



# Fundamentals of Nanoscience (SdM)

## Introduction to Nanophysics (Physics)

Giovanni Mattei



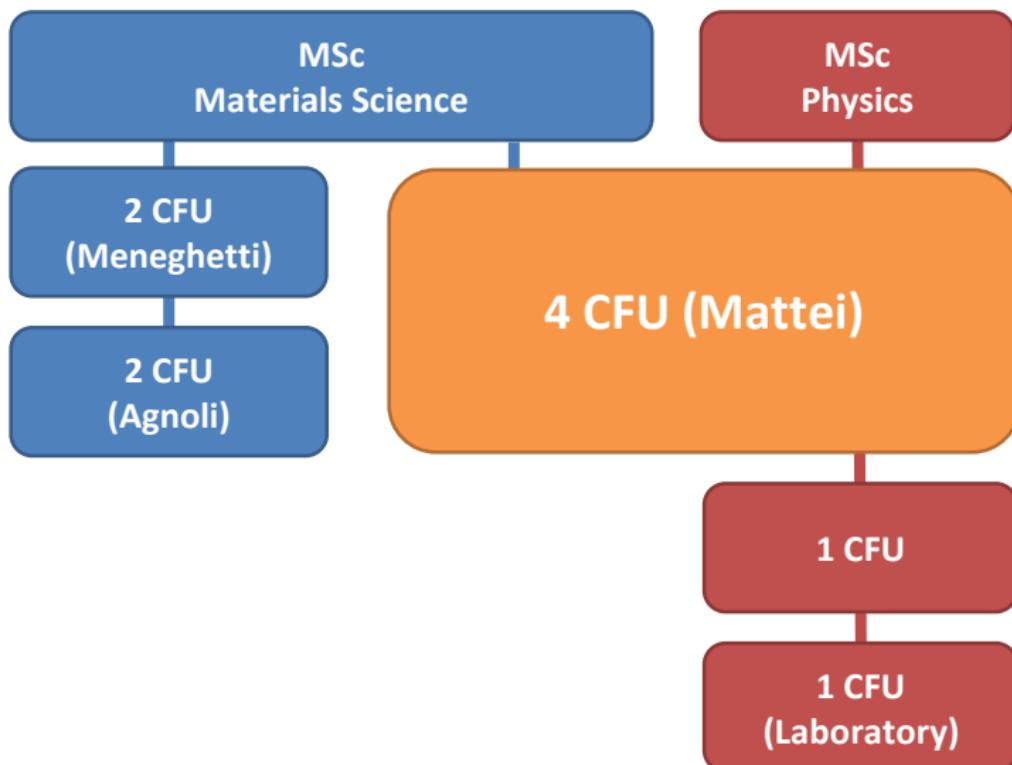
UNIVERSA  
UNIVERSIS  
PATAVINA  
LIBERTAS

NanoStructures Group (NSG)

*Dept. of Physics and Astronomy  
University of Padova  
via Marzolo 8, Padova*

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**Schedule:**      WED 9:30 – 11:30  
                  THU 8:30 – 10:30

**Student Reception:** *on request*

**e-mail:** [giovanni.mattei@unipd.it](mailto:giovanni.mattei@unipd.it)

**URL:** <http://materia.dfa.unipd.it/mattei>

**Room 82** – (ground floor) Dept. of Physics and Astronomy  
(via Marzolo 8)



- Understanding the basic concepts describing the **chemical and physical properties** of nanostructured materials and their applications in **nanotechnology**
- Description of some **techniques** for the **synthesis** and **characterization** of confined nanostructures (nanoclusters) with nanotech application in **photronics, plasmonics** and **magnetism**.

## Materials Science

Exam	Weight
Written (2 hrs)	100 % (weighted average over CFUs)

## Physics

Exam	Weight
Written (2 hrs)	75%
Lab	25%

**Written Exam:**

- Open Question
- +
- Open Question (Meneghetti)
- Multiple Choice Qs & Open Question (Agnoli)

**Written Exam:**

- Open Question
- Numerical Application

**Lab:**

- Written Report

### 4 CFU (SdM + Physics)

- Classification, characteristics and general properties of nanostructured materials: quantum confinement and electronic properties. **Size Equations**.
- Thermodynamic properties of nanostructured materials: **thermodynamic size effect**, nucleation (**Gibbs-Thomson equation**) and growth of nanostructures (**Diffusion-Limited Aggregation and Ostwald Ripening regimes**).
- Nanostructures embedded in solid matrices: ion implantation for the synthesis and processing of metallic nanostructures. **Verification of the nucleation and growth models**.
- Optical properties** of nanostructured materials: (i) **plasmonic** properties of metallic nanostructures (Mie theory and its extensions); (ii) **quantum confinement** and photoluminescence in semiconductor quantum dots
- Magnetic properties** of nanostructured materials: super-paramagnetism.

### 1 CFU (Physics)

- Fundamental description of the **dynamics** of electrons and photons
- Confinement of electrons and photons** in nanostructured or periodic materials:
  - Photon confinement in **photonic crystals**
  - Electron confinement in **metal nanoparticles**
  - Electron confinement in **semiconductor nanoparticles**
- Metamaterials** and **negative-refractive index** materials

### 1 CFU (Lab., Physics)

- Lab** (Synthesis Nano-Au, simulation OD, XRD, SEM on the synthesized Au NPs).



## Notes

Register on the Course Moodle :

- **SdM** -> <https://elearning.unipd.it/chimica/>
- **Physics** -> <https://elearning.unipd.it/dfa/>

## Further Readings

- S. Maier, *Plasmonics, fundamentals and applications*, Springer (2007)
- C. Bohren and D. Huffmann, *Absorption and scattering of light by small particles*, Wiley-Interscience (2004)
- P. Prasad, *Nanophotonics*, Wiley-Interscience (2004)
- C. Poole, F. Owens, *Introduction to Nanotechnology*, Wiley-Interscience (2003)
- G. Schmid, *Nanoparticles*, Wiley-Interscience (2004)

Classical Physics



1 m

1 mm =  $10^{-3}$  m1 μm =  $10^{-6}$  m1 nm =  $10^{-9}$  m1 pm =  $10^{-12}$  m

- hair

- Red blood cell

- Transistor

- Virus, Cluster

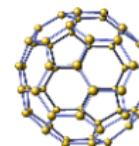
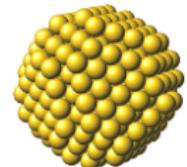
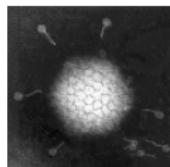
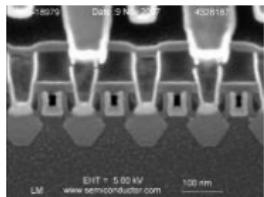
- DNA, Fullerene, Nanotube

- Atom

Quantum Physics

Nanoscience  
Nanotechnology

size &lt; 100 nm



Nanoparticle



1 nm

Tennis Ball



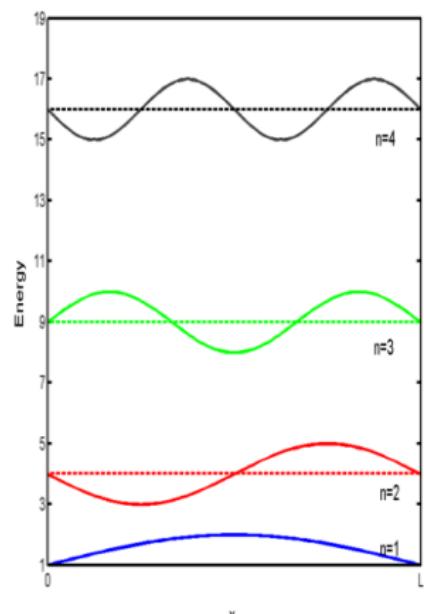
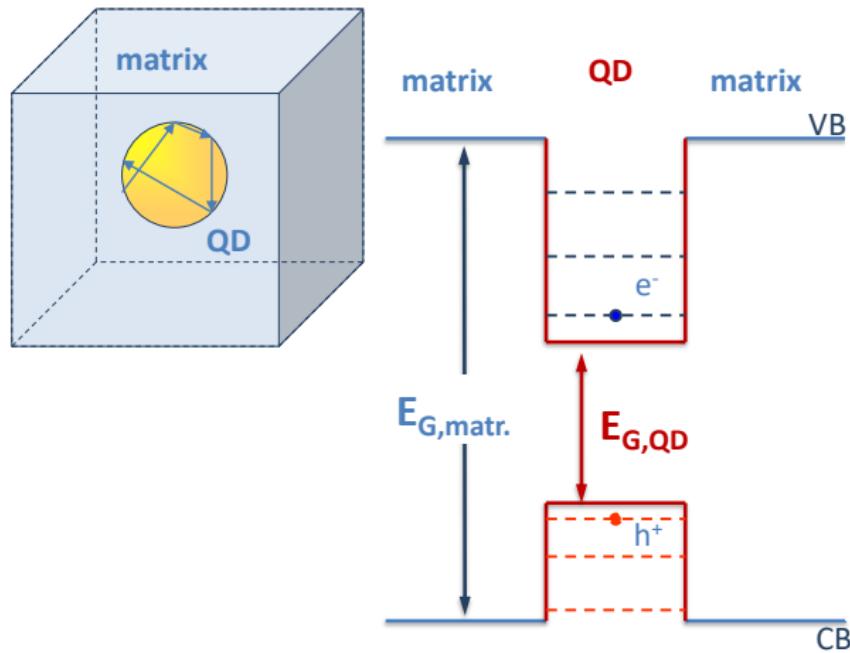
6 cm

Moon



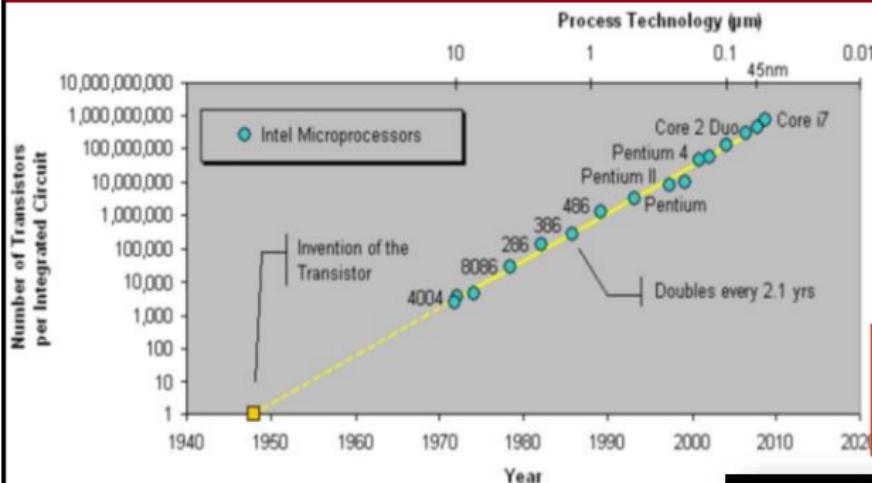
3500 km

A simple proportion...



Wave-particle duality

# Nano-electronics



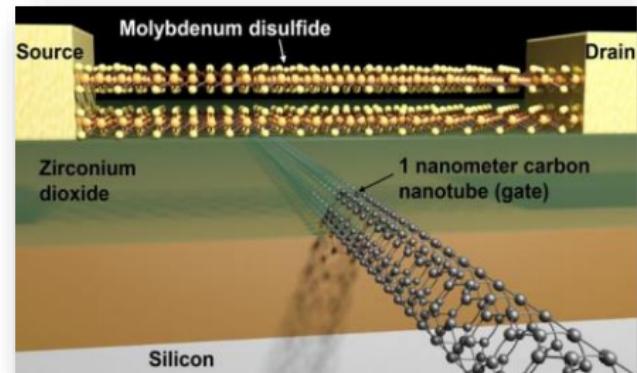
Moore's Law

$$G(t + nT) = 2^n G(t)$$

$T = 1.5 \text{ yrs} - t \text{ in yrs}$



Micro-electronics is about to reach the physical limitations of quantum mechanics...



## (1) civil aviation

New York - Frankfurt:

1980

Time: 7 hrs

Price: 900 €



New York - Frankfurt:

today

Time: 0.02 s

Price: 0.1 cent

## (2) motorbike company



Ducati 2019



In 40 years...

Weight: 1 g

Speed: 60.000 km/s

Price: 5 cent



# Nano-Systems

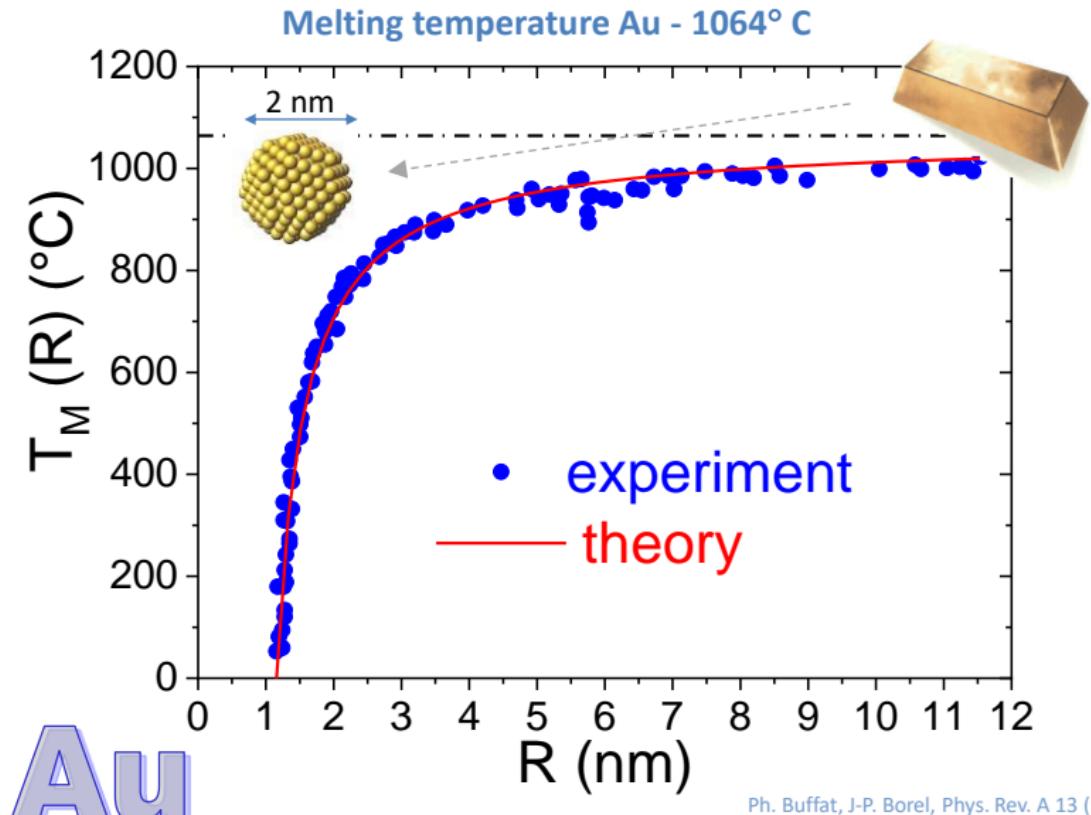
	Bulk Material	Nano Material
Size (L)	$\sim 1 \text{ m}$	$< 100 \text{ nm} = 10^{-7} \text{ m}$
Property (A)	$A \neq A(L)$	$A = A(L)$

- Characteristic lengths  $\lambda_c \sim 1-100 \text{ nm}$
- Nano-physics:  $L < \lambda_c$
- E.g.:
  - $\lambda_e$  = electronic mean free path (10-100 nm)
  - $\lambda_{exc}$  = excitonic Bohr radius (1-10 nm)
  - $\lambda_M$  = magnetic domain (30-50 nm)

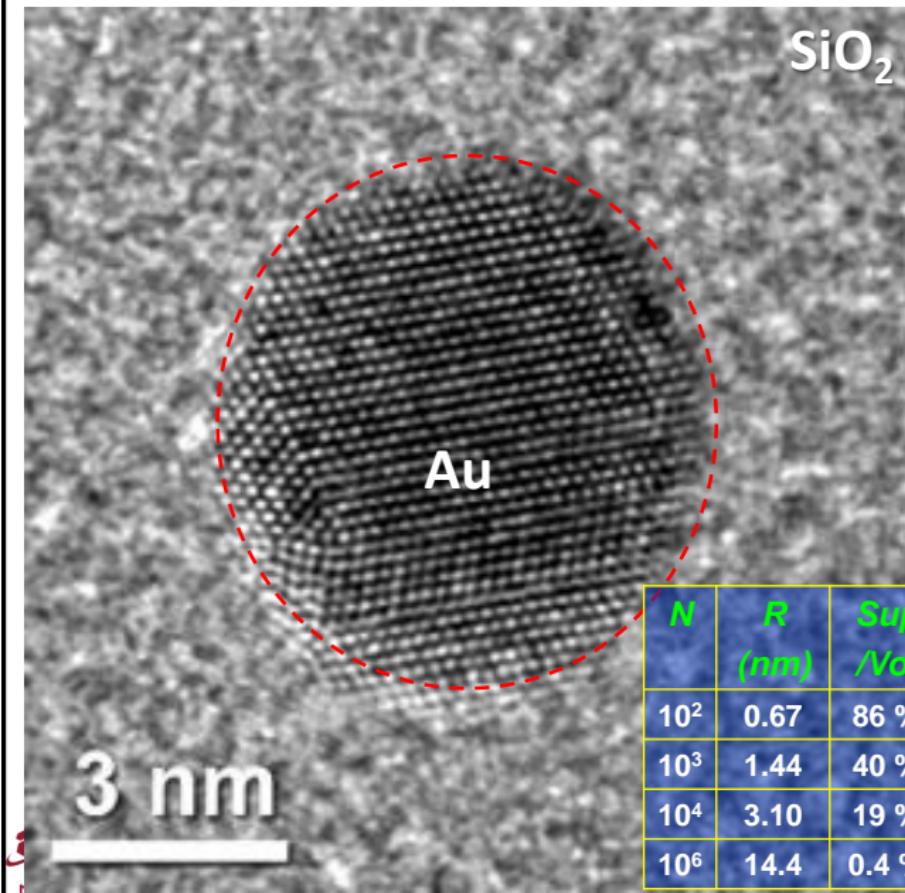
control L = control A(L)



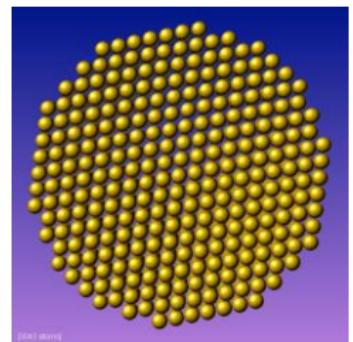
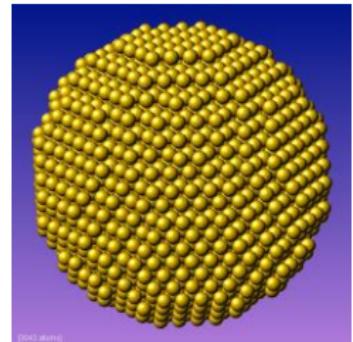
# Nano-Thermodynamics

Example of  $A = A(L)$ 

Ph. Buffat, J-P. Borel, Phys. Rev. A 13 (1976) 2287



<i>N</i>	<i>R</i> (nm)	<i>Sup</i> /Vol
$10^2$	0.67	86 %
$10^3$	1.44	40 %
$10^4$	3.10	19 %
$10^6$	14.4	0.4 %



Au NP along the  
<110> zone axis

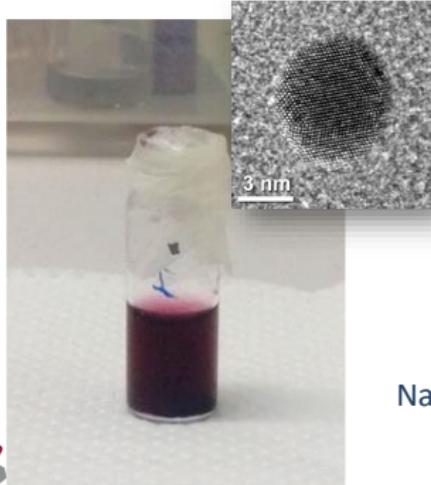
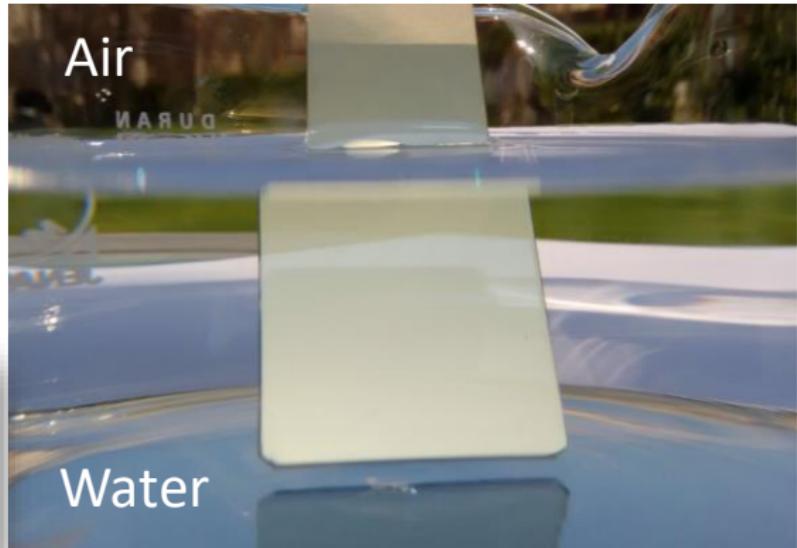


# Nano-Optics

# Which is the color of Au NPs?



Bulk Au



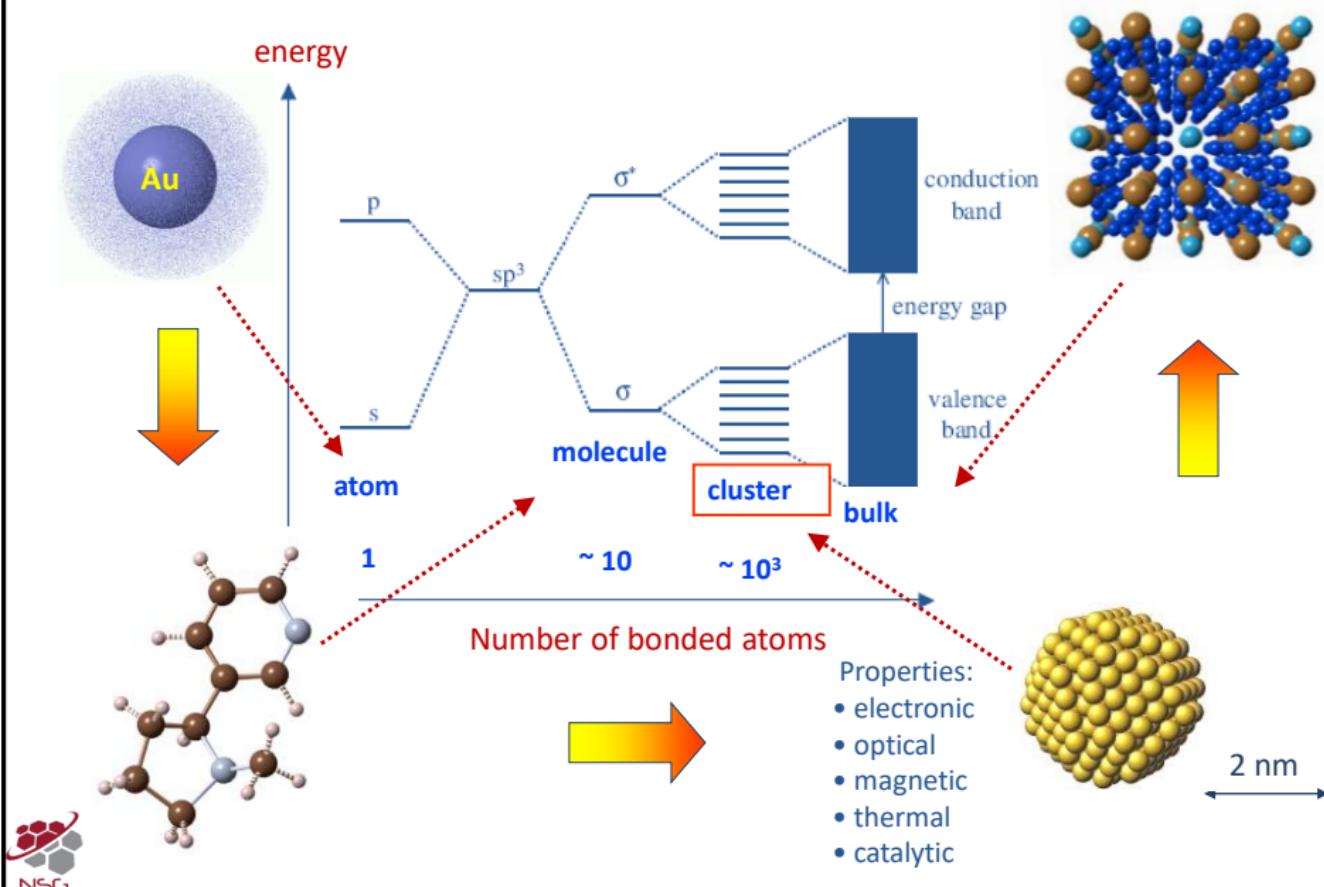
Nano Au





# Electronic structure

## From the atom to the bulk...





# ‘Seeing’ at the Nanoscale

# 'seeing' at the nanoscale



## A typical optical microscope

- photons

$$\lambda = 400 \div 800 \text{ nm}$$

$$E = 1 \div 3 \text{ eV}$$

- resolution

$$\sim \lambda \text{ (500 nm)}$$

- working pressure

ambient

# 'seeing' at the nanoscale



## A typical electron microscope - TEM

- electrons

$\lambda = 1.2 \text{ pm}$  (*Quantum Mechanics*)

$E = 200 \div 300 \text{ keV}$

- resolution

0.1 nm

- working pressure

$10^{-4} \text{ Pa} (\sim 10^{-9} \text{ atm})$

- price

1.5-2.0 M€

## Characteristic size &lt; 100 nm

1.

Bulk Materials  
(3D)

4.

Multi-layered  
Materials  
(1D-2D)

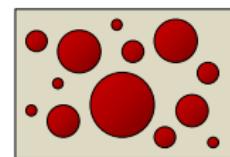
2.

Nanostructured  
Materials (3D)

3.

Nanostructured  
Films  
(1D-2D)

5.

Nanoclusters (~0D)  
(metals,  
semiconductors,  
nanotubes, fullerenes...)

6.

Novel Materials  
(Meta Materials)

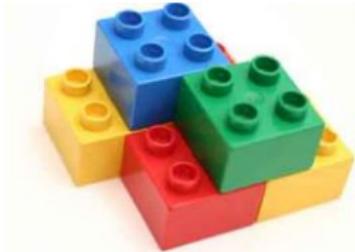


# Synthesis Methods

**Bottom/Up vs. Top/Down**

# Bottom/Up

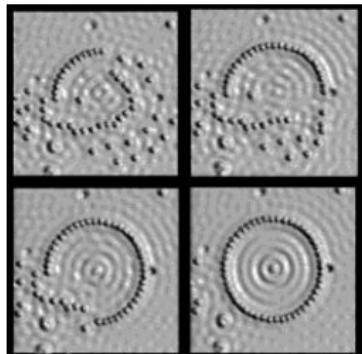
From small to large or from **simple to complex**



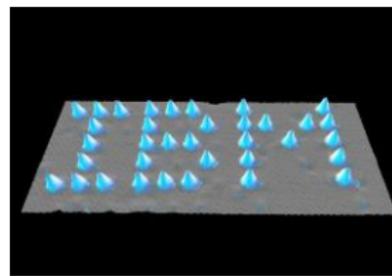
## LEGO

'building block' assembly with quantum supramolecular rules

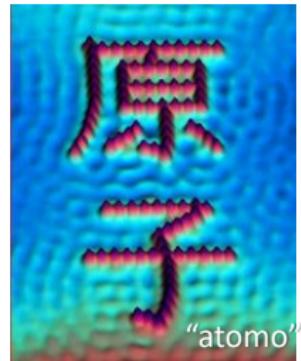
Using atoms or simple units as LEGO blocks one can build artificial nano-objects  
(**nano-positioning** and **self-assembling**)



Quantum corral: 48 atoms of Fe on Cu  
M.F. Crommie, C.P. Lutz, D.M. Eigler.  
*Science* 262, 218-220 (1993)

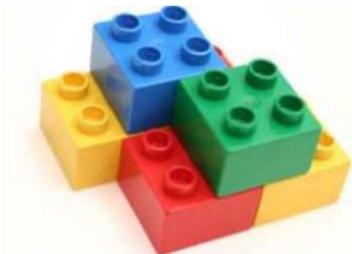


Xe on Ni (111)  
D.M. Eigler, E.K. Schweizer,  
*Nature* 344, 524-526 (1990)



Fe on Cu (111)  
C.P. Lutz, D.M. Eigler, IBM

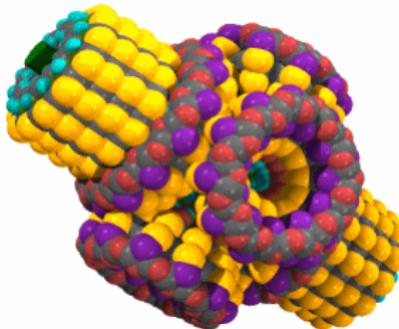
From small to large or from **simple to complex**



**LEGO**

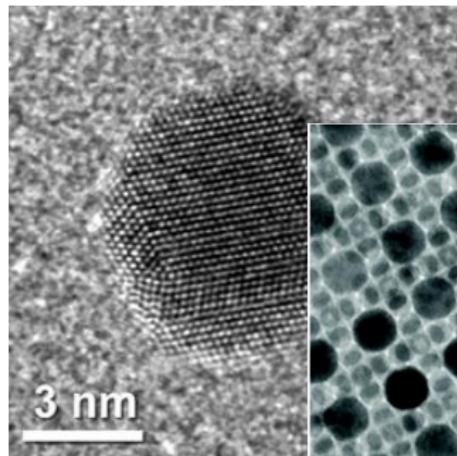
'building block' assembly with  
quantum supramolecular rules

Using atoms or simple units as LEGO blocks one can build artificial nano-objects  
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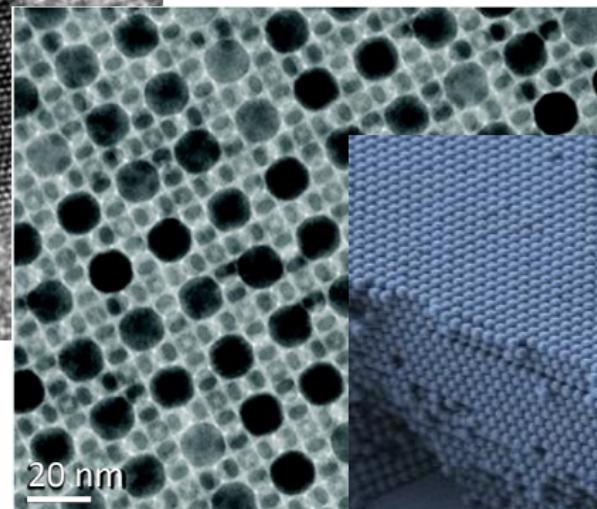


Nano-machine (*E. Drexler, Nanorex Inc.*)

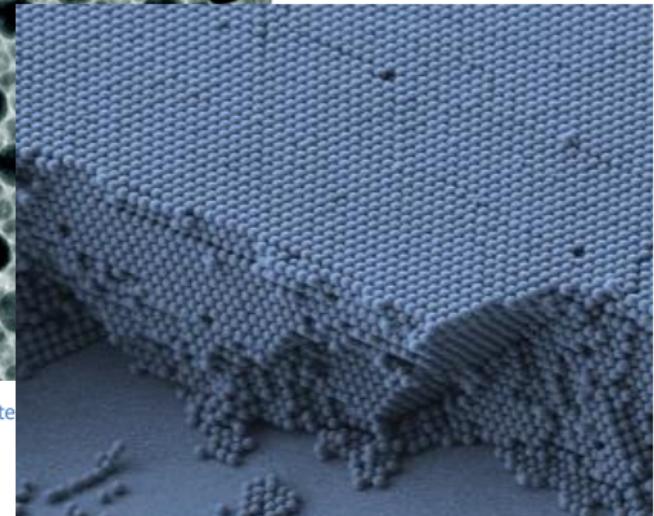
# Bottom/Up



Au NC in  $\text{SiO}_2$  (UniPD)



$\text{Fe}_3\text{O}_4$  NC: Chen, J. et al. Nano Lette



Photonic crystal: 3D self-assembly of  $\text{SiO}_2$  NPs (1  $\mu\text{m}$ ).



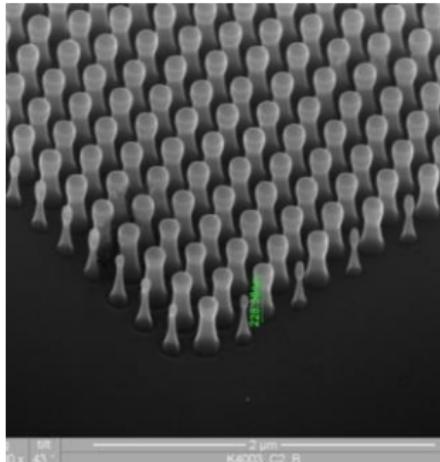
From large to small

### Lithography

A bulk material is processed ('sculpted') and reshaped down to the nanosize: **nanofabrication** and **nanolithography**

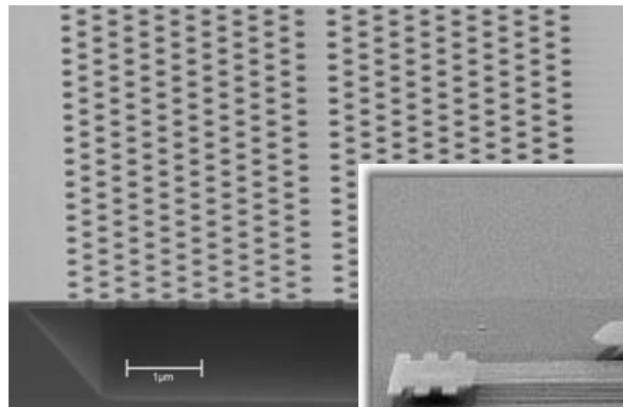
Nanostructures and nanomaterials (electron beam lithography **EBL**: resol. 10 nm)

Anti-reflective  
coating made by  
a pillar array  
(EBL) for optical  
and photonic  
applications

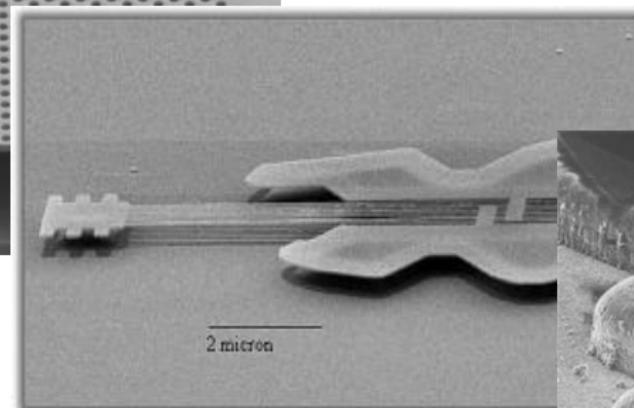


Close-up view of a moth's eye

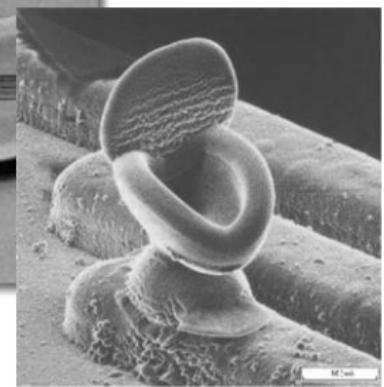
# Top/Down



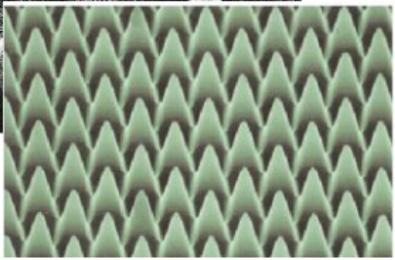
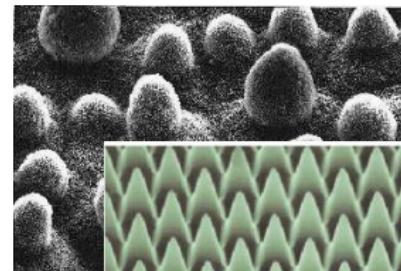
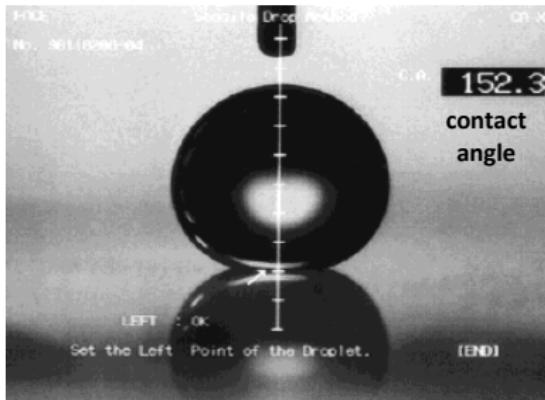
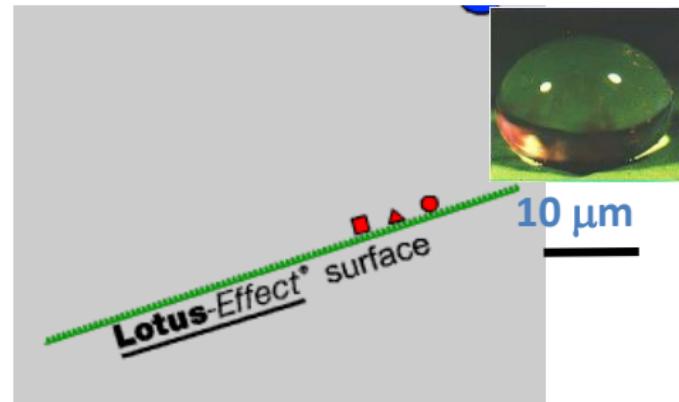
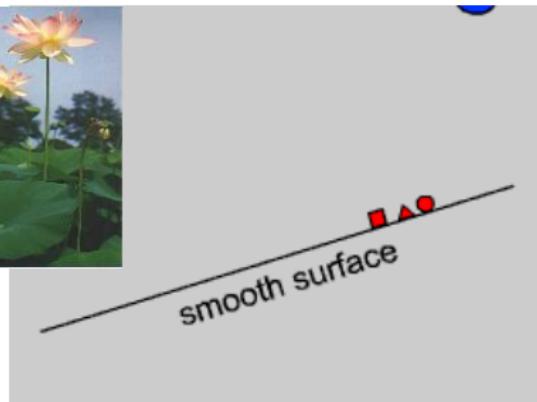
Photonic Crystal



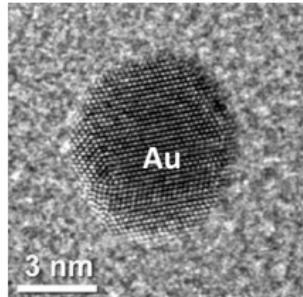
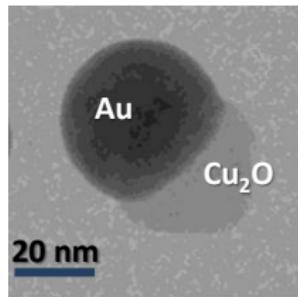
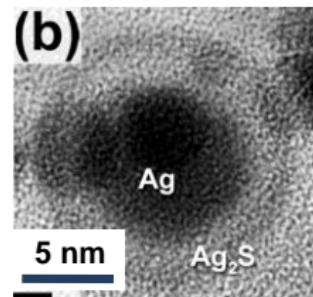
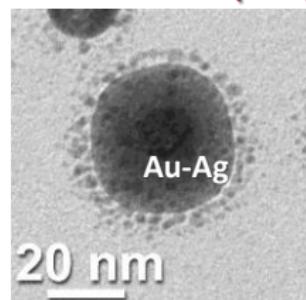
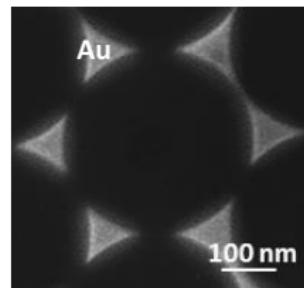
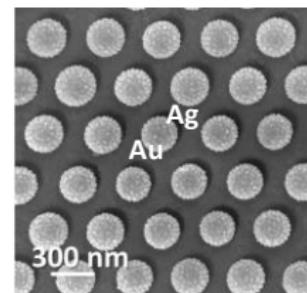
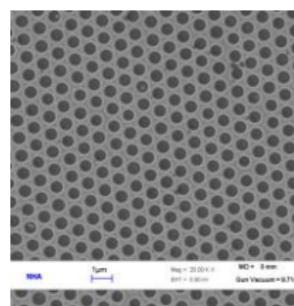
Nano-guitar



...Nano-toilet

bio-mimetic systems: **Lotus Effect** (super-hydrophobicity)

REM recording of a a  
holo-graphically pro-  
duced self-cleaning  
surface.  
© Fraunhofer ISE

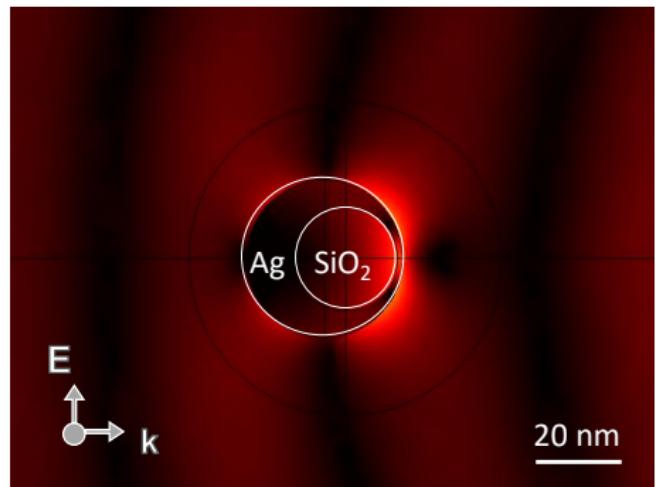
**Simple NP****Janus Particles****Core-shell****Nano-Planets (NPL)****DLA Fractals****Nano-Prism (NPA)****Nano-Shell (NSA)****Nano-Hole (NHA)****Monoelemental**

Au, Ag, Cu, Pt, Co, Ni, Fe

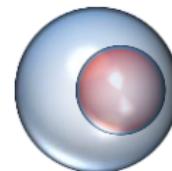
**Biometallic**

Au-Cu, Au-Ag, Au-Fe, Pd-Cu, Co-Ni, Co-Fe, Co-Cu, Fe-Pd

# Nano-eclipse



Solar Eclipse 2015



Asymmetric – NanoShell  
 $\text{SiO}_2 @ \text{Ag}$

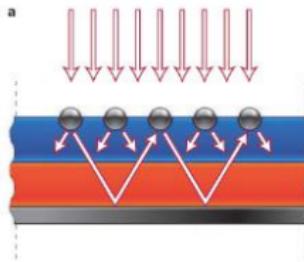


# Metallic Nanostructures

## Optical Properties (Plasmonics):

1. Plasmonic sensors
2. Plasmonic waveguides
3. Nano-Antennas
4. Iperthermia (cancer therapy)

Light confinement  $< \lambda$



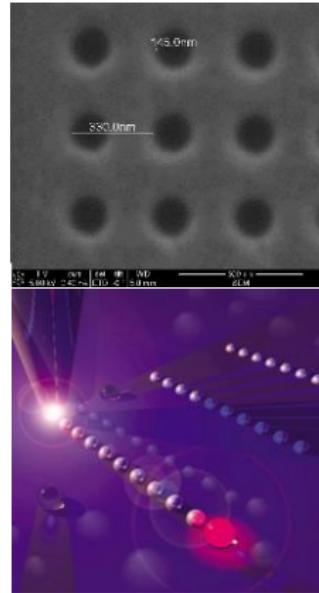
$$Re[\epsilon(\omega, R)] < 0$$

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18					
hydrogen <b>H</b> 1.00794(47)	boron <b>B</b> 10.81(1)	carbon <b>C</b> 12.0107(8)	nitrogen <b>N</b> 14.0067(7)	oxygen <b>O</b> 15.9994(3)	fluorine <b>F</b> 18.9984032(5)	neon <b>Ne</b> 20.1797(5)																
lithium <b>Li</b> 6.941(2)	beryllium <b>Be</b> 9.01218(3)	magnesium <b>Mg</b> 24.3052(5)	sodium <b>Na</b> 22.989770(2)	potassium <b>K</b> 39.0583(1)	calcium <b>Ca</b> 40.076(4)	scandium <b>Sc</b> 44.955910(8)	titanium <b>Ti</b> 47.87(1)	vanadium <b>V</b> 50.9415(1)	chromium <b>Cr</b> 51.9961(6)	manganese <b>Mn</b> 54.53049(9)	iron <b>Fe</b> 55.845(2)	cobalt <b>Co</b> 58.932020(8)	nickel <b>Ni</b> 58.6934(1)	copper <b>Cu</b> 63.546(2)	zinc <b>Zn</b> 65.38(2)	gallium <b>Ga</b> 69.723(1)	germanium <b>Ge</b> 72.64(1)	arsenic <b>As</b> 74.9216(2)	seleium <b>Se</b> 78.96(3)	antimony <b>Sb</b> 79.904(1)	bromine <b>Br</b> 83.79(2)	krypton <b>Kr</b> 83.80(1)
rubidium <b>Rb</b> 85.4673(3)	strontium <b>Sr</b> 87.62(1)	yttrium <b>Y</b> 88.90565(2)	zirconium <b>Zr</b> 91.224(2)	niobium <b>Nb</b> 92.90565(2)	hafnium <b>Hf</b> 95.95(2)	tantalum <b>Ta</b> 96.95(1)	tin <b>Tc</b> 98(1)	technetium <b>Ru</b> 101.97(2)	ruthenium <b>Ru</b> 102.95550(2)	osmium <b>Os</b> 106.42(1)	iridium <b>Ir</b> 107.85152(2)	platinum <b>Pt</b> 112.47(1)	gold <b>Au</b> 116.71(9)	mercury <b>Hg</b> 119.71(7)	thallium <b>Tl</b> 121.76(1)	lead <b>Pb</b> 121.50(1)	bismuth <b>Bi</b> 127.60(3)	polonium <b>Po</b> 125.80(4)(7)	radon <b>At</b> 131.203(5)	rhenium <b>Rn</b> 132.22(2)		
cesium <b>Cs</b> 132.90546(2)	lithium <b>Ba</b> 137.327(7)	barium <b>Lu</b> 174.9668(1)	hafnium <b>Hf</b> 178.49(2)	yttrium <b>Ta</b> 180.9479(1)	thorium <b>Db</b> 183.94(1)	cerium <b>Sg</b> 186.207(1)	neptunium <b>Bh</b> 190.23(3)	curium <b>Hs</b> 192.217(3)	neptunium <b>Mt</b> 195.0776(1)	curium <b>Ds</b> 196.95555(2)	neptunium <b>Rg</b> 196.959(2)	curium <b>Uub</b> 204.9833(2)	curium <b>Uut</b> 207.21(1)	curium <b>Uuq</b> 209.98038(2)	curium <b>Uup</b> 210.98038(2)	curium <b>Uuh</b> 215.98038(2)	curium <b>Uus</b> 216.98038(2)	curium <b>Uuo</b> 217.98038(2)				
francium <b>Fr</b> [223]	radium <b>Ra</b> [226]	lanthanum <b>Lr</b> [242]	cerium <b>Rf</b> [267]	praseodymium <b>Db</b> [268]	rutherfordium <b>Sg</b> [271]	neodymium <b>Bh</b> [272]	curium <b>Hs</b> [270]	promethium <b>Mt</b> [276]	samarium <b>Ds</b> [281]	europium <b>Rg</b> [286]	europium <b>Uub</b> [284]	europium <b>Uut</b> [286]	europium <b>Uuq</b> [288]	europium <b>Uup</b> [288]	europium <b>Uuh</b> [293]	europium <b>Uuo</b> [294]						

Lanthanoids	lanthanum <b>La</b> 138.9055(2)	cerium <b>Ce</b> 140.116(1)	praseodymium <b>Pr</b> 140.92765(2)	neodymium <b>Nd</b> 144.24(3)	promethium <b>Pm</b> 146(1)	samarium <b>Sm</b> 150.36(3)	europlum <b>Eu</b> 151.954(1)	europium <b>Gd</b> 157.25(3)	terbium <b>Dy</b> 158.92574(2)	dysprosium <b>Tb</b> 162.900(1)	holmium <b>Ho</b> 164.23032(2)	erbium <b>Er</b> 167.259(3)	thulium <b>Tm</b> 169.93421(2)	yterbium <b>Yb</b> 173.056(5)
Actinoids	actinium <b>Ac</b> [227]	thorium <b>Th</b> [232]	protactinium <b>Pa</b> [238]	curium <b>U</b> [231]	neptunium <b>Np</b> [237]	plutonium <b>Pu</b> [244]	americium <b>Am</b> [243]	curium <b>Cm</b> [247]	berkelium <b>Bk</b> [247]	curium <b>Cf</b> [251]	curium <b>Es</b> [252]	curium <b>Fm</b> [257]	curium <b>Md</b> [258]	curium <b>No</b> [259]

## 1. Extraordinary transmission of light (EOT):

from array of nanoholes with sub- $\lambda$  size in metal thin film.



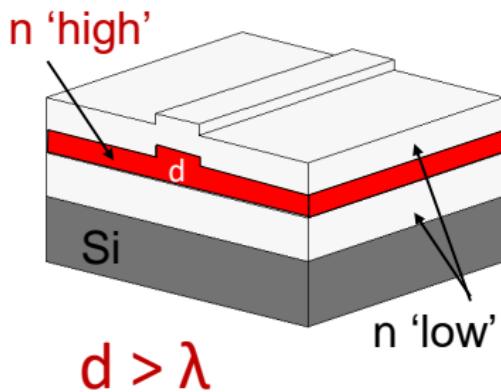
## 2. Plasmonic waveguides:

from array of NP or at the dielectric-metal interface

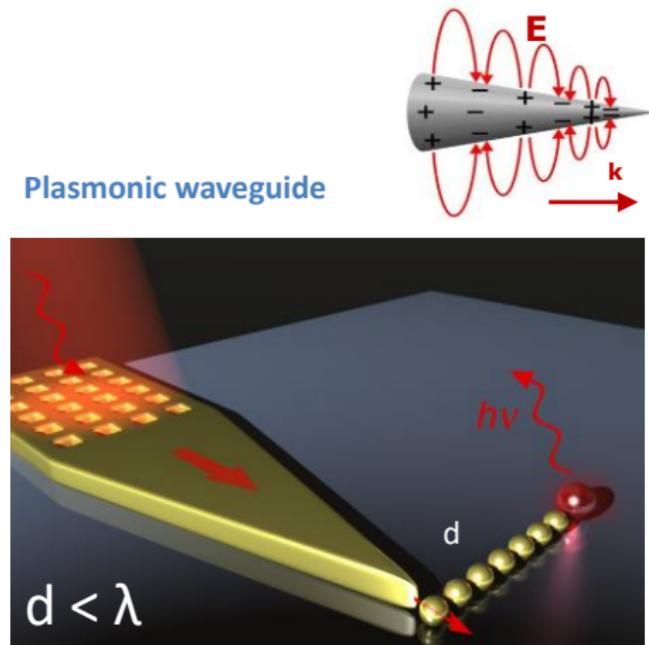


## 3. MetaMaterials: negative refractive index materials (invisibility cloak)

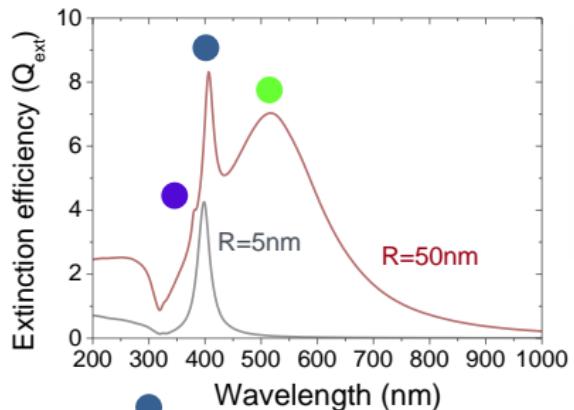
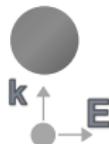
## Optical waveguide



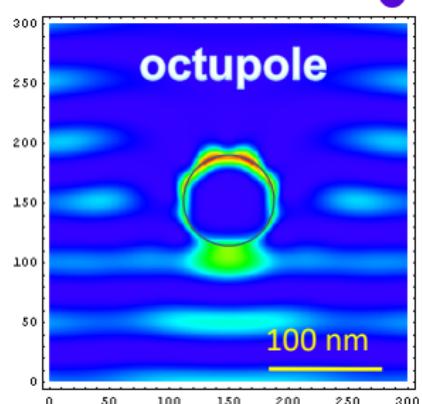
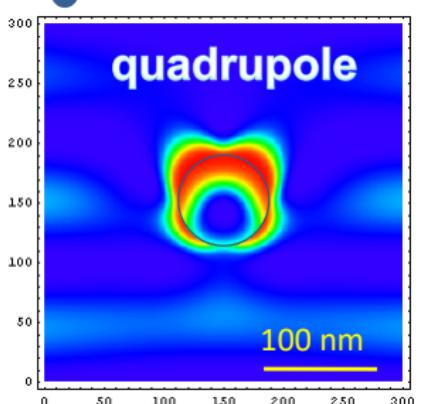
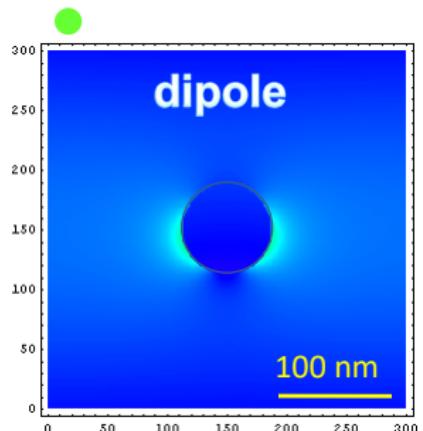
## Plasmonic waveguide



Ag nanoparticles  
( $R = 50$  nm) in  $\text{SiO}_2$



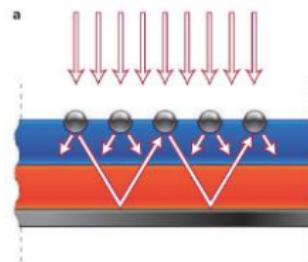
La Sainte-Chapelle  
(Paris, France, 1248)



### Optical Properties (Plasmonics):

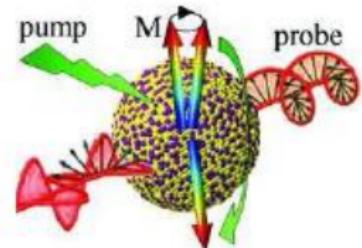
1. Plasmonic sensors
2. Plasmonic waveguides
3. Nano-Antennas
4. Iperthermia (cancer therapy)

Light confinement  $< \lambda$



### Magnetic Properties:

1. Super-paramagnetism
2. Magneto-optical properties
3. Medical diagnosis (Fe-oxides, NMR)





# Materials for magnetism

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
hydrogen <b>H</b> 1.00794(7)	boron <b>B</b> 10.811(7)	carbon <b>C</b> 12.0107(8)	nitrogen <b>N</b> 14.0267(7)	oxygen <b>O</b> 15.9994(3)	fluorine <b>F</b> 18.999402(5)	helium <b>He</b> 4.00000(2)													
lithium <b>Li</b> 6.941(2)	beryllium <b>Be</b> 9.012182(3)	magnesium <b>Mg</b> 24.3052(5)	aluminum <b>Al</b> 26.95133(2)	silicon <b>Si</b> 28.056(3)	phosphorus <b>P</b> 30.97761(2)	sulfur <b>S</b> 32.056(3)	chlorine <b>Cl</b> 35.453(2)	argon <b>Ar</b> 39.948(1)											
potassium <b>K</b> 39.0983(1)	calcium <b>Ca</b> 40.0776(4)	scandium <b>Sc</b> 44.955910(8)	titanium <b>Ti</b> 47.871(1)	vanadium <b>V</b> 50.9415(1)	chromium <b>Cr</b> 51.9951(1)	manganese <b>Mn</b> 54.932049(9)	iron <b>Fe</b> 55.845(5)	cobalt <b>Co</b> 58.93200(9)	nickel <b>Ni</b> 58.6934(3)	copper <b>Cu</b> 63.546(3)	zinc <b>Zn</b> 65.882(2)	gallium <b>Ga</b> 69.723(1)	germanium <b>Ge</b> 72.641(1)	arsenic <b>As</b> 73.96(3)	seleium <b>Se</b> 73.904(1)	bromine <b>Br</b> 79.798(2)	krypton <b>Kr</b> 83.798(2)		
rubidium <b>Rb</b> 85.4673(3)	strontium <b>Sr</b> 87.62(1)	yttrium <b>Y</b> 88.90589(2)	zirconium <b>Zr</b> 91.234(2)	niobium <b>Nb</b> 92.90535(2)	molybdenum <b>Mo</b> 95.96(2)	technetium <b>Tc</b> 98(1)	ruthenium <b>Ru</b> 101.27(2)	rhodium <b>Rh</b> 102.9059(2)	palladium <b>Pd</b> 104.42(1)	silver <b>Ag</b> 107.6582(2)	cadmium <b>Cd</b> 112.41(1)	tin <b>In</b> 114.518(3)	lead <b>Sn</b> 115.719(7)	tin <b>Sb</b> 121.760(1)	antimony <b>Te</b> 127.60(3)	iodine <b>I</b> 126.90447(3)	xenon <b>Xe</b> 131.293(6)		
caesium <b>Cs</b> 132.95545(2)	barium <b>Ba</b> 137.327(7)	lutetium <b>Lu</b> 174.9566(1)	hafnium <b>Hf</b> 178.49(2)	tantalum <b>Ta</b> 180.9479(1)	wolfram <b>W</b> 181.86(1)	rhenium <b>Re</b> 185.2071(1)	osmium <b>Os</b> 190.23(3)	iridium <b>Ir</b> 192.21(3)	platinum <b>Pt</b> 195.076(2)	gold <b>Au</b> 195.95555(2)	mercury <b>Hg</b> 204.59(2)	thallium <b>Tl</b> 204.383(2)	lead <b>Pb</b> 204.953(2)	tin <b>Bi</b> 207.2(1)	polonium <b>Po</b> 209(1)	astatine <b>At</b> 210(1)	radon <b>Rn</b> 222(1)		
francium <b>Fr</b> [223]	radium <b>Ra</b> [226]	lawrencium <b>Lr</b> [262]	rutherfordium <b>Rf</b> [267]	subbrium <b>Db</b> [268]	seaborgium <b>Sg</b> [271]	bhertium <b>Bh</b> [272]	hseniium <b>Hs</b> [270]	mtanyium <b>Mt</b> [276]	dsomium <b>Ds</b> [281]	rgesium <b>Rg</b> [286]	uutium <b>Uut</b> [284]	uuniquadium <b>Uuq</b> [289]	uunupium <b>Uup</b> [288]	uunupium <b>Uuh</b> [293]	uunupium <b>Uus</b> [294]	uunupium <b>Uuo</b> [294]			

Lanthanoids

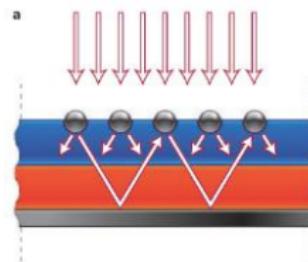
lanthanum <b>La</b> 57	cerium <b>Ce</b> 58	praseodymium <b>Pr</b> 59	neodymium <b>Nd</b> 60	promethium <b>Pm</b> 61	samarium <b>Sm</b> 62	europtium <b>Eu</b> 63	europium <b>Gd</b> 64	europium <b>Tb</b> 65	europium <b>Dy</b> 66	holmium <b>Ho</b> 67	erbium <b>Er</b> 68	thulium <b>Tm</b> 69	yterbium <b>Yb</b> 70			
actinium <b>Ac</b> 89	thorium <b>Th</b> 90	protactinium <b>Pa</b> 91	uranium <b>U</b> 92	neptunium <b>Np</b> 93	plutonium <b>Pu</b> 94	americium <b>Am</b> 95	curium <b>Cm</b> 96	berkelium <b>Bk</b> 97	curium <b>Cf</b> 98	dysonium <b>Es</b> 99	einsteiniun <b>Fm</b> 100	fermium <b>Md</b> 101	mercury <b>No</b> 102			

Actinoids

### Optical Properties (Plasmonics):

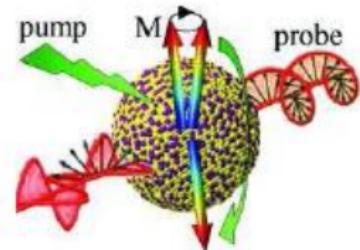
1. Plasmonic sensors
2. Plasmonic waveguides
3. Nano-Antennas
4. Iperthermia (cancer therapy)

Light confinement  $< \lambda$



### Magnetic Properties:

1. Super-paramagnetism
2. Magneto-optical properties
3. Medical diagnosis (Fe-oxides, NMR)



### Catalytic Properties:

1. Catalysis e photo-catalysis (metal oxides,  $TiO_2$ )
2. Water splitting and hydrogen storage



# Materials for catalysis

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
hydrogen <b>H</b> 1.00794(7)	boron <b>B</b> 10.811(7)	carbon <b>C</b> 12.0107(8)	nitrogen <b>N</b> 14.0267(7)	oxygen <b>O</b> 15.9994(3)	fluorine <b>F</b> 18.9994(2)	helium <b>He</b> 4.00000(2)													
lithium <b>Li</b> 6.941(2)	beryllium <b>Be</b> 9.012182(3)	magnesium <b>Mg</b> 24.3052(5)	aluminum <b>Al</b> 26.951335(2)	silicon <b>Si</b> 28.0566(3)	phosphorus <b>P</b> 30.97761(2)	sulfur <b>S</b> 32.0565(3)	chlorine <b>Cl</b> 35.453(2)	argon <b>Ar</b> 39.948(1)	neon <b>Ne</b> 20.177(7)										
potassium <b>K</b> 39.0983(1)	calcium <b>Ca</b> 40.0776(4)	scandium <b>Sc</b> 44.955910(8)	titanium <b>Ti</b> 47.8771(1)	vandium <b>V</b> 50.9415(1)	chromium <b>Cr</b> 51.9951(1)	manganese <b>Mn</b> 54.932049(3)	iron <b>Fe</b> 55.845(5)	cobalt <b>Co</b> 58.932020(9)	nickel <b>Ni</b> 59.693(3)	copper <b>Cu</b> 63.546(3)	zinc <b>Zn</b> 65.382(2)	gallium <b>Ga</b> 69.723(1)	germanium <b>Ge</b> 72.641(1)	arsenic <b>As</b> 74.9216(2)	seelenium <b>Se</b> 78.96(3)	broamine <b>Br</b> 79.904(1)	krayton <b>Kr</b> 83.798(2)		
rubidium <b>Rb</b> 85.4673(3)	strontium <b>Sr</b> 87.62(1)	yttrium <b>Y</b> 88.90589(2)	zirconium <b>Zr</b> 91.234(2)	niobium <b>Nb</b> 92.90535(2)	tin <b>Ta</b> 95.96(2)	technetium <b>Tc</b> [98]	ruthenium <b>Ru</b> 101.072(2)	rhodium <b>Rh</b> 102.9559(2)	palladium <b>Pd</b> 104.42(1)	silver <b>Ag</b> 107.8652(2)	cadmium <b>Cd</b> 112.411(8)	indium <b>In</b> 116.518(3)	tin <b>Tl</b> 118.719(7)	antimony <b>Sn</b> 121.760(1)	tellurium <b>Te</b> 127.60(3)	iodine <b>I</b> 131.293(6)			
caesium <b>Cs</b> 132.95545(2)	barium <b>Ba</b> 137.327(7)	lutetium <b>Lu</b> 174.9566(1)	hafnium <b>Hf</b> 178.49(2)	tantalum <b>Ta</b> 180.9479(1)	tungsten <b>W</b> 181.98(1)	rhenium <b>Re</b> 186.2071(1)	osmium <b>Os</b> 187.97(2)	iridium <b>Ir</b> 189.647(2)	platinum <b>Pt</b> 191.0555(2)	gold <b>Au</b> 196.9555(2)	mercury <b>Hg</b> 204.59(2)	thallium <b>Tl</b> 204.3833(2)	lead <b>Pb</b> 204.59(2)	bismuth <b>Bi</b> 207.2(1)	polonium <b>Po</b> [209]	astatine <b>At</b> [210]	radon <b>Rn</b> [222]		
francium <b>Fr</b> [223]	radium <b>Ra</b> [226]	lanthanum <b>La</b> [262]	cerium <b>Ce</b> [262]	praseodymium <b>Pr</b> [268]	neodymium <b>Nd</b> [271]	promethium <b>Pm</b> [272]	samarium <b>Sm</b> [270]	europium <b>Eu</b> [276]	gadolinium <b>Gd</b> [281]	terbium <b>Tb</b> [286]	dysprosium <b>Dy</b> [284]	holmium <b>Ho</b> [289]	erbium <b>Er</b> [288]	thulium <b>Tm</b> [293]	yterbium <b>Yb</b> [294]				
actinium <b>Ac</b> [227]	thorium <b>Th</b> [232]	protactinium <b>Pa</b> [238]	uranium <b>U</b> [239]	neptunium <b>Np</b> [237]	plutonium <b>Pu</b> [244]	americium <b>Am</b> [243]	curium <b>Cm</b> [247]	berkelium <b>Bk</b> [247]	californium <b>Cf</b> [251]	einsteinium <b>Es</b> [252]	fermium <b>Fm</b> [257]	mendelevium <b>Md</b> [258]	nobelium <b>No</b> [259]						

Lanthanoids

lanthanum <b>La</b> 57	cerium <b>Ce</b> 58	praseodymium <b>Pr</b> 59	neodymium <b>Nd</b> 60	promethium <b>Pm</b> 61	samarium <b>Sm</b> 62	europium <b>Eu</b> 63	gadolinium <b>Gd</b> 64	terbium <b>Tb</b> 65	dysprosium <b>Dy</b> 66	holmium <b>Ho</b> 67	erbium <b>Er</b> 68	thulium <b>Tm</b> 69	yterbium <b>Yb</b> 70			
actinium <b>Ac</b> [227]	thorium <b>Th</b> [232]	protactinium <b>Pa</b> [238]	uranium <b>U</b> [239]	neptunium <b>Np</b> [237]	plutonium <b>Pu</b> [244]	americium <b>Am</b> [243]	curium <b>Cm</b> [247]	berkelium <b>Bk</b> [247]	californium <b>Cf</b> [251]	einsteinium <b>Es</b> [252]	fermium <b>Fm</b> [257]	mendelevium <b>Md</b> [258]	nobelium <b>No</b> [259]			

Actinoids



# Semiconductor Nanostructures



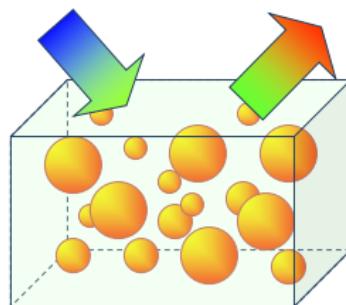
# Semiconductor Materials

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hydrogen 1 <b>H</b> 1.00794(7)	beryllium 2 <b>Be</b> 9.01215(3)	lithium 3 <b>Li</b> 6.941(2)	boron 4 <b>B</b> 10.809770(2)	carbon 5 <b>C</b> 12.01070(3)	nitrogen 6 <b>N</b> 14.01264(3)	oxygen 8 <b>O</b> 15.99940(3)	fluorine 9 <b>F</b> 18.99840(3)	neon 10 <b>Ne</b> 20.1737(6)											
sodium 11 <b>Na</b> 22.989770(2)	magnesium 12 <b>Mg</b> 24.30505(6)	potassium 19 <b>K</b> 39.0803(1)	cadmium 20 <b>Ca</b> 45.075(4)	scandium 21 <b>Sc</b> 44.955910(8)	titanium 22 <b>Ti</b> 47.875(1)	vanadium 23 <b>V</b> 50.9415(1)	chromium 24 <b>Cr</b> 51.9951(6)	manganese 25 <b>Mn</b> 54.93049(9)	iron 26 <b>Fe</b> 55.845(2)	cobalt 27 <b>Co</b> 58.93320(9)	nickel 28 <b>Ni</b> 58.934(4)	copper 29 <b>Cu</b> 63.546(3)	zinc 30 <b>Zn</b> 65.38(2)	aluminum 13 <b>Al</b> 26.981538(2)	silicon 14 <b>Si</b> 28.0856(3)	phosphorus 15 <b>P</b> 30.97376(1)	sulfur 16 <b>S</b> 32.056(5)	chlorine 17 <b>Cl</b> 35.453(2)	argon 18 <b>Ar</b> 39.948(1)
rubidium 37 <b>Rb</b> 55.4673(3)	strontium 38 <b>Sr</b> 88.50555(2)	yttrium 39 <b>Y</b> 87.62(1)	zirconium 40 <b>Zr</b> 88.90535(2)	niobium 41 <b>Nb</b> 91.224(2)	tin 42 <b>Ti</b> 92.90535(2)	niobium 43 <b>Nb</b> 95.95(2)	technetium 44 <b>Tc</b> [98]	ruthenium 45 <b>Ru</b> 101.57(2)	rhodium 46 <b>Rh</b> 102.55550(2)	palladium 47 <b>Pd</b> 106.42(1)	silver 48 <b>Ag</b> 107.8552(2)	cadmium 49 <b>Cd</b> 112.411(8)	indium 50 <b>In</b> 116.518(3)	germanium 31 <b>Ga</b> 69.723(1)	germanium 32 <b>Ge</b> 72.64(1)	arsenic 33 <b>As</b> 74.92160(2)	selenium 34 <b>Se</b> 78.96(3)	bromine 35 <b>Br</b> 79.904(1)	krypton 36 <b>Kr</b> 83.798(2)
caesium 55 <b>Cs</b> 132.9545(2)	barium 56 <b>Ba</b> 137.327(7)	lutetium 71 <b>Lu</b> 174.9568(1)	hafnium 72 <b>Hf</b> 178.49(2)	tantalum 73 <b>Ta</b> 180.9479(1)	europium 74 <b>W</b> 182.84(1)	mercury 75 <b>Re</b> 186.207(1)	osmium 76 <b>Os</b> 190.23(3)	iridium 77 <b>Ir</b> 192.217(3)	platinum 78 <b>Pt</b> 195.078(2)	gold 79 <b>Au</b> 196.96555(2)	mercury 80 <b>Hg</b> 200.59(2)	thallium 81 <b>Tl</b> 204.3833(2)	tin 82 <b>Pb</b> 207.2(1)	lead 83 <b>Bi</b> 211.750(1)	lead 84 <b>Po</b> 217.50(3)	radon 85 <b>At</b> 25.90447(3)	radon 86 <b>Rn</b> 131.23(6)		
francium 87 <b>Fr</b> [223]	radium 88 <b>Ra</b> [226]	lawrencium 103 <b>Lr</b> [262]	rutherfordium 104 <b>Rf</b> [267]	dubnium 105 <b>Db</b> [268]	seaborgium 106 <b>Sg</b> [271]	bohrium 107 <b>Bh</b> [272]	hassium 108 <b>Hs</b> [270]	meitnerium 109 <b>Mt</b> [276]	darmstadtium 110 <b>Ds</b> [281]	roentgenium 111 <b>Rg</b> [286]	ununtrium 112 <b>Uub</b> [288]	ununtrium 113 <b>Uut</b> [284]	ununquadium 114 <b>Uuo</b> [286]	ununpentium 115 <b>Uup</b> [288]	ununhexium 116 <b>Uuh</b> [293]	ununseptium 117 <b>Uus</b> —	ununoctium 118 <b>Uuo</b> [294]		

Lanthanoids	lanthanum 57 <b>La</b> 138.9055(2)	cerium 58 <b>Ce</b> 140.116(1)	praseodymium 59 <b>Pr</b> 140.97765(2)	neodymium 60 <b>Nd</b> 144.24(3)	promethium 61 <b>Pm</b> [145]	samarium 62 <b>Sm</b> 150.36(3)	euroium 63 <b>Eu</b> 151.964(1)	gadolinium 64 <b>Gd</b> 157.25(3)	terbium 65 <b>Tb</b> 158.92534(2)	dysprosium 66 <b>Dy</b> 162.500(1)	holmium 67 <b>Ho</b> 164.93032(2)	erbium 68 <b>Er</b> 167.259(3)	thulium 69 <b>Tm</b> 169.93421(2)	yterbium 70 <b>Yb</b> 173.054(5)
Actinoids	actinium 89 <b>Ac</b> [227]	thorium 90 <b>Th</b> 232.0368(1)	protactinium 91 <b>Pa</b> 231.03588(2)	uraniium 92 <b>U</b> 238.02991(3)	neptuniun 93 <b>Np</b> [237]	plutonium 94 <b>Pu</b> [244]	americium 95 <b>Am</b> [243]	curium 96 <b>Cm</b> [247]	berkelium 97 <b>Bk</b> [247]	californium 98 <b>Cf</b> [251]	einsteinium 99 <b>Es</b> [252]	fermium 100 <b>Fm</b> [257]	mendelevium 101 <b>Md</b> [258]	nobelium 102 <b>No</b> [259]

Higher energy  
excitation  
(UV)

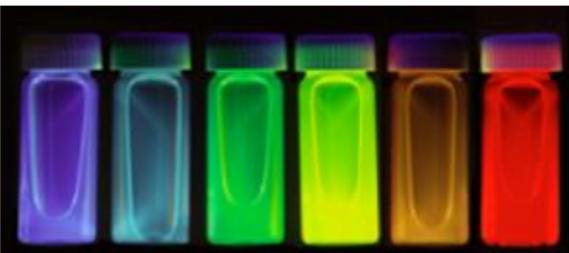
### photoluminescence



Emission at  
lower energy  
(visible)

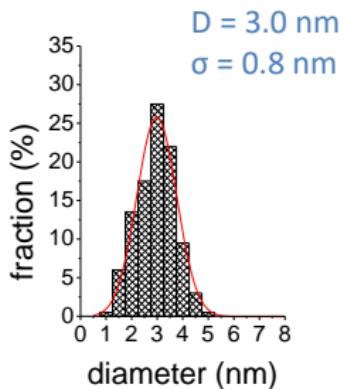
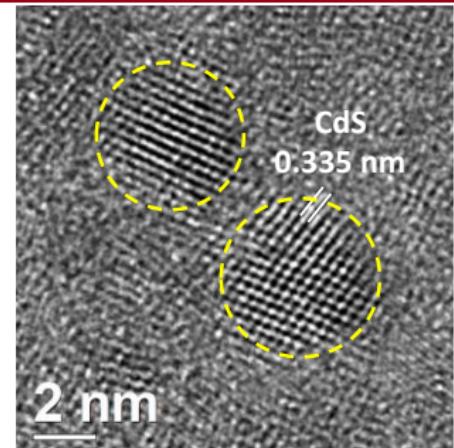
CdS, CdSe,  
ZnS, ZnSe,  
Si...

Colloidal solutions CdSe in esane with  
decreasing size



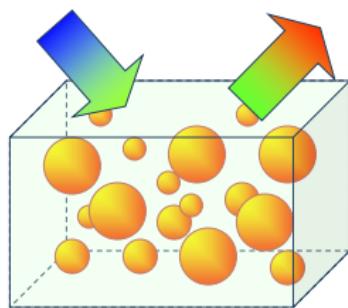
3 eV (UV)  
D = 1.2 nm

1.8 eV (IR)  
D = 11.5 nm



Higher energy  
excitation  
(UV)

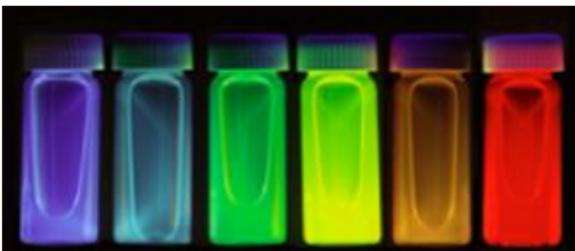
### photoluminescence



Emission at  
lower energy  
(visible)

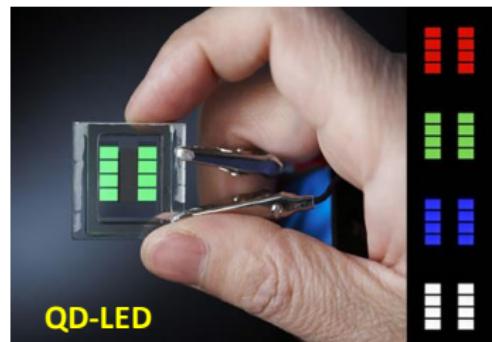
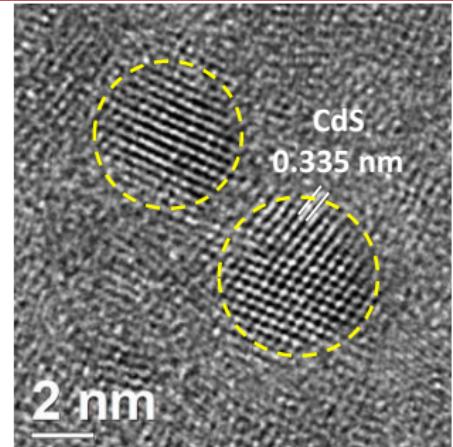
CdS, CdSe,  
ZnS, ZnSe,  
Si...

Colloidal solutions CdSe in esane with  
decreasing size

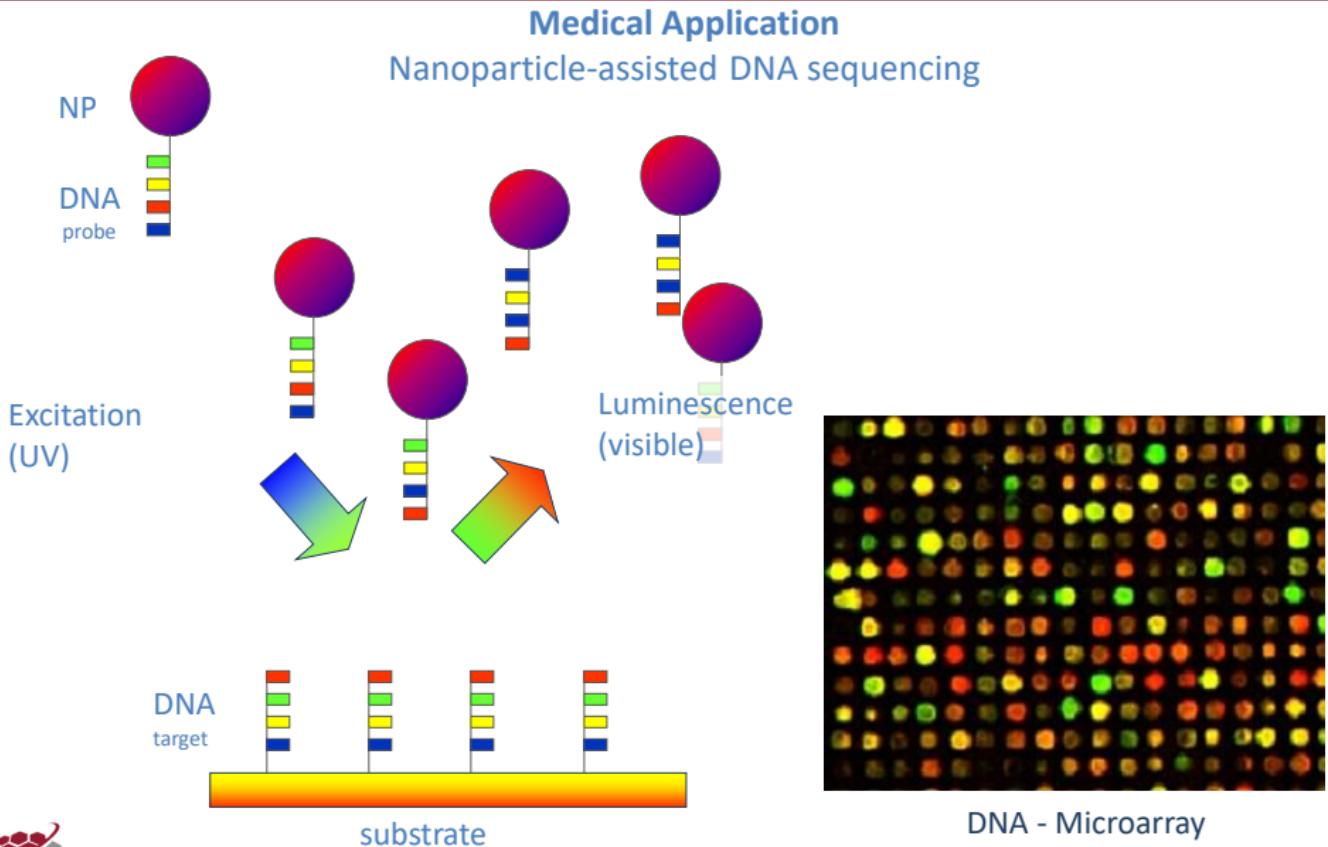


3 eV (UV)  
 $D = 1.2 \text{ nm}$

1.8 eV (IR)  
 $D = 11.5 \text{ nm}$



QD-LED



# Optical Semiconductors



Giant Blue Morpho  
(15 cm, Perù)

