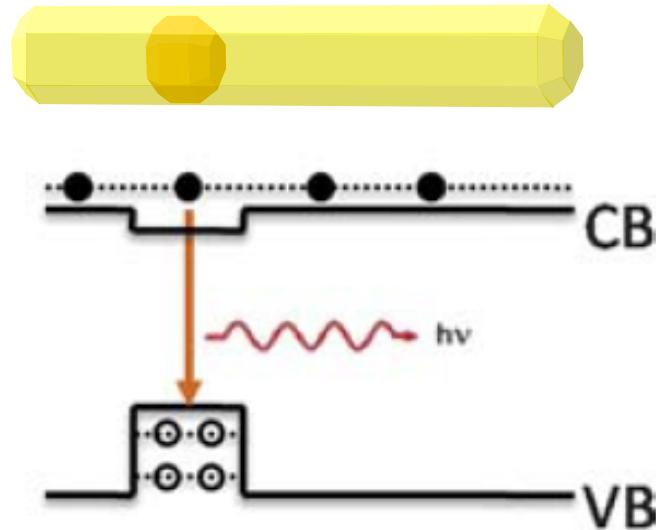


Hu et al., Science (2001)

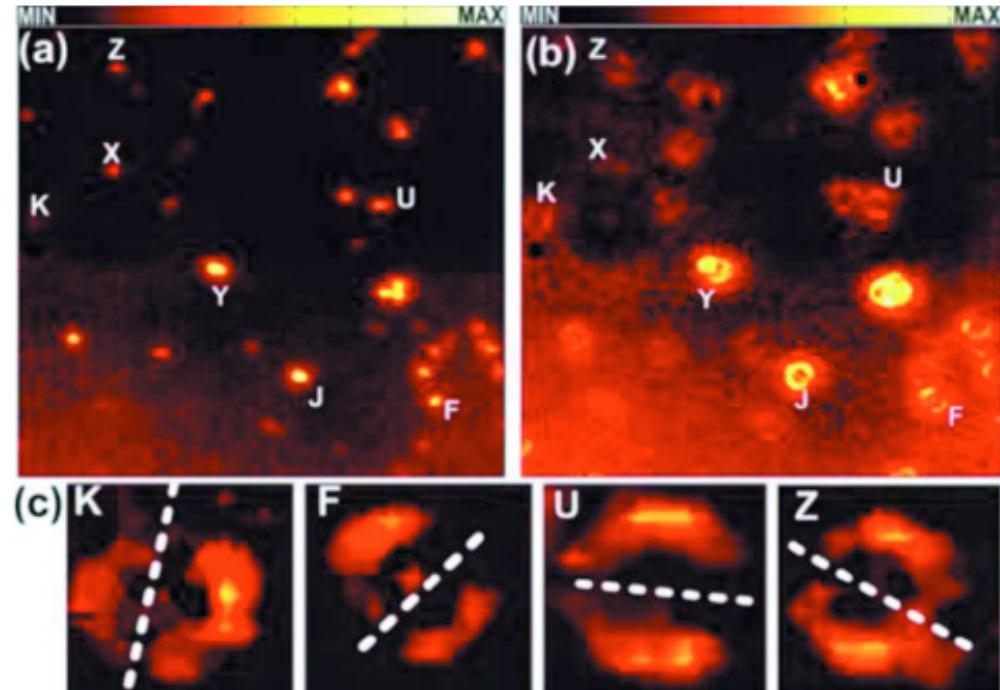
Polarized light emitting diode



Core-shell nanorods



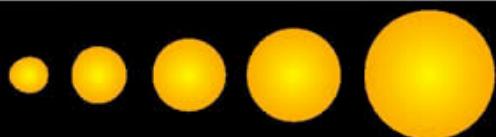
Dipole antenna emission

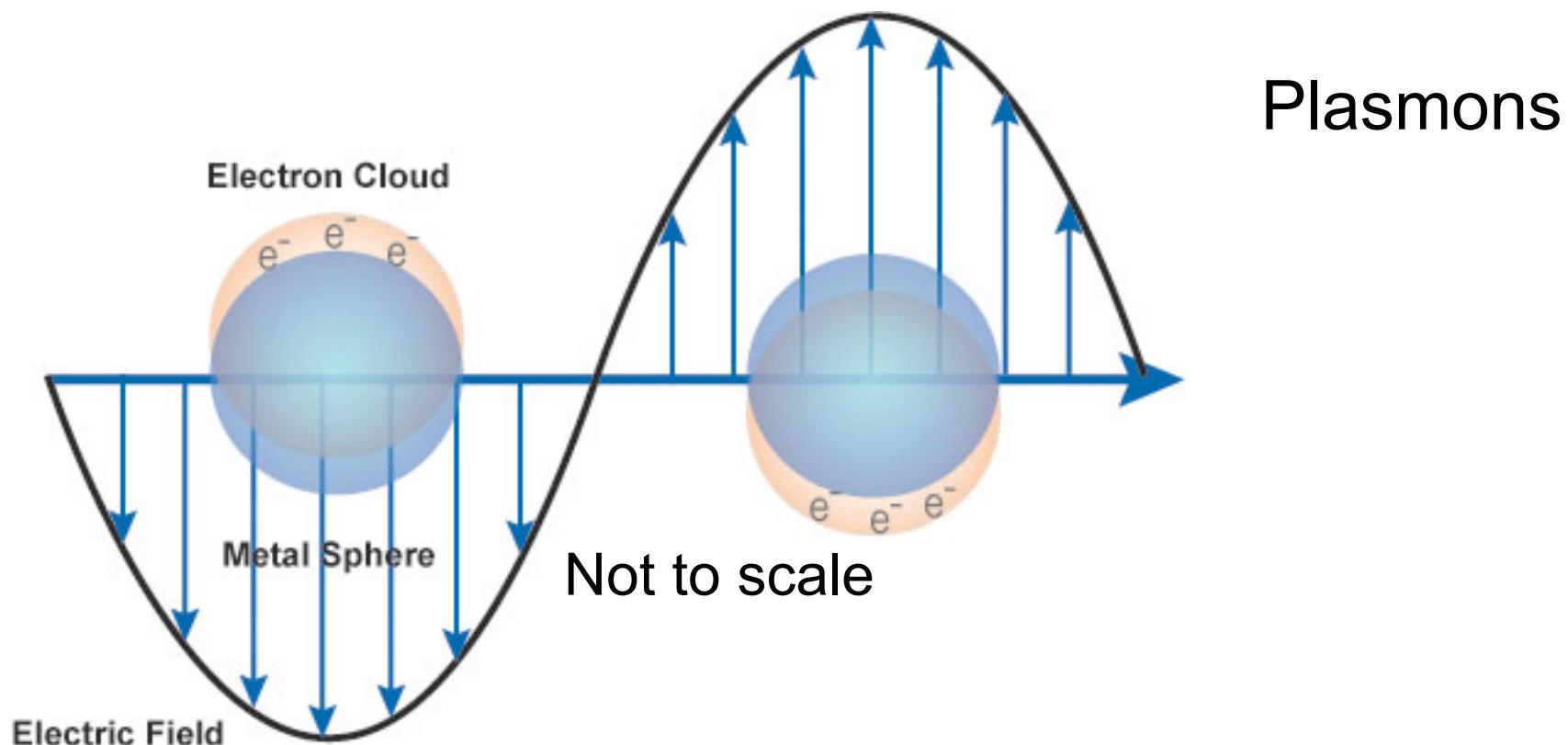


Pisanello et al., APL 96, 33101 (2010)

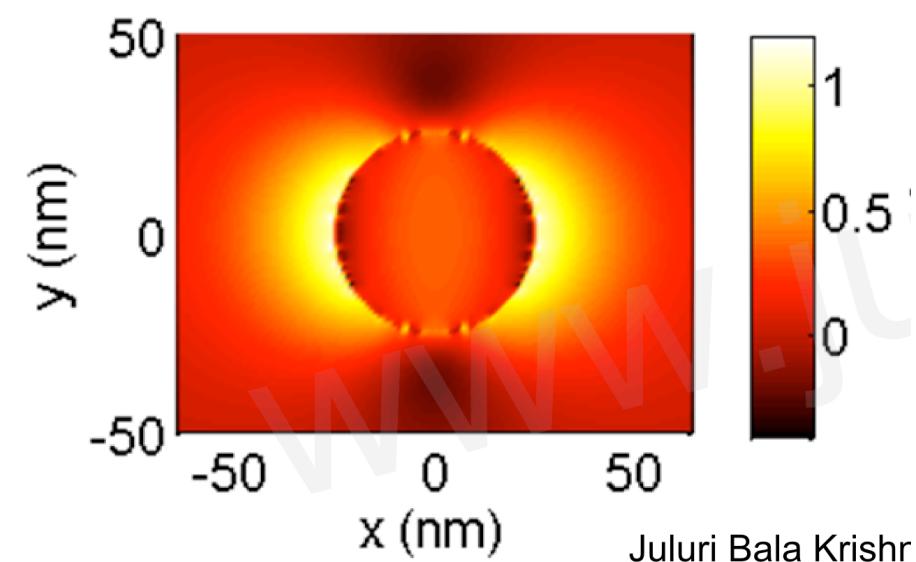
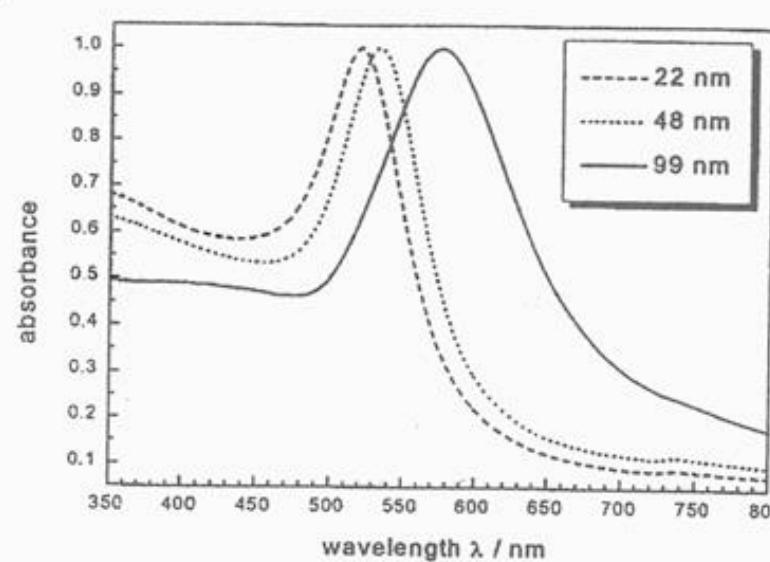
Light is absorbed by full rod volume,
but color depends on core size
very bright emitting material!

Metal Nanoparticles



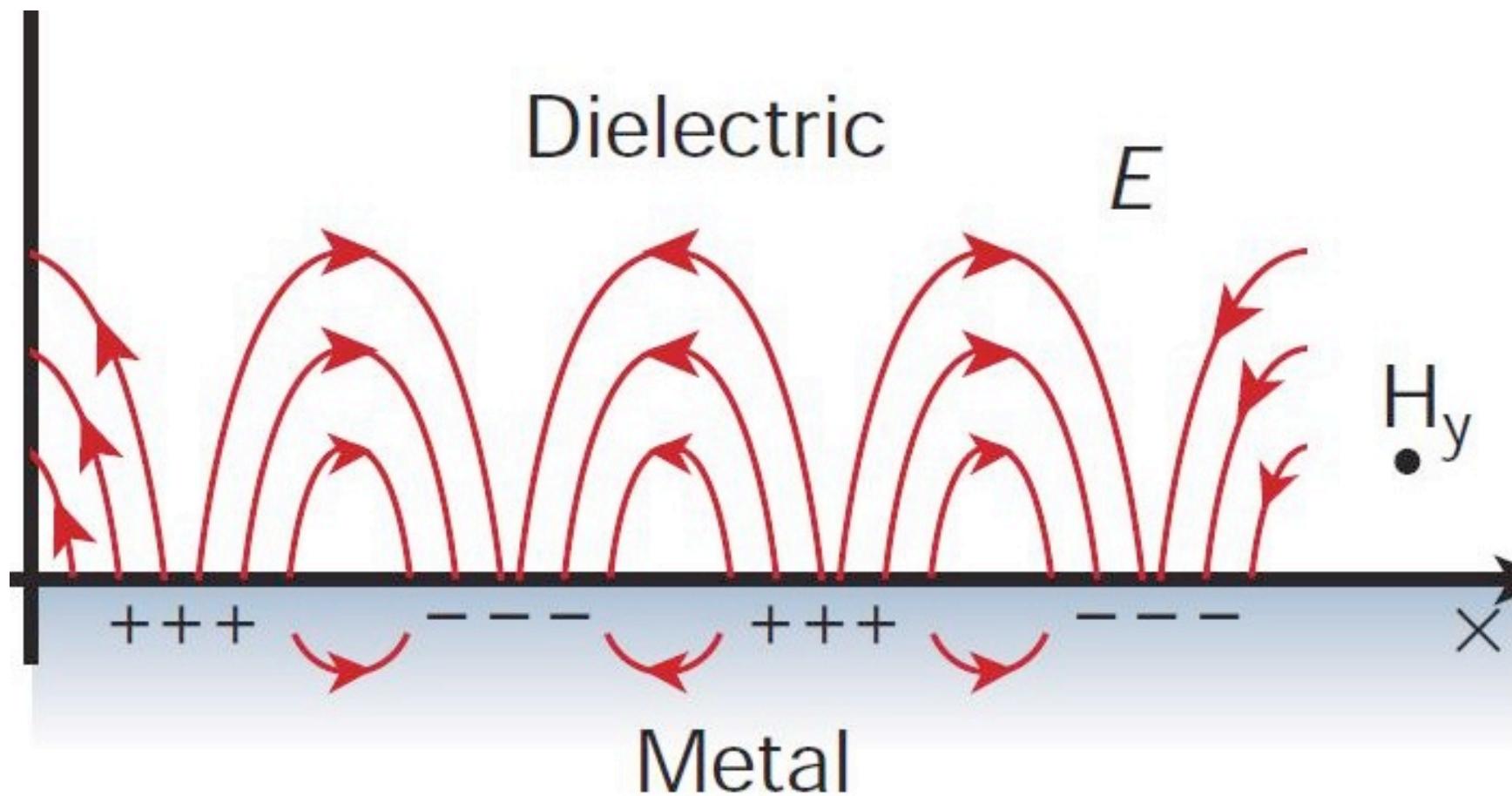


Plasmons



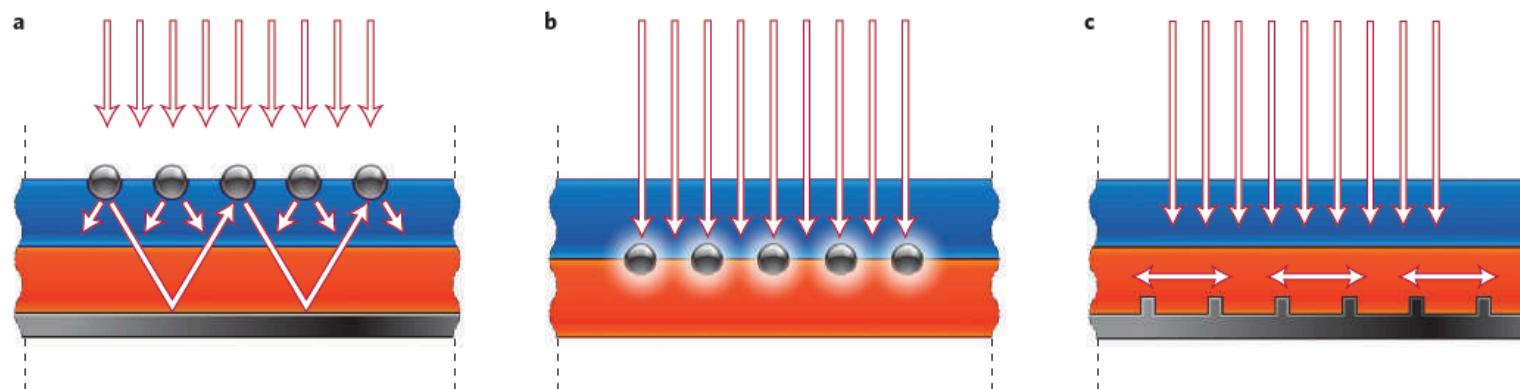
Juluri Bala Krishr

Surface plasmons on planar interfaces

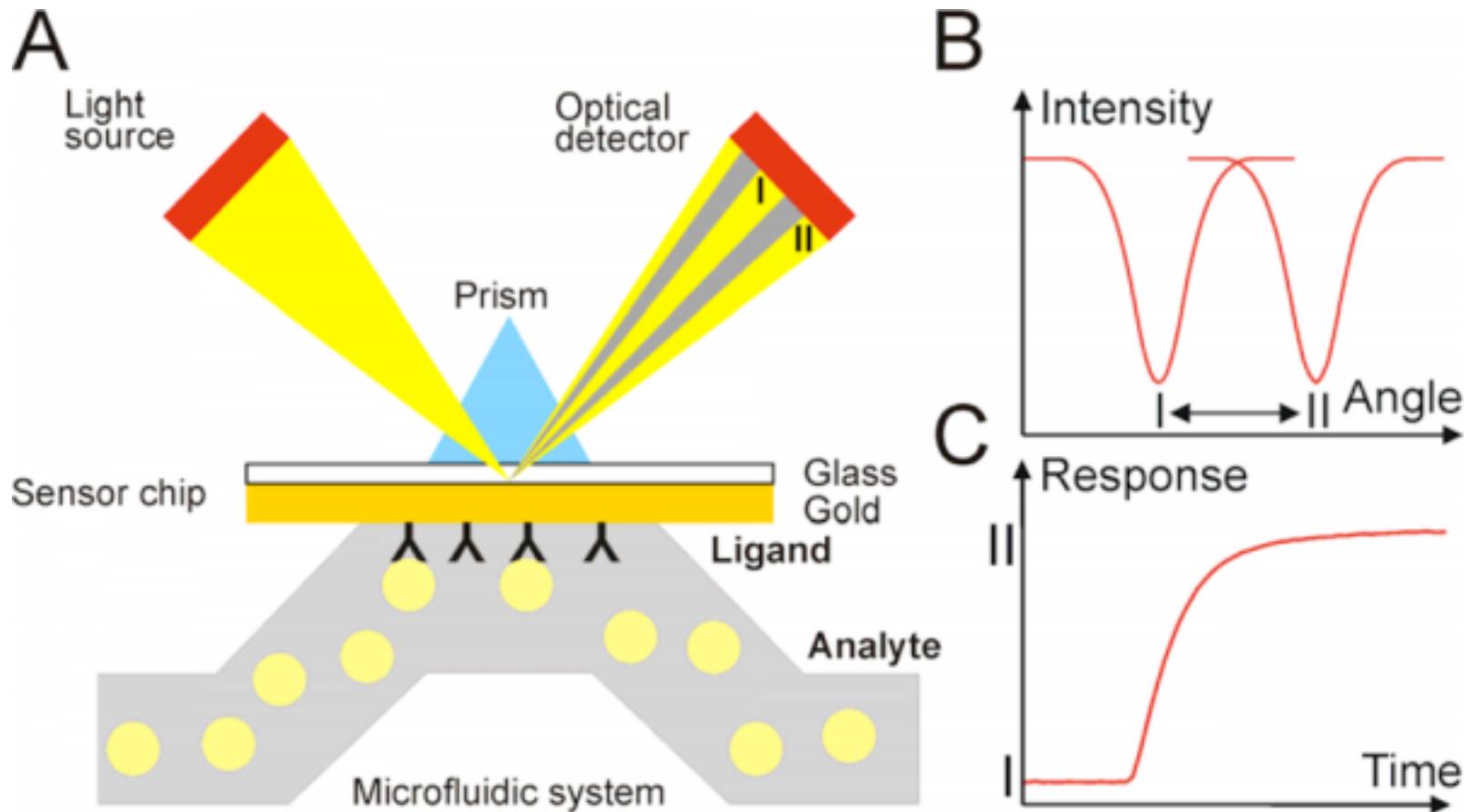


Plasmonics for improved photovoltaic devices

Harry A. Atwater^{1*} and Albert Polman^{2*}

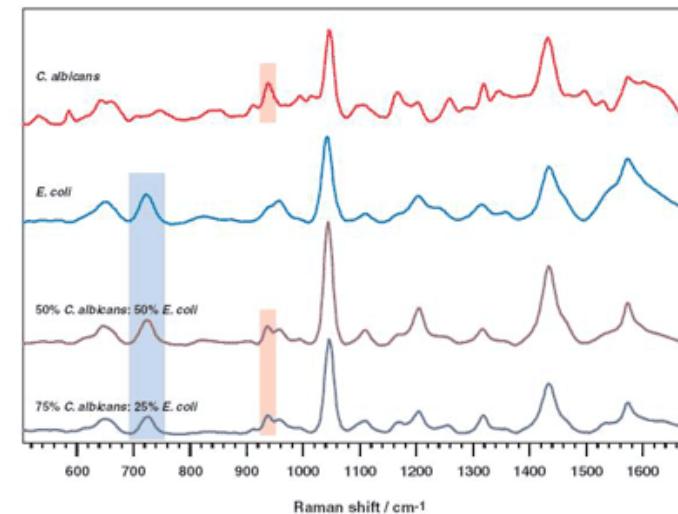
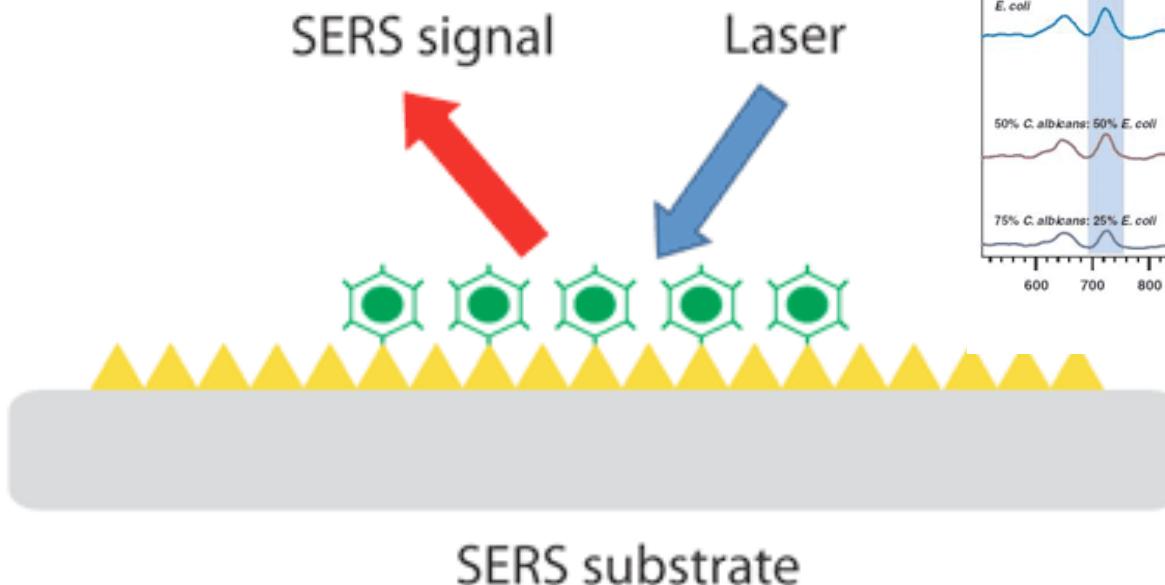


Plasmonics for biodetection



Plasmonics for Raman Spectroscopy

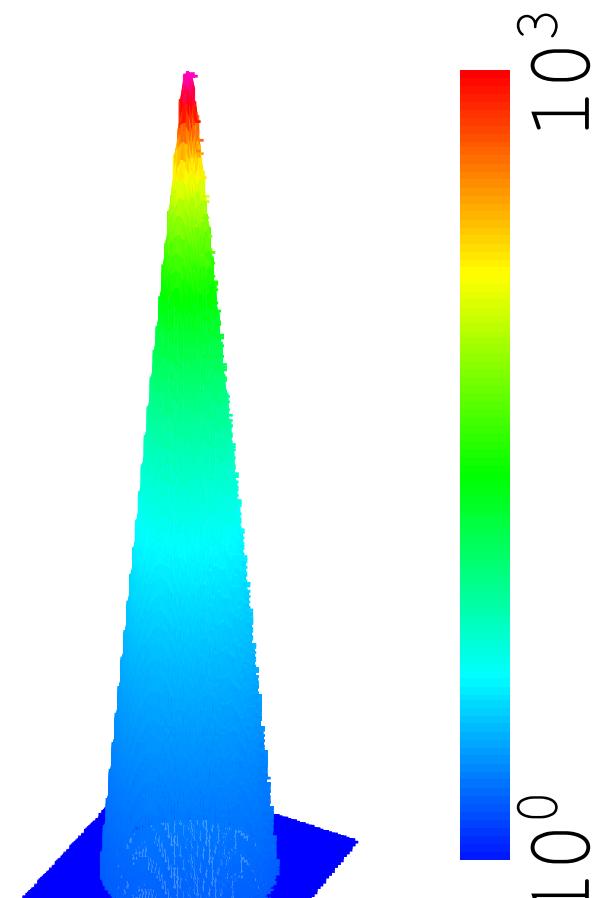
Raman spectroscopy is an extremely useful tool for obtaining chemical information,
But has very low signal (2nd order process)
-> plasmonics can be used to amplify the stimulating light intensity (SERS)



Manipulation: Adiabatic compression of plasmons

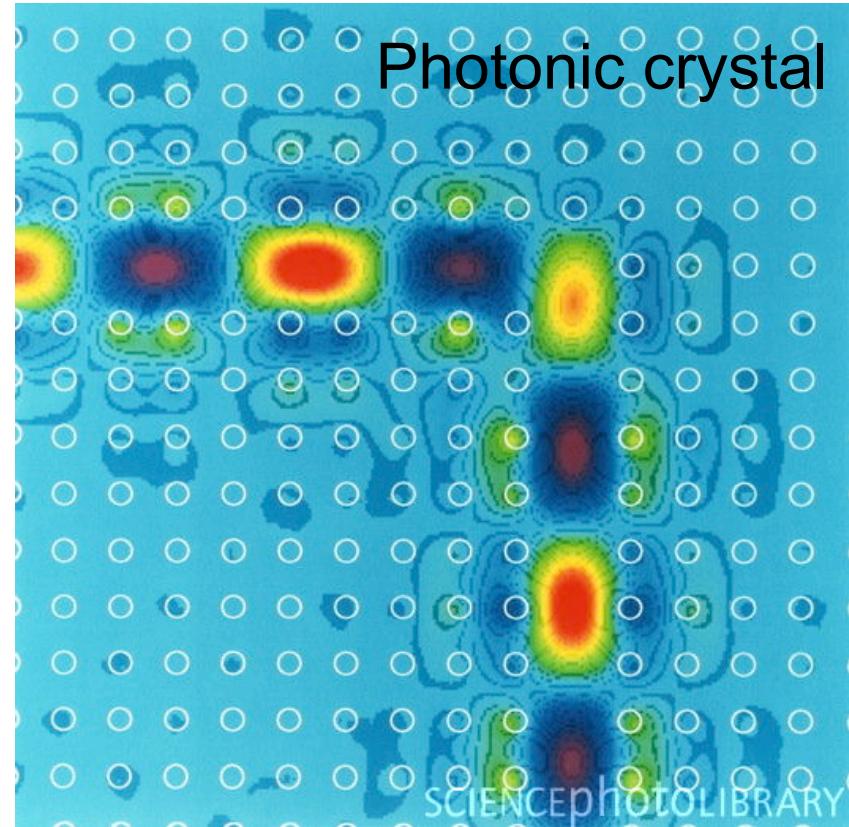
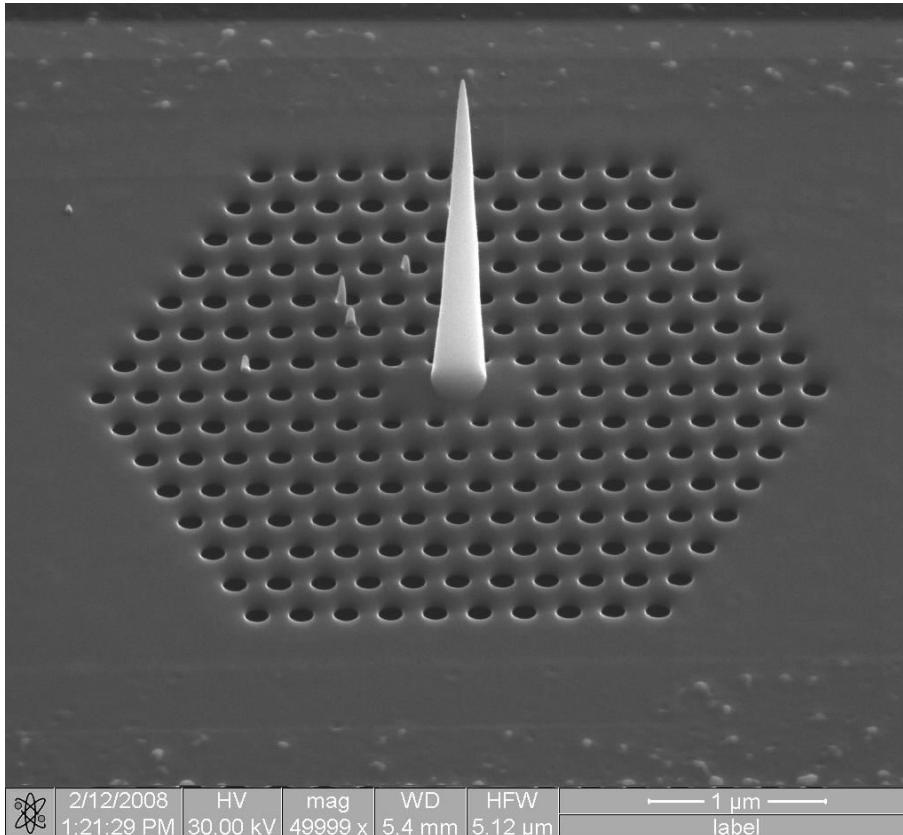


De Angelis, Di Fabrizio et al.



Matchmaking: Plasmonics + Excitons

White light → green light → plasmon → compression



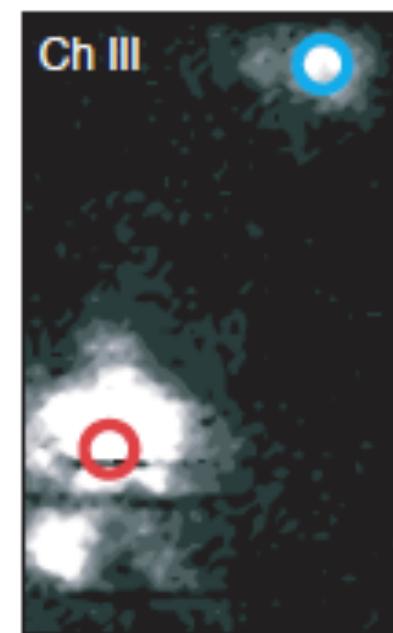
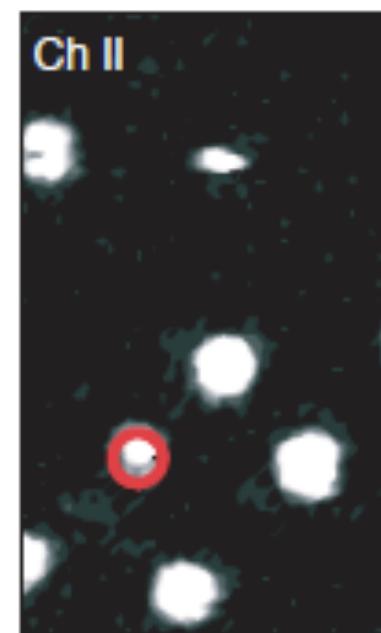
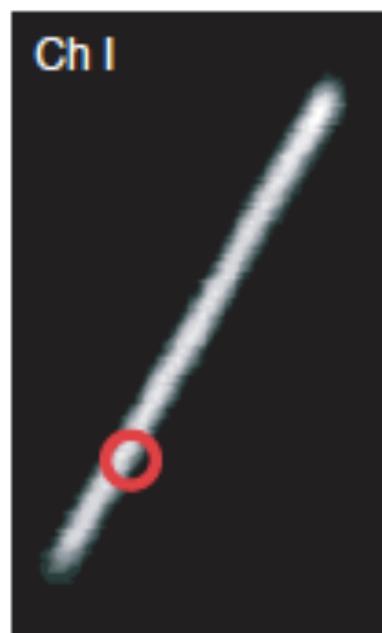
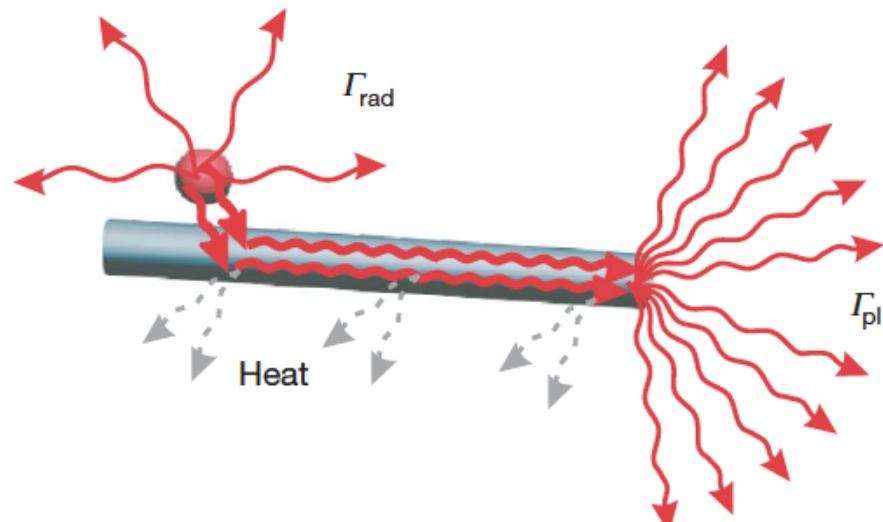
PHOTONIC CRYSTAL

Regular lattice with spacing of the order of the optical wavelength

→ Physics similar to electronics in solid state crystal

BUT at this length scale it can be precisely designed!

Coupling QD emission into metallic guides



Akimov et al., Nature 450 (2007)

Coupling light into electrical circuits

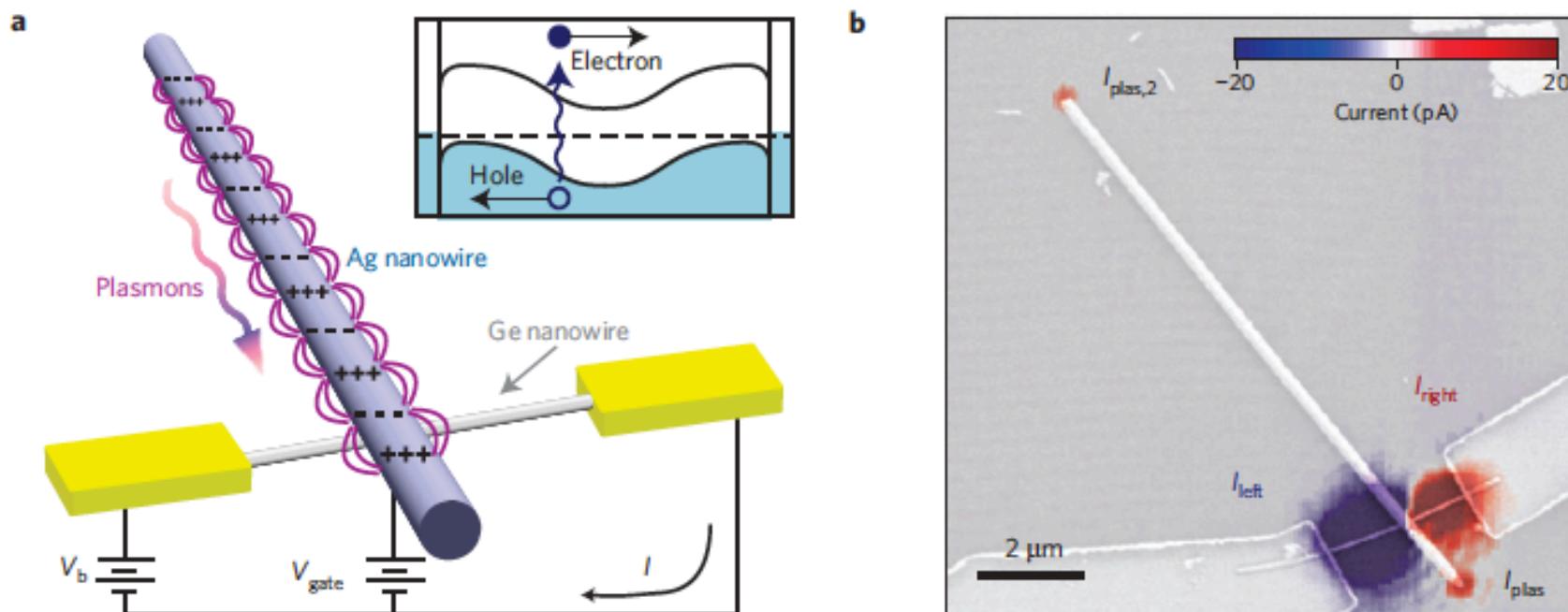
nature
physics

LETTERS

PUBLISHED ONLINE: 24 MAY 2009 | DOI: 10.1038/NPHYS1284

Near-field electrical detection of optical plasmons and single-plasmon sources

Abram L. Falk^{1*}, Frank H. L. Koppens^{1*}, Chun L. Yu², Kibum Kang³, Nathalie de Leon Snapp², Alexey V. Akimov¹, Moon-Ho Jo³, Mikhail D. Lukin^{1†} and Hongkun Park^{1,2†}



Nanotechnology applications

- Cosmetics/Sun screen
- Food containers
- clothing
- Paints
- Lubricants

BUT THE BIG CHALLENGES ARE

- Energy
- Medicine
- Information Communication technologies

Nanotechnology advantages

- Photovoltaics: large surface to volume ratio -> large absorption area for incoming light.
- Energy consumption: small wires, precise energy level structure
-> low current

Low fabrication cost due to bottom up approaches

-> material self-assembles into functional structures (like coffee stain laser)