Fundamentals of Nanoscience (SdM)

Introduction to Nanophysics (Physics)

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NSG

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UNIVERSIS
PATAVINA
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NSG

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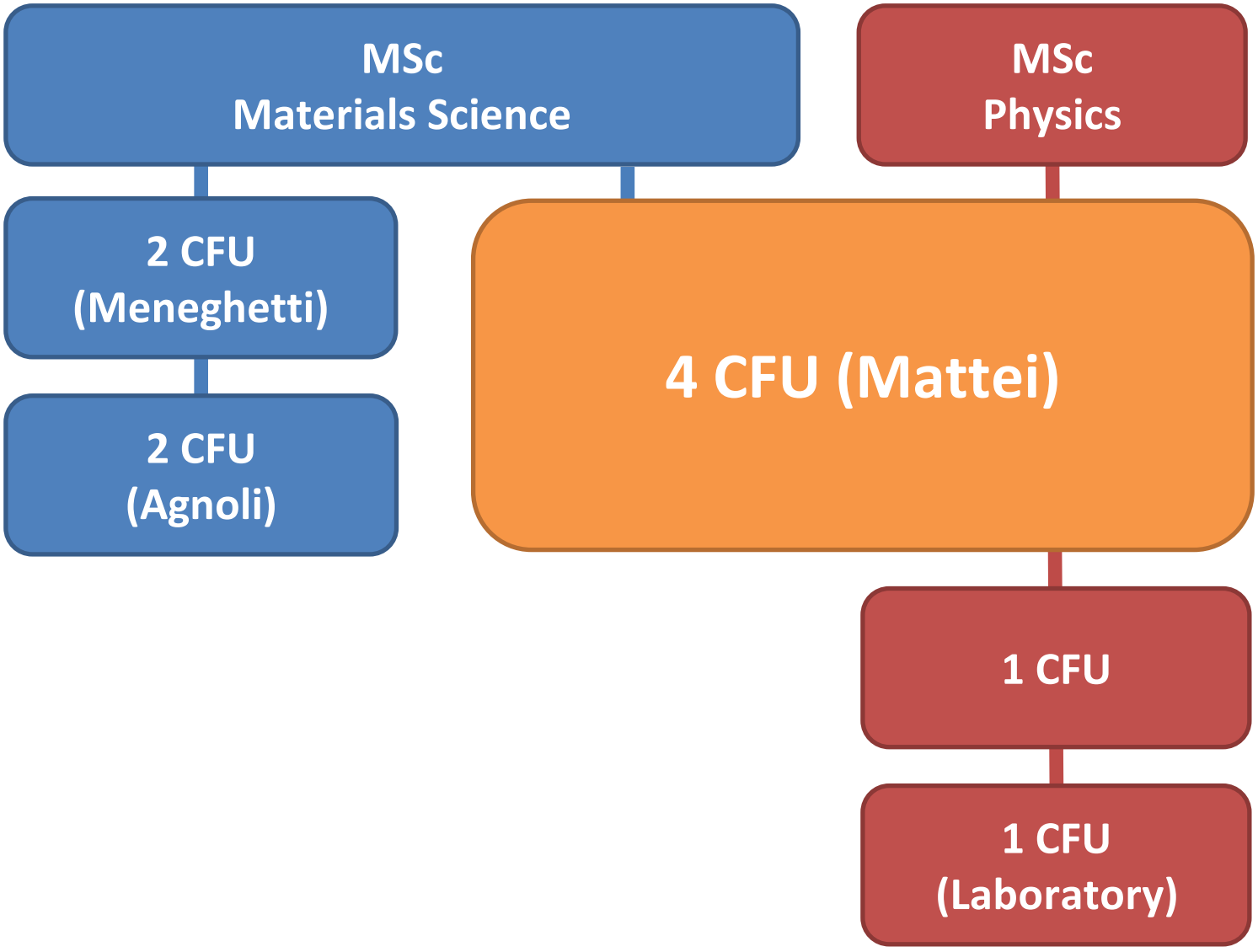
Course Structure



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

Student Reception: *on request*

e-mail: giovanni.mattei@unipd.it

URL: http://materia.dfa.unipd.it/mattei

Room 82 – (ground floor) Dept. of Physics and Astronomy

(via Marzolo 8)

Learning Objectives

- 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 **photonics**, **plasmonics** and **magnetism**.

Final Exam

Materials Science

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

Written Exam:

- Open Question

+

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

Physics

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

Written Exam:

- Open Question
- Numerical Application

Lab:

- Written Report

Course Content

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 and Suggested Readings

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)

Nanoscience & Nanotechnology

Classical Physics

Quantum Physics

1 m

1 mm =10^{-3} m

- hair
- Red blood cell

1 µm =10^{-6} m

- Transistor
- Virus, Cluster

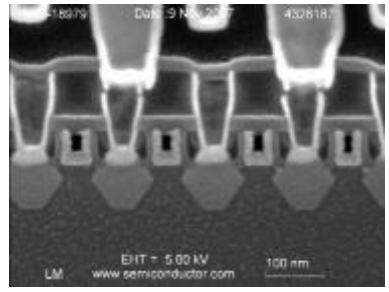
1 nm =10^{-9} m

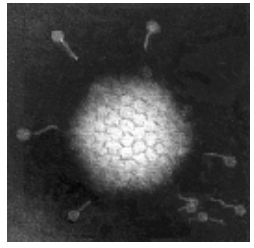
- DNA, Fulleren, Nanotube
- Atom

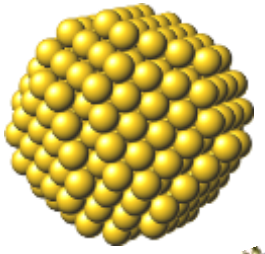
1 pm =10^{-12} m

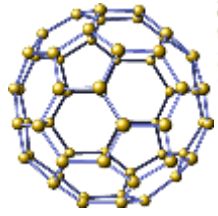
Nanoscience
Nanotechnology

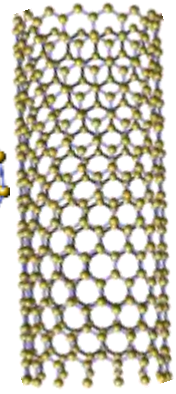
size < 100 nm





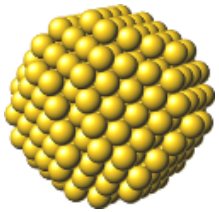






(nano)-size matters…

Nanoparticle



1 nm

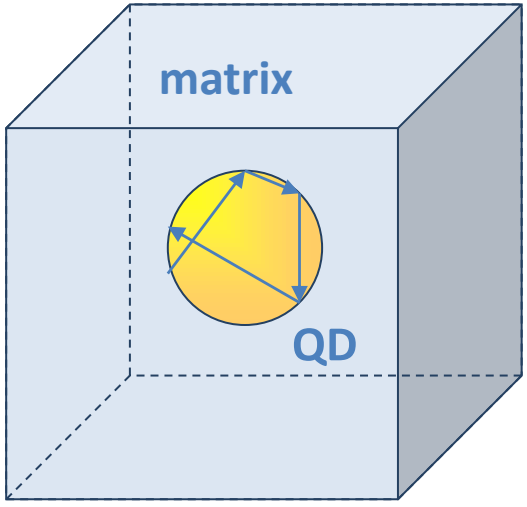
Tennis Ball

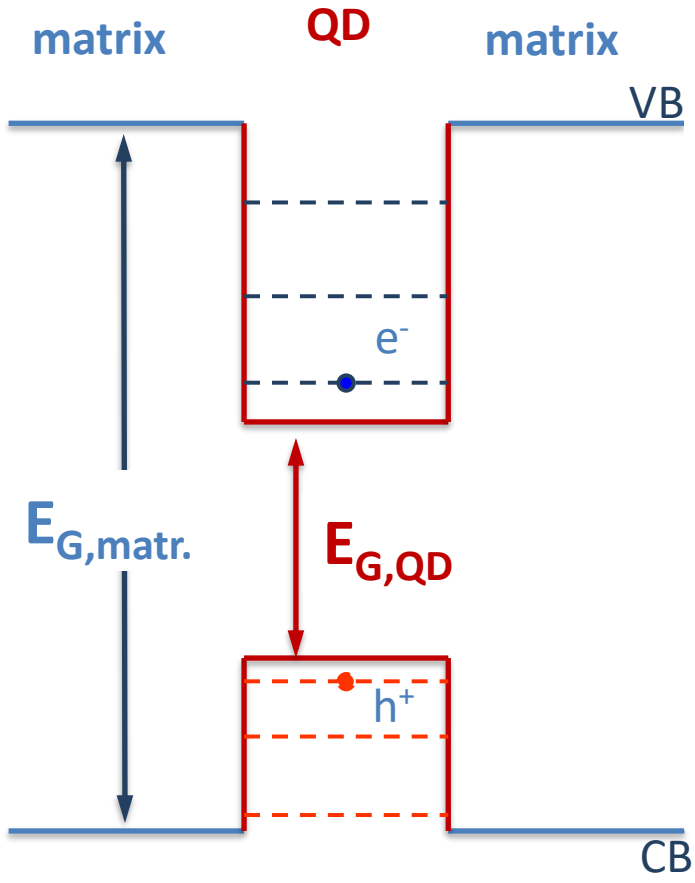
6 cm

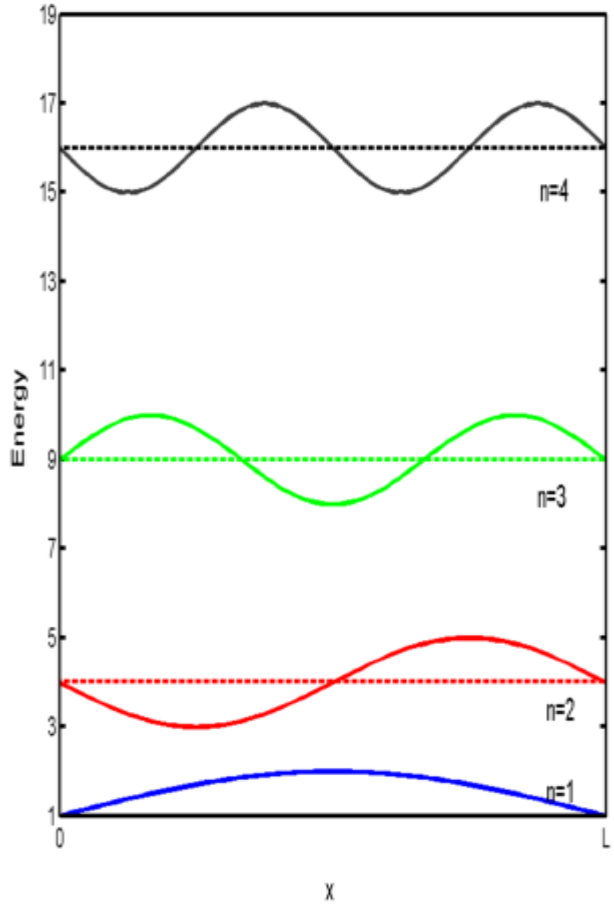
Moon

3500 km

A simple proportion…

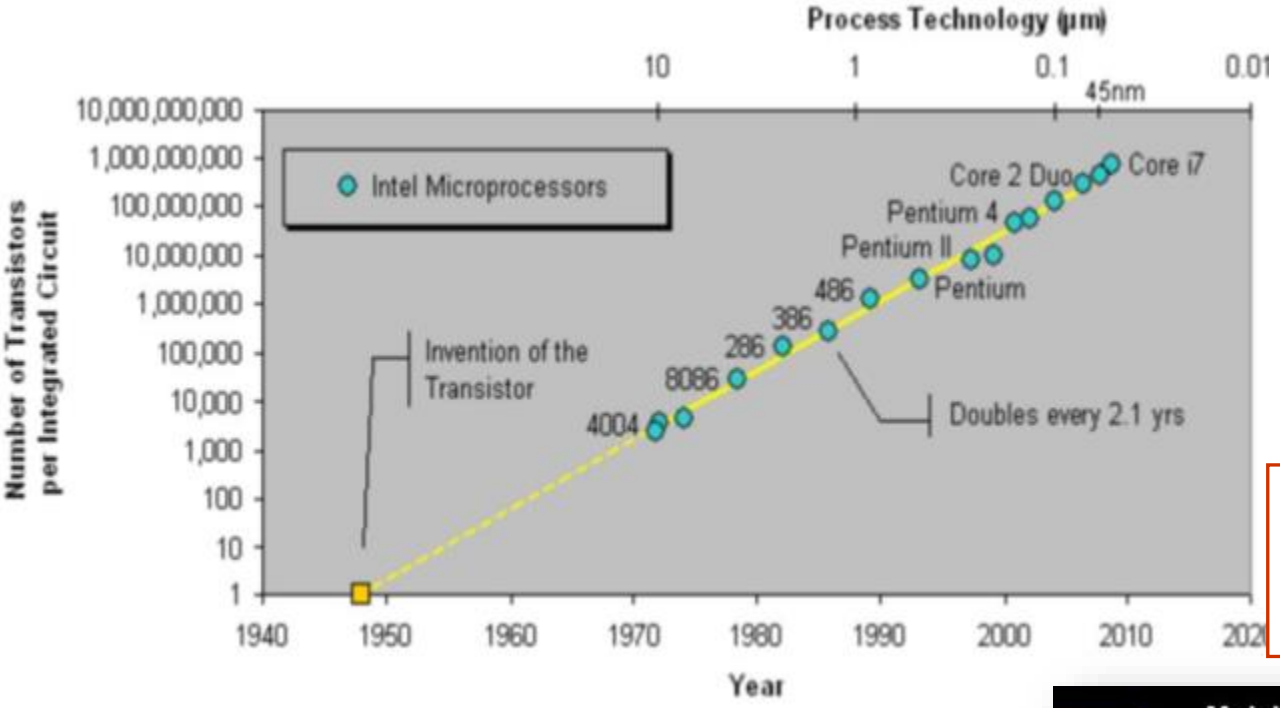






Wave-particle duality

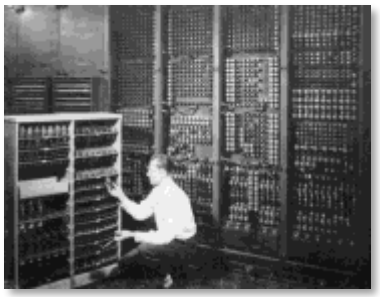
Nano-electronics



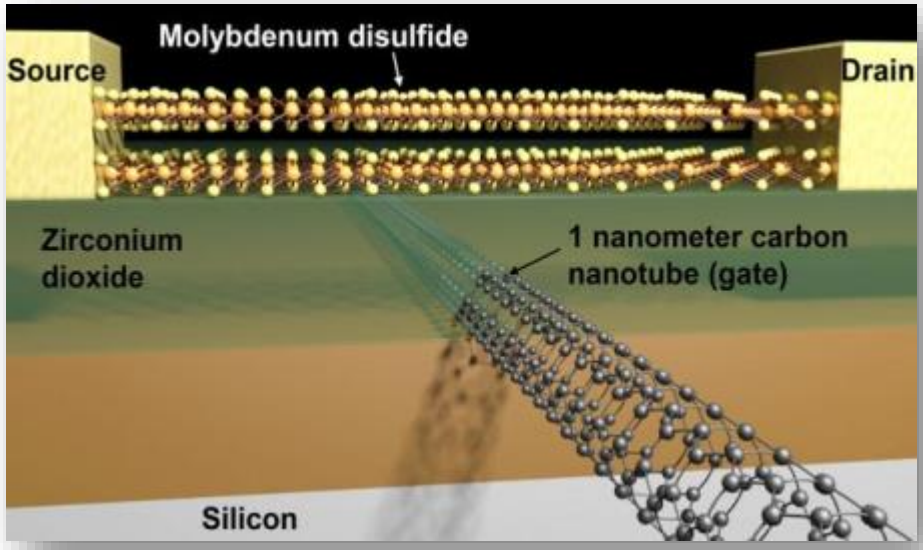
Moore's Law

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

T = 1.5 yrs - t in yrs



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



S. Desai et al., Science 354 (2016) 99

What if Moore's Law were valid for...

(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

Nano-size

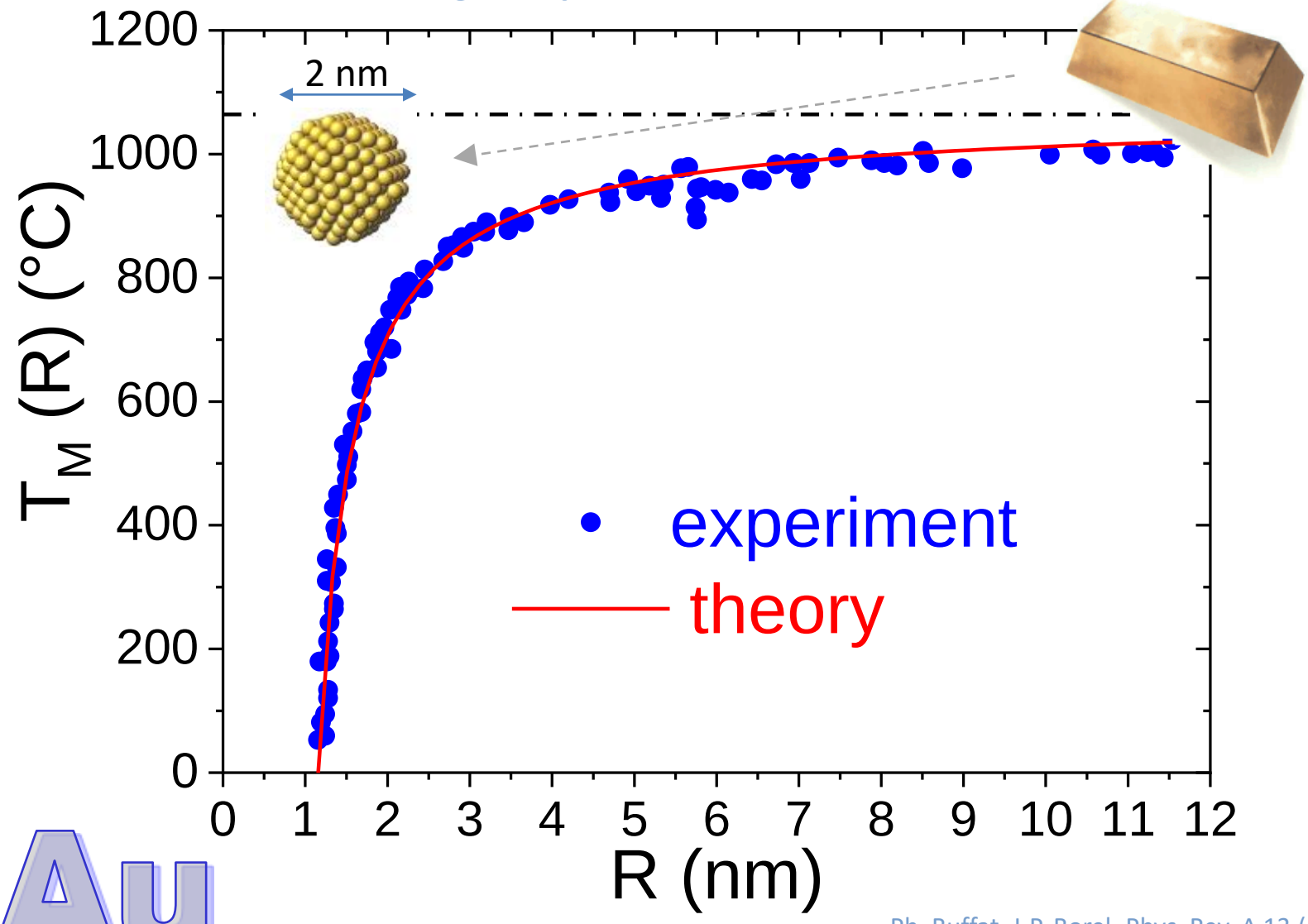
	Bulk Material	Nano Material
Size (L)	~ 1 m	< 100 nm = 10^{-7} m
Property (A)	A ≠ A(L)	A = A(L)

- Characteristic lengths λ_C ~ 1- 100 nm
- Nano-physics: $L < \lambda_C$
- E.g.:
  - λ_e = electronic mean free path (10-100 nm)
  - λ_{exc} = excitonic Bohr radius (1-10 nm)
  - λ_M = magnetic domain (30-50 nm)

control L = control A(L)

Nano-Thermodynamics

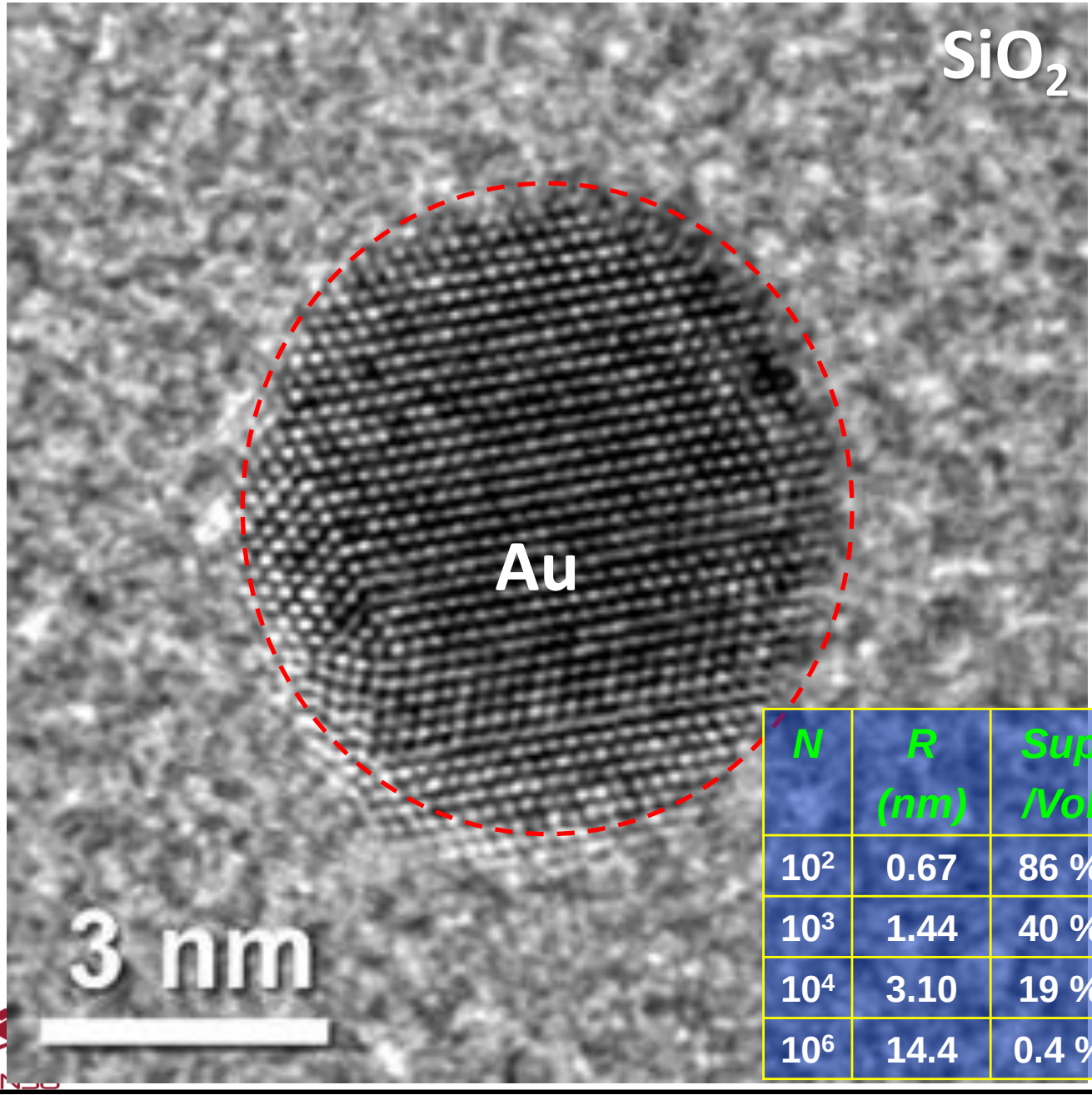
Example of A = A(L)



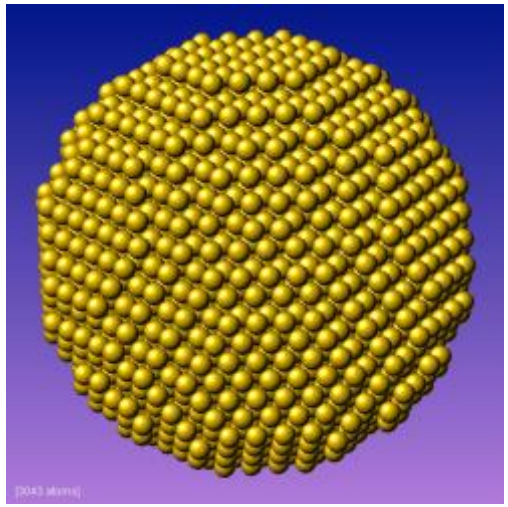
Au

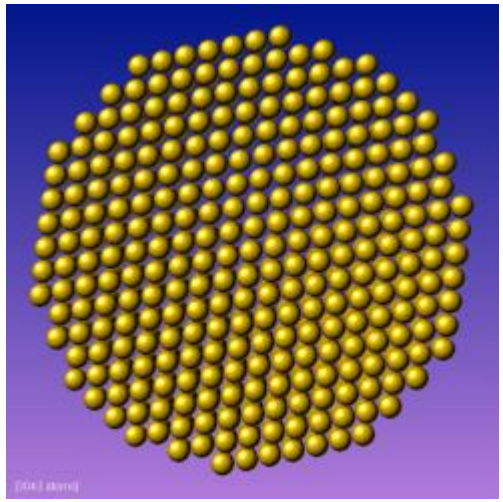
Ph. Buffat, J-P. Borel, Phys. Rev. A 13 (1976) 2287

Au NPs obtained by ion implantation in SiO_2 @ NSG



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





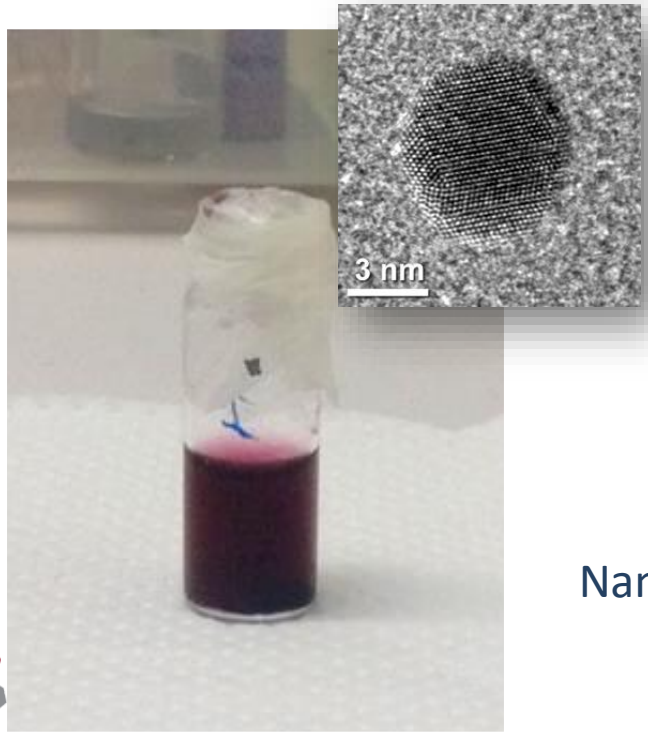
Au NP along the <110> zone axis

Nano-Optics

Which is the color of Au NPs?

Bulk Au

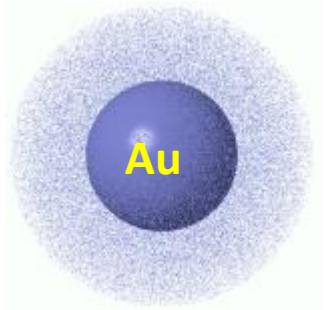
Thin film (30 nm) Au



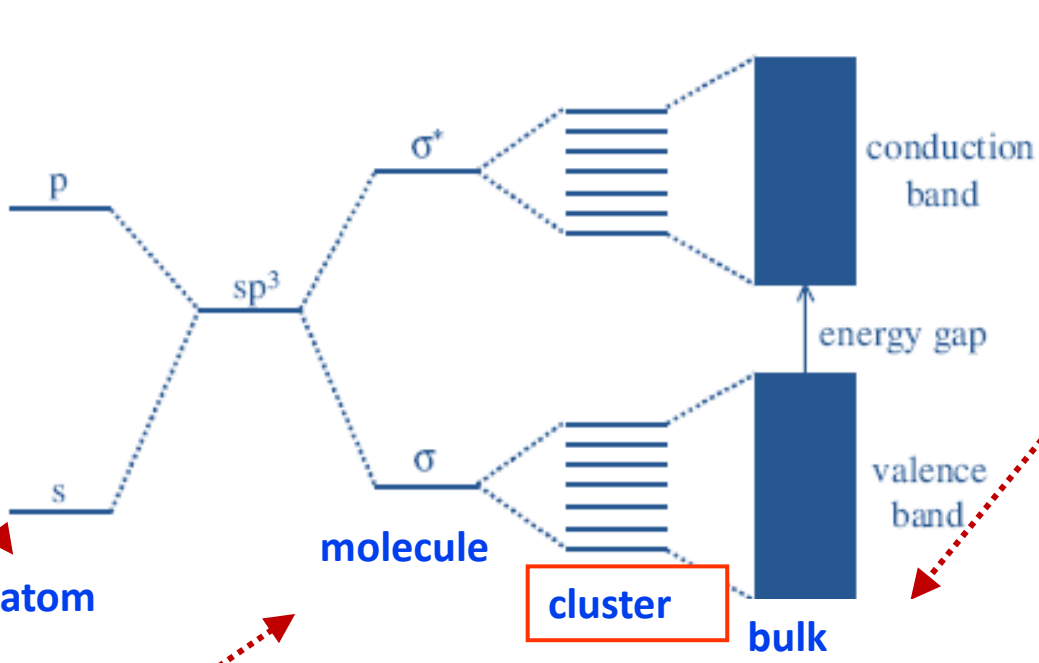
Nano Au

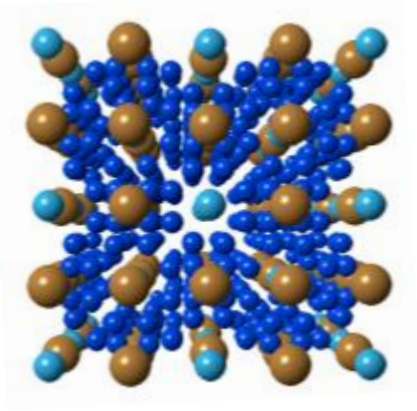
Electronic structure

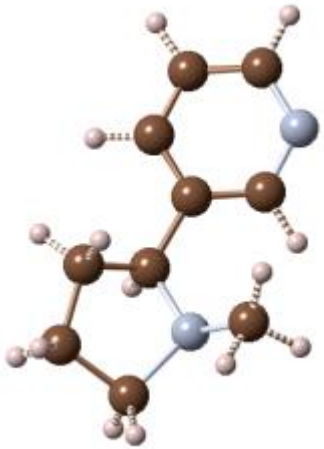
From the atom to the bulk...



energy



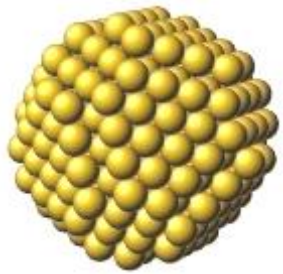




1 ~ 10 ~ 10^3

Number of bonded atoms

Properties:
- electronic
- optical
- magnetic
- thermal
- catalytic



2 nm

‘Seeing’ at the Nanoscale

‘seeing’ at the nanoscale

A typical optical microscope

- **photons**

  $\lambda = 400 \div 800$ nm

  $E = 1 \div 3$ eV

- **resolution**

  $\sim \lambda$ (500 nm)

- **working pressure**

  ambient

'seeing' at the nanoscale

A typical electron microscope - TEM

- **electrons**

  $\lambda = 1.2$ pm *(Quantum Mechanics)*

  $E = 200 \div 300$ keV

- **resolution**

  0.1 nm

- **working pressure**

  10^{-4} Pa (~ 10^{-9} atm)

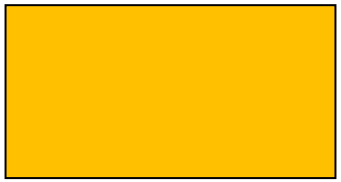
- **price**

  1.5-2.0 M€

Nano-Materials

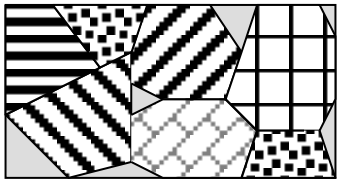
Characteristic size < 100 nm

1.



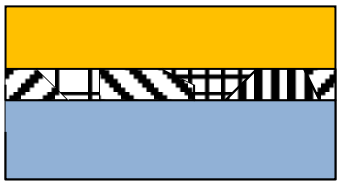
Bulk Materials
(3D)

2.



Nanostructured
Materials (3D)

3.

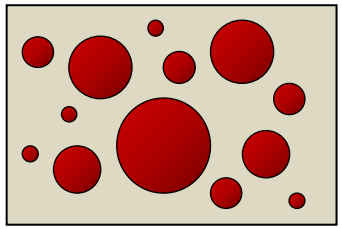


Nanostructured Films
(1D-2D)

4.

Multi-layered
Materials
(1D-2D)

5.



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

6.

Novel Materials
(Meta Materials)

Synthesis Methods

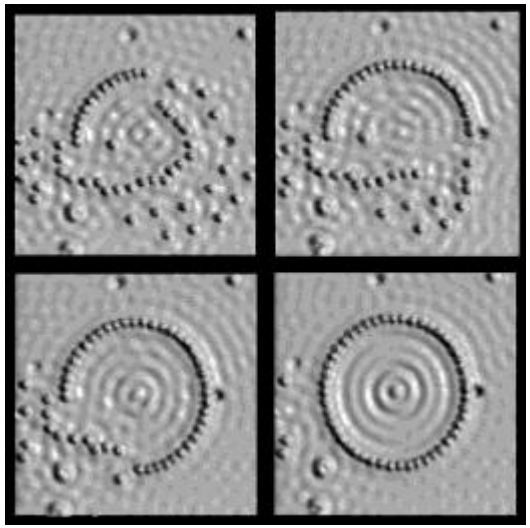
Bottom/Up vs. Top/Down

Bottom/Up

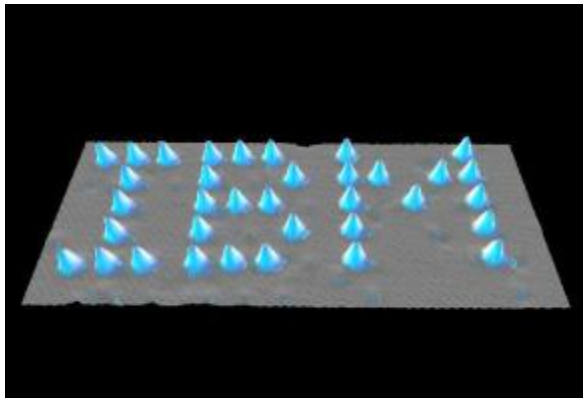
From small to large or from **simple to complex**

LEGO
'**building block**' assembly with
quantum supramolecular rules

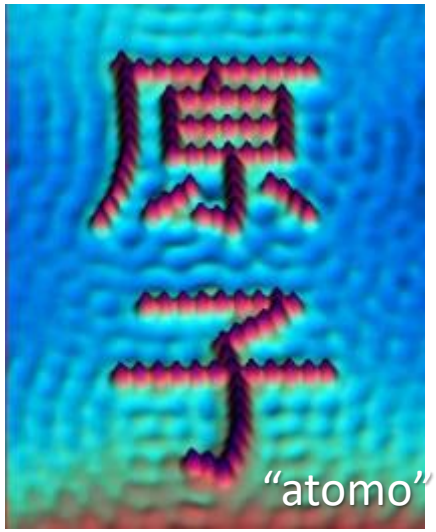
Using atoms or simple units as LEGO blocks one can build artificial nano-objects
(**nano-positioning** and **self-assembling**)



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



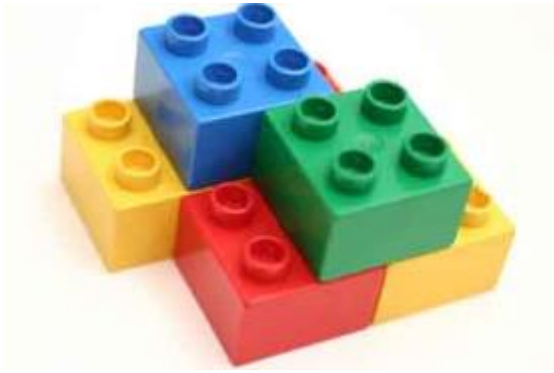
Xe on Ni (111)
D.M. Eigler, E.K. Schweizer,
Nature 344, 524-526 (1990)



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

Bottom/Up

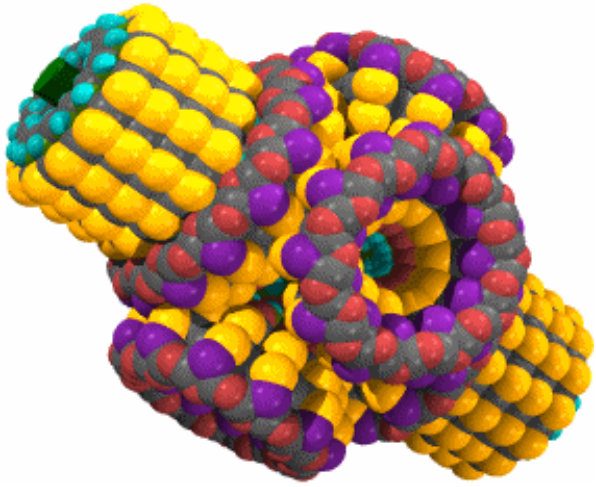
From small to large or from **simple to complex**



LEGO

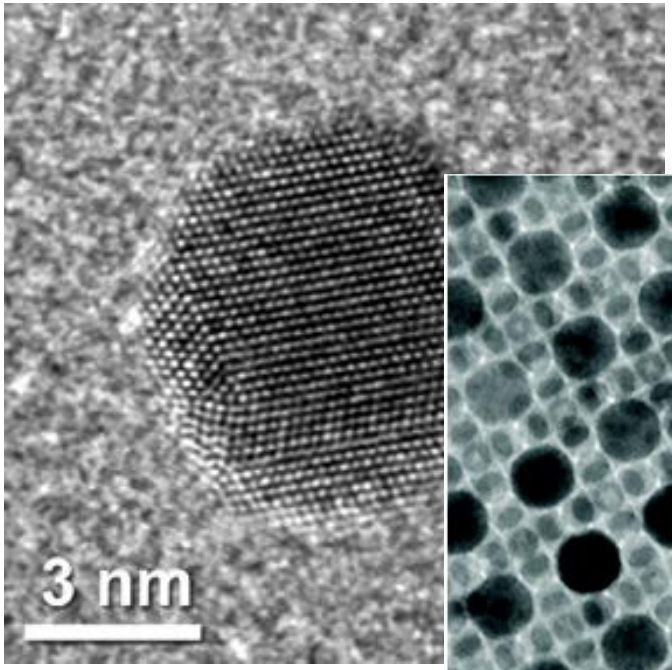
'**building block**' assembly with quantum supramolecular rules

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

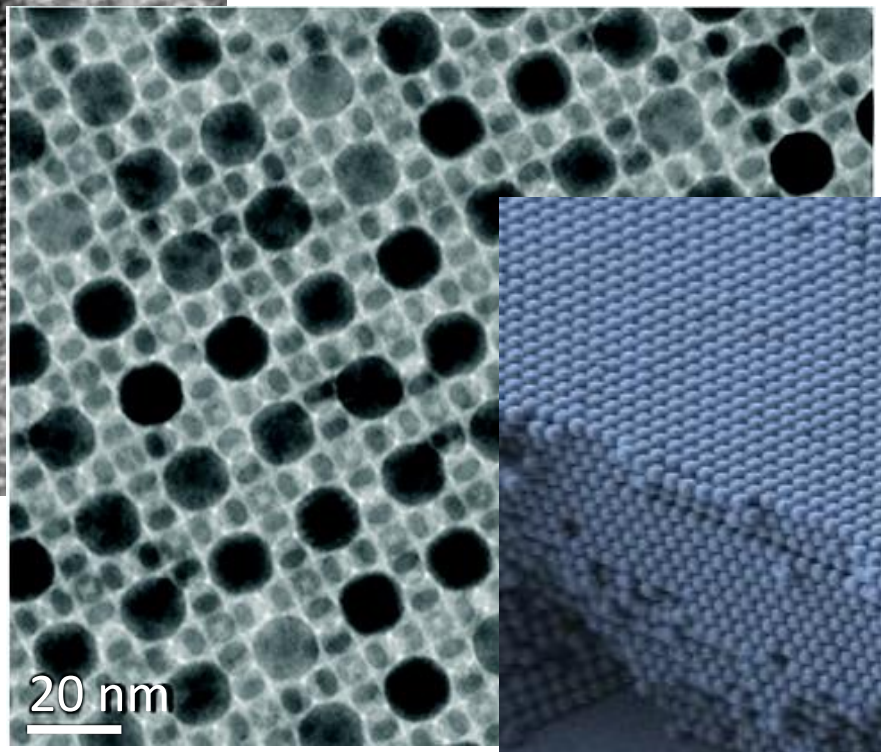


Nano-machine *(E. Drexler, Nanorex Inc.)*

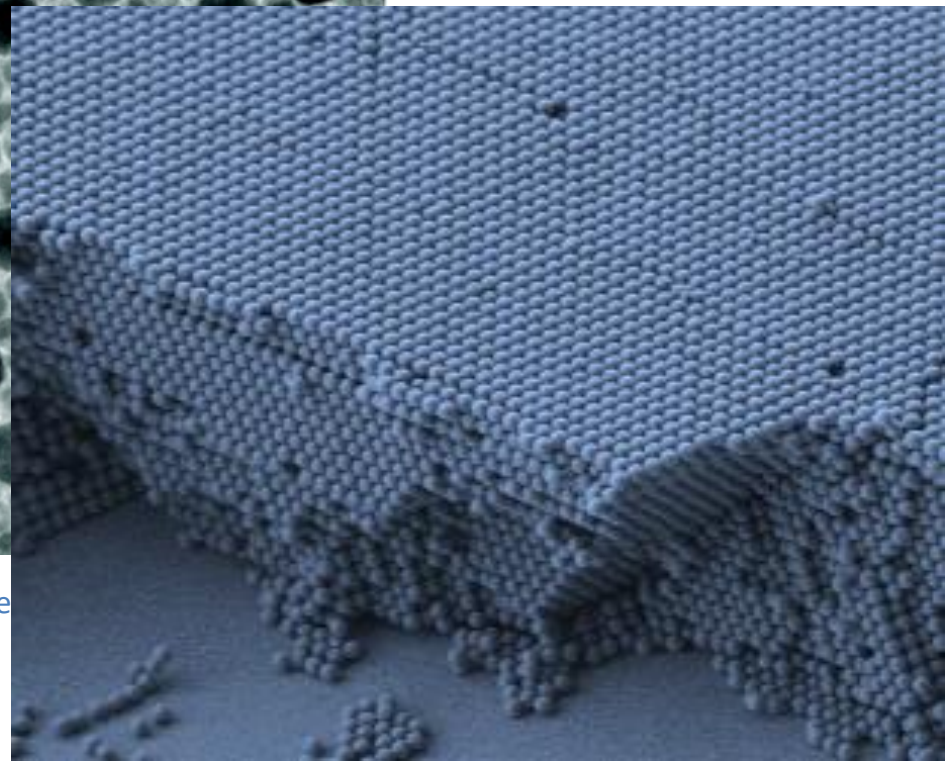
Bottom/Up



Au NC in SiO_2 (UniPD)



Fe_3O_4 NC: Chen, J. et al. Nano Lette



Photonic crystal: 3D self-assembly of SiO_2 NPs (1 µm).

Top/Down

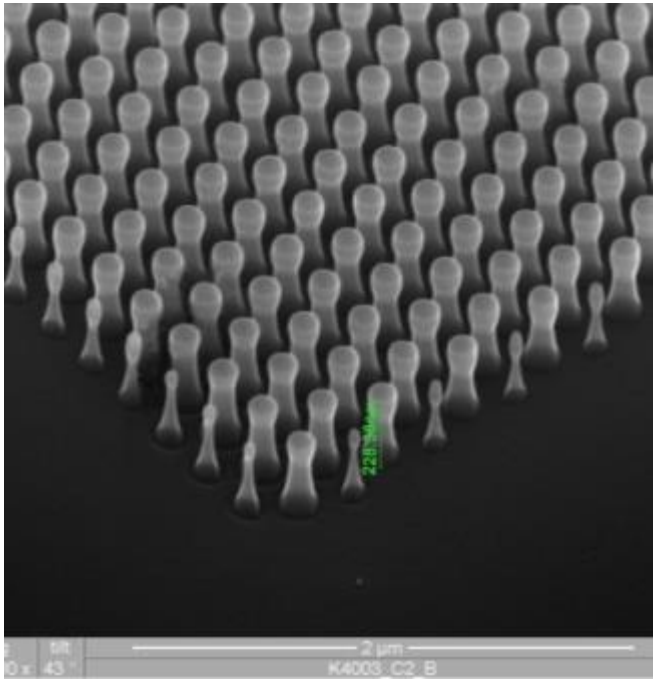
From large to small

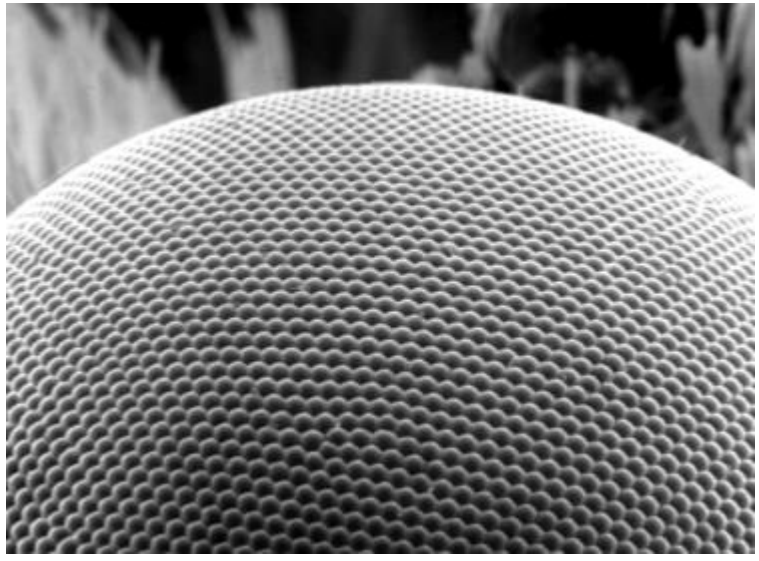
Lithography

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

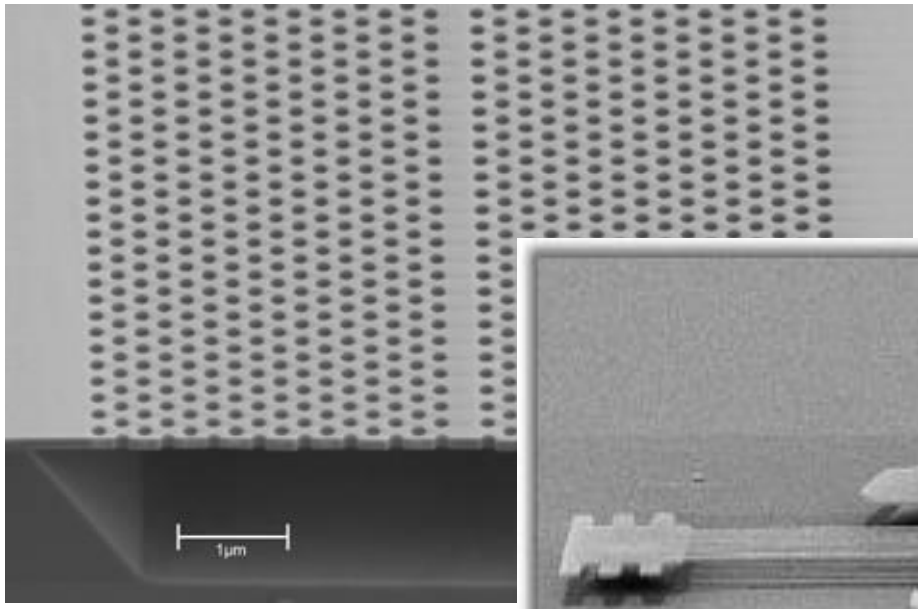
Nanostructures and nanomaterials (electron beam lithography **EBL**: resol. 10 nm)

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

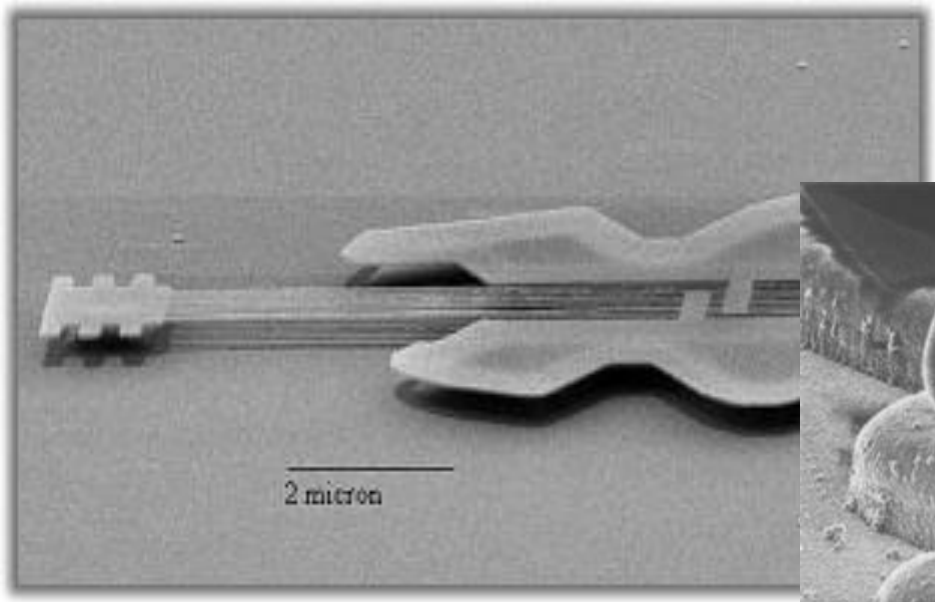




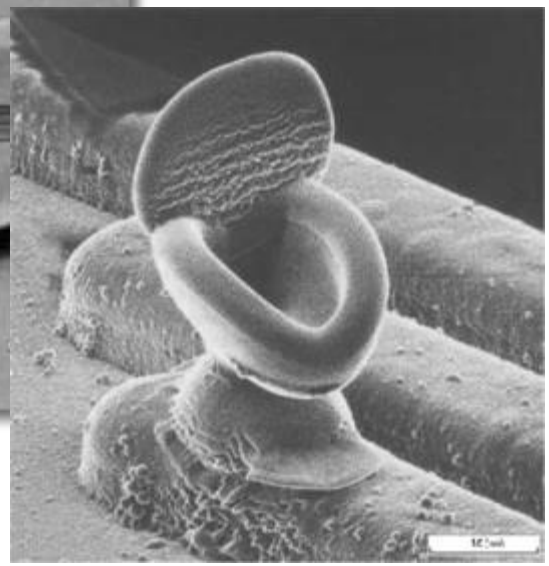
Close-up view of a moth's eye



Photonic Crystal

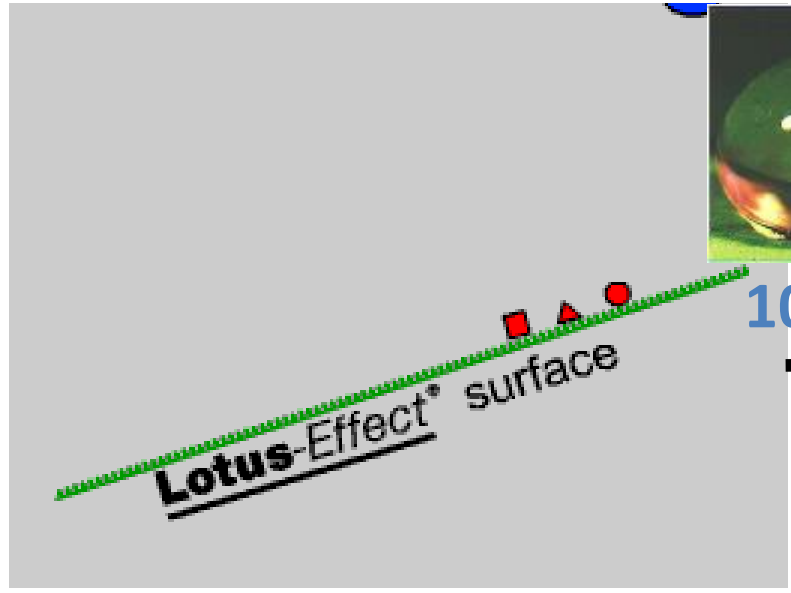


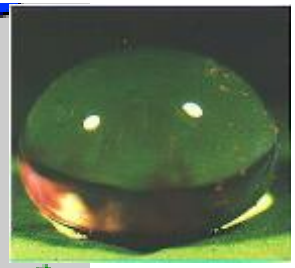
Nano-guitar



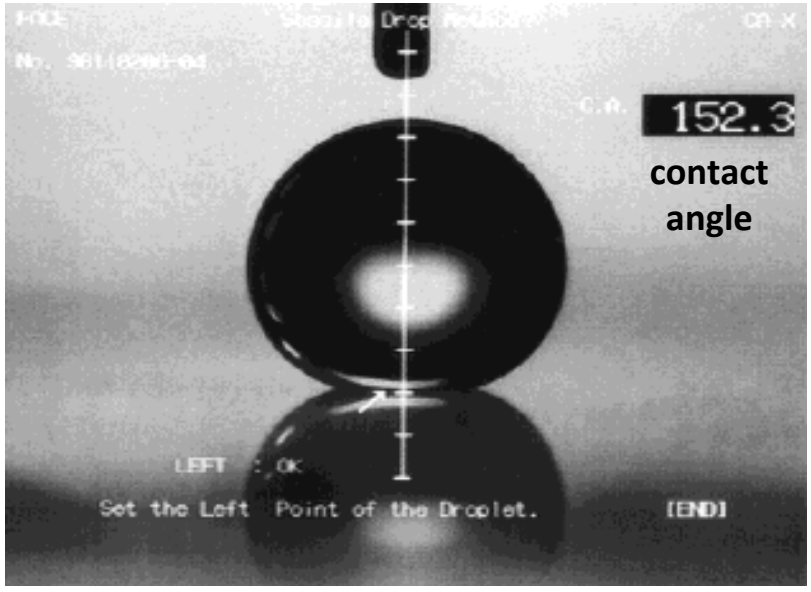
…Nano-toilet

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

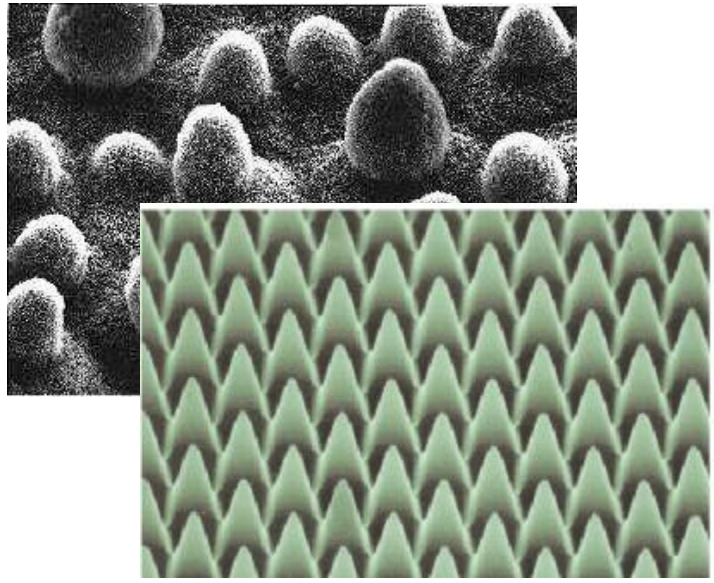




10 µm



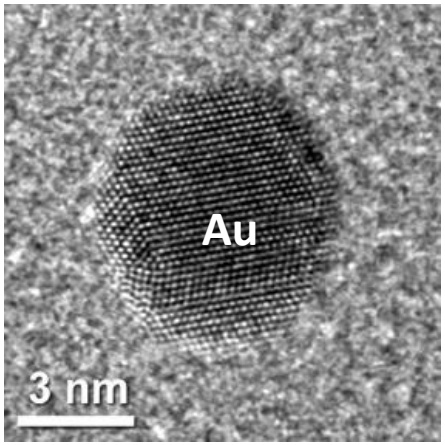
contact angle



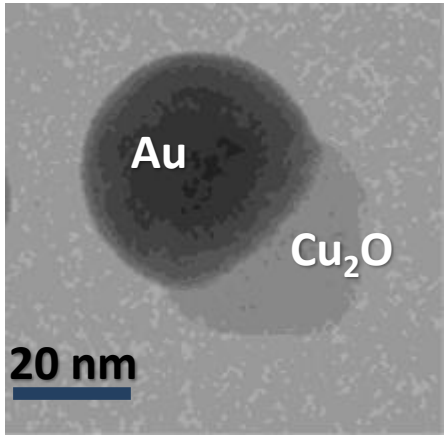
REM recording of a holographically produced self-cleaning surface.
© Fraunhofer ISE

Some nano-structures produced @ NSG

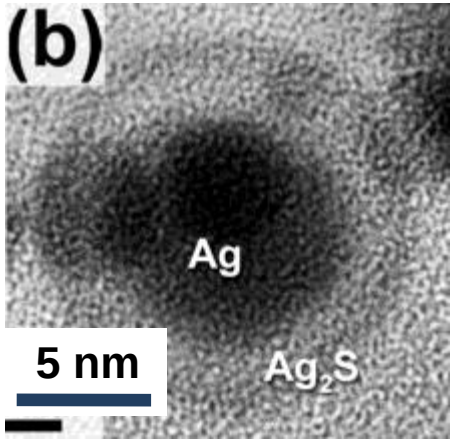
Simple NP



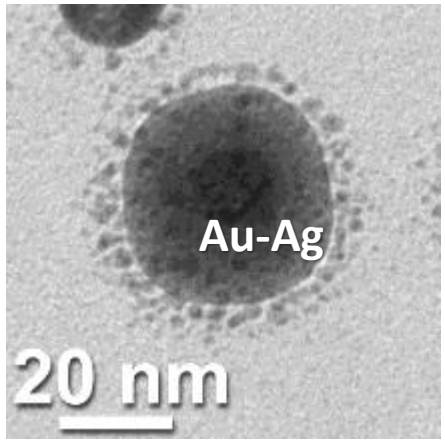
Janus Particles



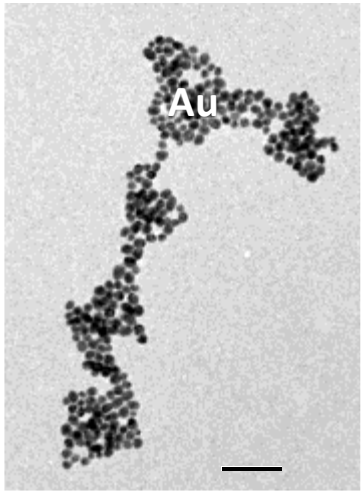
Core-shell



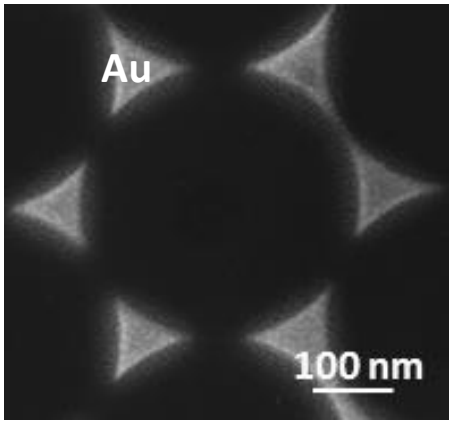
Nano-Planets (NPL)



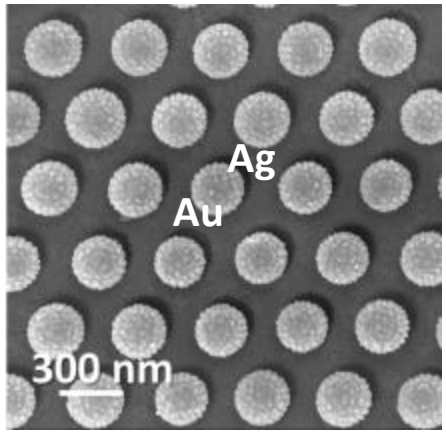
DLA Fractals



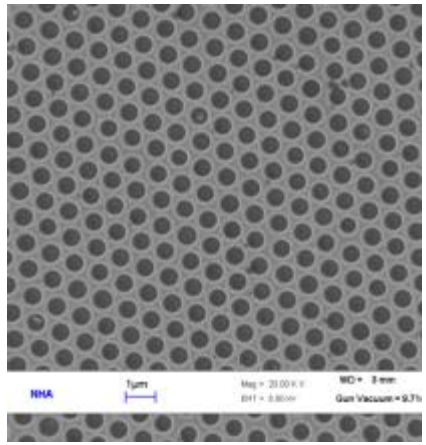
Nano-Prism (NPA)



Nano-Shell (NSA)



Nano-Hole (NHA)



Monoelemental

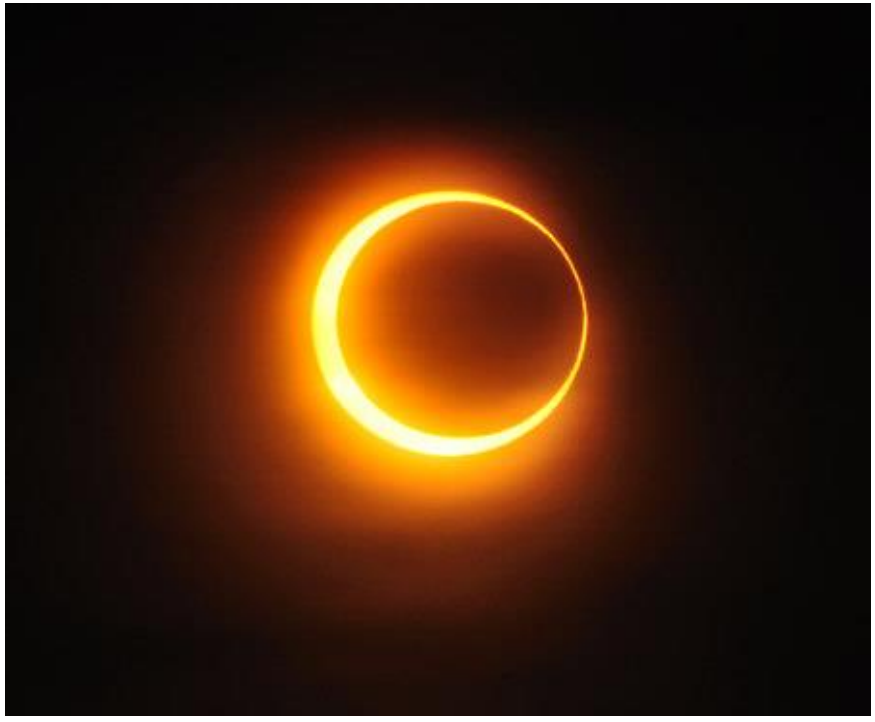
Au, Ag, Cu, Pt, Co, Ni, Fe

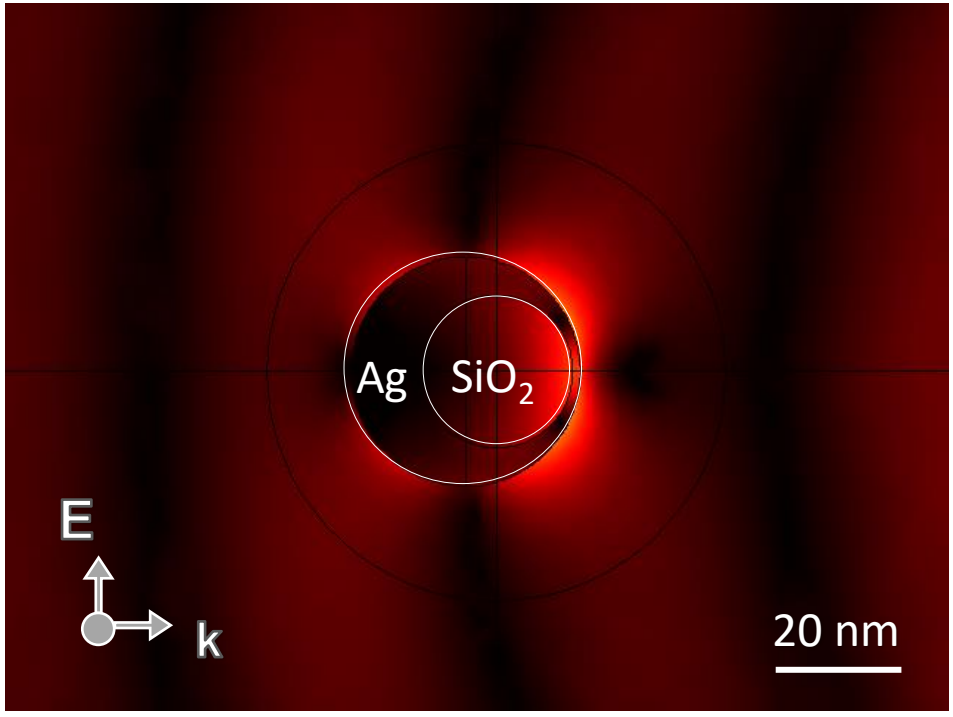
Bimetallic

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

NSG

Nano-eclipse





Solar Eclipse 2015

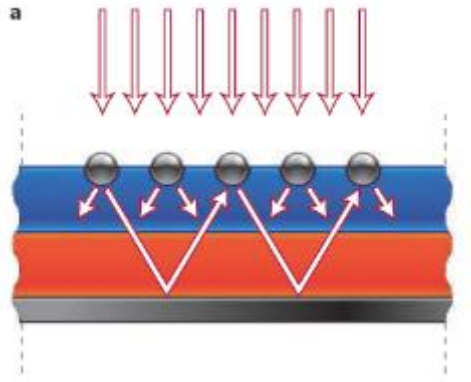
Asymmetric – NanoShell
SiO_2 @ Ag

Metallic Nanostructures

Optical Properties (Plasmonics):

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

Light confinement < λ



Materials for plasmonics

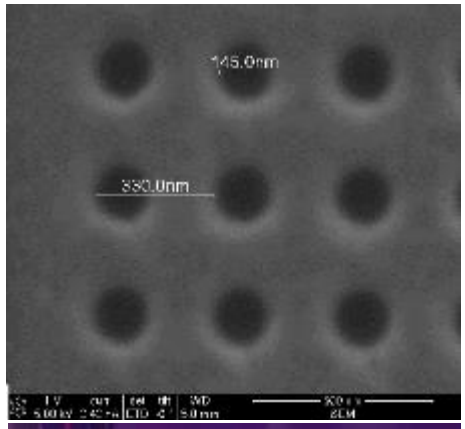
$$Re[\epsilon(\omega, R)] < 0$$

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
hydrogen 1 **H** 1.00794(7)			Key: element name atomic number **symbol** 2003 atomic weight (mean relative mass)														helium 2 **He** 4.002602(2)
lithium 3 **Li** 6.941(2)	beryllium 4 **Be** 9.012182(3)											boron 5 **B** 10.811(7)	carbon 6 **C** 12.0107(8)	nitrogen 7 **N** 14.0067(7)	oxygen 8 **O** 15.9994(3)	fluorine 9 **F** 18.9984032(5)	neon 10 **Ne** 20.1797(6)
sodium 11 **Na** 22.989770(2)	magnesium 12 **Mg** 24.3050(6)											aluminium 13 **Al** 26.981538(2)	silicon 14 **Si** 28.0855(3)	phosphorus 15 **P** 30.973761(2)	sulfur 16 **S** 32.065(5)	chlorine 17 **Cl** 35.453(2)	argon 18 **Ar** 39.948(1)
potassium 19 **K** 39.0983(1)	calcium 20 **Ca** 40.078(4)	scandium 21 **Sc** 44.955910(8)	titanium 22 **Ti** 47.867(1)	vanadium 23 **V** 50.9415(1)	chromium 24 **Cr** 51.9961(6)	manganese 25 **Mn** 54.938049(9)	iron 26 **Fe** 55.845(2)	cobalt 27 **Co** 58.933200(9)	nickel 28 **Ni** 58.6934(2)	copper 29 **Cu** 63.546(3)	zinc 30 **Zn** 65.38(2)	gallium 31 **Ga** 69.723(1)	germanium 32 **Ge** 72.64(1)	arsenic 33 **As** 74.92160(2)	selenium 34 **Se** 78.96(3)	bromine 35 **Br** 79.904(1)	krypton 36 **Kr** 83.798(2)
rubidium 37 **Rb** 85.4678(3)	strontium 38 **Sr** 87.62(1)	yttrium 39 **Y** 88.90585(2)	zirconium 40 **Zr** 91.224(2)	niobium 41 **Nb** 92.90638(2)	molybdenum 42 **Mo** 95.96(2)	technetium 43 **Tc** [98]	ruthenium 44 **Ru** 101.07(2)	rhodium 45 **Rh** 102.90550(2)	palladium 46 **Pd** 106.42(1)	silver 47 **Ag** 107.8682(2)	cadmium 48 **Cd** 112.411(8)	indium 49 **In** 114.818(3)	tin 50 **Sn** 118.710(7)	antimony 51 **Sb** 121.760(1)	tellurium 52 **Te** 127.60(3)	iodine 53 **I** 126.90447(3)	xenon 54 **Xe** 131.293(6)
caesium 55 **Cs** 132.90545(2)	barium 56 **Ba** 137.327(7)	lutetium 71 **Lu** 174.9668(1)	hafnium 72 **Hf** 178.49(2)	tantalum 73 **Ta** 180.9479(1)	tungsten 74 **W** 183.84(1)	rhenium 75 **Re** 186.207(1)	osmium 76 **Os** 190.23(3)	iridium 77 **Ir** 192.217(3)	platinum 78 **Pt** 195.078(2)	gold 79 **Au** 196.96655(2)	mercury 80 **Hg** 200.59(2)	thallium 81 **Tl** 204.3833(2)	lead 82 **Pb** 207.2(1)	bismuth 83 **Bi** 208.98038(2)	polonium 84 **Po** [209]	astatine 85 **At** [210]	radon 86 **Rn** [222]
francium 87 **Fr** [223]	radium 88 **Ra** [226]	lawrencium 103 **Lr** [262]	rutherfordium 104 **Rf** [267]	dubnium 105 **Db** [268]	seaborgium 106 **Sg** [271]	bohrium 107 **Bh** [272]	hassium 108 **Hs** [270]	meitnerium 109 **Mt** [276]	darmstadtium 110 **Ds** [281]	roentgenium 111 **Rg** [280]	ununbium 112 **Uub** [285]	ununtrium 113 **Uut** [284]	ununquadium 114 **Uuq** [289]	ununpentium 115 **Uup** [288]	ununhexium 116 **Uuh** [293]	ununseptium 117 **Uus** —	ununoctium 118 **Uuo** [294]

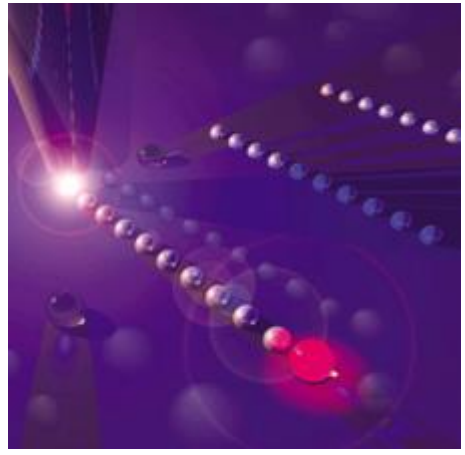
	57	58	59	60	61	62	63	64	65	66	67	68	69	70
Lanthanoids	lanthanum **La** 138.9055(2)	cerium **Ce** 140.116(1)	praseodymium **Pr** 140.90765(2)	neodymium **Nd** 144.24(3)	promethium **Pm** [145]	samarium **Sm** 150.36(3)	europium **Eu** 151.964(1)	gadolinium **Gd** 157.25(3)	terbium **Tb** 158.92534(2)	dysprosium **Dy** 162.500(1)	holmium **Ho** 164.93032(2)	erbium **Er** 167.259(3)	thulium **Tm** 168.93421(2)	ytterbium **Yb** 173.054(5)
Actinoids	actinium **Ac** [227]	thorium **Th** 232.0381(1)	protactinium **Pa** 231.03588(2)	uranium **U** 238.02891(3)	neptunium **Np** [237]	plutonium **Pu** [244]	americium **Am** [243]	curium **Cm** [247]	berkelium **Bk** [247]	californium **Cf** [251]	einsteinium **Es** [252]	fermium **Fm** [257]	mendelevium **Md** [258]	nobelium **No** [259]

"Cool" Plasmonic Properties

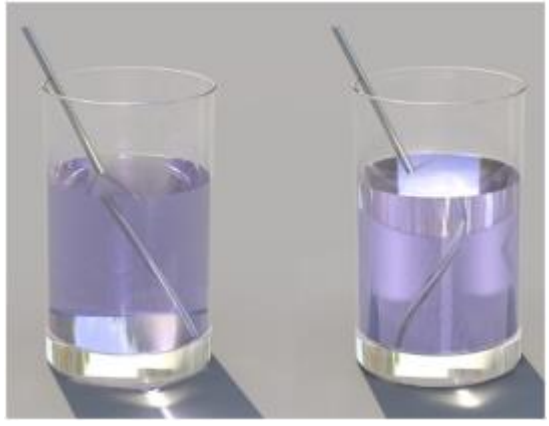
1. **Extraordinary transmission of light (EOT):** from array of nanoholes with sub-λ size in metal thin film.



2. **Plasmonic waveguides:** from array of NP or at the dielectric-metal interface

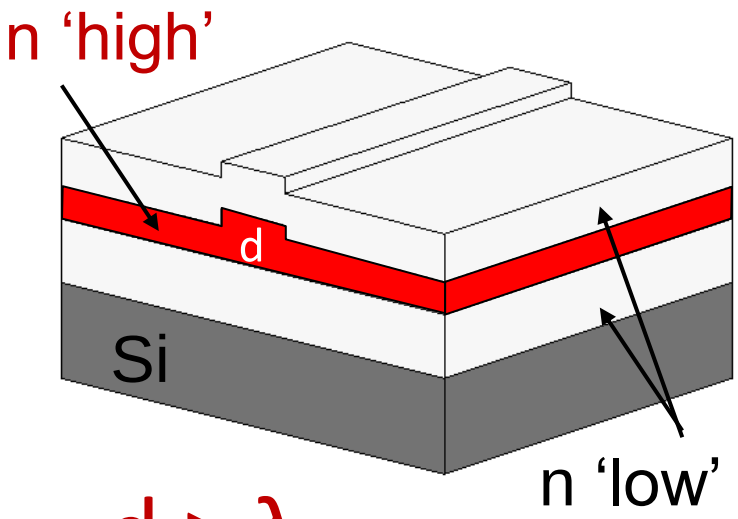


3. **MetaMaterials:** negative refractive index materials (invisibility cloak)



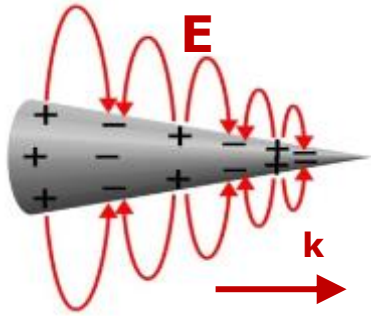
Plasmonic waveguides

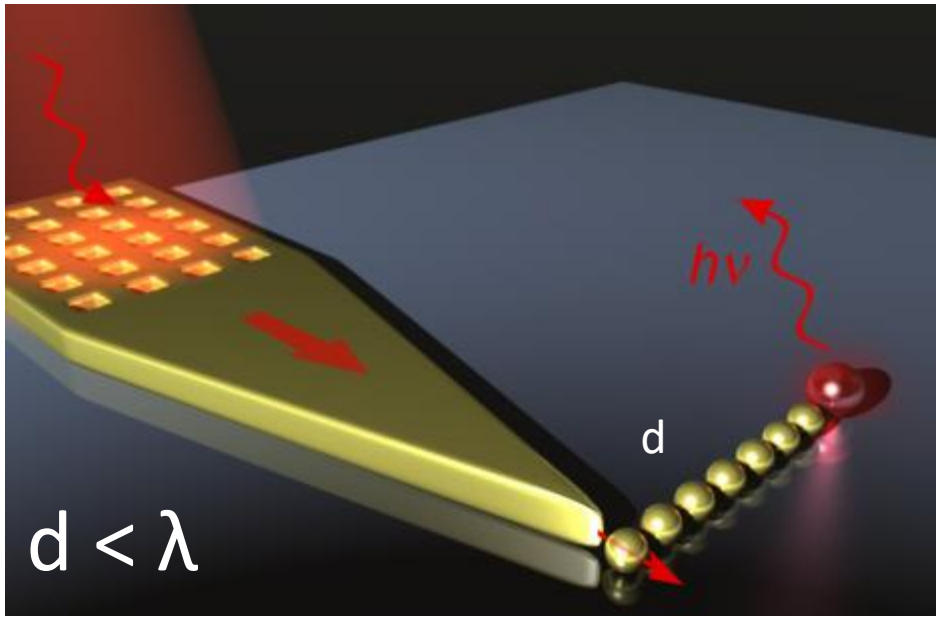
Optical waveguide



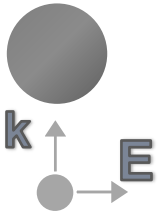
$d > \lambda$

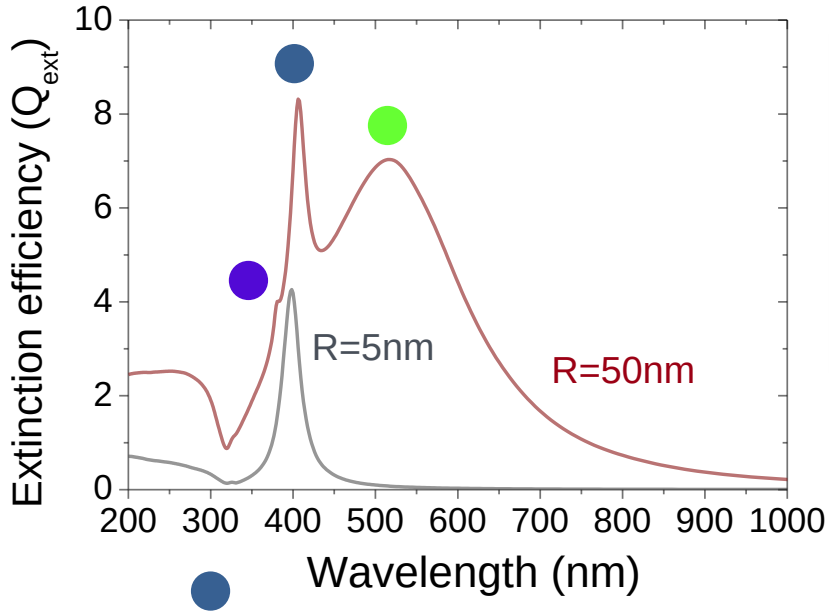
Plasmonic waveguide



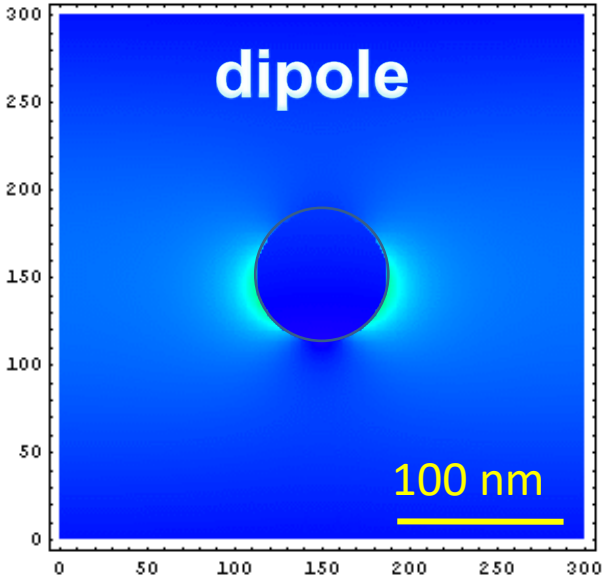


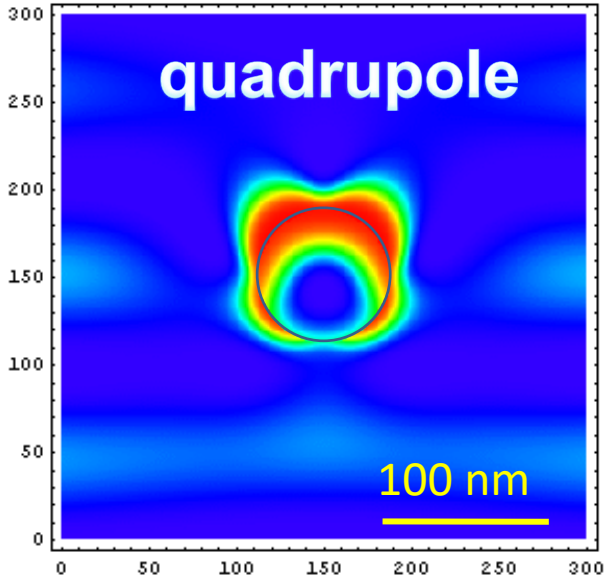
Ag nanoparticles
(R = 50 nm) in SiO_2

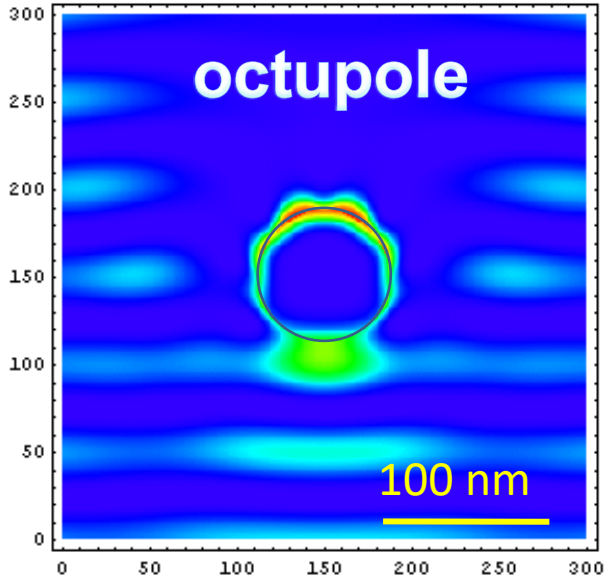




La Sainte-Chapelle
(Paris, France, 1248)







λ = 520 nm **λ = 406 nm** **λ = 380 nm**

Metallic Nanostructures

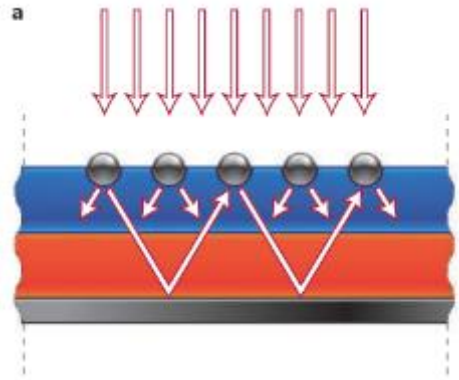
Optical Properties (Plasmonics):

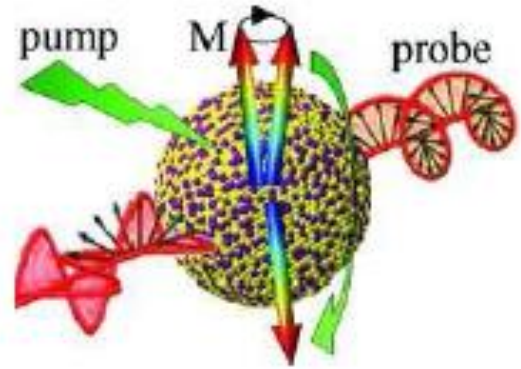
1. Plasmonic sensors
2. Plasmonic waveguides
3. Nano-Antennas
4. Iperthermia (cancer therapy)

Magnetic Properties:

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

Light confinement < λ





Materials for magnetism

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
hydrogen 1 **H** 1.00794(7)																	helium 2 **He** 4.002602(2)
lithium 3 **Li** 6.941(2)	beryllium 4 **Be** 9.012182(3)		Key: element name, atomic number, **symbol**, 2003 atomic weight (mean relative mass)									boron 5 **B** 10.811(7)	carbon 6 **C** 12.0107(8)	nitrogen 7 **N** 14.0067(7)	oxygen 8 **O** 15.9994(3)	fluorine 9 **F** 18.9984032(5)	neon 10 **Ne** 20.1797(6)
sodium 11 **Na** 22.989770(2)	magnesium 12 **Mg** 24.3050(6)											aluminium 13 **Al** 26.981538(2)	silicon 14 **Si** 28.0855(3)	phosphorus 15 **P** 30.973761(2)	sulfur 16 **S** 32.065(5)	chlorine 17 **Cl** 35.453(2)	argon 18 **Ar** 39.948(1)
potassium 19 **K** 39.0983(1)	calcium 20 **Ca** 40.078(4)	scandium 21 **Sc** 44.955910(8)	titanium 22 **Ti** 47.867(1)	vanadium 23 **V** 50.9415(1)	chromium 24 **Cr** 51.9961(6)	manganese 25 **Mn** 54.938049(9)	iron 26 **Fe** 55.845(2)	cobalt 27 **Co** 58.933200(9)	nickel 28 **Ni** 58.6934(4)	copper 29 **Cu** 63.546(3)	zinc 30 **Zn** 65.38(2)	gallium 31 **Ga** 69.723(1)	germanium 32 **Ge** 72.64(1)	arsenic 33 **As** 74.92160(2)	selenium 34 **Se** 78.96(3)	bromine 35 **Br** 79.904(1)	krypton 36 **Kr** 83.798(2)
rubidium 37 **Rb** 85.4678(3)	strontium 38 **Sr** 87.62(1)	yttrium 39 **Y** 88.90585(2)	zirconium 40 **Zr** 91.224(2)	niobium 41 **Nb** 92.90638(2)	molybdenum 42 **Mo** 95.96(2)	technetium 43 **Tc** [98]	ruthenium 44 **Ru** 101.07(2)	rhodium 45 **Rh** 102.90550(2)	palladium 46 **Pd** 106.42(1)	silver 47 **Ag** 107.8682(2)	cadmium 48 **Cd** 112.411(8)	indium 49 **In** 114.818(3)	tin 50 **Sn** 118.710(7)	antimony 51 **Sb** 121.760(1)	tellurium 52 **Te** 127.60(3)	iodine 53 **I** 126.90447(3)	xenon 54 **Xe** 131.293(6)
caesium 55 **Cs** 132.90545(2)	barium 56 **Ba** 137.327(7)	lutetium 71 **Lu** 174.9668(1)	hafnium 72 **Hf** 178.49(2)	tantalum 73 **Ta** 180.9479(1)	tungsten 74 **W** 183.84(1)	rhenium 75 **Re** 186.207(1)	osmium 76 **Os** 190.23(3)	iridium 77 **Ir** 192.217(3)	platinum 78 **Pt** 195.078(2)	gold 79 **Au** 196.96655(2)	mercury 80 **Hg** 200.59(2)	thallium 81 **Tl** 204.3833(2)	lead 82 **Pb** 207.2(1)	bismuth 83 **Bi** 208.98038(2)	polonium 84 **Po** [209]	astatine 85 **At** [210]	radon 86 **Rn** [222]
francium 87 **Fr** [223]	radium 88 **Ra** [226]	lawrencium 103 **Lr** [262]	rutherfordium 104 **Rf** [267]	dubnium 105 **Db** [268]	seaborgium 106 **Sg** [271]	bohrium 107 **Bh** [272]	hassium 108 **Hs** [270]	meitnerium 109 **Mt** [276]	darmstadtium 110 **Ds** [281]	roentgenium 111 **Rg** [280]	ununbium 112 **Uub** [285]	ununtrium 113 **Uut** [284]	ununquadium 114 **Uuq** [289]	ununpentium 115 **Uup** [286]	ununhexium 116 **Uuh** [293]	ununseptium 117 **Uus** —	ununoctium 118 **Uuo** [294]

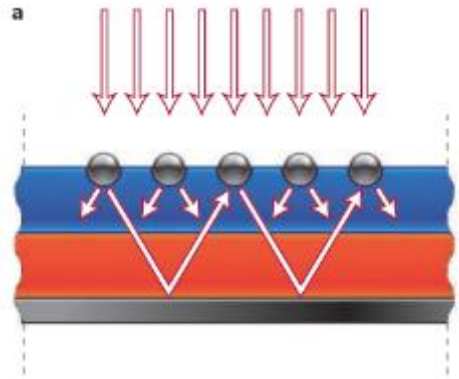
Lanthanoids	lanthanum 57 **La** 138.9055(2)	cerium 58 **Ce** 140.116(1)	praseodymium 59 **Pr** 140.90765(2)	neodymium 60 **Nd** 144.24(3)	promethium 61 **Pm** [145]	samarium 62 **Sm** 150.36(3)	europium 63 **Eu** 151.964(1)	gadolinium 64 **Gd** 157.25(3)	terbium 65 **Tb** 158.92534(2)	dysprosium 66 **Dy** 162.500(1)	holmium 67 **Ho** 164.93032(2)	erbium 68 **Er** 167.259(3)	thulium 69 **Tm** 168.93421(2)	ytterbium 70 **Yb** 173.054(5)
Actinoids	actinium 89 **Ac** [227]	thorium 90 **Th** 232.0381(1)	protactinium 91 **Pa** 231.03588(2)	uranium 92 **U** 238.02891(3)	neptunium 93 **Np** [237]	plutonium 94 **Pu** [244]	americium 95 **Am** [243]	curium 96 **Cm** [247]	berkelium 97 **Bk** [247]	californium 98 **Cf** [251]	einsteinium 99 **Es** [252]	fermium 100 **Fm** [257]	mendelevium 101 **Md** [258]	nobelium 102 **No** [259]

Metallic Nanostructures

Optical Properties (Plasmonics):

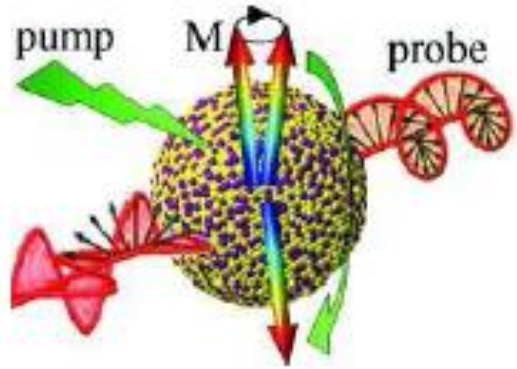
1. Plasmonic sensors
2. Plasmonic waveguides
3. Nano-Antennas
4. Iperthermia (cancer therapy)

Light confinement < λ



Magnetic Properties:

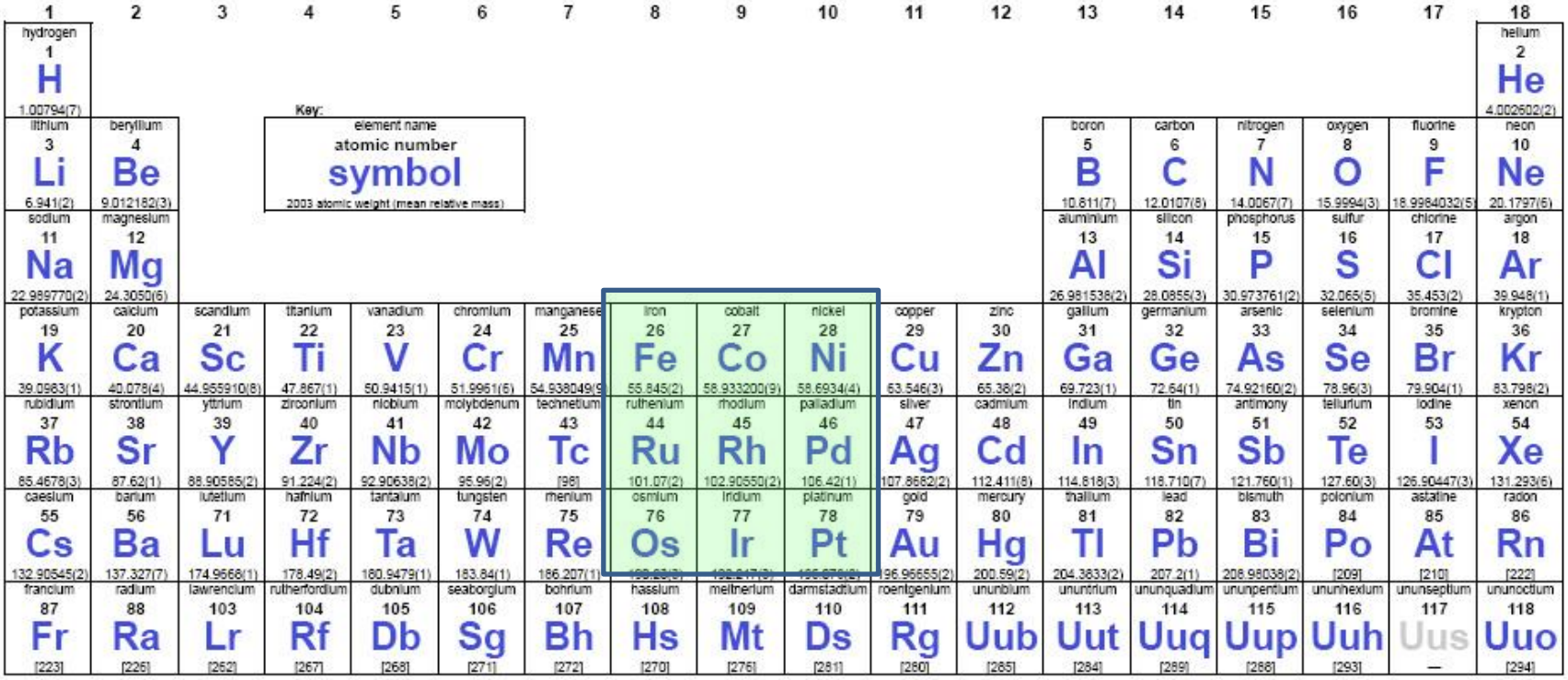
1. Super-paramagnetism
2. Magneto-optical properties
3. Medical diagnosis (Fe-oxides, NMR)

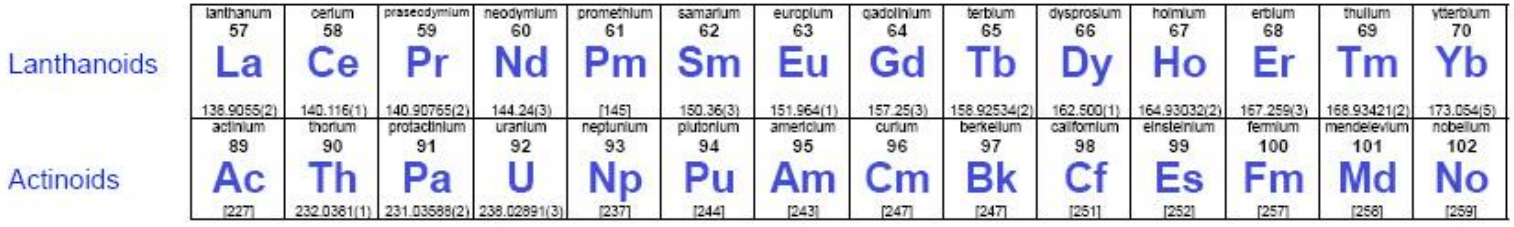


Catalytic Properties:

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

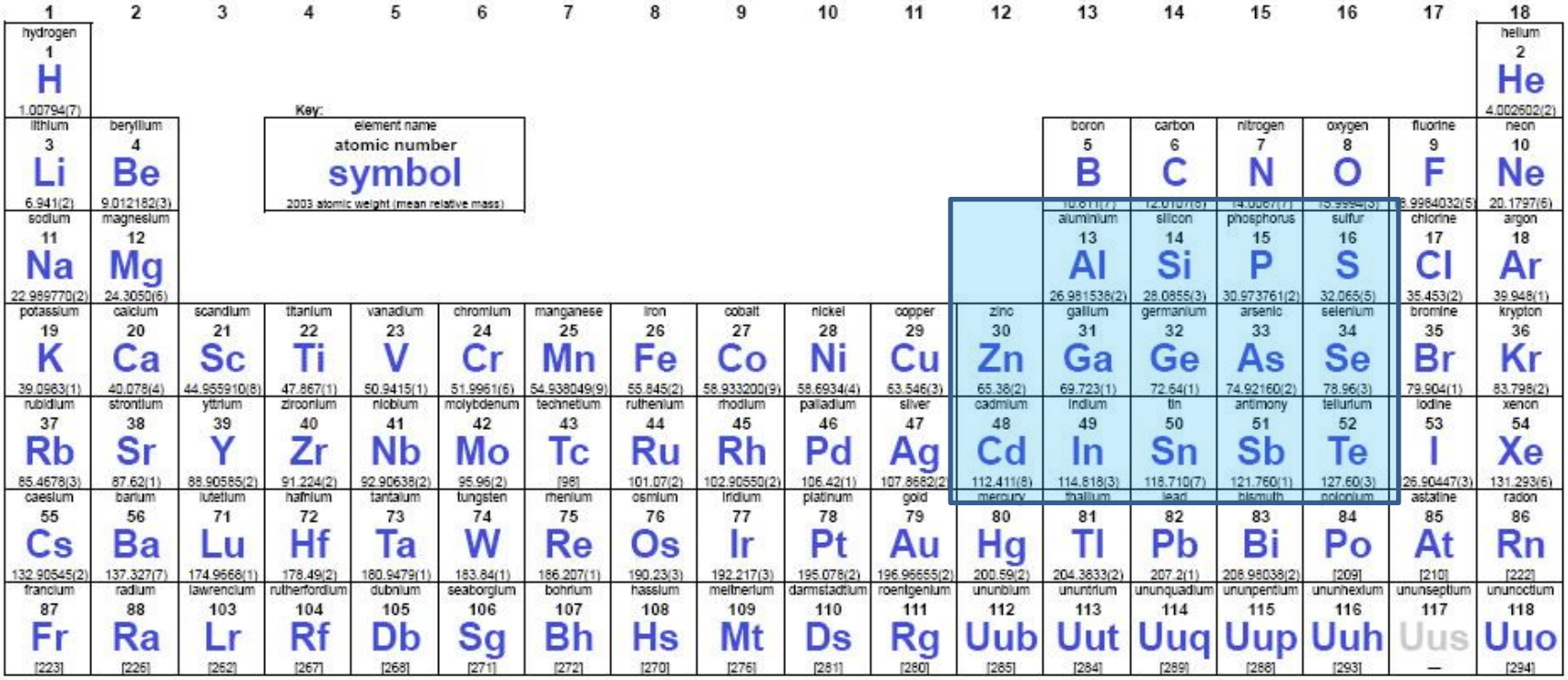
Materials for catalysis





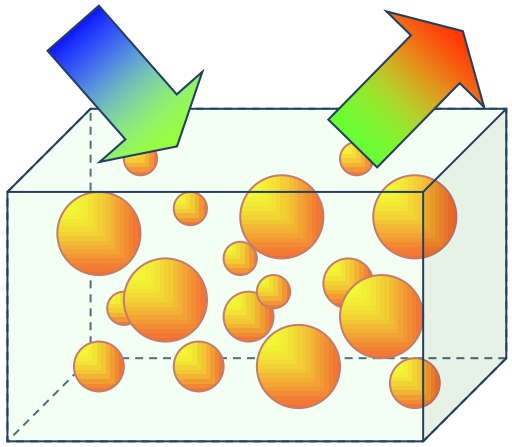
Semiconductor Nanostructures

Semiconductor Materials



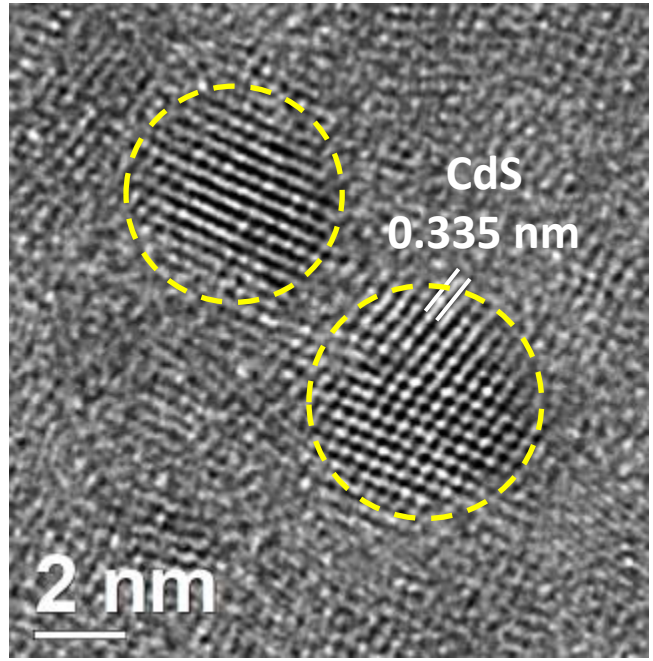
photoluminescence

Higher energy excitation (UV)

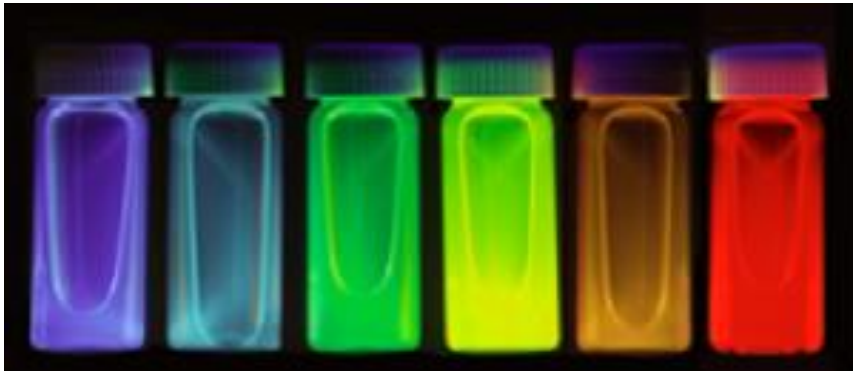


Emission at lower energy (visible)

CdS, CdSe, ZnS, ZnSe, Si…



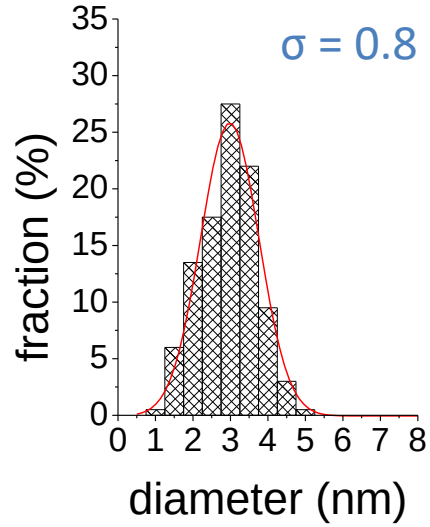
Colloidal solutions CdSe in esane with decreasing size



3 eV (UV)
D = 1.2 nm

1.8 eV (IR)
D = 11.5 nm

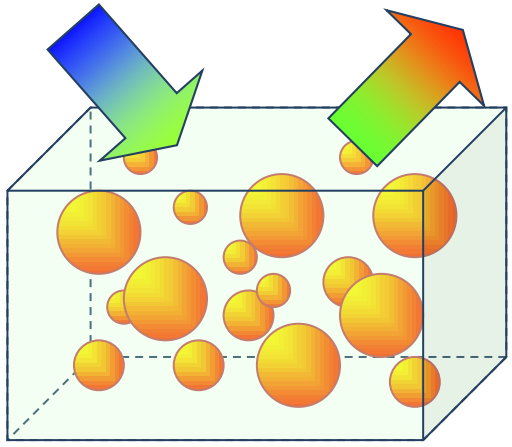
D = 3.0 nm
σ = 0.8 nm



Semiconductor Nanostructures

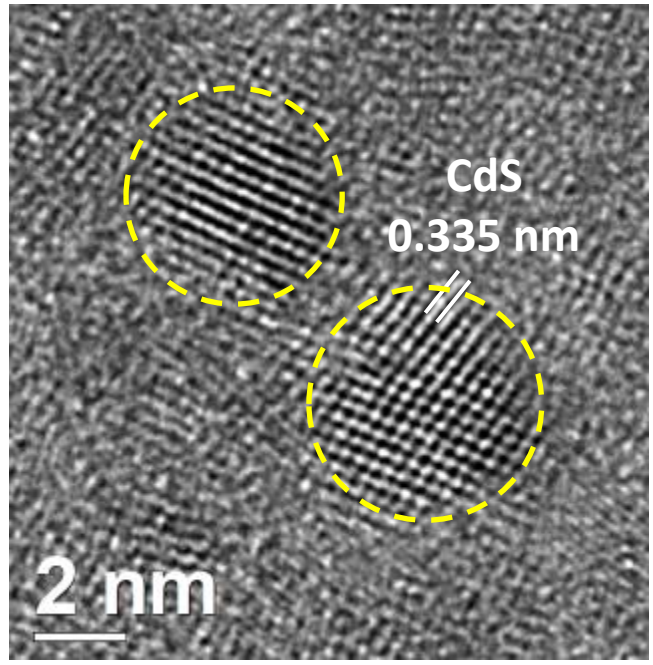
photoluminescence

Higher energy excitation (UV)

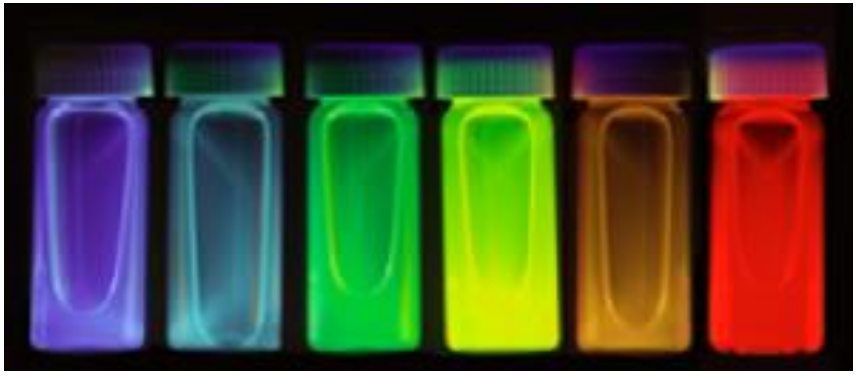


Emission at lower energy (visible)

CdS, CdSe, ZnS, ZnSe, Si…

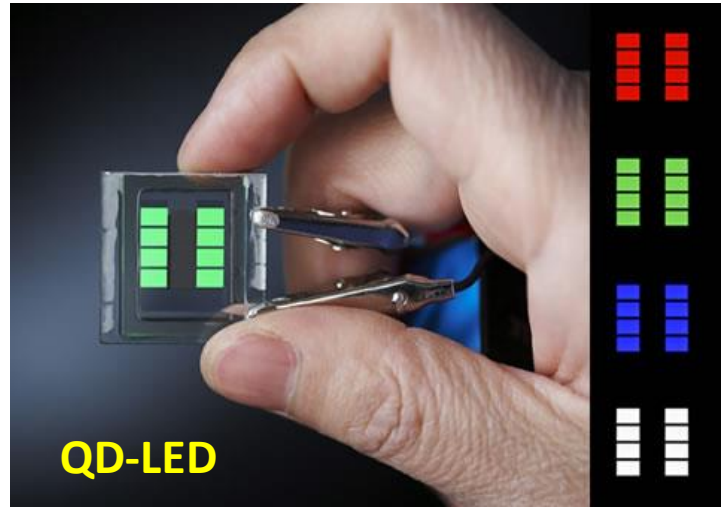


Colloidal solutions CdSe in esane with decreasing size



3 eV (UV)
D = 1.2 nm

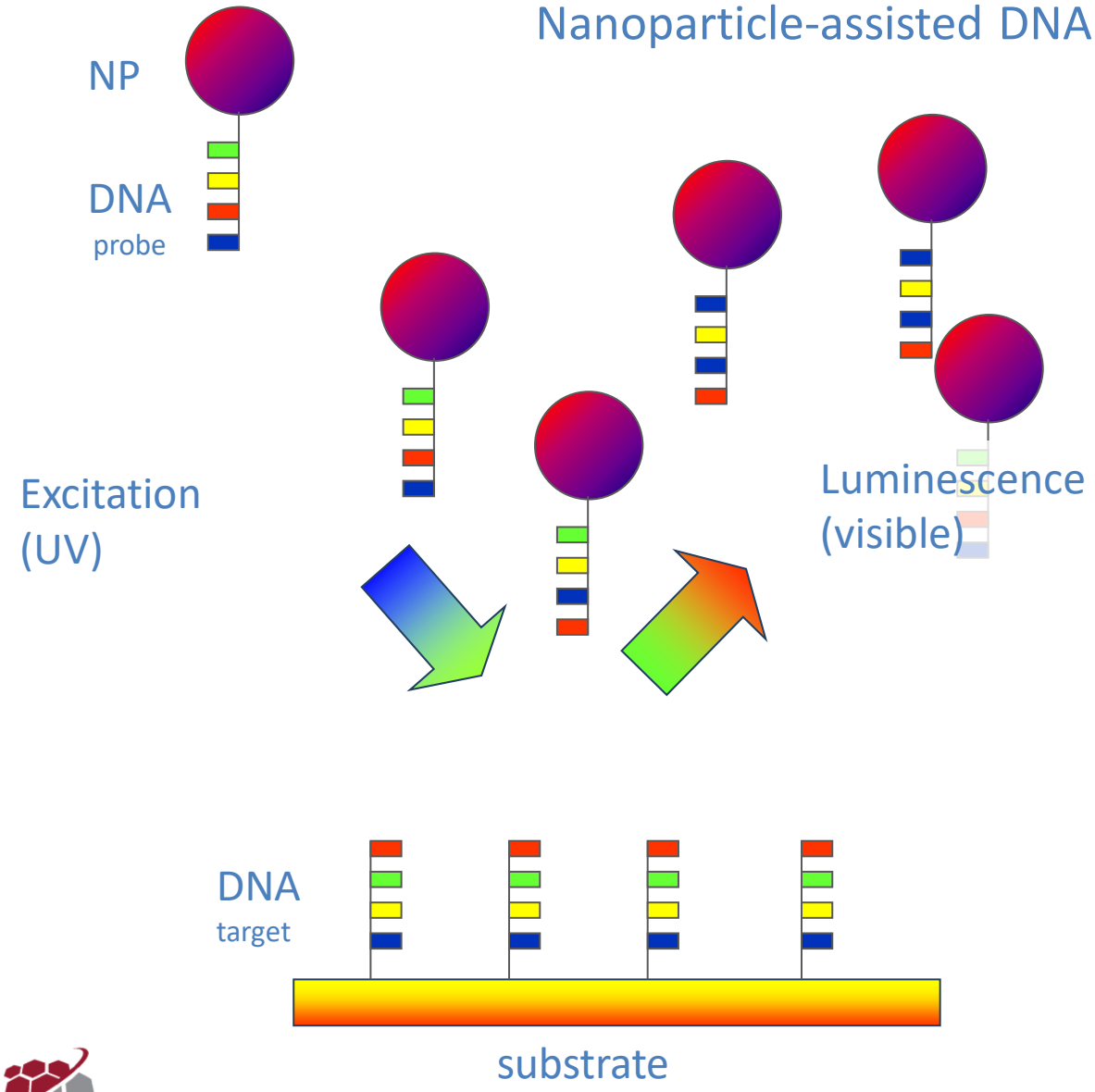
1.8 eV (IR)
D = 11.5 nm

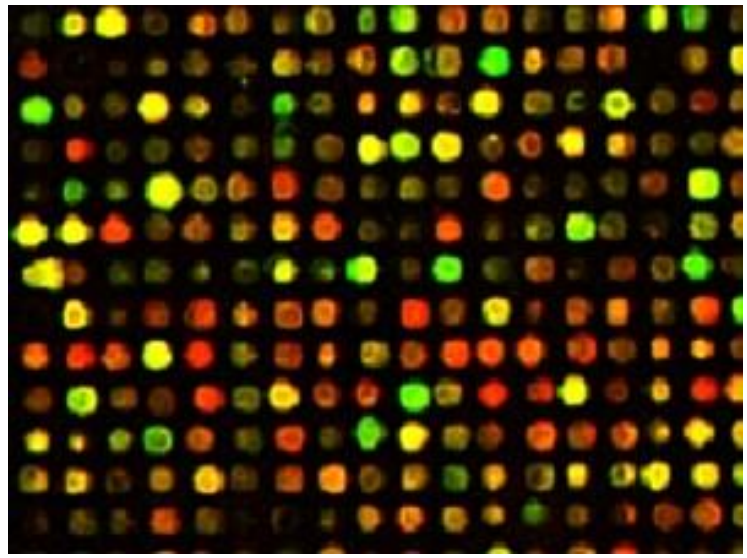


NSG

Medical Application

Nanoparticle-assisted DNA sequencing





DNA - Microarray

Optical Semiconductors

Giant Blue Morpho
(15 cm, Perù)