Multifunctional magneto-optical nanoparticles for medical imaging and biosensing

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Outline

- **Introduction: Magnetic particles as probes for homogeneous diagnostics**
  - Motivation
  - Examples

- **Our approach: Observe changes in the dynamics of magnetic nanorod probes**
  - Measurement principle
  - Measurement setup
    - **Electrodeposited Ni nanorods**
      - Fabrication scheme
      - Surface modification
    - **Noble-metal shell coated Co nanorods**
      - Nanoprobe synthesis & characteristics
      - Protein results
    - **Nanoimprint lithography based nanoparticles**
      - Fabrication scheme
      - Surface modification

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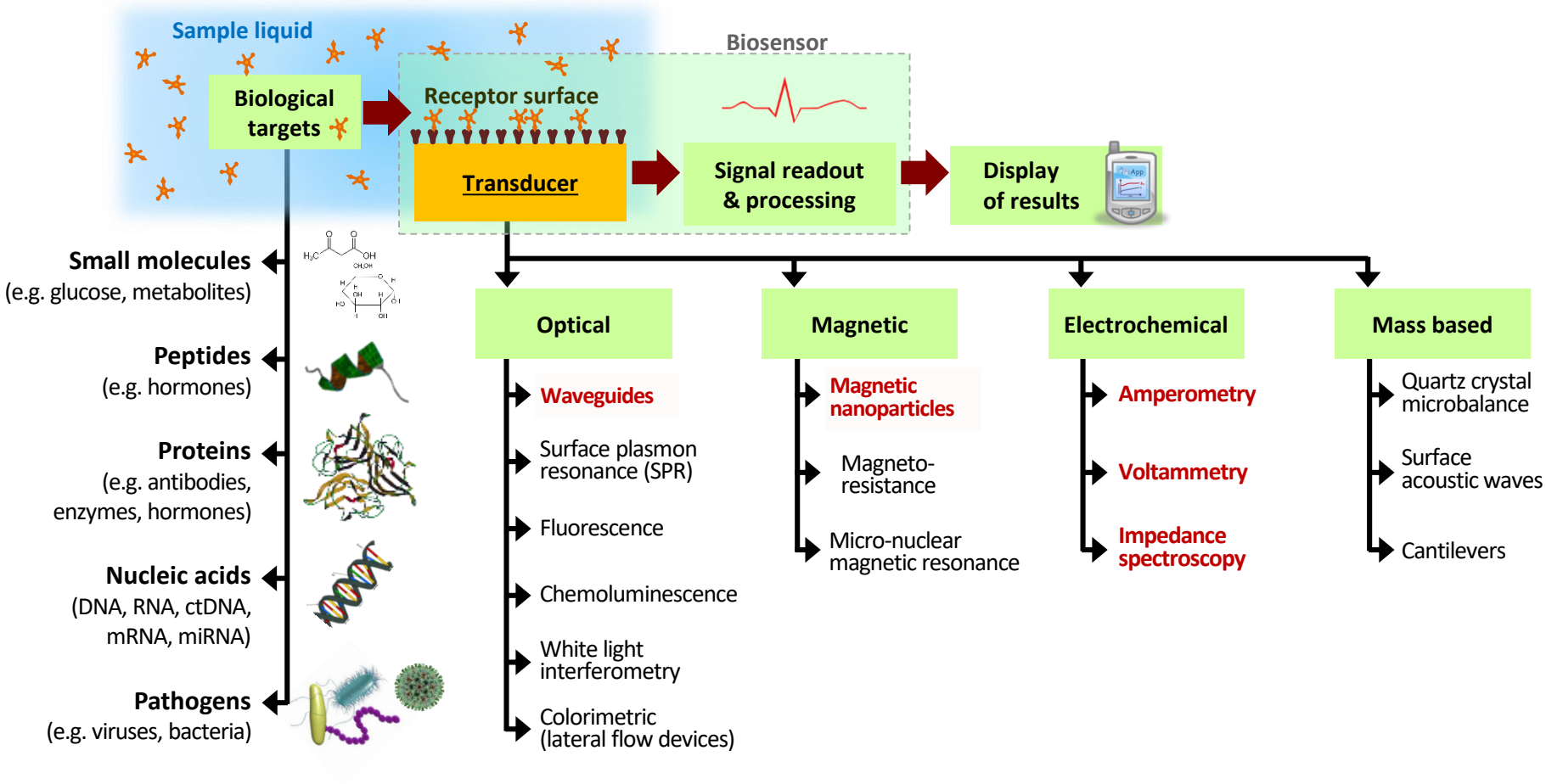
Biosensing principles

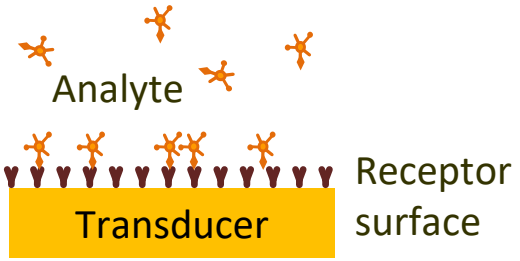
What is a biosensor



Biosensing principles

Heterogeneous assays

- Analyte binds to receptors and is detected via transducer
- Often realized in sandwich assay format
- Relies on diffusion of analyte to receptor surface
- Assay protocol usually involves multiple washing steps

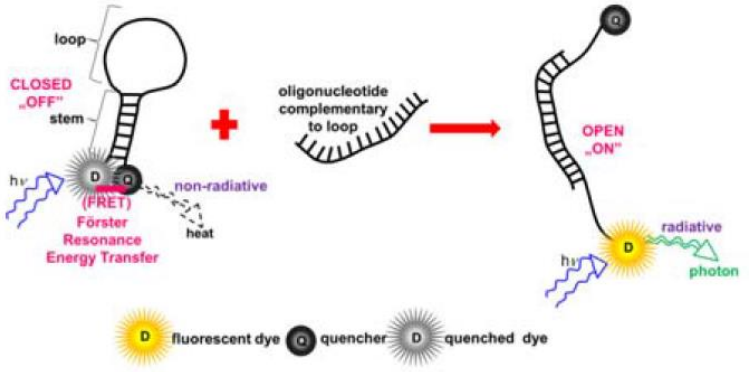


Homogeneous assays

- Probes are mixed with the sample solution
- Analyte is detected within the entire sample volume
- Examples:
  - Fluorescence polarization
  - Fluorescence correlation spectroscopy
  - Molecular beacons
  - Thermophoresis
  - Methods based on nanoparticle probes

➢ Simple mix & measure detection

➢ Fast due to 3d diffusion of probes and analyte



Stobiecka et al., Chem. Pap. ***2015****,* 69

⇨ **Homogeneous assays well suited for point-of-care detection**

Magnetic particle based homogeneous assays

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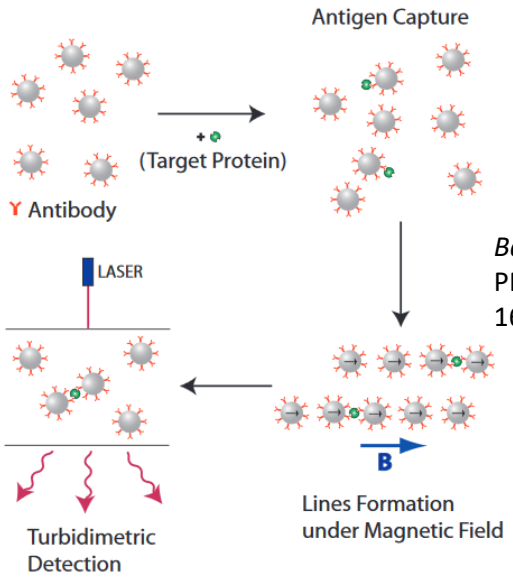
⇨ Added control of probes by magnetic fields

Acceleration of incubation processes

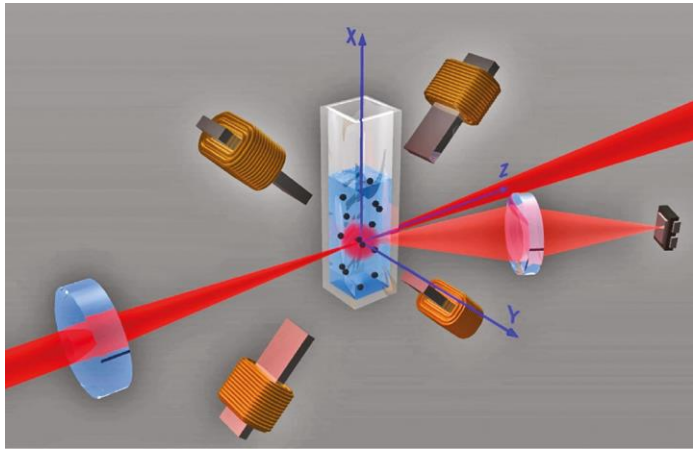
- Application of static linear magnetic field leads to chain formation of magnetic particle probes
- Accelerated analyte-proportional formation of particle dimers is induced
- The concentration of particle dimers is quantified by optical extinction measurements
- Example: Ovalbumin detection in buffer within 5 min compared to > 8 h without magnetic field acceleration



Baudry et al., PNAS 103 (2006) 16076–16078

Frequency-selective detection

- Magnetic particle probes form dimers via bound analyte
- Dimers are agitated by an applied rotating magnetic field
- Background-free detection of particle dimers by optical scattering measurements at the 2nd harmonic of the rotating magnetic field frequency
- Analysis of frequency spectra of the rotating magnetic field frequency enable independent determination of magnetic particle probe properties
- Example: biotinylated BSA detection directly in plasma



Ranzoni et al., Nano Lett. 11 (2011) 2017–2022.

S. Schrittwieser, B. Pelaz, W. J. Parak, S. Lentijo-Mozo, K. Soulantica, J. Dieckhoff, F. Ludwig, A. Guenther, A. Tschöpe, J. Schotter. Homogeneous biosensing based on magnetic particle labels. Review article, Sensors 16 (2016) 828

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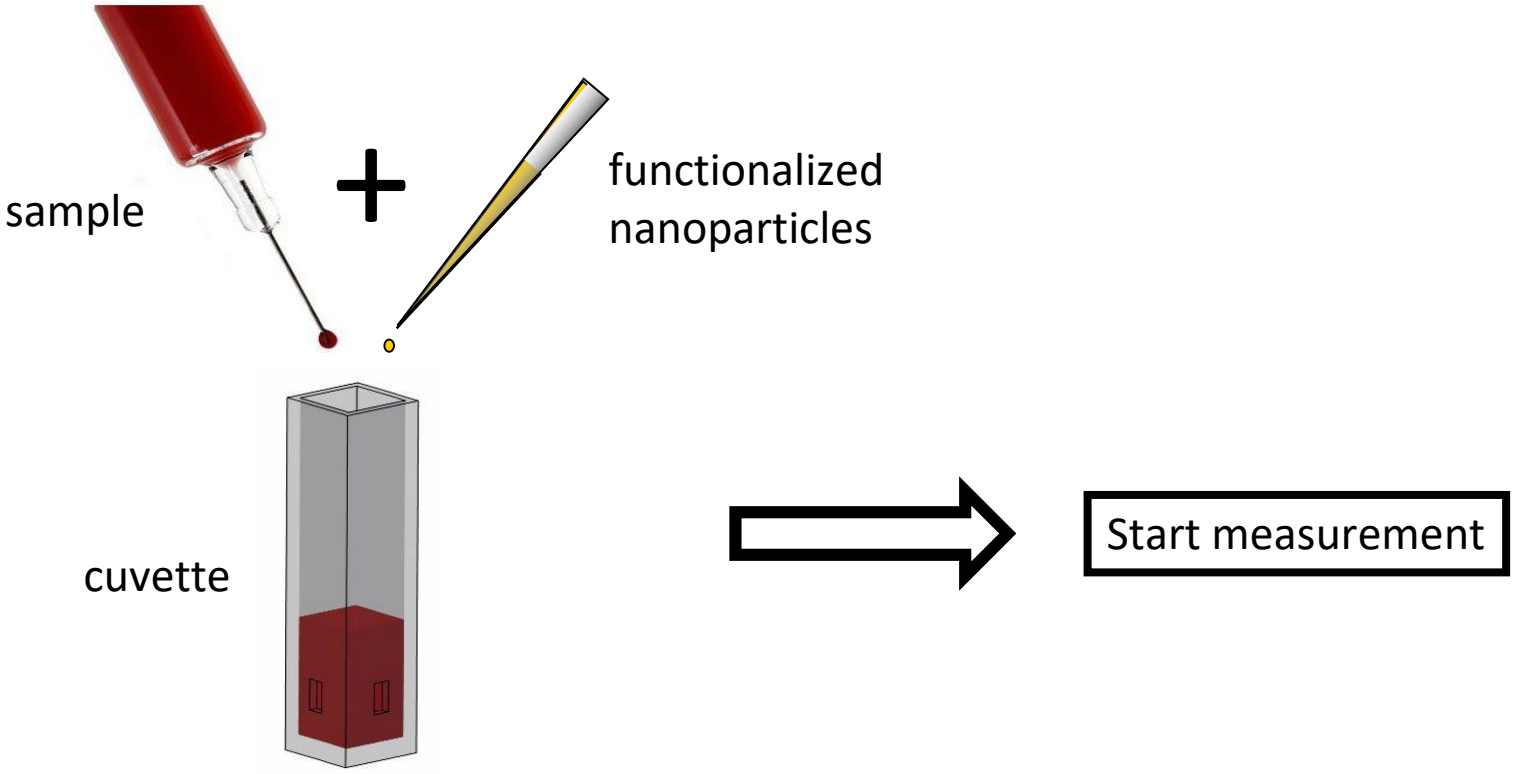
Introduction: nanoparticle-based homogeneous immunodiagnostics

Mix & measure detection principle



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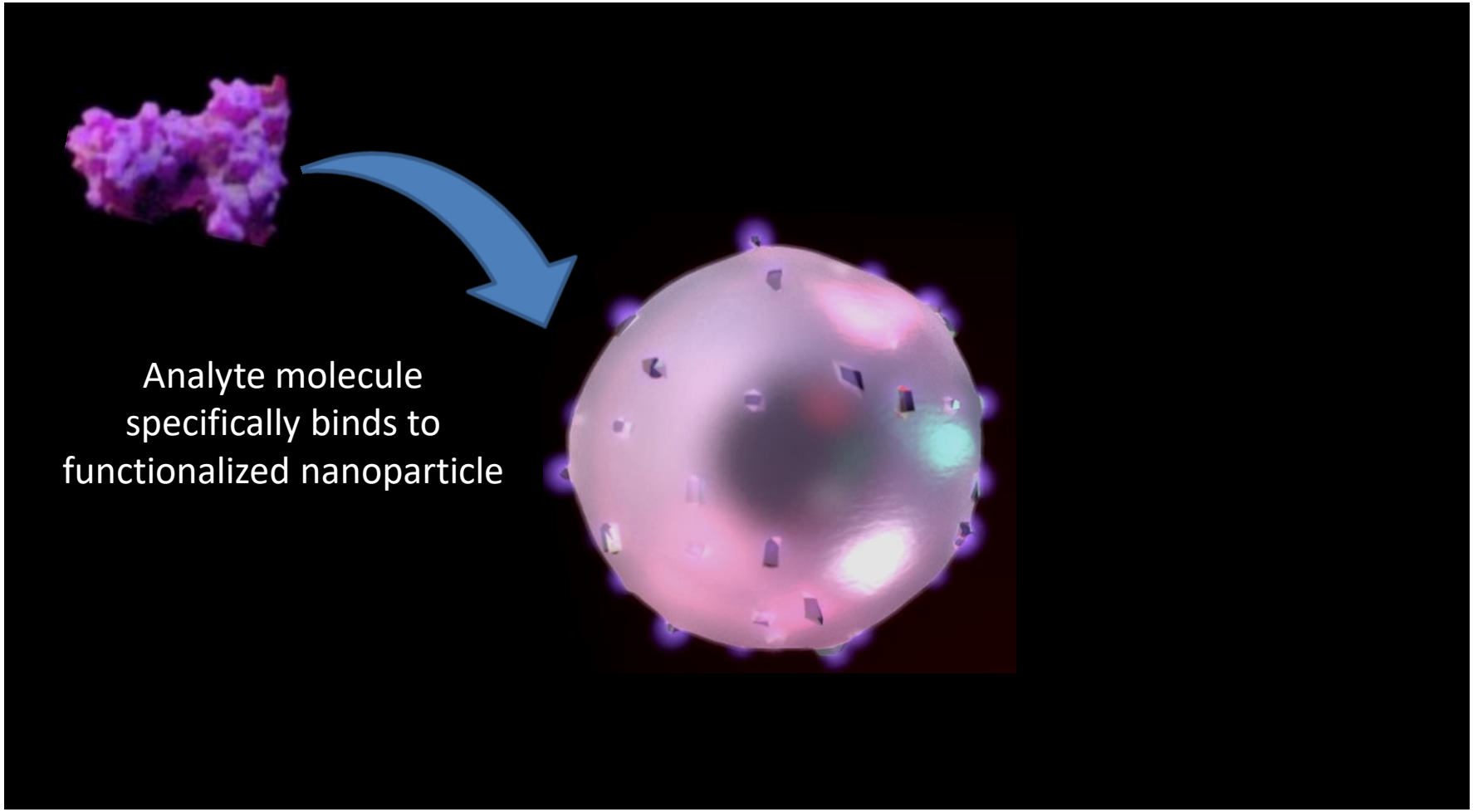
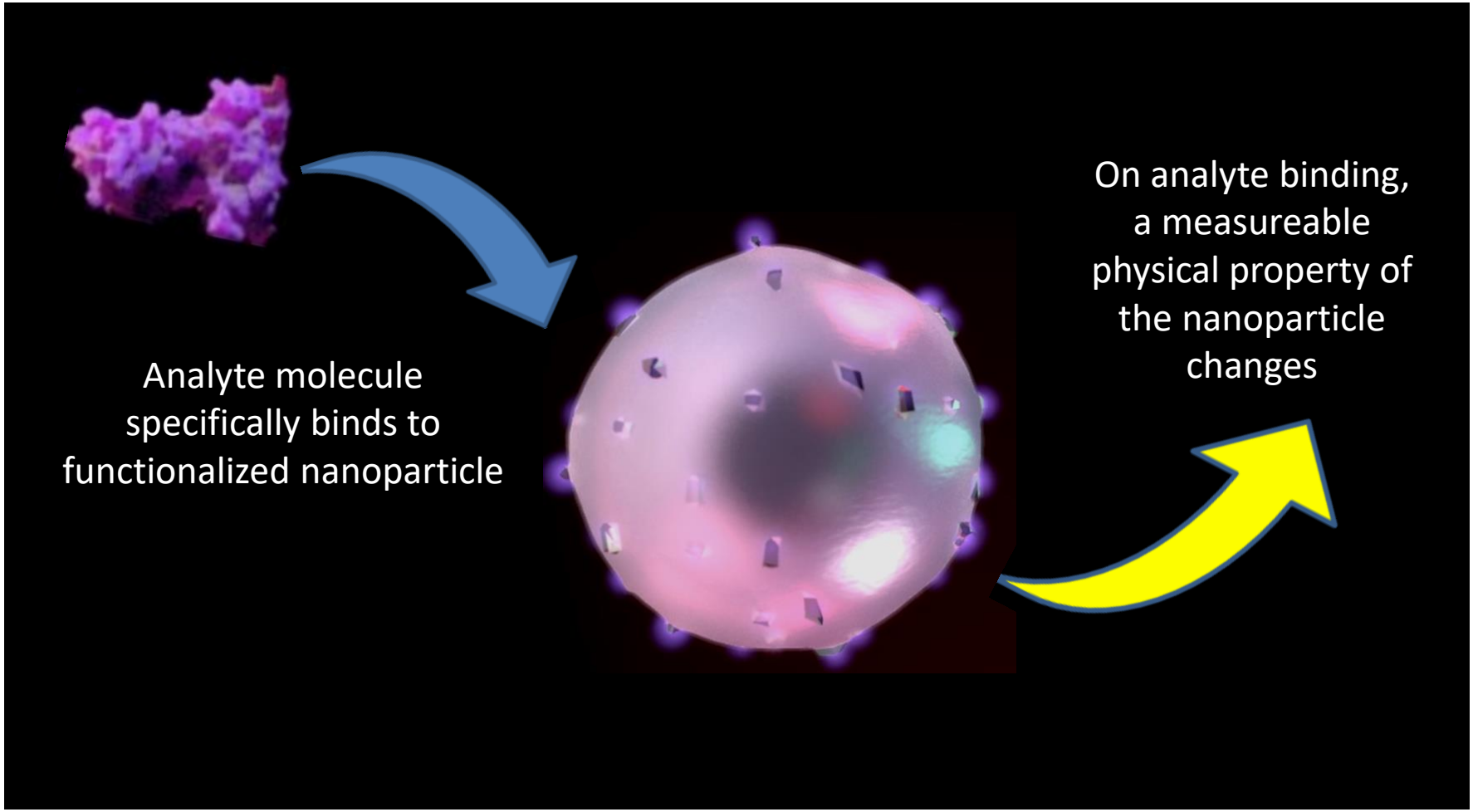


Scheme by Darragh Crotty, www.darraghcrotty.com

Introduction: nanoparticle-based homogeneous immunodiagnostics

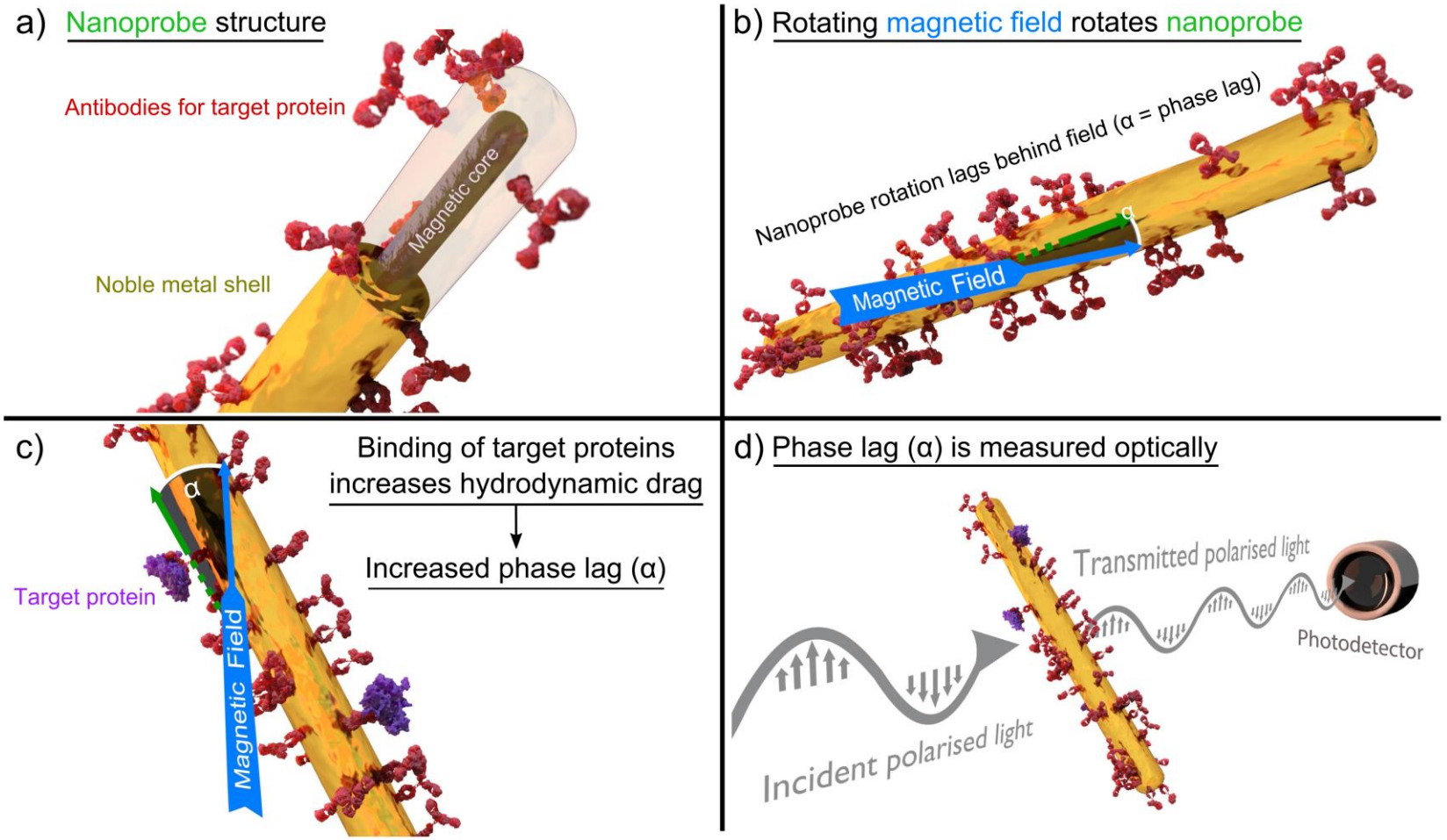
Mix & measure detection principle



Scheme by Darragh Crotty, www.darraghcrotty.com

Introduction: measurement principle

Rotational dynamics changes of magnetic nanorod probes on analyte binding



Animation by Darragh Crotty, www.darraghcrotty.com

S. Schrittwieser, F. Ludwig, J. Dieckhoff, K. Soulantica, G. Viau, L.-M. Lacroix, S. Mozo Lentijo, R. Boubekri, J. Maynadié, A. Huetten, H. Brueckl, J. Schotter. Modeling and development of a biosensor based on optical relaxation measurements of hybrid nanoparticles. ACS Nano 6 (2012) 791

S. Schrittwieser, B. Pelaz, W. J. Parak, S. Lentijo-Mozo, K. Soulantica, J. Dieckhoff, F. Ludwig, T. Altantzis, S. Bals, J. Schotter. Homogeneous protein analysis by magnetic core-shell nanorod probes. ACS Appl. Mater. Interfaces 8 (2016) 8893

Introduction: measurement principle

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Advantages of the technique

- **Simple mix & measure technique**
  - ⇨ Only minimal sample preparation requirements (e.g. sample loading)

- **Fast**
  - ⇨ Reduced incubation time due to 3d diffusion
  - ⇨ Continuous monitoring of binding events (real-time measurements)

- **Cost-effective**
  - ⇨ Easy to integrate & simple instrumentation
  - ⇨ Small sample volumes

→ Ideally suited for point-of-care applications

Introduction: measurement principle

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Possible applications of our measurement platform

Protein-protein interaction:

- Protein oligomerization (Alzheimer's and Parkinson's disease, spongiform encephalopathies or type II diabetes)

Protein-DNA interaction:

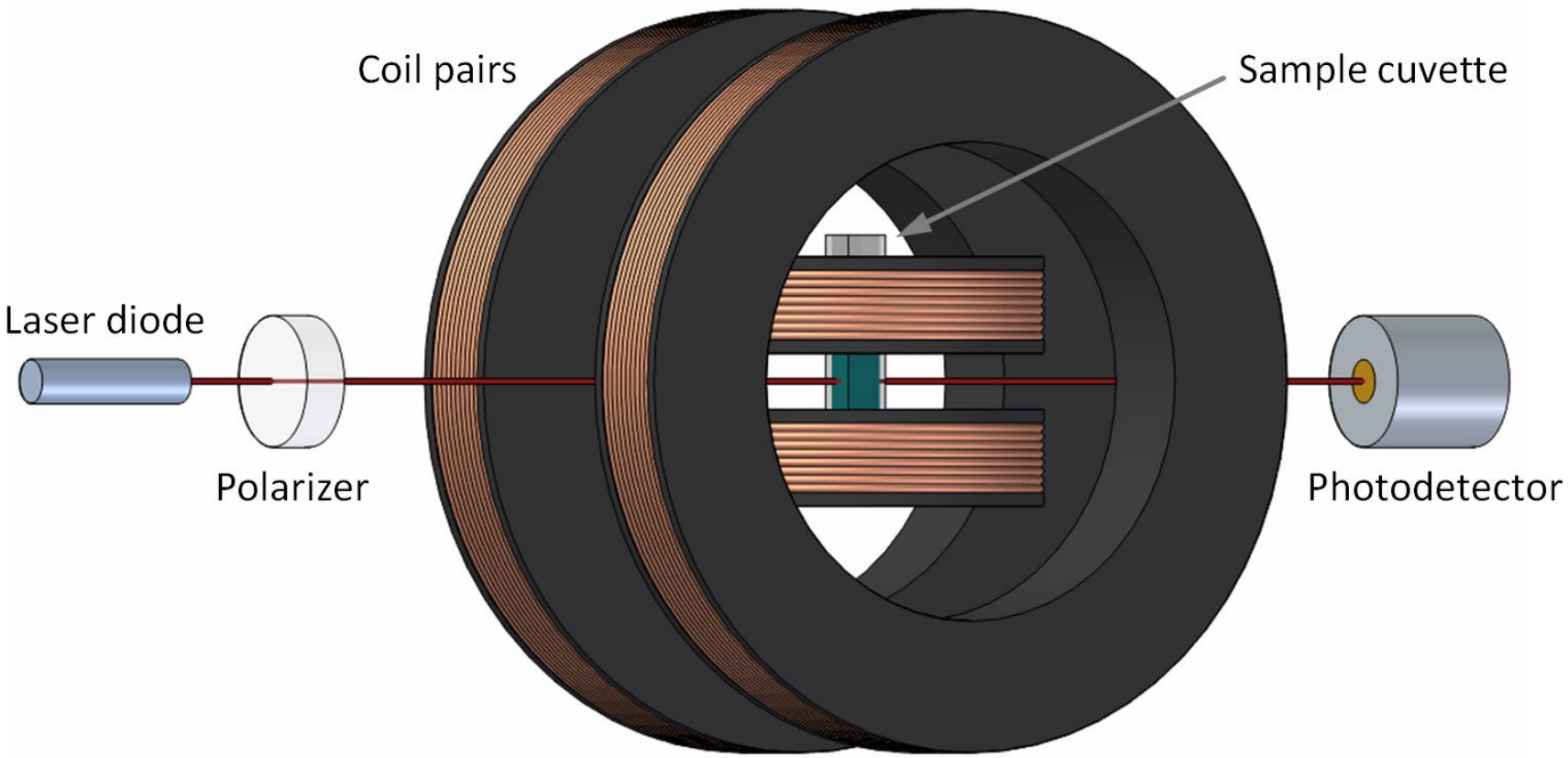
- Helicases and translocases (separating double-stranded DNA)
- Transcription factors (DNA looping in genomes for regulating specific gene activity)

Molecular diagnostics:

- Detection of biomarkers (cancer, inflammation, cardiovascular disease, traumatic brain injury, …)

Introduction: measurement setup

Schematic setup



S. Schrittwieser, F. Ludwig, J. Dieckhoff, A. Tschoepe, A. Guenther, M. Richter, A. Huetten, H. Brueckl, J. Schotter. Direct Protein Detection in the Sample Solution by Monitoring Rotational Dynamics of Nickel Nanorods. Small 10 (2014) 407

Introduction: nanoparticles

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Required nanoparticle properties for our measurement principle

- **Alignment can be manipulated by applied magnetic fields**
  - Uniaxial magnetic anisotropy & ferromagnetic at room temperature
- **Alignment can be measured by absorption of linearly polarized light**
  - Uniaxial optical anisotropy
  - Optical and magnetic anisotropy axis must be correlated
- **Antibody-functionalized particles stable in aqueous buffer solutions**
  - Prevention of oxidation
  - Prevention of agglomeration (single particle dispersions needed)
- **Measurable phase lag changes when analyte molecules bind to nanoparticles**
  - Hydrodynamic nanoparticle size of the order of analyte proteins (~100 nm)
- **Sufficient fabrication batch size**
  - Currently required for one measurement (10 pM in 200 µl): ~$1.2 \cdot 10^9$ particles

→ Best fulfilled by magnetic nanorods, ideally in combination with localized plasmon resonances

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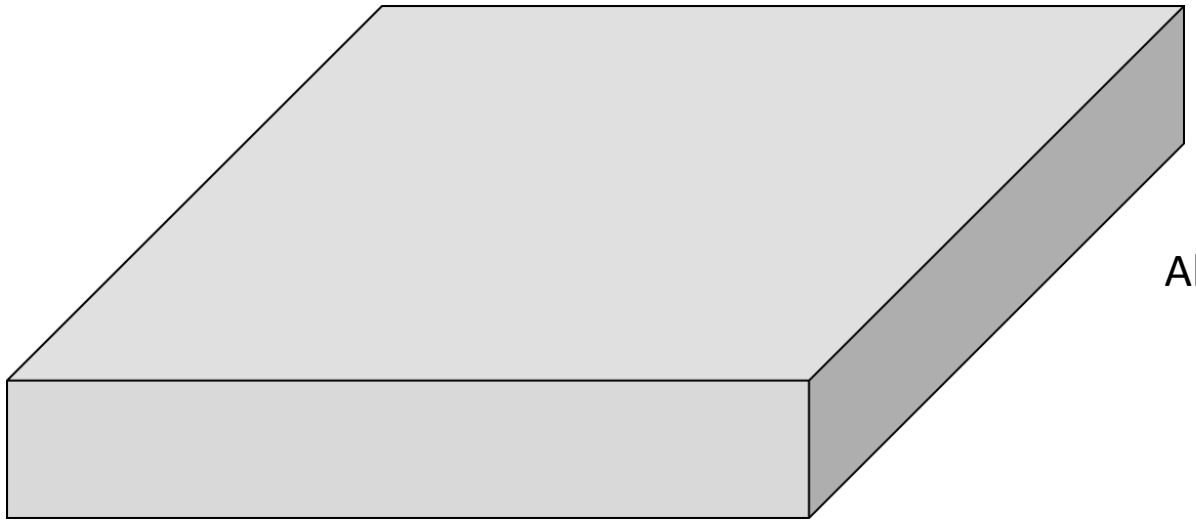
Electrodeposited Ni nanorods

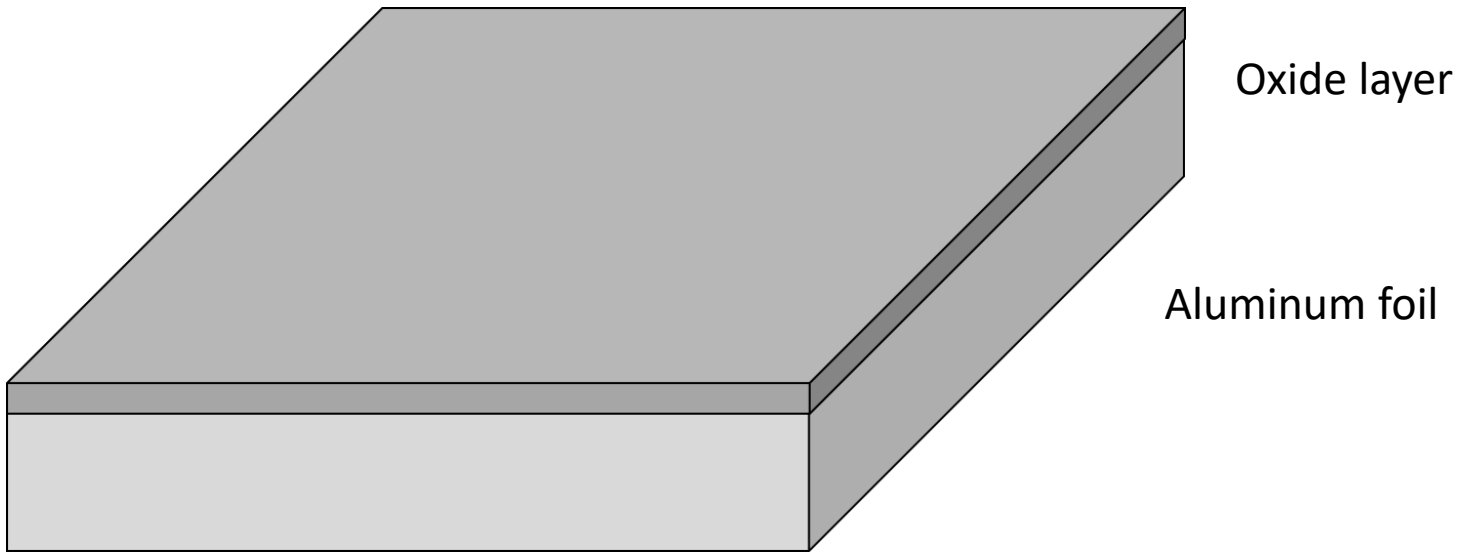
Schematic synthesis procedure



Aluminum foil

Electrodeposited Ni nanorods

Schematic synthesis procedure



Electrodeposited Ni nanorods

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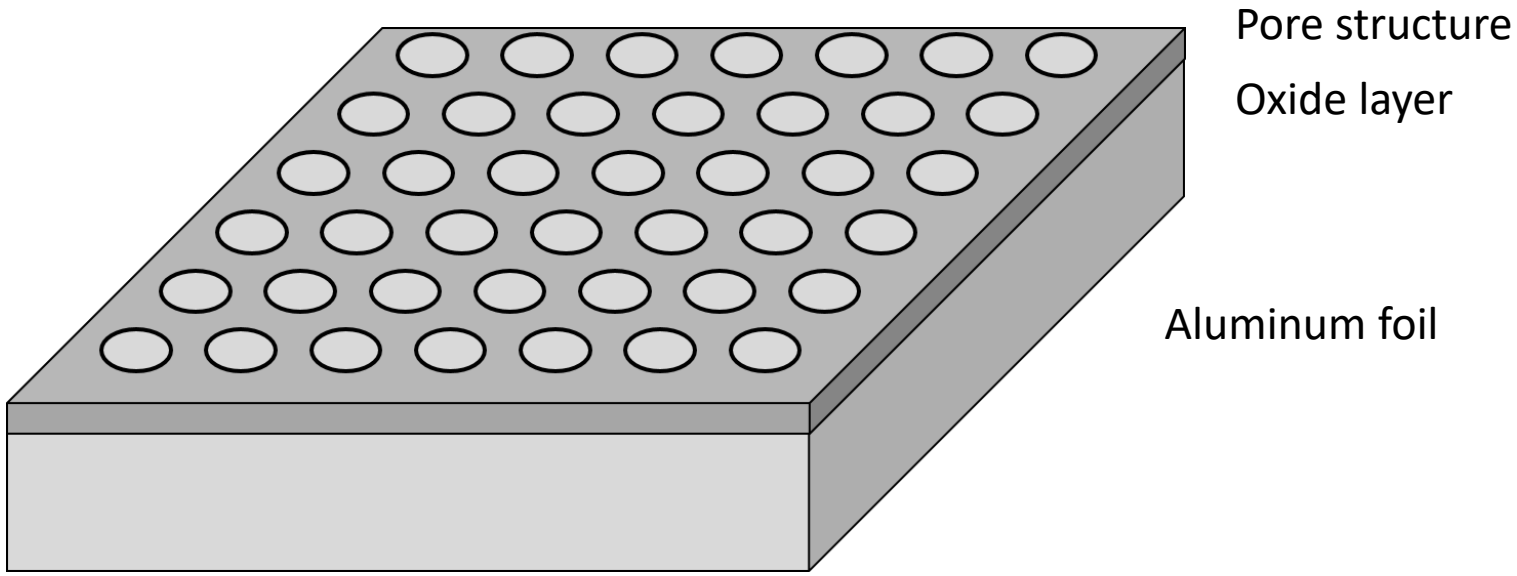
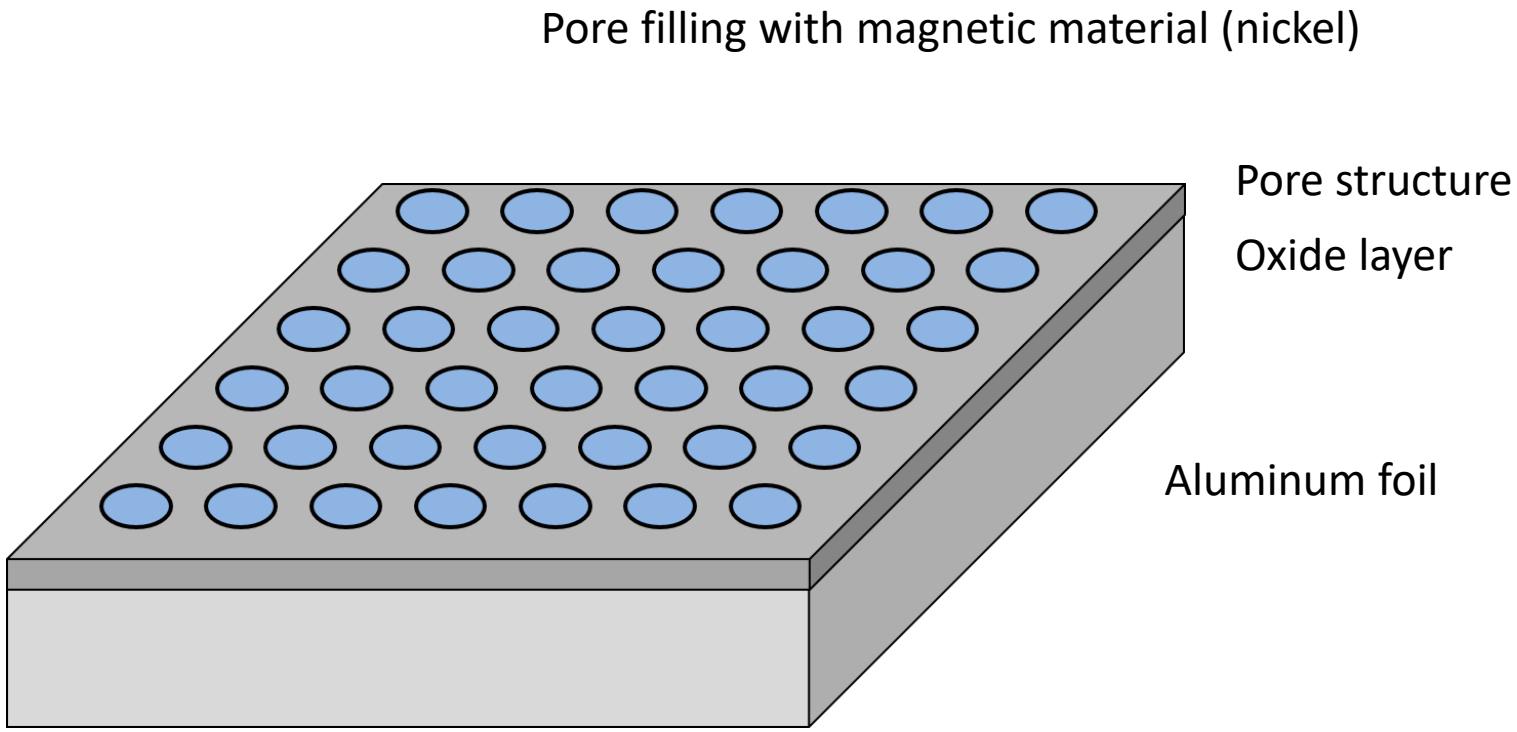


Electrodeposited Ni nanorods

Schematic synthesis procedure



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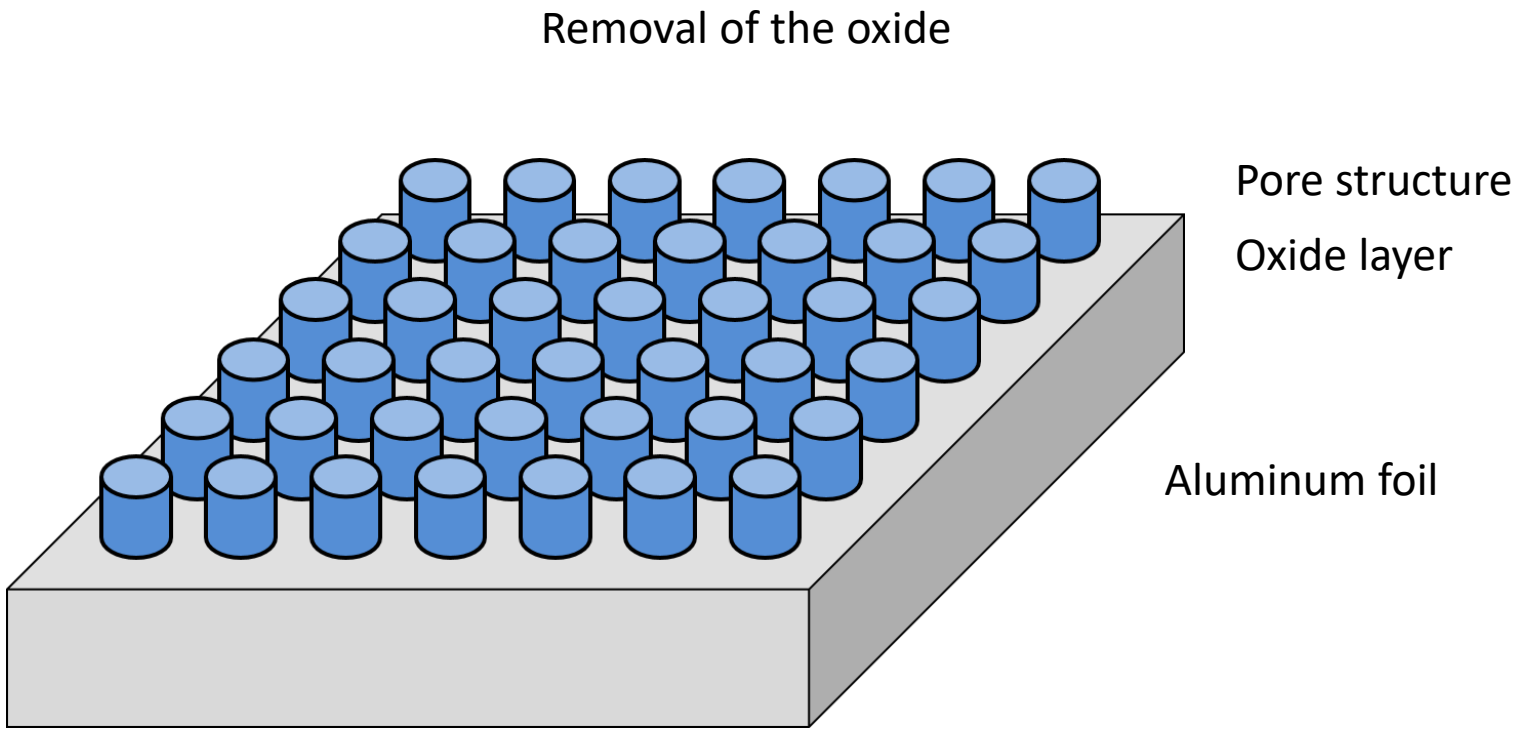
Schematic synthesis procedure



Electrodeposited Ni nanorods

Schematic synthesis procedure

Stabilization of the nanorods in solution to avoid particle agglomeration

Stabilization by suitable nanorod surface chemistry (electrostatic stabilization, steric stabilization)

Surface molecules for stabilization have to provide the possibility for further antibody functionalization

Electrodeposited Ni nanorods

Aluminum template fabrication – preparatory steps

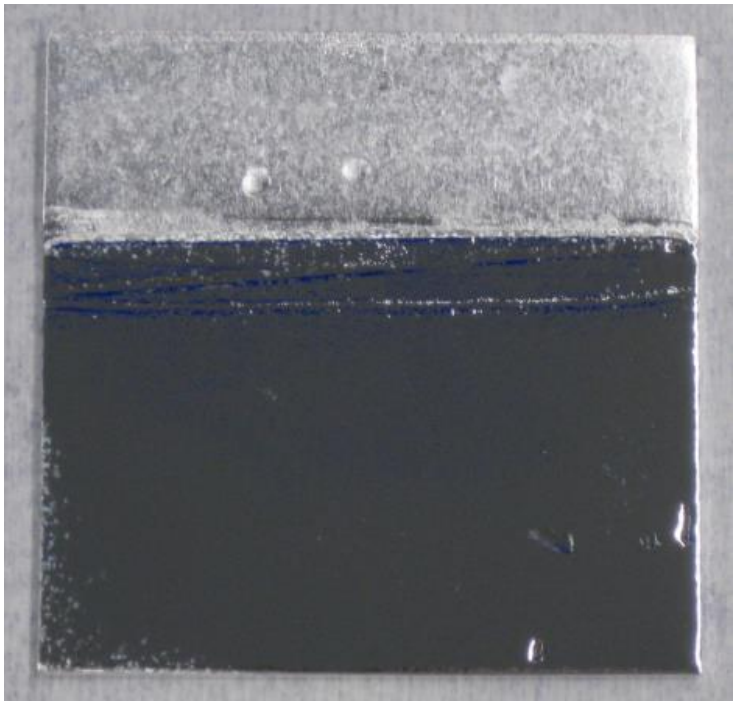
Commercial aluminum foils (5 cm x 5 cm)

Heating process to reduce mechanical stress
Vacuum oven for 2 h at 350°C (just once for every new foil)

Electropolishing to reduce surface roughness
Mixture of perchloric acid & ethanol, 400 s at 15 V (aluminum foil as anode, stainless steel sheet as cathode), 0°C

rough aluminum

electropolished



Electrodeposited Ni nanorods

Aluminum template fabrication – pore structure formation

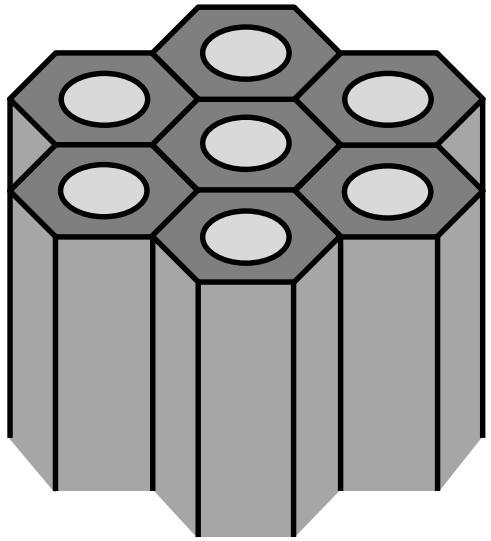
Anodization I
Sulfuric acid, overnight at 15 V (aluminum foil as anode, platinum wire as cathode), 2°C

Dissolving of Al_2O_3 and surface chromating
Mixture of chromic and phosphoric acid, 4 h, 60°C

Anodization II
Sulfuric acid, at 14 V (aluminum foil as anode, platinum wire as cathode), 2°C, end anodization once flow of overall charge quantity of 2 C/cm² is reached (~10 min)
=> ~ 800 nm pore length

Homogenization of pores
Phosphoric acid, 5 min at room temperature

Ordered hexagonal pore structure in the aluminum oxide layer



Electrodeposited Ni nanorods

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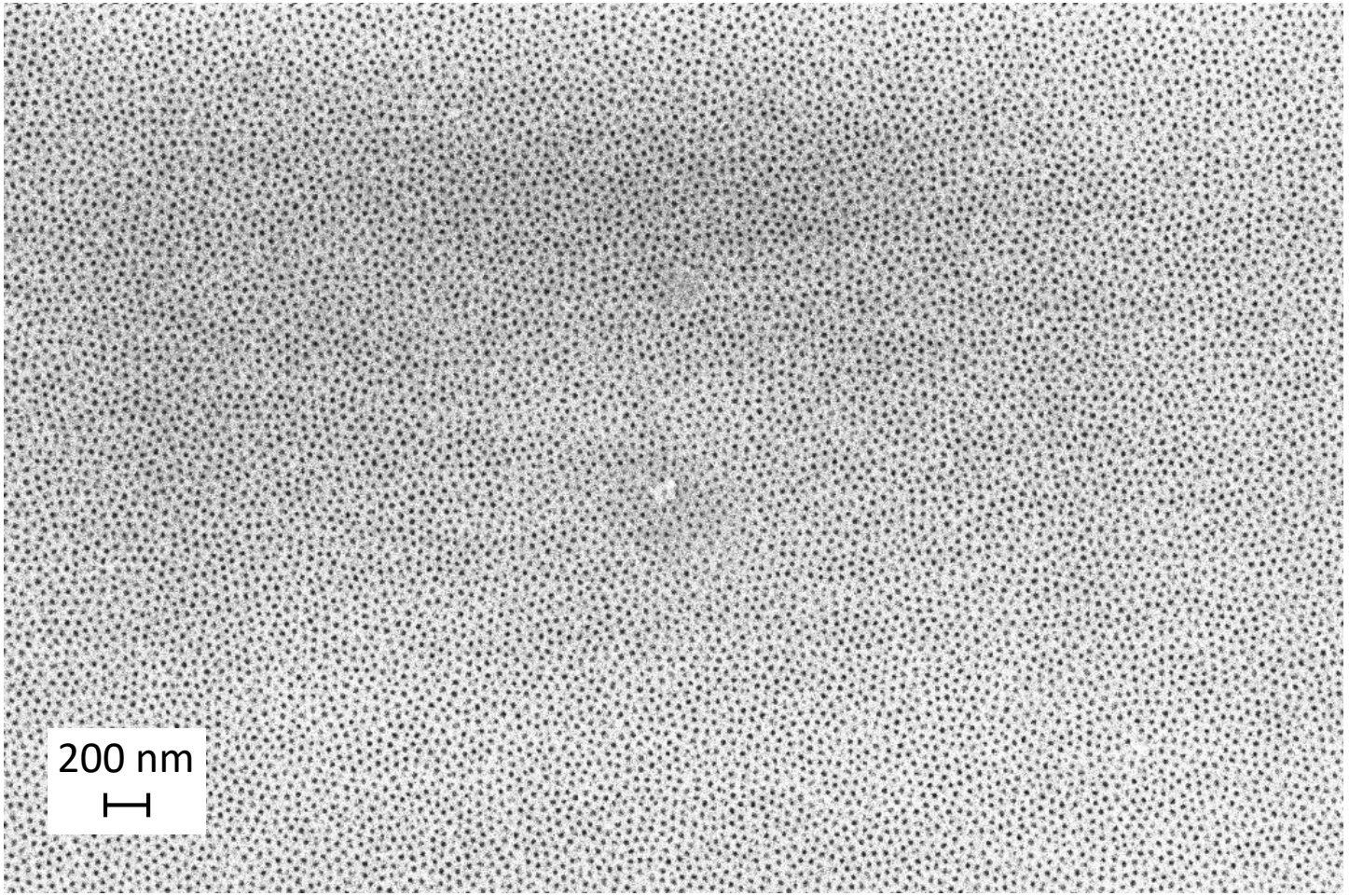
Aluminum template fabrication – pore structure formation



SEM image of the template surface with its pore structure

Pore diameter ~15 nm

Electrodeposited Ni nanorods

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Aluminum template fabrication – pore filling

Pulsed electrodeposition

Mixture of nickel salts and boric acid, overall current density of 50 mA /cm², 35°C

A single cycle:

Negative pulse duration 16 ms
Positive pulse duration 2 ms
Time till next cycle 200 ms

150 cycles for nanorod length of ~200 nm

Electrodeposited Ni nanorods

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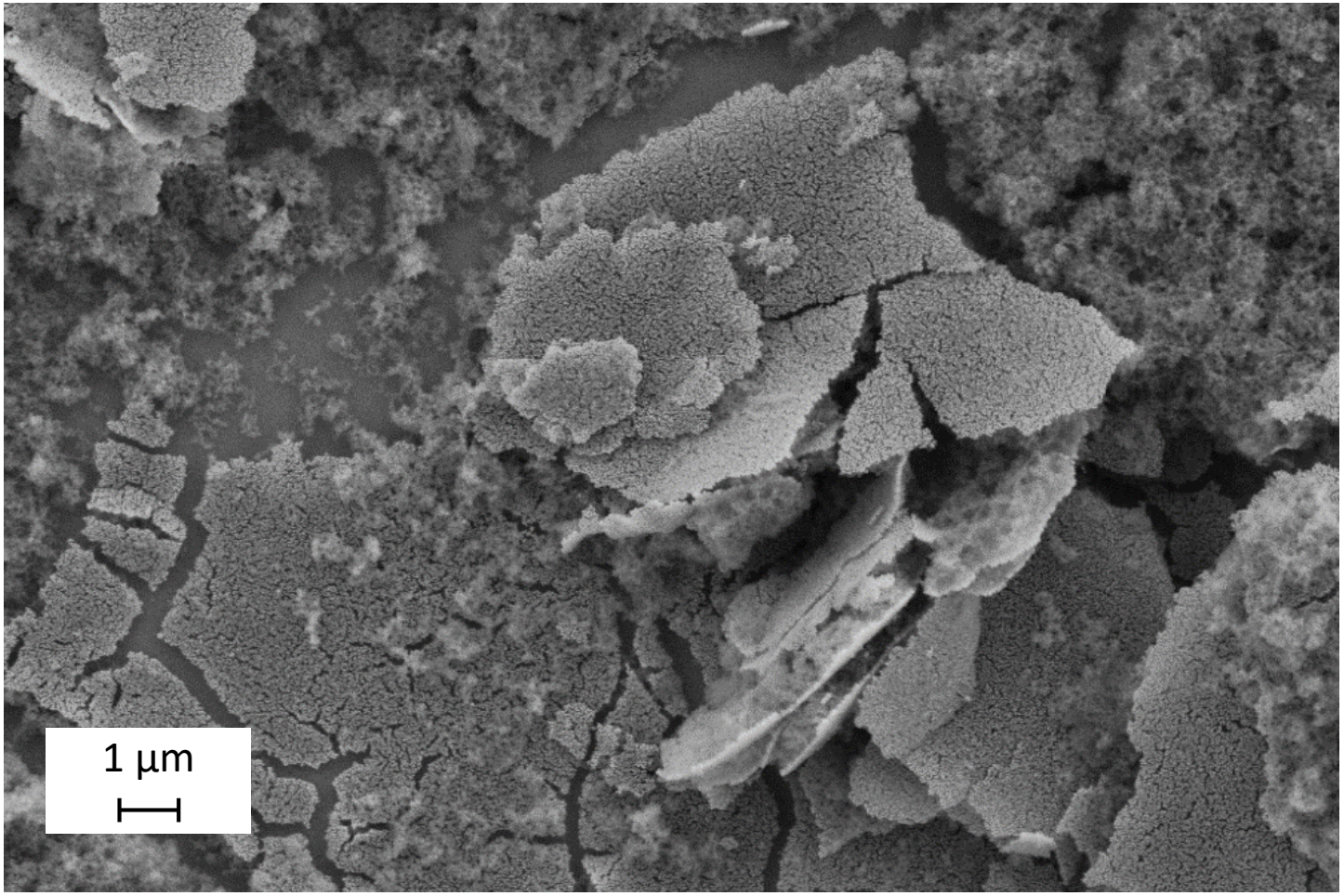
Partial oxide removal



SEM image of the nanorods still on the template in their ordered structure

Electrodeposited Ni nanorods

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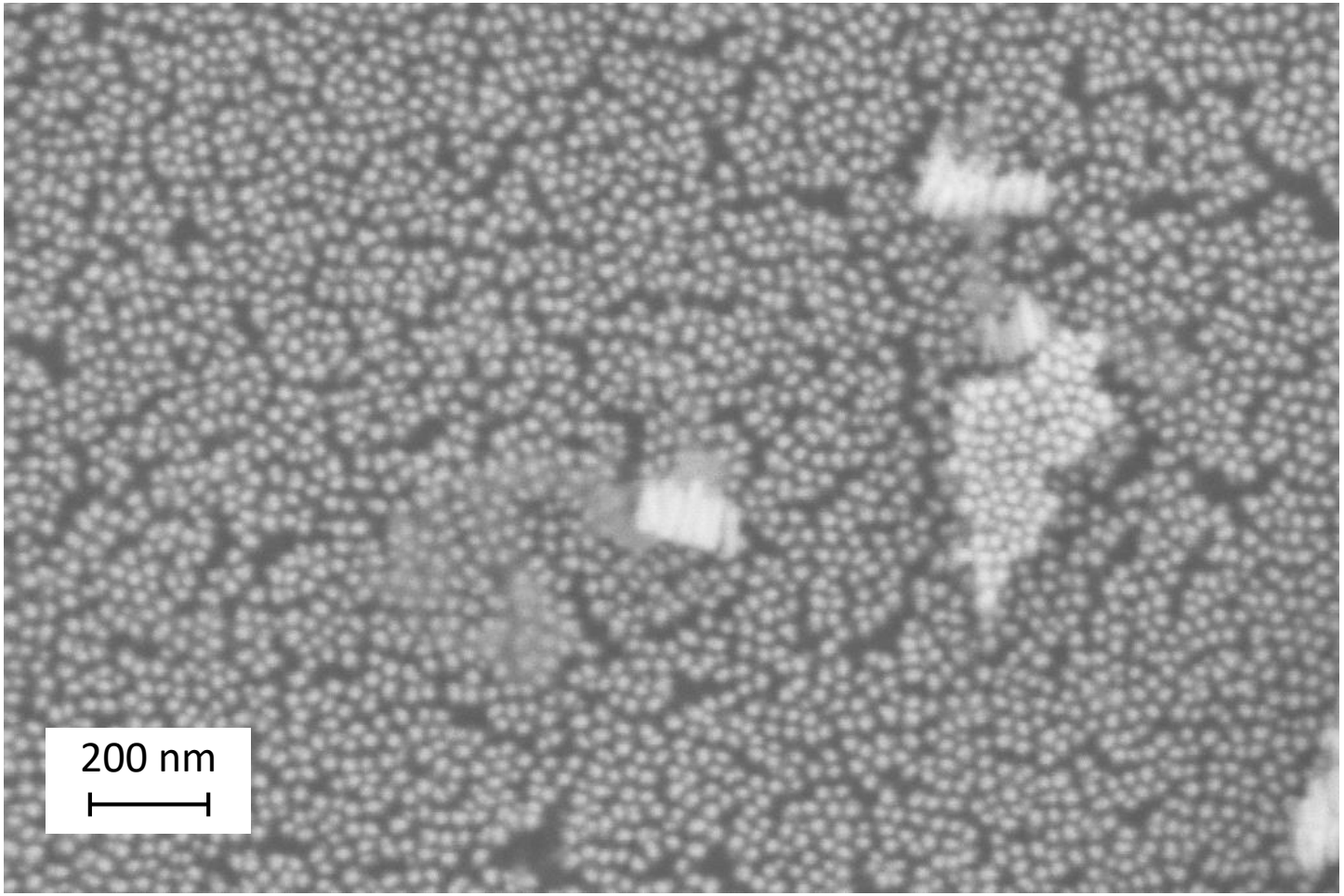
Partial oxide removal

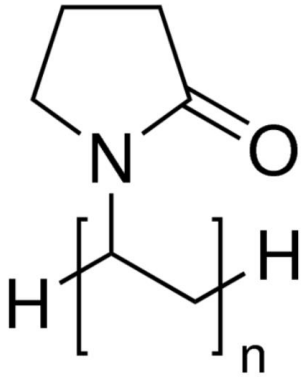


SEM image of the nanorods still on the template in their ordered structure

Electrodeposited Ni nanorods

Single particle dispersion - steric stabilization

Employed polymer: PVP (Polyvinylpyrrolidone)



Lactam ring binds to the nickel nanorod surface

Experimentally: Addition of PVP in NaOH solution (binding is a self-organized process)

=> Stable single-particle dispersion after a washing step to remove excess PVP

Electrodeposited Ni nanorods

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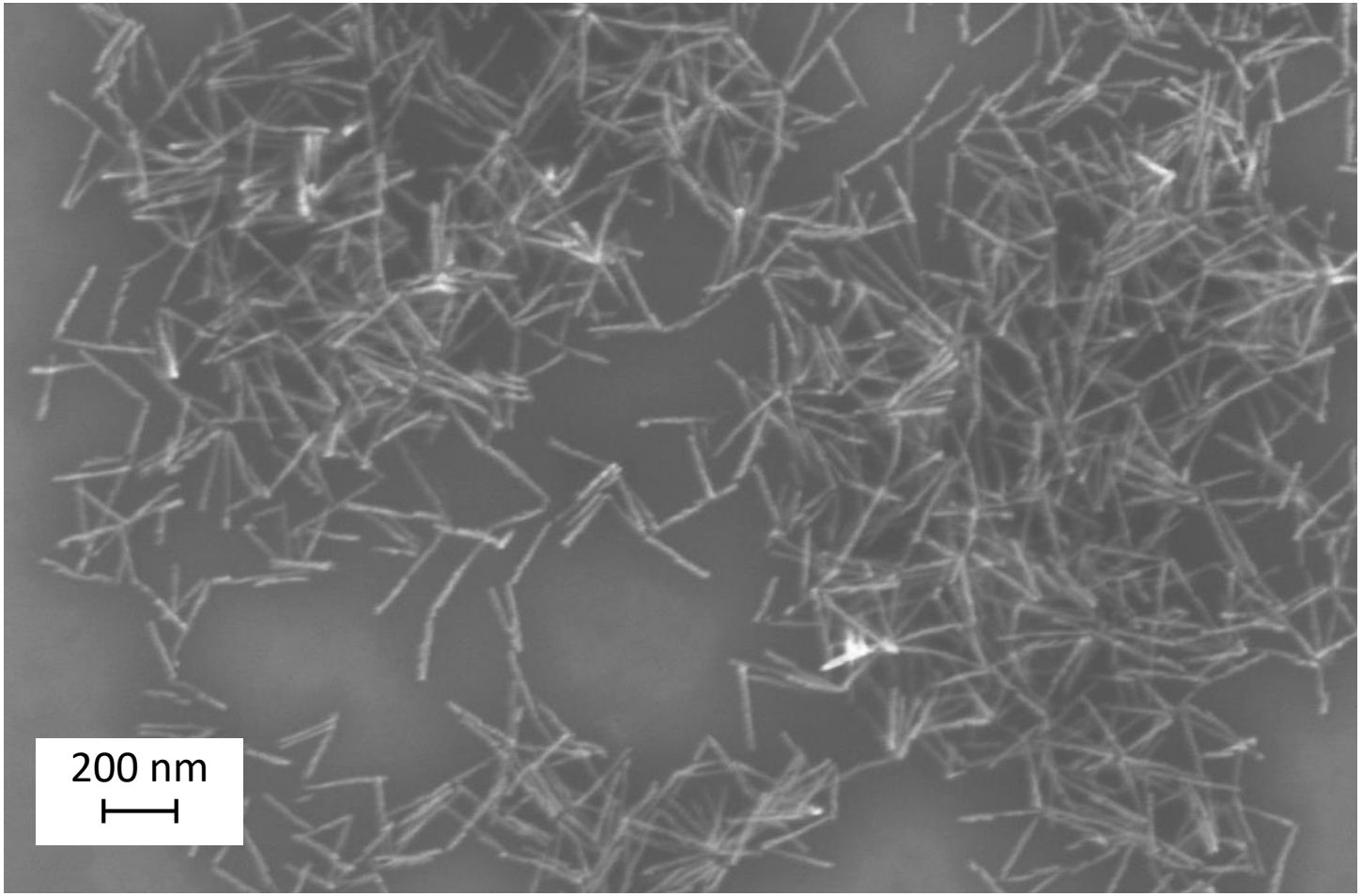
Single particle dispersion - steric stabilization



SEM image of the nanorods coated by PVP (stable nanorod dispersion)

Electrodeposited Ni nanorods

Single particle dispersion - steric stabilization

Advantage of PVP:

Stable single-particle dispersion

Disadvantage of PVP:

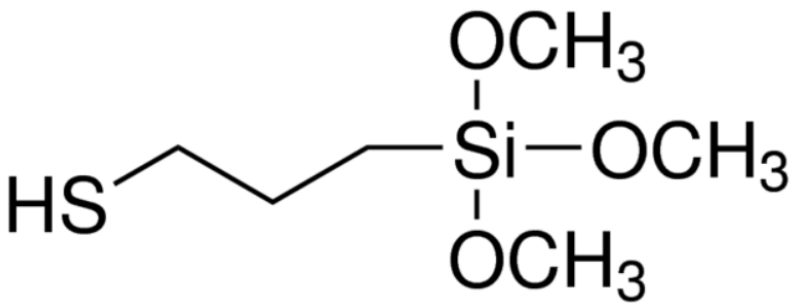
PVP is rather unreactive and does not allow for further binding of antibodies

But it serves as good positive control for further experiments

Electrodeposited Ni nanorods

Single particle dispersion - electrostatic stabilization

Employed molecule: MPTMS ((3-Mercaptopropyl)trimethoxysilane)



Binding of MPTMS to the nanorod surface through a silanization process

Experimentally: Addition of MPTMS and acetic acid to the nanorod solution (self organized process conducted overnight) & dialysis against water to remove excess reagents

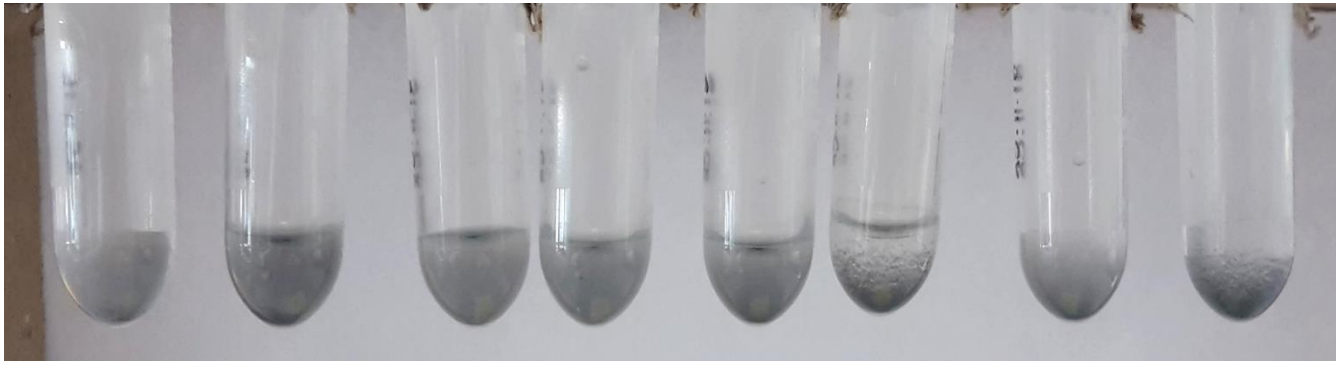
=> Stable single-particle dispersion via electrostatic repulsion

=> Possibility to further bind antibodies via the thiol group

Electrodeposited Ni nanorods

Single particle dispersion - electrostatic stabilization

Time after completed dialysis
3 days



1.) 2.) 3.) 4.) 5.) 6.) PC NC

1-6: different concentrations of MPTMS
PC: positive control (steric stabilization by PVP)
NC: negative control (no stabilizing reagents added)

Samples 3 & 4 look best
Stability period is long enough to prepare for further binding steps

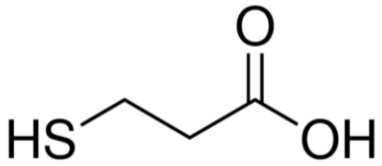
Electrodeposited Ni nanorods

Possible antibody functionalization strategies

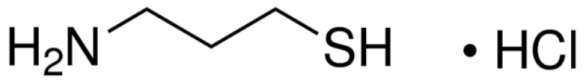
Two main possibilities:

- Directly bind thiol-modified antibodies to the free thiol group
- Use of an additional linker molecule to allow for EDC/S-NHS binding chemistry (amine-carboxy coupling)

3-Mercaptopropionic acid



3-Amino-1-propanethiol hydrochloride



Antibodies can be linked either via their free carboxy or their free amine groups

Electrodeposited Ni nanorods

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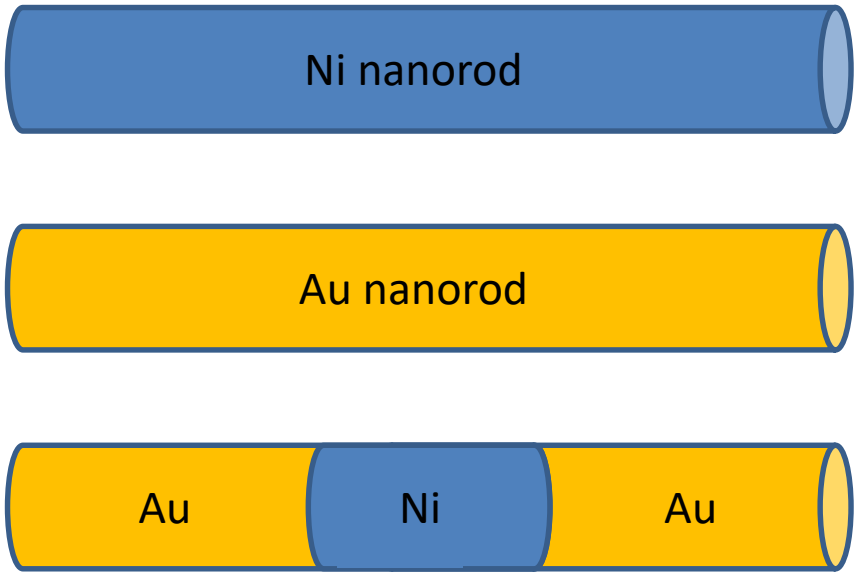
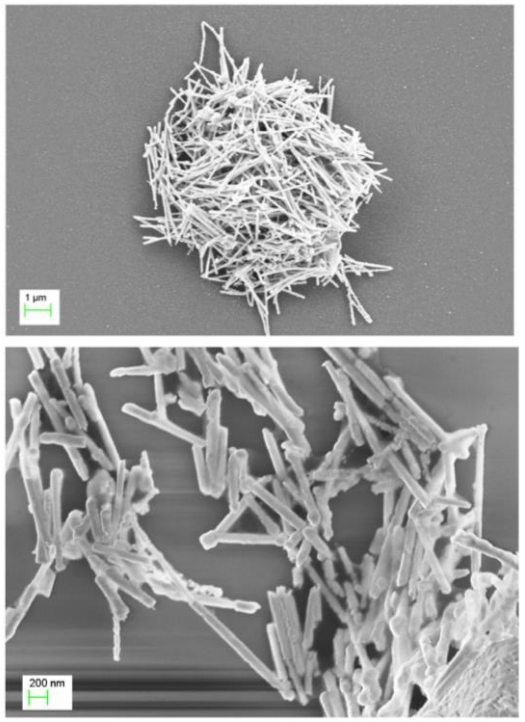
Aluminum template fabrication – pore filling

Pulsed electrodeposition with Au, Zn, etc.



Segmented nanorod



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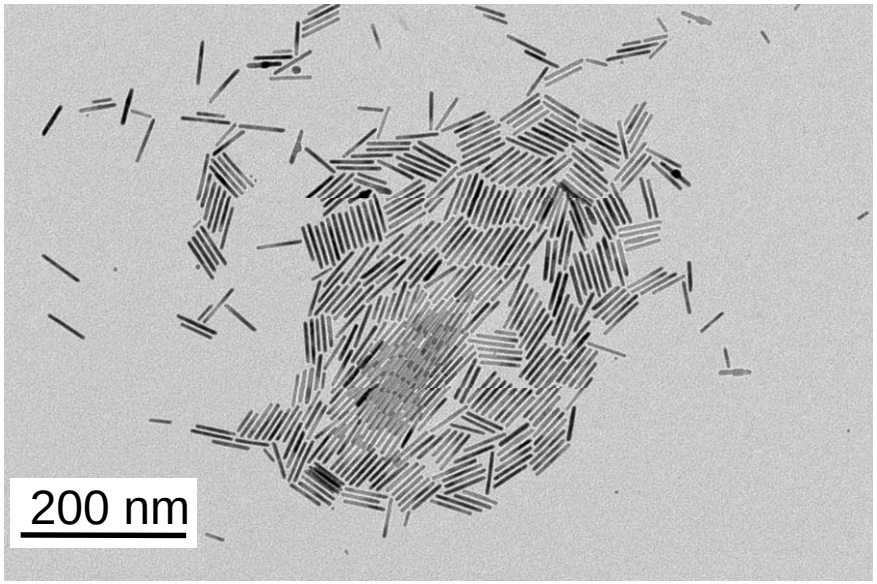
Noble-metal shell coated Co nanorods

Nanoprobes: noble-metal shell coated Co-nanorods

Co-nanorods synthesized by organometallic approach

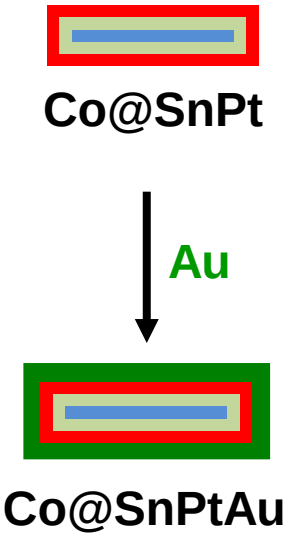
- Single crystalline hcp Co
- Usually dissolved in organic solvents with HDA as ligand

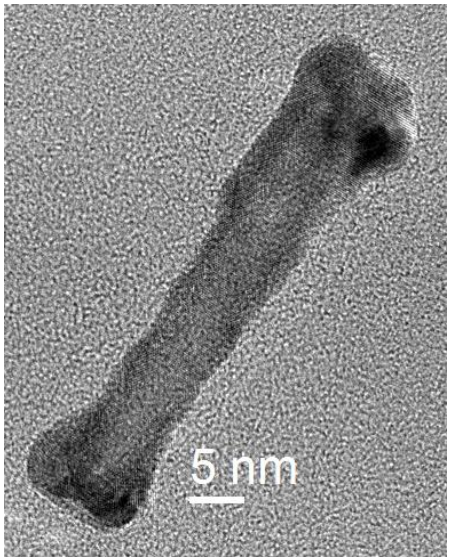


magnetic core length 40..200 nm
magnetic core Ø ~ 6 nm

Nobel metal coating procedure

- Sn interlayer on Co-nanorods reduces interface energy between Co and Pt/Au
- Overgrowth of Au on Pt-coated Co-nanorods





S. Lentijo-Mozo, R. P. Tan, C. Garcia-Marcelot, T. Altantzis, P.-F. Fazzini, T. Hungria, B. Cormary, J. R. Gallagher, J. T. Miller, H. Martinez, S. Schrittwieser, J. Schotter, M. Respaud, S. Bals, G. Van Tendeloo, C. Gatel, K. Soulantica. Air- and Water-Resistant Noble Metal Coated Ferromagnetic Cobalt Nanorods. ACS Nano 9 (2015) 2792

Noble-metal shell coated Co nanorods

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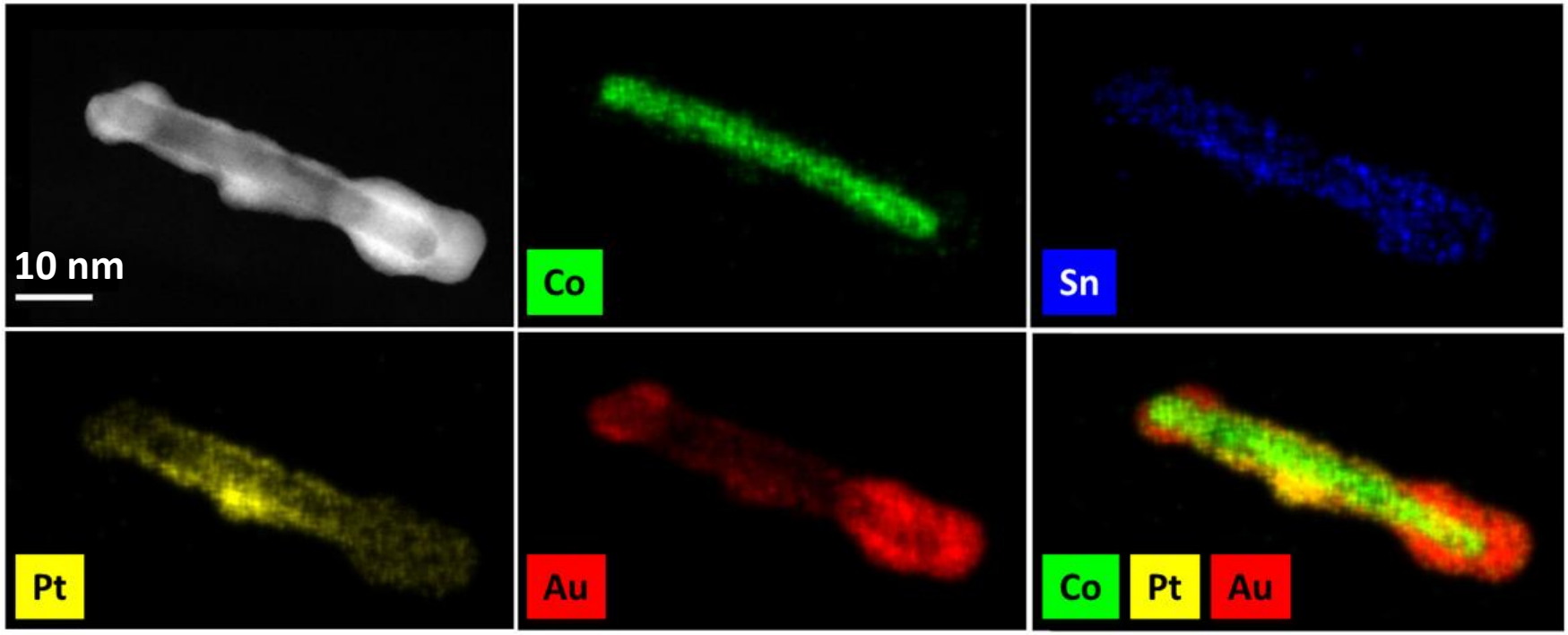
Nanoprobes: Pt/Au shell on Co core via Sn interlayer



- Preferential growth of Au where the Pt layer is thinner
- Shell protects Co-core against oxidation in water for > 9 weeks

→ Well suitable base material for nanoprobes

S. Lentijo-Mozo, R. P. Tan, C. Garcia-Marcelot, T. Altantzis, P.-F. Fazzini, T. Hungria, B. Cormary, J. R. Gallagher, J. T. Miller, H. Martinez, S. Schrittwieser, J. Schotter, M. Respaud, S. Bals, G. Van Tendeloo, C. Gatel, K. Soulantica. Air- and Water-Resistant Noble Metal Coated Ferromagnetic Cobalt Nanorods. ACS Nano 9 (2015) 2792

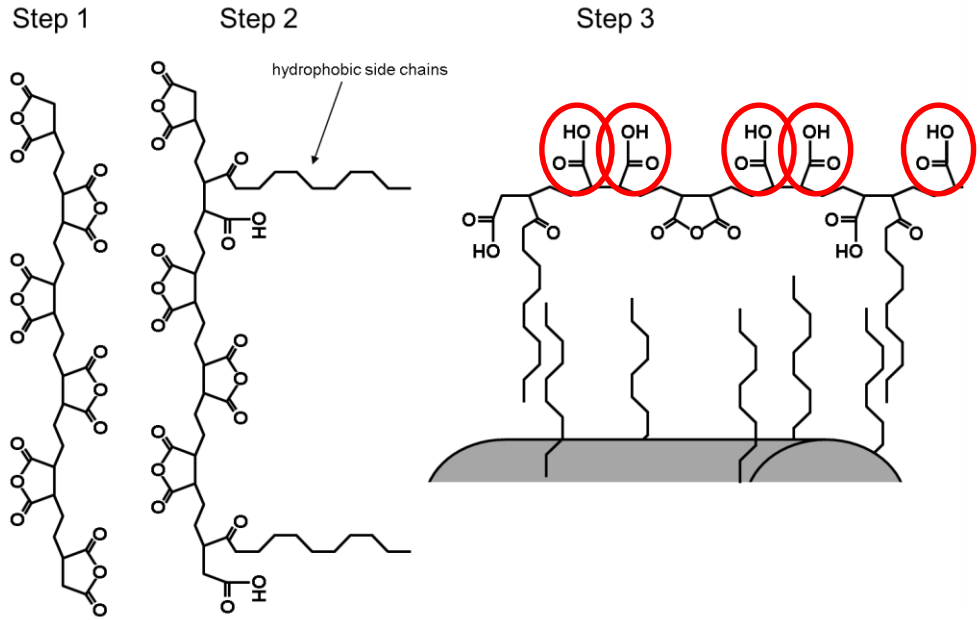
Noble-metal shell coated Co nanorods

Nanoprobes: water transfer and functionalization

- Coated Co-nanorods stabilized in organic solvent by hydrophobic surfactant
- Adsorption of an amphiphilic polymer (PMA = polymaleic anhydride)

  → breaking of the backbone rings into carboxy groups

  => water solubility and dispersion stabilization via electrostatic repulsion



- Functionalization by applying linker chemistry to the carboxy groups

S. Schrittwieser, B. Pelaz, W. J. Parak, S. Lentijo-Mozo, K. Soulantica, J. Dieckhoff, F. Ludwig, T. Altantzis, S. Bals, J. Schotter. Homogeneous protein analysis by magnetic core-shell nanorod probes. ACS Appl. Mater. Interfaces 8 (2016) 8893

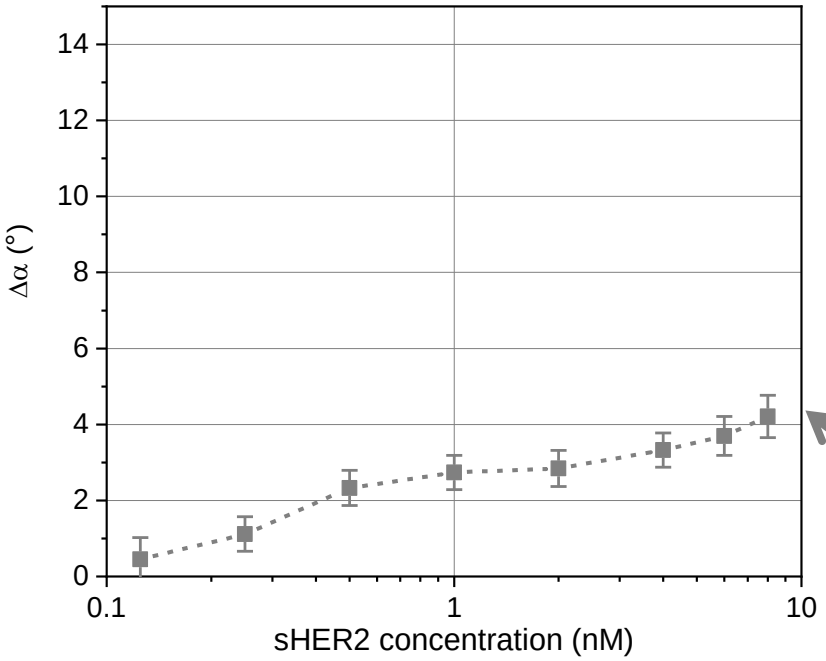
Noble-metal shell coated Co nanorods

Results for sHER2 detection – Signal vs. sHER2 concentration

Phase difference evolution with sHER2 concentration

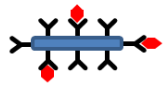
Nanorod conc.: 10 pM; mag. field: 10 mT & 1000 Hz

Buffer: 10 mM HEPES, 150 mM NaCl, 0.05 v% Tween 20, pH 7.4



analyte only spiked in buffer

LoD ~ 310 pM



S. Schrittwieser, B. Pelaz, W. J. Parak, S. Lentijo-Mozo, K. Soulantica, J. Dieckhoff, F. Ludwig, J. Schotter.
Direct protein quantification in complex sample solutions by surface-engineered nanorod probes. Scientific Reports 7 (2017) 4752

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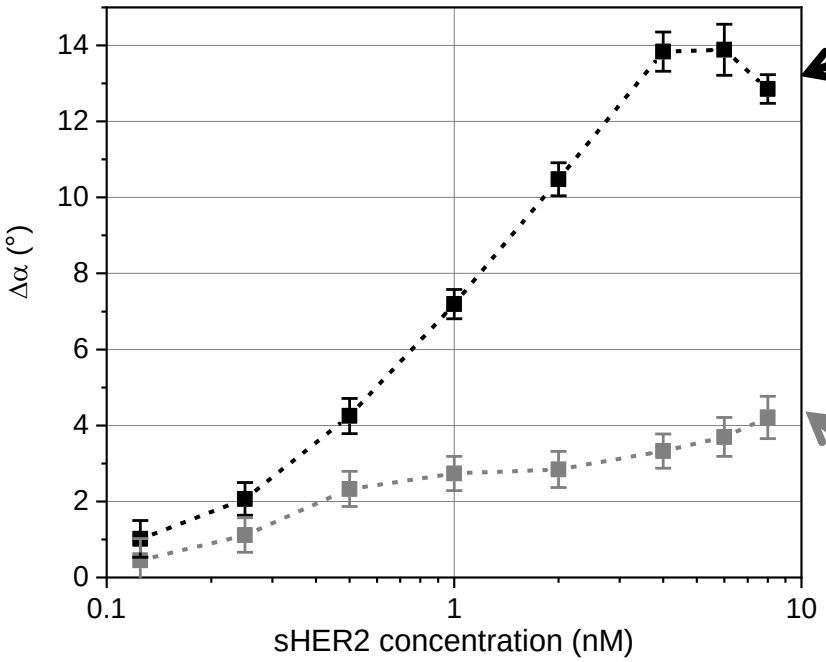
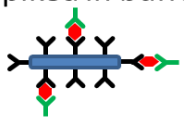
25 nM 2nd Ab



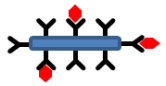
analyte & 2nd Ab spiked in buffer

LoD ~ 200 pM



analyte only spiked in buffer

LoD ~ 310 pM



- Secondary antibodies enhance signal & LoD

S. Schrittwieser, B. Pelaz, W. J. Parak, S. Lentijo-Mozo, K. Soulantica, J. Dieckhoff, F. Ludwig, J. Schotter.
Direct protein quantification in complex sample solutions by surface-engineered nanorod probes. Scientific Reports 7 (2017) 4752

Noble-metal shell coated Co nanorods

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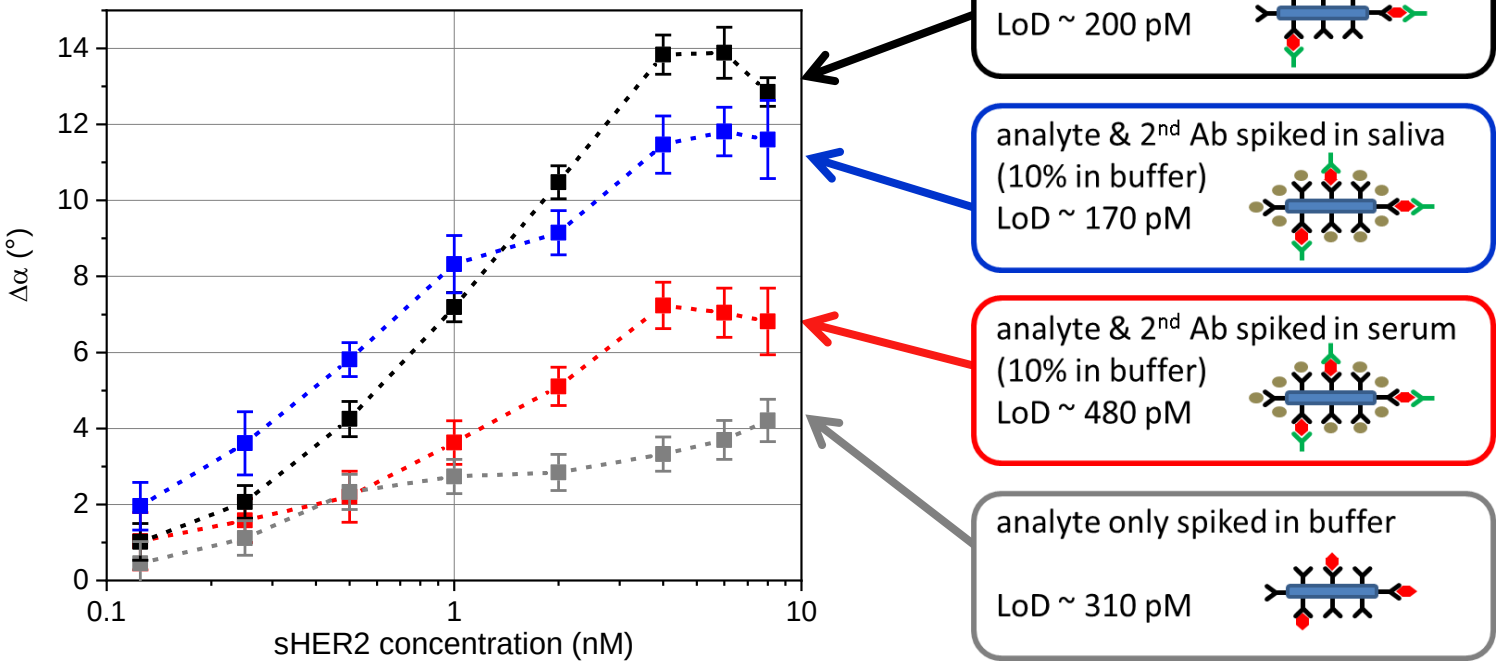
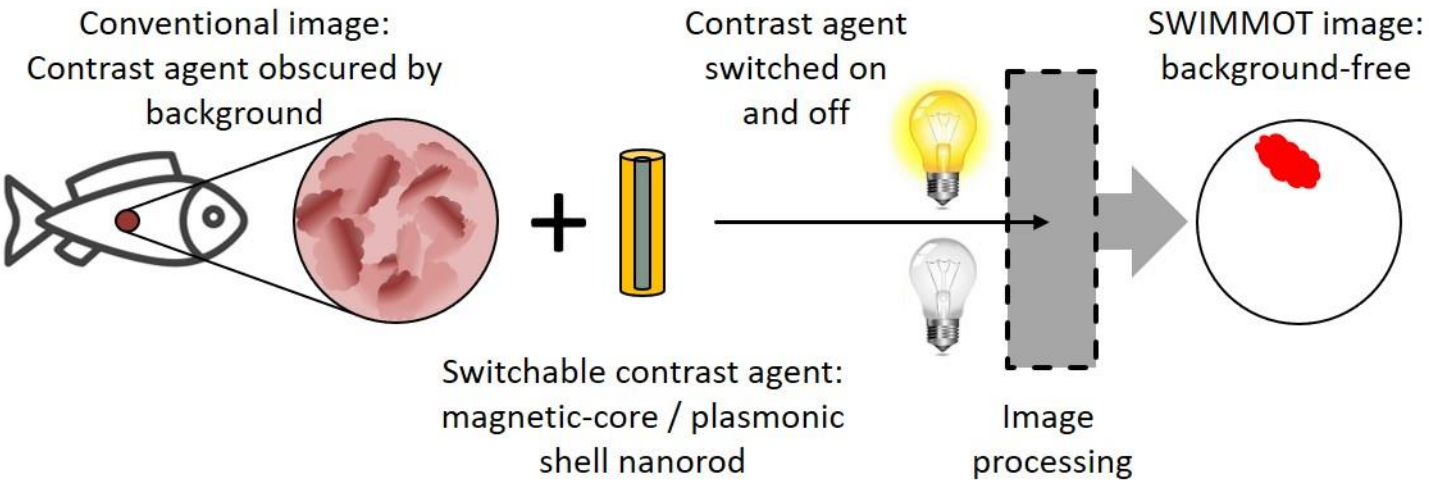


- Secondary antibodies required for real samples (protein corona formation)
- Extrapolated LoD in the lower nM regime (e.g. 1.7 nM for saliva)

S. Schrittwieser, B. Pelaz, W. J. Parak, S. Lentijo-Mozo, K. Soulantica, J. Dieckhoff, F. Ludwig, J. Schotter.
Direct protein quantification in complex sample solutions by surface-engineered nanorod probes. Scientific Reports 7 (2017) 4752

Noble-metal shell coated Co nanorods

Molecular imaging approach



Magneto-plasmonic imaging technique based on magnetic excitation and plasmonic signal generation to realize multimodal optical coherence tomography / photoacoustic imaging modes.

SWIMMOT project

SWIMMOT

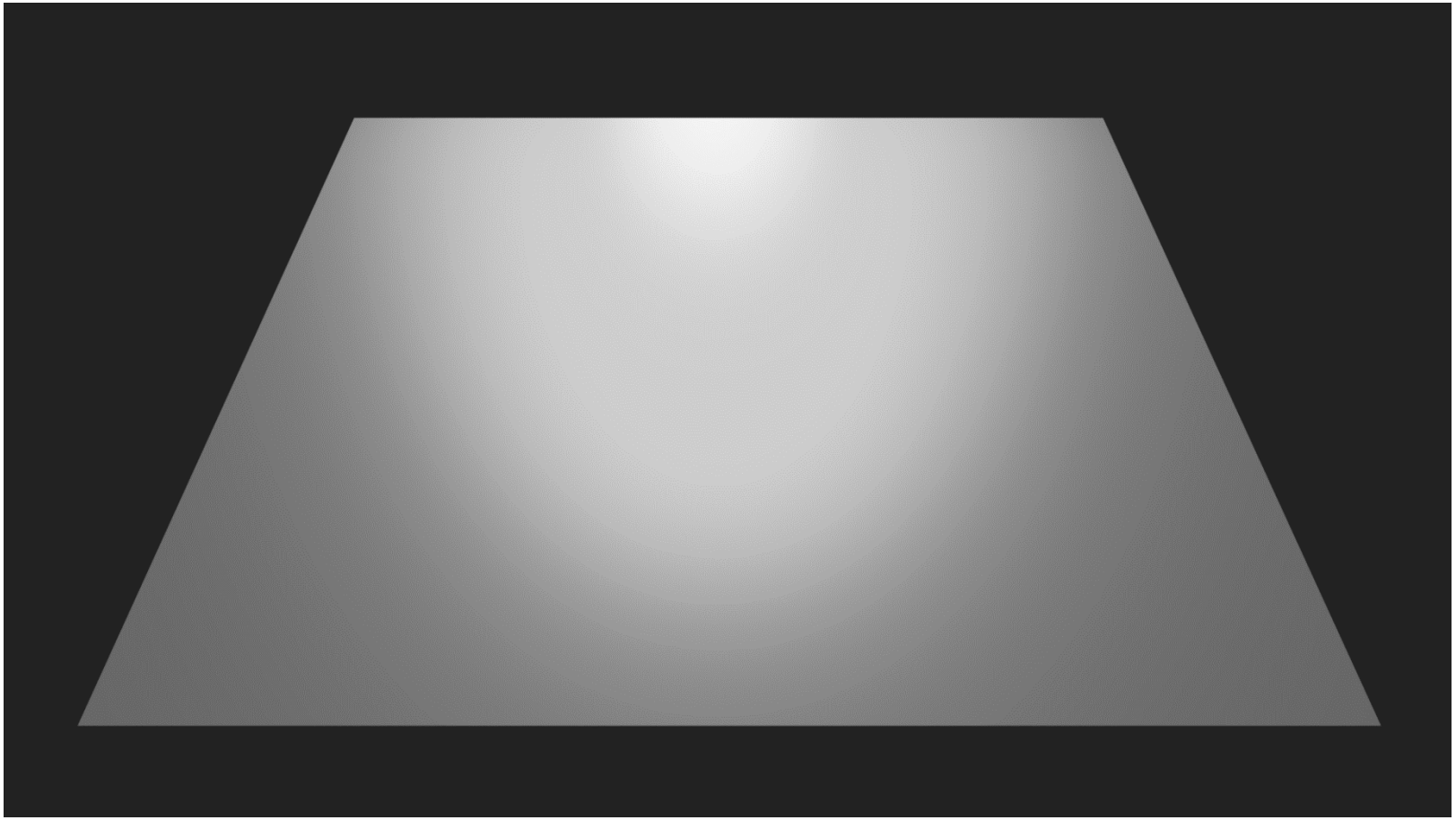
Outline

- **Introduction: Magnetic particles as probes for homogeneous diagnostics**
  - Motivation
  - Examples

- **Our approach: Observe changes in the dynamics of magnetic nanorod probes**
  - Measurement principle
  - Measurement setup
    - **Electrodeposited Ni nanorods**
      - Fabrication scheme
      - Surface modification
    - **Noble-metal shell coated Co nanorods**
      - Nanoprobe synthesis & characteristics
      - Protein results
    - **Nanoimprint lithography based nanoparticles**
      - Fabrication scheme
      - Surface modification

Nanoimprint lithography based nanoparticles

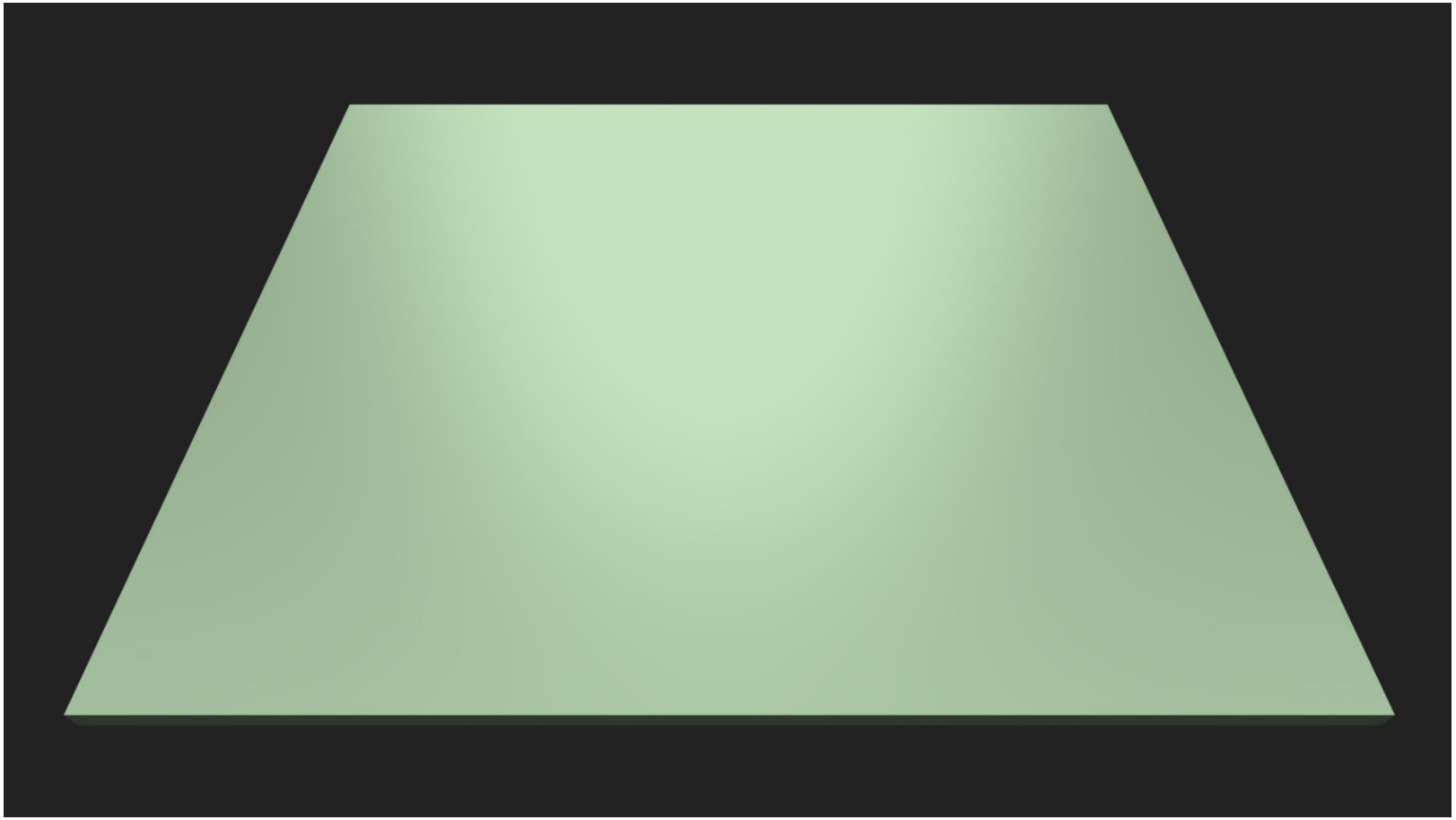
NIL-fabricated nanoparticles - fabrication technique



Si wafer

Nanoimprint lithography based nanoparticles

NIL-fabricated nanoparticles - fabrication technique



LOR resist deposition

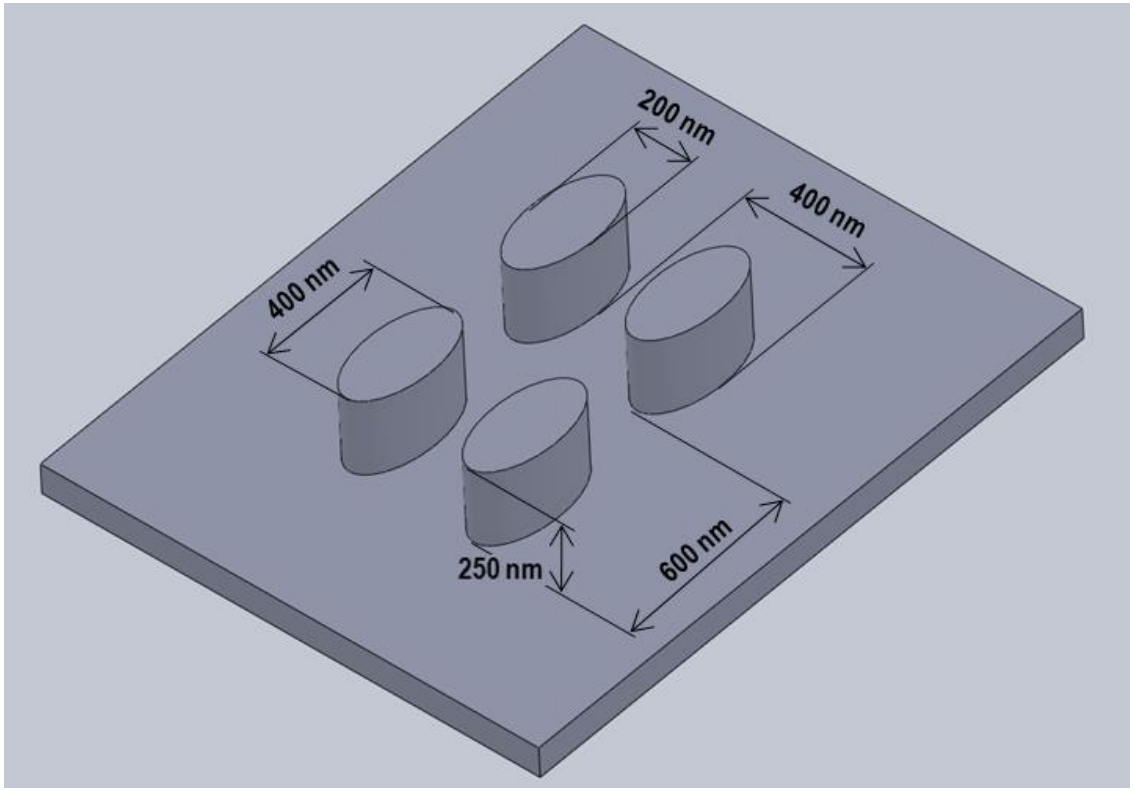
Nanoimprint lithography based nanoparticles

NIL-fabricated nanoparticles - fabrication technique

NIL resist deposition

Nanoimprint lithography based nanoparticles

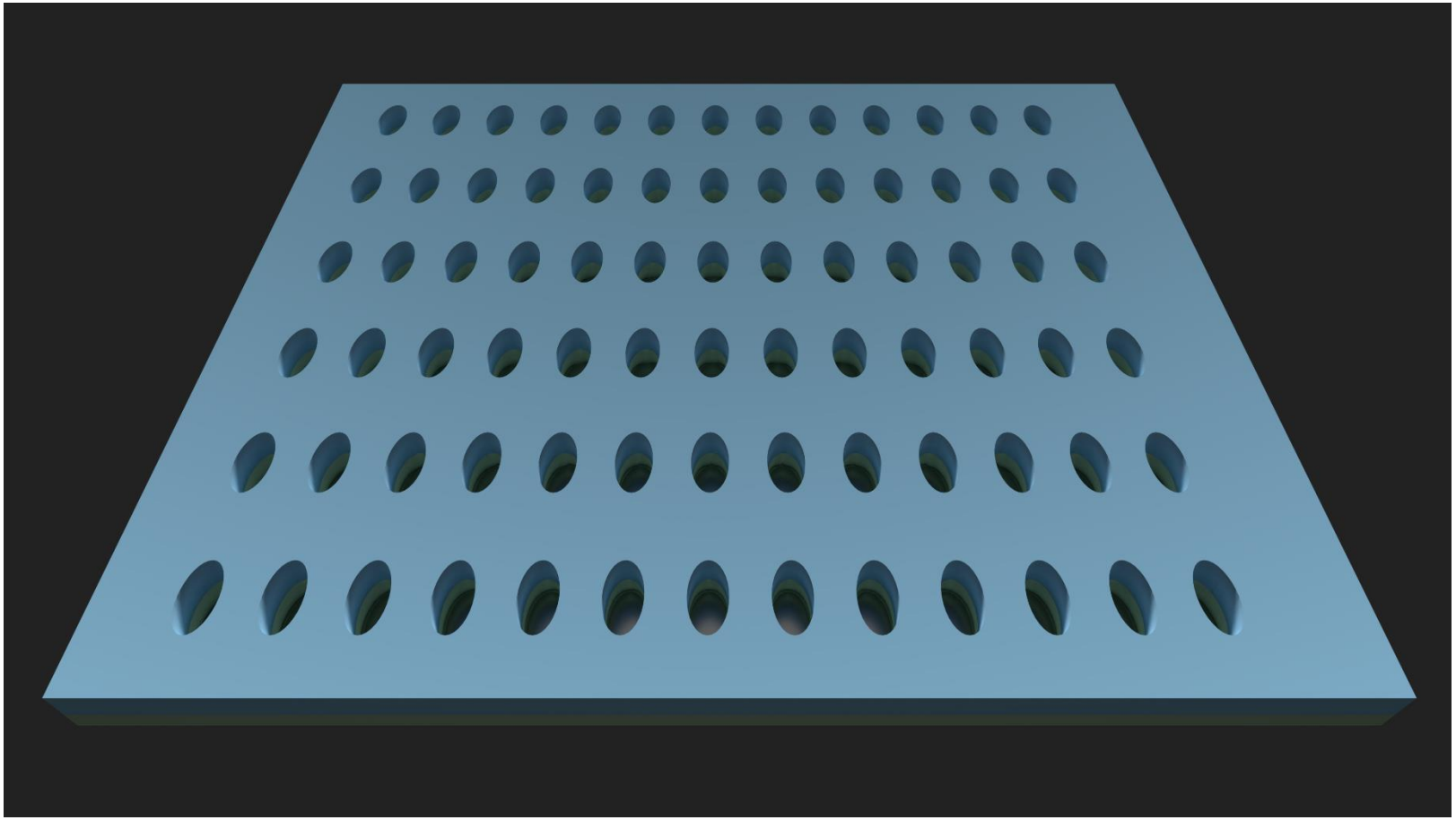
NIL-fabricated nanoparticles - fabrication technique



NIL stamp master parameters

Nanoimprint lithography based nanoparticles

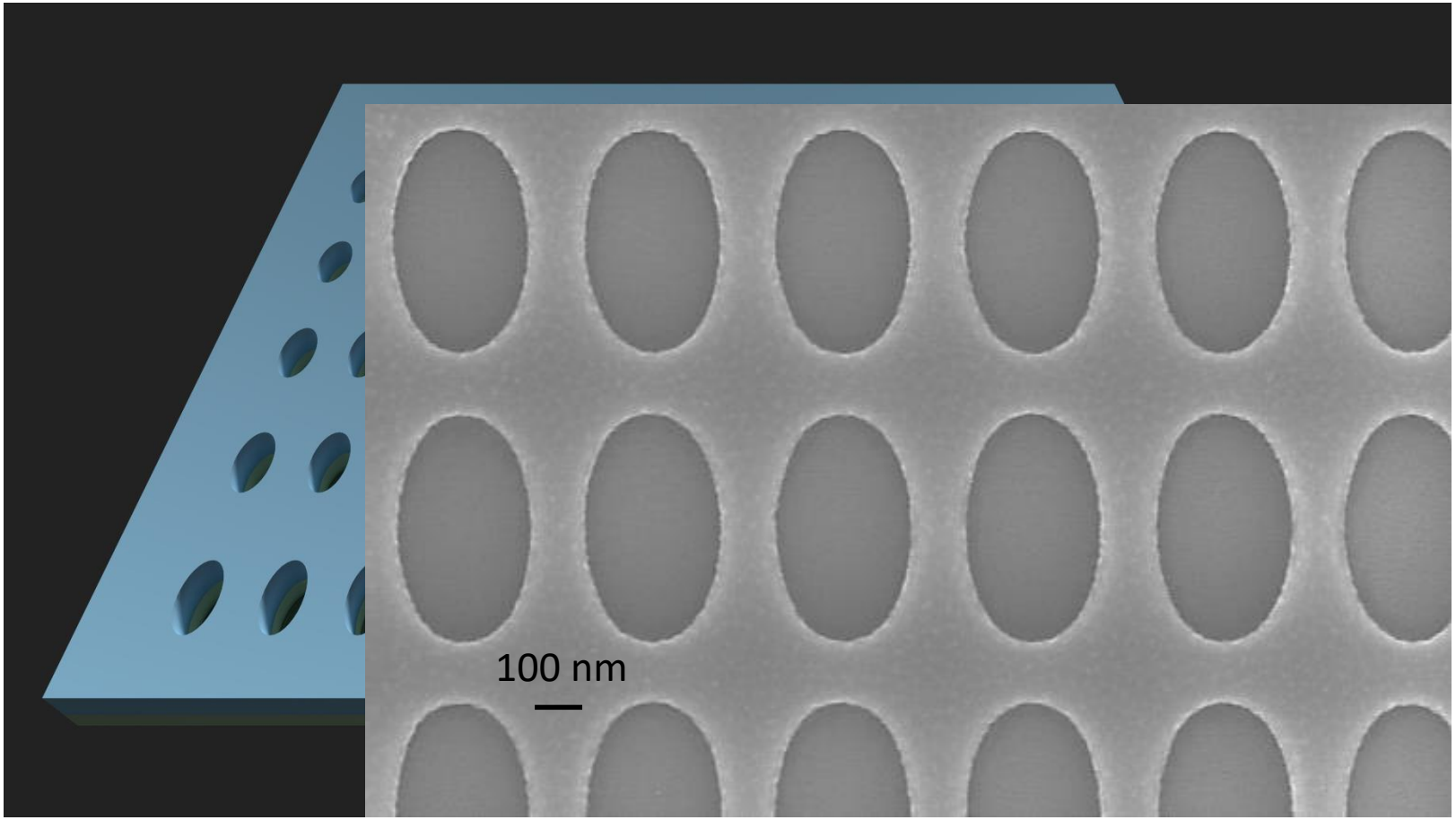
NIL-fabricated nanoparticles - fabrication technique



Imprint and curing of the resist
by UV exposure

Nanoimprint lithography based nanoparticles

NIL-fabricated nanoparticles - fabrication technique



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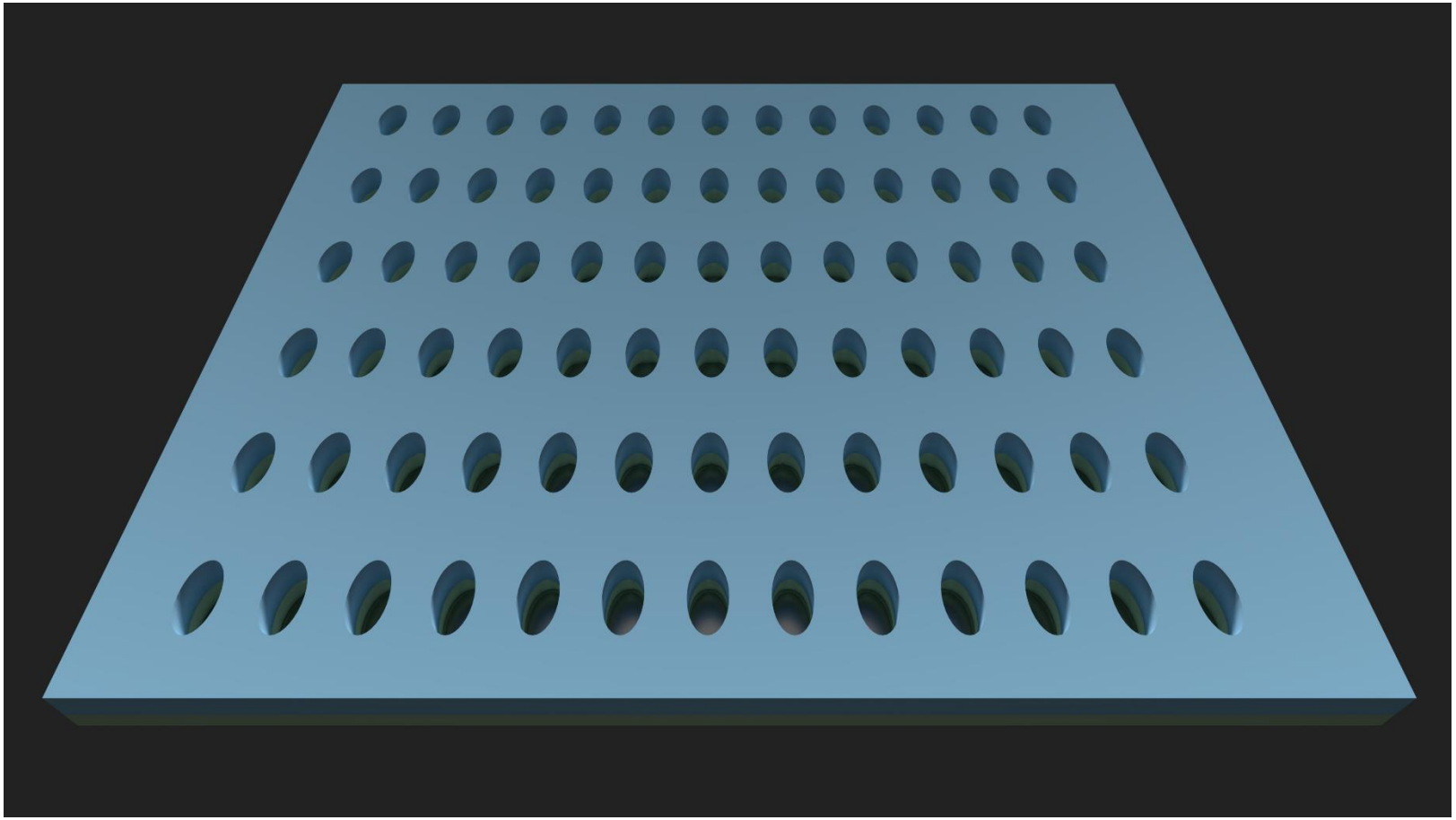
Nanoimprint lithography based nanoparticles

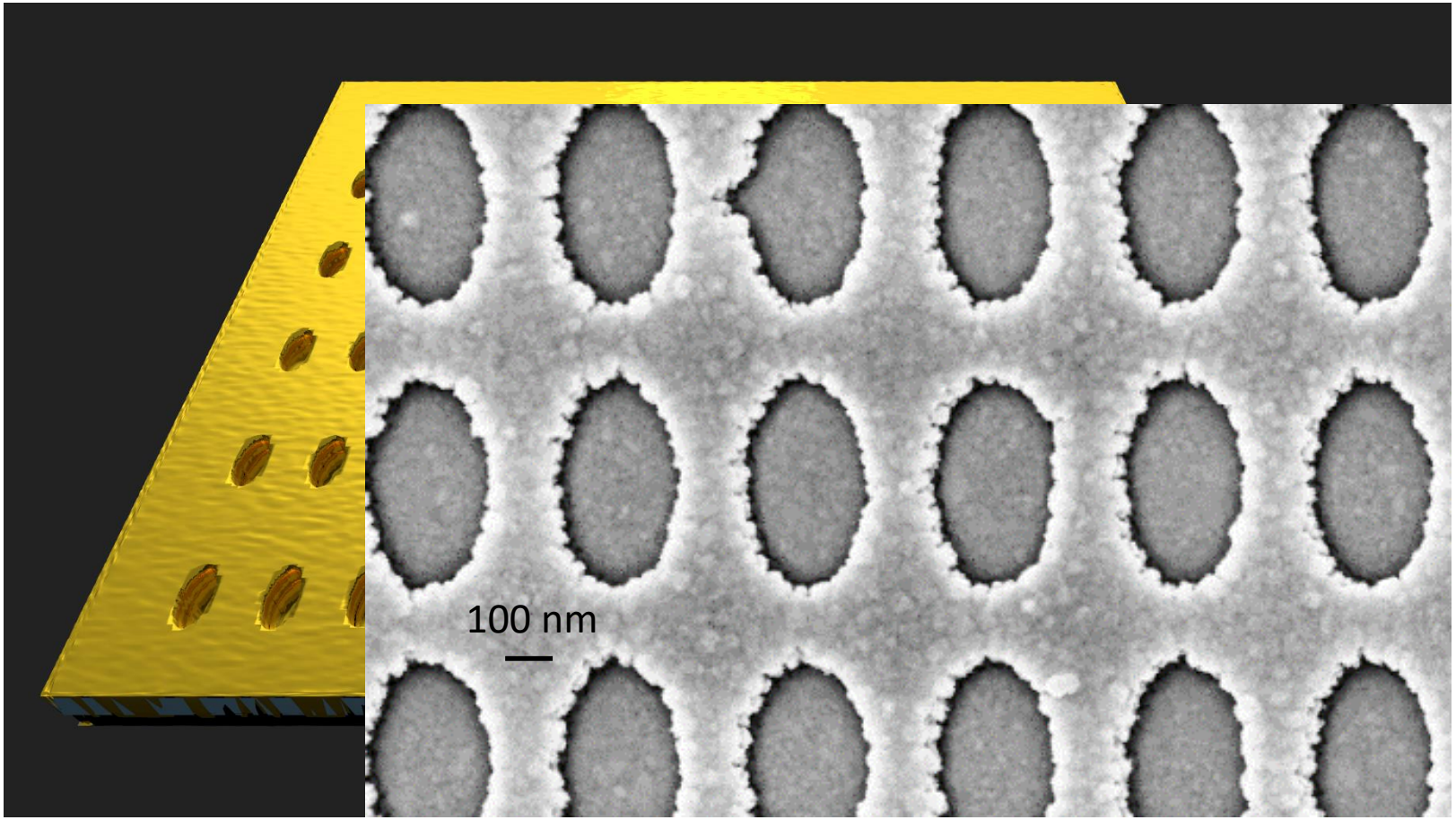
NIL-fabricated nanoparticles - fabrication technique



Deposition of metal layer by sputtering

Nanoimprint lithography based nanoparticles

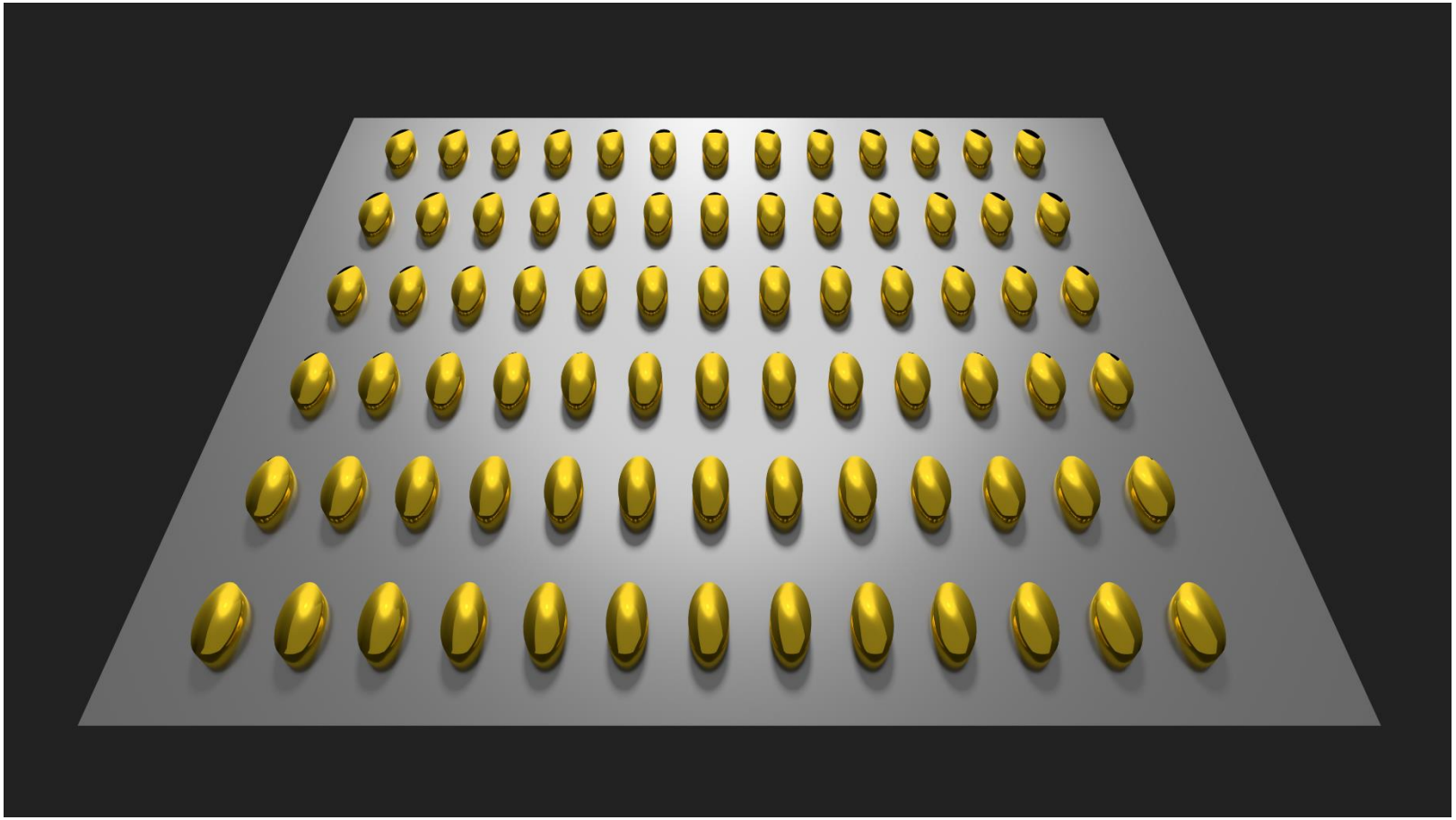
NIL-fabricated nanoparticles - fabrication technique



Deposition of metal layer by sputtering

Nanoimprint lithography based nanoparticles

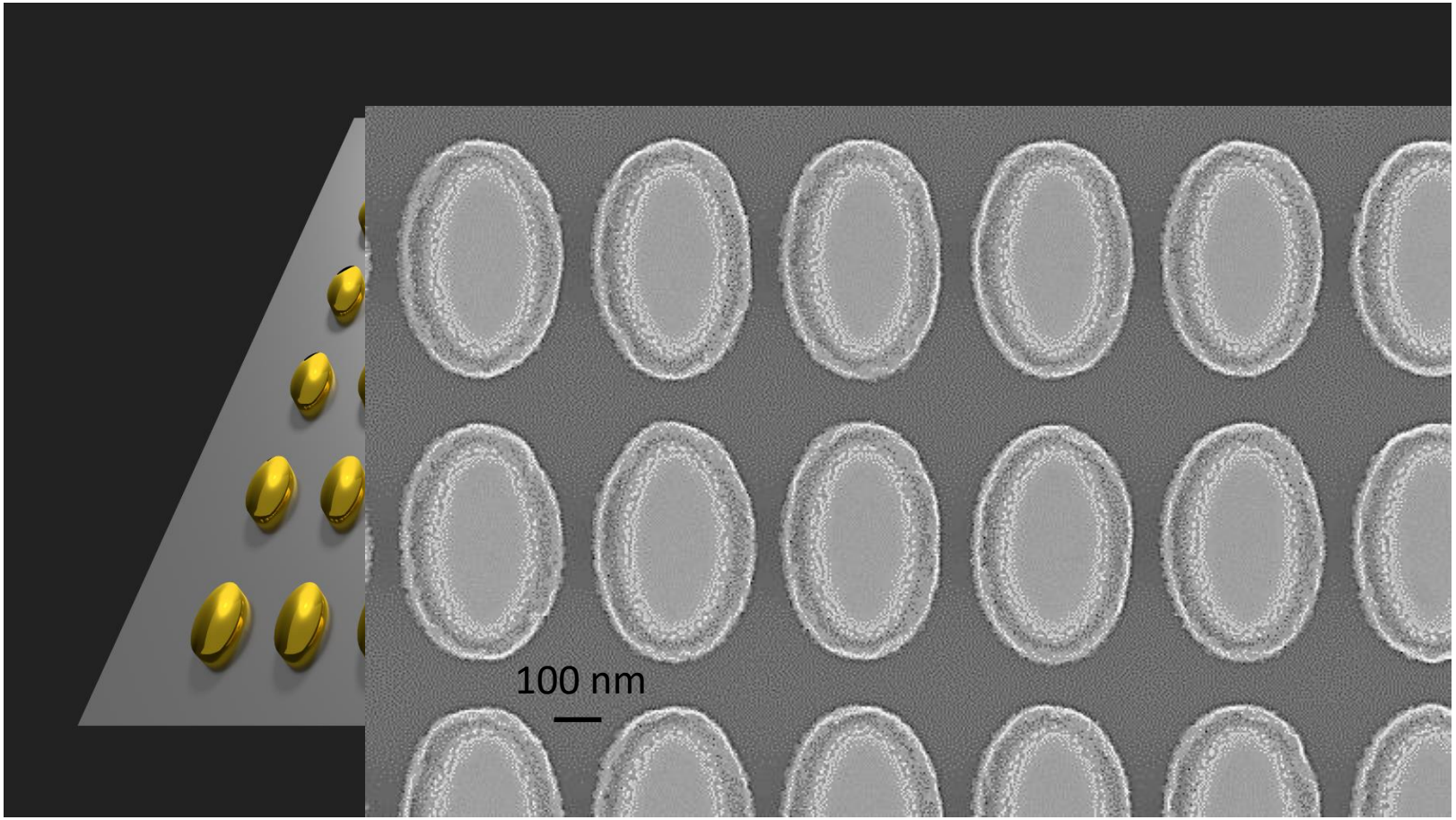
NIL-fabricated nanoparticles - fabrication technique



Lift-off to remove the resist layers

Nanoimprint lithography based nanoparticles

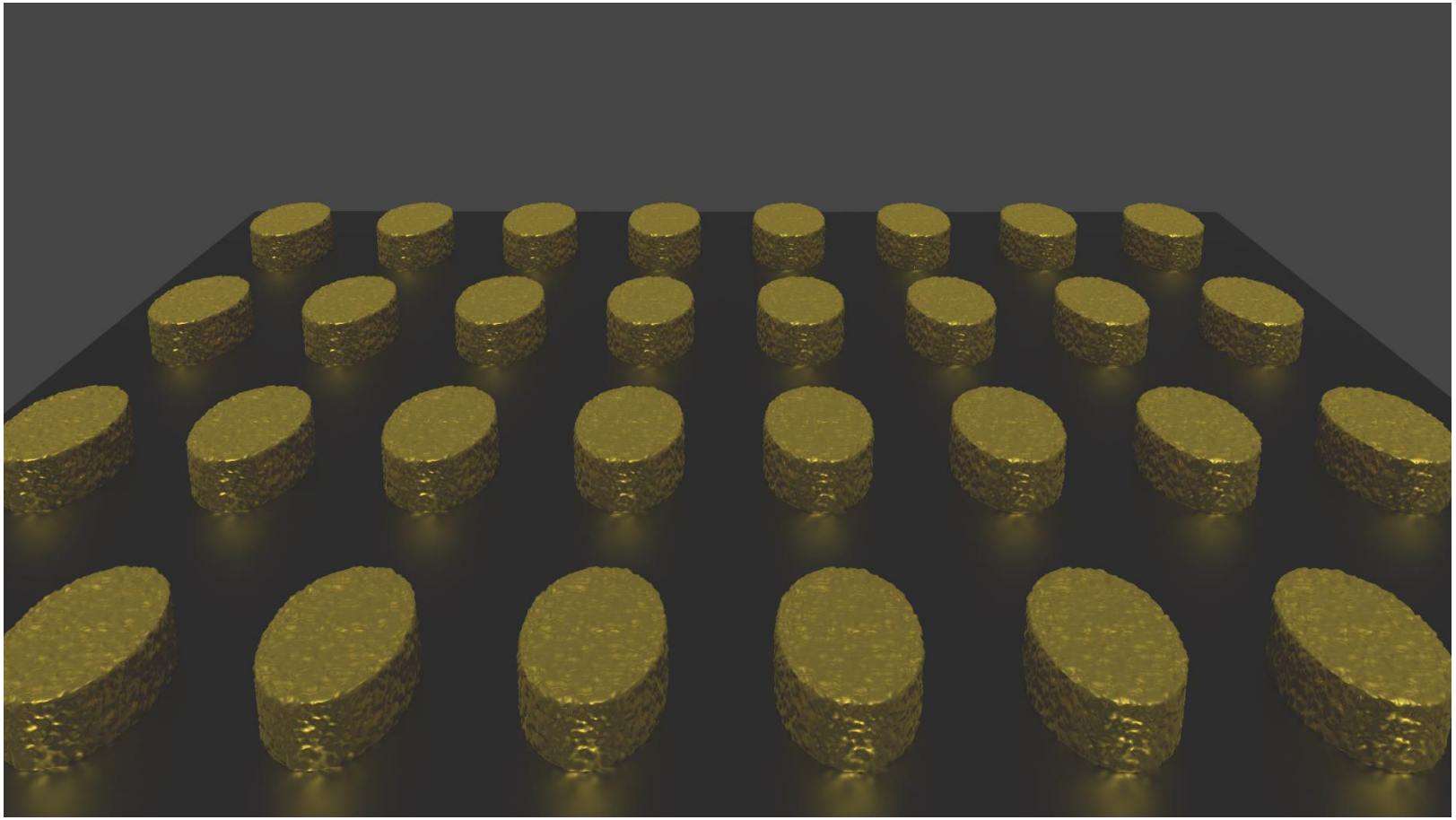
NIL-fabricated nanoparticles - fabrication technique



Lift-off to remove the resist layers

Nanoimprint lithography based nanoparticles

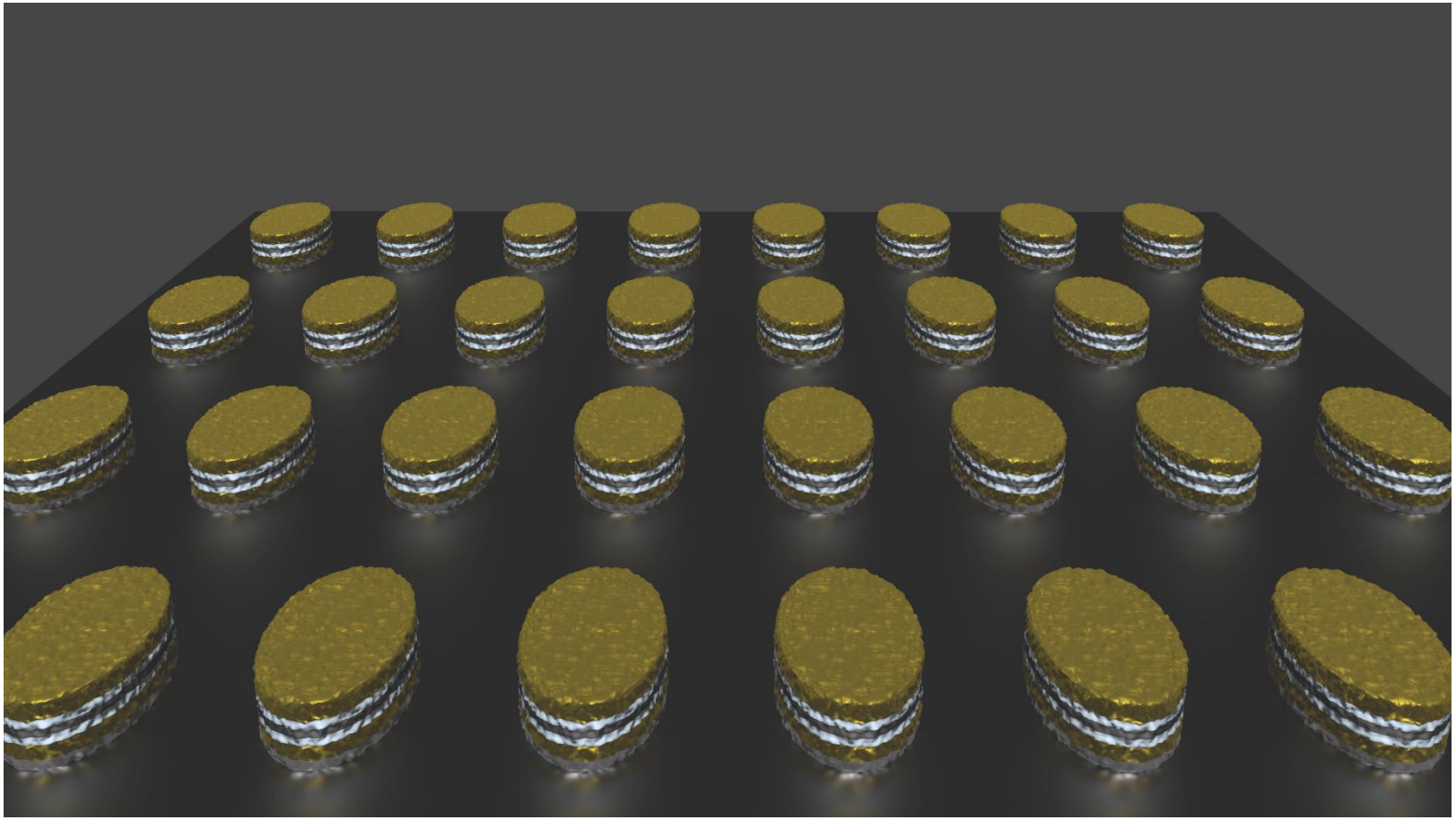
NIL-fabricated nanoparticles - fabrication technique



Array of top-down fabricated nanoparticles on Si-wafer

Nanoimprint lithography based nanoparticles

NIL-fabricated nanoparticles - fabrication technique



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Nanoimprint lithography based nanoparticles

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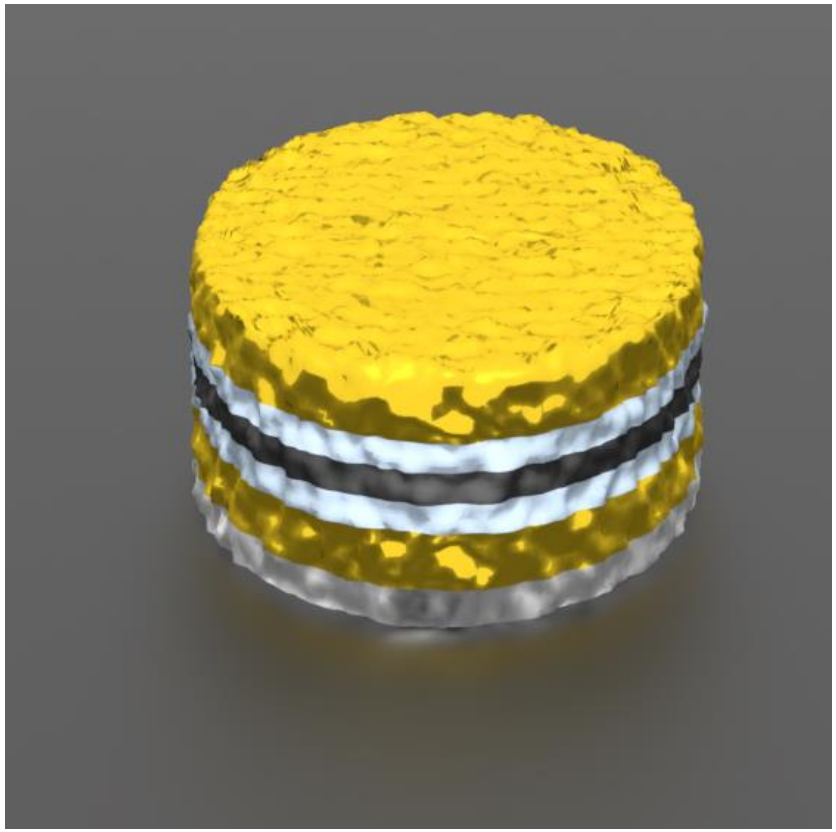
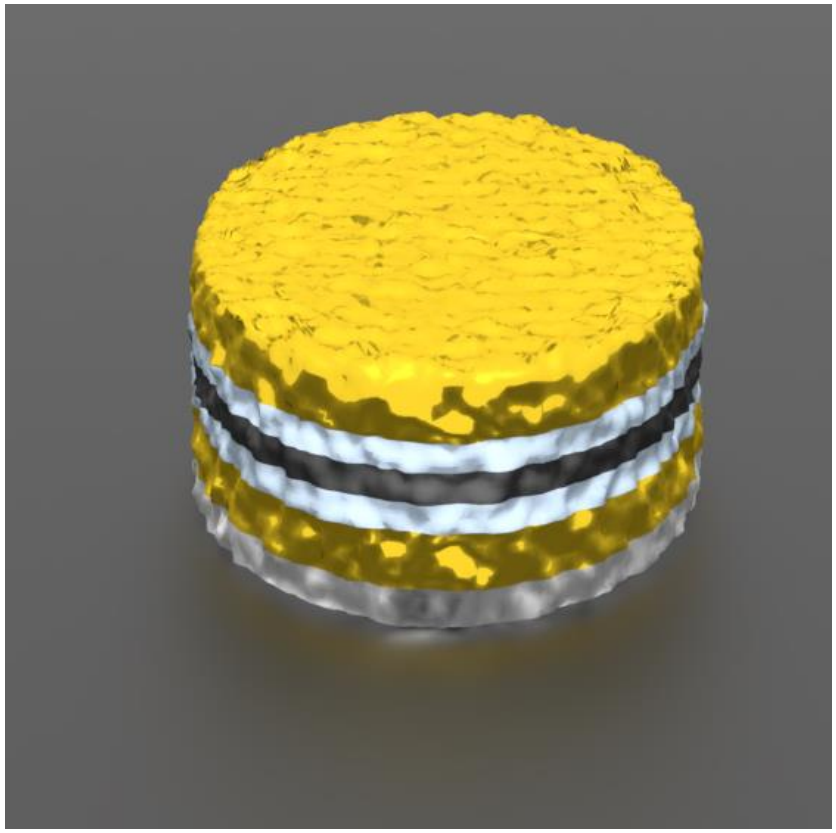


Nanoimprint lithography based nanoparticles

NIL-fabricated nanoparticles - fabrication technique



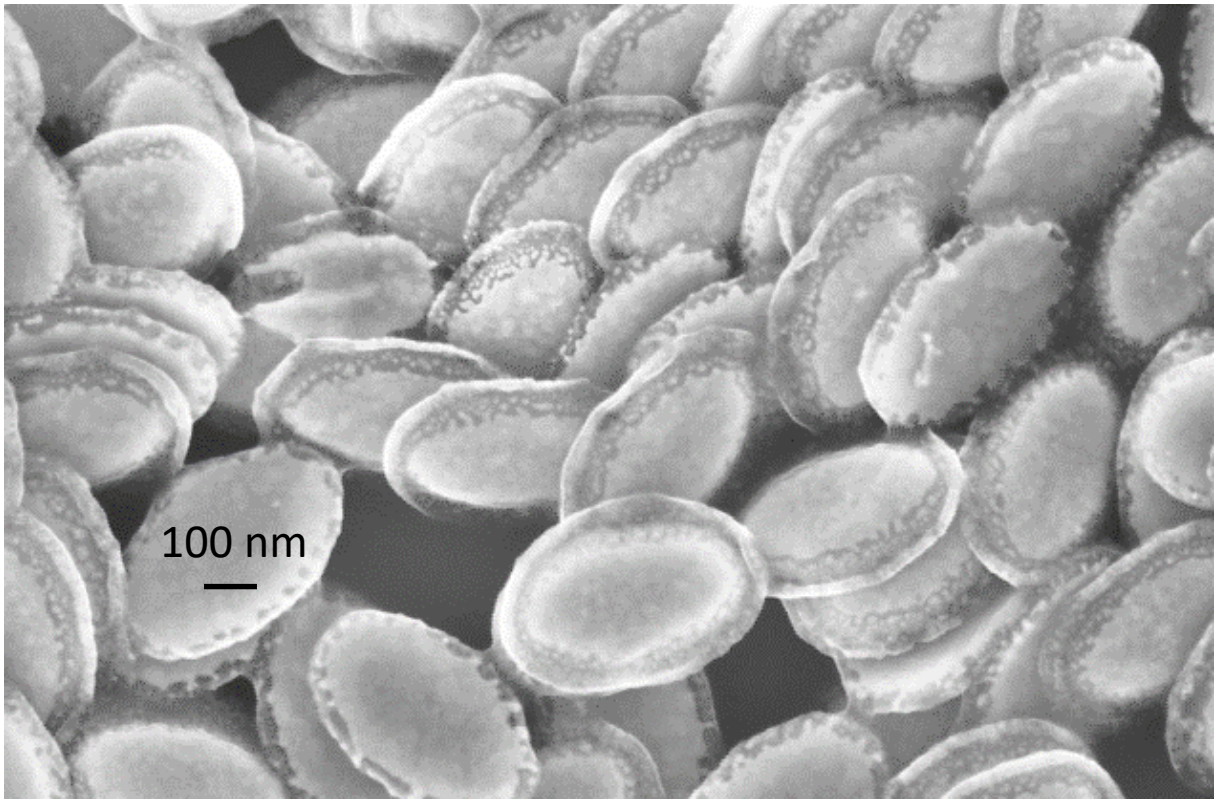
Layer system		
Material	**Thickness (nm)**	**Functionality**
Au	30	Plasmon layer
TiO_x	10	Decoupling layer
NiFe	10	Magnetic layer
TiO_x	10	Decoupling layer
Au	30	Plasmon layer
AZO	20	Release layer

Ellipse axes: 200 / 400 nm
Stack height 90 nm (without release layer)

(AZO: Al-doped Zn-oxide)

Nanoimprint lithography based nanoparticles

NIL-fabricated nanoparticles - fabrication technique



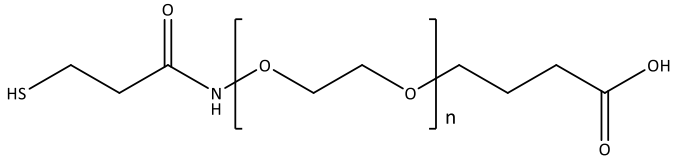
NIL-nanoparticles after surface removal and re-deposition from solution onto an imaging substrate (Si-wafer)

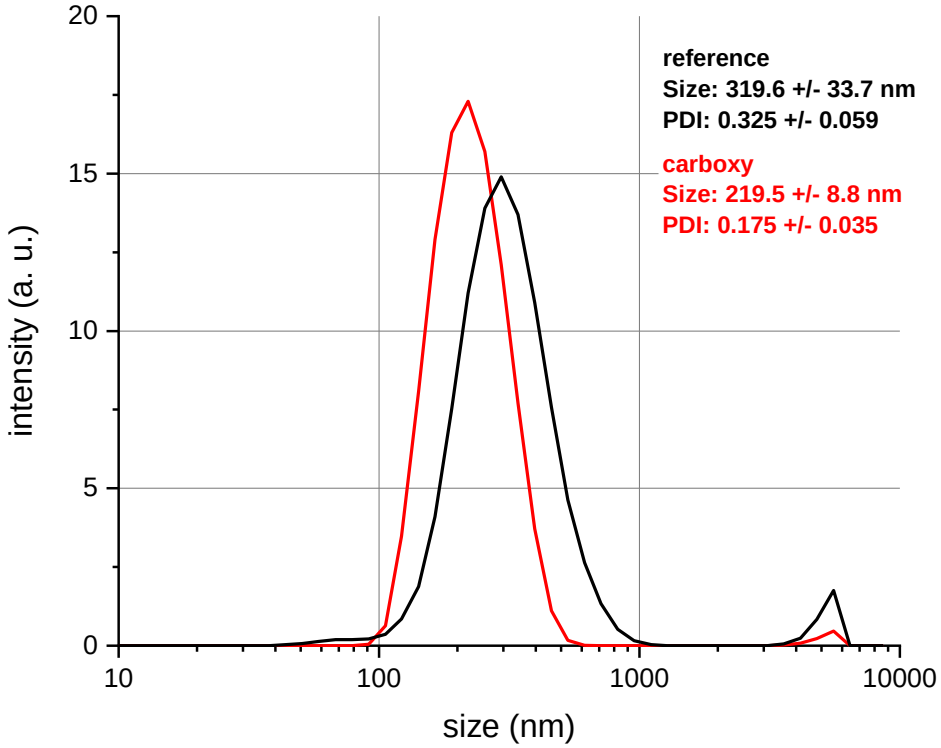
Nanoimprint lithography based nanoparticles

NIL-fabricated nanoparticles – surface modification

Use of an additional linker molecule to stabilize nanoparticle dispersions and to allow for carbodiimide crosslinker chemistry (EDC/S-NHS)

thiol-PEG-carboxy



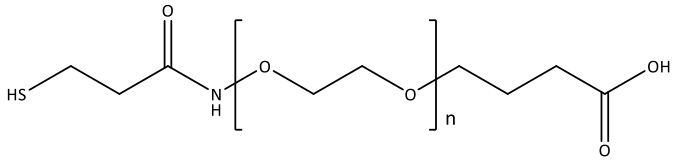


Equivalent sphere diameter
221 nm

Nanoimprint lithography based nanoparticles

NIL-fabricated nanoparticles – surface modification

Use of an additional linker molecule to stabilize nanoparticle dispersions and to allow for carbodiimide crosslinker chemistry (EDC/S-NHS)

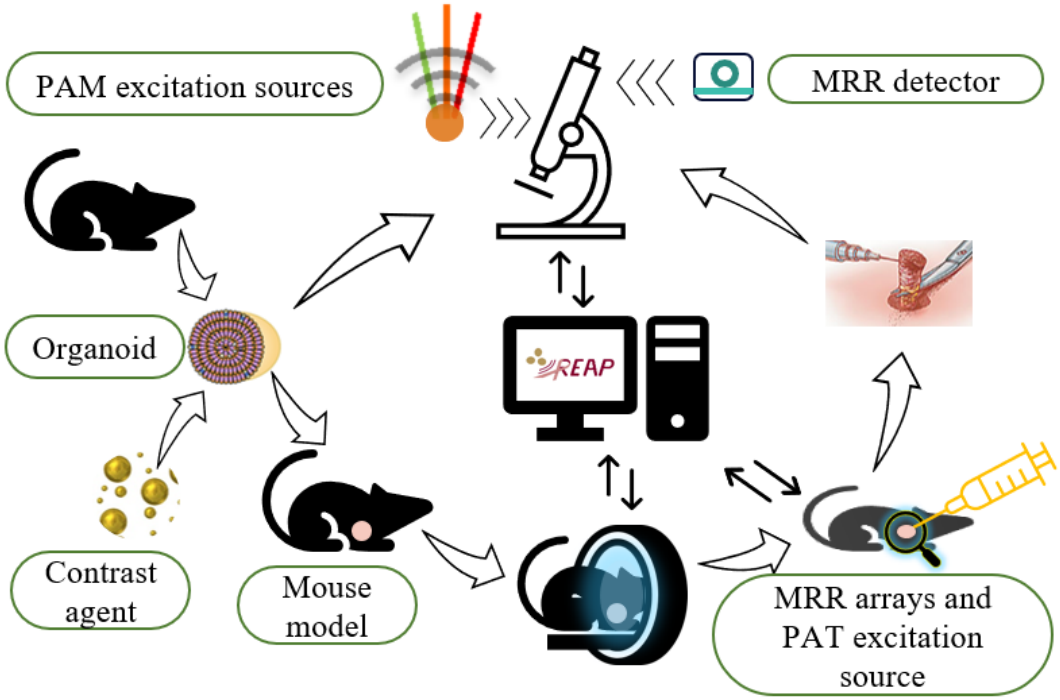
thiol-PEG-carboxy 

Different antibodies (FGF23, NTproCNP, sHER2) bound to the nanoparticle surface. Antibody presence verified by protein-G HRP assay

Multifunctional nanoparticles
Plasmonic properties
Magnetic properties
Biofunctional antibody surface

Nanoimprint lithography based nanoparticles

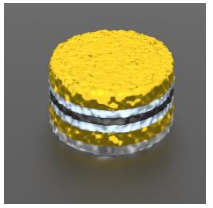
Molecular imaging approach



- Cancer organoid
- Mouse model
- Contrast agent
- Laser
- Detector
- Reconstruction

REAP project

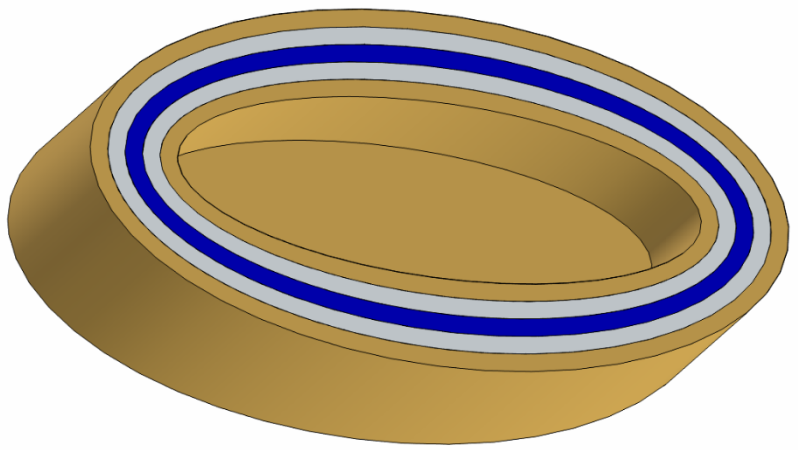
Nanoparticles as the base for a contrast agent

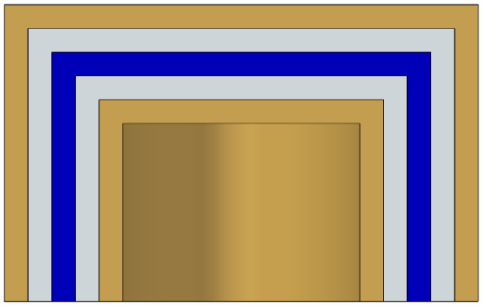


PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets





Particle structure

Gold

Titanium oxide

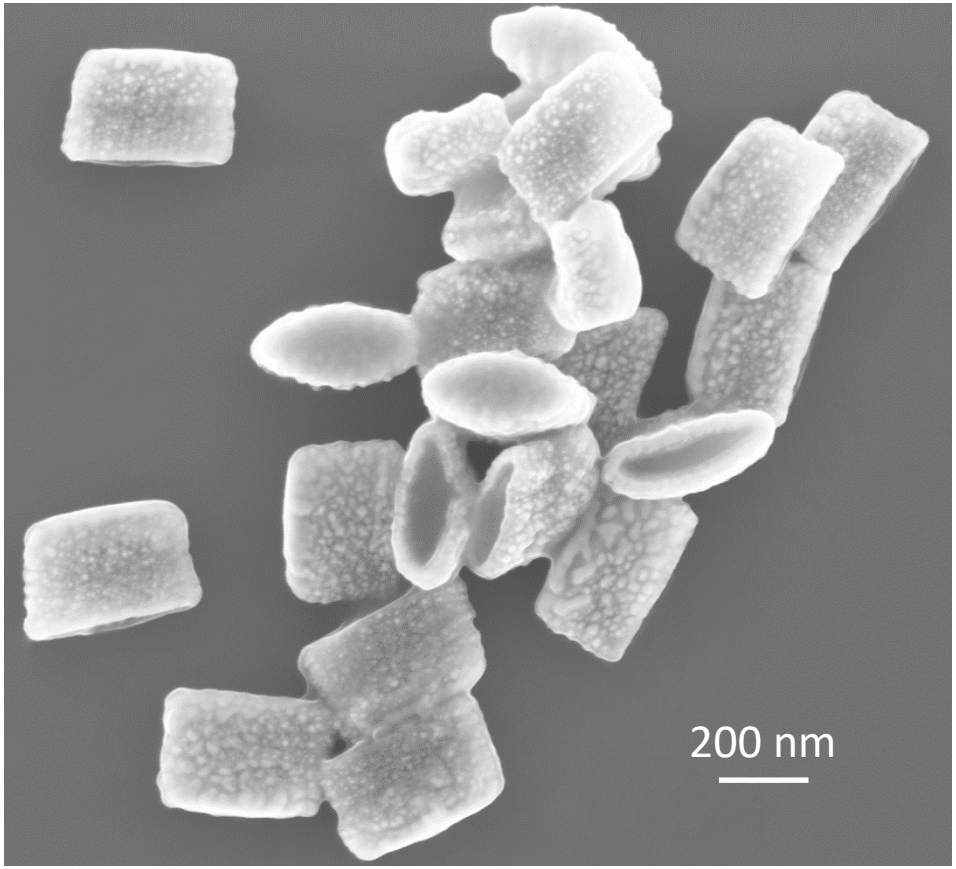
Permalloy

Particle structure cut

Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets

SEM image after drying a drop on a silicon wafer



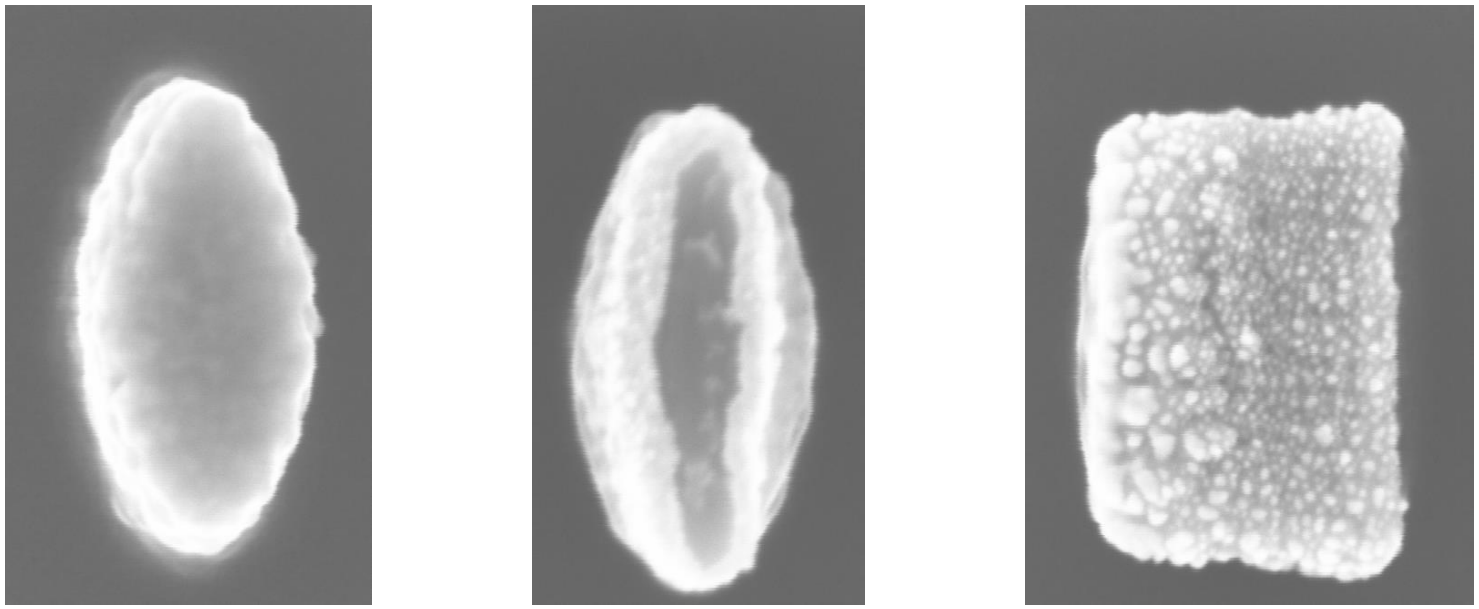
S. Schrittwieser, M. Haslinger, T. Mitteramskogler, M. Muehlberger, A. Shoshi, H. Brueckl, M. Bauch, T. Dimopoulos, B. Schmid, J. Schotter. Multifunctional Nanostructures and Nanopocket Particles Fabricated by Nanoimprint Lithography. Nanomaterials 9 (2019) 1790

Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets

SEM image after drying a drop on a silicon wafer

Top **Bottom** **Side**



100 nm

Outer dimensions:
~ 380 x 170 nm, height: 250 nm

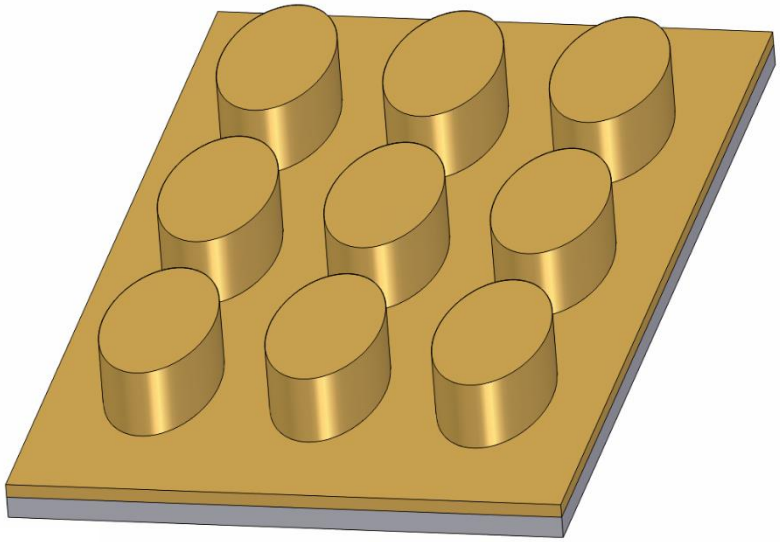
Layer thickness 50 nm

S. Schrittwieser, M. Haslinger, T. Mitteramskogler, M. Muehlberger, A. Shoshi, H. Brueckl, M. Bauch, T. Dimopoulos, B. Schmid, J. Schotter. Multifunctional Nanostructures and Nanopocket Particles Fabricated by Nanoimprint Lithography. Nanomaterials 9 (2019) 1790

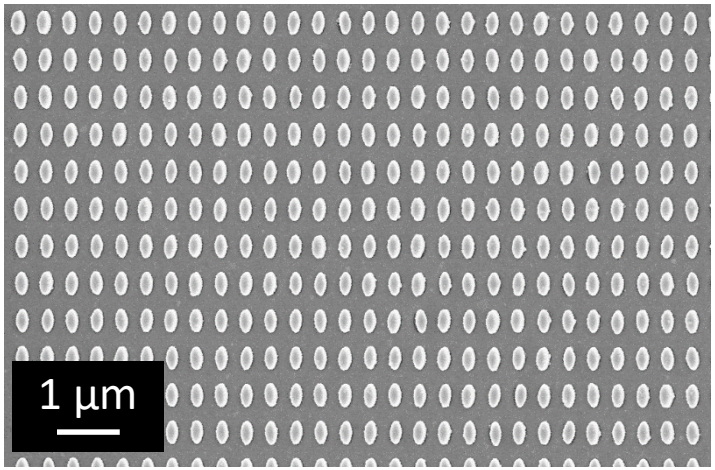
Nanoimprint lithography based nanoparticles

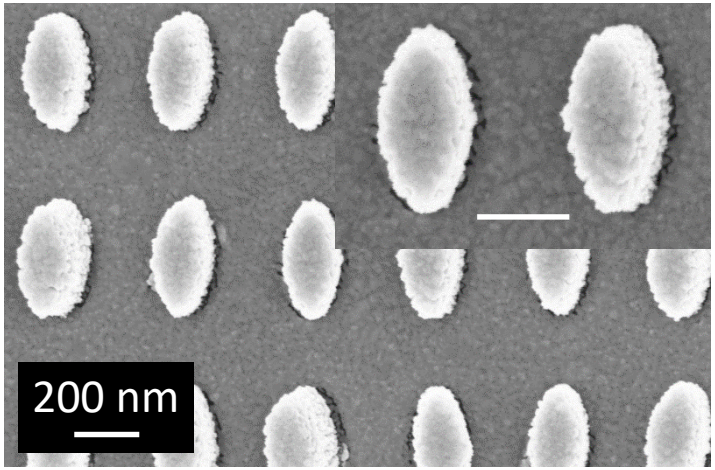
AUSTRIAN INSTITUTE OF TECHNOLOGY

NIL-fabricated nanopockets – array on a substrate



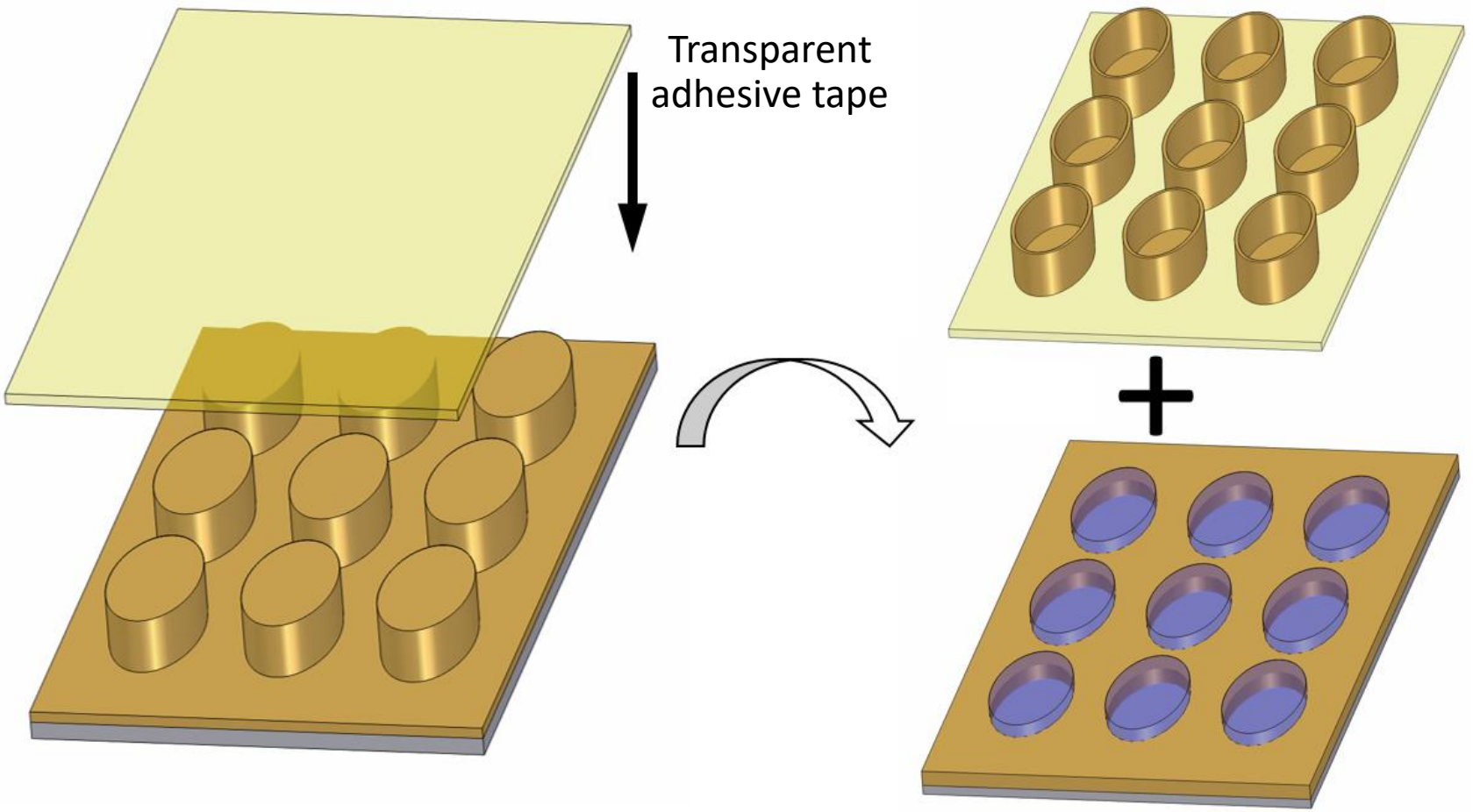
Hollow nanopocket array
Top-down
Au only





Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – array on a substrate

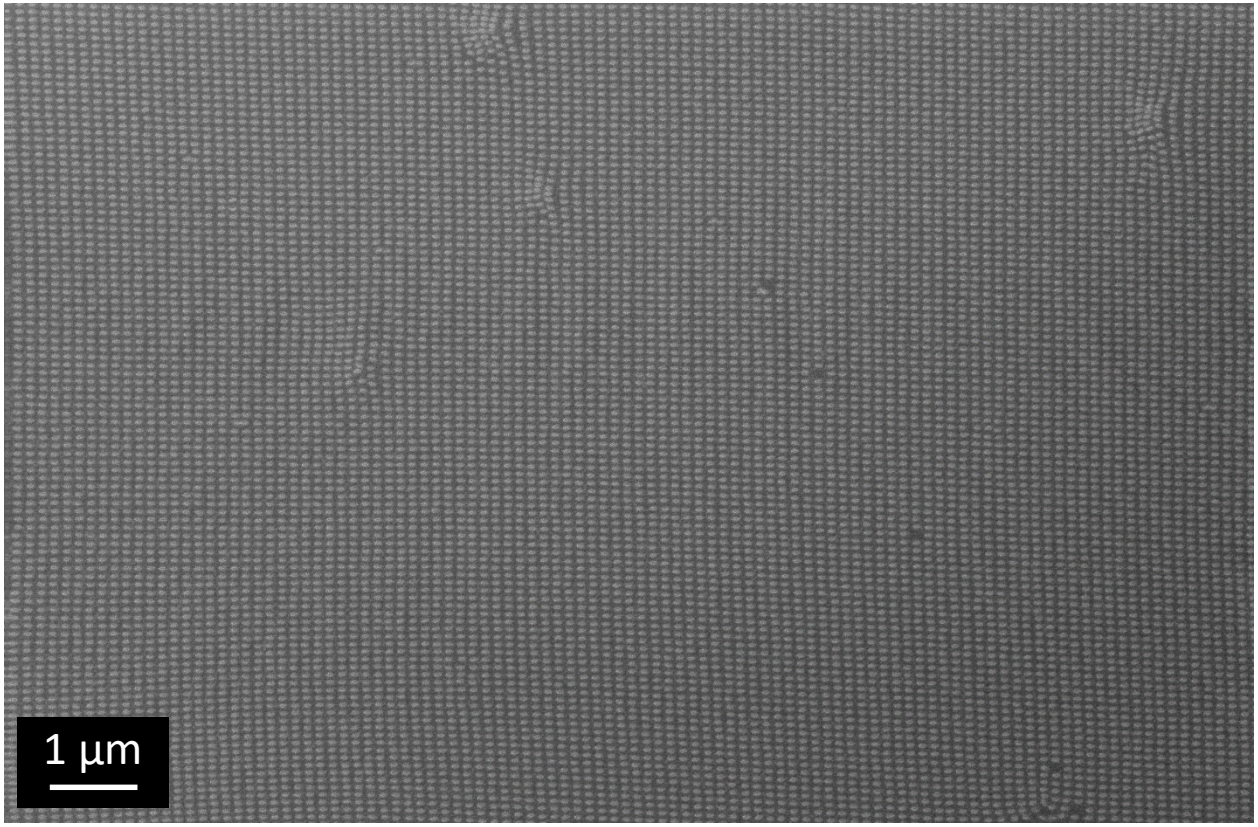


Substrate transfer

Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – array on a substrate

Hollow nanopocket array
Bottom-up



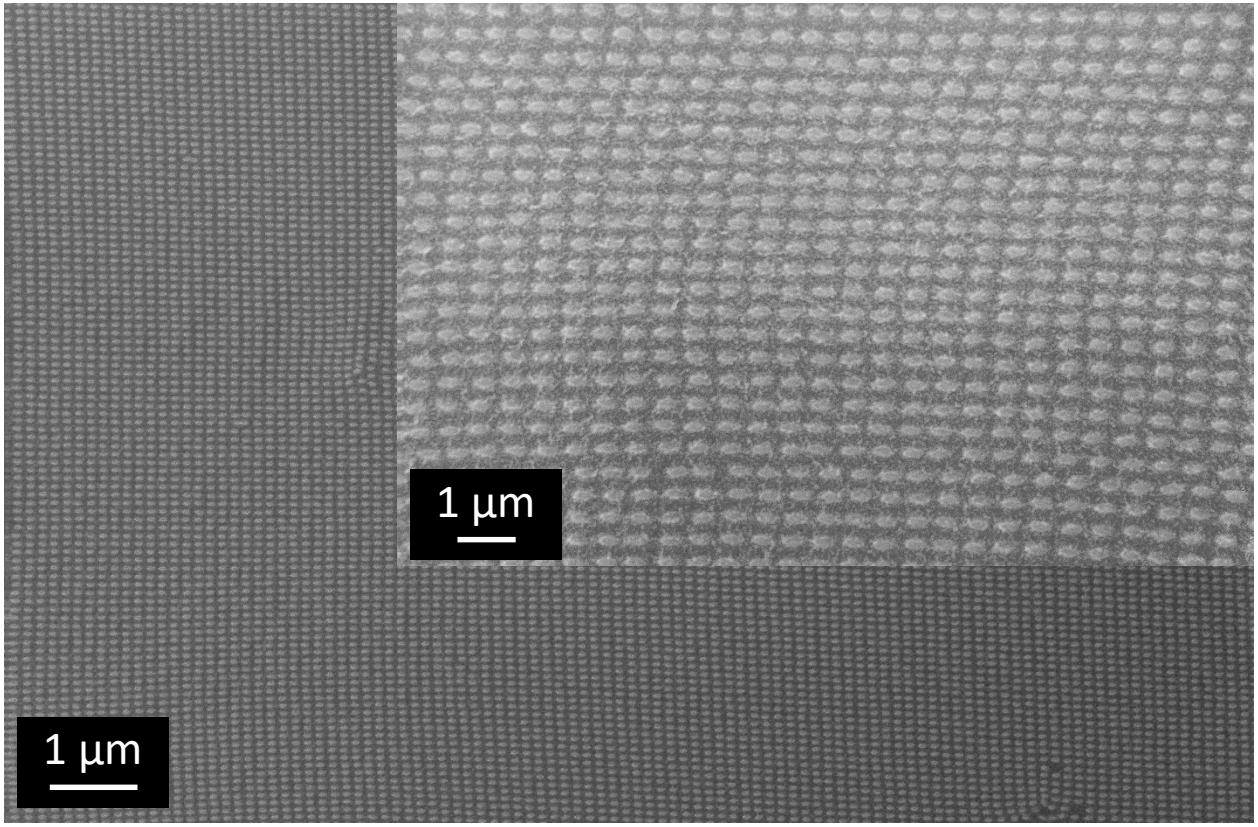
Tape lift-off

Sputter deposition (20 nm Au) to allow for SEM characterization

Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – array on a substrate

Hollow nanopocket array
Bottom-up



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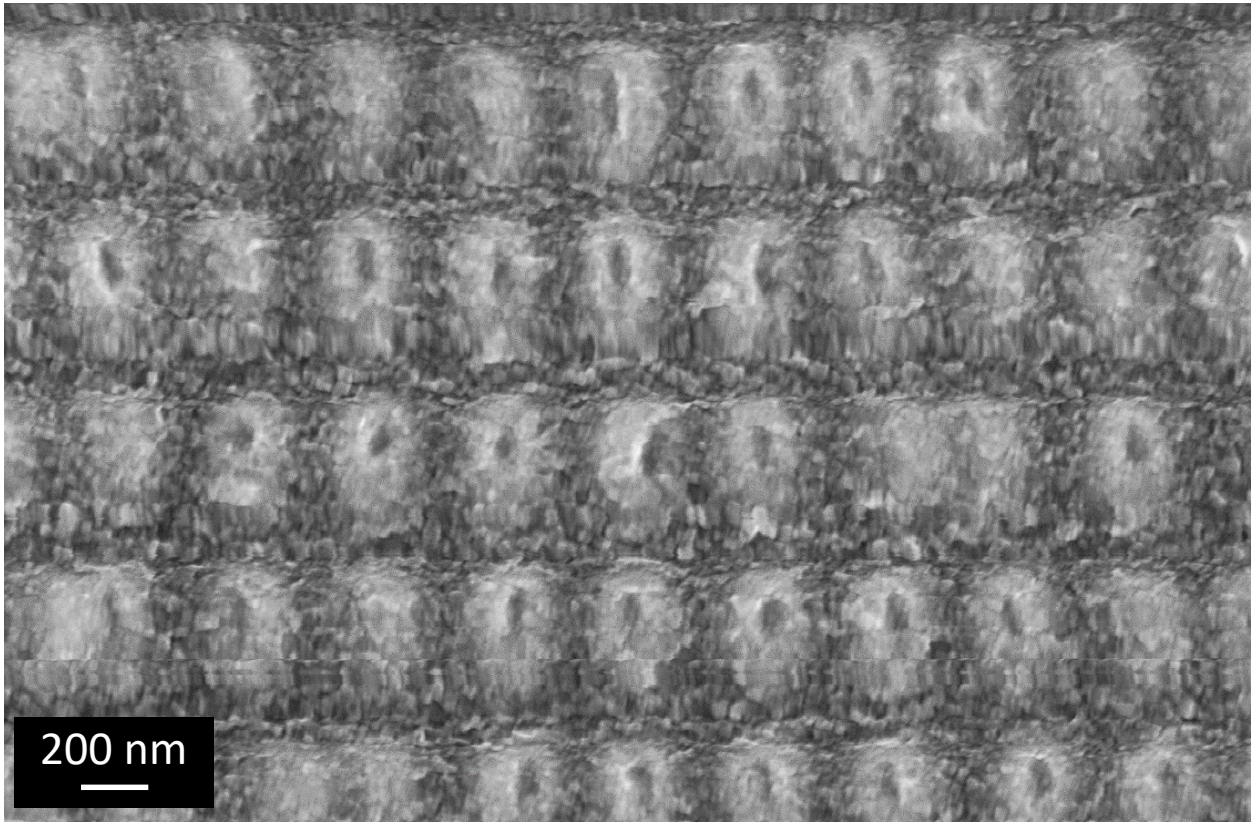
Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – array on a substrate

Hollow nanopocket array
Bottom-up

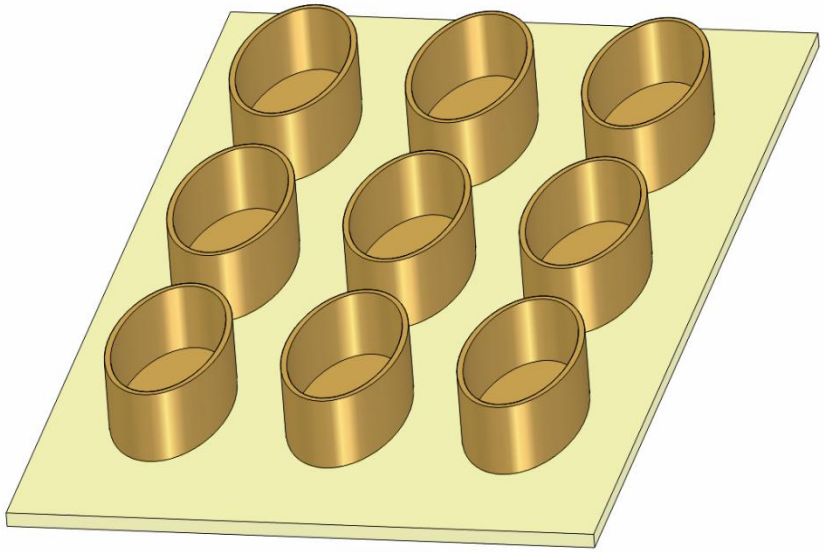


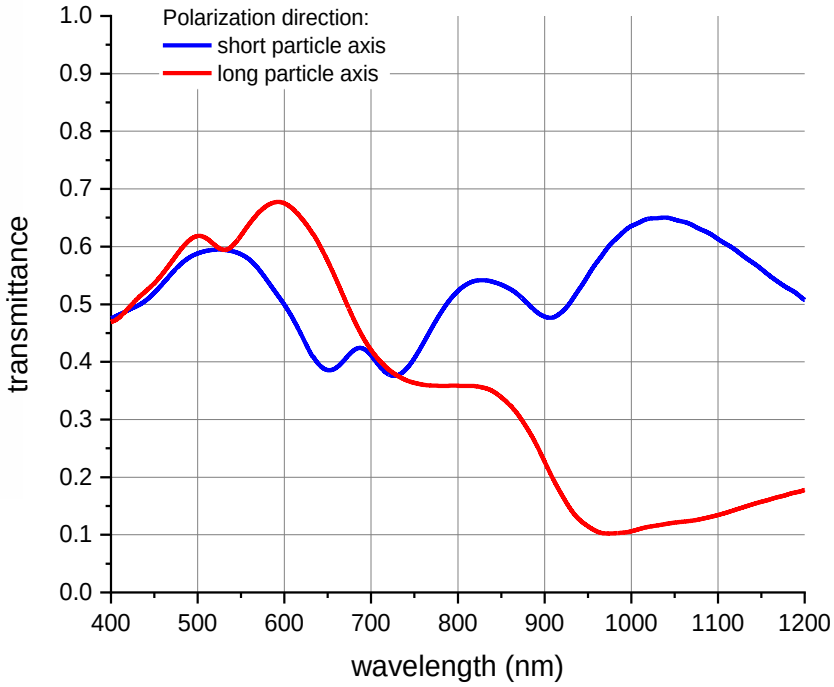
Tape lift-off

Sputter deposition (20 nm Au) to allow for SEM characterization

Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – optical characterization

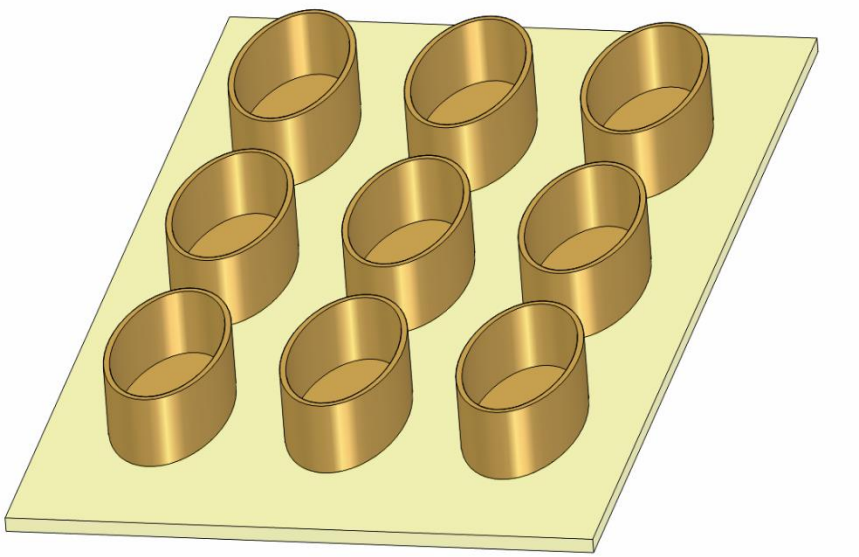


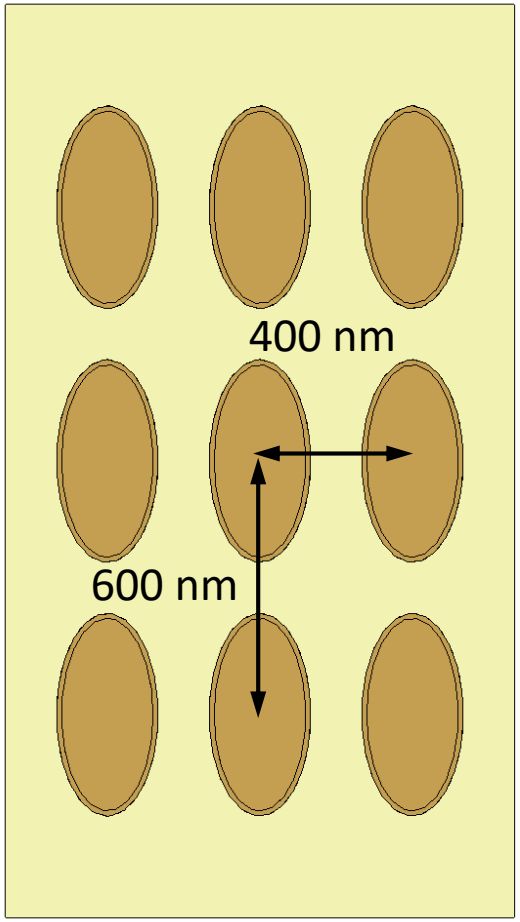


Transmittance measurements

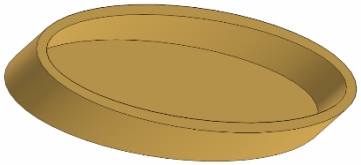
Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – optical characterization
FDTD simulations





Plane wave irradiation perpendicular to the substrate
Substrate: glass
Surrounding medium: air

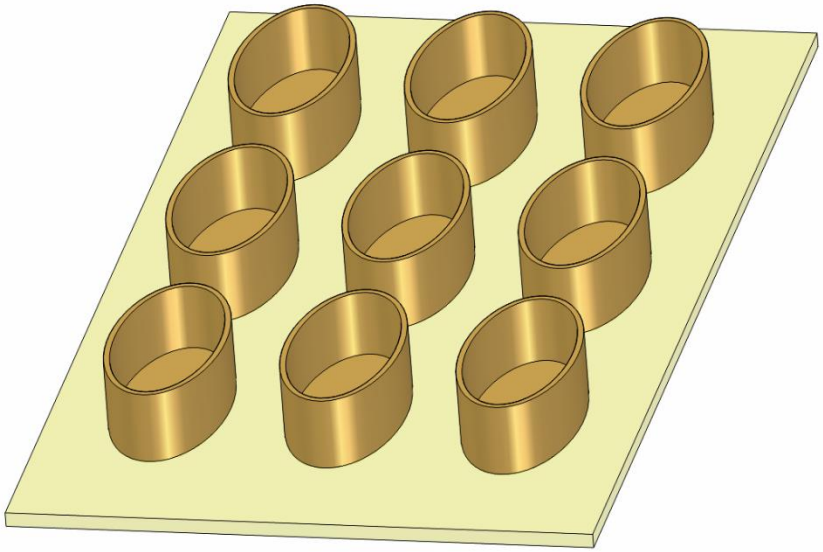


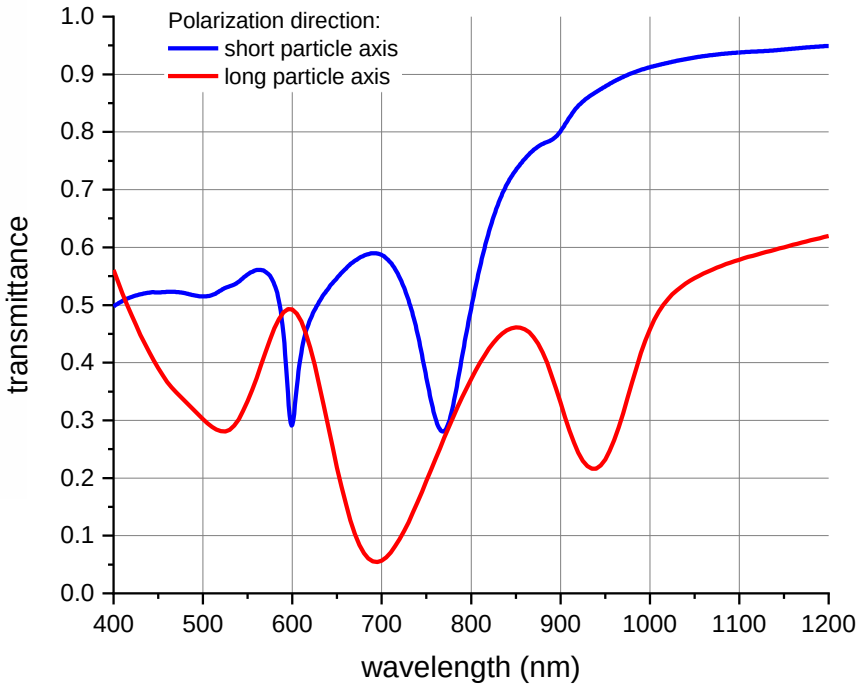
Outer dimensions:
380 x 170 nm, height: 250 nm

Layer thickness 50 nm

Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – optical characterization
FDTD simulations





Transmittance simulations

Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – optical characterization

Minima peak positions

Parallel polarization		Perpendicular polarization	
experiment	**simulation**	**experiment**	**simulation**
531 nm	525 nm	652 nm	599 nm
771 nm [1]	695 nm	727 nm	768 nm
974 nm	938 nm	907 nm	885 nm [1]

[1] Inflection point

Good agreement of measured with simulated values

→ Optical properties can be tailored to specific demands by predictive modeling steps

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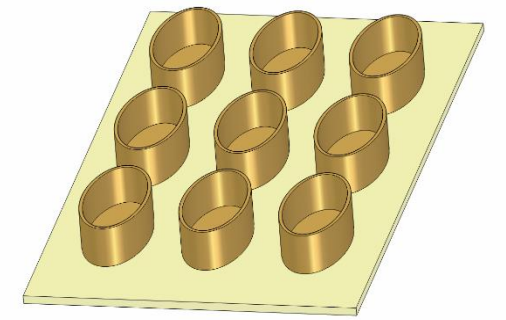
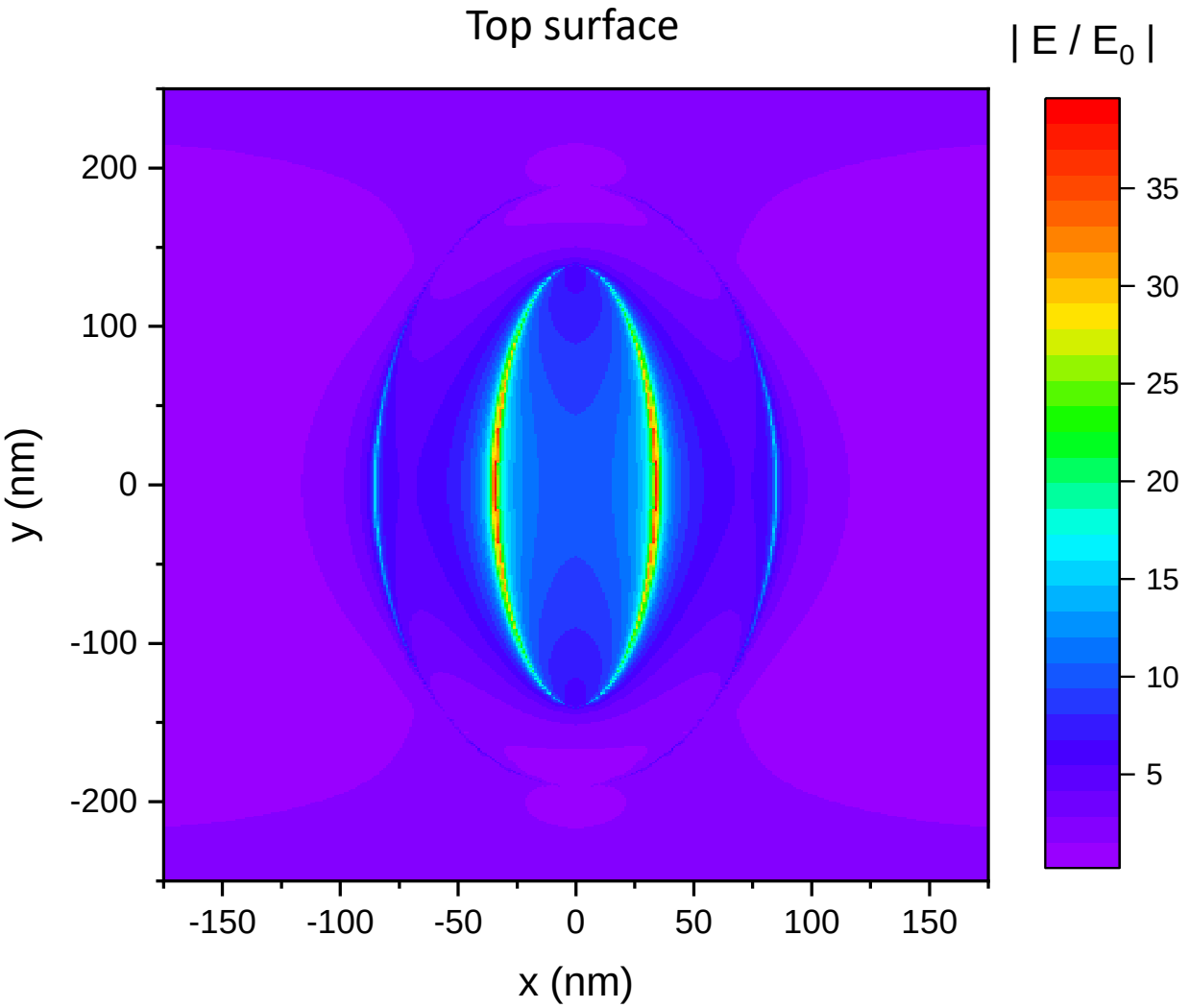
NIL-fabricated nanopockets – optical characterization
FDTD simulations

@ 768 nm

Polarization direction

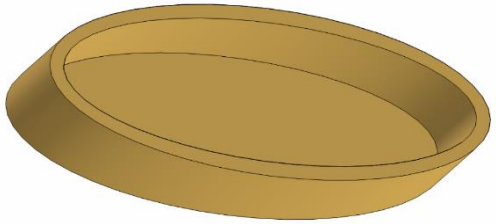




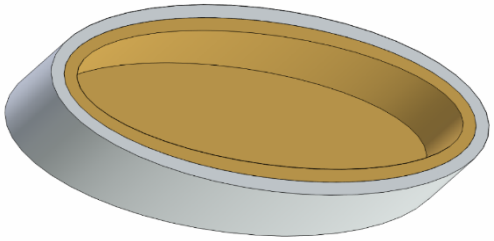
Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – outlook

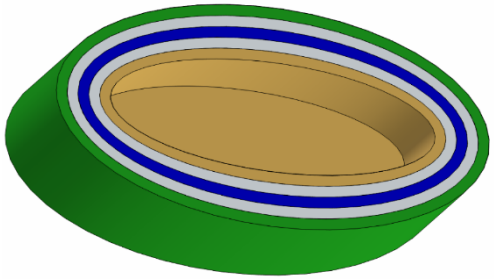
- Vary the nanopocket size
- Test different materials and layers
- Biofunctionalize the nanopockets



Single material nanopocket



Nanopocket with 2-layer shell structure

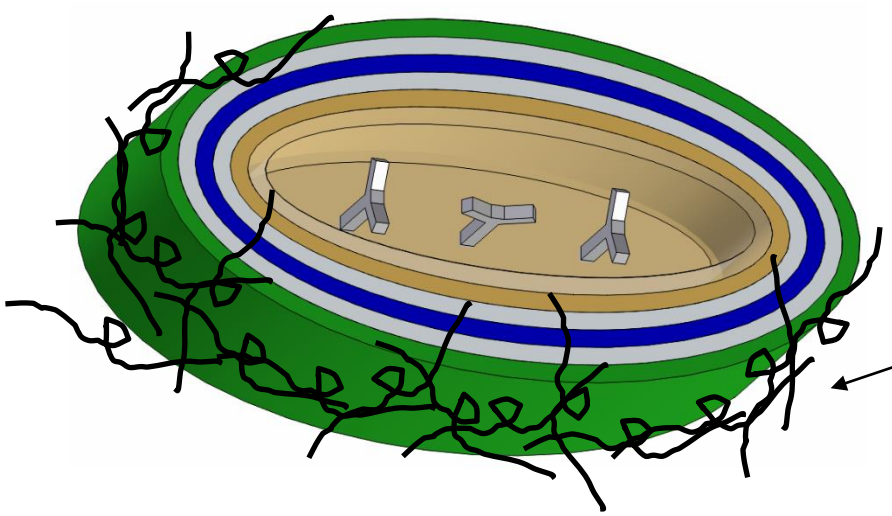


Nanopocket with multilayer structure and
different materials for the inner and the outer shell layer

Nanoimprint lithography based nanoparticles

NIL-fabricated nanopockets – outlook

- Vary the nanopocket size
- Test different materials and layers
- Biofunctionalize the nanopockets



small molecules, polymers, peptides, antibodies, …

Nanoimprint lithography based nanoparticles

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NIL-fabricated nanopockets – possible application areas

- Drug delivery
- Surface-enhanced Raman spectroscopy
- Nanopockets as probes for different imaging techniques (optical coherence tomography, photoacoustic tomography, magnetic resonance imaging, …)
- Non biological applications (e.g. nanolasing, photocatalysis)

Acknowledgements

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Collaborators

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Thank you for your attention!