Manufacturing Nano-optics

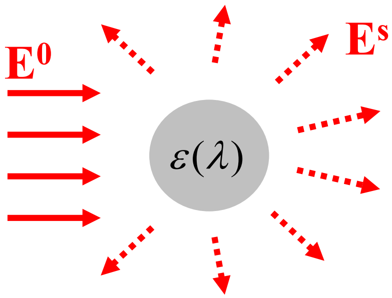
Olivier J.F. Martin
Nanophotonics & Metrology Laboratory
Swiss Federal Institute of Technology Lausanne (EPFL)
www.nanophotonics.ch

EPFL

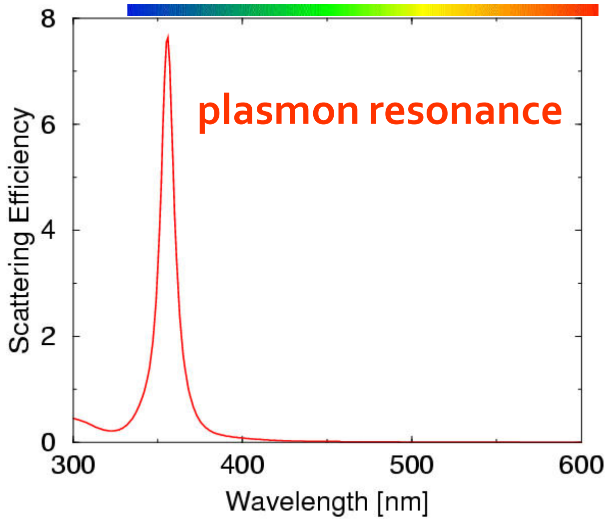
Outline

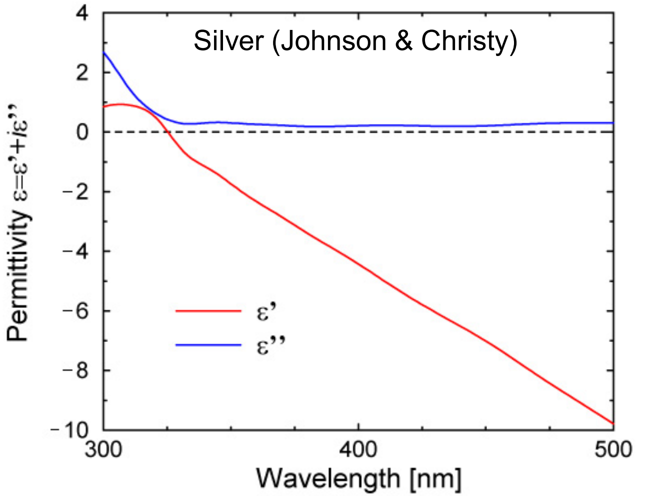
- Plasmonics
- Basic fabrication principles with electron-beam lithography
- Adhesion issues
- Other metals than Au
- Au-Ag alloys
- Hybrid nanostructures
- Chemical synthesis
- Medieval stained-glass windows

Mie scattering by a small sphere



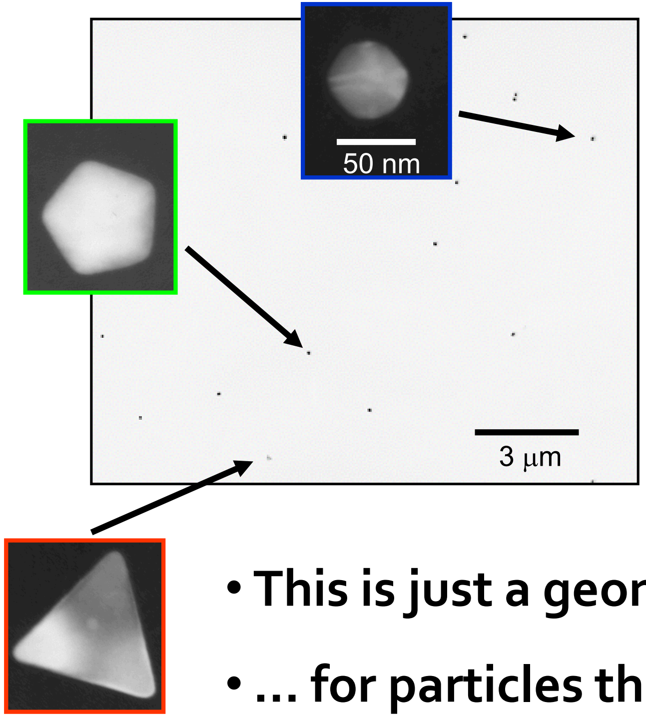
$$Q_{scat}(\lambda) = \frac{8}{3}\left(\frac{2\pi R}{\lambda}\right)^4 \left|\frac{\varepsilon(\lambda)-1}{\varepsilon(\lambda)+2}\right|^2$$

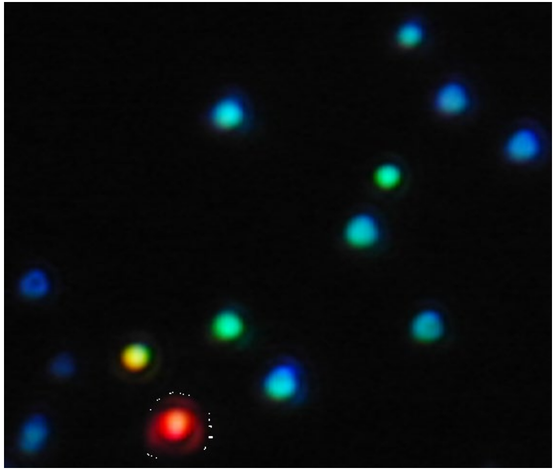




Plasmon resonances

• **Same material, similar sizes, but different colors ?**

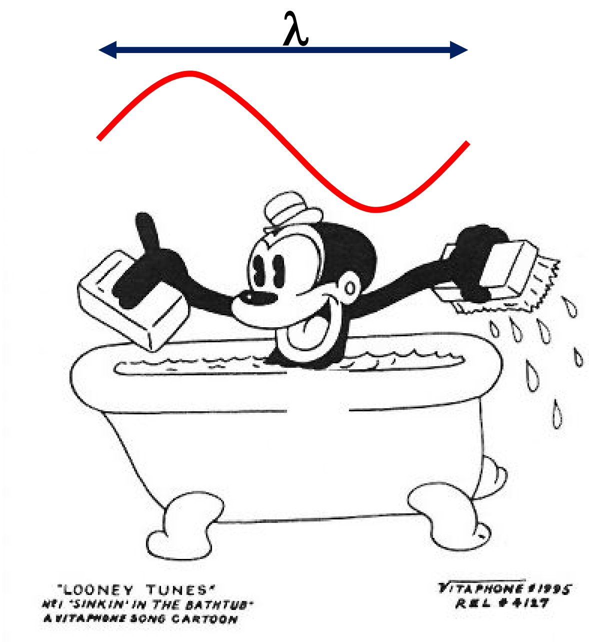


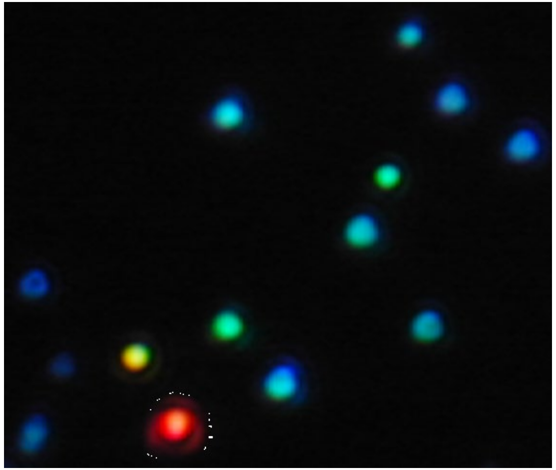


• **This is just a geometrical optical resonance effect…**

• **… for particles that are << λ !**

Plasmon resonances

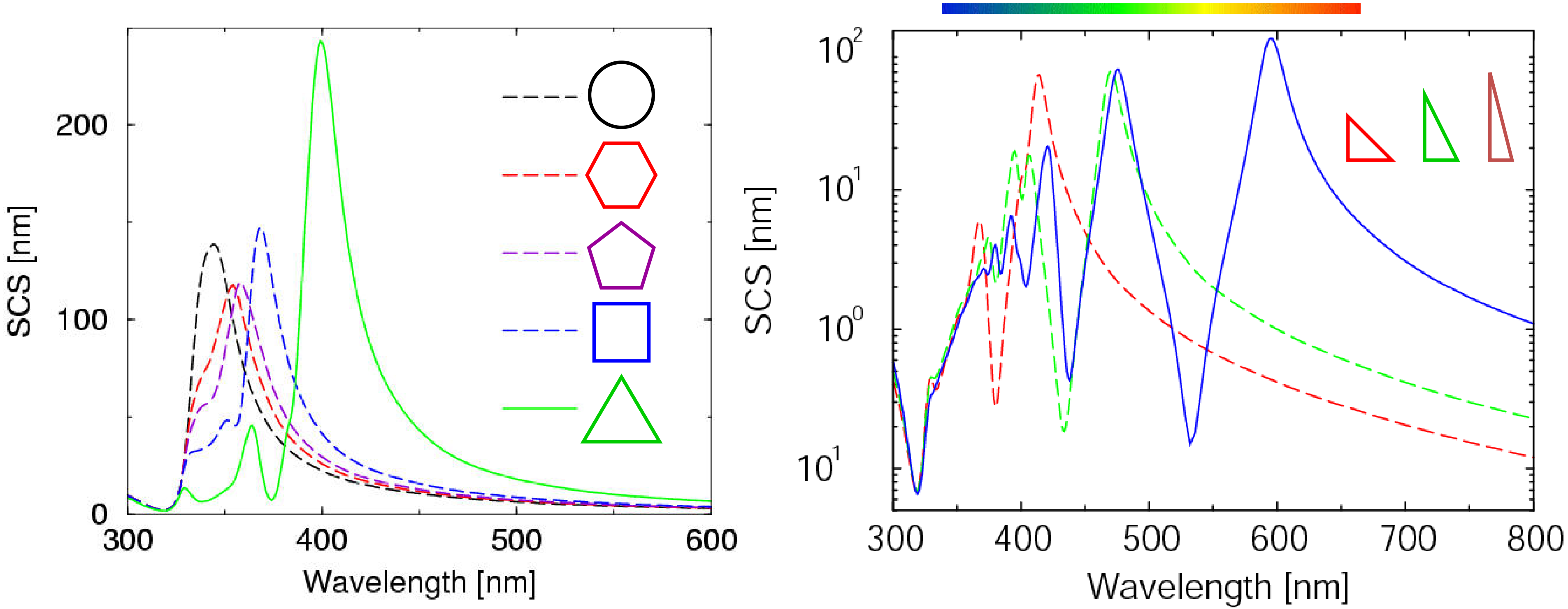




- This is just a geometrical optical resonance effect…
- … for particles that are << λ !

Plasmonics simplexes

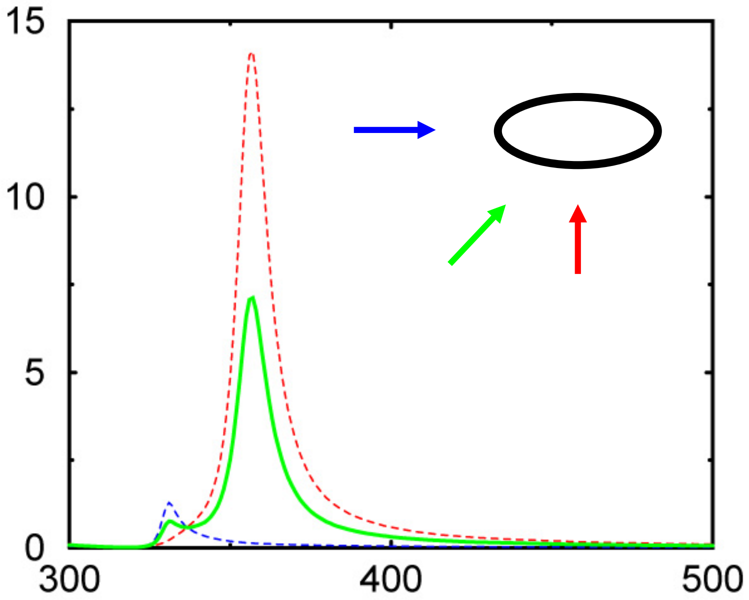
- **More complex spectra as the particle symmetry decreases**

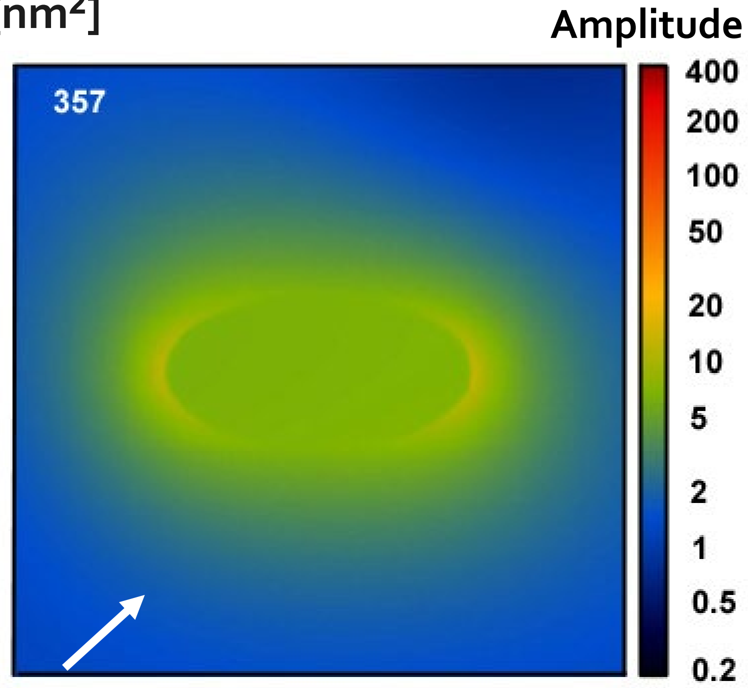


J. Kottmann, Applied Physics B vol. 73, p. 299 (2001)

Plasmon resonances – Elliptical particle

Ag, 20 x 10 [nm^2]

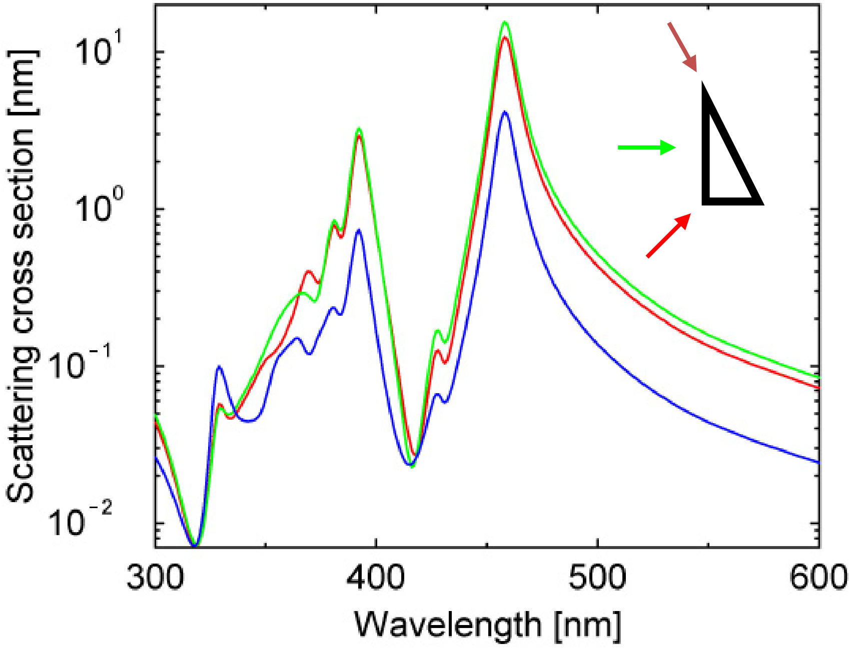


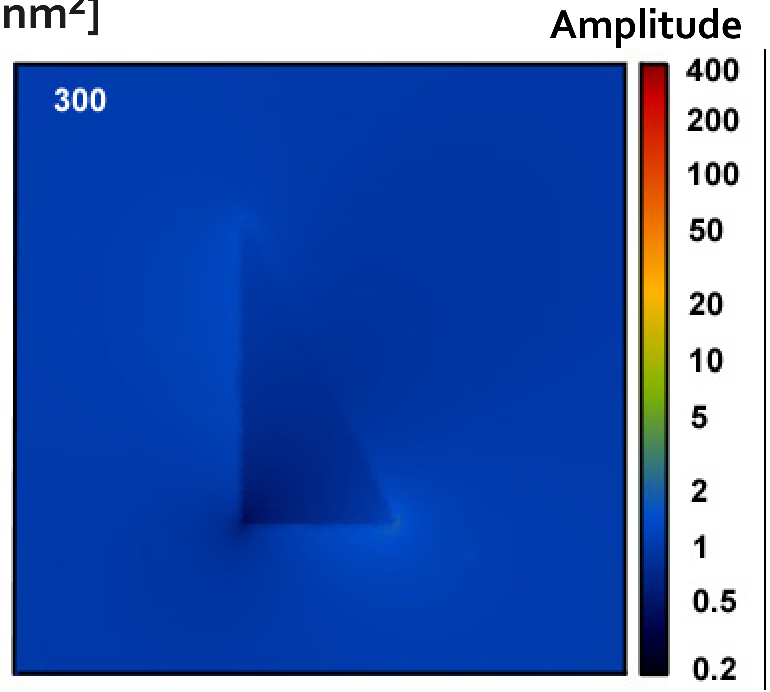


J. Kottmann, New Journal of Physics vol. 2, p. 27 (2000)

Plasmon resonances – Triangular particle

Ag, 10 x 20 [nm²]

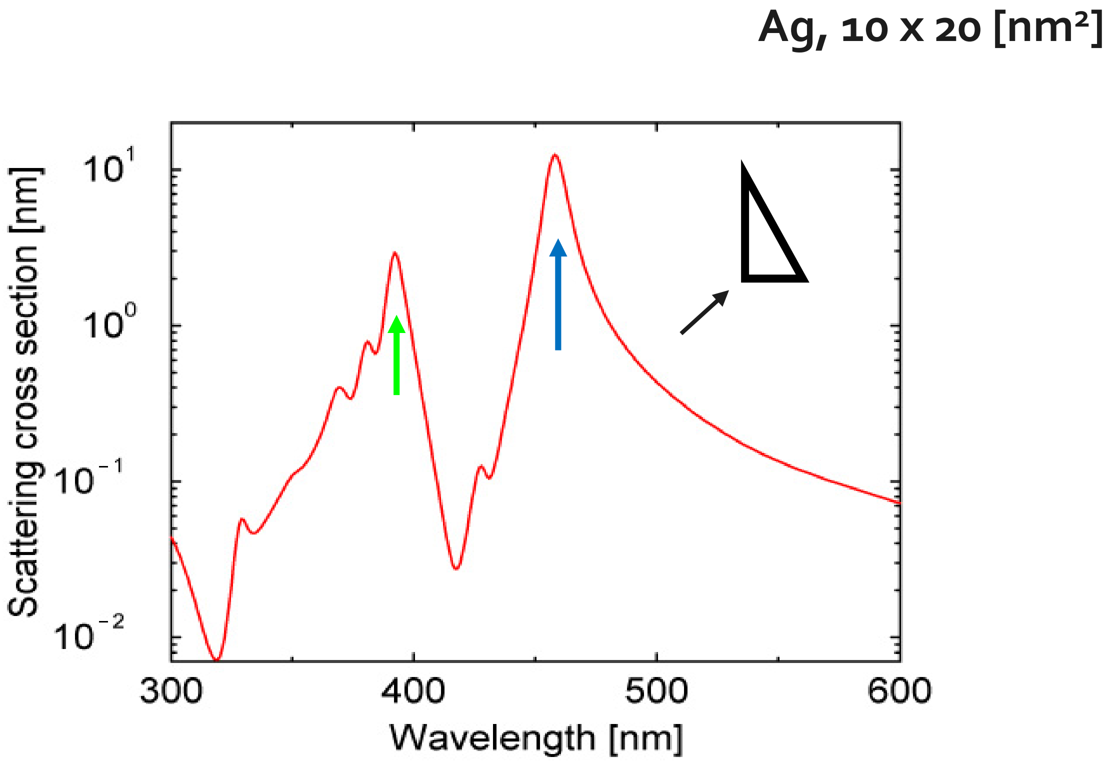


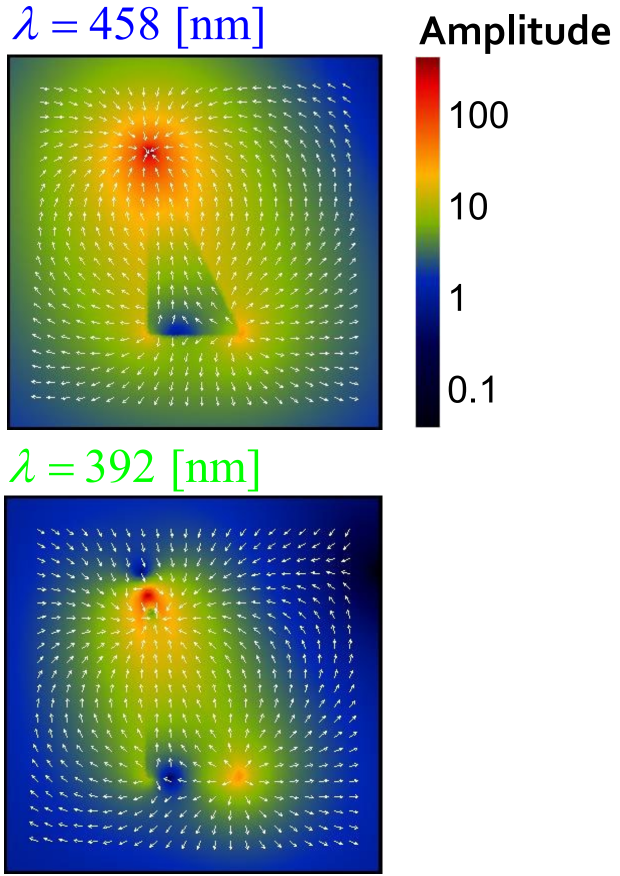


- **Dramatic near-field enhancement**

J. Kottmann, New Journal of Physics vol. 2, p. 27 (2000)

Field distribution at different wavelengths





www.nanophotonics.ch

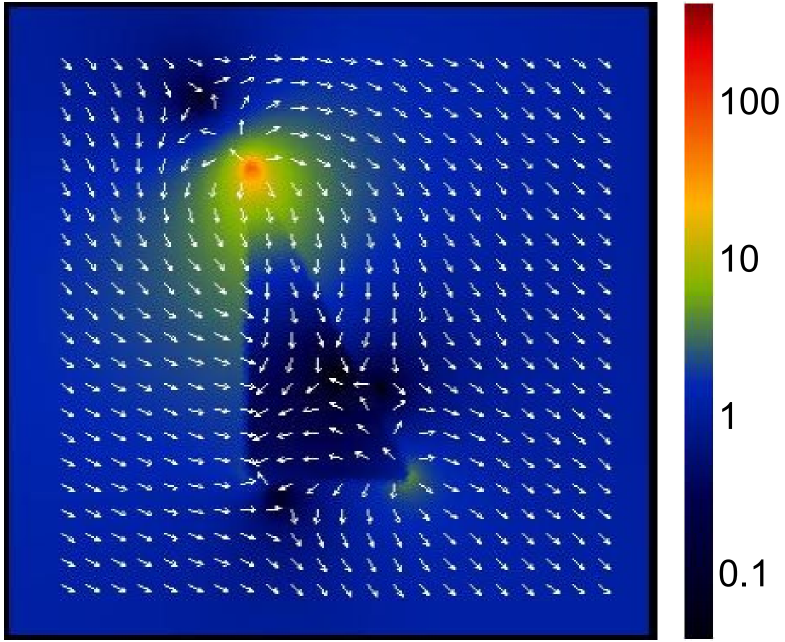
J. Kottmann, New Journal of Physics vol. 2, p. 27 (2000)

Field distribution at different wavelengths

$\lambda = 458$ [nm]

Ag, 10 x 20 [nm²]

Amplitude



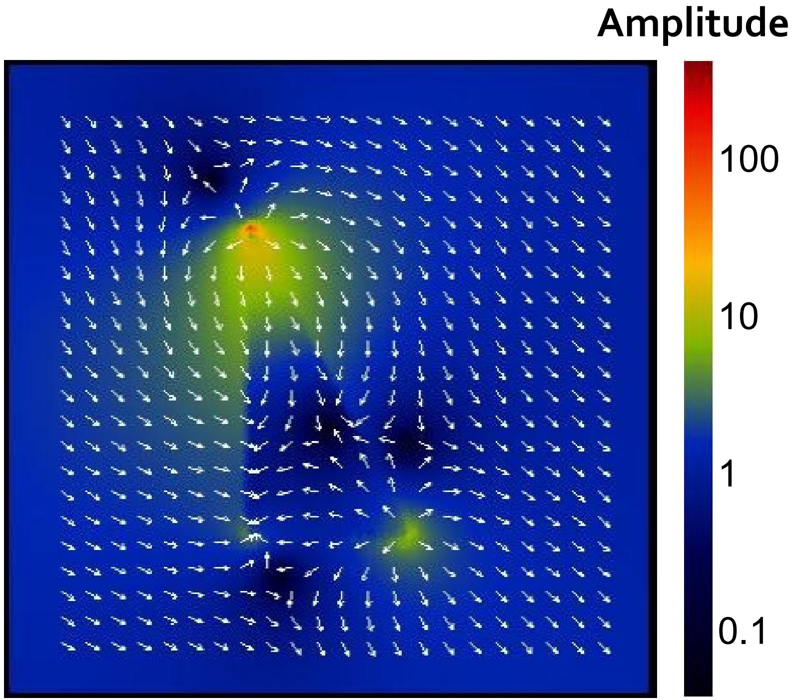
Polarization charge: $\nabla \cdot \mathbf{E}$

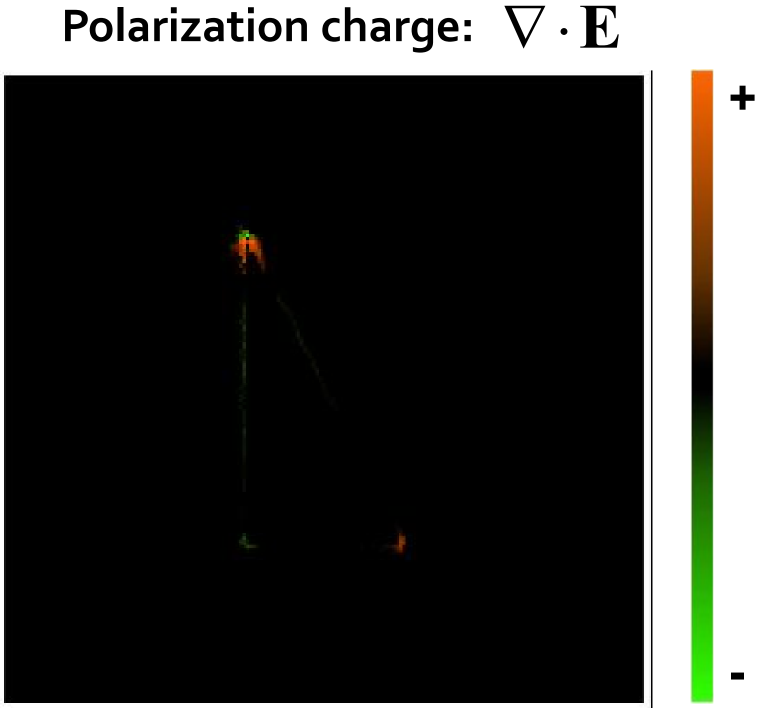
J. Kottmann, New Journal of Physics vol. 2, p. 27 (2000)

Field distribution at different wavelengths

$\lambda = 392$ [nm]

Ag, 10 x 20 [nm²]

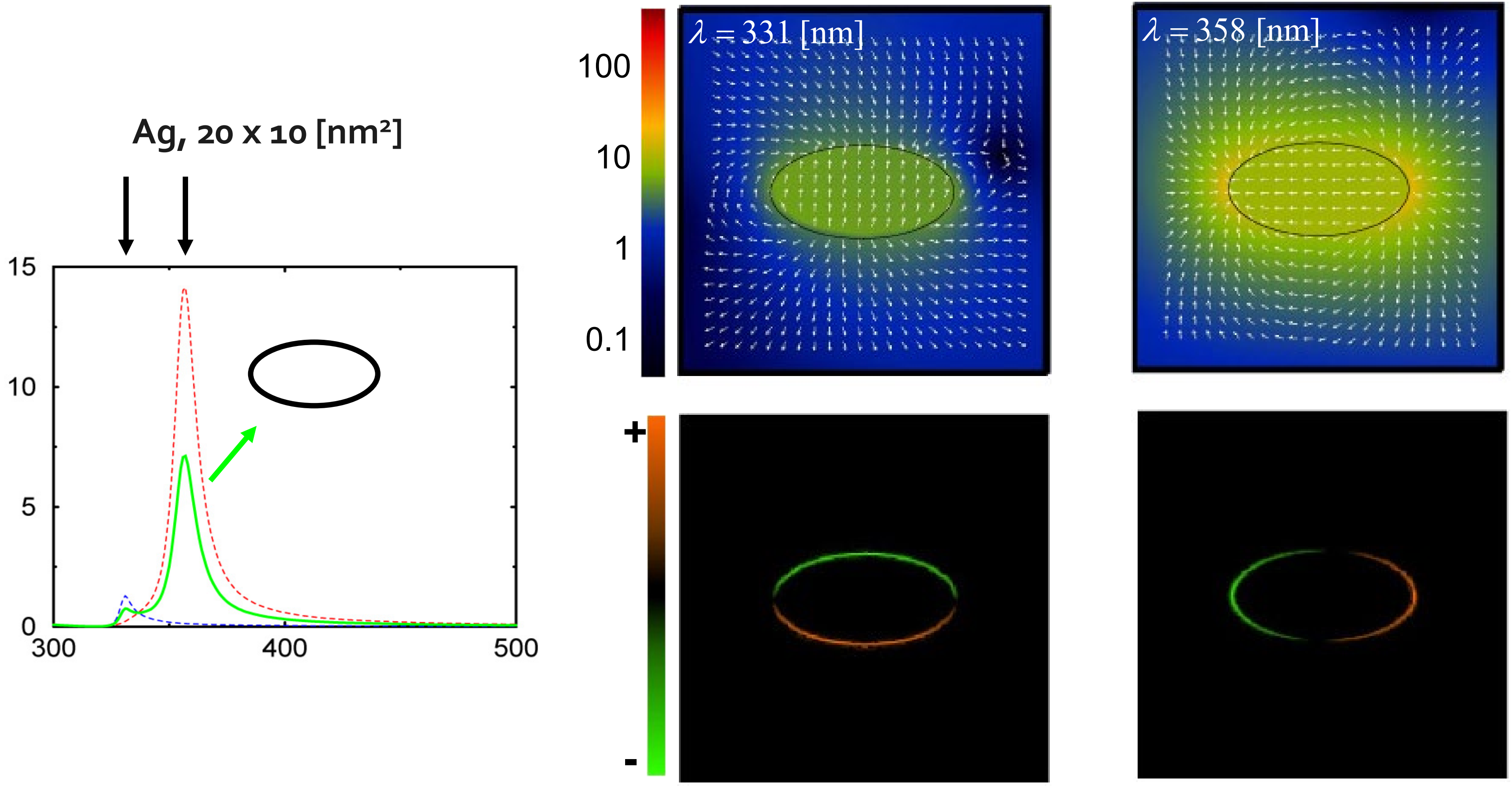




www.nanophotonics.ch

J. Kottmann, New Journal of Physics vol. 2, p. 27 (2000)

Elliptical particle

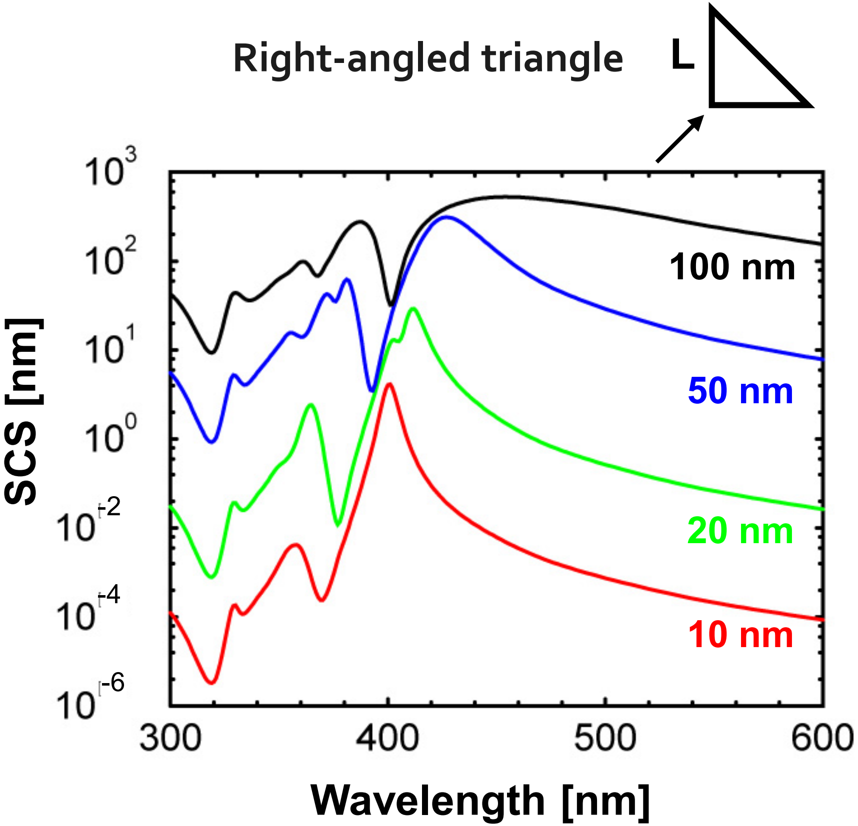


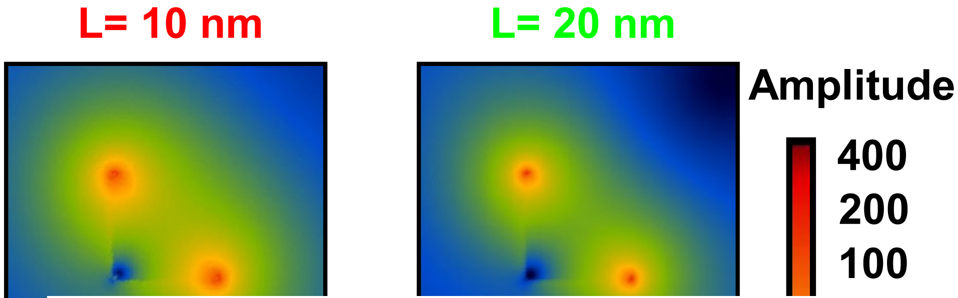
www.nanophotonics.ch

J. Kottmann, New Journal of Physics vol. 2, p. 27 (2000)

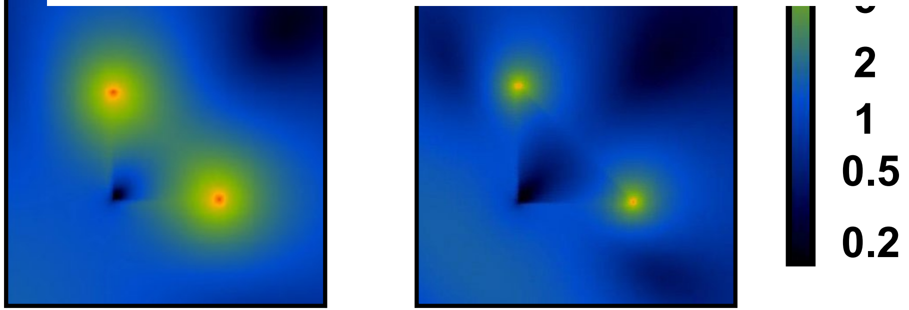
Size effects

- The maximum enhancement decreases for particles > 50 [nm]





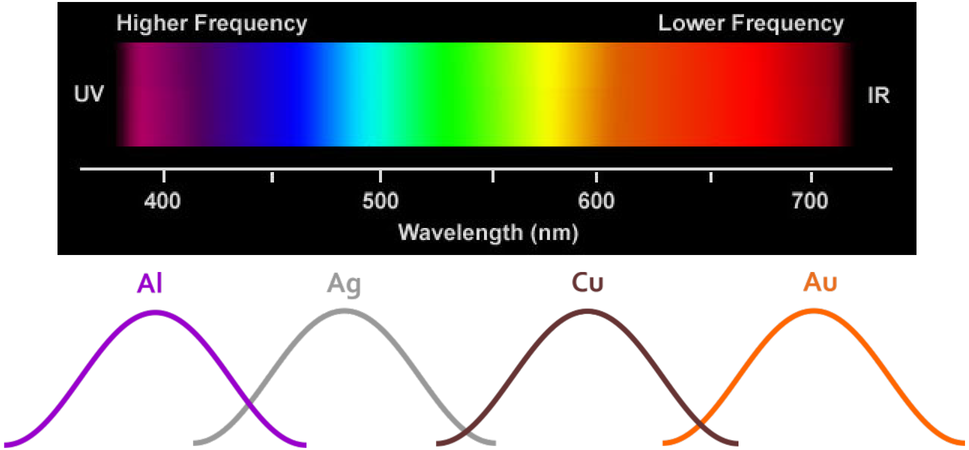
- Resonance broadening
- Red shift



J. Kottmann, New Journal of Physics vol. 2, p. 27 (2000)

Plasmonic metals

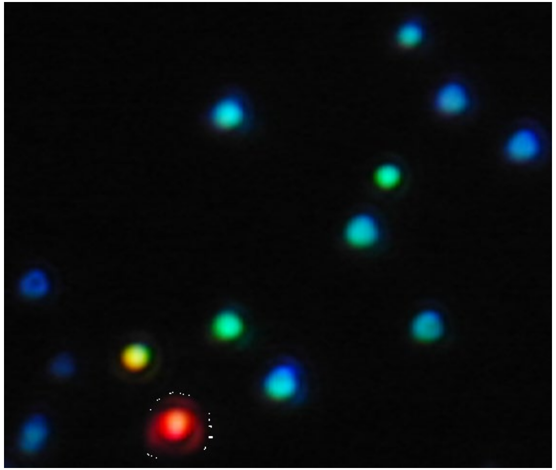
- Only a few plasmonic metals are available
- Coinage metals: Au, Ag, Al, Cu, W
- Very high electron density (> 10^{22} / cm^3)
- Each metal works in a specific wavelength range determined by the real part of its permittivity



Plasmon resonances

- **Nanostructures have a completely different optical response than bulk materials**

  - Silver bar:



What have we learned so far…

- Plasmon resonances depend on the material and shape of the particle
- Each plasmon resonance is associated with a specific polarization charges distribution
- The field enhancement can be extremely significant
- The lower the symmetry of a particle, the more plasmon resonances and the strongest field enhancement

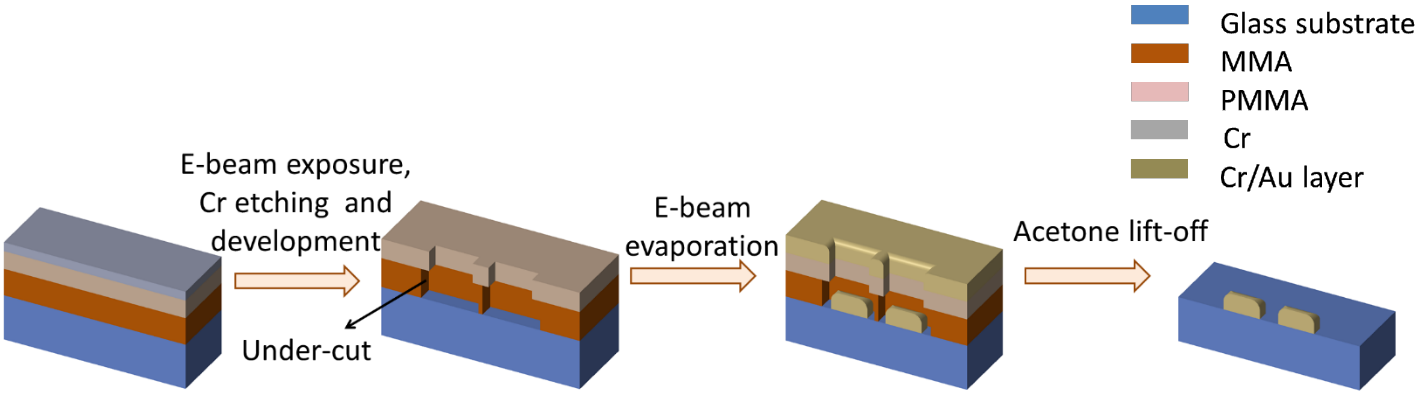
- Constrains for nanofabrication:
  – Sub-100 nm structures
  – Control dimensions down to 10 nm
  – Use appropriate materials

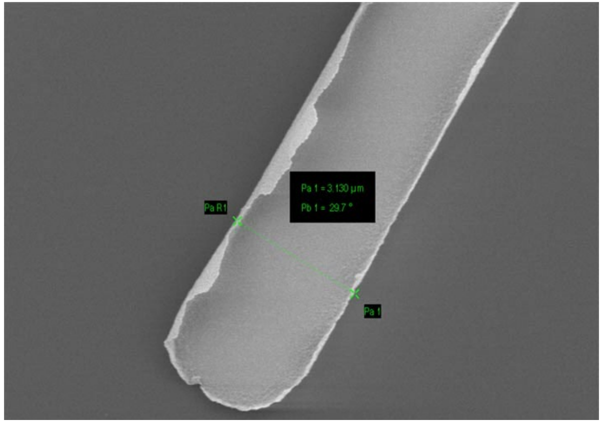
Outline

- Plasmonics
- Basic fabrication principles with electron-beam lithography
- Adhesion issues
- Other metals than Au
- Au-Ag alloys
- Hybrid nanostructures
- Chemical synthesis
- Medieval stained-glass windows

Nanofabrication of plasmonic structures

- **Lift-off (positive resist) vs. ion etching (negative resist)**

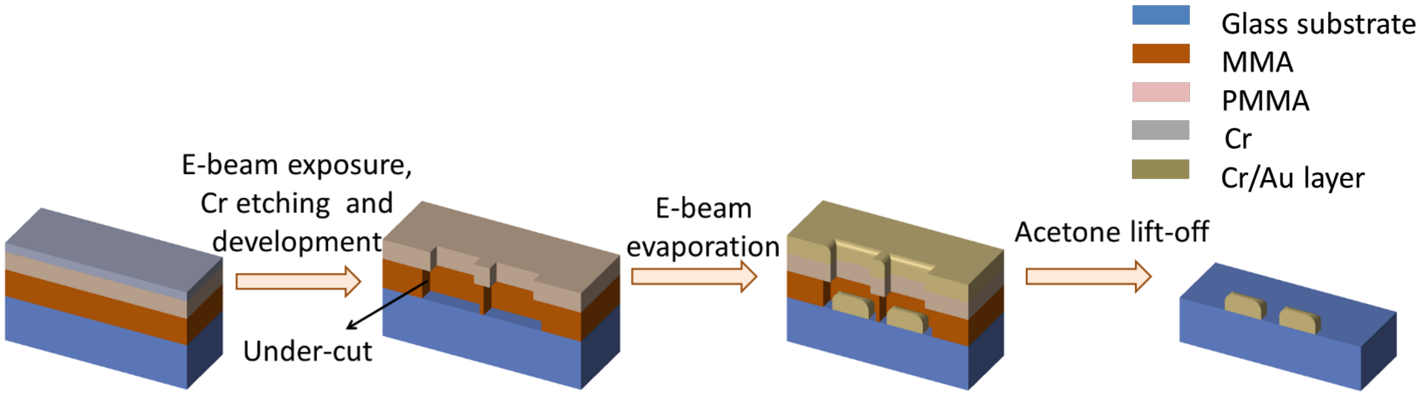


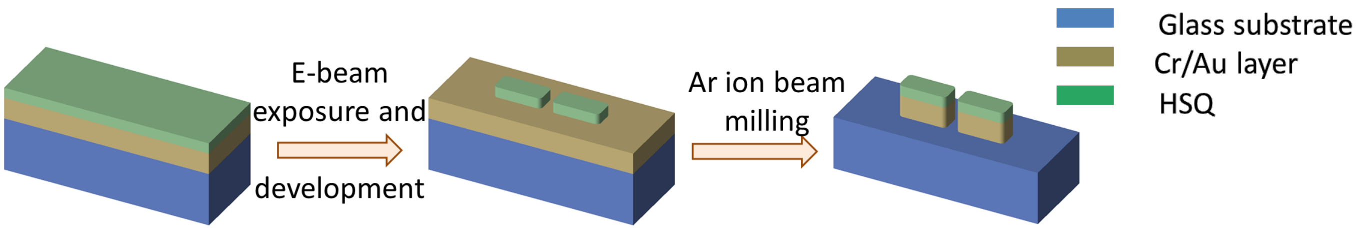


B. Abasahl, Nanotechnology vol. 32, p. 475202 (2021)

Nanofabrication of plasmonic structures

- **Lift-off (positive resist) vs. ion etching (negative resist)**

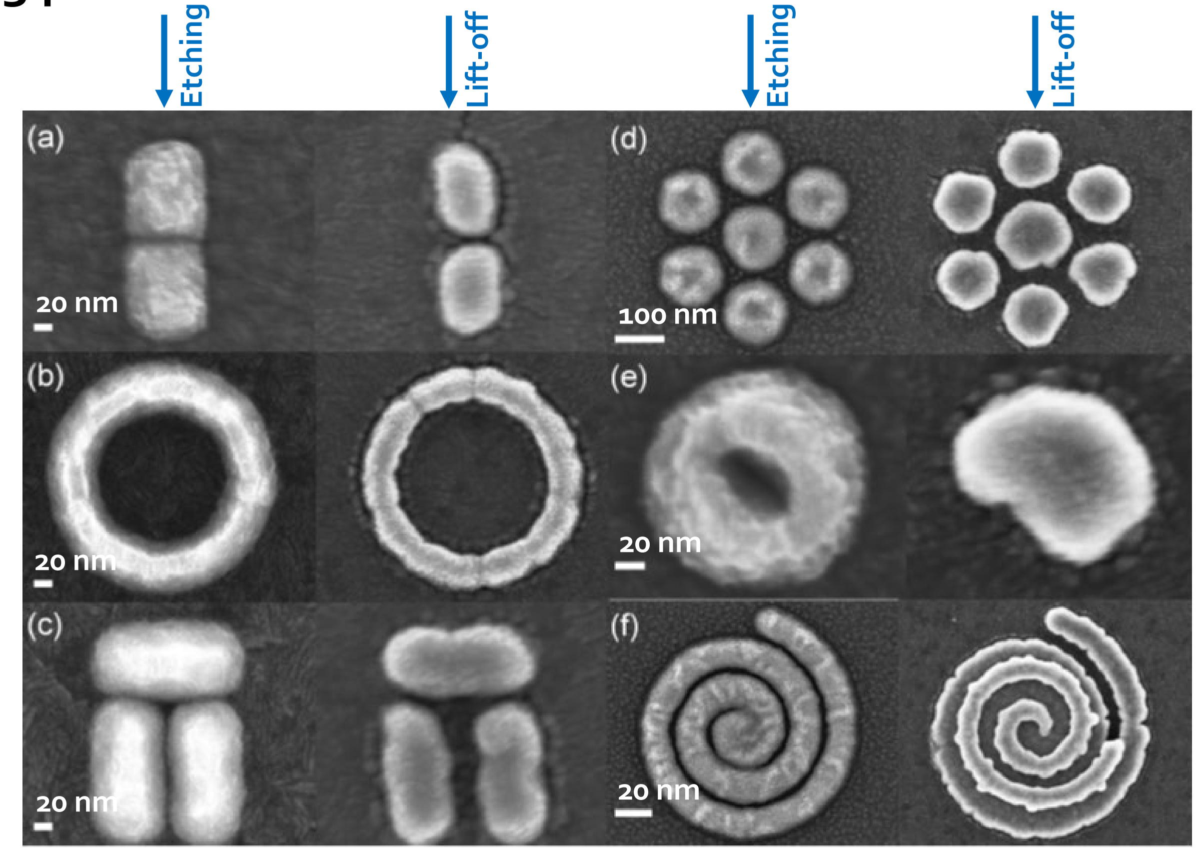




B. Abasahl, Nanotechnology vol. 32, p. 475202 (2021)

Lift-off vs. ion etching (gold nanostructures)

- Ion etching provides smaller features and better control

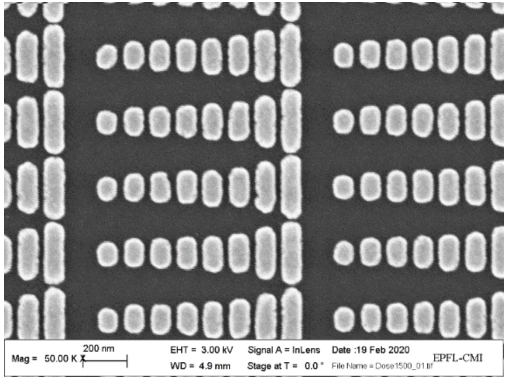


B. Abasahl, Nanotechnology vol. 32, p. 475202 (2021)

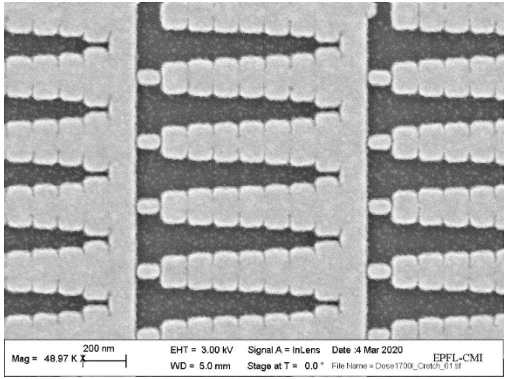
Dose test

- **Both positive and negative resists require to perform a series of tests with different doses (for each sample geometry)**

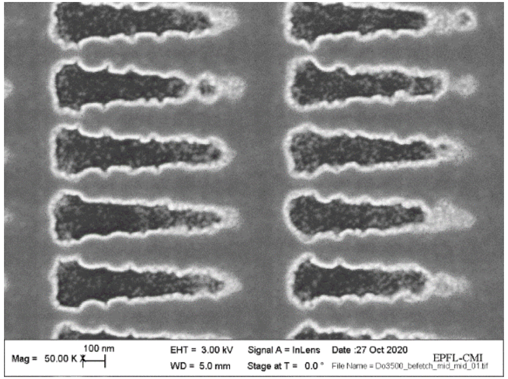
1'500 $\mu C/cm^2$



1'700 $\mu C/cm^2$



3'500 $\mu C/cm^2$



What have we learned so far…

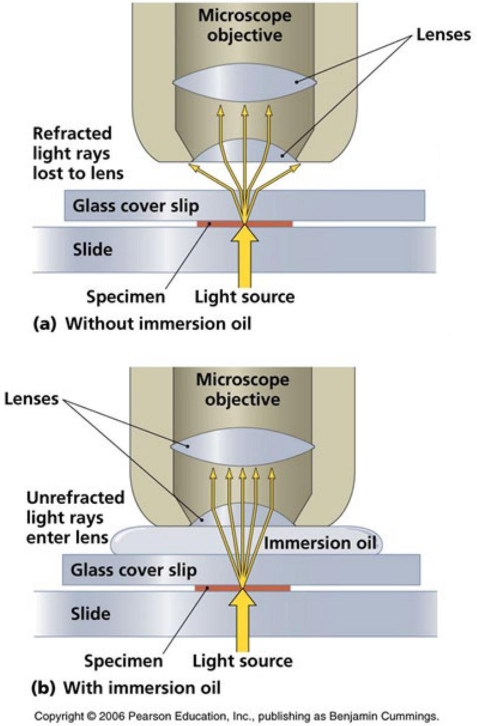
- Positive (lift-off) and negative (etching) electron beam resists
- Lift-off:
  - Double layer resist to facilitate lift-off
  - Metal diffusion within the mask creates "fuzzy" outlines
  - No residual resist (Oxygen plasma required, though)
- Etching:
  - Good outline definition
  - Very small features, including gaps
  - Residual resist on top of the structure (can be dealt with)
- Some tricky issues related to electron beam exposure (dose, proximity effects, stitching, fracturing,…)

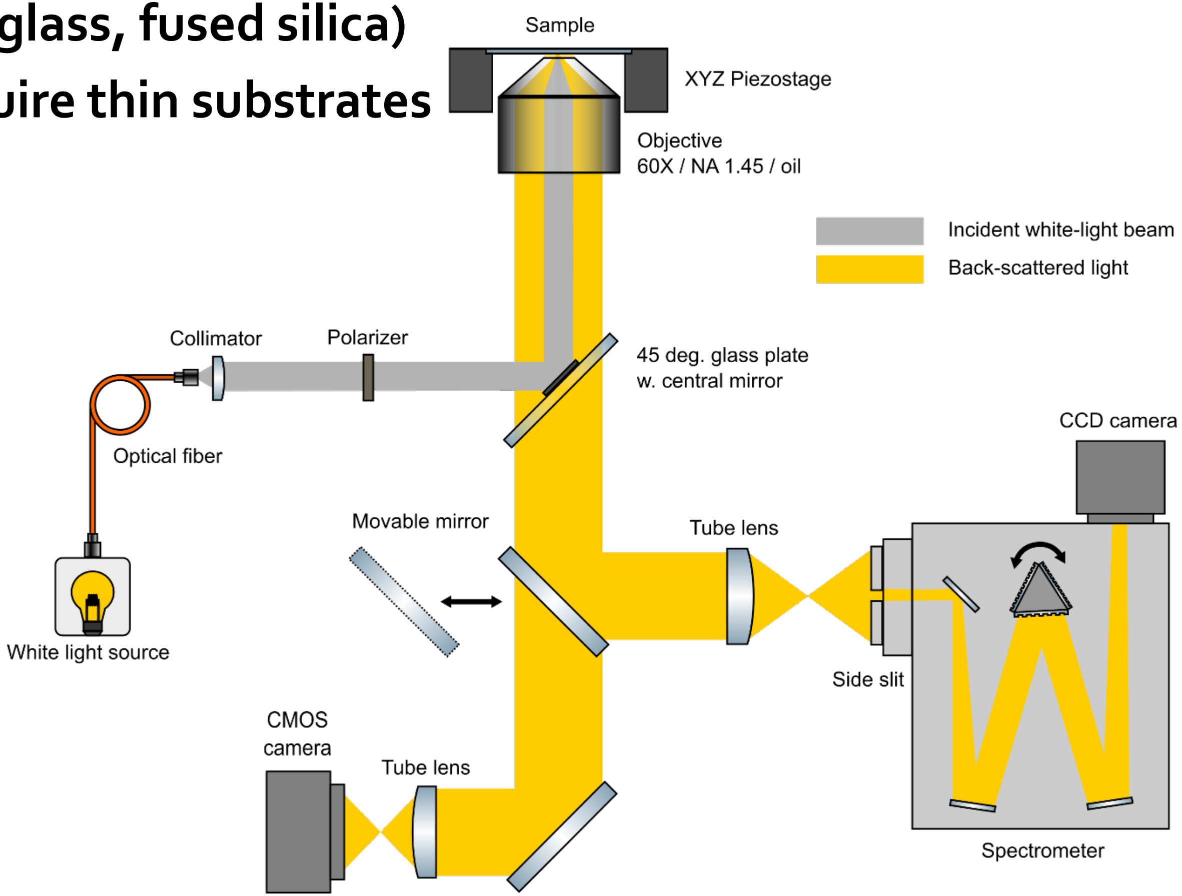
Outline

- Plasmonics
- Basic fabrication principles with electron-beam lithography
- **Adhesion issues**
- Other metals than Au
- Au-Ag alloys
- Hybrid nanostructures
- Chemical synthesis
- Medieval stained-glass windows

Optical measurements

- **Transparent substrate (glass, fused silica)**
- **High NA objectives require thin substrates**

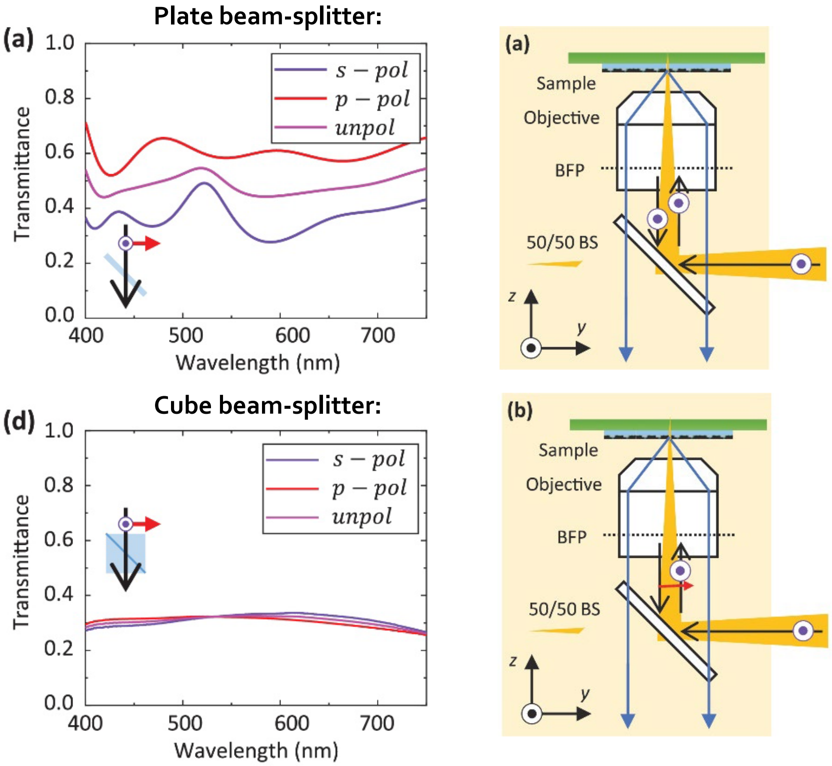


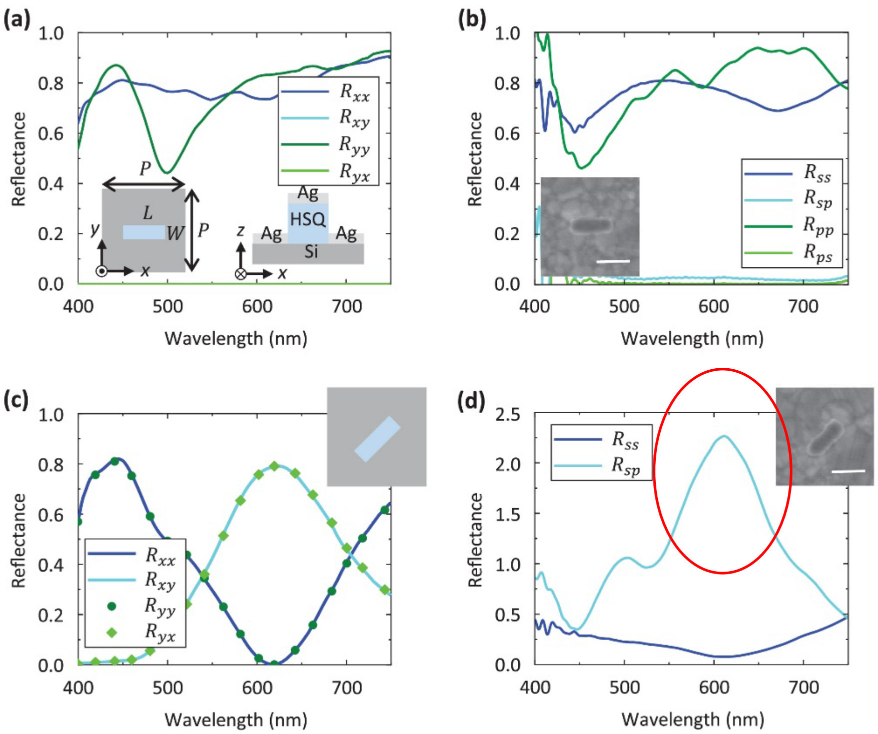


www.nanophotonics.ch

Careful when measuring samples that alter the polarization

- **Some components (e.g. beam-splitters) in a microscope do not transmit/reflect both polarizations in a similar way**

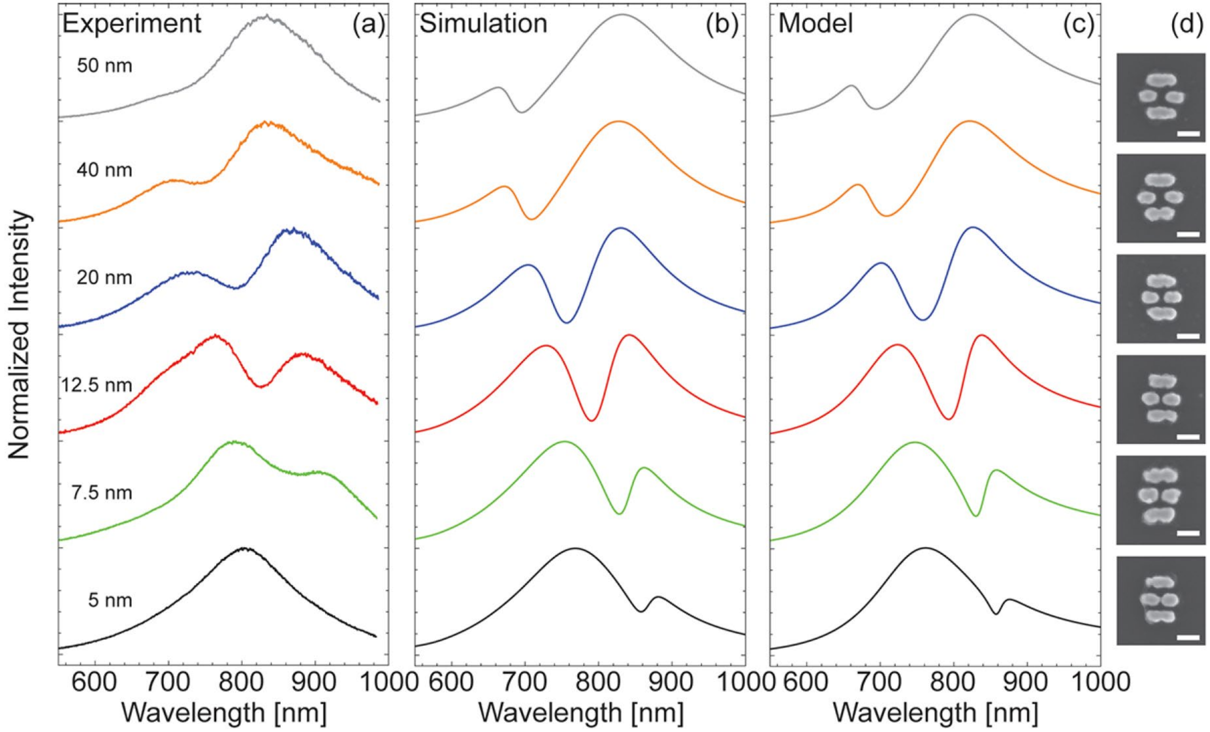




H.-S. Wang, Applied Optics vol. 61, p. 8100 (2022)

Optical measurements

- **Spectroscopy of individual nanostructures**



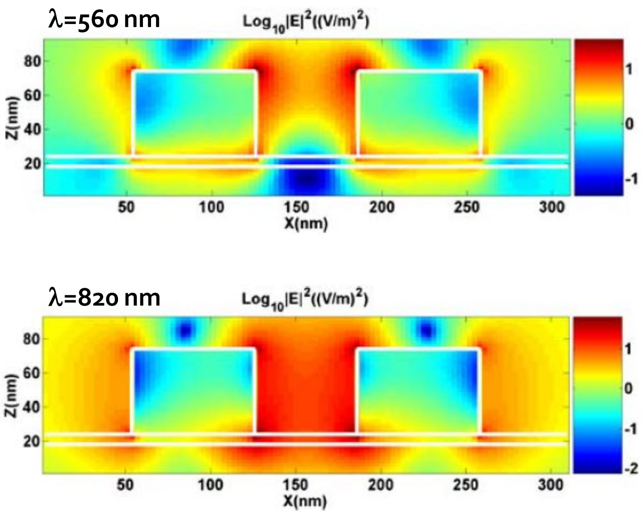
- **Gold nanostructures**
- **Central gap 5…50 nm**
- **Scalebar 100 nm**

A. Lovera, ACS Nano vol. 7, p. 4527 (2013)

Metal adhesion on SiO_2 is poor

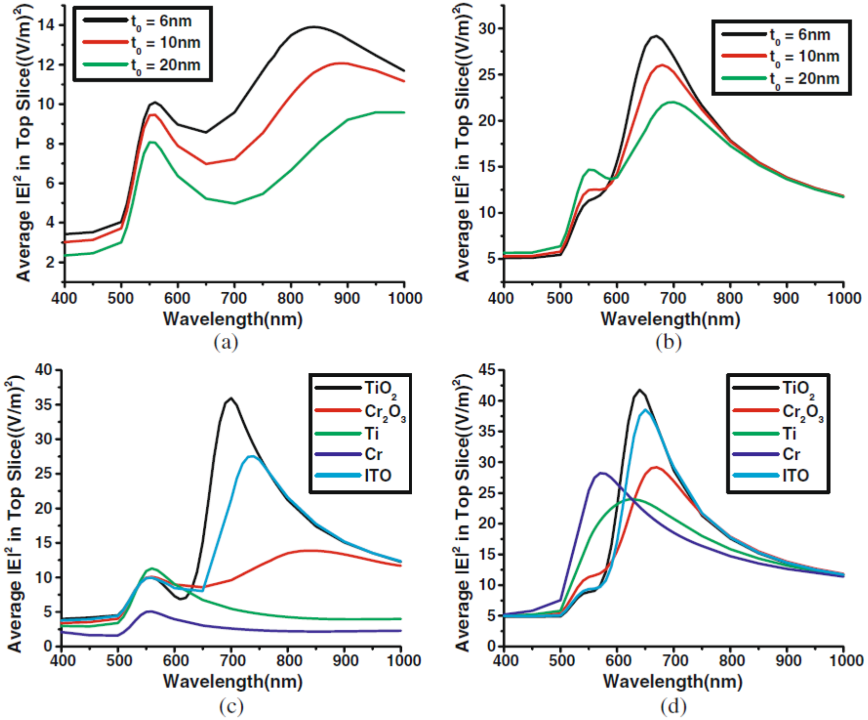
- Usually, one resorts to an extremely thin inorganic adhesion layer: Cr, Ti
- Unfortunately, these layers can disturb the plasmon resonances

Au bowtie antenna with 6 nm Cr_2O_3



Continuous adhesion film:

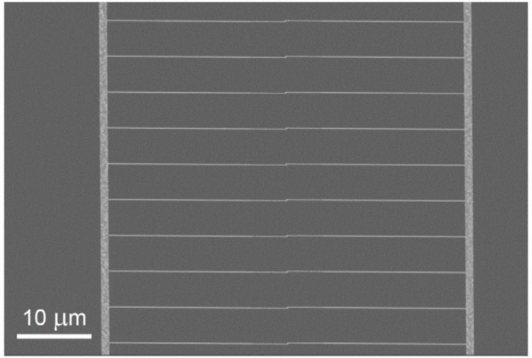
Etched adhesion film:

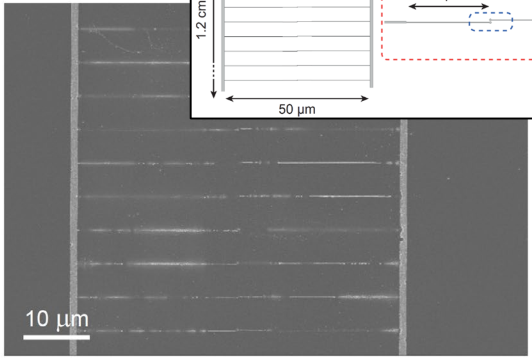


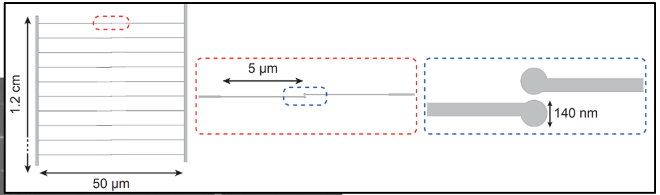
X. Jiao, Plasmonics vol. 4. p. 37 (2009)

Metal adhesion on SiO_2 is poor

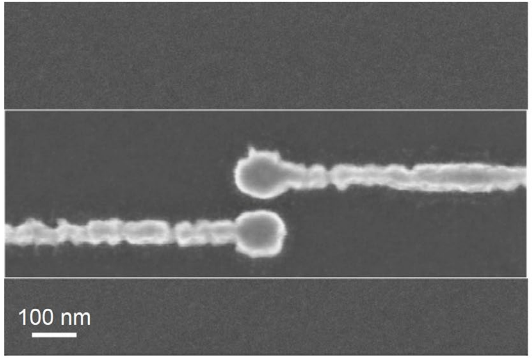
- **Fabrication with Cr adhesion of very high aspect ratio Au electrodes to combine dielectrophoresis with optical forces**

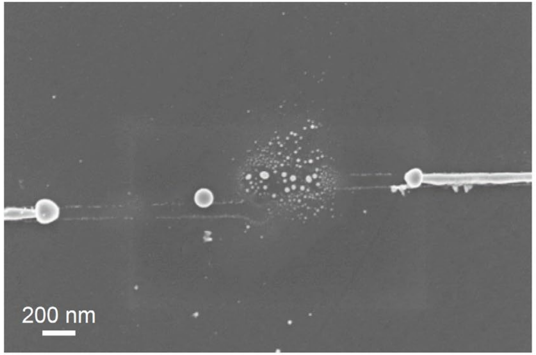






Immediately after deposition





After a few hours

M. Riccardi, Microelectronic Engineering, vol. 263, p. 111856 (2022)

At the nanoscale, materials behave very differently

- **When a gold particle shrinks, it becomes liquid!**

Size effect on the melting temperature of gold particles*

Ph. Buffat and J-P. Borel
Laboratoire de Physique Experimentale, Ecole Polytechnique Fédérale-Lausanne, Lausanne, Switzerland
(Received 2 December 1975)

Recently, small particles have been shown to exhibit a melting temperature which depends on the particle size. The various possible experimental methods have been compared and measurements of the melting points of small gold particles have been made using a scanning electron-diffraction technique. This method was applied to particles having diameters down to 20 Å. Consideration of the size distribution over an entire sample makes it necessary to carry out a careful analysis of the experimental results in order to deduce the melting temperature of particles having a well-defined diameter. The experimental results are quantitatively in good agreement with two phenomenological models. The first model describes the equilibrium condition for a system formed by a solid particle, a liquid particle having the same mass, and their saturating vapor phase. The second model assumes the preexistence of a liquid layer surrounding the solid particle and describes the equilibrium of such a system in the presence of the vapor phase. In order to permit a better comparison between both models, a new expression for the thermodynamic equilibrium condition has been derived in the present work. In the case of the first model, the agreement was obtained using only the physical constants of massive gold. In applying the second model, however, one is compelled to assume the existence of a liquid layer having a thickness of about 6 Å.

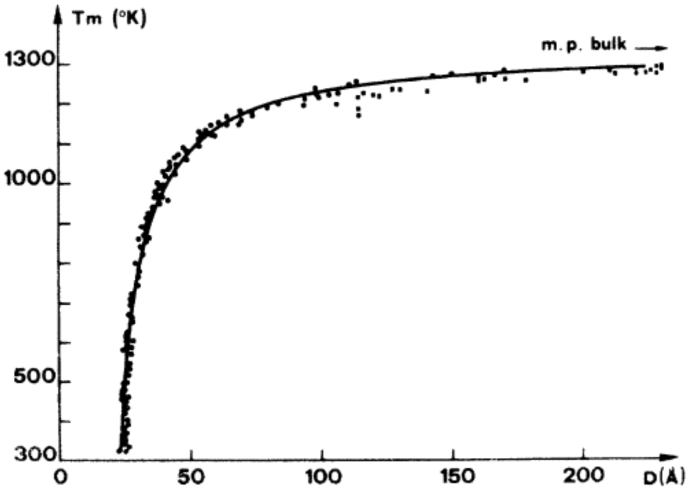
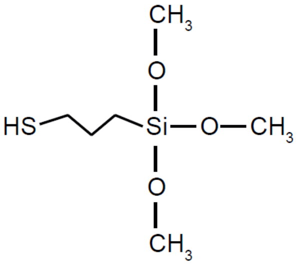


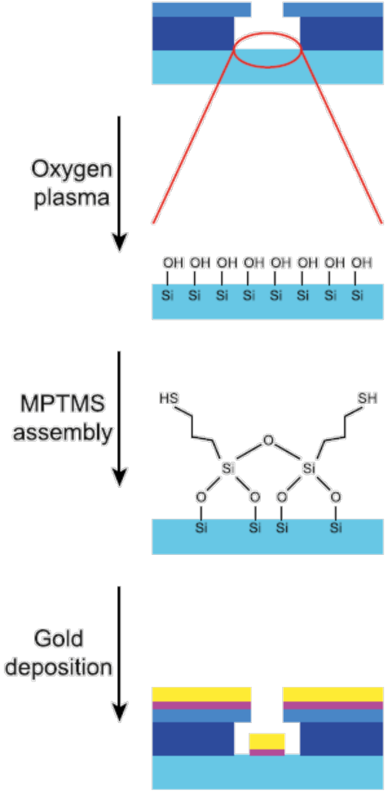
FIG. 6. Experimental and theoretical values of the melting-point temperature of gold particles, assuming validity of the first model in order to calculate the diffracted intensities and obtain the Debye-Waller factors: circles, present work; squares, Sambles (Ref. 28); the solid line results from a least-squares fit to Eq. (13) using all of the experimental points.

Ph. Buffat, Physical Review A vol. 13, p. 2287 (1976)

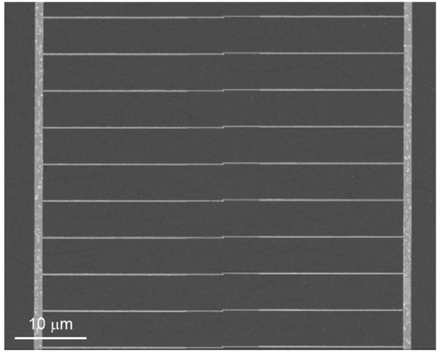
Metal adhesion on SiO_2 is poor

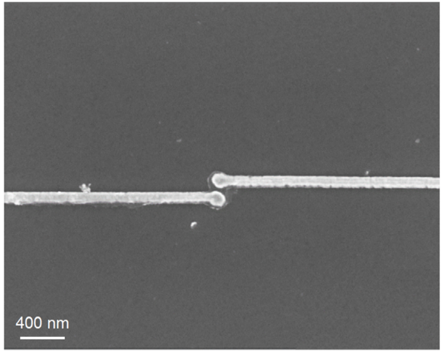
- **An organic adhesion layer can work better, without disturbing the optical resonances**

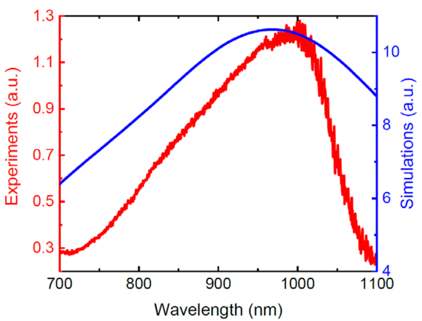


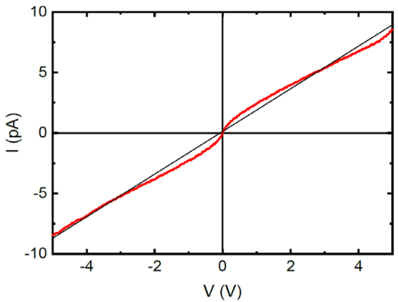


Robust structures even after several weeks







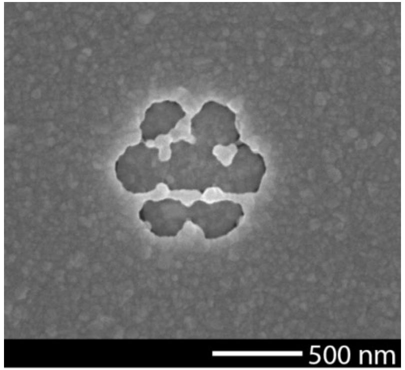


M. Riccardi, Microelectronic Engineering, vol. 263, p. 111856 (2022)

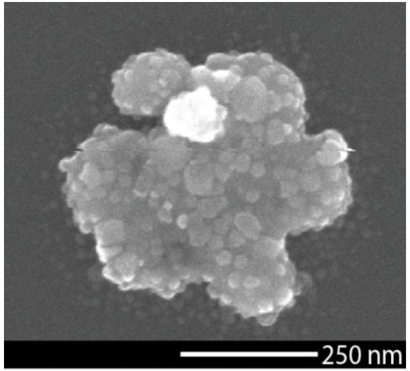
Cooking… disasters

Cooking… disasters with silver

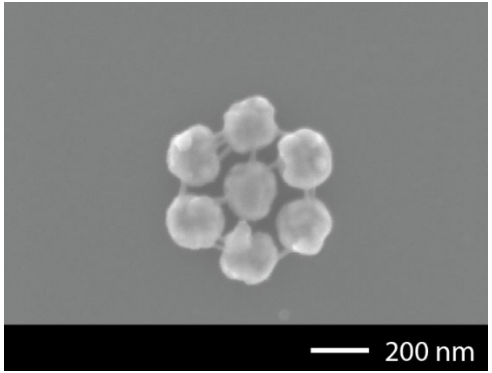
Poor lift-off



Large grains



Bridges between neighboring elements



K. Thyagarajan, Advanced Optical Materials vol. 4, p. 871 (2016)

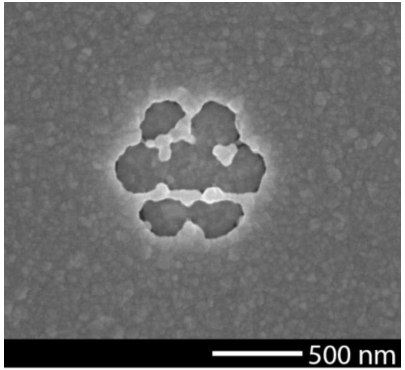
Fabrication difficulties associated with silver

- Poor surface wetting of silver, leading to early nucleation and large grains
- Formation of silver oxyde (reversible process at low O_2 pressure)
- Dissociation of Ag_2O takes place to establish equilibrium
- Activated layer energetically favourable for incoming Ag atoms to produce metallic Ag
- A very thin Ag_2O layer provides such an activated substrate

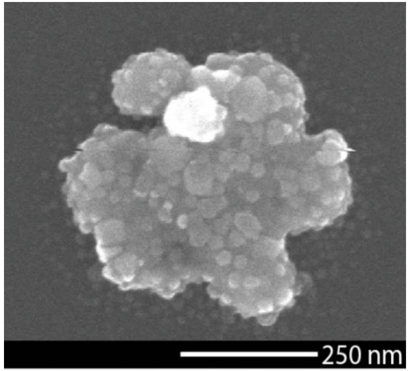
K. Thyagarajan, Advanced Optical Materials vol. 4, p. 871 (2016)

Our first attempts at Ag nanostructures…

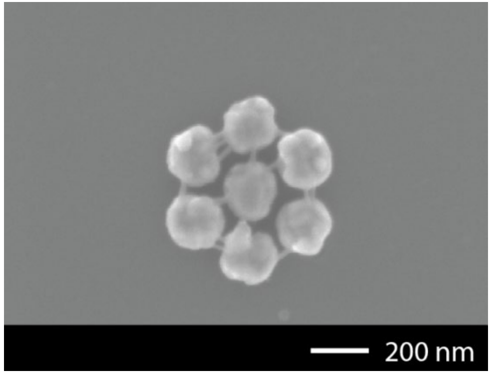
Poor lift-off



Large grains



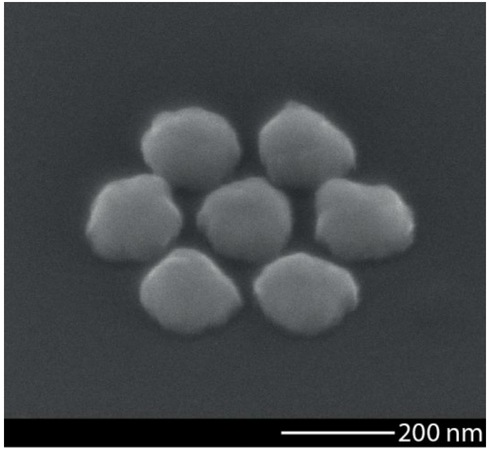
Bridges between neighboring elements

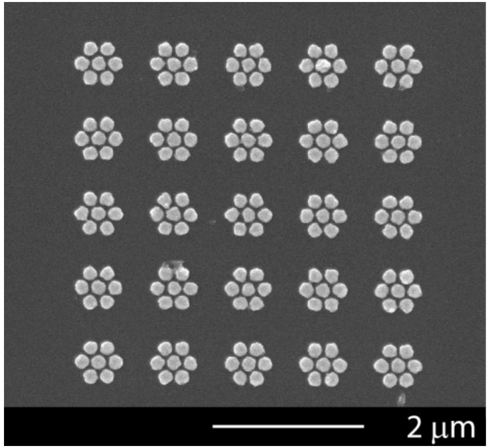


K. Thyagarajan, Advanced Optical Materials vol. 4, p. 871 (2016)

… and then we got better at it !

- **Deposition of a very thin Ag_2O layer on the substrate enables the fabrication of Ag nanostructures with well-controlled dimensions, including for the gaps down to 10 nm**

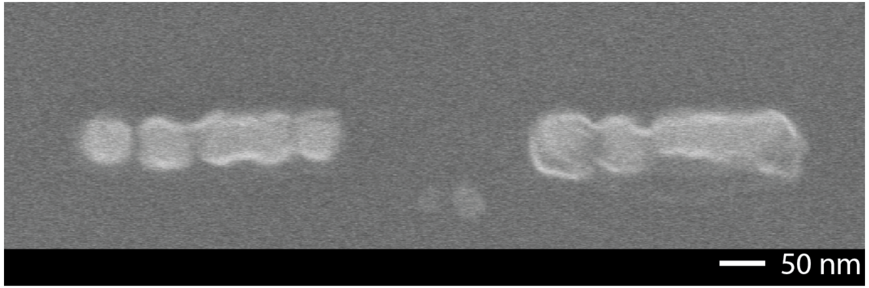




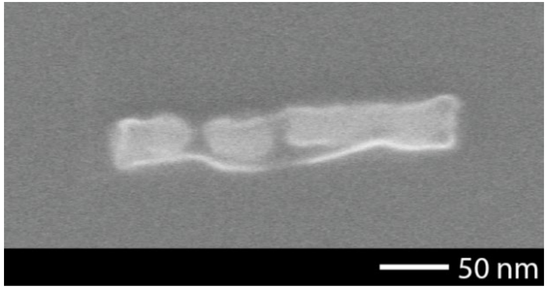
K. Thyagarajan, Advanced Optical Materials vol. 4, p. 871 (2016)

Aluminum is not easy either…

Poor lift-off



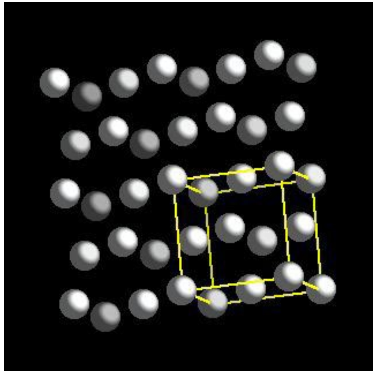
Large grains, bridges between neighboring elements



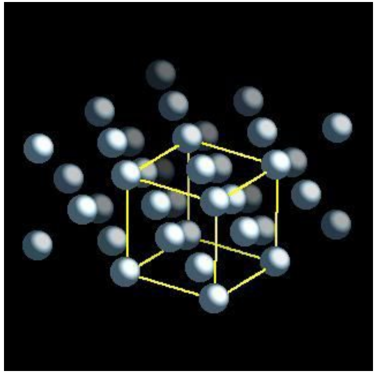
K. Thyagarajan, Advanced Optical Materials vol. 4, p. 871 (2016)

Aluminum is not easy either…

- Poor surface wetting of alumminum → early nucleation and large grains
- Formation of aluminum oxide (non-reversible process)
- The same trick cannot be used with a thin Al_2O_3 layer…
- However, Al and Ag have a very similar crystalline structure (cubic close-packed)
- We can use again silver oxide as activation layer



Silver 4.08 Å

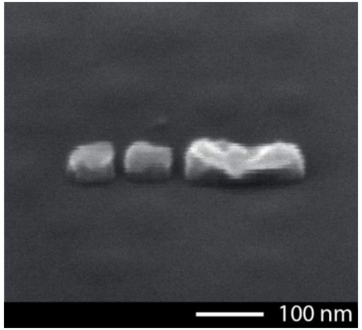


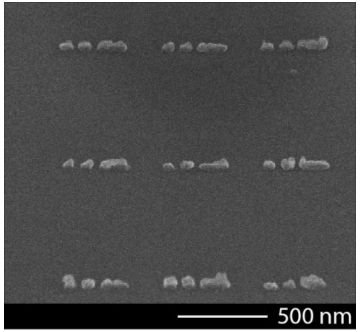
Aluminum 4.04 Å

K. Thyagarajan, Advanced Optical Materials vol. 4, p. 871 (2016)

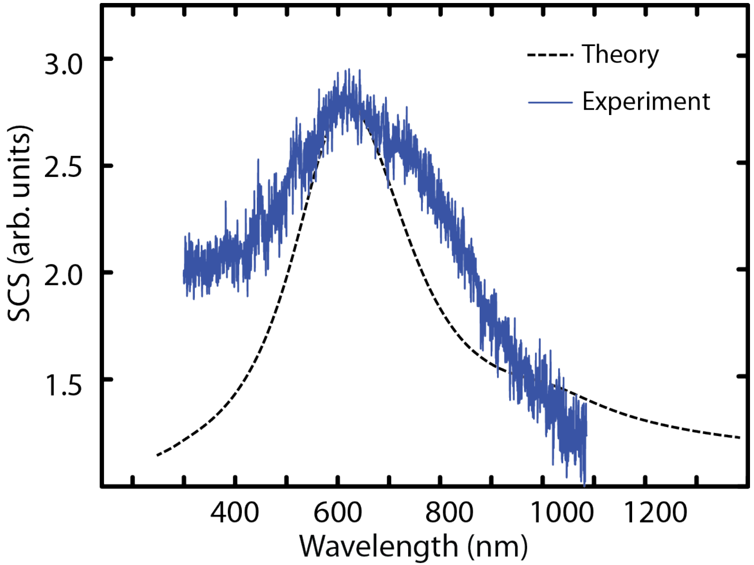
Improved recipe for aluminum

- **Fabrication of double resonant Al antennas, including small gaps and vertical sidewalls**





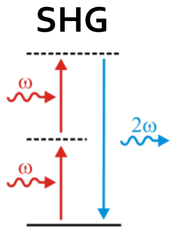
Optical measurements

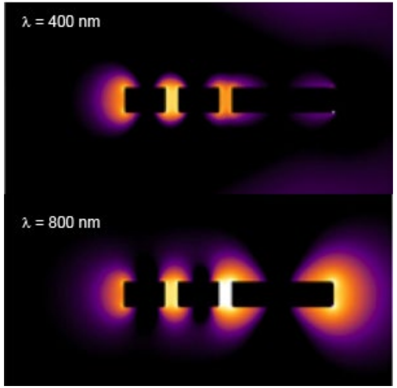


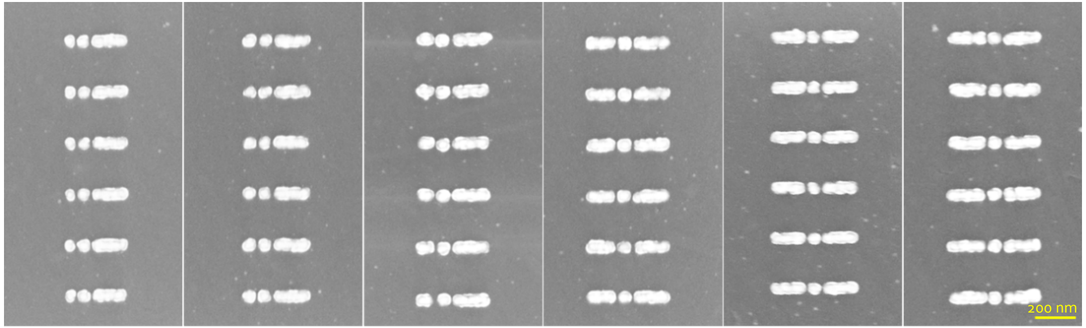
K. Thyagarajan, Advanced Optical Materials vol. 4, p. 871 (2016)

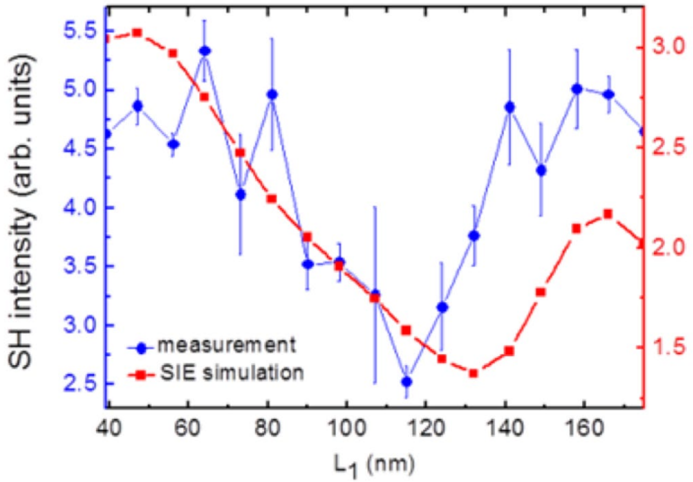
Double-resonant optical antenna in Al for SHG

- The second harmonic generation (SHG) strongly depends on the material and on the geometry









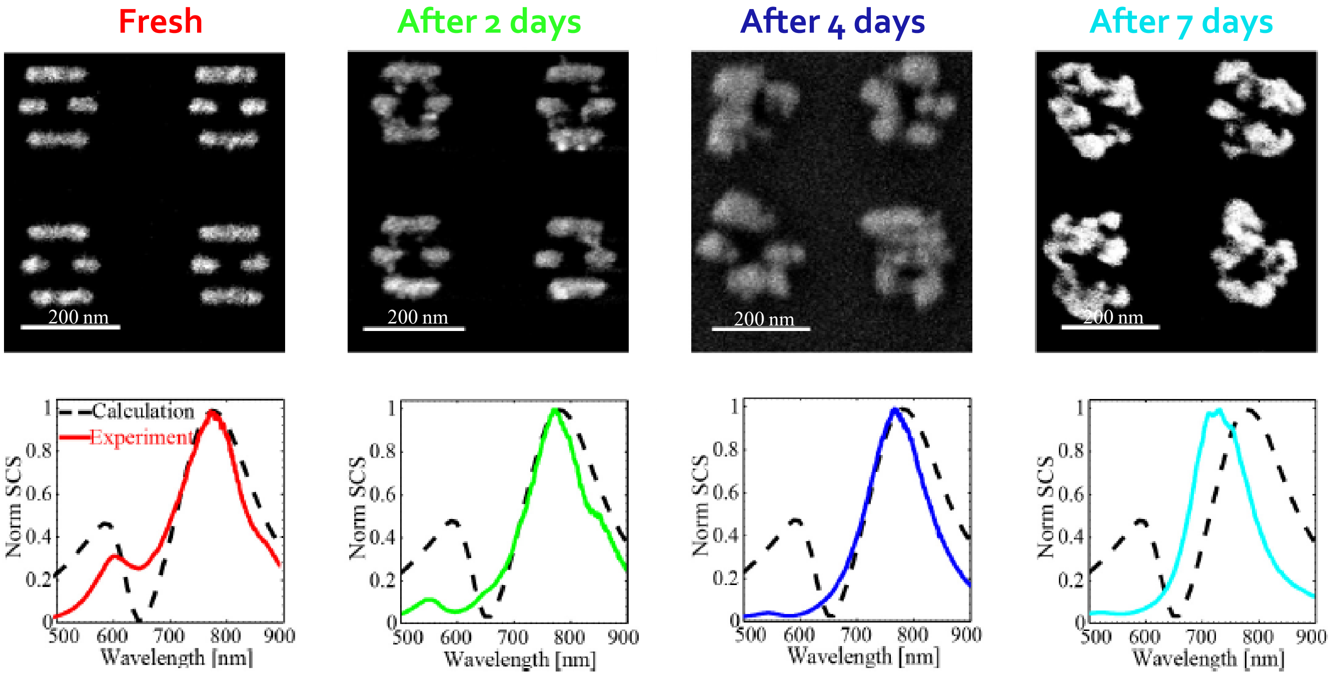
www.nanophotonics.ch

K.Y. Yang, ACS Photonics vol. 4, p. 1522 (2017)

Keeping your silver shiny!

Rapid deterioration of Ag nanostructures

- After just a few days in ambient conditions, silver nanostructures are deteriorated with irreversible changes in their morphology and optical response

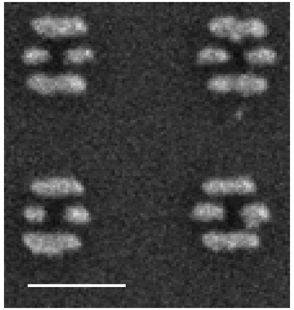


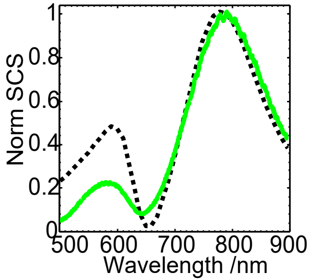
X. Wang, Small vol. 13, p. 1700044 (2017)

Myth #1: Oxygen is responsible for the deterioration of Ag

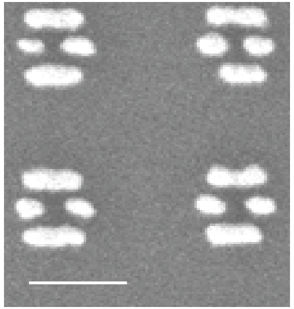
…well, after two weeks exposure to <u>dry</u> oxygen, silver nanostructures do not exhibit any damage (similar to exposure to dry argon):

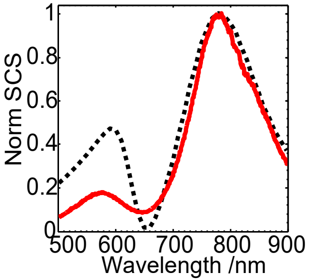
After two weeks in dry O2





After two weeks in dry Ar

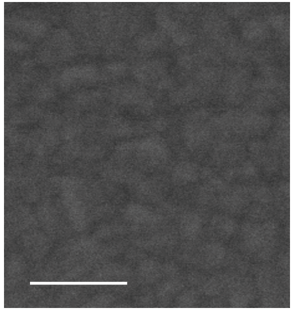


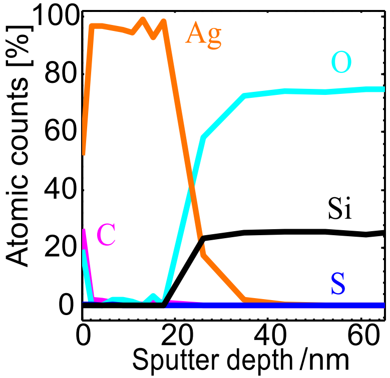


X. Wang, Small vol. 13, p. 1700044 (2017)

Myth #2: Sulfidation is playing a key role for deterioration

…well, XPS analysis of a 40 nm thick silver film stored in ambient conditions does not reveal significant sulfur:





- **Even in rural areas, the total concentration of atmospheric sulfur compounds is as low as a few ppb**

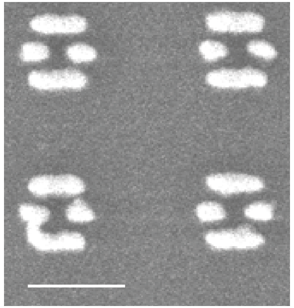
  J.H. Seinfeld and S.N. Pandis, Atmospheric Chemistry and Physics from Air Pollution to Climate Change: Problem Solution Manual (Wiley, New York, 1989)

X. Wang, Small vol. 13, p. 1700044 (2017)

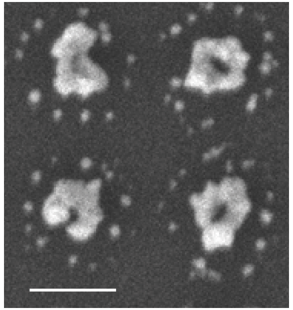
… so, what is responsible for Ag deterioration?

- Water !
- Silver nanostructures kept two weeks in 0 % relative humidity do not deteriorate, while those kept in 100 % relative humidity are destroyed:

0 % Rel. humidity



100 % Rel. humidity



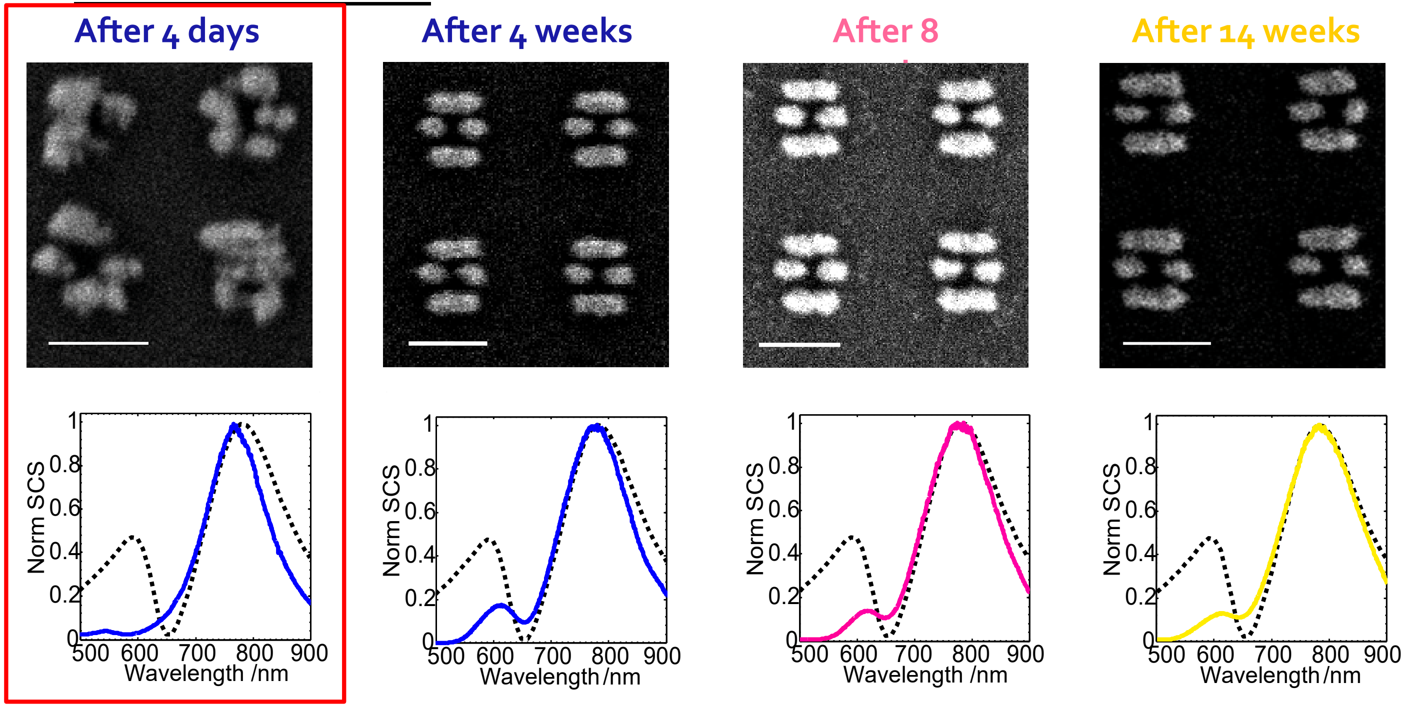
- Oxidation of silver by O_2 dissolved in water enables the migration of silver:

$$2Ag^0 + \frac{1}{2}O_{2(aq)} + 2H^+_{(aq)} \rightarrow 2Ag^+_{(aq)} + H_2O$$

X. Wang, Small vol. 13, p. 1700044 (2017)

Ag nanostructures can be stabilized with a dehydration process

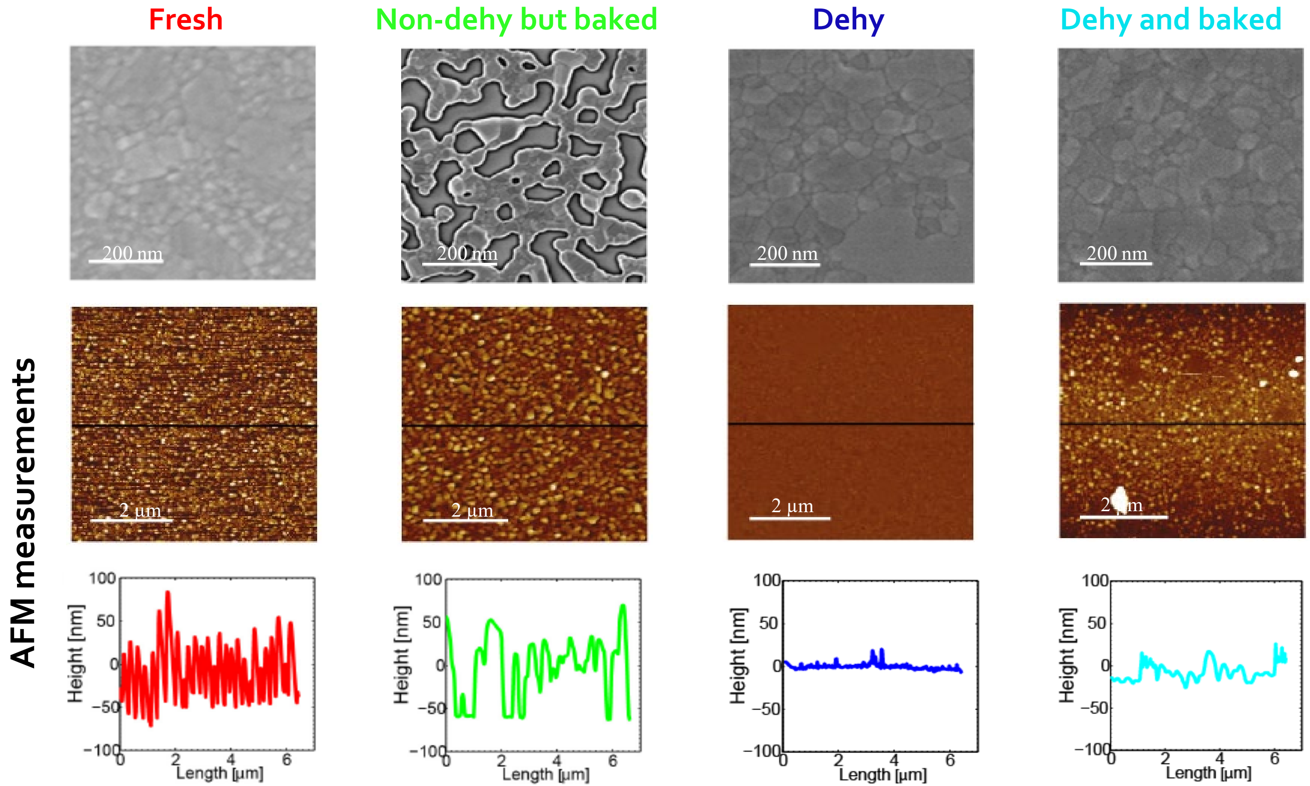
- Fabricated nanostructures are transferred to a desiccator cabinet at 20 °C and purged continuously with a 5 nl/min Ar gas flow under a 1.013 Pa pressure for three weeks



X. Wang, Small vol. 13, p. 1700044 (2017)

The dehydration process modifies the Ag surface

- **Dramatic reduction of the surface roughness and thermally stable:**



Baked 5 min @ 180° C

X. Wang, Small vol. 13, p. 1700044 (2017)

What have we learned so far…

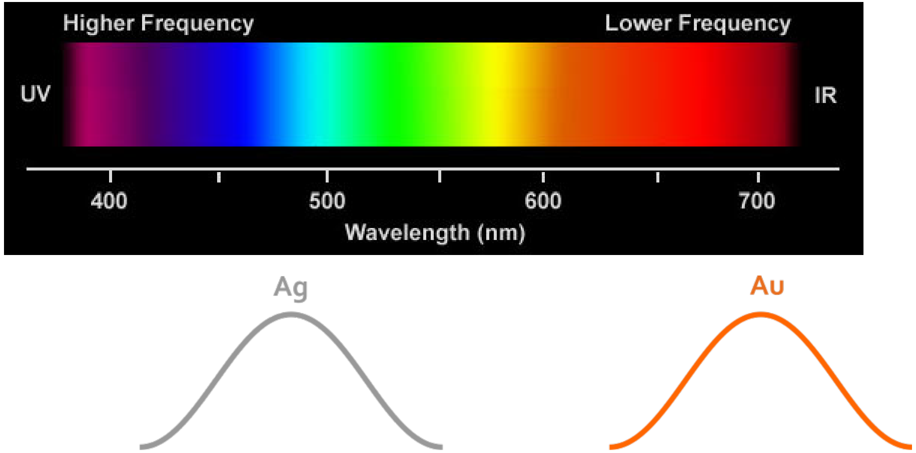
- The characterization techniques put constraints on the nanotechnology
- Metal adhesion on glass is an issue
- Look sideways: other fields can bring original solutions
- At the nanoscale, solids can behave very differently from what we are used to at our macroscopic scale
- Don't be discouraged by disasters
- Always question well-established Myths!
- It is possible to fabricate nice and robust nanostructures in Ag and Al
- Read the "ancient" scientific literature

Outline

- Plasmonics
- Basic fabrication principles with electron-beam lithography
- Adhesion issues
- Other metals than Au
- **Au-Ag alloys**
- Hybrid nanostructures
- Chemical synthesis
- Medieval stained-glass windows

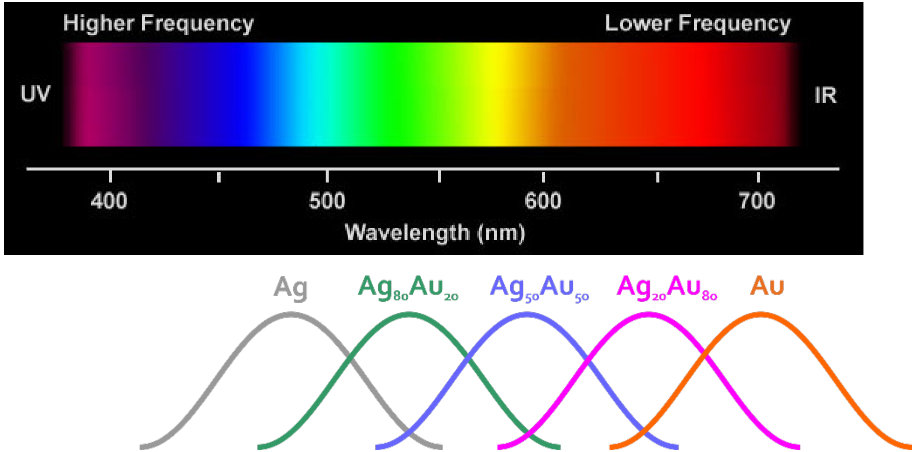
Plasmonic metals

- Only a few plasmonic metals are available
- Coinage metals: Au, Ag, Al, Cu, W
- Very high electron density (> 10^{22} / cm^3)
- Each metal works in a specific wavelength range determined by the real part of its permittivity



Plasmonic alloys

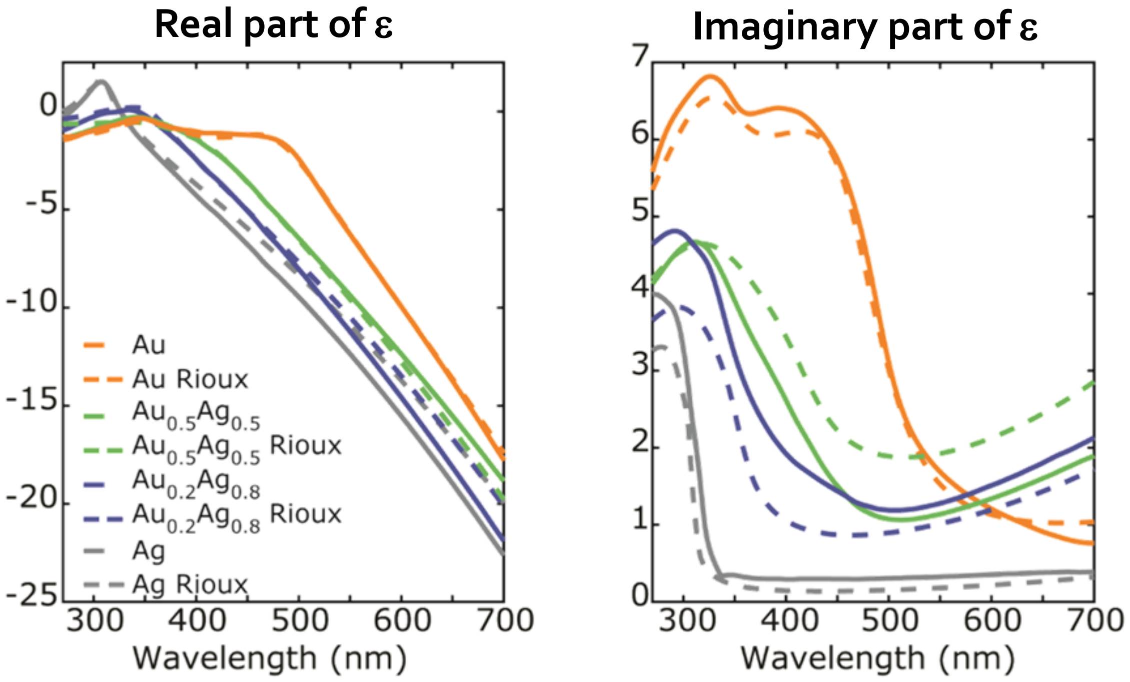
- **Can we extend the range of available plasmonic metals?**



D. Ray, Advanced Materials vol. 2022, p. 2108225 (2022)

Plasmonic alloys

- **Can we extend the range of available plasmonic metals?**
- **Alloys are certainly an interesting approach to engineer the dielectric function:**

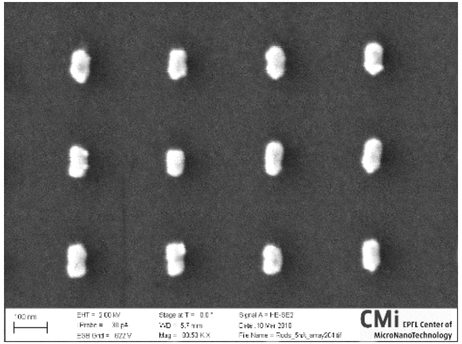


D. Ray, Advanced Materials vol. 2022, p. 2108225 (2022)

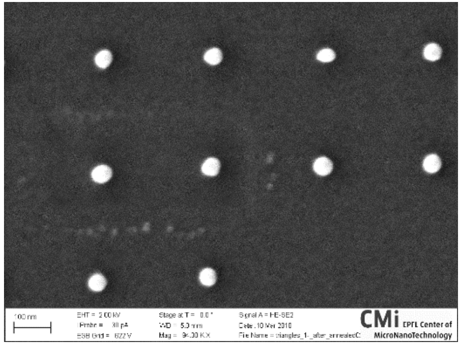
Alloyed plasmonic nanostructures

- Normally, Au_xAg_{1-x} alloying is performed at high temperature
- Can we maintain the shape of nanostructures during the alloying process…?

Before annealing



After annealing



- … no! the shape is lost during the high temperature annealing

D. Ray, Advanced Materials vol. 2022, p. 2108225 (2022)

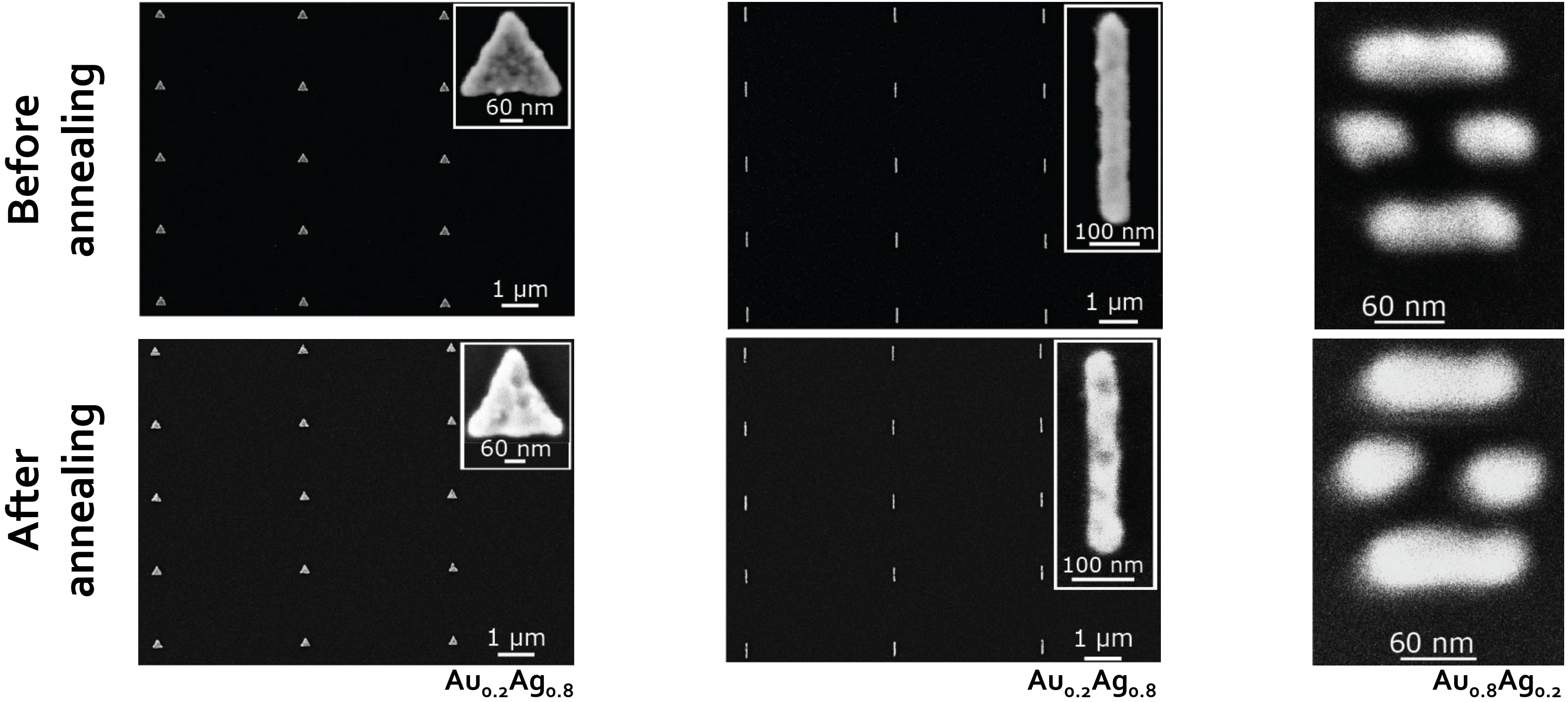
Alloyed plasmonic nanostructures

- Challenge:
  - Find a low temperature alloying procedure…
  - … that enables any alloy composition
- Solution:
  - Define the composition by the Au and Ag thicknesses
  - Alloy at 300°C for 8 hours and 450°C for 30 mins

D. Ray, Advanced Materials vol. 2022, p. 2108225 (2022)

Alloyed plasmonic nanostructures

- **A low temperature annealing process can maintain the particle shape, whilst producing well alloyed materials**

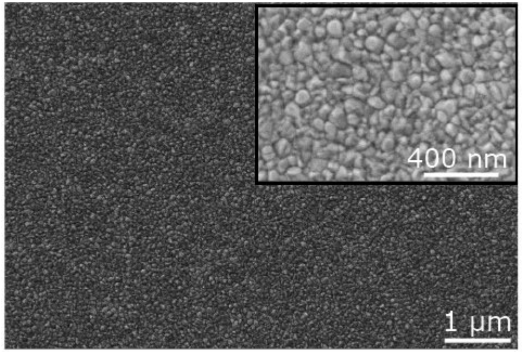


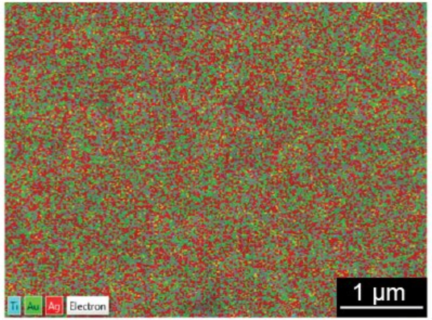
D. Ray, Advanced Materials vol. 2022, p. 2108225 (2022)

Alloyed plasmonic nanostructures

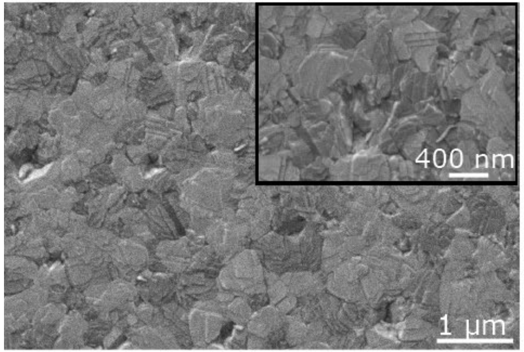
- **Well alloyed materials (EDX and XPS)**

Before annealing

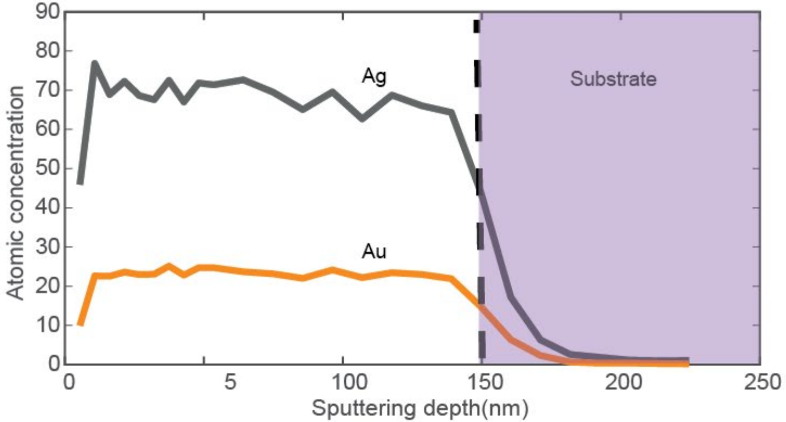




After annealing



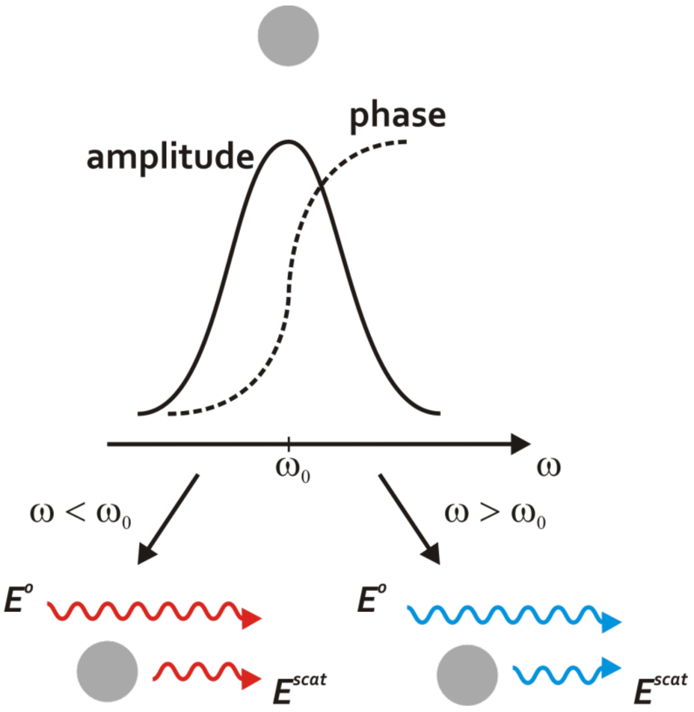
$Au_{0.2}Ag_{0.8}$

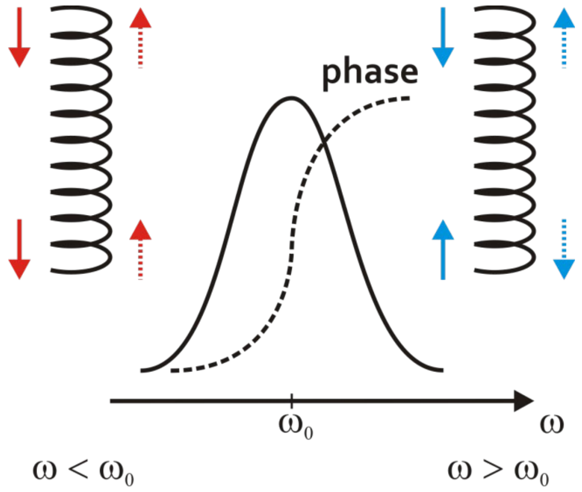


D. Ray, Advanced Materials vol. 2022, p. 2108225 (2022)

Plasmonic metasurfaces

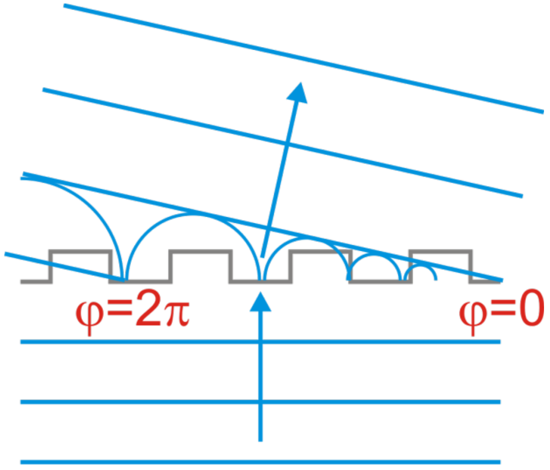
- Optical resonances can control the phase of the scattered light



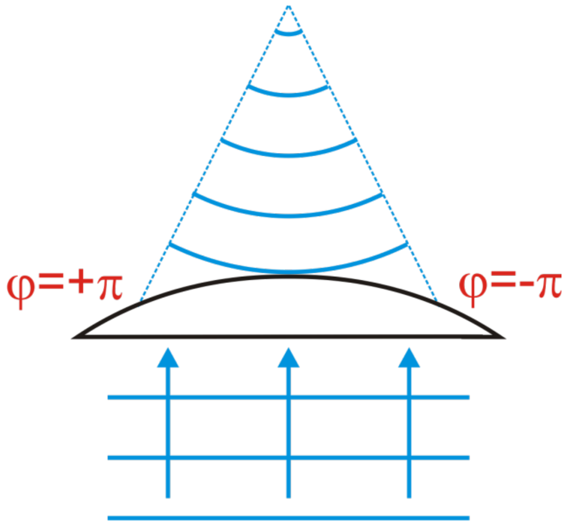


All optical components manipulate the phase of light

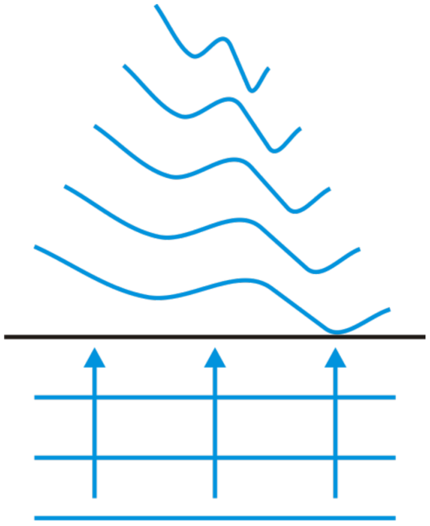
- **Grating:**



- **Lens:**

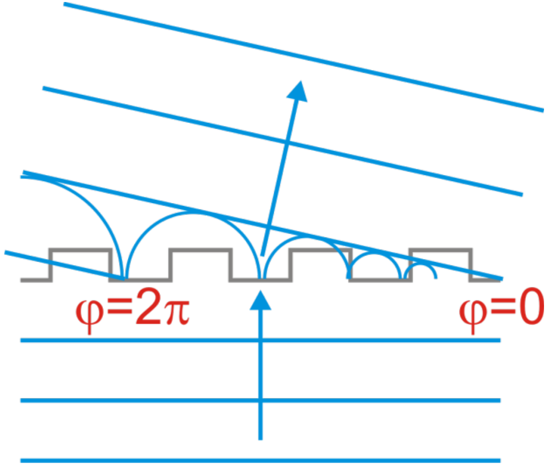


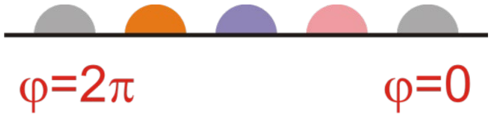
- **Hologram:**



Plasmonic metasurfaces

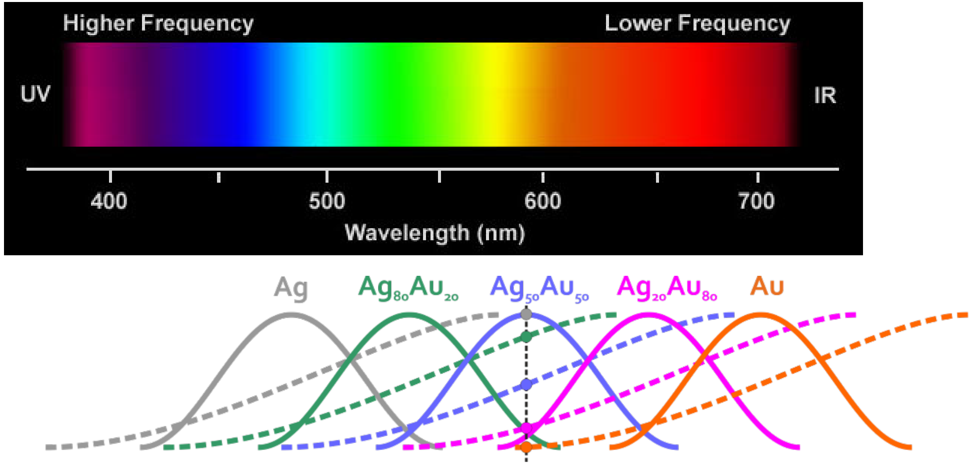
- Can we mimic the response of an optical component using plasmonic nanostructures on a surface?
- Yes, if we use nanostructures that produce different phases! (different shapes, geometries, metals, or alloys)





Plasmonic metasurfaces

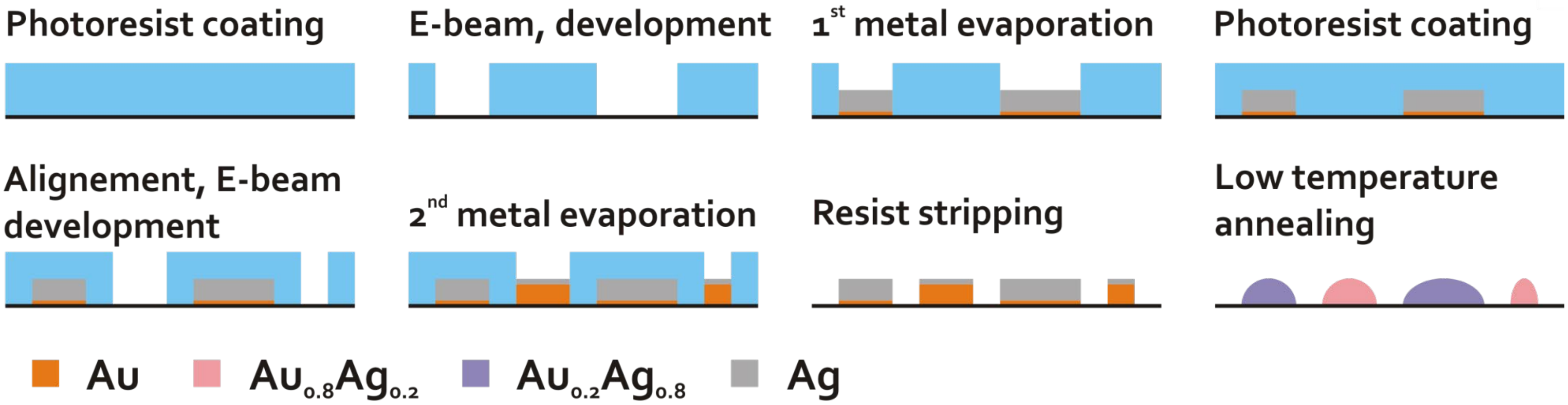
- Can we mimic the response of an optical component using plasmonic nanostructures on a surface?
- Yes, if we use nanostructures that produce different phases! (different shapes, geometries, metals, or alloys)



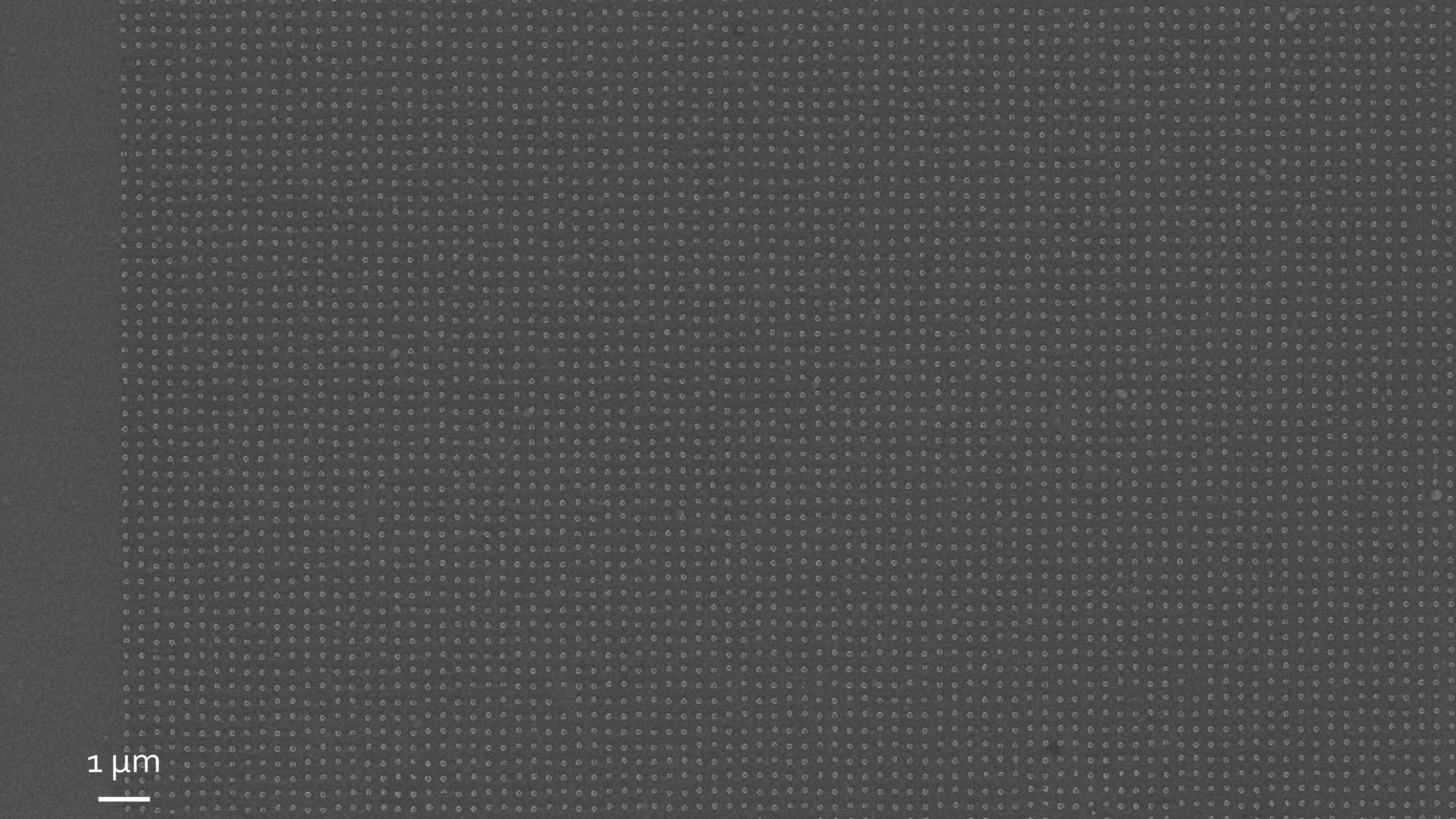
D. Ray, Advanced Materials vol. 2022, p. 2108225 (2022)

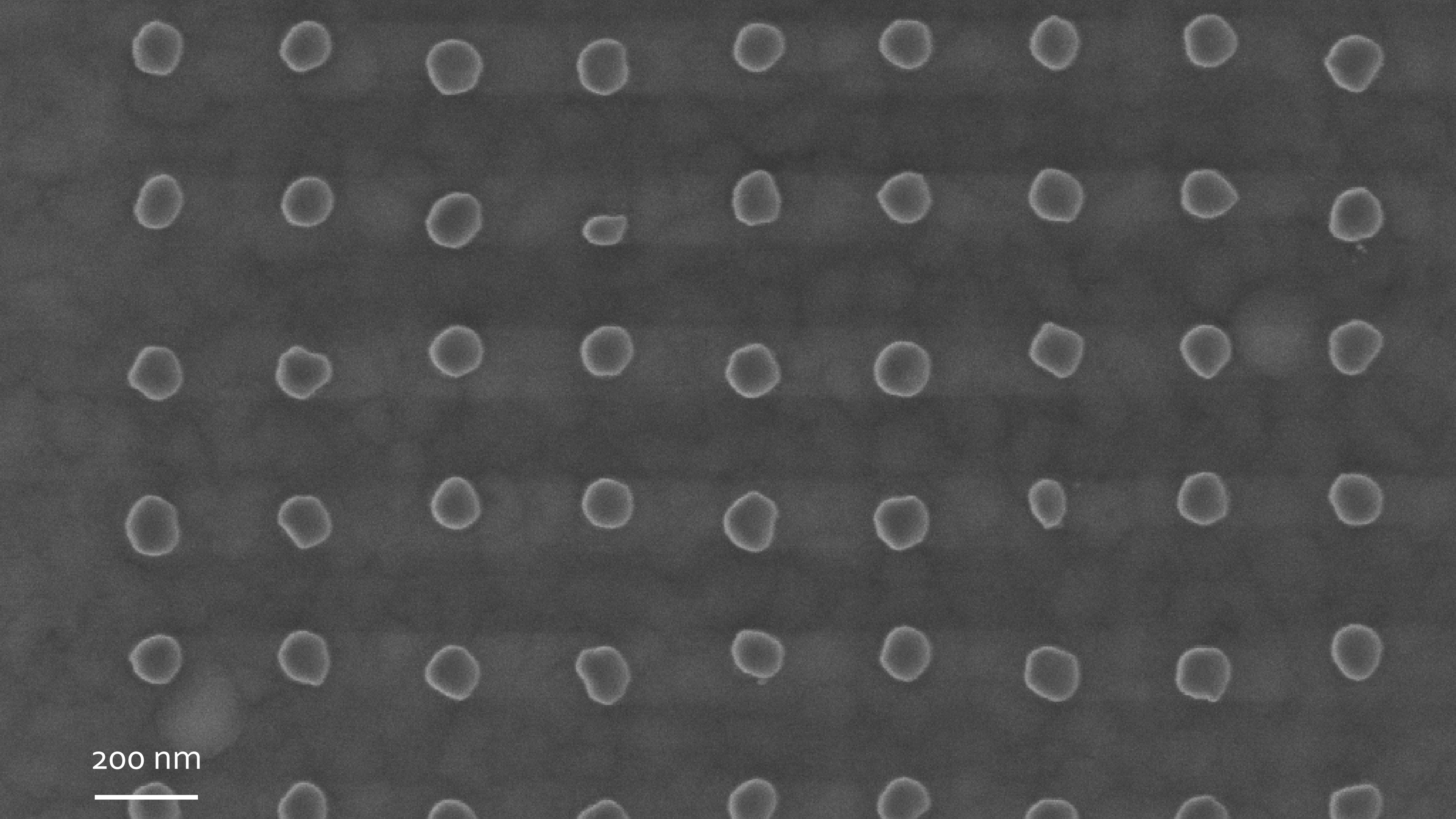
Alloyed plasmonic metasurfaces

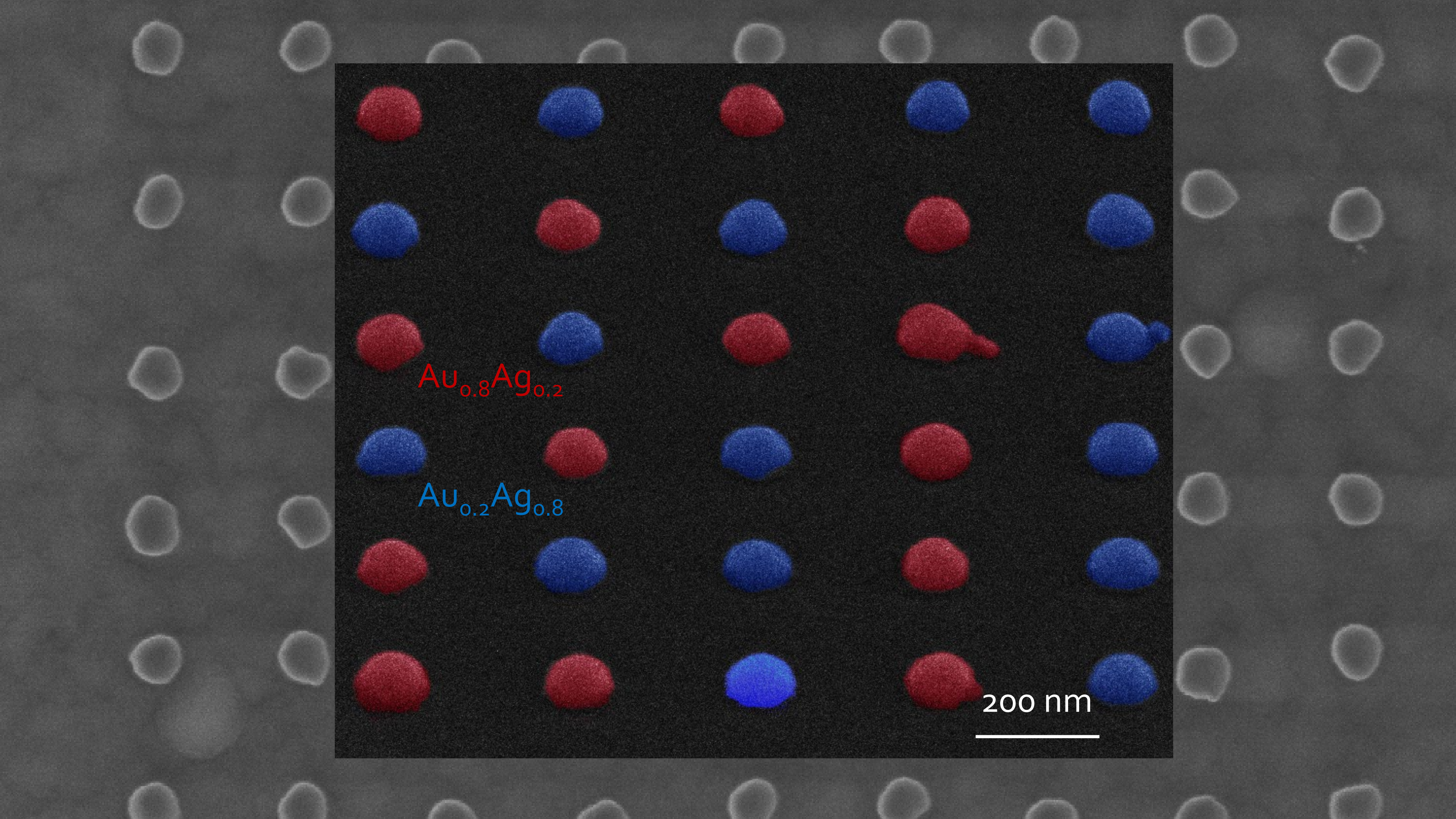
- Combinations of different alloy compositions on the same sample to produce more complex optical effects



D. Ray, Advanced Materials vol. 2022, p. 2108225 (2022)


1 μm


200 nm



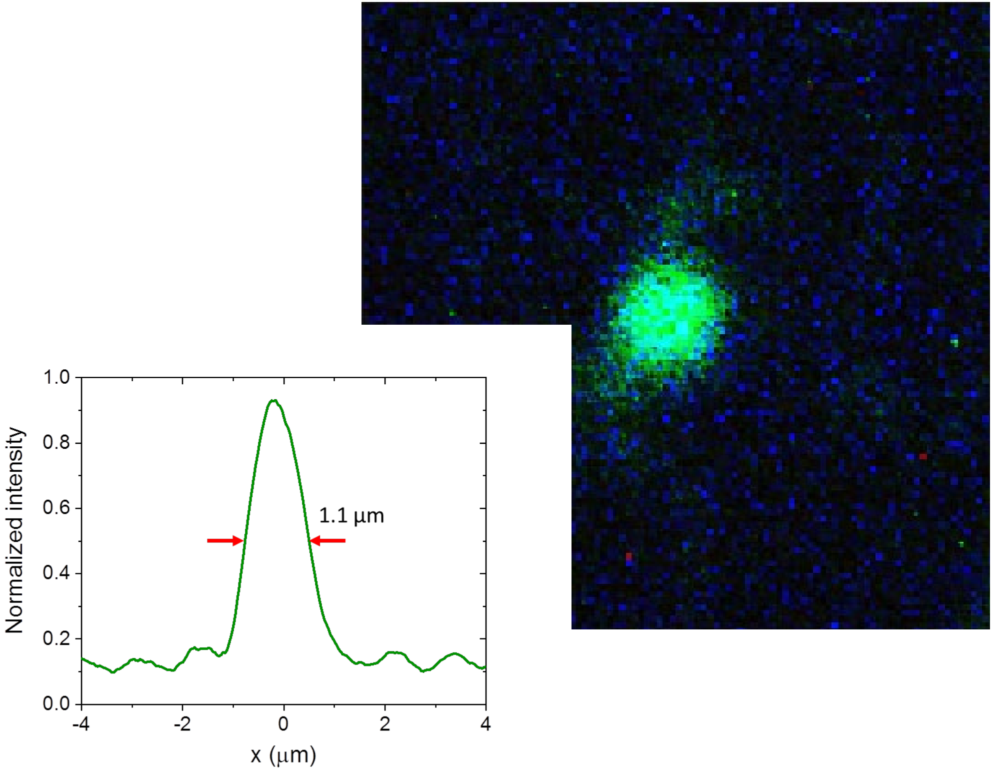
$Au_{0.8}Ag_{0.2}$
$Au_{0.2}Ag_{0.8}$
200 nm

Complex metasurfaces

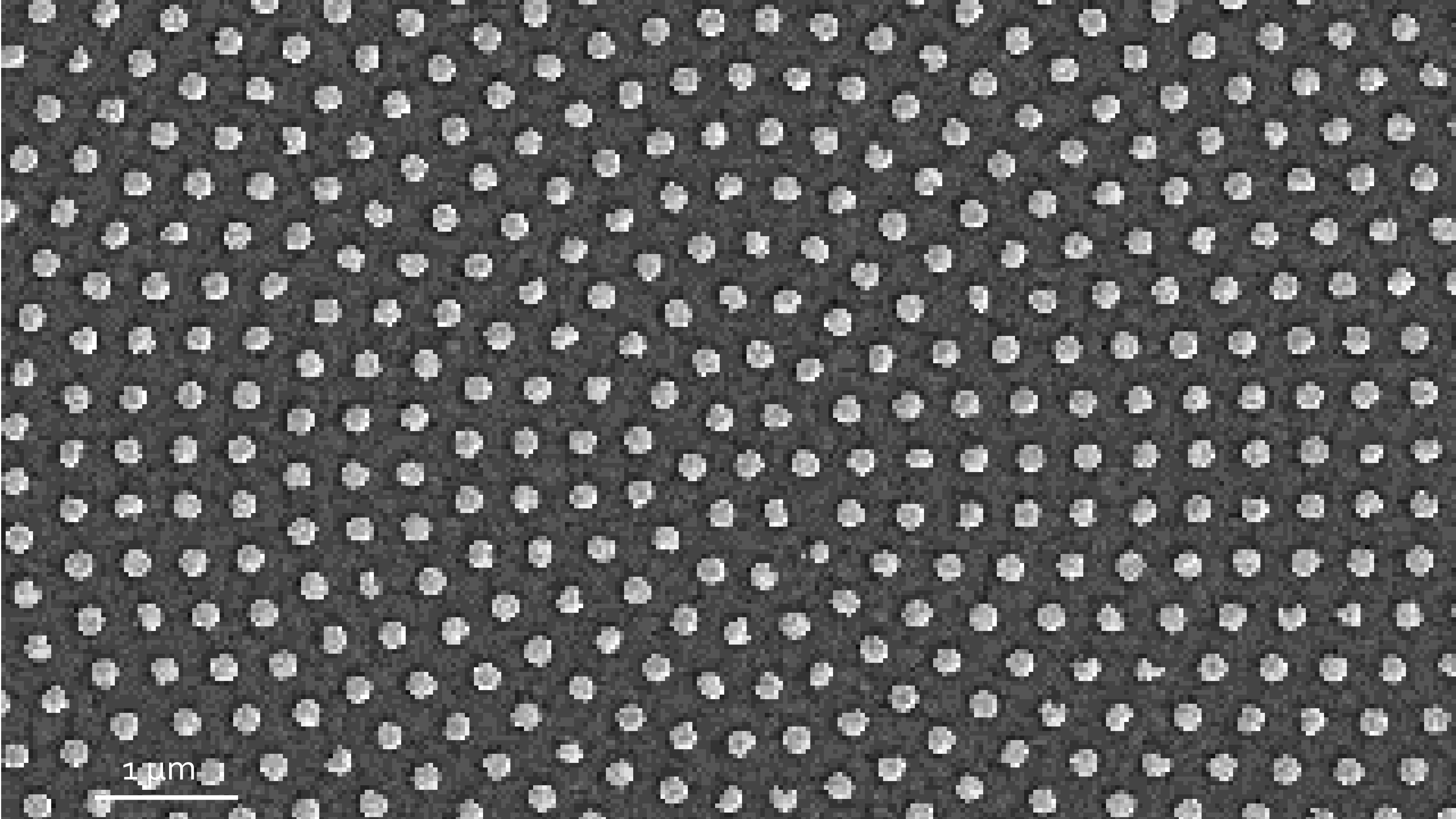
- **Hologram:**

λ=532 nm

- Lens:



D. Ray, Advanced Materials vol. 2022, p. 2108225 (2022)


1 µm

What have we learned so far…

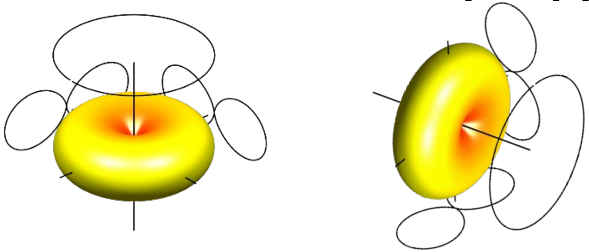
- If you don't get the property you wish from pure materials, why not mix several together?
- You don't need to follow well-established recipes, you can try completely novel approaches (if you have time and money…)
- Alloying does not necessarily require high temperature
- Scattering from a nanostructure also manipulates the phase of light
- This can be used to produce all sorts of flat optical elements (metasurfaces)
- Multiple Ebeam lithography opens new possibilities

Outline

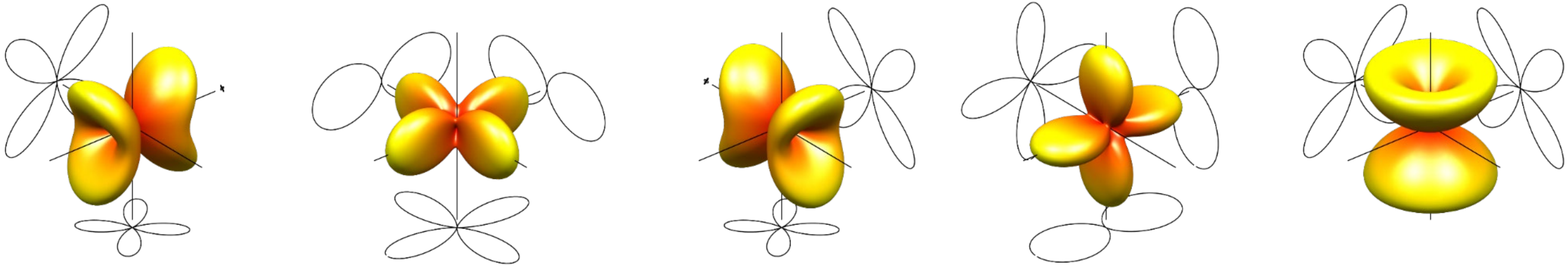
- Plasmonics
- Basic fabrication principles with electron-beam lithography
- Adhesion issues
- Other metals than Au
- Au-Ag alloys
- **Hybrid nanostructures**
- Chemical synthesis
- Medieval stained-glass windows

Optical modes determine the response of the system

- Simple plasmonic nanostructures essentially support electric dipolar modes



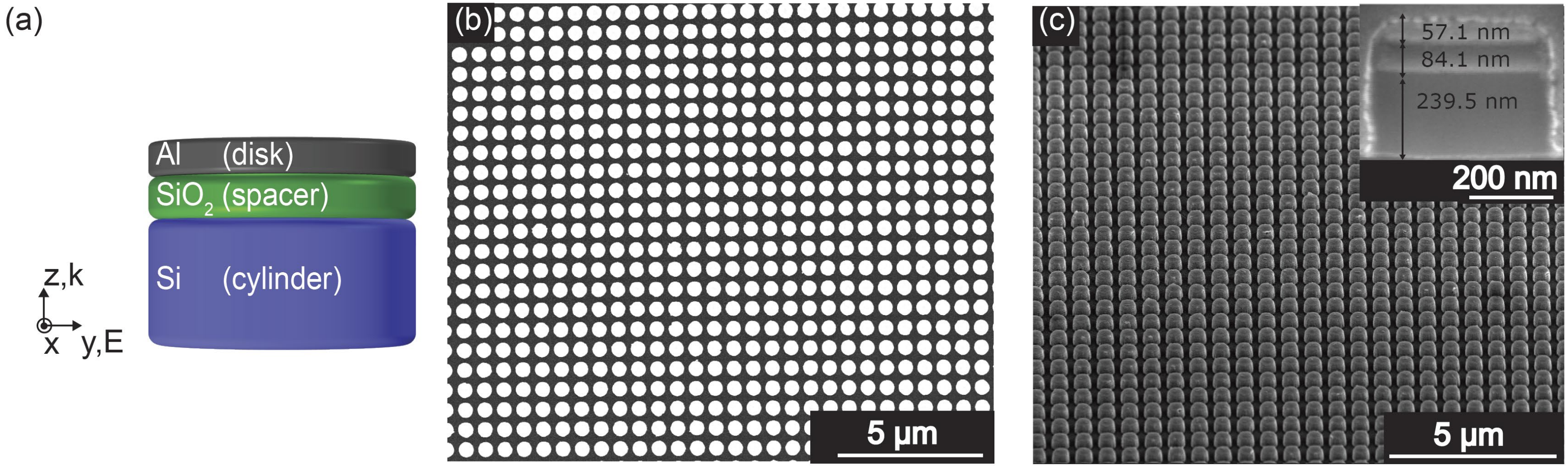
- Dielectric resonators can support magnetic and higher order modes



- Can we combine both to access interesting effects?

Hybrid metasurface for sensing

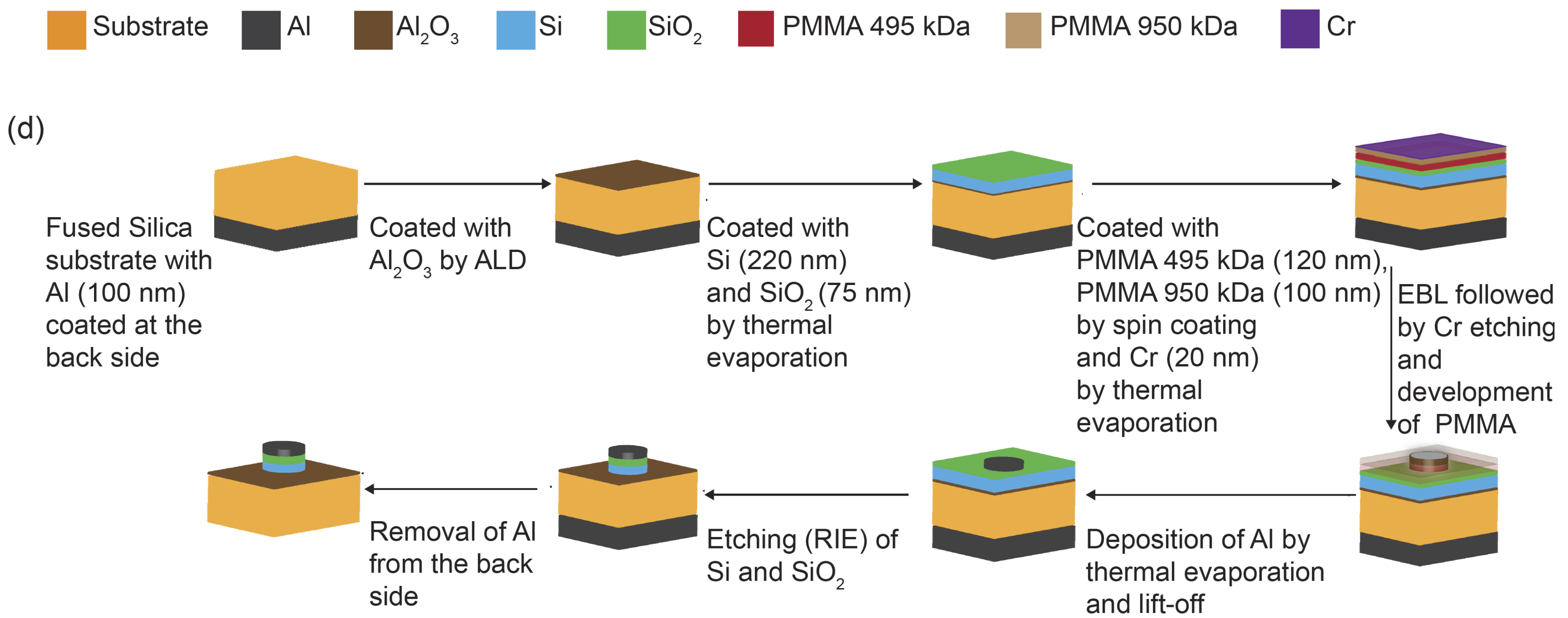
- **Combining a dielectric resonator (Si) with a plasmonic disk (Al)**



D. Ray, Nano Letters vol. 20, p. 8752 (2020)

Hybrid metasurface for sensing

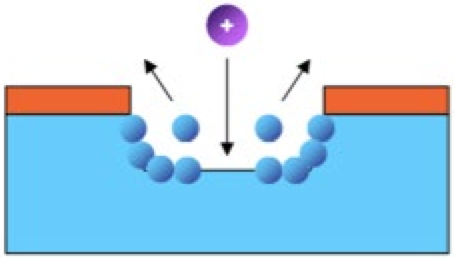
- **The Al disk serves both as plasmonic structure and mask for etching**



D. Ray, Nano Letters vol. 20, p. 8752 (2020)

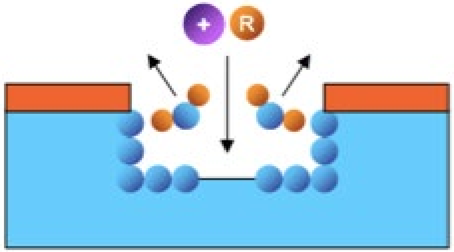
Ion etching vs. Reactive ion etching (RIE)

- Ion etching, physical sputtering



  - High anisotropy
  - Poor selectivity

- Reactive ion etching

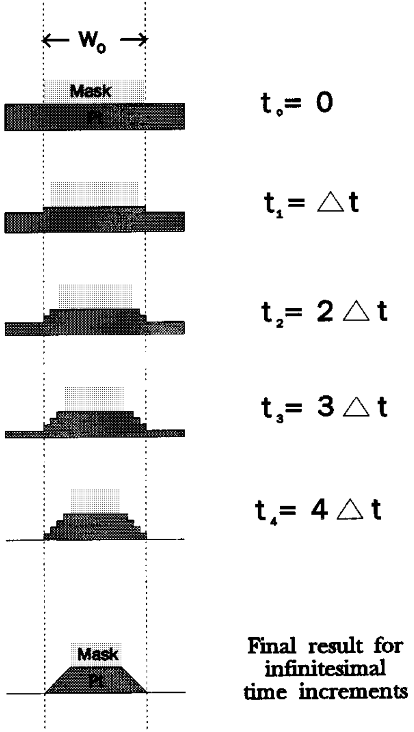


  - Medium anisotropy (can be controlled)
  - Good selectivity
  - Cl or F chemistry
  - Not well-suited for Au (but possible)

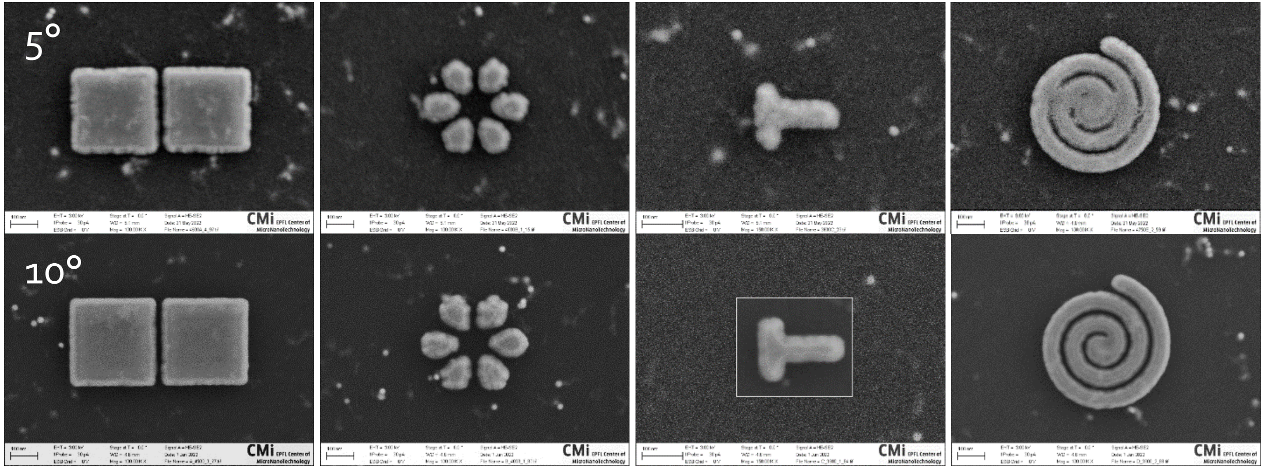
Materean.com/dry-etching

Fencing and redeposition

- During dry etching, some of the etched material can redeposit
- The mask can also be etched, producing slanted sidewalls



Tilting and rotating the substrate during etching helps avoid redeposition

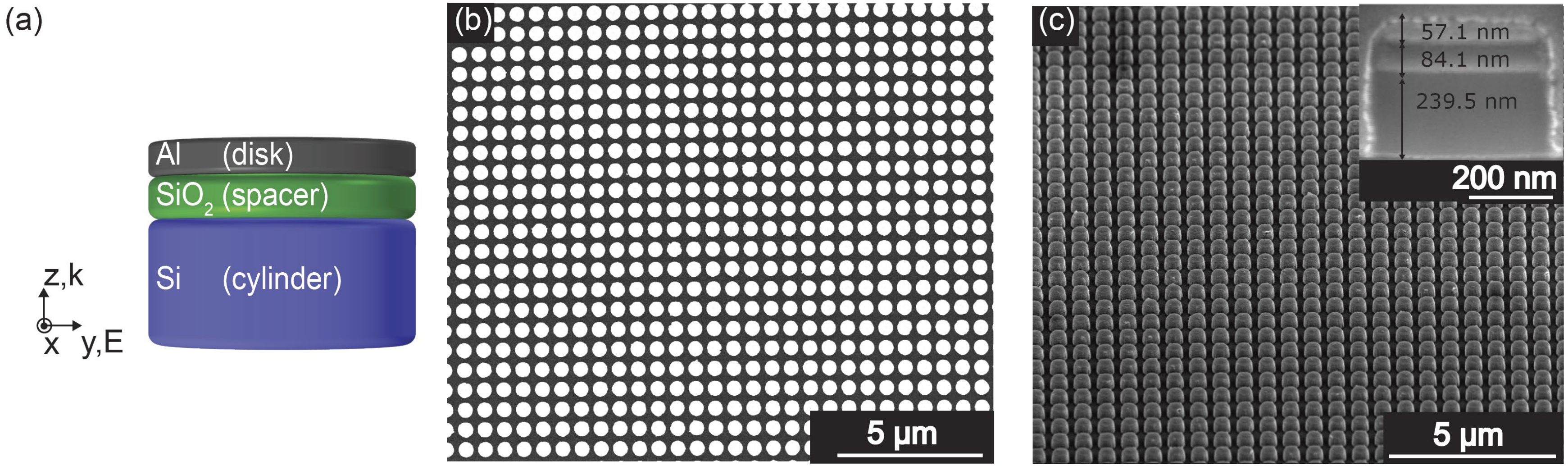


www.nanophotonics.ch

K.R. Milkove, Journal of Vacuum Science & Technology A 15, 596 (1997

Hybrid metasurface for sensing

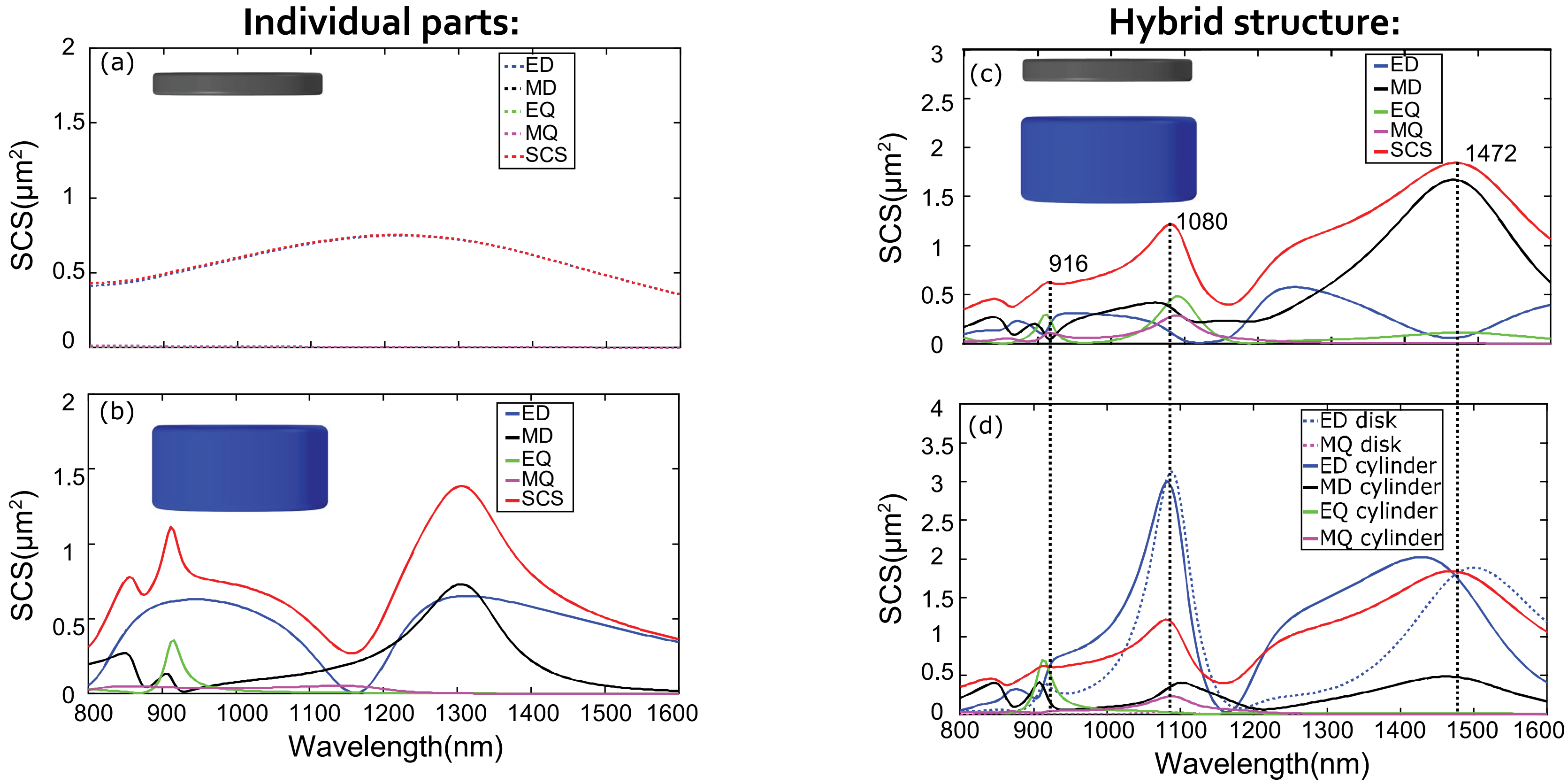
- **Combining a dielectric resonator (Si) with a plasmonic disk (Al)**



D. Ray, Nano Letters vol. 20, p. 8752 (2020)

Hybrid metasurface for sensing

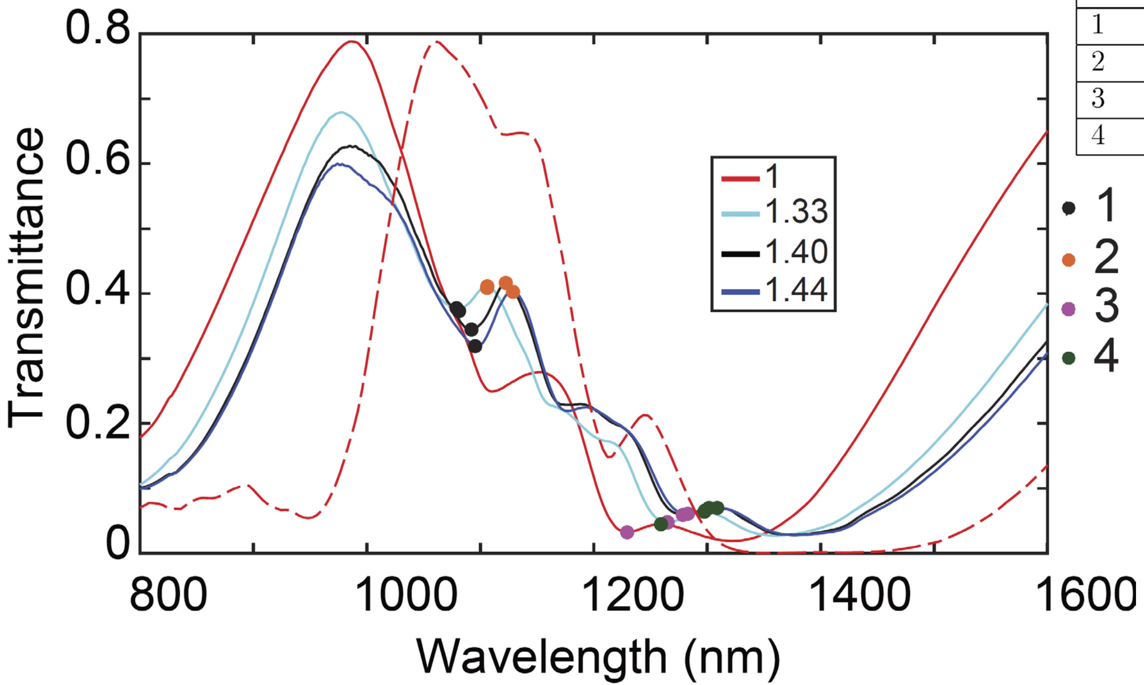
- **Interplay between the modes supported by the different parts**



D. Ray, Nano Letters vol. 20, p. 8752 (2020)

Hybrid metasurface for sensing

- **Multiple features can be used for bulk refractive index sensing (experimental data)**



Sensitivity:

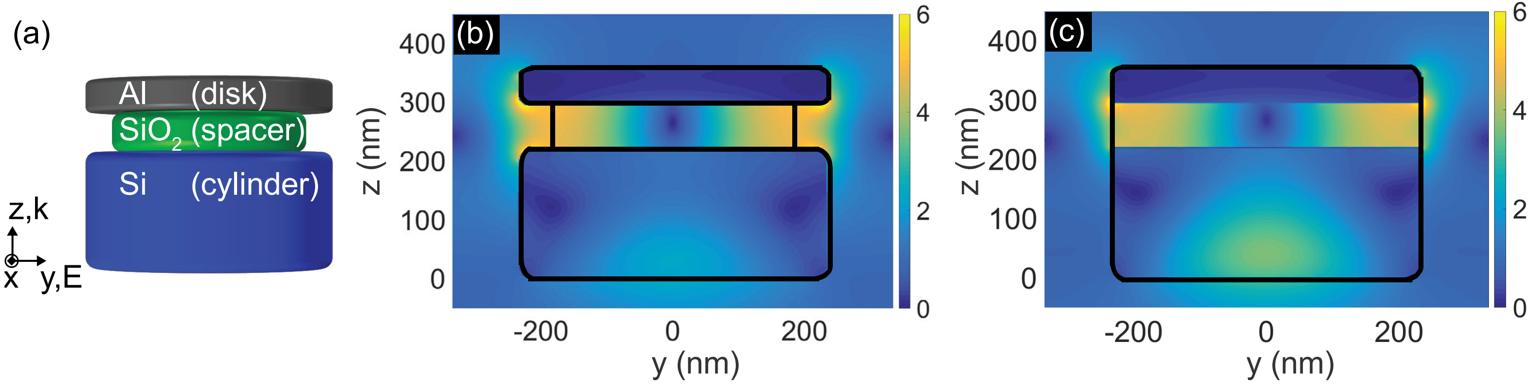
Feature no.	S=$\Delta\lambda/\Delta n$ (nm/RIU)	Range (nm)
1	144	1079–1095
2	208	1106–1129
3	120	1229–1283
4	111	1259–1309

Reference sensitivities:
- **Dielectric: 300 nm/RIU**
- **Plasmonic: 600 nm/RIU**

D. Ray, Nano Letters vol. 20, p. 8752 (2020)

Hybrid metasurface for sensing

- **Can we improve the overlap between near-field and analyte?**

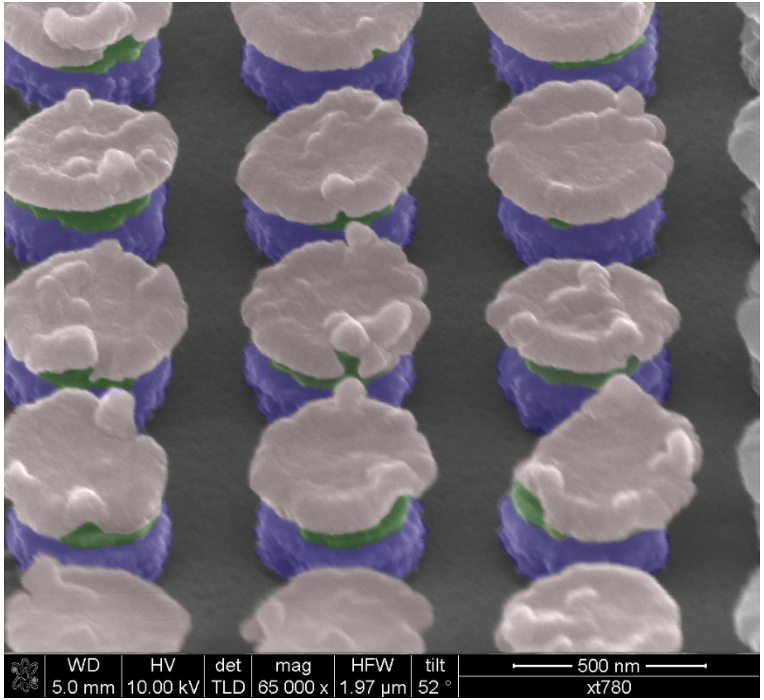


- **Additional wet etch step to produce an undercut**

D. Ray, Nano Letters vol. 20, p. 8752 (2020)

Hybrid metasurface for sensing

- **Can we improve the overlap between near-field and analyte?**



Sensitivity improvement of 40 nm/RIU (S=245 nm/RIU)

D. Ray, Nano Letters vol. 20, p. 8752 (2020)

What have we learned so far…

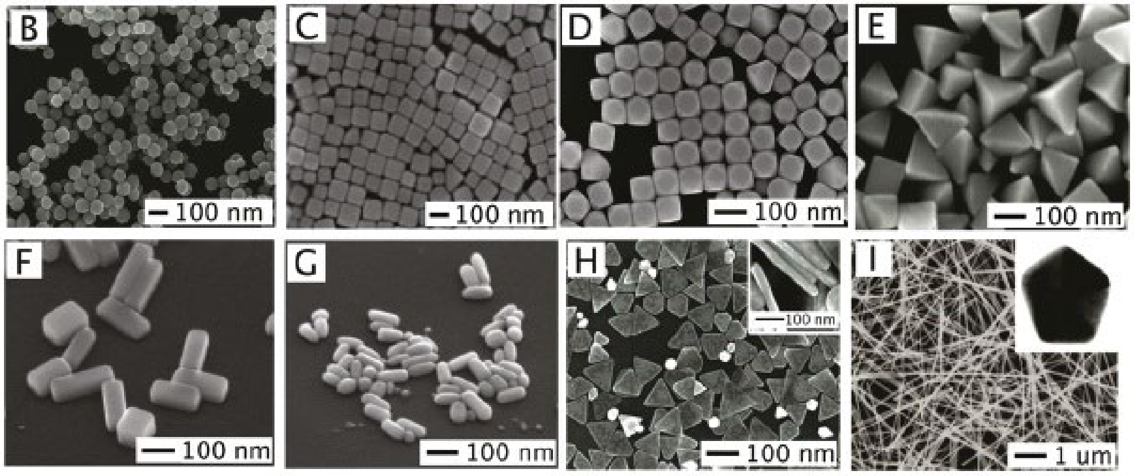
- Ion etching (reactive or not) is an interesting, but subtle, approach
- A variety of materials can be processed this way
- Do not hesitate to combine several processes to produce your samples
- Close the loop: numerical simulations → fabrication → experiments → numerical simulations → fabrication again → …
- Don't be disappointed if at the end all your efforts provide only limited improvements

Outline

- Plasmonics
- Basic fabrication principles with electron-beam lithography
- Adhesion issues
- Other metals than Au
- Au-Ag alloys
- Hybrid nanostructures
- **Chemical synthesis**
- Medieval stained-glass windows

Different types of plasmonic nanostructures

- Two approaches exist for fabricating plasmonic nanostructures:
  - Top-down nanofabrication (conventional clean-room fabrication)
  - Bottom-up (chemical, self-assembled fabrication):

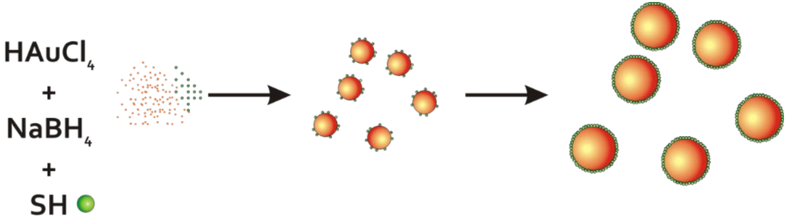


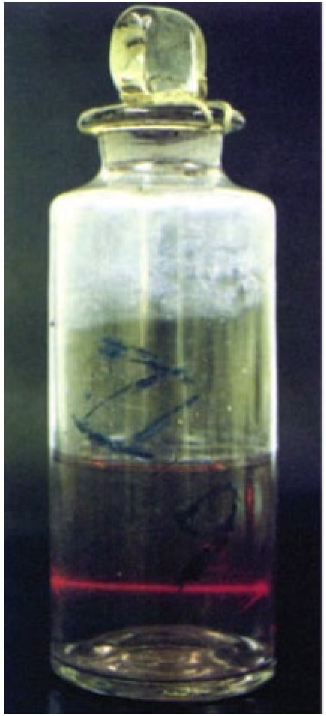
M. Rycenga, Chemical Reviews vol. 111, p. 3669 (2011)

Conventional gold nanoparticle synthesis

- Reduction of Au^{III} compounds to form metallic Au (e.g. with borohydride)
- Ostwald ripening process: over time small particles dissolve redeposit onto larger particles, which are more favorable er one single large particle:

- A capping agent (thiol-based for Au) stabilizes the process, monodispersed nanoparticles:

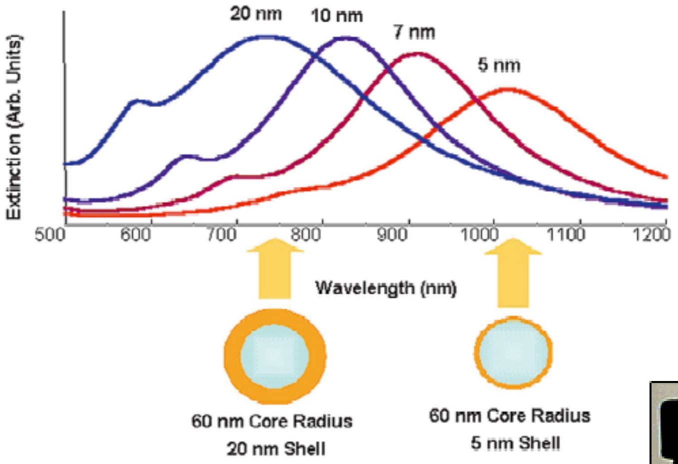


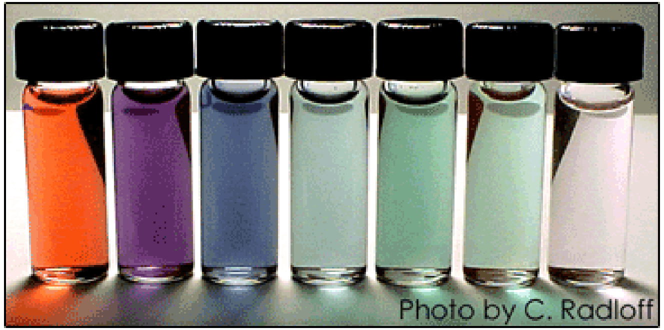


Faraday's colloidal suspension of gold or « gold fluid »

Different types of plasmonic nanostructures

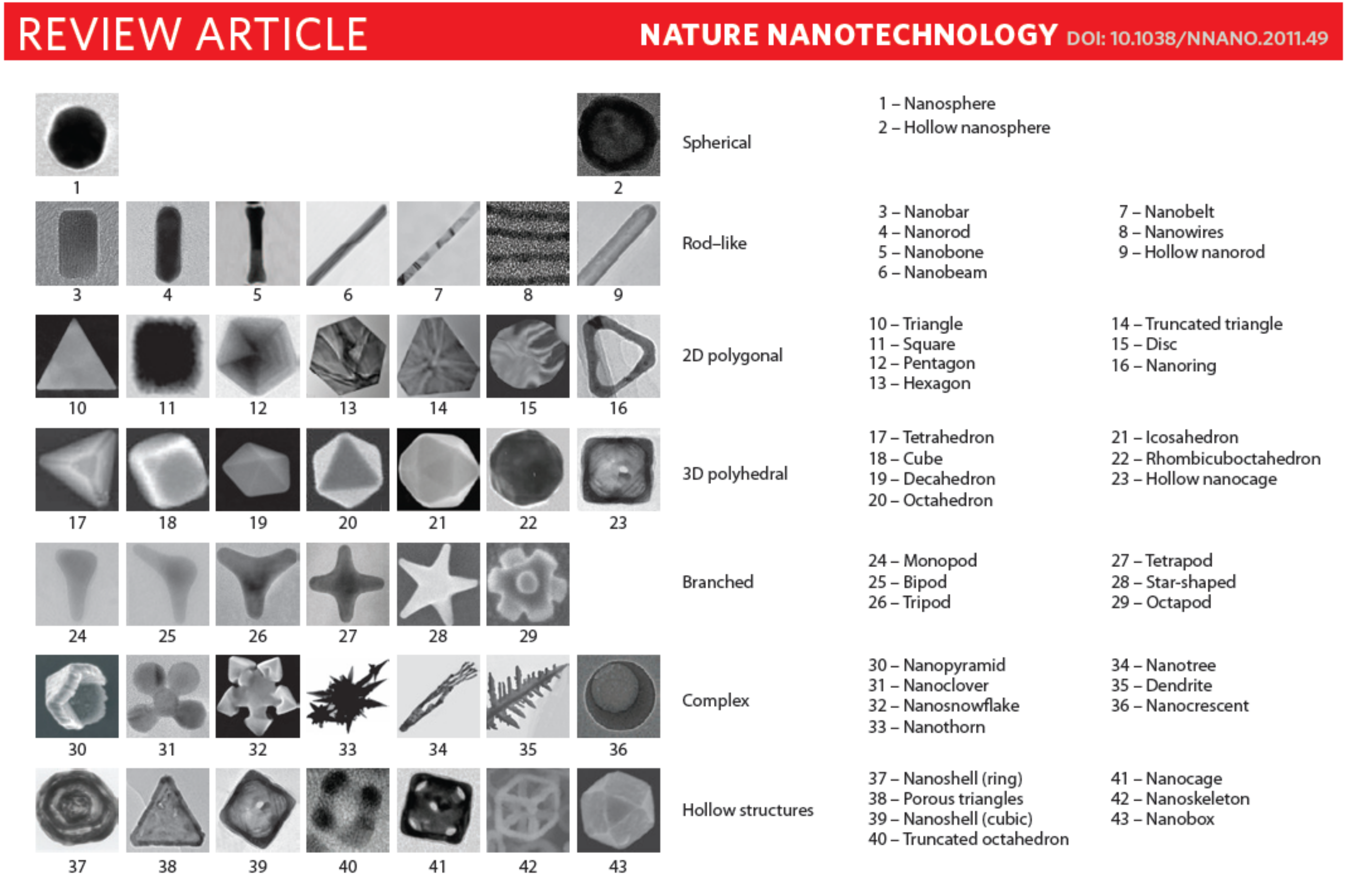
- **Core-shell nanoparticles are highly tunable:**





N.J. Halas, Rice University, U.S.A.

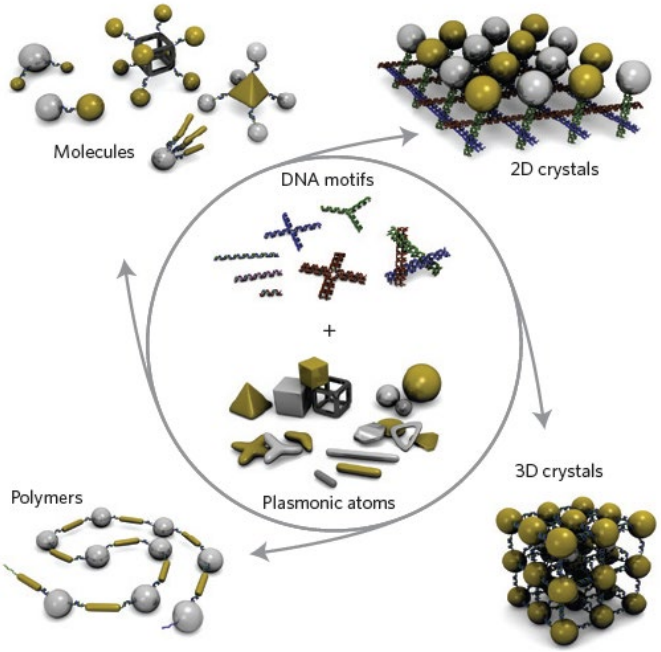
A broad variety of plasmonic "atoms" can be fabricated

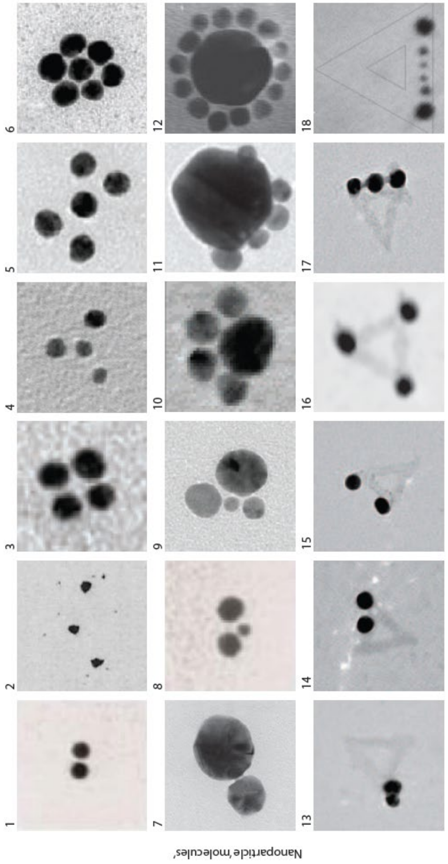


S.J. Tan, Nature Nanotechnology vol. 6, p. 268 (2011)

Larger structures can be ralized from these "atoms"

- **DNA origami**





S.J. Tan, Nature Nanotechnology vol. 6, p. 268 (2011)


Plasmonic colors in medieval stained-glass windows:
Myth or reality?

Medieval stained-glass windows

C. Santschi, in preparation (2022)

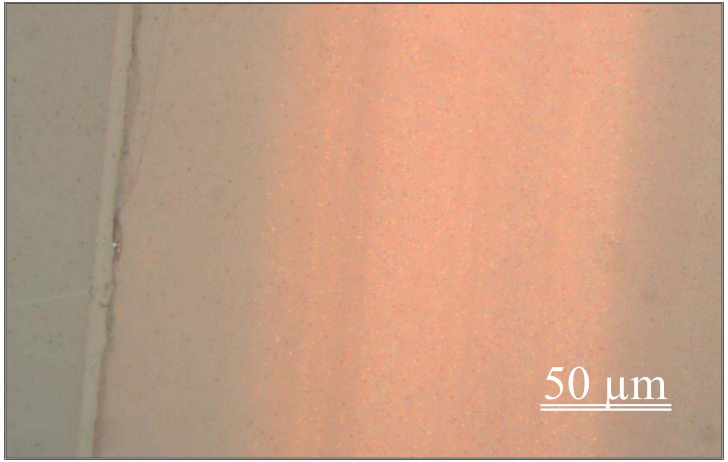
Medieval stained-glass windows

Stained-glass window
ca 1480

Ulm minster
built from 1377
wikipedia

C. Santschi, in preparation (2022)

Medieval stained-glass windows



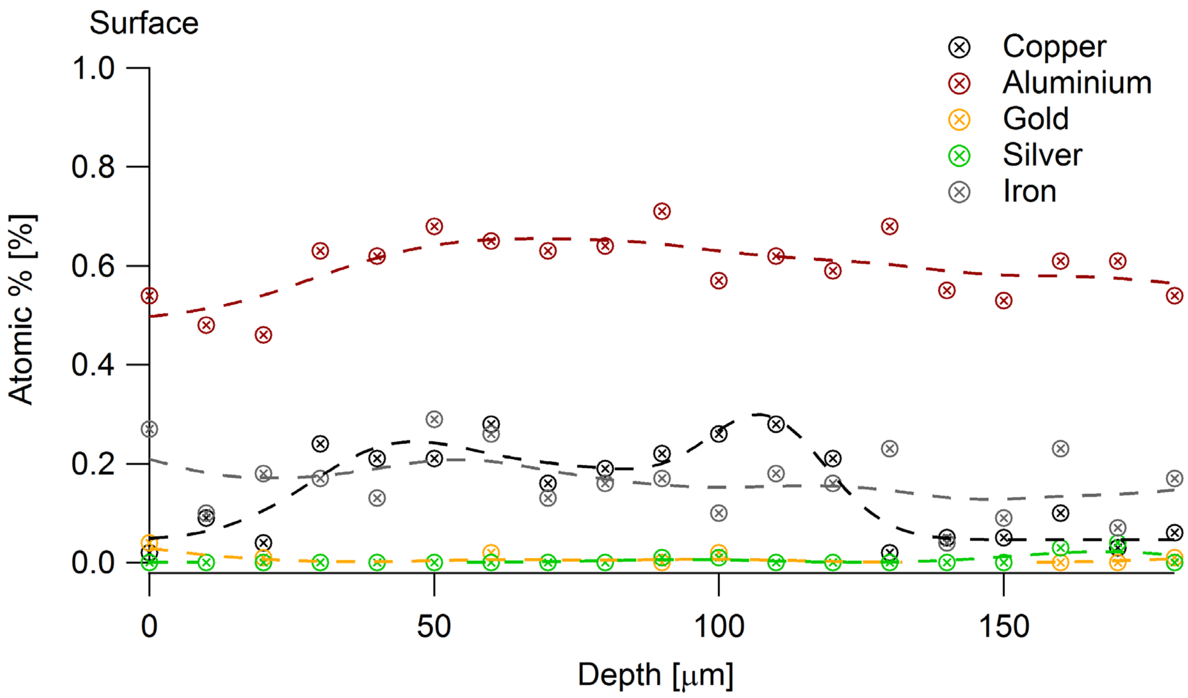
Colored layer, approx. 150 µm

Interfacial layer, approx. 65 µm

Glue

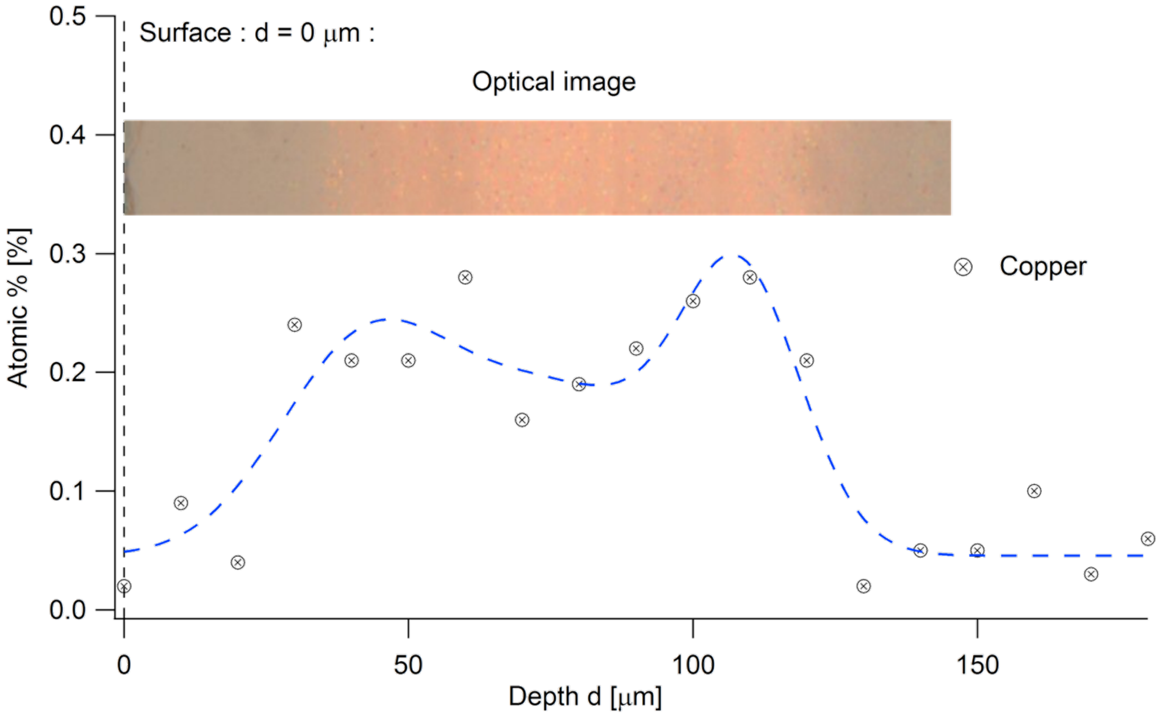
C. Santschi, in preparation (2022)

Energy dispersive X-ray spectroscopy (EDX)



C. Santschi, in preparation (2022)

Correlation between color and density of Cu particles



Cu particles: – size: 63 nm ± 15 nm

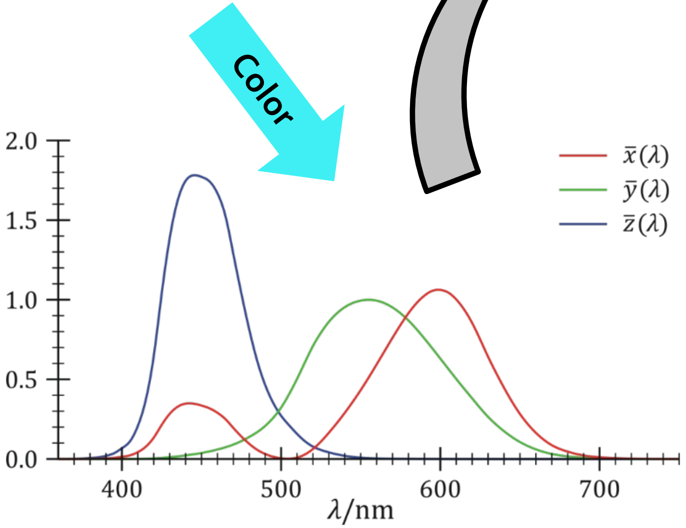
– density: 0.38 μm^{-3}

– average distance between particles 3.6 µm

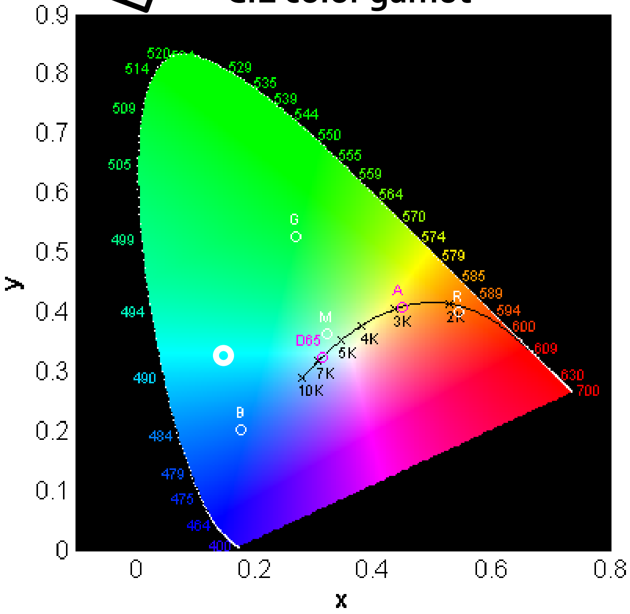
C. Santschi, in preparation (2022)

Color perception

- Two families of receptors enable human vision:
  - Rods (high sensitivity, black & white)
  - Cones (3 types with max. sensitivity @ λ=420, 530 or 560 nm)



CIE color gamut



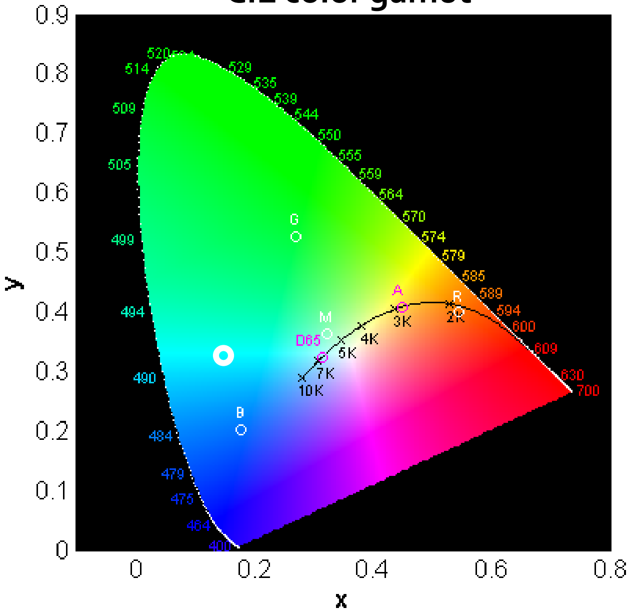
S. Westland and C. Ripamonti, Computational Color Science using Matlab (Wiley 2004)

Color perception

- Two families of receptors enable human vision:
  - Rods (high sensitivity, black & white)
  - Cones (3 types with max. sensitivity @ λ=420, 530 or 560 nm)

- Any color can be represented as a point (x,y) in the color gamut

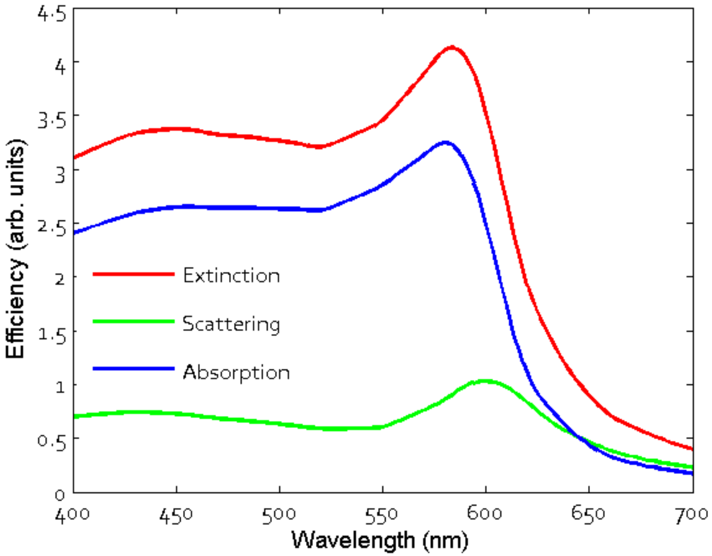
CIE color gamut



S. Westland and C. Ripamonti, Computational Color Science using Matlab (Wiley 2004)

Comparison with Mie calculations

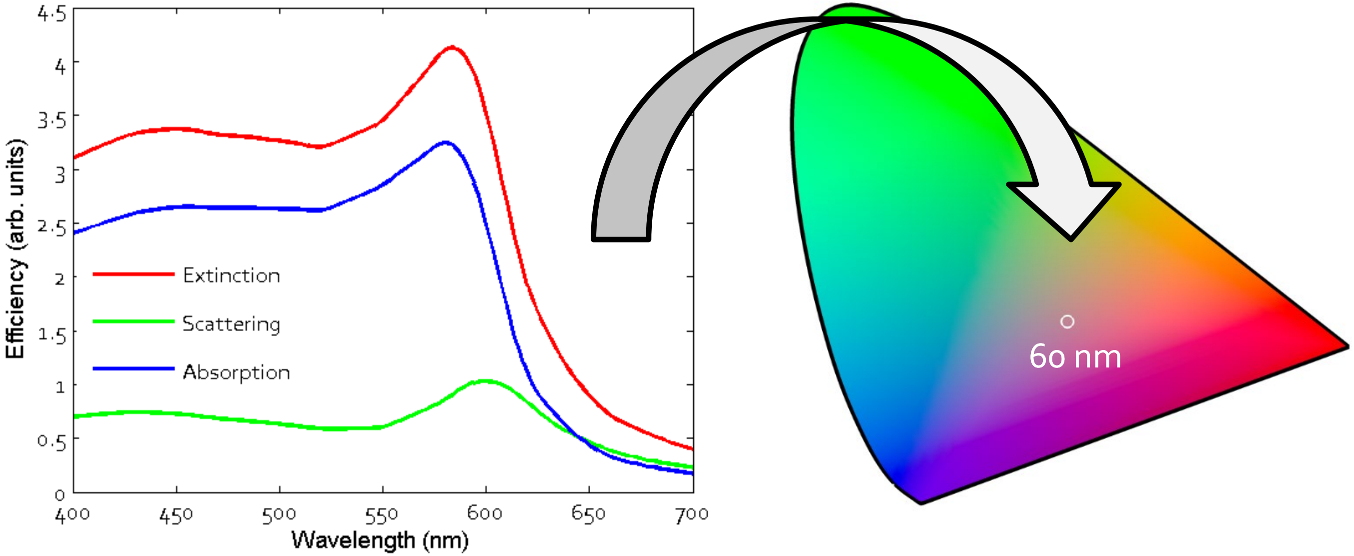
60 nm Cu particle



Mie Plot: www.philiplaven.com

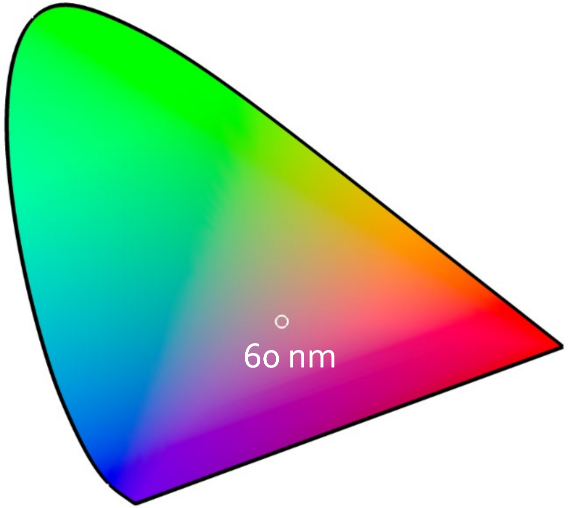
Comparison with Mie calculations

60 nm Cu particle



Mie Plot: www.philiplaven.com

Comparison with Mie calculations



- **Good agreement with the observed color**

Mie Plot: www.philiplaven.com

What have we learned so far…

- Chemical synthesis provides an alternative route to cleanroom nanotechnology
- This approach can be used independently or together with top-down approaches
- Quite deterministic nanostructures can be produced this way
- Interesting LEGO approach to build complex structures
- Remain fascinated by Nature and the world around us !

EPFL

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

erc

GEBERT RÜF STIFTUNG
WISSENSCHAFT.BEWEGEN

HORIZON 2020

www.nanophotonics.ch