Electromagnetic waves interaction with various metallic nanomaterials

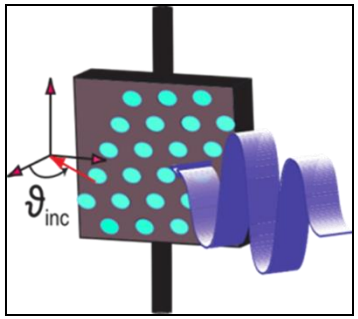
Michael Giersig

e-mail: giersig@helmholtz-berlin.de

Institute Nano-Architectures for Energy Conversion

EE-IN Nano Architectures

Helmholtz-Zentrum Berlin für Materialien und Energie



4th International Conference on Photonics
July 28-29 2016, Berlin, Germany

Fabrication of nanomaterials: application in electronics

Solar Cell

Photonic

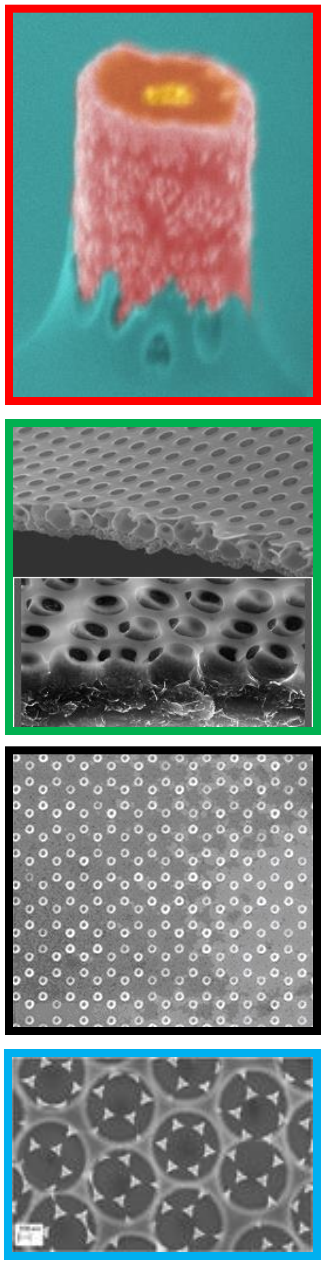
Memory devices

Detection devices

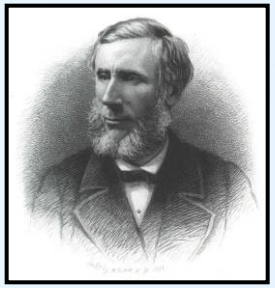
Nano Materials:

antenna, dots, tubes, 2-D and 3-D rods, rings, photonic crystals, Hybrides

semiconductor: CdTe, CdS, ZnO
metallic: Au, Ag, Pt
magnetic: Co, FexOy, Ni
Graphene, SWCNT, MWCNT
Polymer



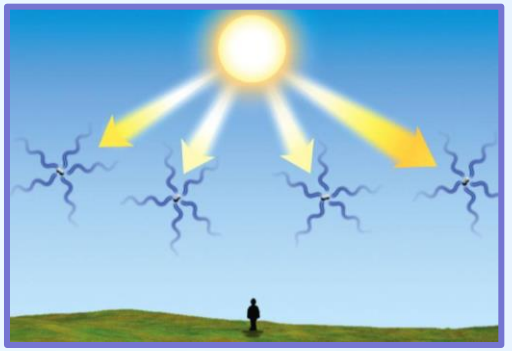
Light Scattering



The scattering of light was first studied in a careful manner by **Tyndall in 1859.**



A major step to explain the phenomenon was taken in **1871 by Rayleigh.**

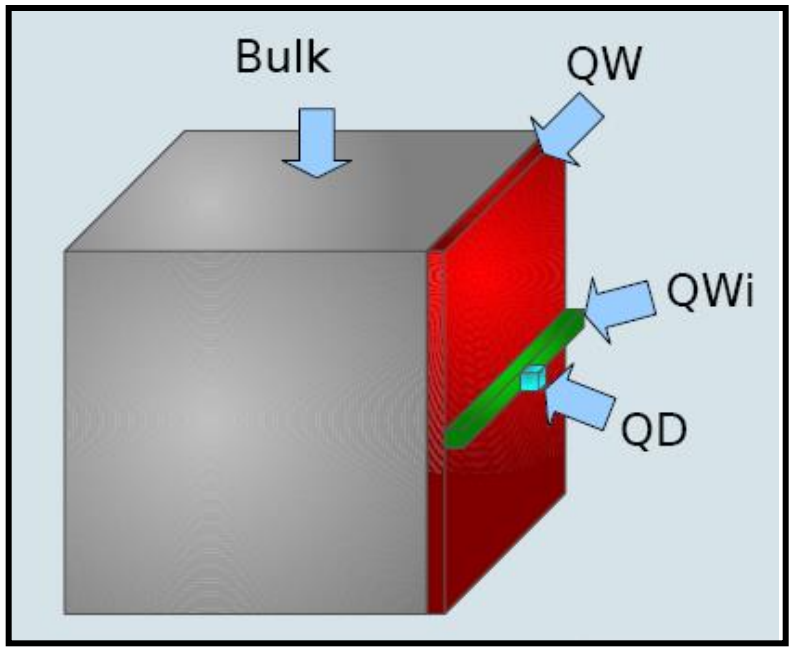


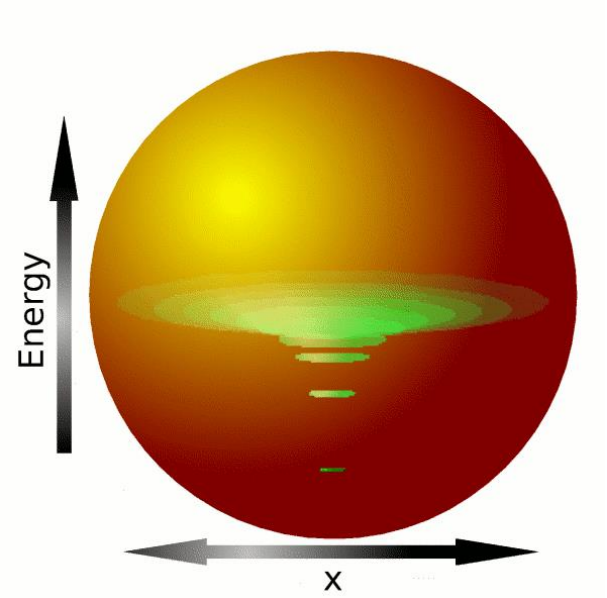
Rayleigh found that the **molecular scattering** by **blue light** is **many times more than that by red light** and so explained the **blue color of the sky** as the result of scattering from the air molecules.

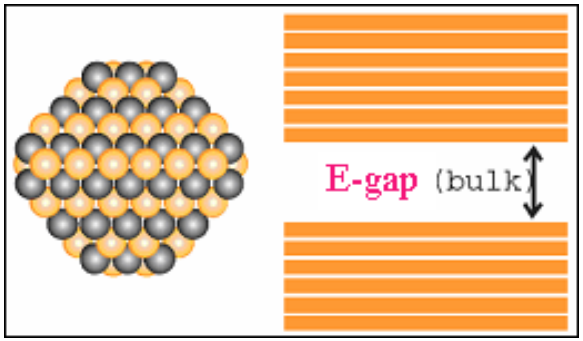


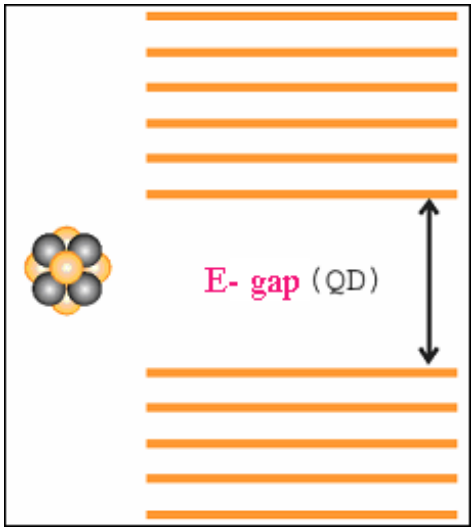
Gustav Mie, 1908

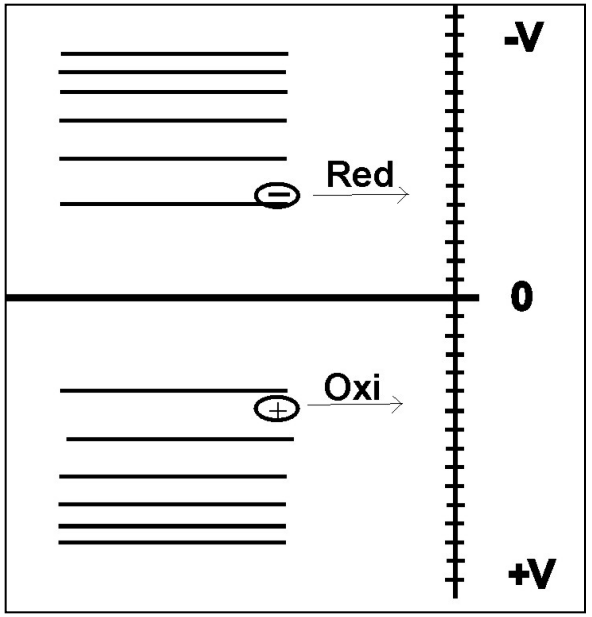
When the **wavelength of light becomes comparable to the size of the scattering particles**, like dust particles, the mutual interference from the scattering by the different portions of the dust particle become important and this is called **Mie scattering**.


Bulk
QW
QWi
QD

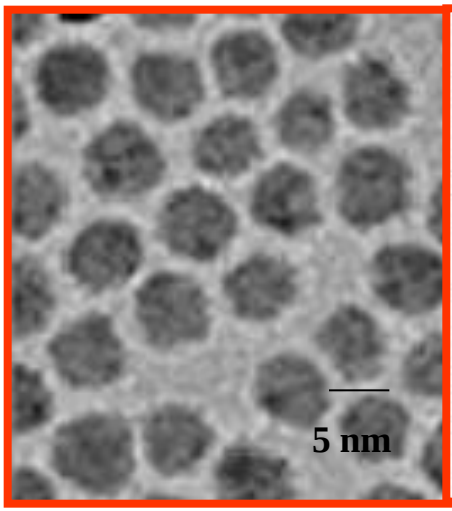

Energy
x

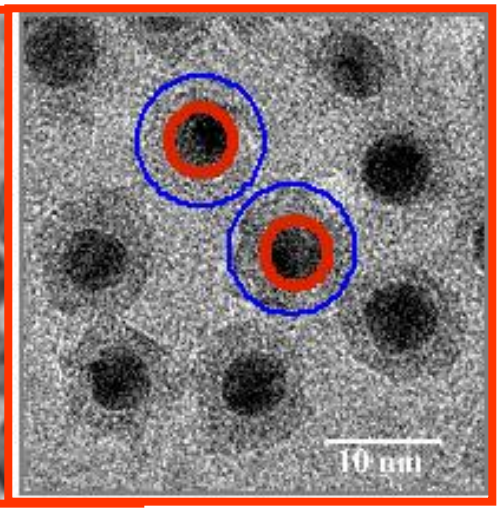

E-gap (bulk)

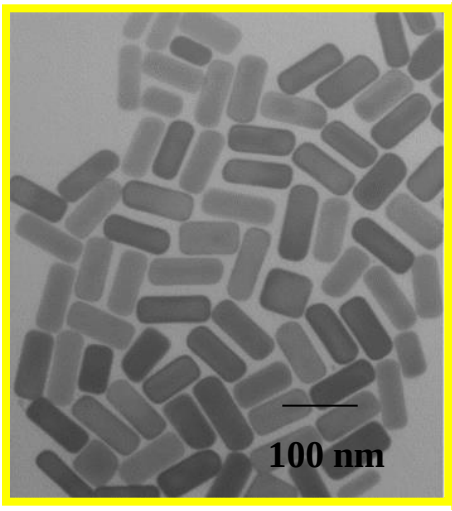

E- gap (QD)

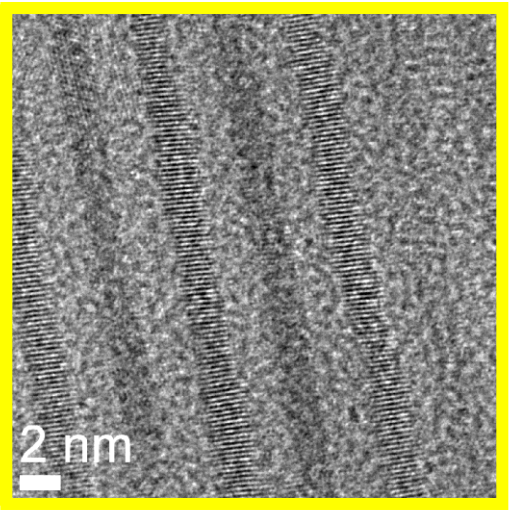

-V
Red
0
Oxi
+V

Selected Nanostructures produced by wet chemistry method

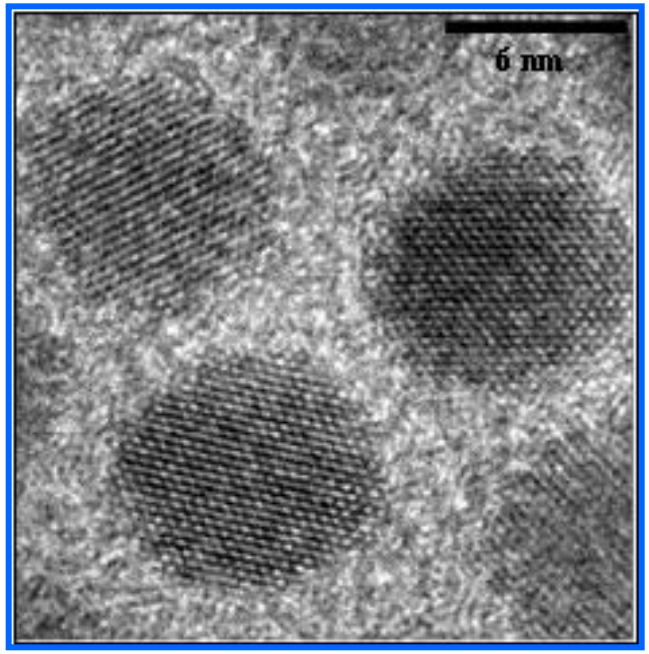


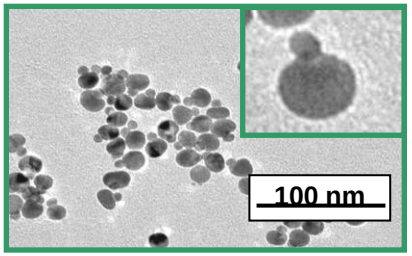




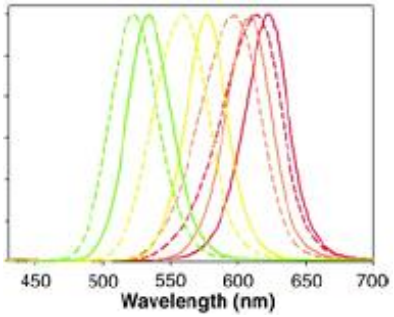


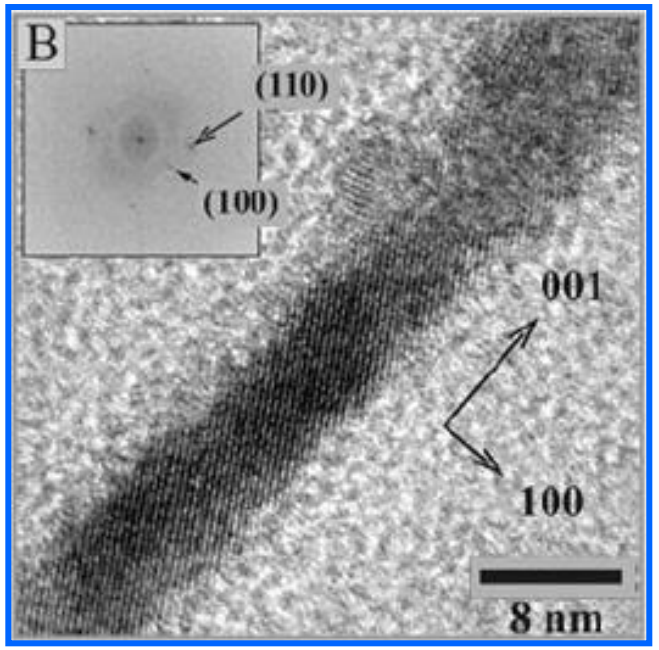
Particle / Q-dots /Bimetallic/ core –shell/ Wires





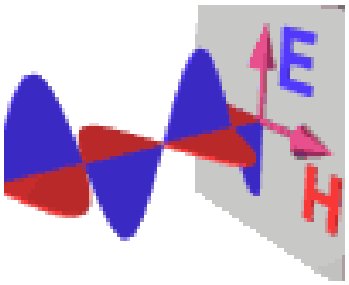


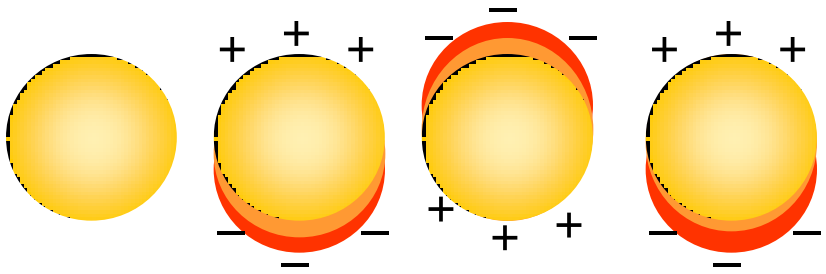


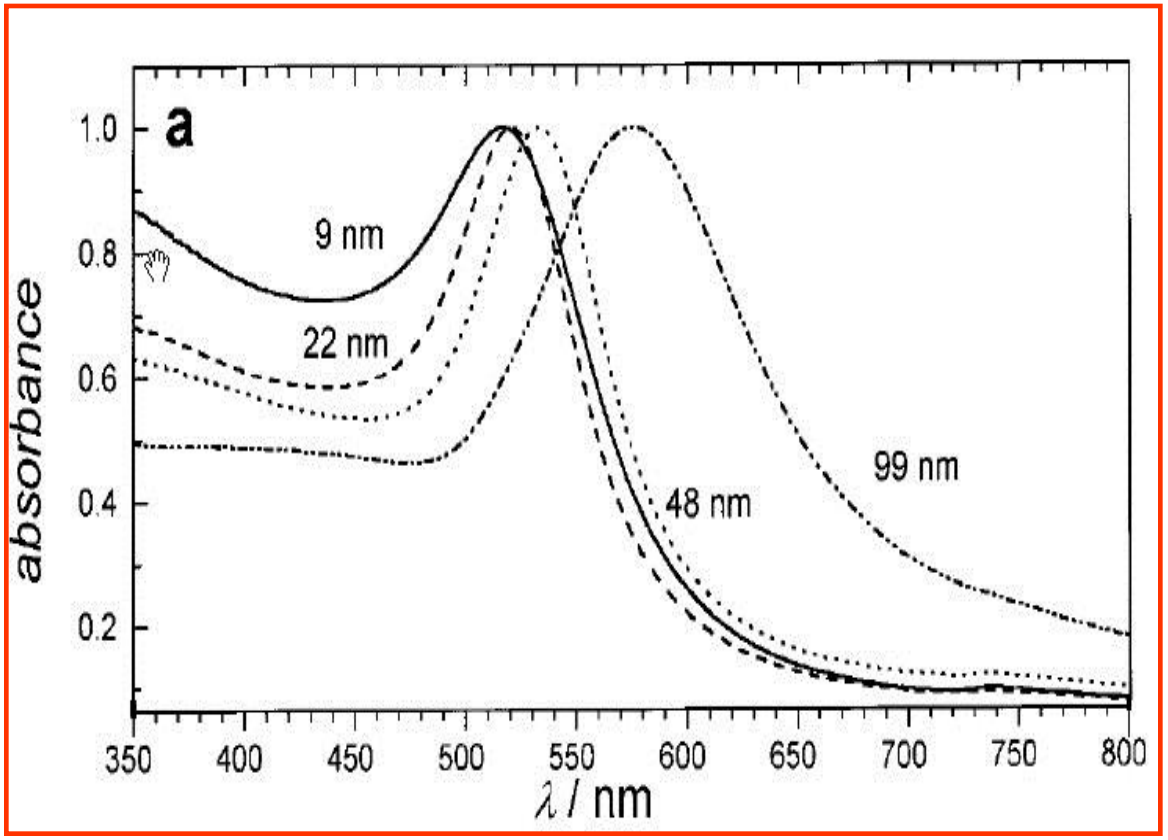


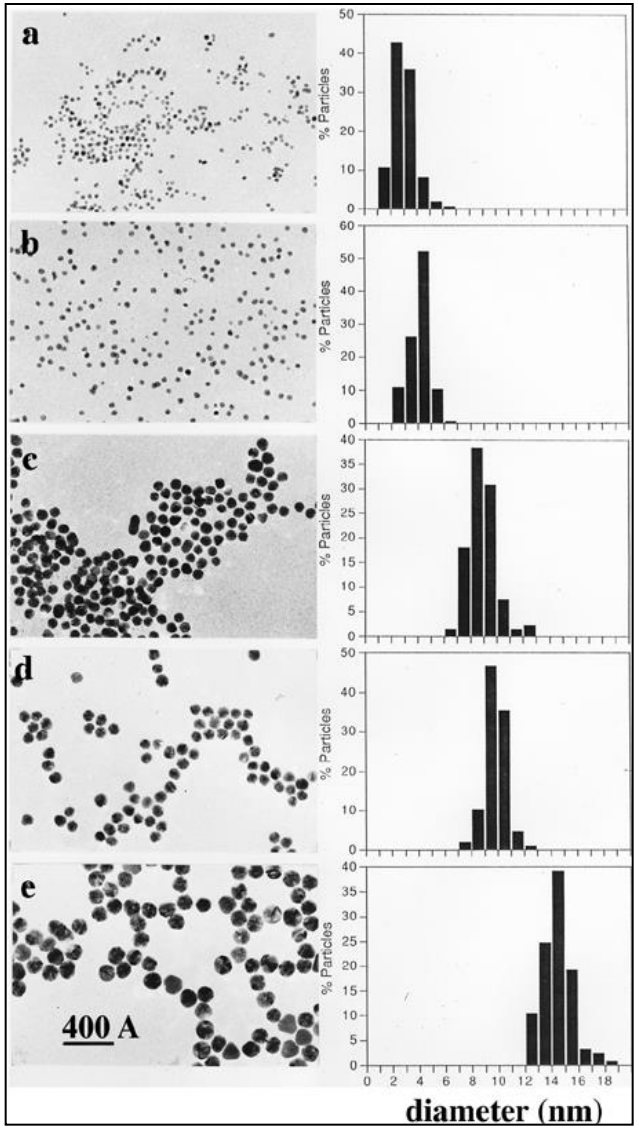
Metal: (Ag, Cu, Pt..) Au-particles

$$\omega_p = \sqrt{\frac{4\pi n e^2}{m}}$$





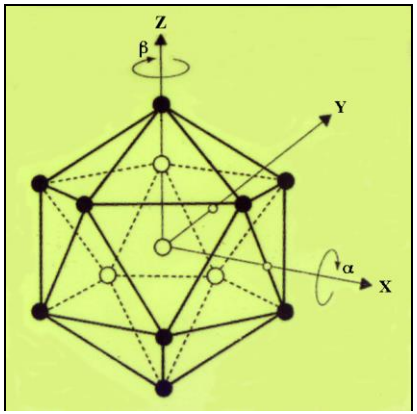


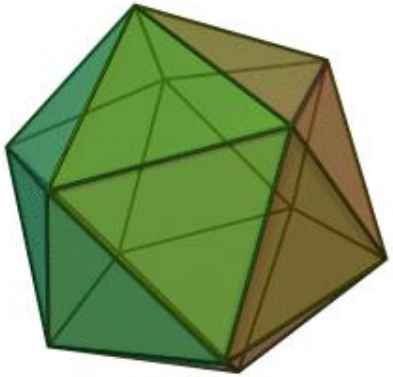


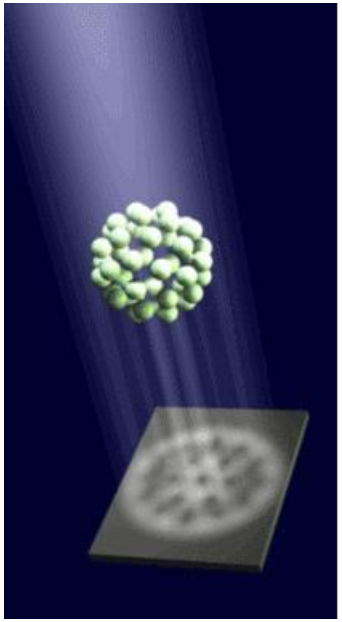
Formation of colloidal silver nanoparticles: Capping action of citrate by Henglein, A; Giersig, M
JOURNAL OF PHYSICAL CHEMISTRY B 103 44 9533-9539 1999

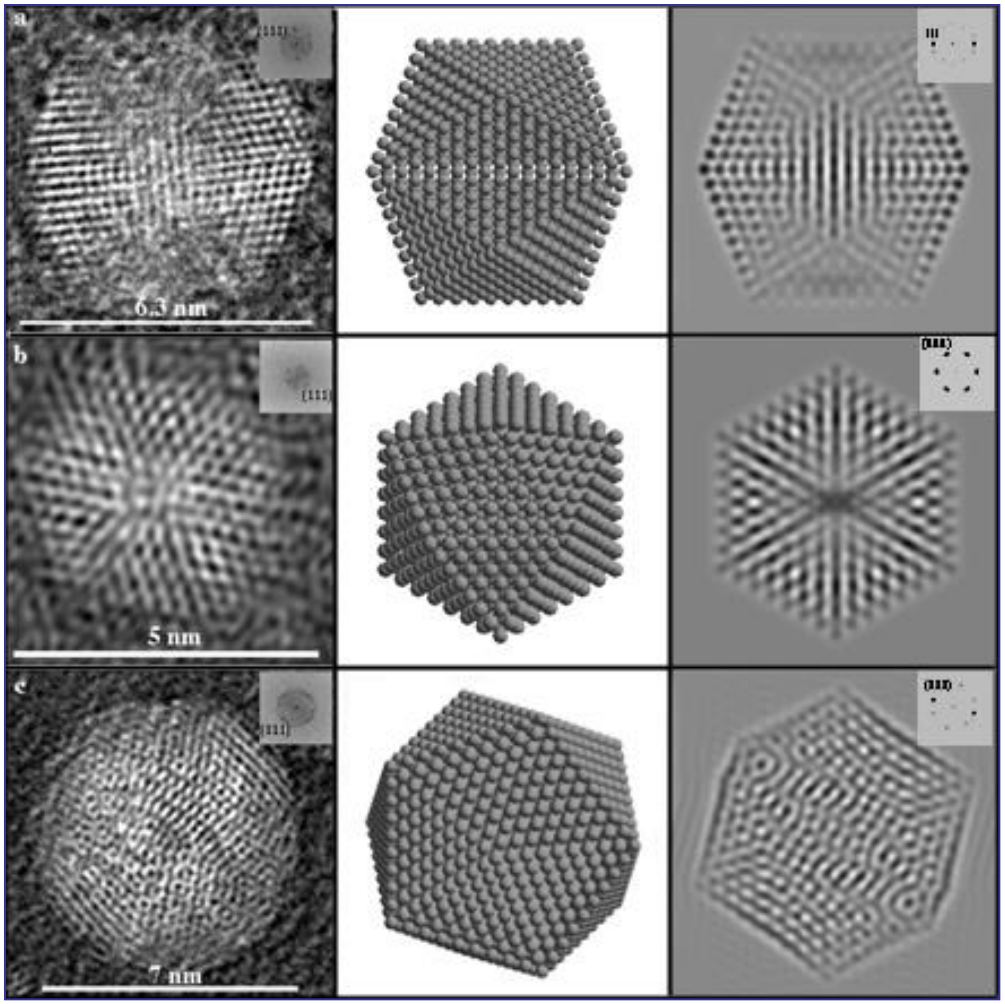
Experimental results and theory





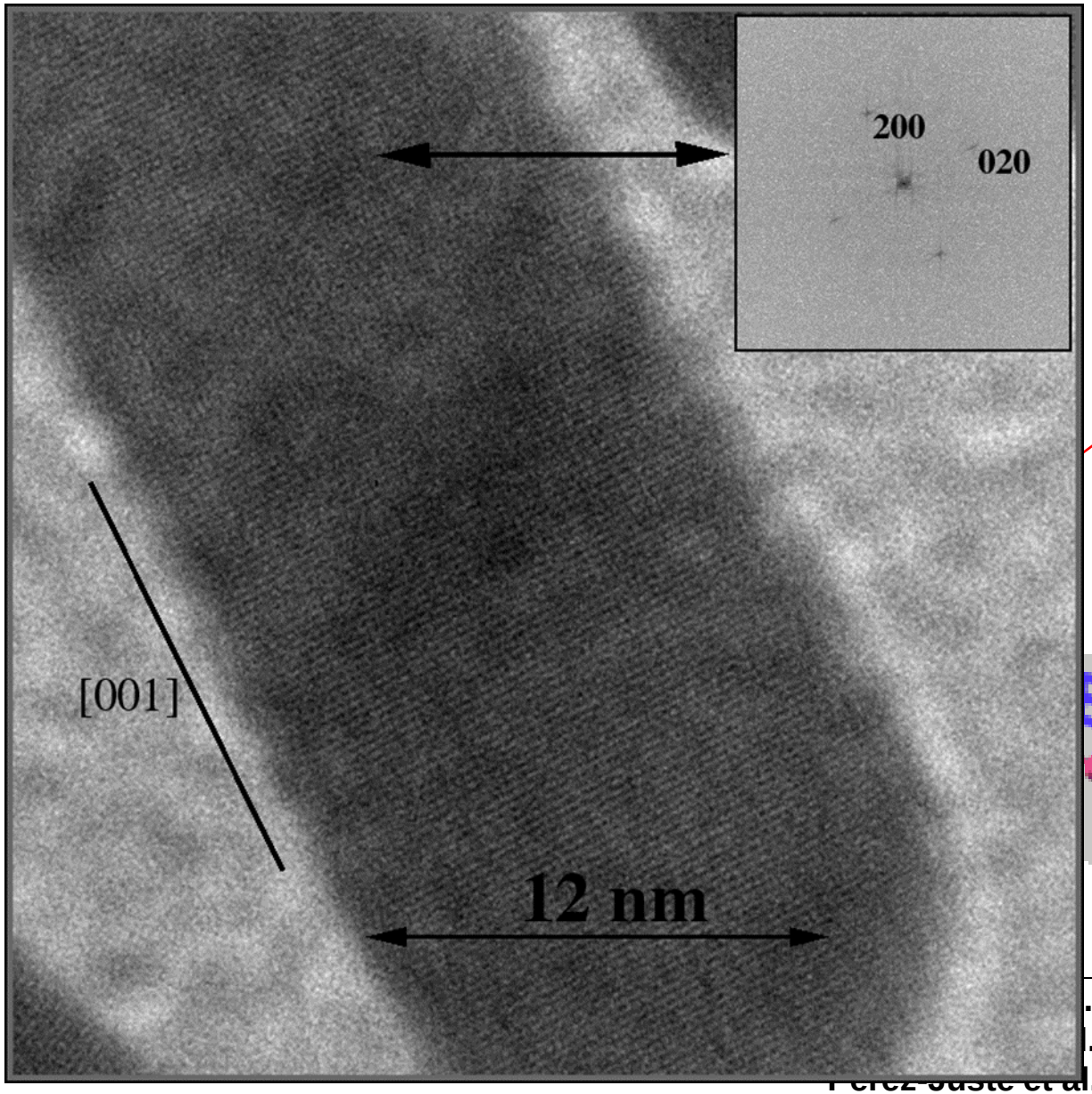


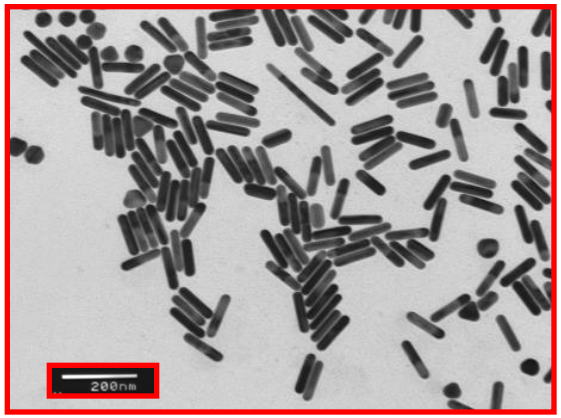




Giersig, M. et al., J. Phys. Chem., B 103, 9533-9539, 1999

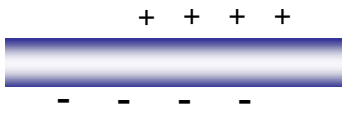
Different Aspect Ratios - Different Colours





A.R.: **4.75**
Width: **22.8 nm**
Length**: 108 nm**





$$\omega_p = \sqrt{\frac{4\pi n e^2}{m}}$$



. Adv. Funct. Mat. 14, 571-579 (2004).
.; Chem Soc Rev 37, 1783-91 (2008).
. Coord Chem Rev 249, 1870 (2005).

Fabrication of nanomaterials by Nanosphere Lithography

Components and their important parameters:

- Monodispersed PS-latex particles in the range of 100 – 2000 nm
- Substrate: metal, semiconductor, glass, isulator
- Size distribution PS particles; (SD<1%)
- Low substrate roughness (RA<2 nm)
- Adjustable: Reactive Ion Etching, Evaporation

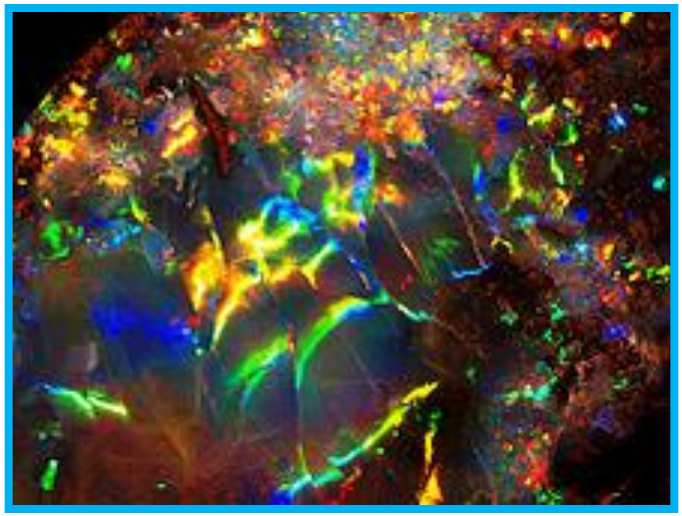
Which nanostructures are possible

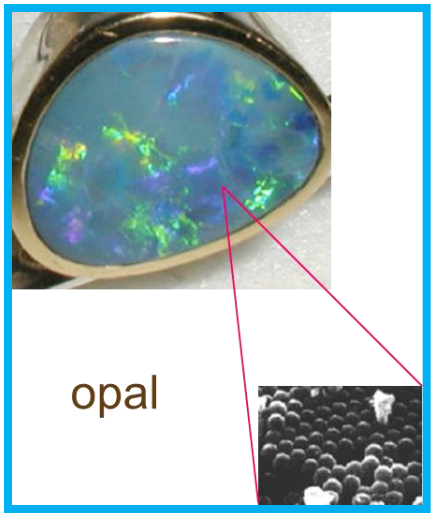
- large 2-D and 3-D arrays of particles with various morphologies such as: triangles; dots; wires; rings; spring resonators; core-shell and holes,
- composition : metallic, semiconductor, magnetic
- properities : plasmonic, superparamagnetic, ferromagnetic

Giersig, M., et al., Langmuir 9: (12) 3408-3413, 1993

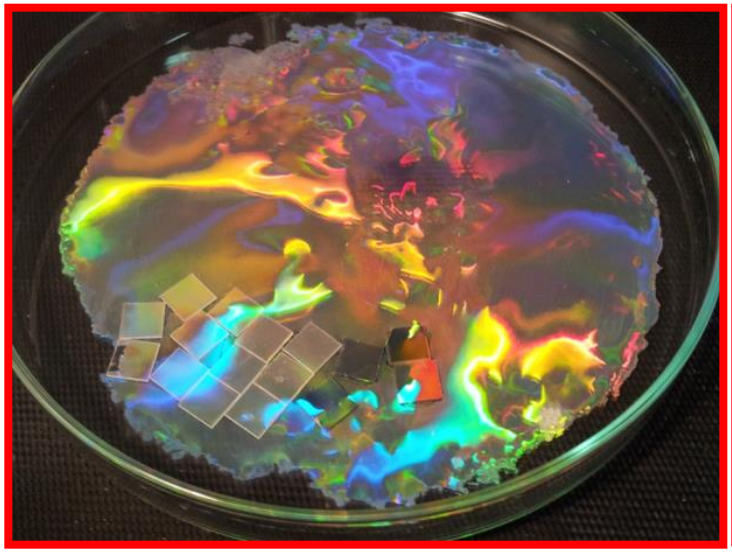
van Duyne, P., et al., J. Vac. Technol. A, 13, 1995

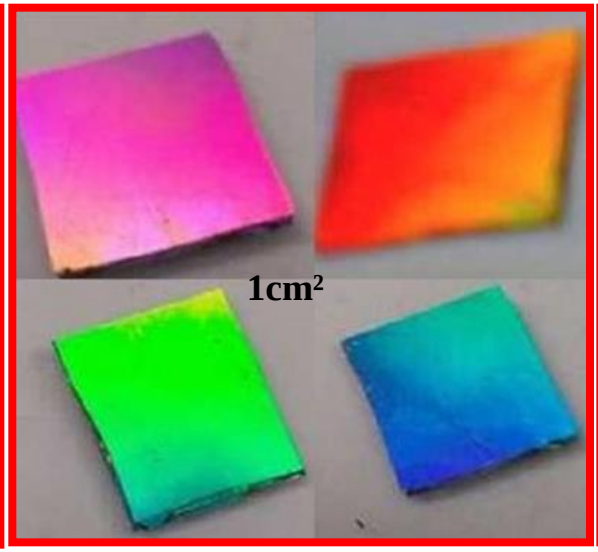
Examples of natural and artificial made Opals





An opal bracelet.
The stone size is 18 by 15 mm.
Opal is composed of silica spheres some 150 to 300 nm in diameter in a hexagonal or cubic close-packed lattice

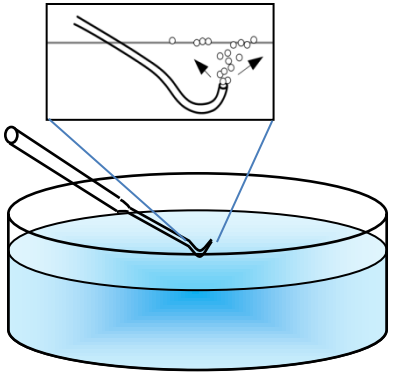


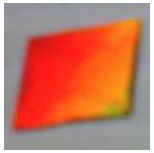


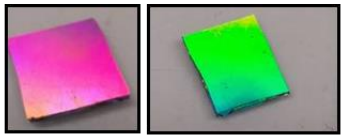


Photographs of 2-D a hexagonal close-packed lattice based on 490 nm and 1700 nm in diameter Latex particles

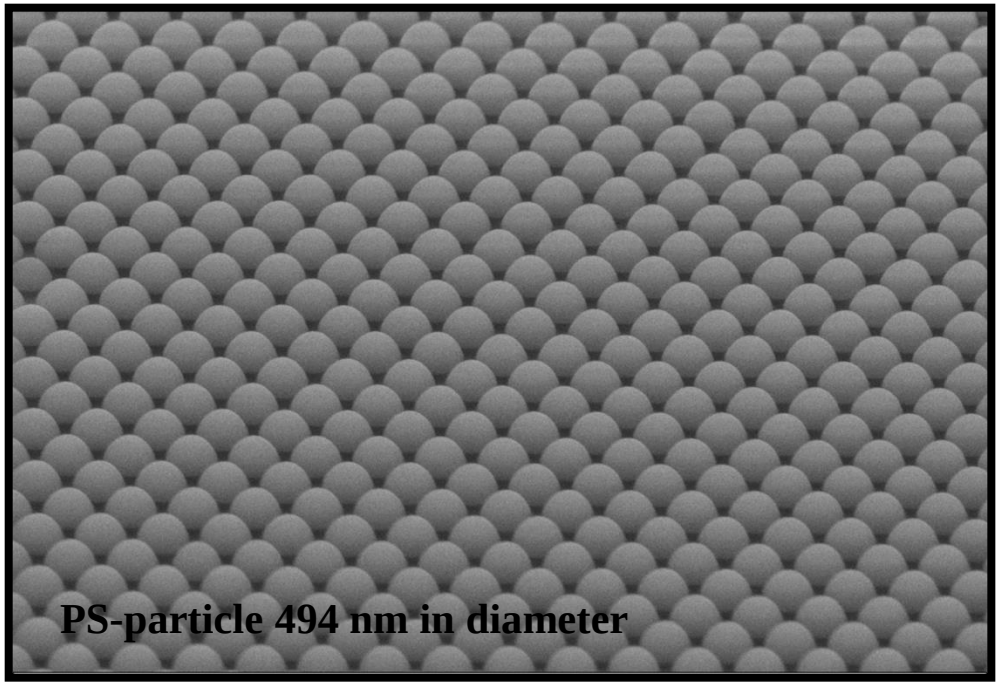
General introduction to NSL

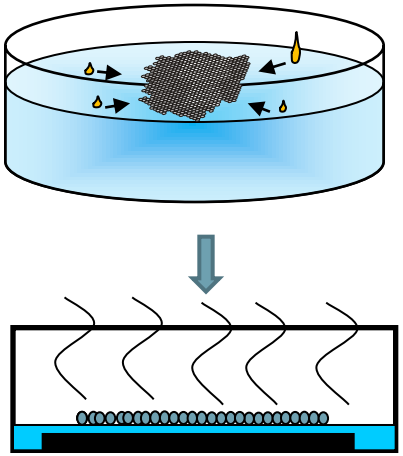




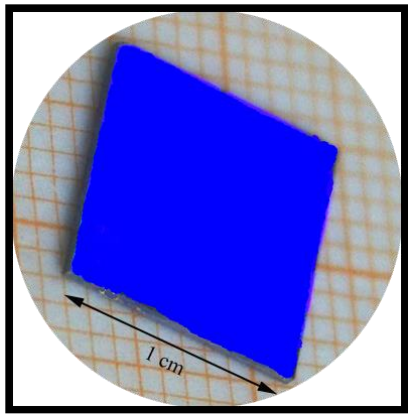


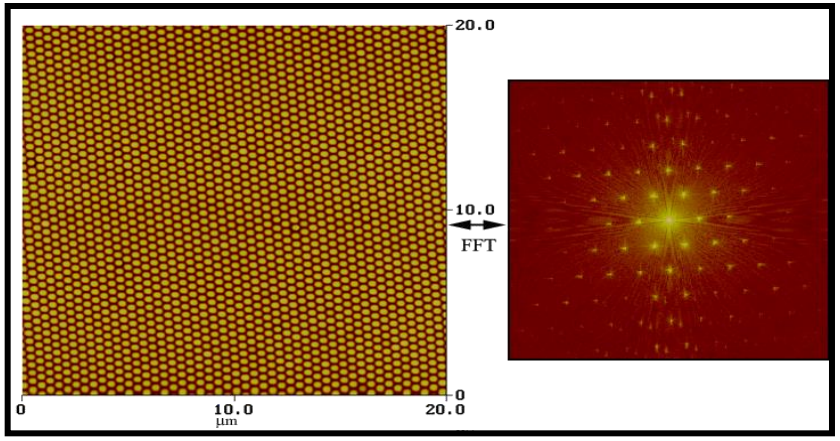
hcp masks on Si substrates











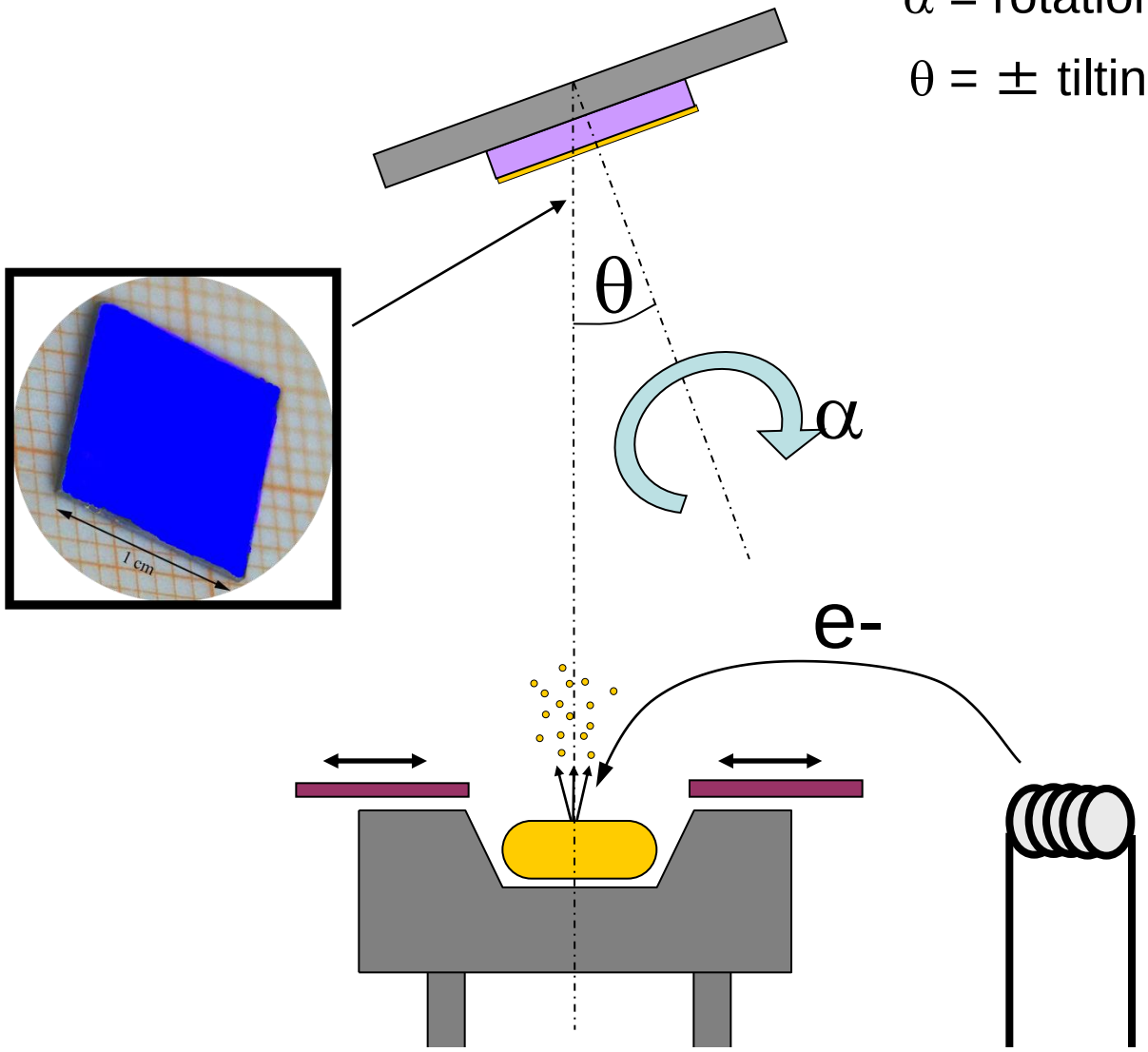
Rybczynski J, Ebels U, Giersig M

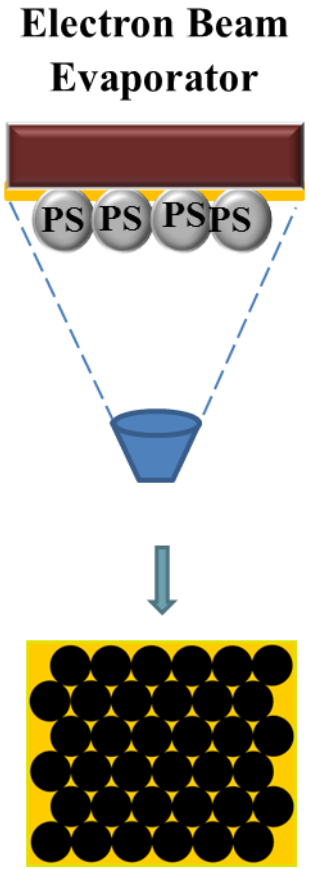
Large-scale, 2D arrays of magnetic nanoparticles; COLLOIDS AND SURFACES A 219 1-3 1-6 2003

Geometry of an electron beam evaporation system

α = rotation

θ = ± tilting angle

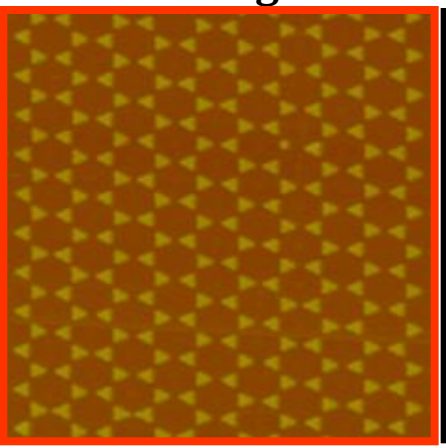




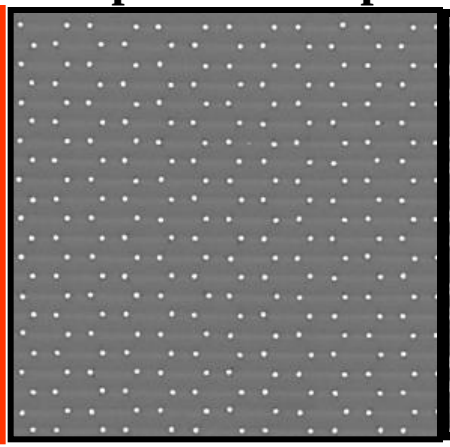
Kosiorek, A; et al.
Fabrication of nanoscale rings, dots, and rods by combining shadow nanosphere lithography and annealed polystyrene nanosphere masks SMALL 1 4 439-444 2005

Selected Nanostructures produced by physical method

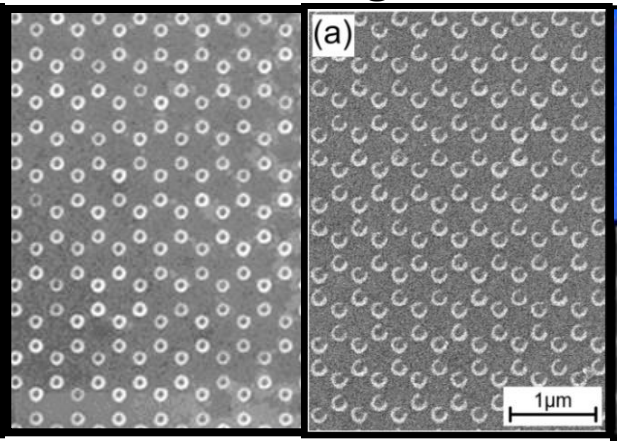
Triangles



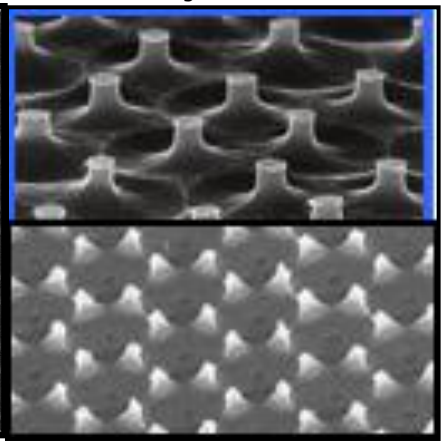
spherical shape



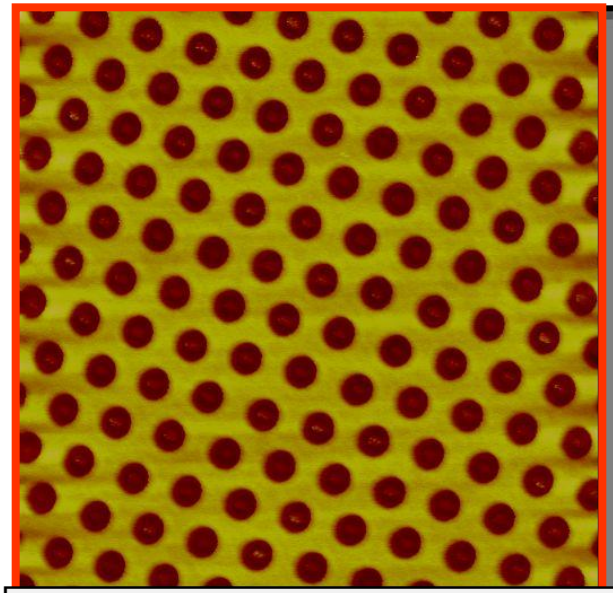
Nanorings



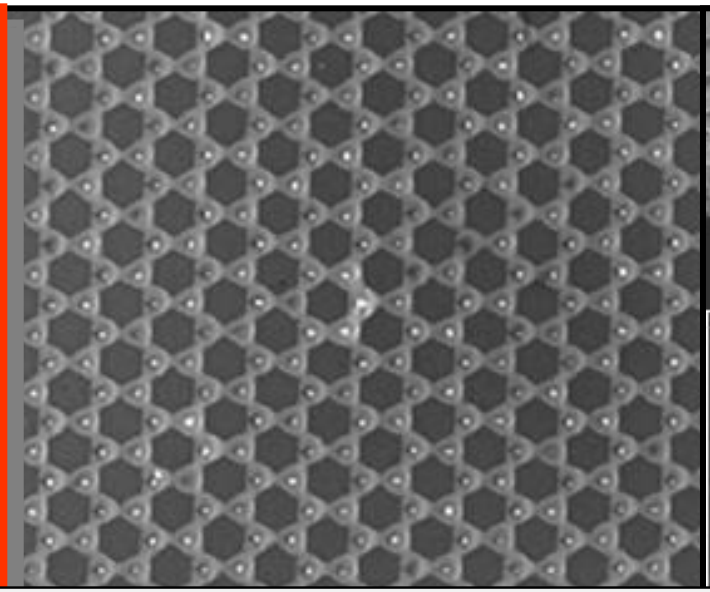
Pillars/Pyramids



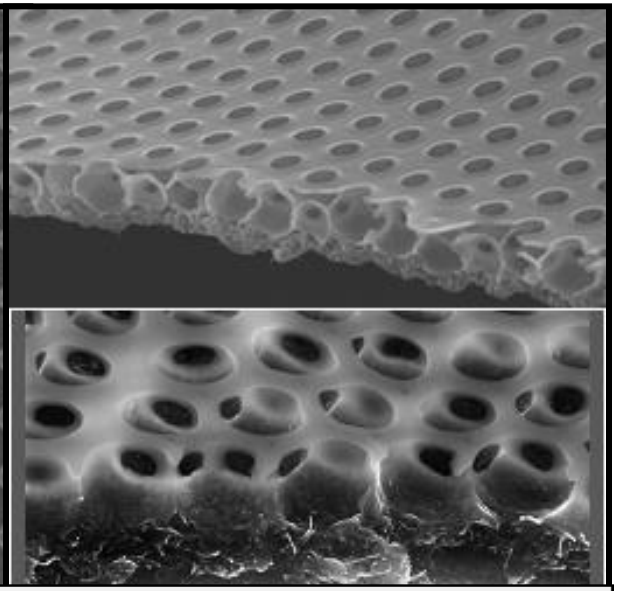
Nanoholes



Bimetallic

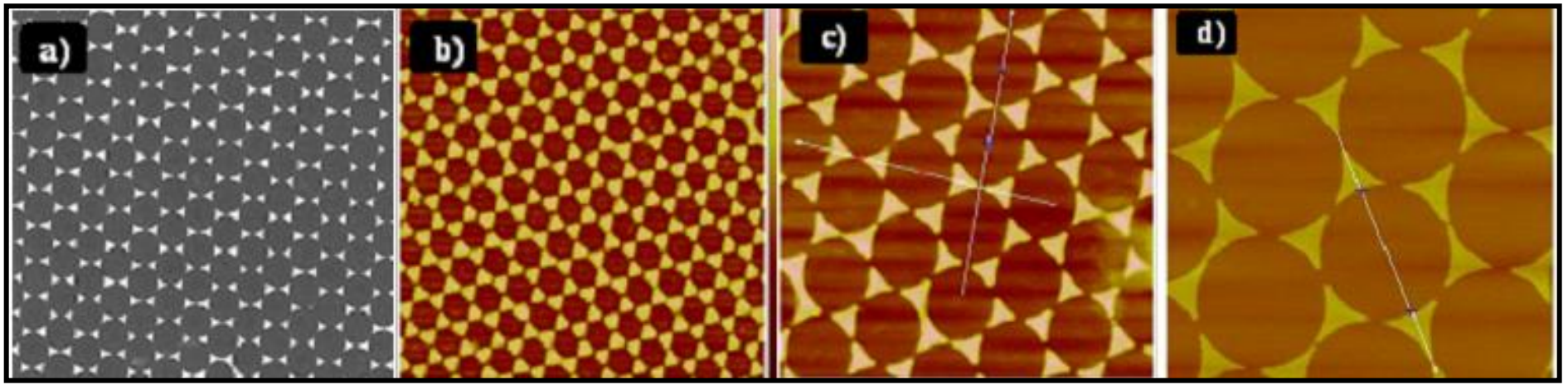


3-D Structures

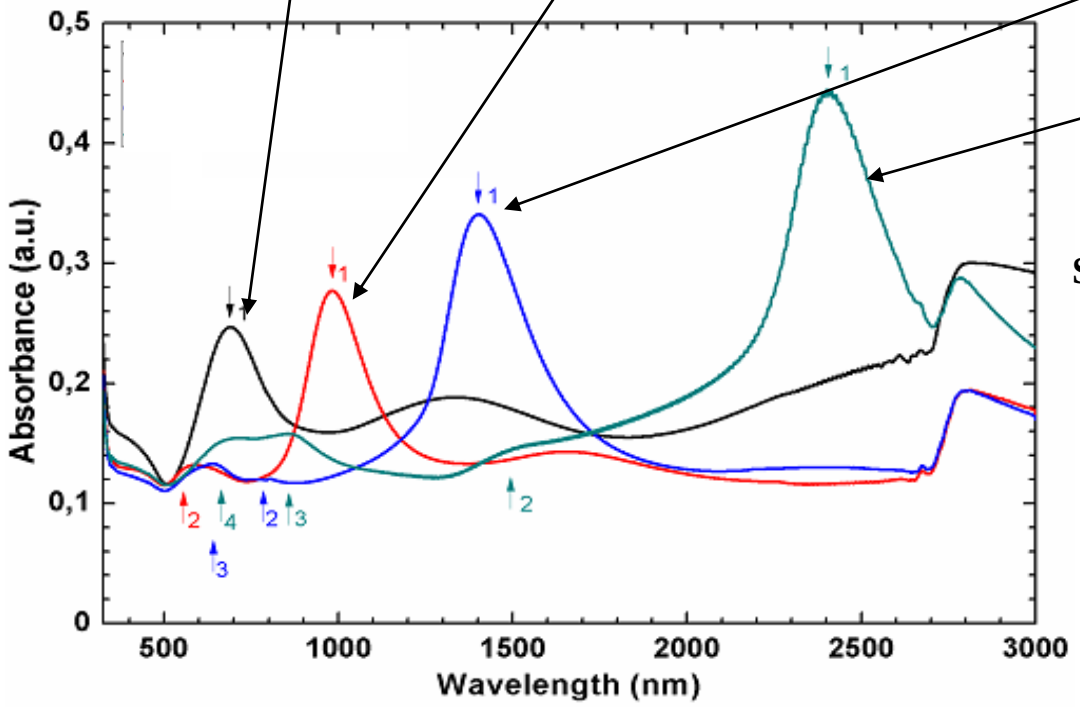


Kosiorek A, et al.
Shadow nanosphere lithography: Simulation and experiment; NANO LETTERS 4 1359-1363 2004

Plasmonic properties of array of triangular shaped gold nanoislands



PS-diameter a = 380 540 980 1710 nm



Important!!

The spectra exhibit first (most pronounced) Second and third and fourth absorbance peaks

It is expected, that these resonances are from a highly dispersive, plasmon polaritonic mode since similar resonances have been observed in metallic particles

The experimental spectra for 20 nm thick Au triangles on a sapphire substrates

Theoretical approach

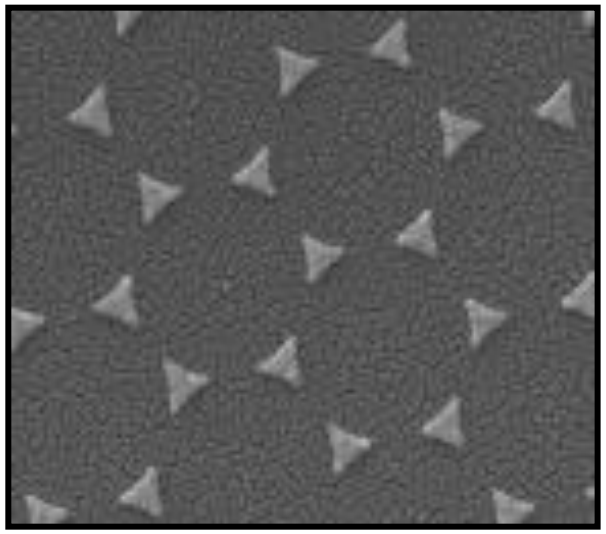
The experimental spectra shown for structures obtained with sphere diameters a = 380, 540, 980, 1710 nm, that each spectrum is dominated by a pronounced resonance peak, position of which strongly depends on a.

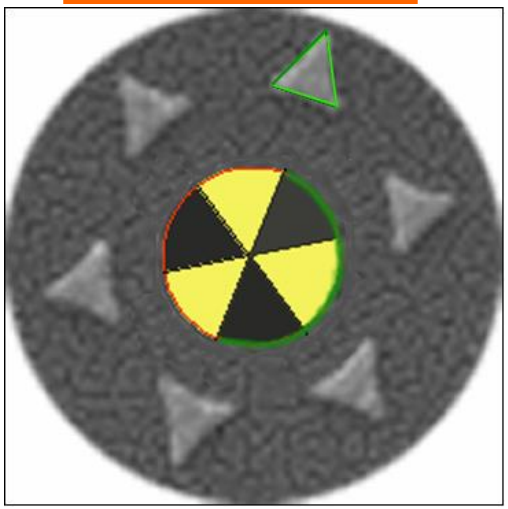
We assume, that these resonances can be viewed as circumferentially quantized surface plasmon waves and ignore the particle-particle interactions.

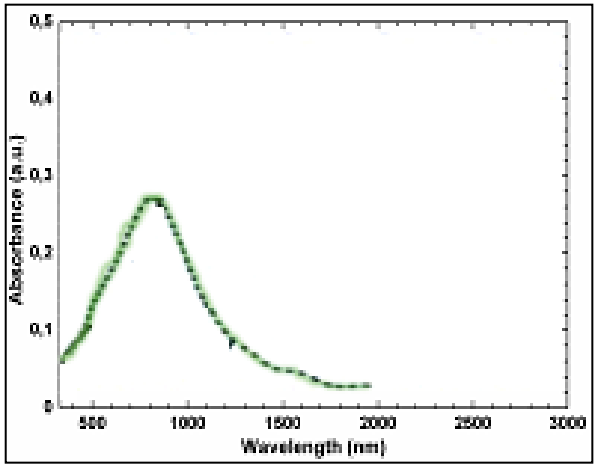
Since each side of the quasi-triangular particle equals approximately 1/6 of the sphere circumference  **π a**

The circumference of the particle $\sim \pi a/2$ and thus the circumference quantization condition requires that this circumference is equal an integral multiple (l) of the wavelengths of the resonating surface/edge plasmon wave (λ_p)

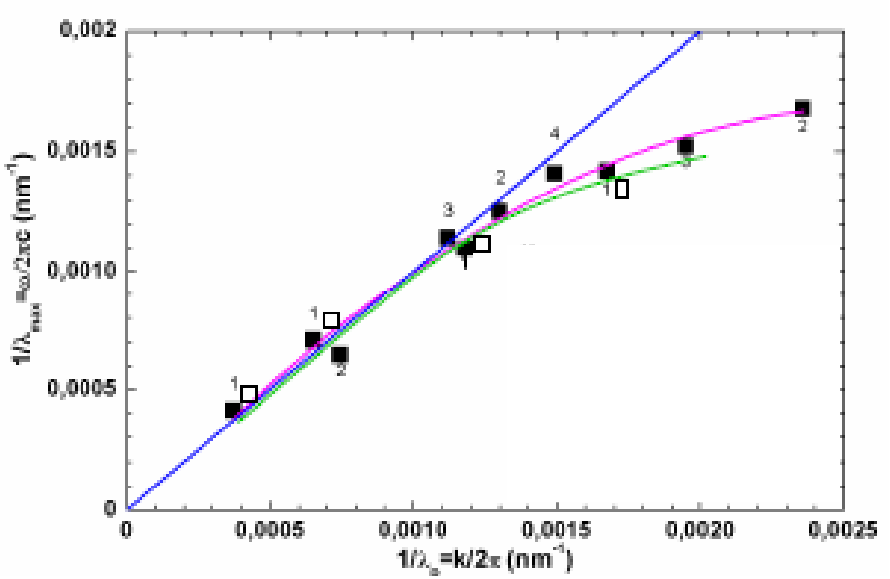
$$l \lambda_p \sim \pi a/2$$



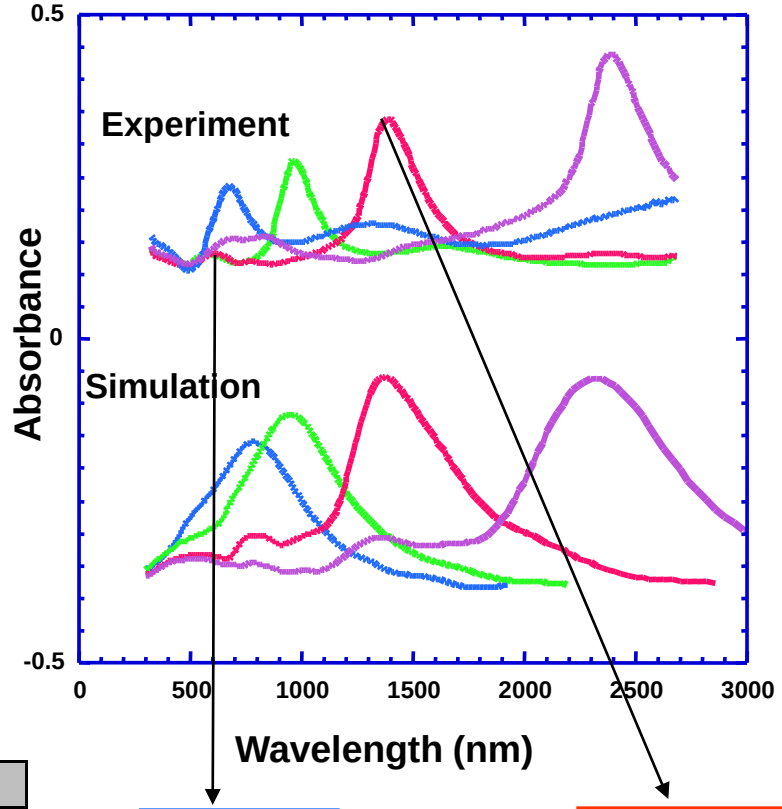




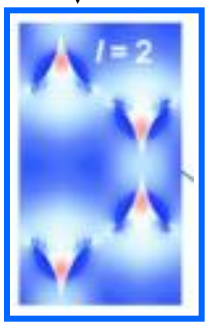
Surface plasmon resonances in metallic nanoparticles:



Simulated dispersion of the resonating surface/edge plasmon (white squares)



	D_0[nm]							
	380		540		980		1710	
l	λ_{max}	λ_{SP}	λ_{max}	λ_{SP}	λ_{max}	λ_{SP}	λ_{max}	λ_{SP}
1	704	597	996	848	1417	1539	2417	2686
2	-	298	596	424	799	769	1551	1343
3	-	198	-	282	658	513	875	895
4	-	149	-	212	-	385	709	671

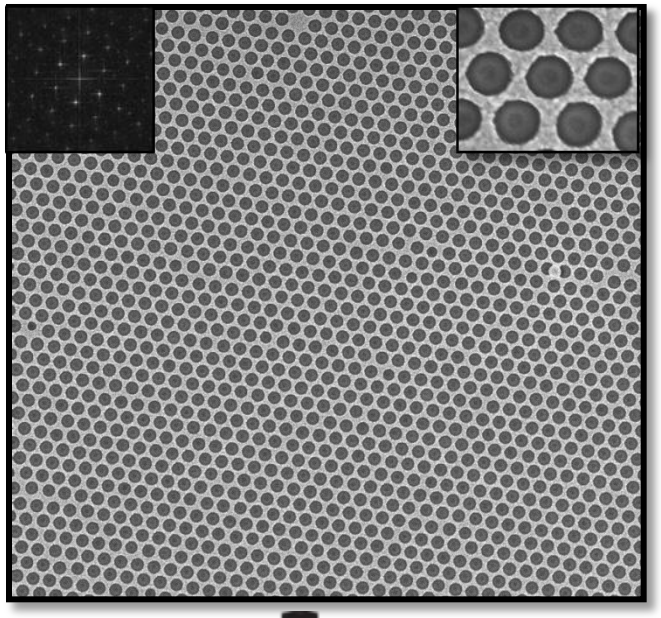


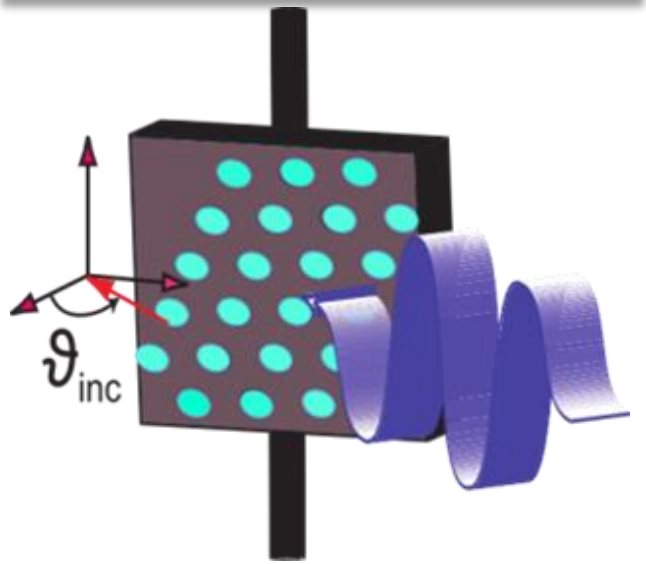


- Simulated results are in excellent agreement with the experiment
- the physics is due to a surface/edge plasmon polariton resonating in the nanoparticles

Y. Peng, et al.
Appl. Phys. Lett. 96, 133104 **2010**

Plasmonic properties of submicron holes in metallic film





The transmission properties of a sub- wavelength hole in a metal film was predicted in **1944 by Bethe**

An extraordinary transmission through sub-wavelength holes in a metal film was shown in **1998** by **Ebbesen**

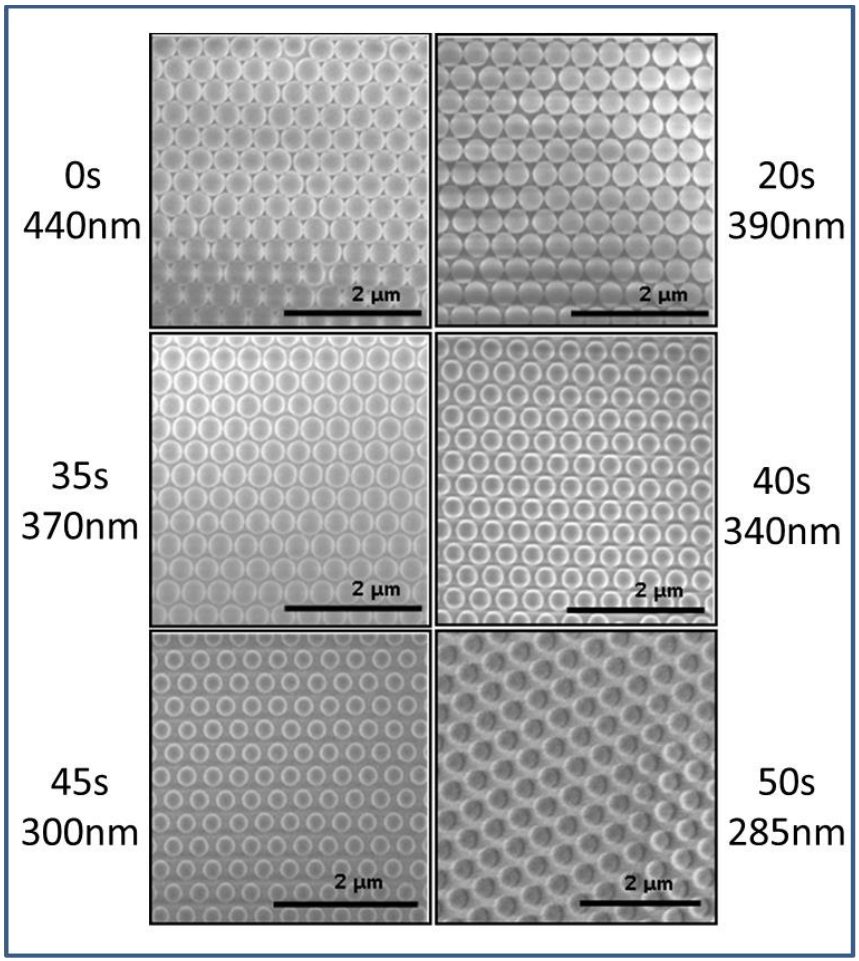
Bethe, H. A. Phys. ReV. 1944, 66, 163

Ebbesen, T. W.; Lezec, H. J.; Ghaemi, H. F.; Thio, T.; Wolff, P. A. Nature 1998, 391, 667

Nowadays, the excitation of surface plasmons is widely accepted to be responsible for this enhanced transmission

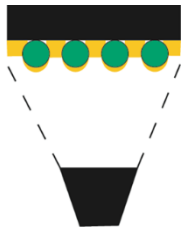
Mask modification - reactive ion etching (RIE) for reduction of PS-diameter





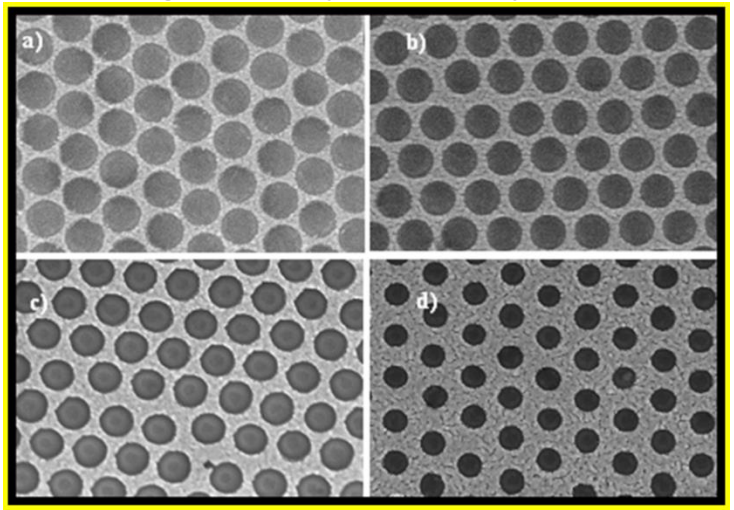
Ctistis, G.; et al. NANO LETTERS 9 1 1-6 2009
Ctistis, G.; et al. NANO LETTERS 7 9 2926-2930 2007

Preparation of 2-D nanocylinders different diameters



Evaporation of desired material with MBE

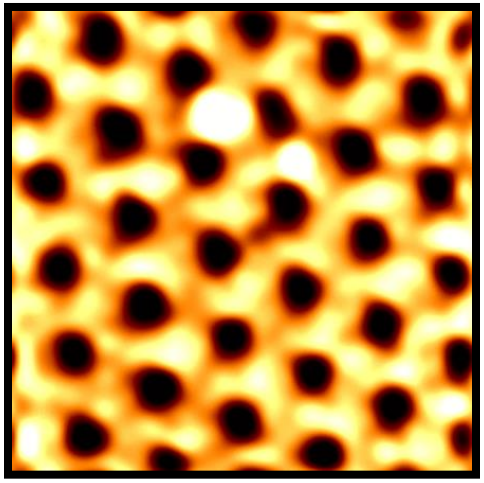
Removal of PS-spheres leads to film with hexagonal array of nano -cylinders



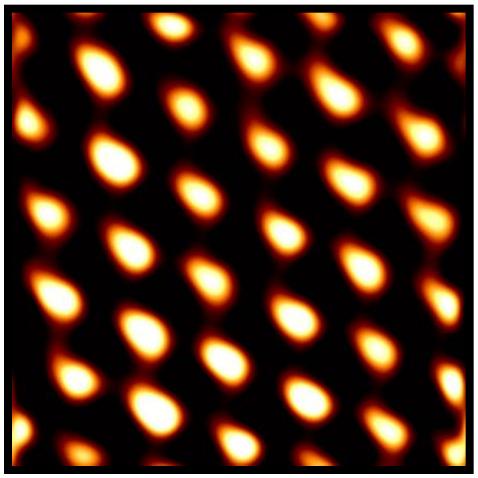
SEM images of nanocylinder arrays. Diameter of single hole is a) 385nm, b) 340nm, c) 325nm and d) 265nm

Nano-hole arrays / Plasmonic metal

SNOM pictures for a 50 nm thick gold film

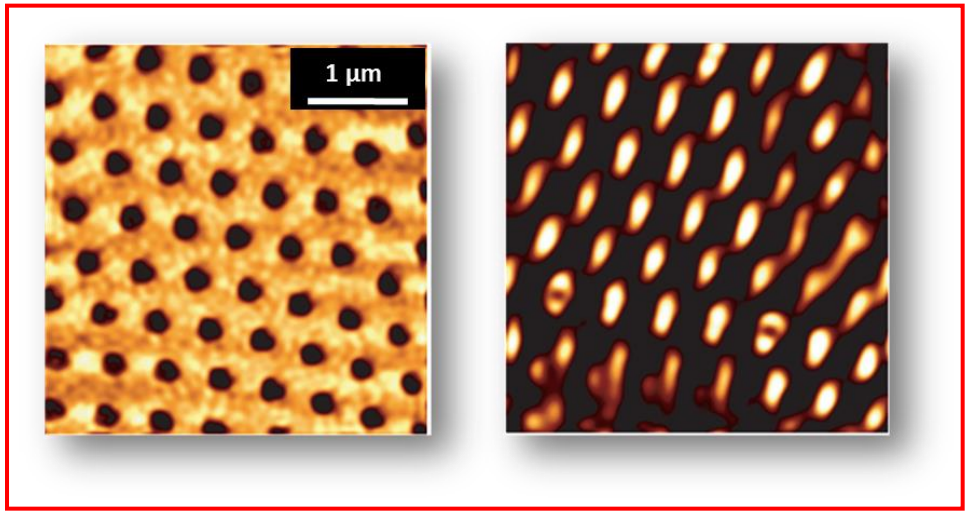


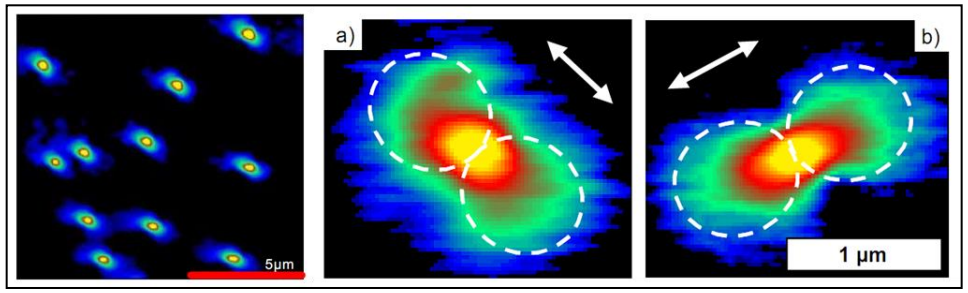
topography



near-field optics

Plasmonic properties of Al submicron holes





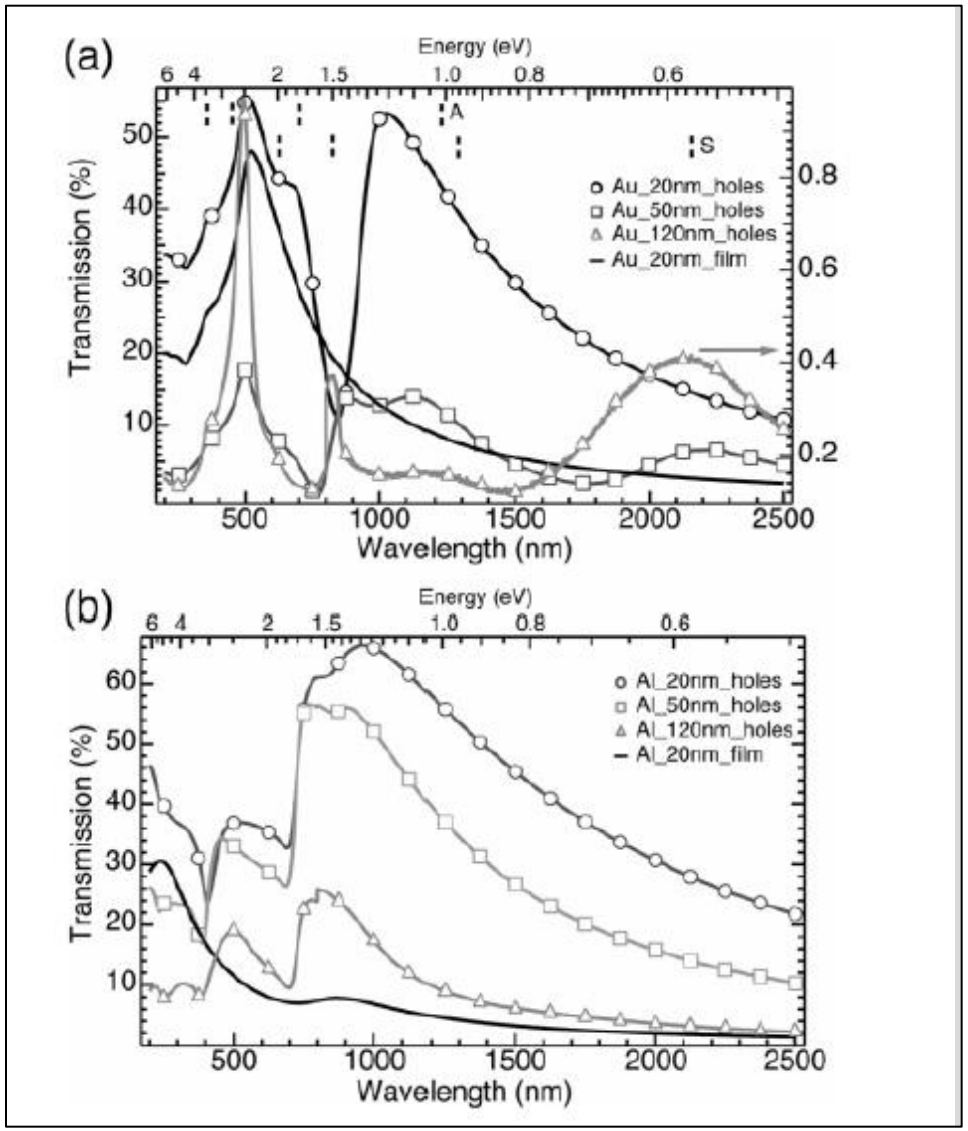
Gold is a high-conductive noble metal with strong d-s interband transitions and a well-pronounced bulk plasmon excitation, strongly contributing to the optical response in the visible.

Aluminum, on the other hand, is a high-conductive free-electron metal (only a weak interband absorption in the visible) with the bulk and regular surface plasmon excitations in the far-UV range

UV-vis transmission spectra

The transmission of the light through a hexagonal array of subwavelength holes in a metallic film is highly dependent on the optical properties of the metal.

The transmission is governed by surface plasmons and Wood anomalies, which determine the position of the transmission maxima.

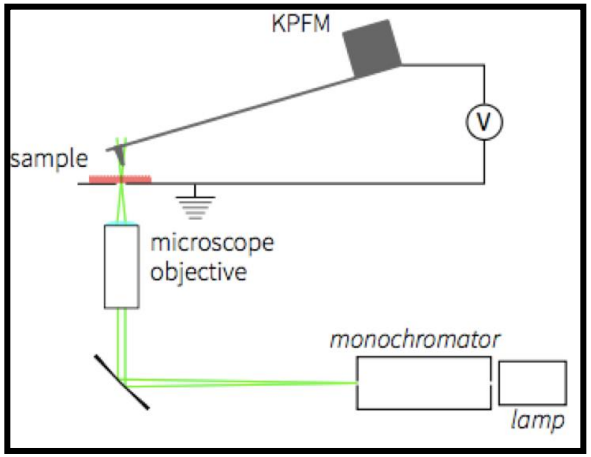


Ctistis, G.; Papaioannou, E.; Patoka, P.; et al.
NANO LETTERS 9 1 1-6 2009

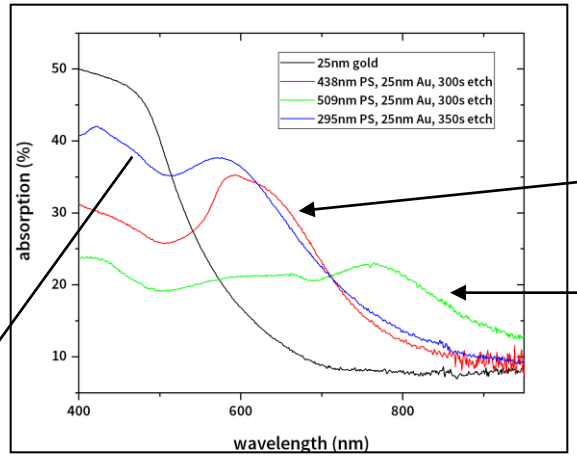
Ctistis, G.; Patoka, P.; Wang, X.; et al.
NANO LETTERS 7 9 2926-2930 2007

Current project

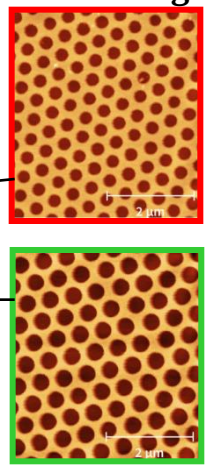
Kelvin probe force microscopy: Surface potential measurements on various nanostructures

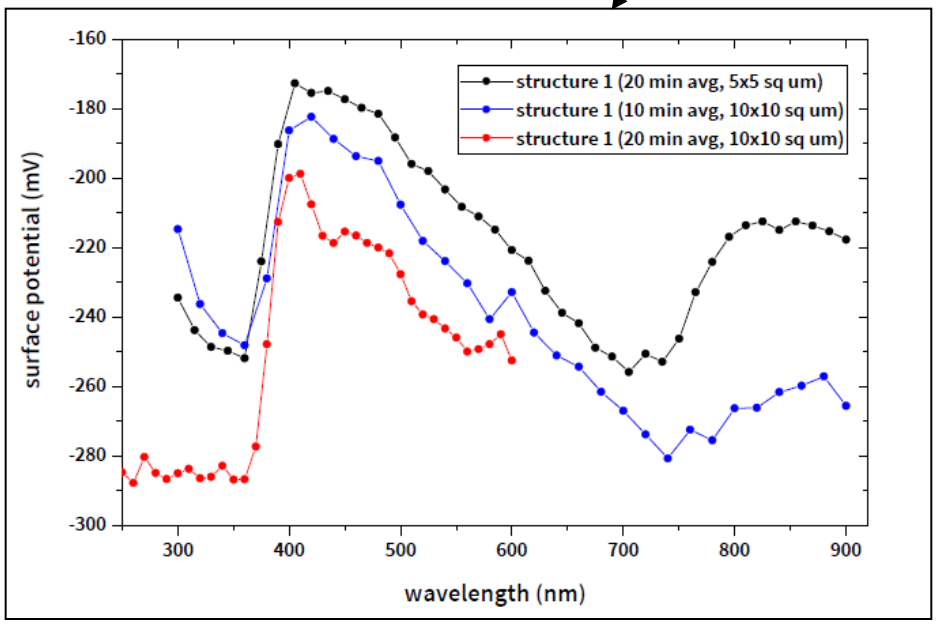


Absorption spectra



AFM- Images



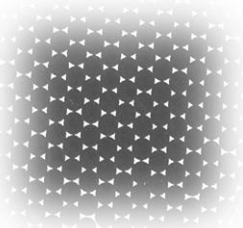


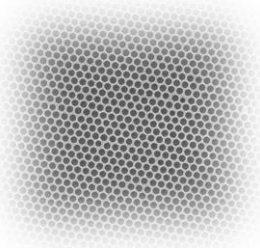
Surface potential: ca 100 mV
Theoretical explanation : ??

Sheldon et al . Science, 2014

Summary

Fabrication of various shaped nanostructures



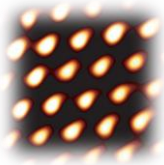


Different structures exhibit different optical properties:

surface / edge plasmon

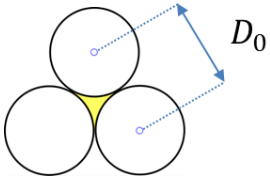


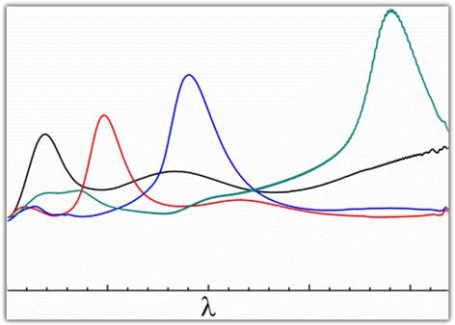
surface plasmon polariton driven extraordinary light transmission

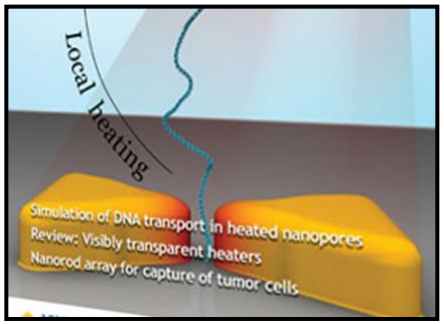


Control of plasmonic properties with:

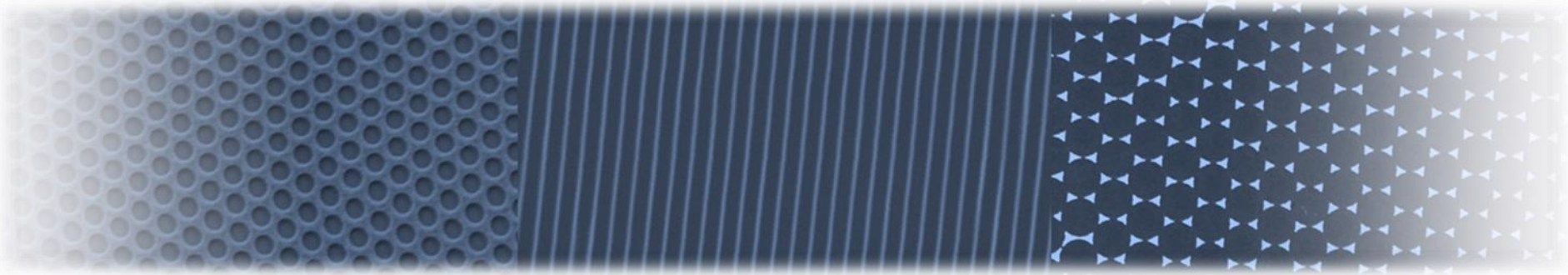
structural properties







Preliminary results : surface potential on metallic nanostructures



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