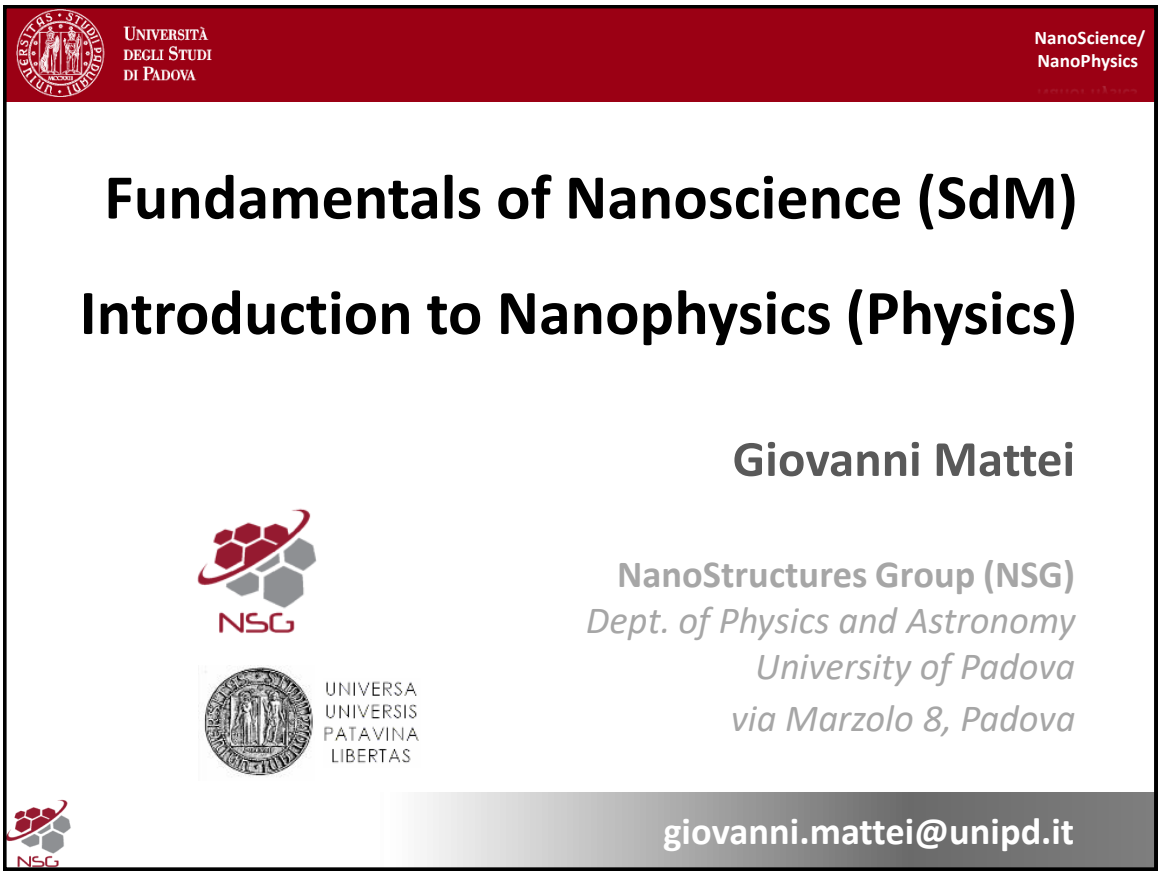
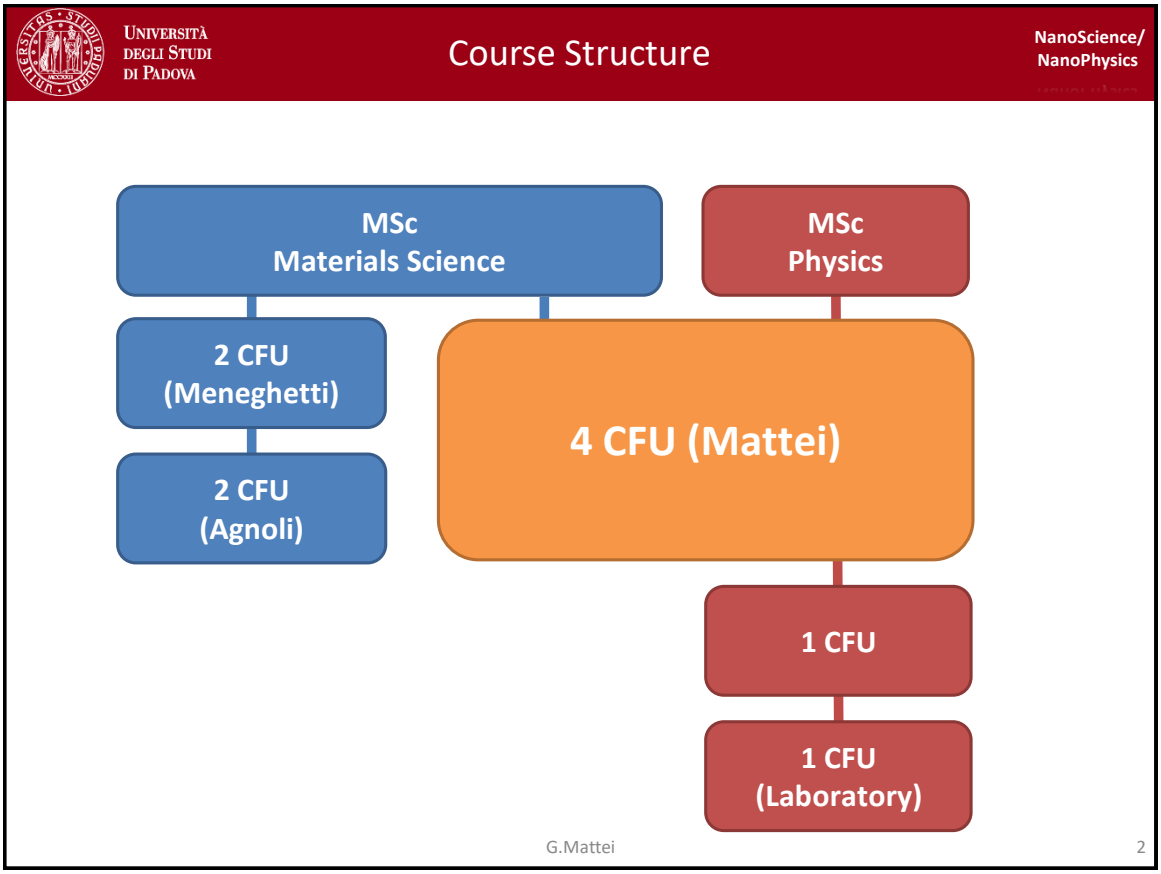
0.1 Lecture 1-2

Thursday 12th March, 2020. Compiled: Monday 1st June, 2020. Alice.





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**.

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Final Exam

NanoScience/ NanoPhysics

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

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Course Content

NanoScience/ NanoPhysics

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

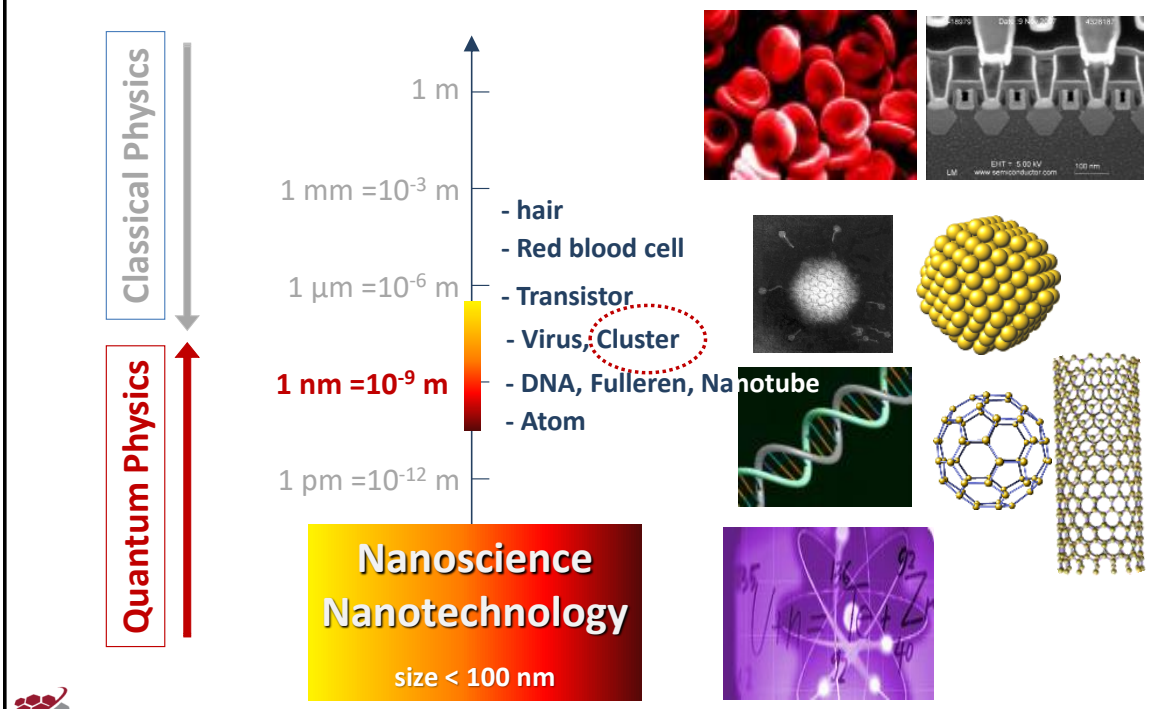
Register on the Course Moodle :

- 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



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(nano)-size matters…

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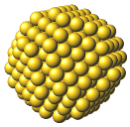
Nanoparticle



1 nm

Tennis Ball

6 cm

Moon

3500 km

A simple proportion…

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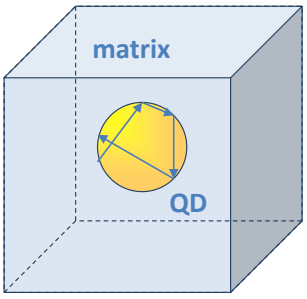
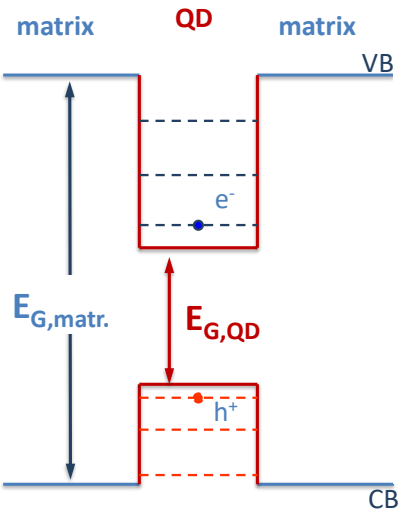
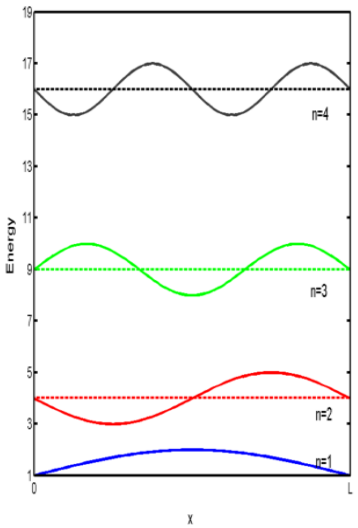
…from classical to quantum physics

NanoScience/ NanoPhysics







Wave-particle duality

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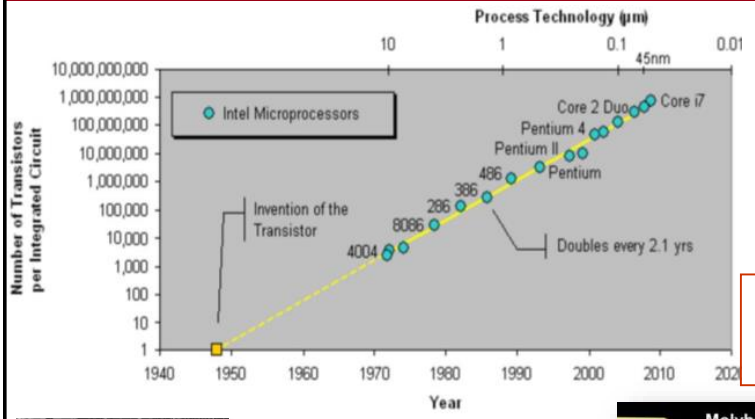
Nano-electronics

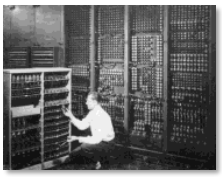
NanoScience/ NanoPhysics



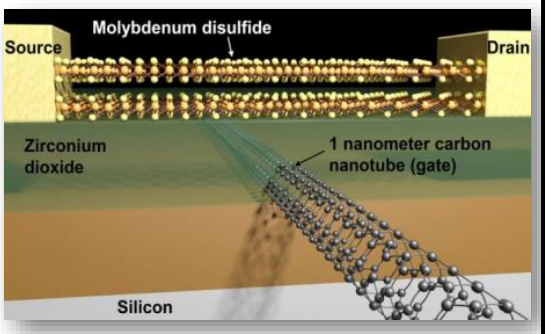
Moore's Law

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

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

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

NanoScience/ NanoPhysics

(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

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)

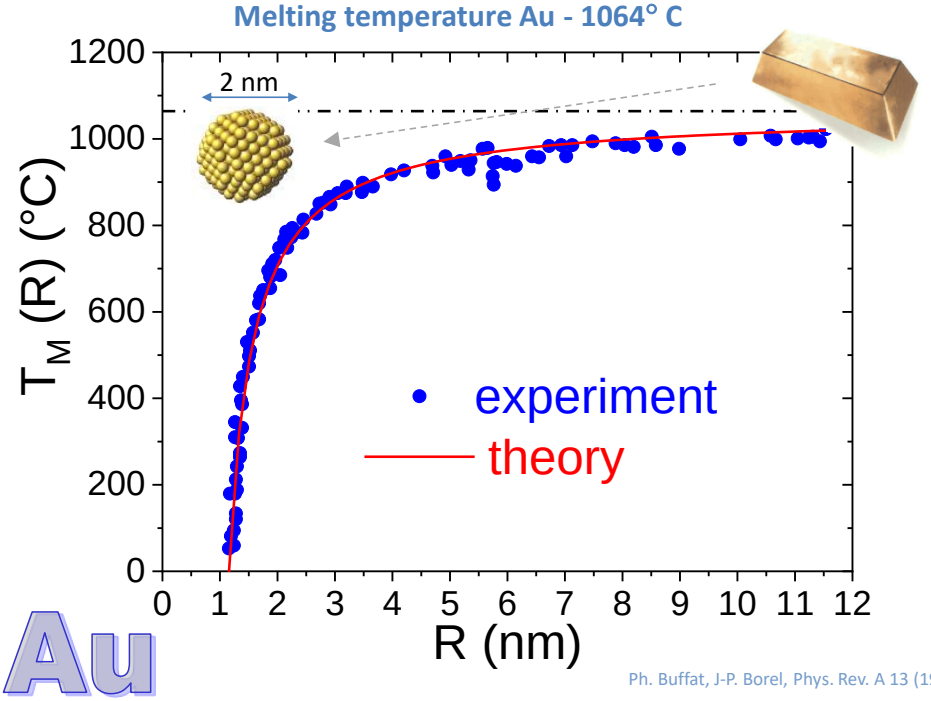
- Characteristic lengths λ_C ~ 1- 100 nm
- Nano-physics: $L < \lambda_C$
- E.g.:
  - λ_e = electronic mean free path (10-100 nm)
  - λ_{exc} = excitonic Bohr radius (1-10 nm)
  - λ_M = magnetic domain (30-50 nm)

control L = control A(L)

Nano-Thermodynamics

Example of A = A(L)

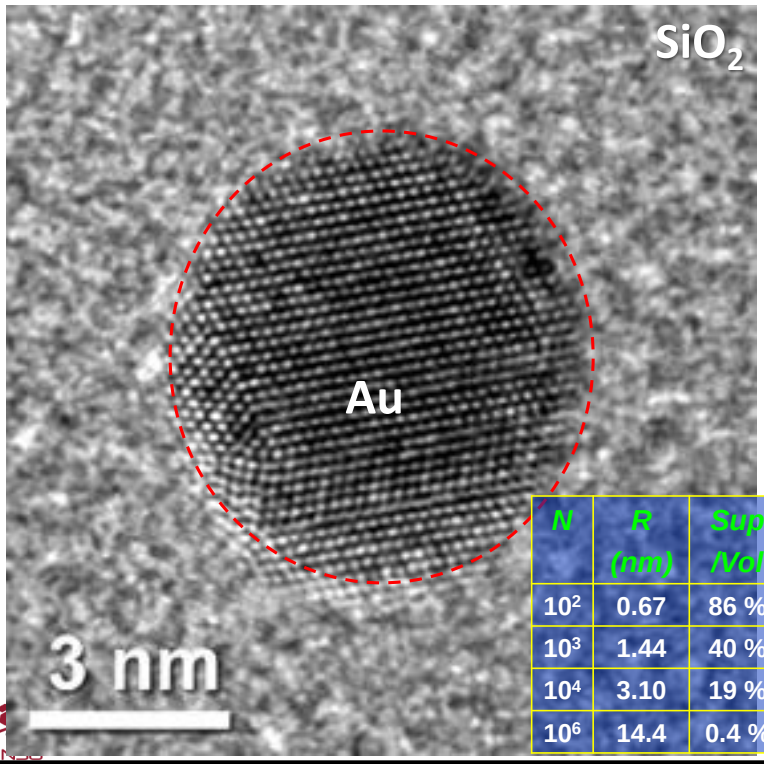
Melting temperature Au - 1064° C



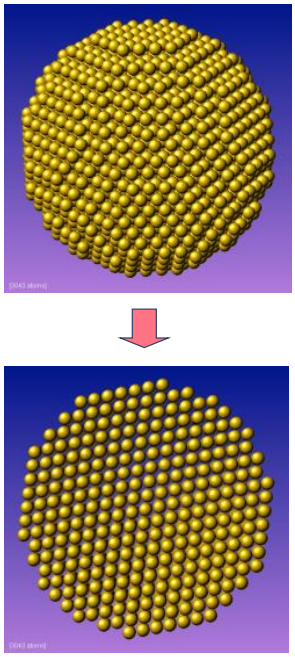
Au

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 %

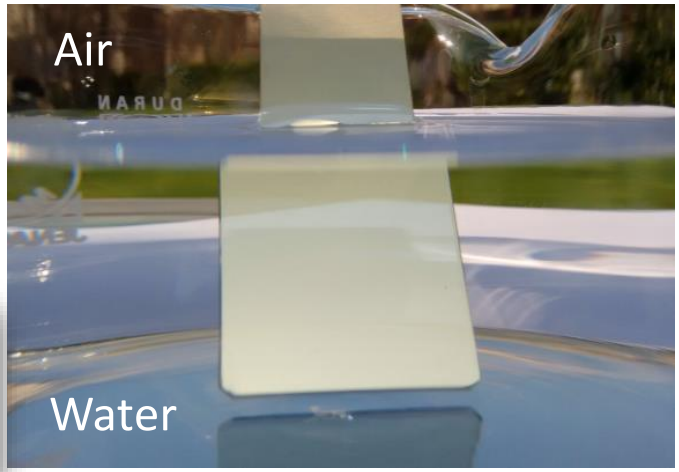


Au NP along the <110> zone axis

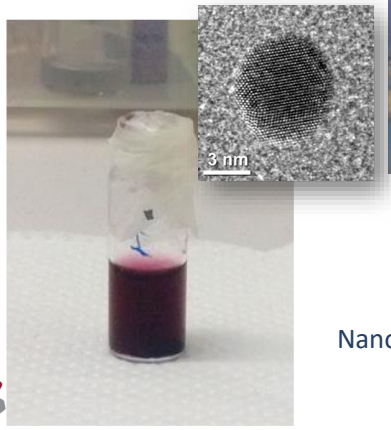
Nano-Optics

Which is the color of Au NPs?

Bulk Au



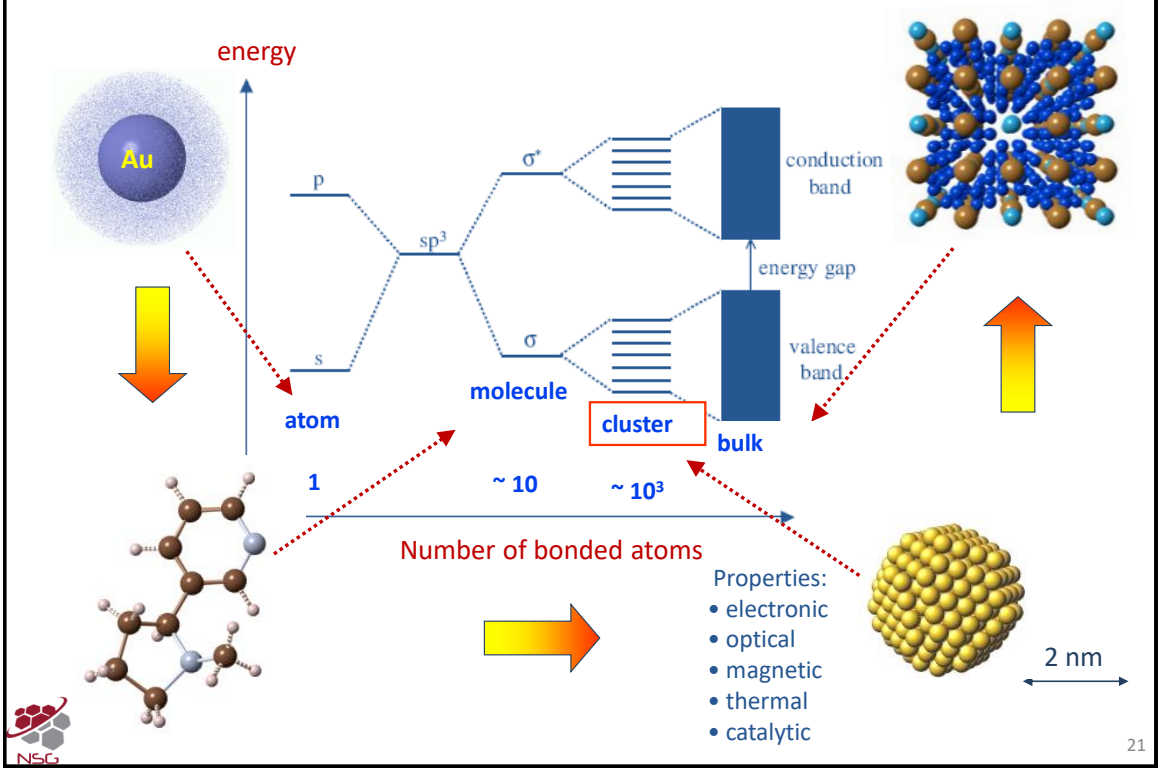
Thin film (30 nm) Au



Nano Au

Electronic structure

From the atom to the bulk…



‘Seeing’ at the Nanoscale

'seeing' at the nanoscale

A typical optical microscope

- **photons**
  λ = 400 ÷ 800 nm
  E = 1 ÷ 3 eV
- **resolution**
  ~ λ (500 nm)
- **working pressure**
  ambient

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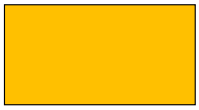
'seeing' at the nanoscale

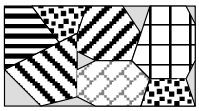
A typical electron microscope - TEM

- **electrons**
  λ = 1.2 pm *(Quantum Mechanics)*
  E = 200 ÷ 300 keV
- **resolution**
  0.1 nm
- **working pressure**
  10^{-4} Pa (~ 10^{-9} atm)
- **price**
  1.5-2.0 M€

Nano-Materials

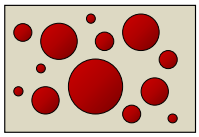
Characteristic size < 100 nm

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

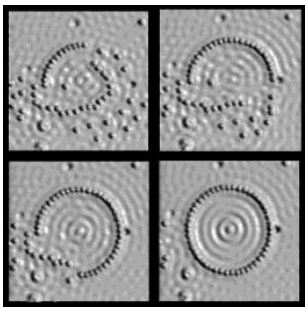
Bottom/Up vs. Top/Down

Bottom/Up

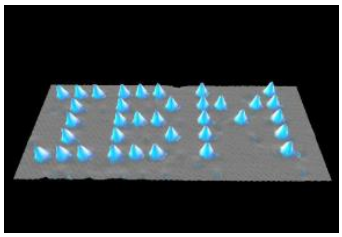
From small to large or from **simple to complex**

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

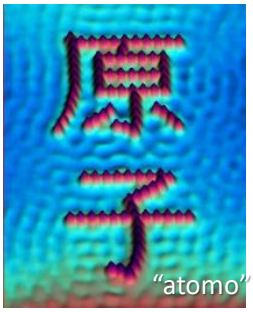
Using atoms or simple units as LEGO blocks one can build artificial nano-objects
(**nano-positioning** and **self-assembling**)



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*

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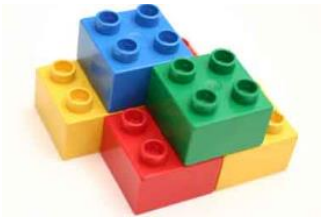
Bottom/Up

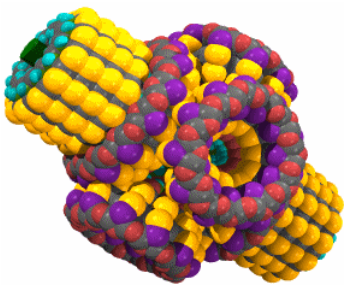
NanoScience/ NanoPhysics

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.)*

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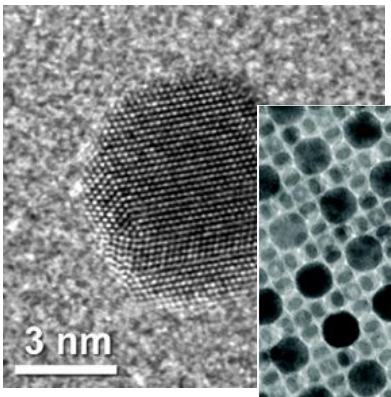
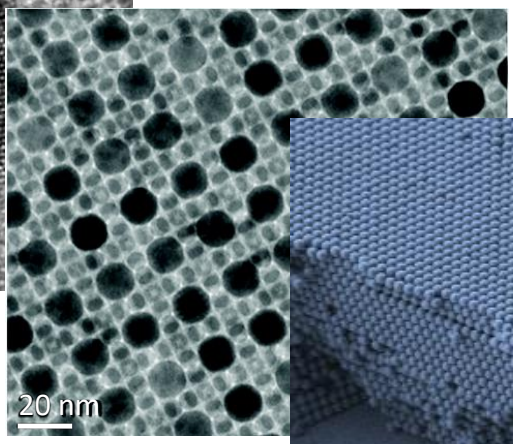
Bottom/Up

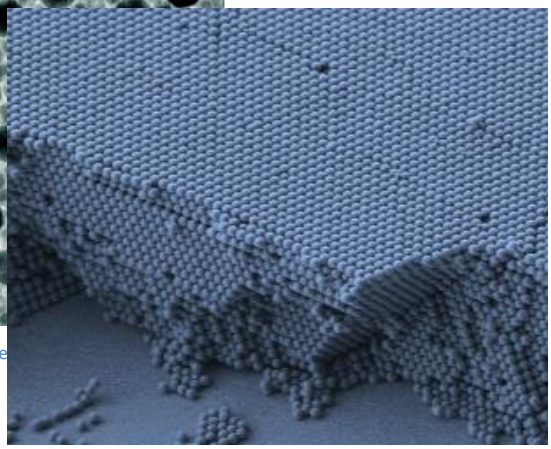
NanoScience/ NanoPhysics



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).

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Top/Down

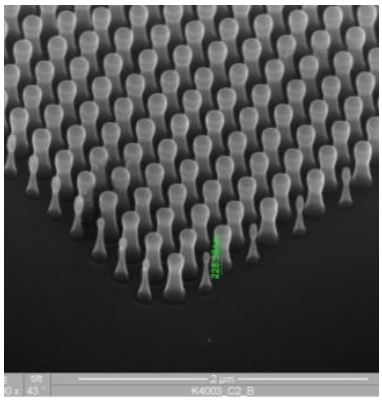
NanoScience/ NanoPhysics

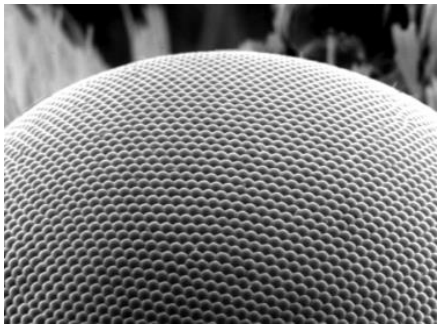
From large to small

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

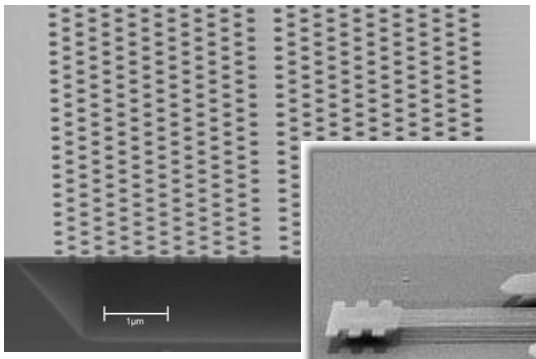




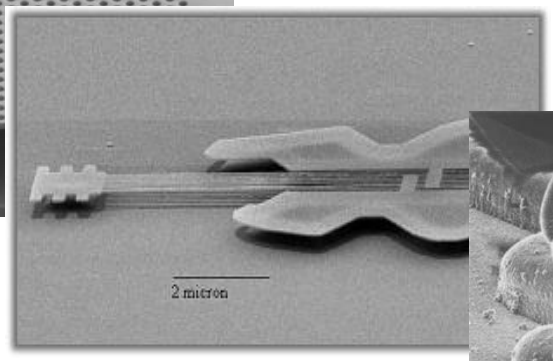
Close-up view of a moth's eye

30

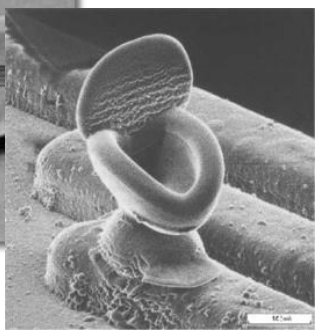
Top/Down



Photonic Crystal



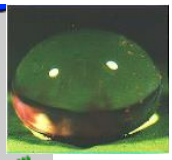
Nano-guitar

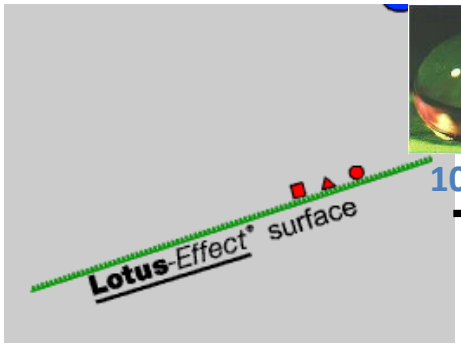


…Nano-toilet

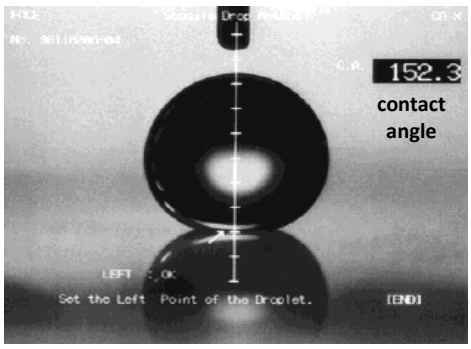
Top/Down

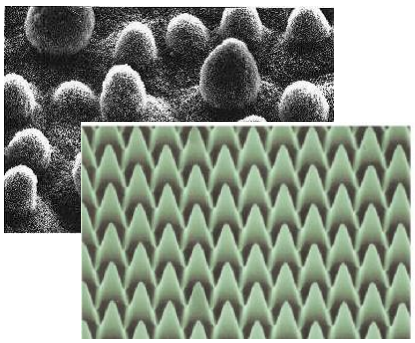
bio-mimetic systems: **Lotus Effect** (super-hydrophobicity)





10 µm





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

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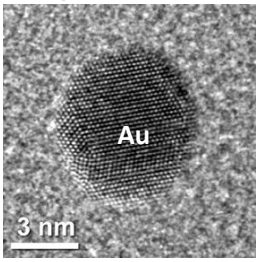
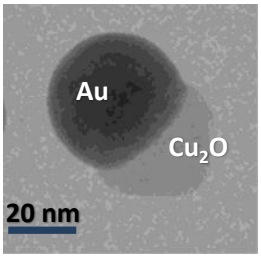
Some nano-structures produced @ NSG

NanoScience/ NanoPhysics

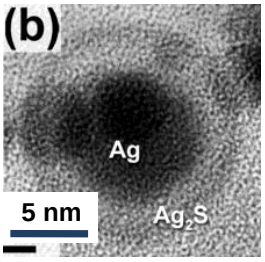
Simple NP



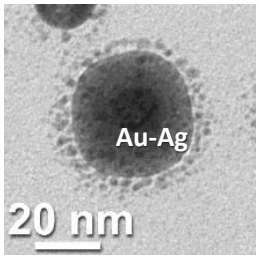
Janus Particles



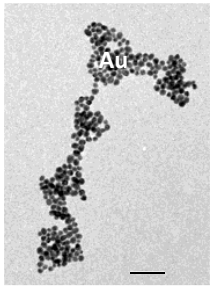
Core-shell



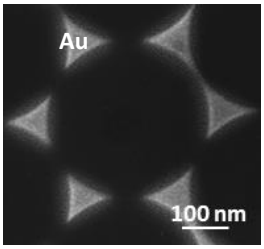
Nano-Planets (NPL)



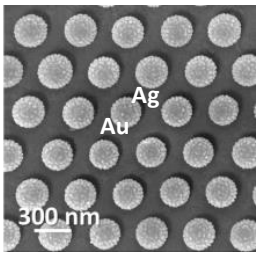
DLA Fractals



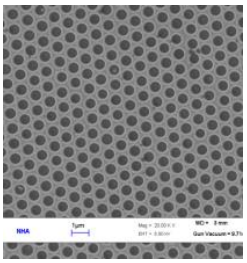
Nano-Prism (NPA)



Nano-Shell (NSA)



Nano-Hole (NHA)



Monoelemental

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

Bimetallic

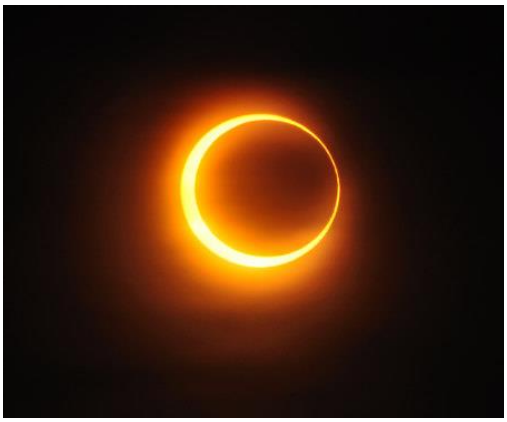
Au-Cu, Au-Ag, Au-Fe, Pd-Cu, Co-Ni, Co-Fe, Co-Cu, Fe-Pd

33

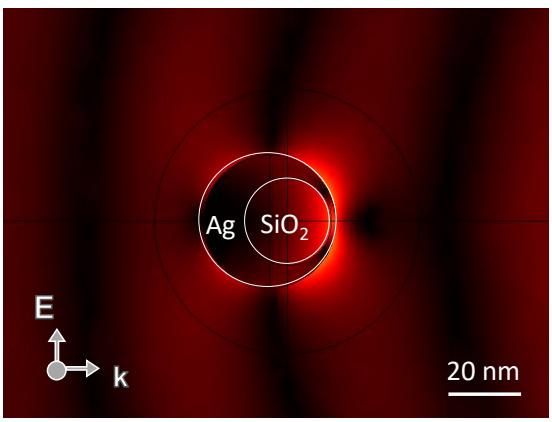
UNIVERSITÀ DEGLI STUDI DI PADOVA

Nano-eclipse

NanoScience/ NanoPhysics



Solar Eclipse 2015



Asymmetric – NanoShell

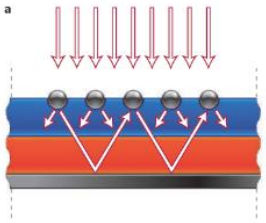
SiO_2 @ Ag

Metallic Nanostructures

Optical Properties (Plasmonics):

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

Light confinement < λ



UNIVERSITÀ DEGLI STUDI DI PADOVA

Materials for plasmonics

NanoScience/ NanoPhysics

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

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(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 [288]	ununhexium 116 Uuh [293]	ununseptium 117 Uus —	ununoctium 118 Uuo [294]

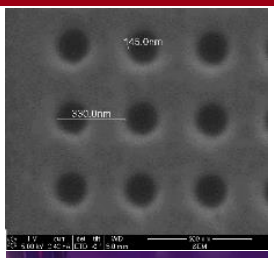
Lanthanoids	lanthanum 57 La 138.9055(2)	cerium 58 Ce 140.116(1)	praseodymium 59 Pr 140.90765(2)	neodymium 60 Nd 144.24(3)	promethium 61 Pm [145]	samarium 62 Sm 150.36(3)	europium 63 Eu 151.964(1)	gadolinium 64 Gd 157.25(3)	terbium 65 Tb 158.92534(2)	dysprosium 66 Dy 162.500(1)	holmium 67 Ho 164.93032(2)	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]

UNIVERSITÀ DEGLI STUDI DI PADOVA

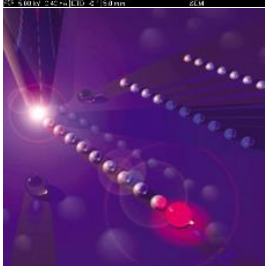
"Cool" Plasmonic Properties

NanoScience/ NanoPhysics

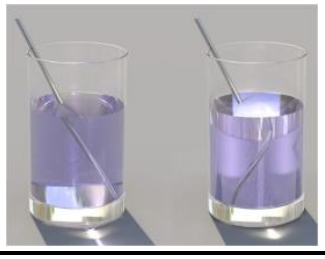
1. **Extraordinary transmission of light (EOT):** from array of nanoholes with sub-λ size in metal thin film.



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

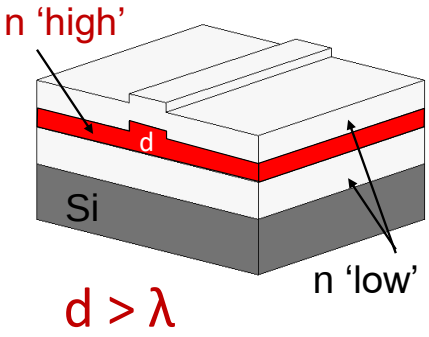


3. **MetaMaterials:** negative refractive index materials (invisibility cloak)

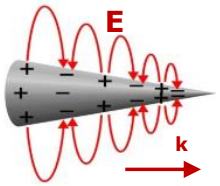


Plasmonic waveguides

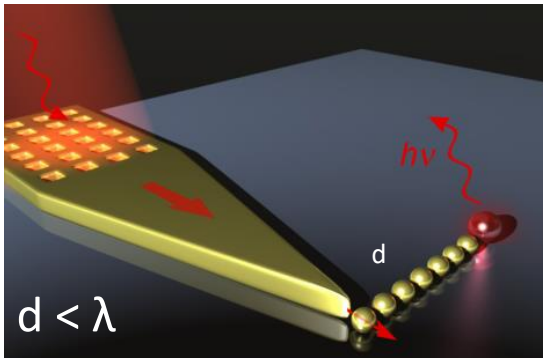
Optical waveguide



$d > \lambda$

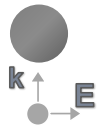


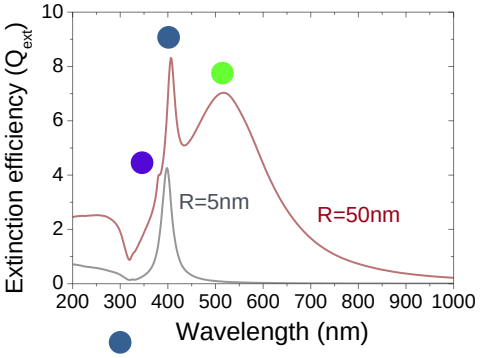
Plasmonic waveguide



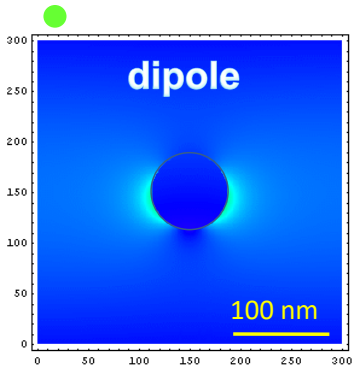
Plasmonics

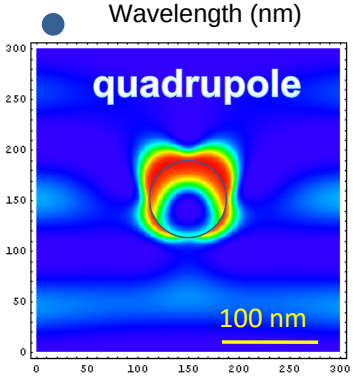
Ag nanoparticles (R = 50 nm) in SiO_2

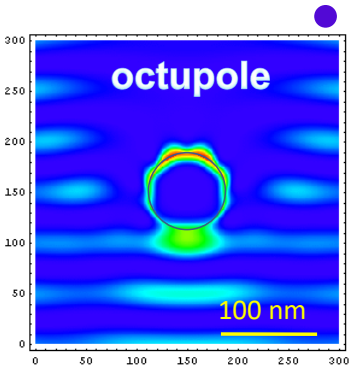




La Sainte-Chapelle
(Paris, France, 1248)







λ = 520 nm λ = 406 nm λ = 380 nm

UNIVERSITÀ DEGLI STUDI DI PADOVA

Metallic Nanostructures

NanoScience/ NanoPhysics

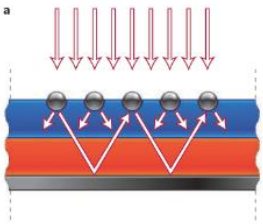
Optical Properties (Plasmonics):

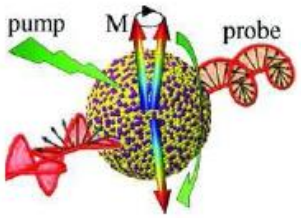
1. Plasmonic sensors
2. Plasmonic waveguides
3. Nano-Antennas
4. Iperthermia (cancer therapy)

Magnetic Properties:

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

Light confinement < λ





UNIVERSITÀ DEGLI STUDI DI PADOVA

Materials for magnetism

NanoScience/ NanoPhysics

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo

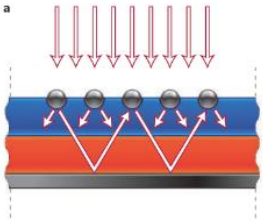
Lanthanoids	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Actinoids	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

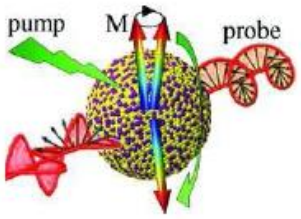
Metallic Nanostructures

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

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo

Key: element name, atomic number, symbol, 2003 atomic weight (mean relative mass)

Lanthanoids	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Actinoids	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

Semiconductor Nanostructures

Semiconductor Materials

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 [10.806(7)]	carbon 6 C [12.0107(8)]	nitrogen 7 N [14.0067(2)]	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 [288]	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]

UNIVERSITÀ DEGLI STUDI DI PADOVA

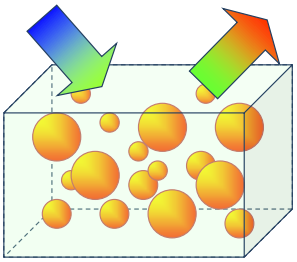
Semiconductor Nanostructures

NanoScience/ NanoPhysics

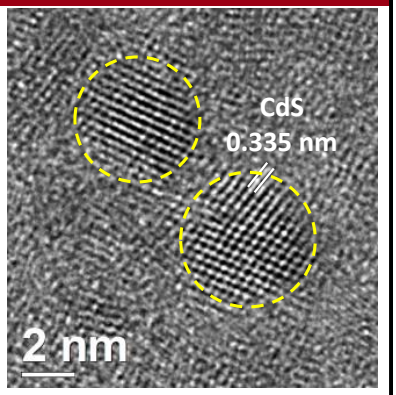
photoluminescence

Higher energy excitation (UV)

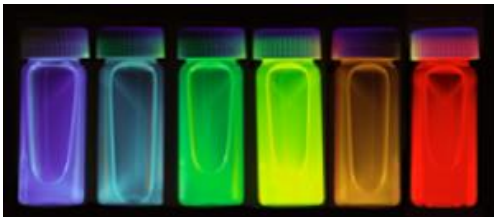
Emission at lower energy (visible)



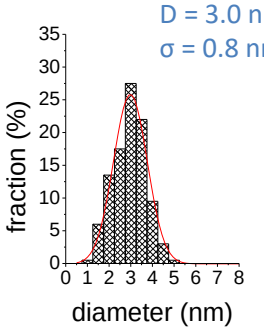
CdS, CdSe, ZnS, ZnSe, Si…



Colloidal solutions CdSe in esane with decreasing size



D = 3.0 nm
σ = 0.8 nm



3 eV (UV)
D = 1.2 nm

1.8 eV (IR)
D = 11.5 nm

NSG

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UNIVERSITÀ DEGLI STUDI DI PADOVA

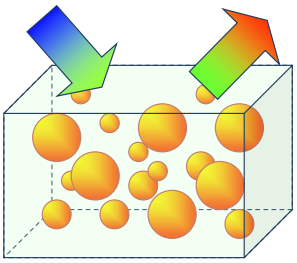
Semiconductor Nanostructures

NanoScience/ NanoPhysics

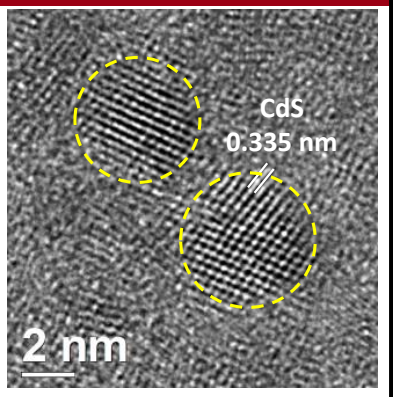
photoluminescence

Higher energy excitation (UV)

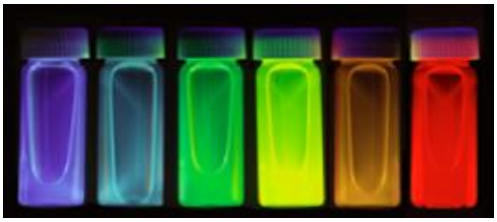
Emission at lower energy (visible)



CdS, CdSe, ZnS, ZnSe, Si…



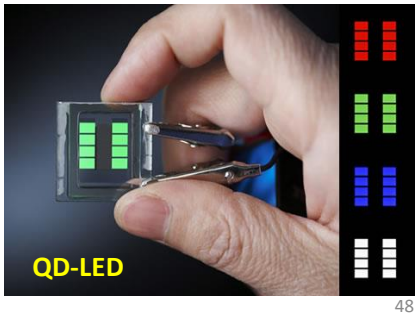
Colloidal solutions CdSe in esane with decreasing size



3 eV (UV)
D = 1.2 nm

1.8 eV (IR)
D = 11.5 nm

NSG



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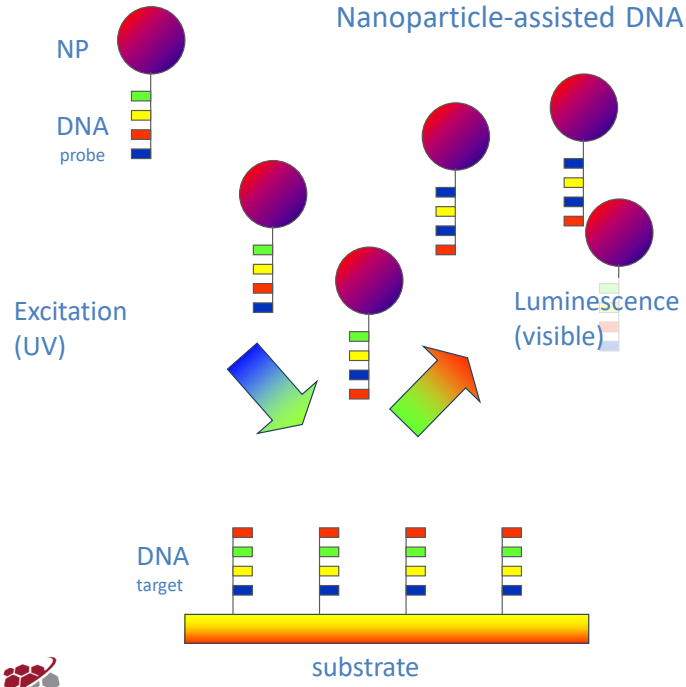
UNIVERSITÀ DEGLI STUDI DI PADOVA

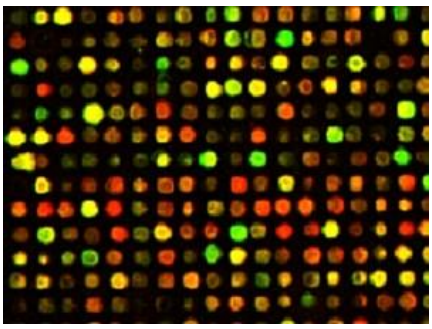
Semiconductor Nanostructures

NanoScience/ NanoPhysics

Medical Application

Nanoparticle-assisted DNA sequencing





DNA - Microarray

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Optical Semiconductors

NanoScience/ NanoPhysics

Giant Blue Morpho
(15 cm, Perù)