AASAP
Aalen School of Applied Photonics

Nanoimprint Lithography

Andreas Heinrich

Hochschule Aalen

AAlen School of Applied Photonics

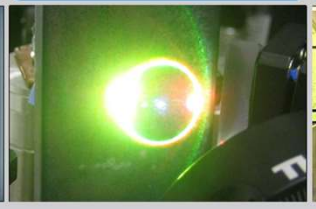
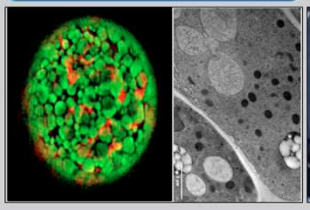
Mission and Vision

1. We want to train young people to a high level in the field of applied photonics at all academic levels
   - Bachelor program Optical Engineering
   - Master program Applied Photonics
   - PhD program Applied Photonics

2. We want to consistently advance our research to a high level in our focus areas with our students
   - Focus on individual research profiles and promotion of collaboration between the working groups
   - Consistent advancement of the research infrastructure
   - Early involvement of students in our research

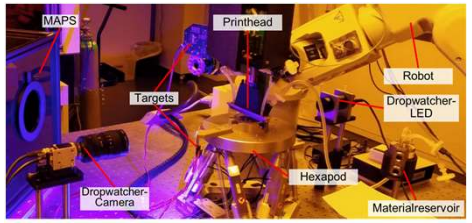
3. We want to push our network, our internationalization and support our students
   - Dedicated partners in industry and research
   - Internationalization with a focus on Africa
   - Focus on the needs of the students

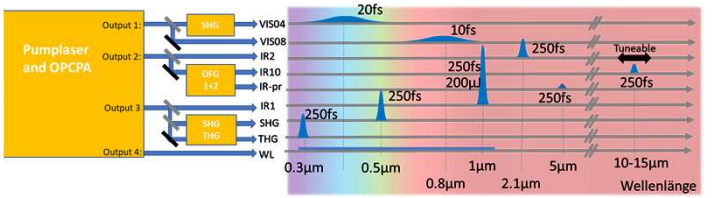
Center for Optical Technologies @ AASAP

Optics Technology	Light – matter interaction	Micro- & Nanophotonics	Bio-Photonics	Opto-Electronics
				

• Robot based
  • polishing
  • metrology
  • 3D printing
• Process simulation
• AI methods
  • processes
  • metrology
	• Ultra short pulse lasers
	• Time resolved spectroscopy
	• Nonlinear Optics and nonlinear frequency conversion
		• Additive manufacturing
		  • µPSL
		  • Ink-Jet printing
		• Nano-Imprinting
		• Dielectrophoresis
		• Neural networks
			• Visualization of cell mechanisms from *µm* to *nm*:
			  • Fluoresz.microscop.
			  • correlative light- & elektronenmicrosc.
			  • Cryo-tomography
			• Data handling
				• Optoelectronics Components
				• Electronic measurement technology
				• Sensor technology

Analysis / Simulation





Agenda

- Principles of NIL
- Master preparation
- Stamp preparation
- Replication
- Examples

Work presented done by PhD-students of the group


Selina Burkert

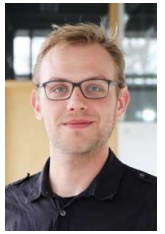

Annika Dehm


Arielle Koffi


Sangeetha Suresh-Nair


Yannick Bauckhage


Mike Dohmen


Christian Eder

and our BA / MA students!

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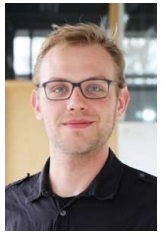
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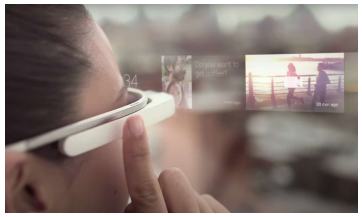
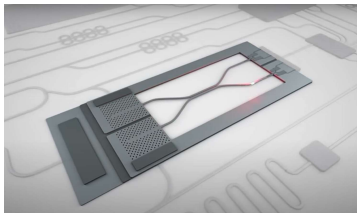
Principles of Nanoimprint-Lithography

- Is there a need for the replication of small structures?

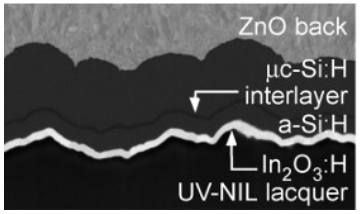


Augmented reality glasses

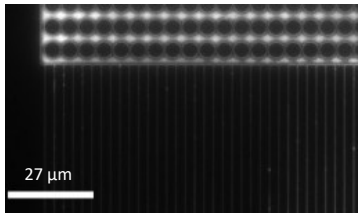
Head-up displays



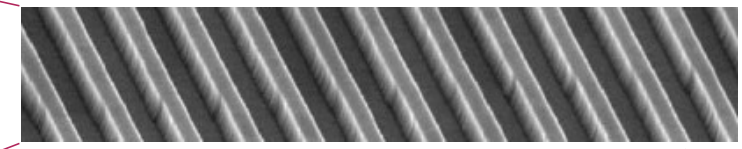
Optical computing



NIL fabricated solar cell layer (In_2O_3:H)



Micro arrays in front of nanochannels to pre-stretch DNA molecules



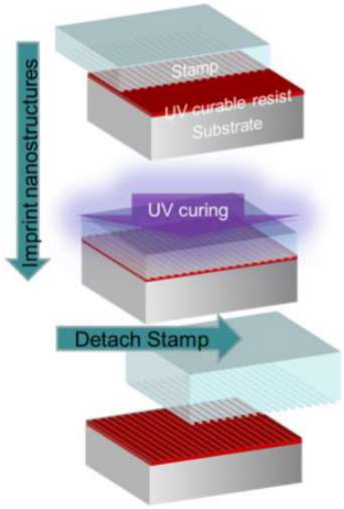
Direct Laser Writing	Focused Ion Beam	e-beam Lithography	Photo-lithography	**Nanoimprint Lithography**	…

Principles of Nanoimprint-Lithography

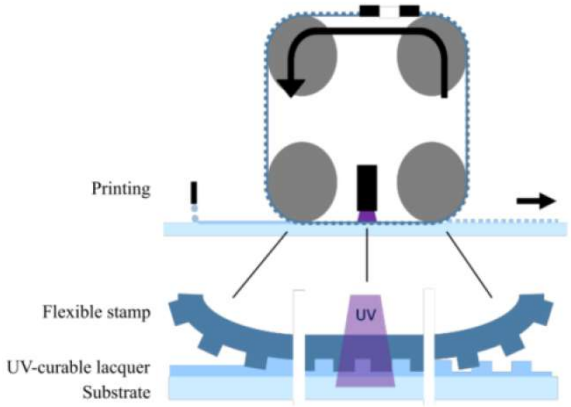
NIL

- Stamp material
  - Hard NIL
  - Soft NIL
  - Smart NIL
- Stamp and Substrate geometry
  - Full wafer
  - Step-and-repeat
  - Roll
    - Roll-to-roll (R2R)
    - Roll-to-plate (R2P)
- Curing
  - Heat (hot embossing)
  - UV
  - Heat and UV

UV NIL

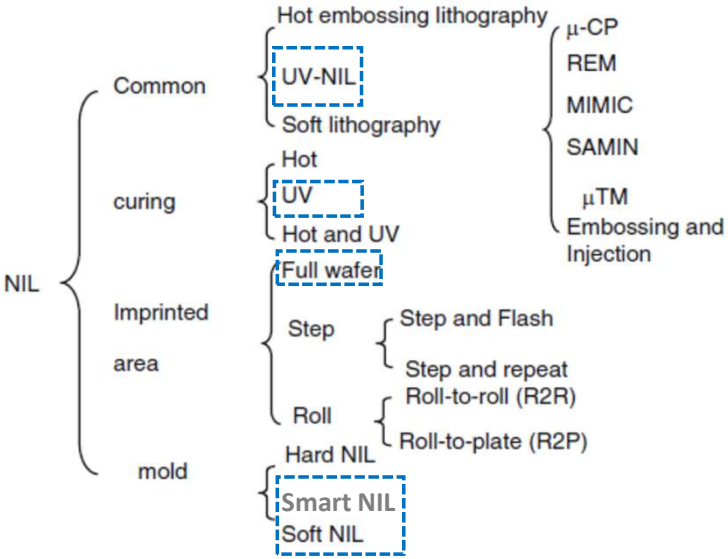


Roll-to-Plate



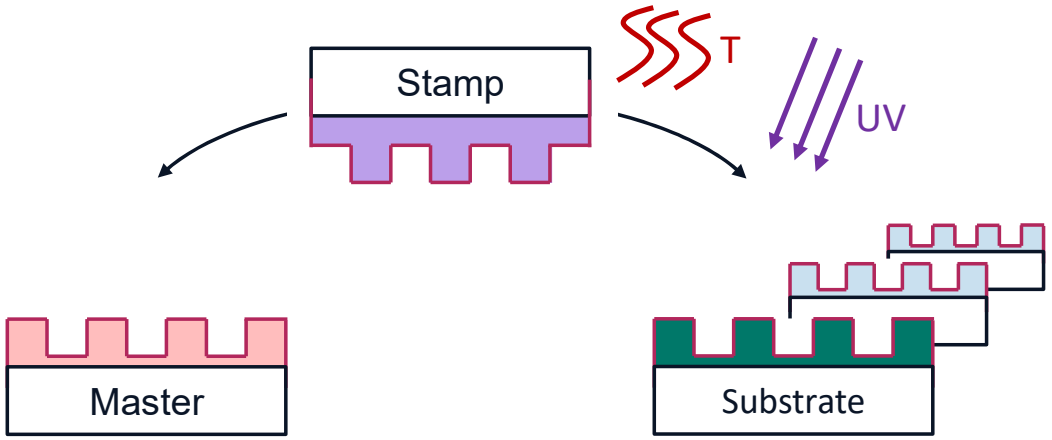
Principles of Nanoimprint-Lithography

- and another categorization…:



Center for Optical Technologies

- Process UV NIL



- Master manufacturing process + surface treatment (passivation)
- Imprint Process
  - Stamp manufacturing process (surface actication)
  - Replication process

Nanoimprint-Lithography

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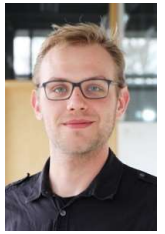
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Nanoimprint-Lithography

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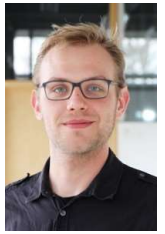
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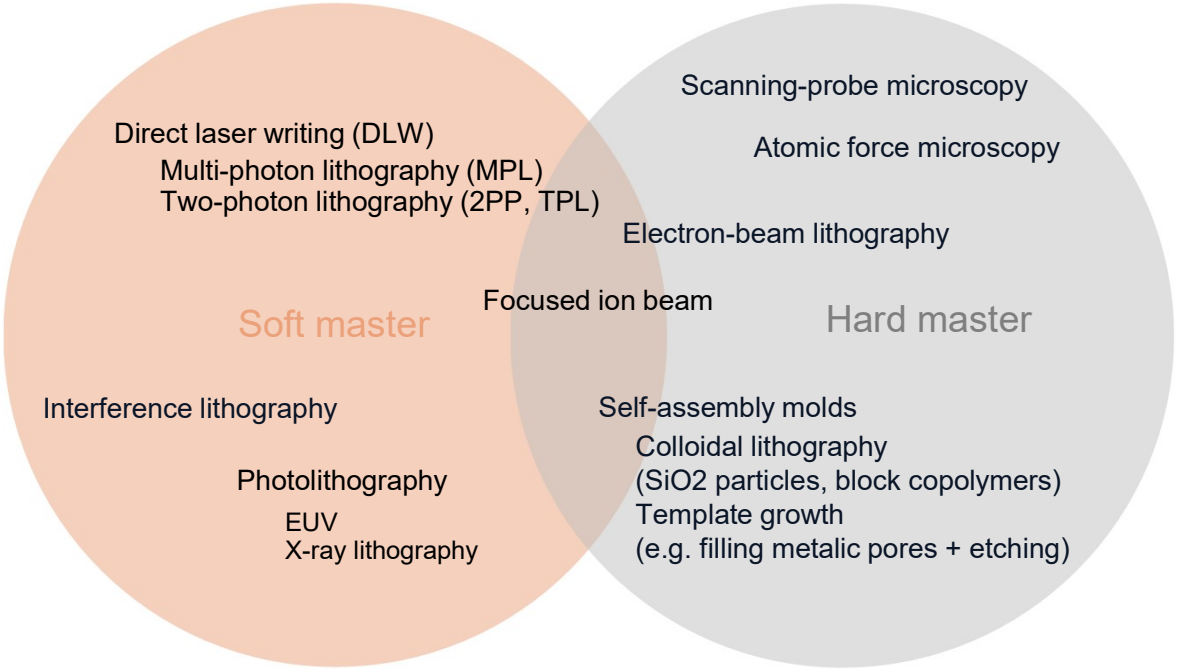
Master preparation

- Requirements:
  - Mechanical stability / robust
  - Precise (e.g. wrt. thickness, flatness, etc.)
  - Clean
  - Polished
  - Compatible with stamp material
  - …

- Materials:

Polymer (hybrid)	Anorganic + ASL
PDMS, PMMA, PUA, PVA, PVC, PTFE, ETFE,…	Si, SiO2, Cr, Borosilicate
Typ. we use: ma-P series (MicroResist), Si-hybrid (EVG)	*Typ. we use: Cr on Borosilicate, Si, ITO*

- There are many techniques to manufacture the master …

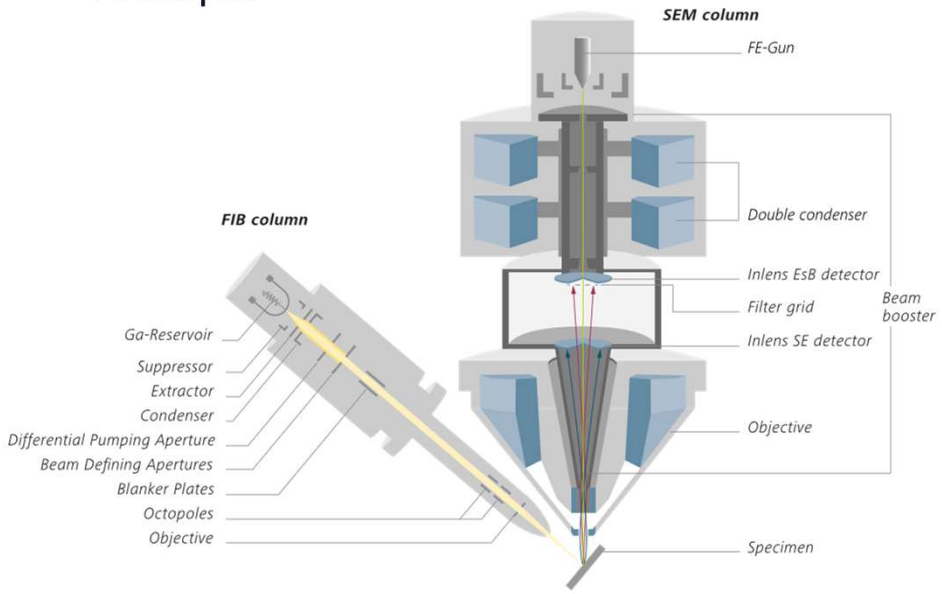


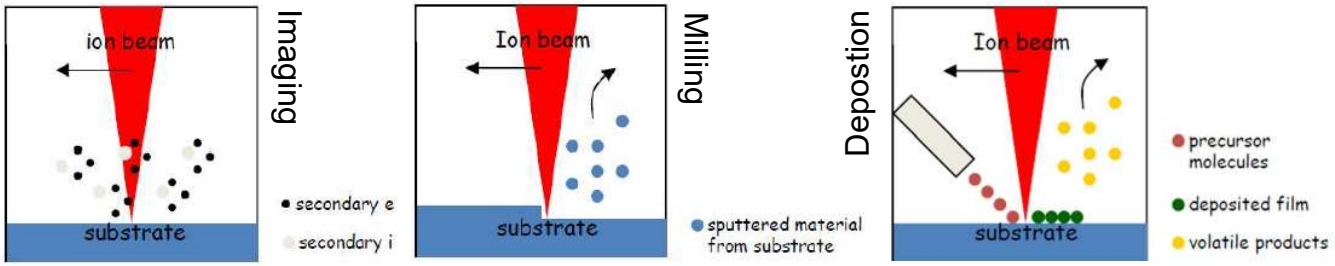
and a lot more ...

Master preparation

- Our processes
  - Focused Ion Beam

- Principle





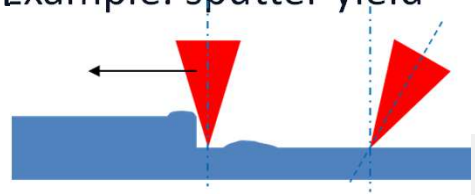
Master preparation

- Our processes
  - Focused Ion Beam

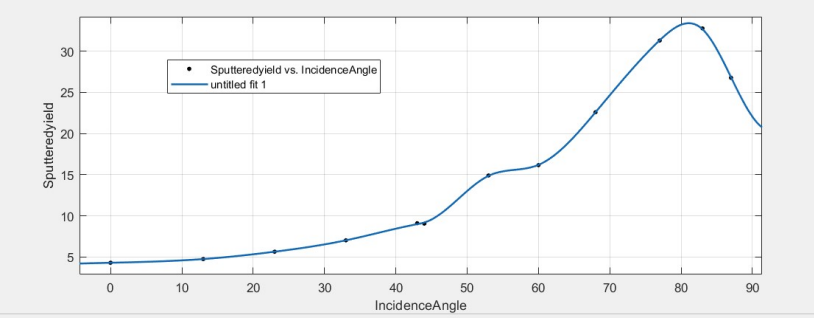
- Parameters

Y	-	Sputtering yield
e	c	Elementary charge
D	ions/cm^2	Ions Dose
A	cm^2	Irradiated Aera
ρ	g/cm^3	Density of the removal materials
V	cm^3	Volume of the removed area c
mt	g	Masse of the target atoms
nt	number/m^3	Density number of the targets atoms
h	m	Depth of the removed material

- Example: sputter yield



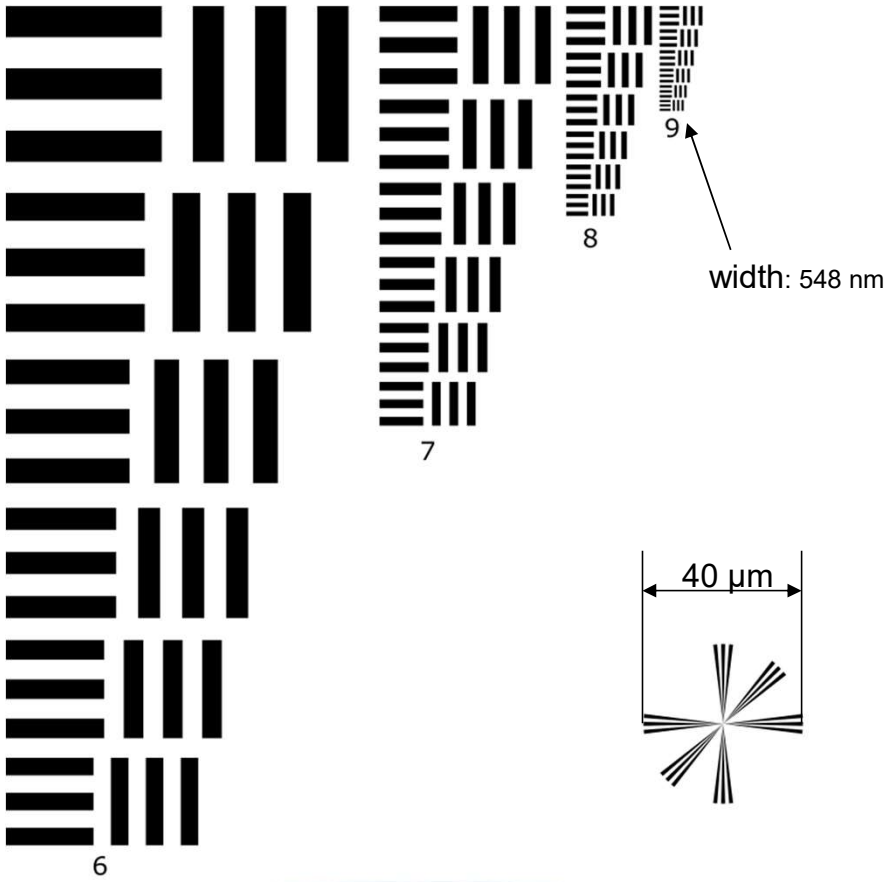
$$Y = \frac{N_{\text{Target}}}{N_{Ga^+}} = \frac{e}{D \cdot A} \cdot \frac{\rho \cdot V}{m_t} = \frac{e}{D \cdot A} \cdot \frac{n_t \cdot V}{1} = \frac{n_t \cdot e \cdot h}{D}.$$



Master preparation

- Our processes
  - Focused Ion Beam

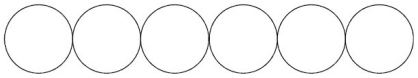
- Typical structures



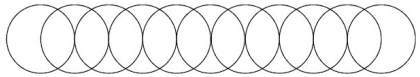
Master preparation

- Our processes
  - Focused Ion Beam

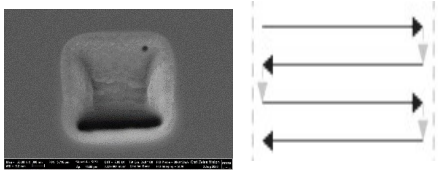
- Scanning direction matters…



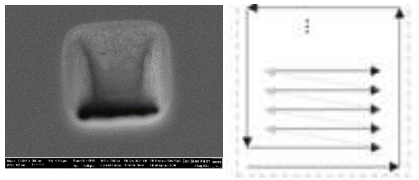
Imaging mode



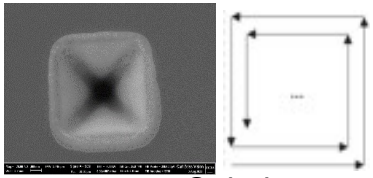
Milling mode area



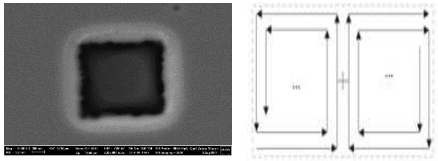
Serpentine



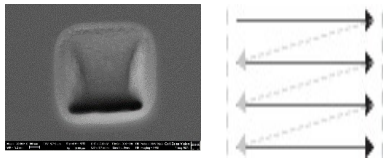
Border Raster



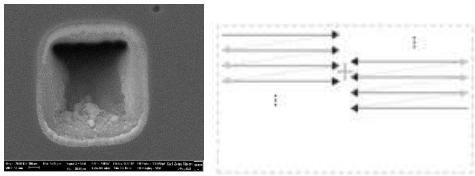
Spiral



Balanced Spiral



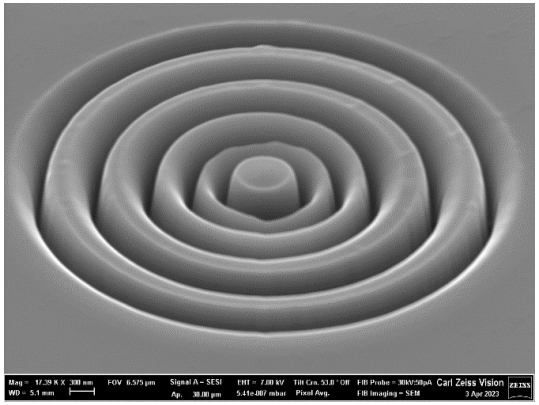
Raster

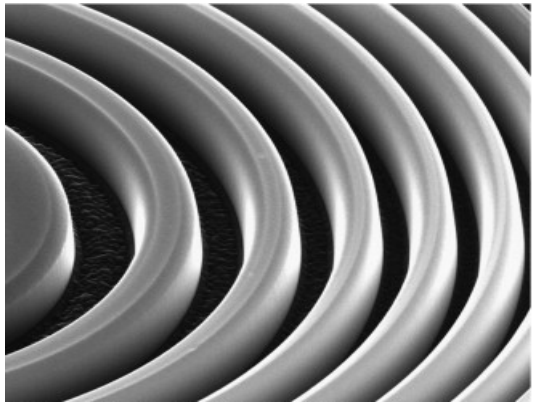


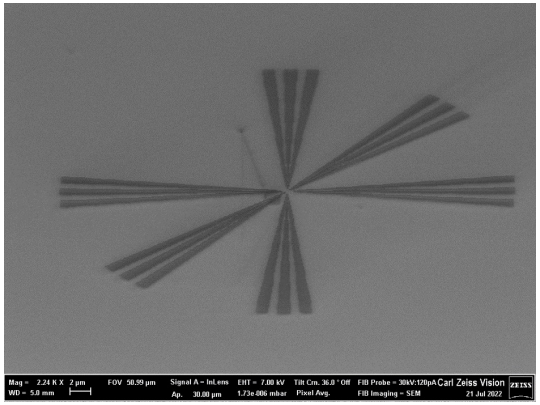
Balanced Raster

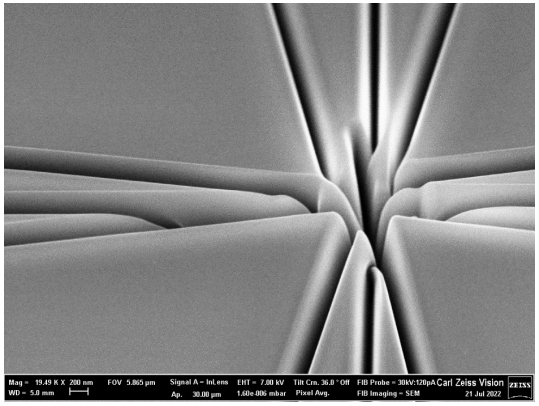
Master preparation

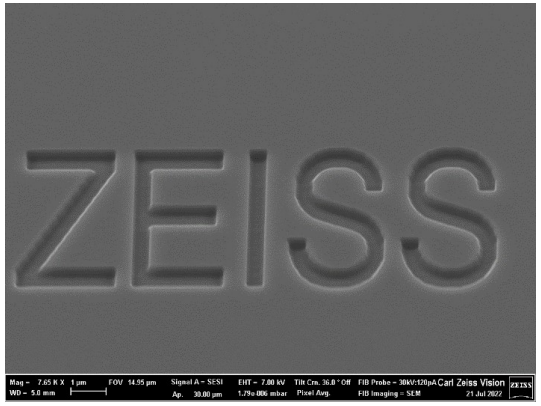
- Our processes
  - Focused Ion Beam
- Examples











Master preparation

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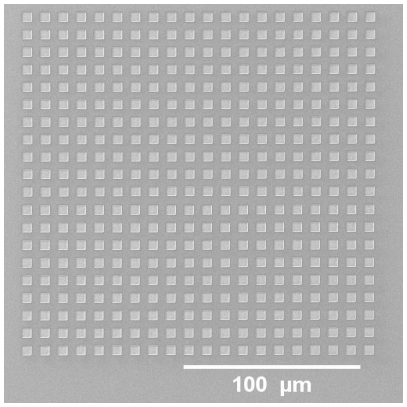
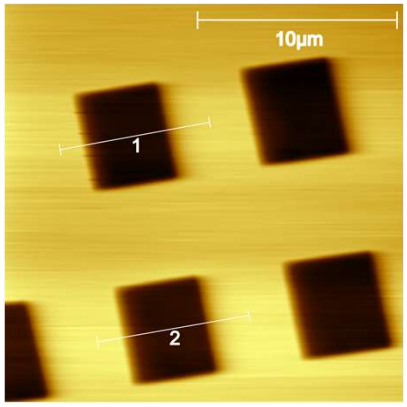
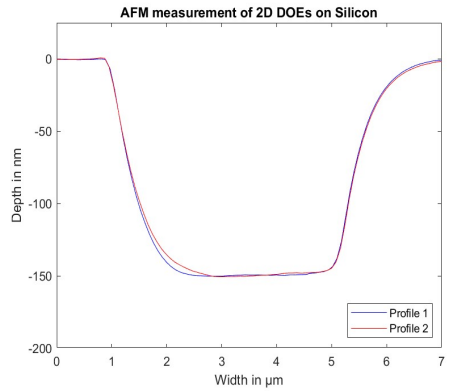
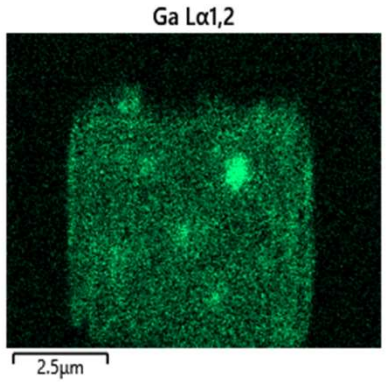
  - Focused Ion Beam

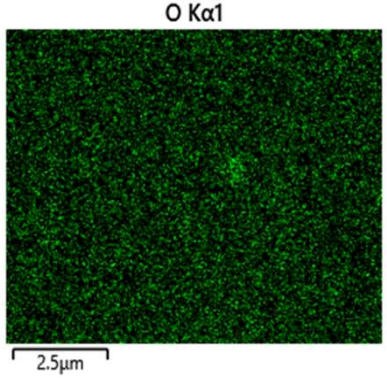
- Note: Ion implantation

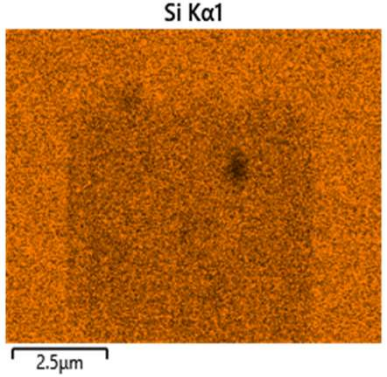








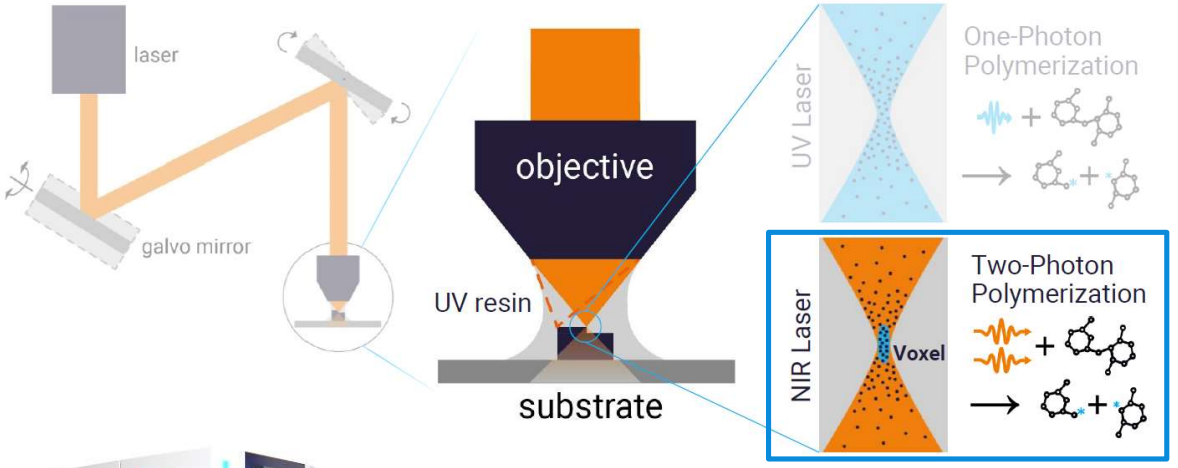




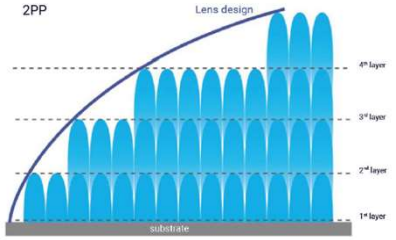
Master preparation

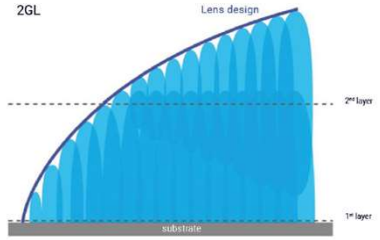
- Our processes
  - Focused Ion Beam
  - 2 Photon Polymerisation

- Curing based on Foto-Polymerization



→ **Nonlinear (2PP) absorbtion**





Master preparation

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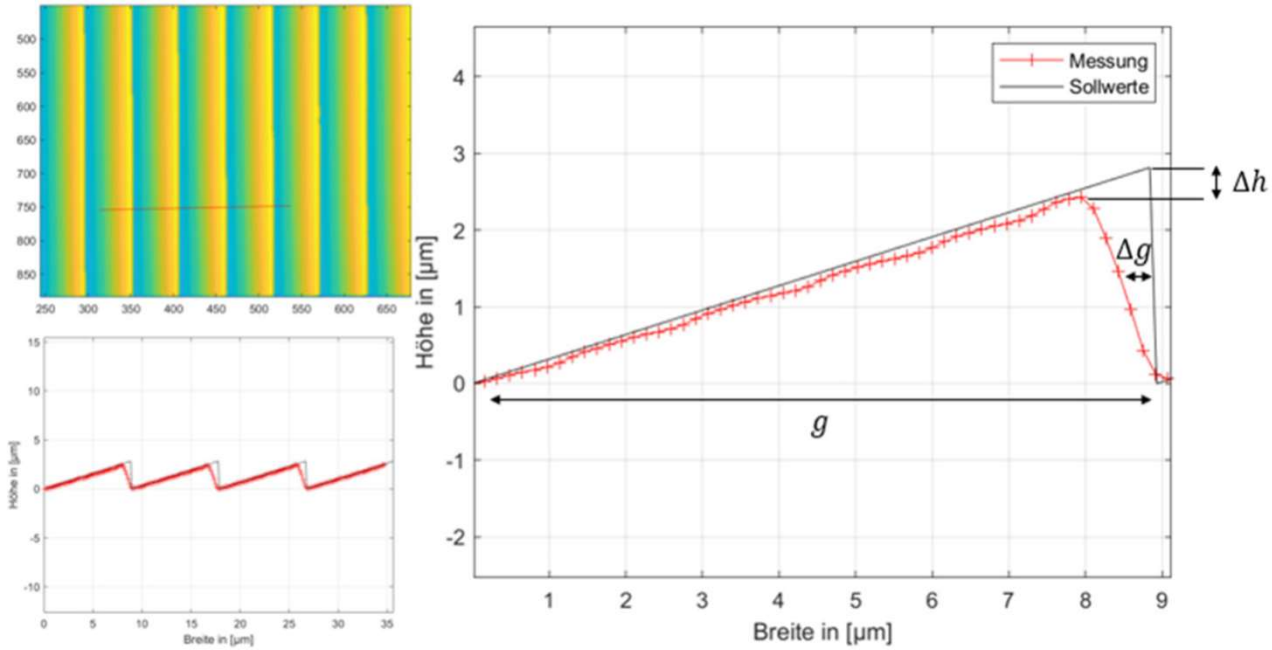
  - 2 Photon Polymerisation

- Example grating



Master preparation

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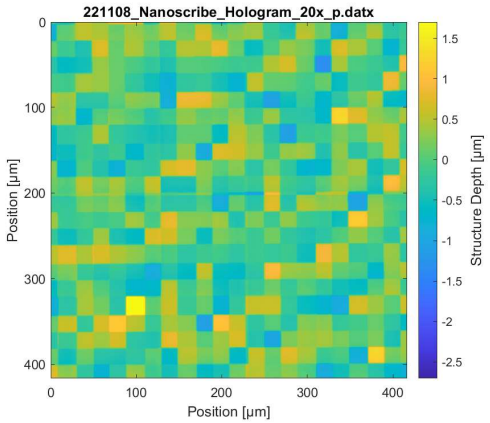
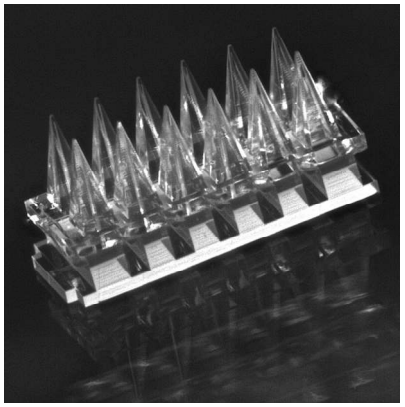
  - 2 Photon Polymerisation

- Some more Examples:

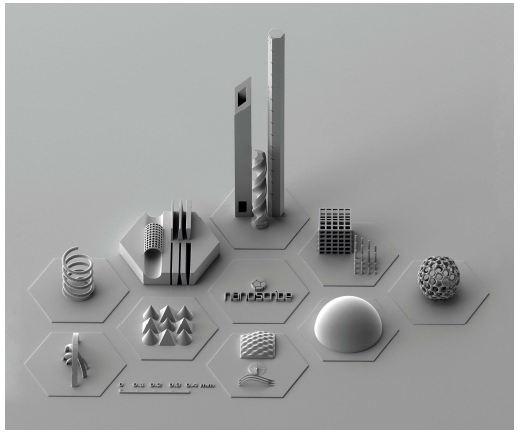


DOE

Periodic pillars with a high aspect ratio 0.8 x 2 µm



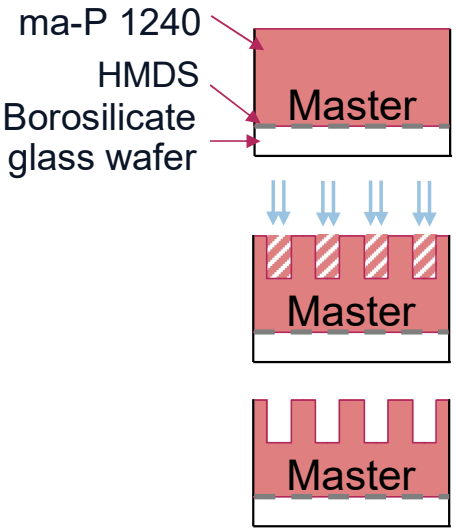
Microneedles (height: 1mm)



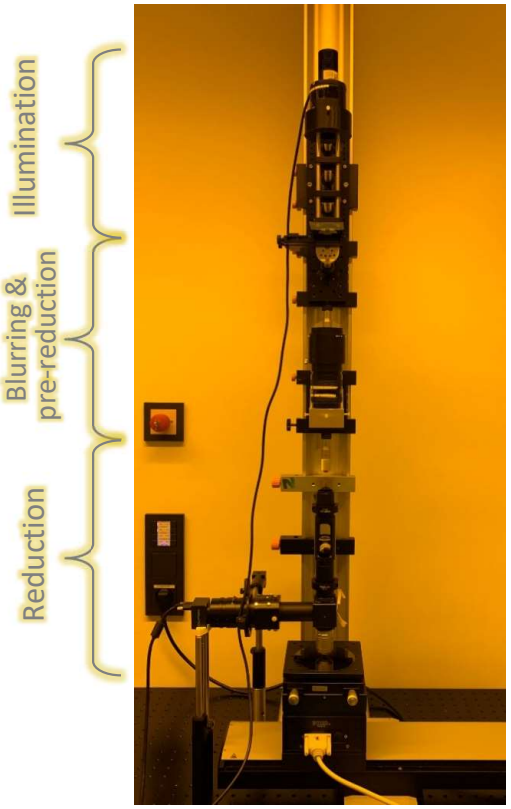
Example Nanoscriebe

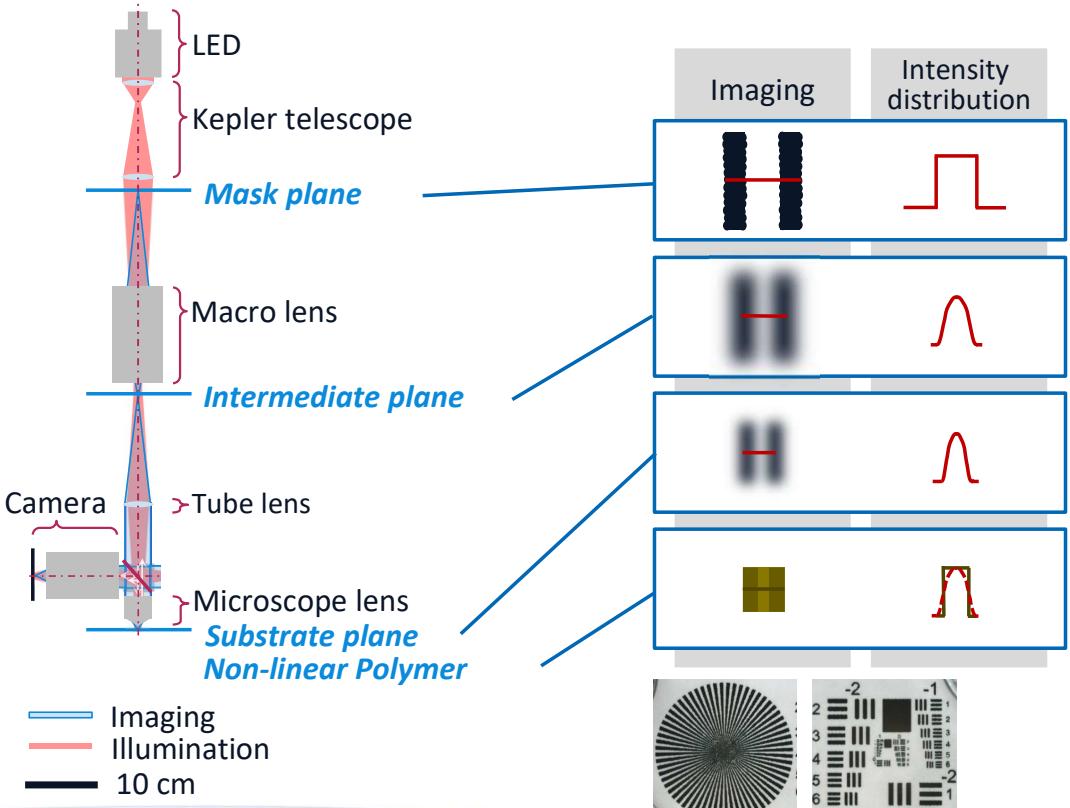
Master preparation

- Our processes
  - Focused Ion Beam
  - 2 Photon Polymerisation
  - Photolithography



- Ink-jet „Maskaligner“ for 2.5D structures (resolution 30 lp/mm)

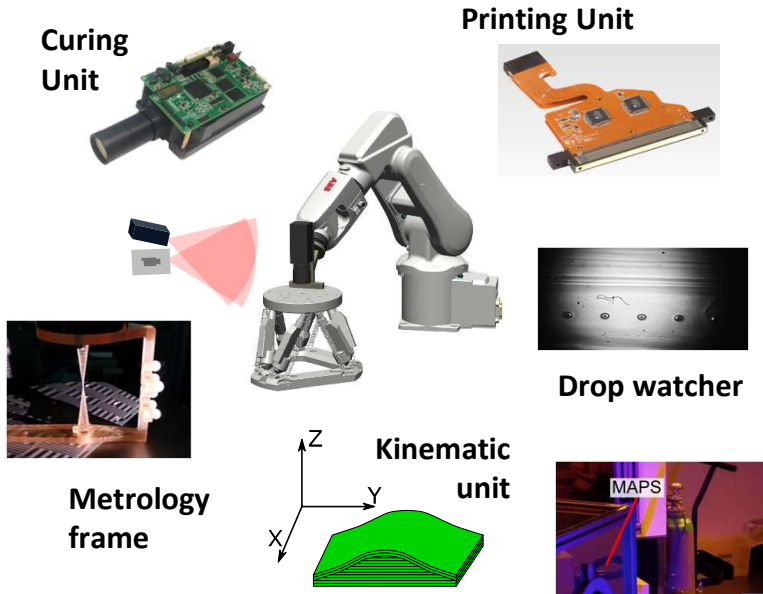


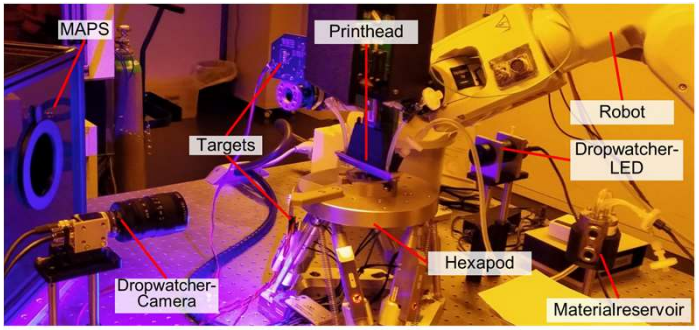


Master preparation

- Our processes
  - Focused Ion Beam
  - 2 Photon Polymerisation
  - Photolithography
  - Micro-projection Stereolithography

- Robot based printing system

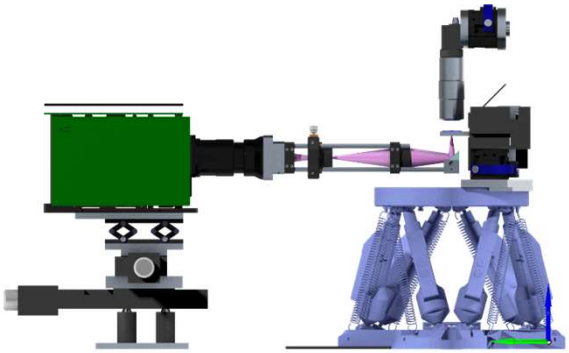


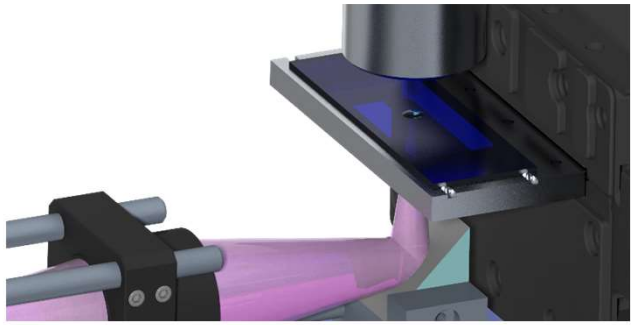


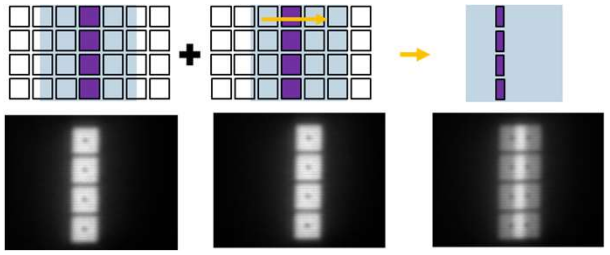
Master preparation

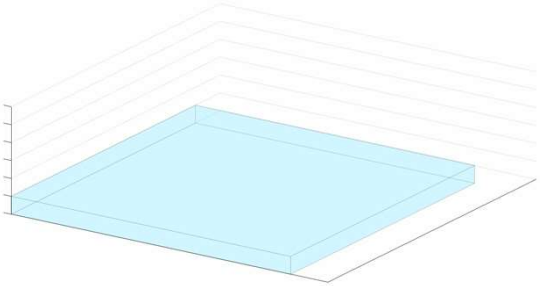
- Our processes
  - Focused Ion Beam
  - 2 Photon Polymerisation
  - Photolithography
  - Micro-projection Stereolithography

- Robot based printing system – curing unit: double patterning





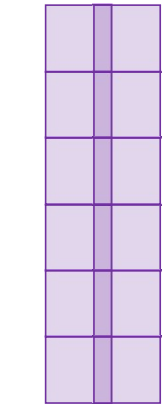




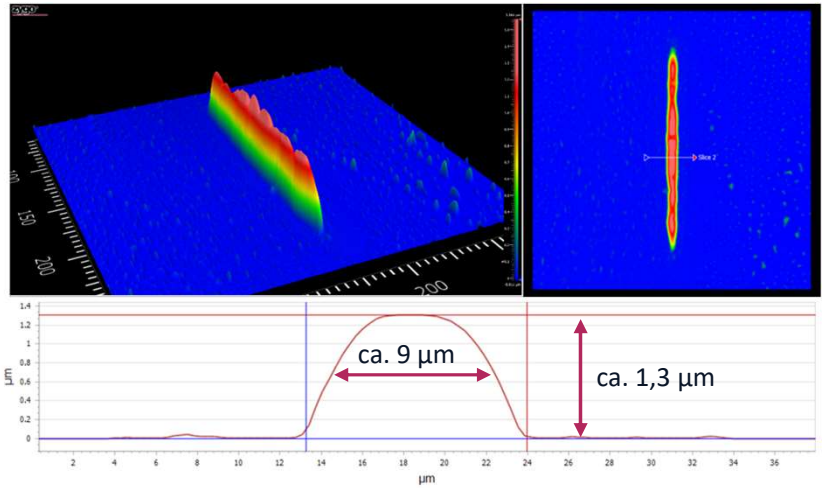
Master preparation

- Our processes
  - Focused Ion Beam
  - 2 Photon Polymerisation
  - Photolithography
  - Micro-projection Stereolithography

- Robot based printing system – example



Mask 1 Mask 2



Master preparation

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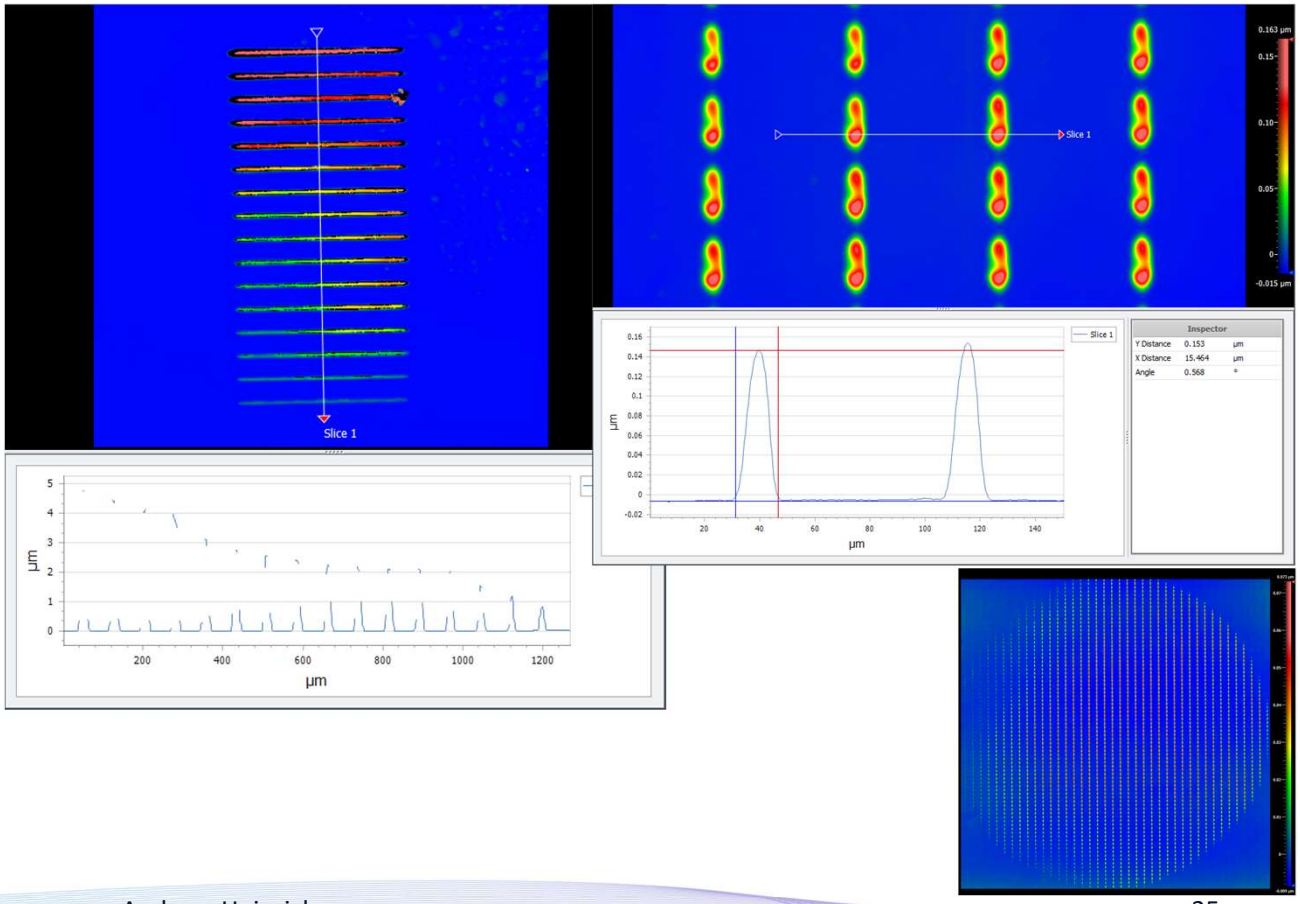
  - Photolithography
  - Micro-projection Stereolithography

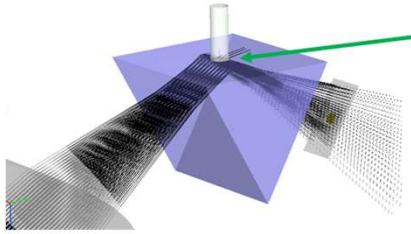
- Robot based printing system – examples

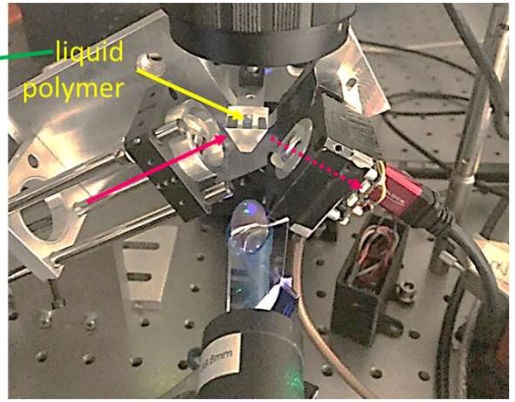


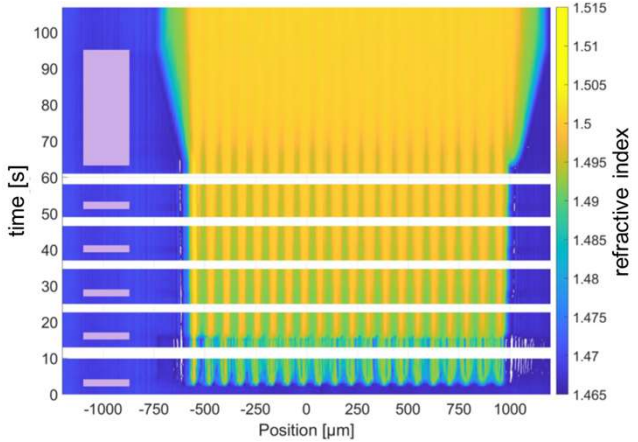
Master preparation

- Our processes
  - Focused Ion Beam
  - 2 Photon Polymerisation
  - Photolithography
  - Micro-projection Stereolithography

- Side note: refractive index



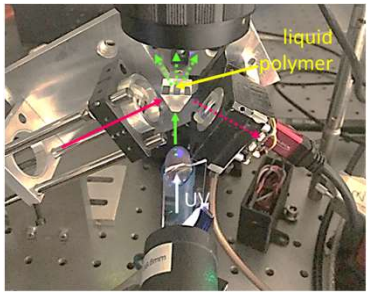


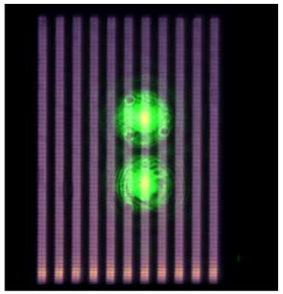
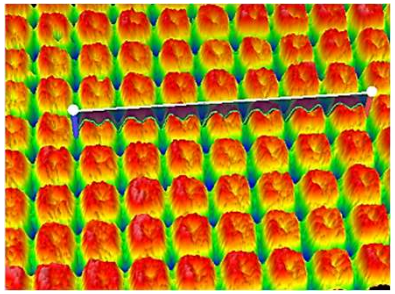


Master preparation

- Our processes
  - Focused Ion Beam
  - 2 Photon Polymerisation
  - Photolithography
  - Micro-projection Stereolithography

- Side note: refractive index

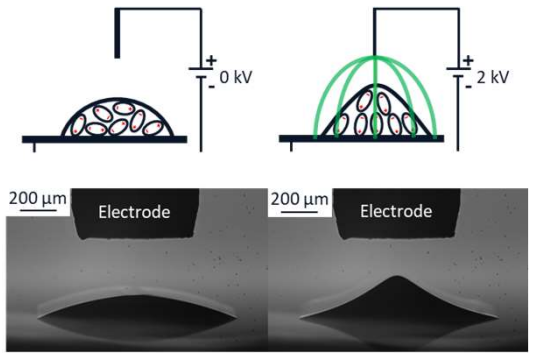


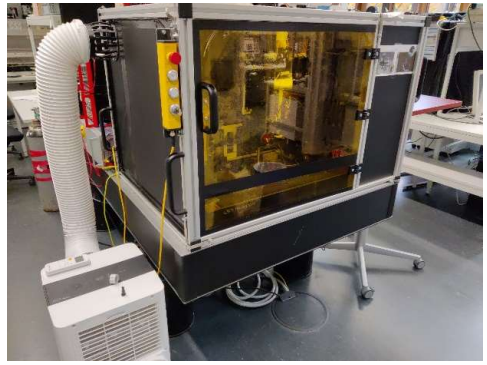



Master preparation

- Our processes
  - Focused Ion Beam
  - 2 Photon Polymerisation
  - Photolithography
  - Micro-projection Stereolithography
  - Dielectrophoresis

- Master fabrication of micro lenses



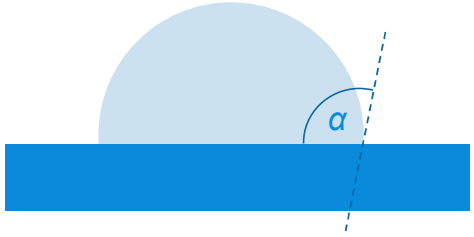
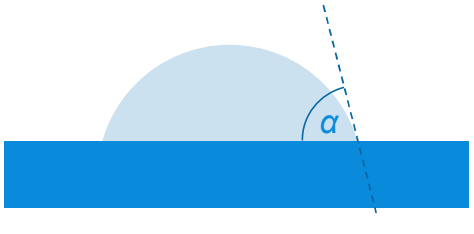
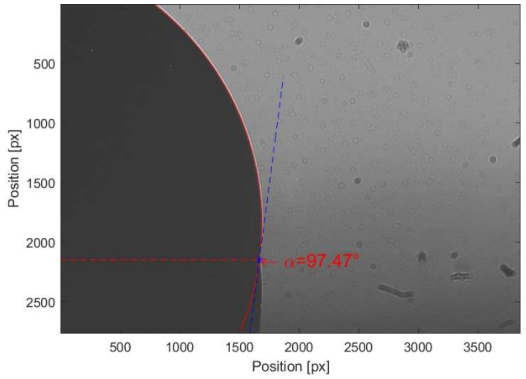
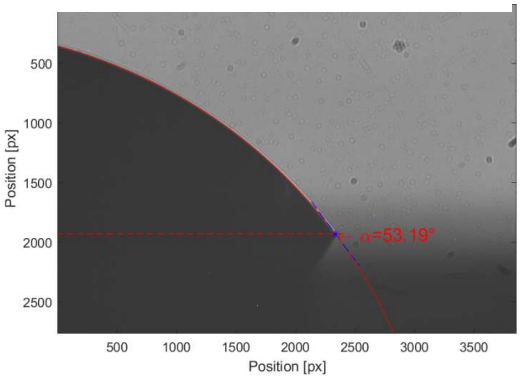


Master preparation

- Materials

Polymer (hybrid)	Anorganic + ASL
PDMS, PMMA, PUA, PVA, PVC, PTFE, ETFE,…	Si, SiO2, Cr, Borosilicate
Typ. we use: ma-P series (MicroResist), Si-hybrid (EVG)	*Typ. we use: Cr on Borosilicate, Si, ITO*

The surface matters as well …

Disperse (hydrophobic)	Polar (hydrophilic)
	
α > 90°	*α < 90°*
	

Master preparation

- Materials

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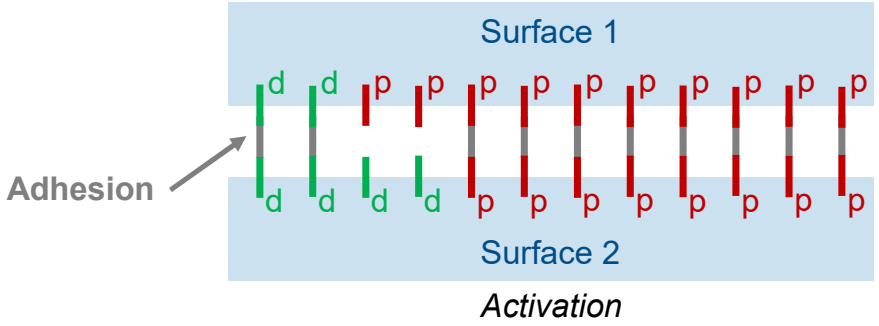
Typ. we use: ma-P series (MicroResist), Si-hybrid (EVG)	*Typ. we use: Cr on Borosilicate, Si, ITO*

The surface matters as well …

- Primers
  - Adhesion promoters (primers) adjust the surfaces → surfaces 1 and 2 bond well.
    - HMDS Primer (Litho script), MircroResist,…
    - Primer20, MicroResist
    - Ti Prime (Litho script), MicroChemicals



Activation

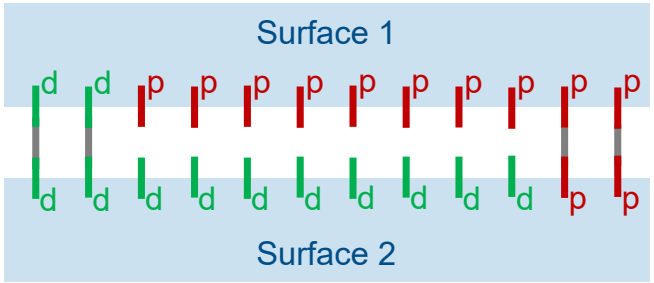
Master preparation

- Materials

Polymer (hybrid)	Anorganic + ASL
PDMS, PMMA, PUA, PVA, PVC, PTFE, ETFE,…	Si, SiO2, Cr, Borosilicate
Typ. we use: ma-P series (MicroResist), Si-hybrid (EVG)	*Typ. we use: Cr on Borosilicate, Si, ITO*

The surface matters as well …

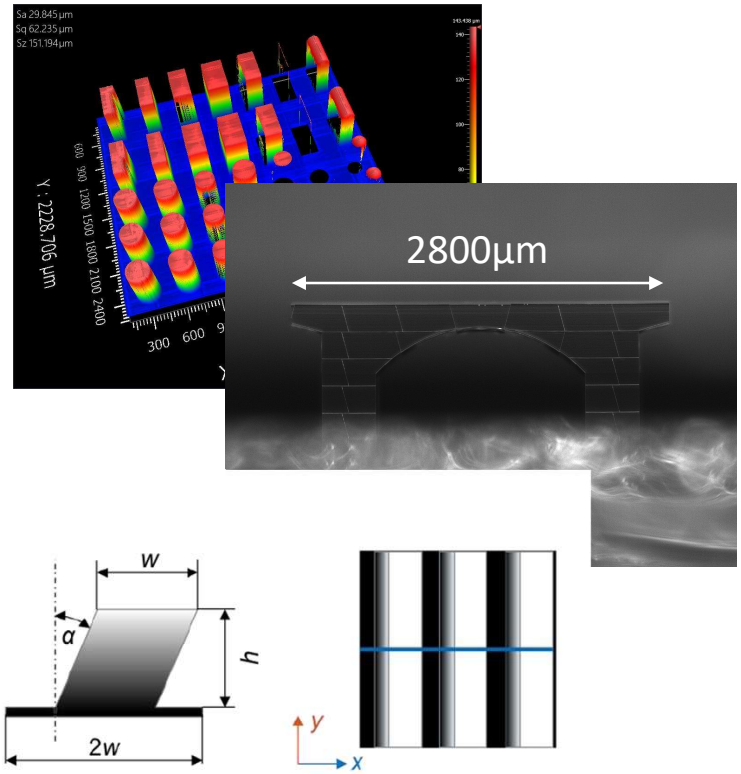
- Passivation / Anti-sticking layers
  - Passivation layers (anti-sticking layers short: ASL) ensure a sufficient difference in surface polarity
    → surfaces 1 and 2 can be separated without damage.
    - F13-TCS (kind of teflon), Sigmar Aldrich
    - BGL-GZ-83 Quarz, Profactor
    - ASL-R36, EV Group



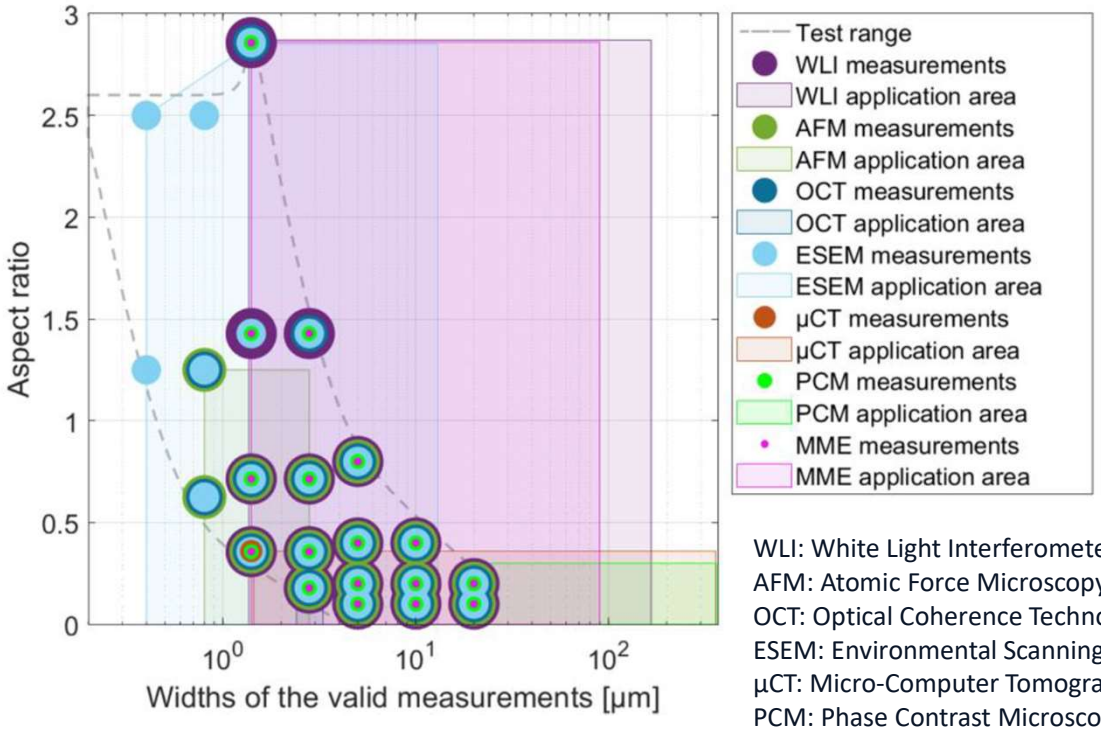
Passivation

Master preparation

- How to measure small structures?



- Comparison of different techniques:



WLI: White Light Interferometer
AFM: Atomic Force Microscopy
OCT: Optical Coherence Technologiy
ESEM: Environmental Scanning Electron Microscope
µCT: Micro-Computer Tomography
PCM: Phase Contrast Microscope
MME: Müller Matrix Ellipsometry

Agenda

- Principles of NIL
- **Master preparation**
- Stamp preparation
- Replication
- Examples

Work presented done by PhD-students of the group


Selina Burkert

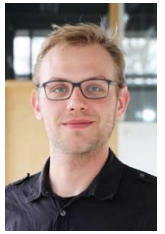

Annika Dehm


Arielle Koffi


Sangeetha Suresh-Nair


Yannick Bauckhage


Mike Dohmen


Christian Eder

and our BA / MA students!

Agenda

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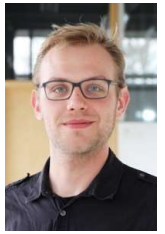
Christian Eder

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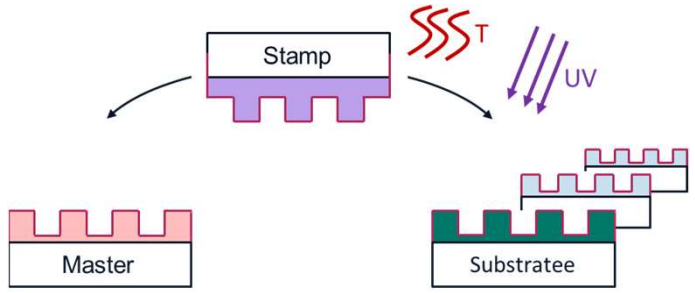
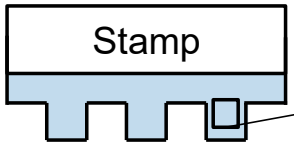
Stamp preparation

- Requirements
  - Robust (mechanical)
  - Presice and small structures
  - If necessary: Passivation using ASL

- Process



- Parameters



Main parameters for a long stamp lifetime
- Hardness
- Thermal and UV stability
- Poisson‘s ratio
- Young‘s modulus
- Roughness
- Resistance

➔ Hybrid polymer stamps

Stamp preparation

- Requirements
  - Robust (mechanical)
  - Presice and small structures
  - If necessary: Passivation using ASL

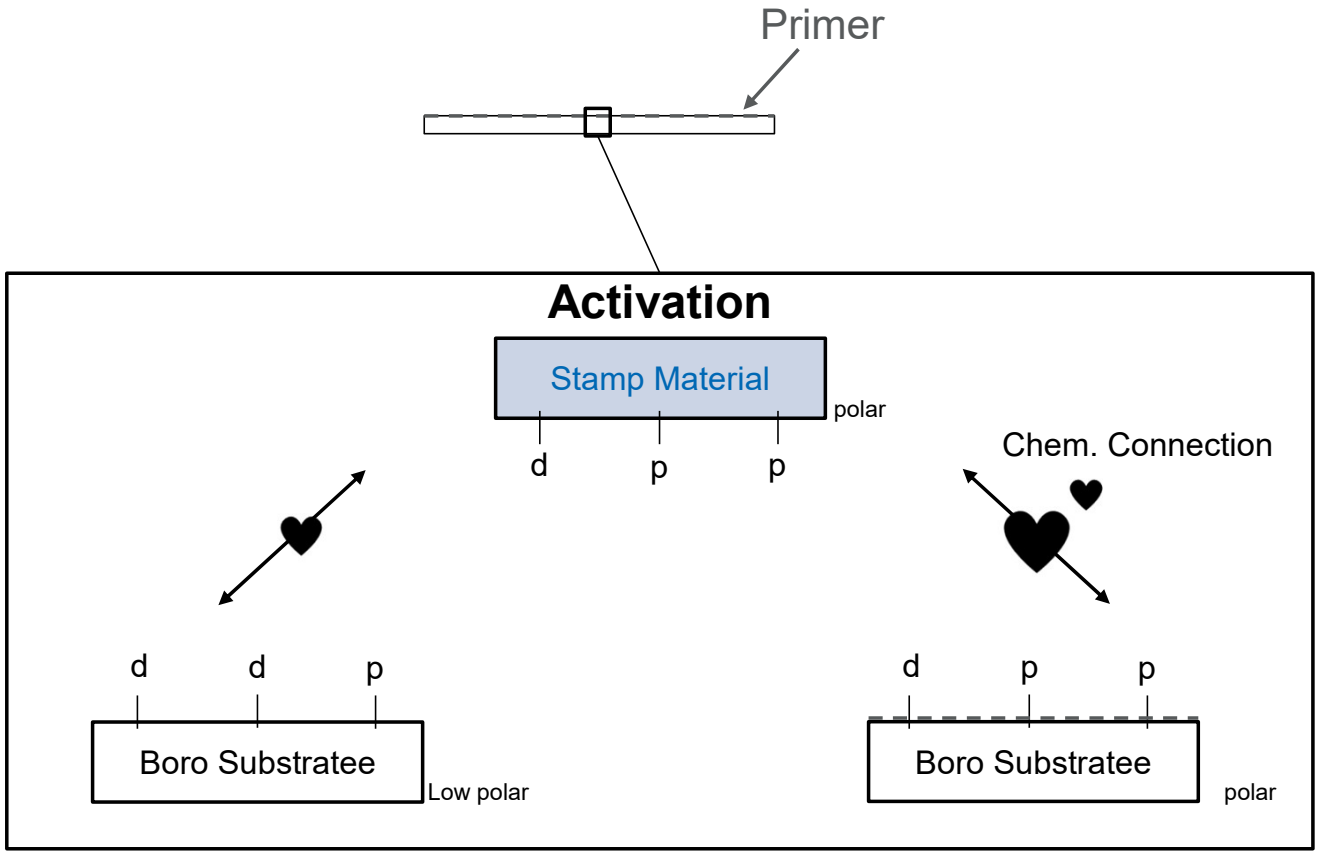
- Materials

Hard-NIL	Soft-NIL
SiO2, Ni, Si, Si3N4, SiC, Cr,…	PDMS, PMMA, PUA, PVA, PVC, PTFE, ETFE,…
	Smart-NIL
	Si-Hybridpolymer,…

Soft stamps	PDMS	Polydimethylsiloxane
	PMMA	Polymethyl methacrylate
	PUA	Polyurethan
	PVA	Polyvinylalcohol
	PVC	Polyvinylchlorid
	PTFE	Polytetrafluoroethylene
	ETFE	Ethylene tetrafluoroethylene

Stamp preparation – Soft NIL

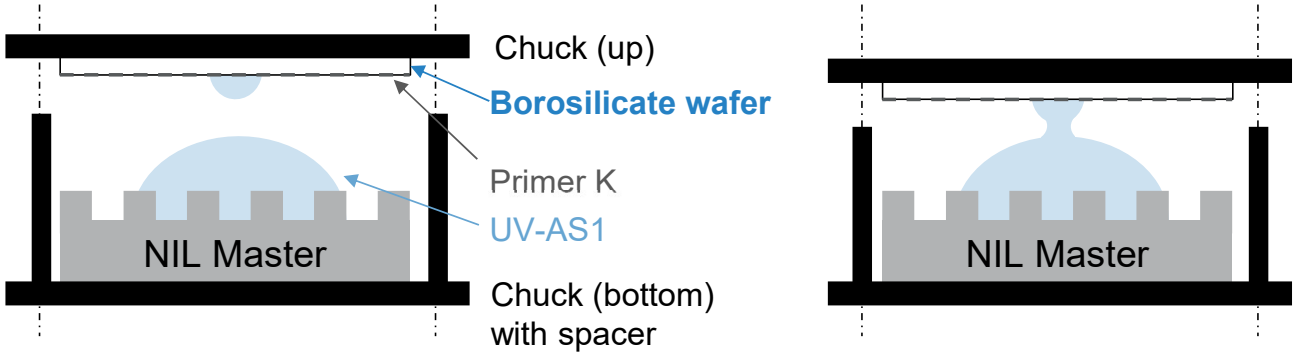
- Soft NIL: Step 1
  - Coating of substrate w/ primer
  - A polar surface and reactive molecules are required to bind the polar stamp material
  - Primer is a monolayer (5-18 nm, in the best case)



Adhesion promoter based polar molecules

Stamp preparation – Soft NIL

- Soft NIL: Step 2
  - Two-piece chuck is brought together. The spacers determine the height of the stamp.

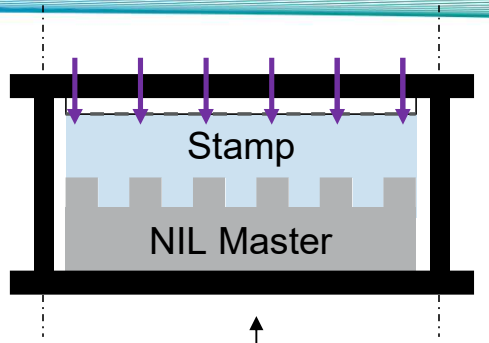


Chuck merge in the stamp manufacturing process

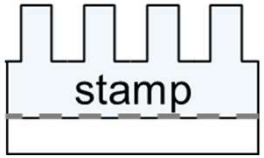
Stamp preparation – Soft NIL

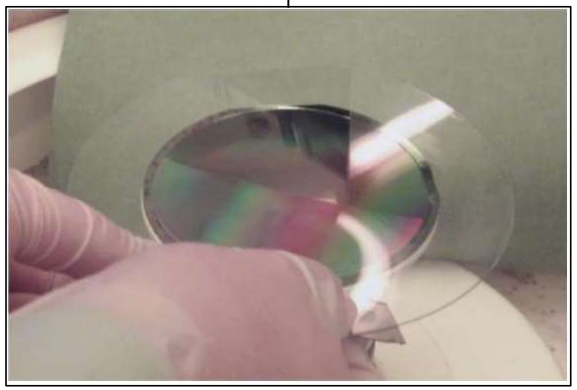
- Soft NIL: Step 3
  - Stamp material is cured by UV light

- Soft NIL: Step 4
  - Mechanical (e.g. using a blade) or chemical separation (e.g. solving master in PGMEA) of stamp and master



UV light (365, 405, 435 nm)

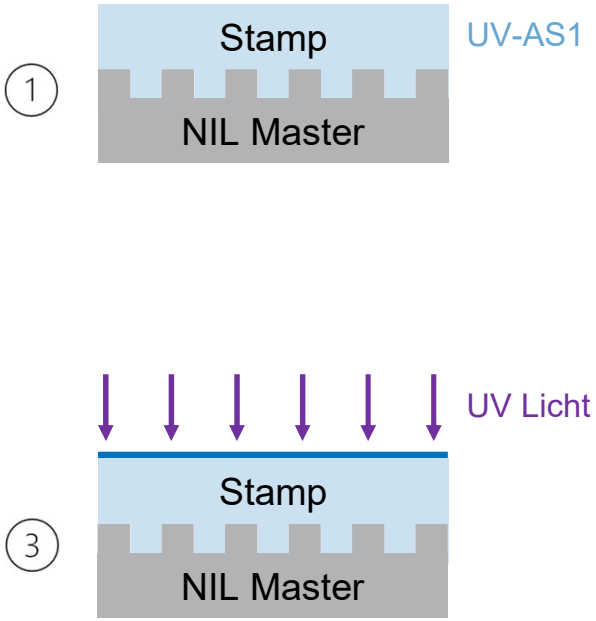




Separation by a blade

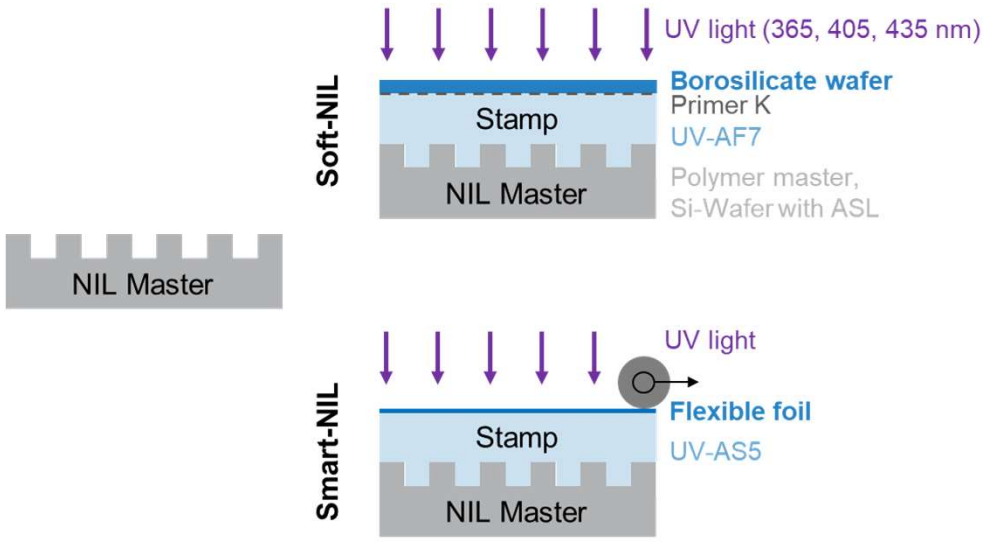
Stamp preparation – Smart NIL

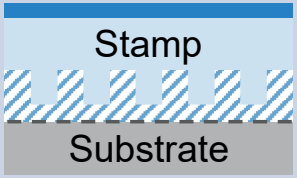
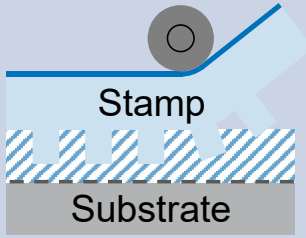
- Smart NIL: Step 1
  - The stamping material is spun onto the master.
- Smart NIL: Step 2
  - A pre-tensioned foil is applied to the stamp material using the roller of the Smart-NIL tool.
- Smart NIL: Step 3
  - The foil and the stamp material are chemically bonded during curing under UV light.



Stamp preparation

- Soft NIL versus Smart NIL



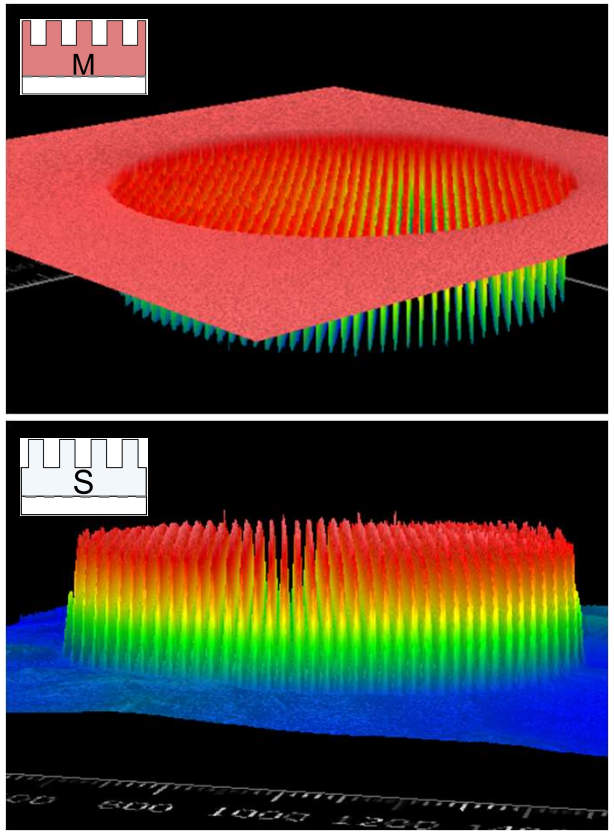
Parameter	Soft-NIL	Smart-NIL
		
Stamp based on	Borosilicate wafer	Flexible foil
Suggested structure size	> 5 µm	< 5 µm
ability for freeform and metasurfaces	"inflexible" stamp must be adapted.	film can adapt better to the individual shape of the substrate.

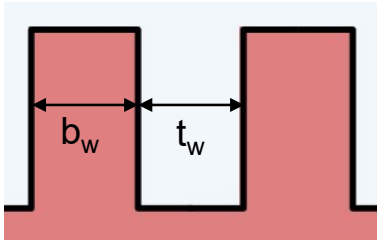
Stamp preparation

- Example

- Ink-Jet Photolithography Master

WLI images of the photoresist master and the respective stamp





	Bar width b_w [µm]	Std [%]	Trench width t_w [µm]	Std [%]
Master	15.45	4.13	11.38	5.07
Stamp	15.58	5.3	10.44	6.5

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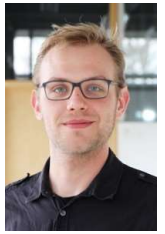
Christian Eder

and our BA / MA students!

Agenda

- Principles of NIL
- Master preparation
- Stamp preparation
- **Replication**
- Examples

Work presented done by PhD-students of the group


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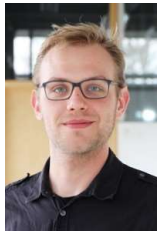
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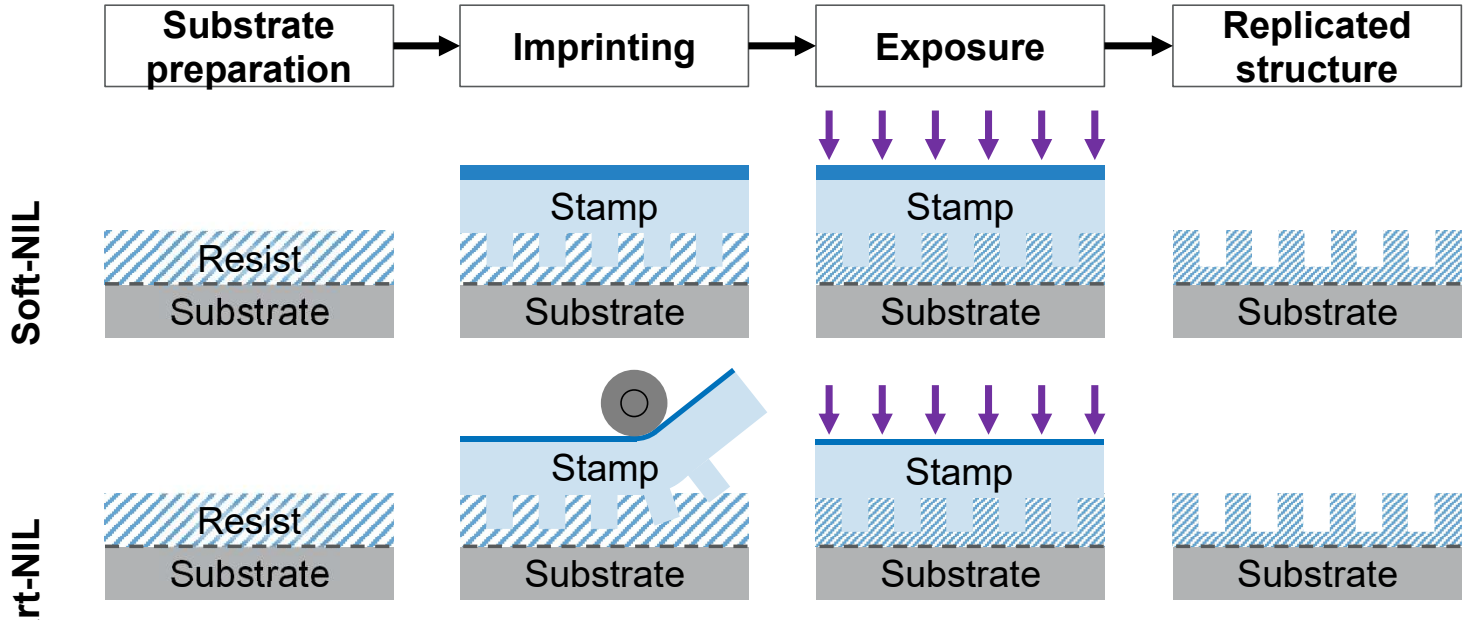
Replication

- Process



The stamp is molded by the master.
Soft-NIL: Polymer stamp on a borosilicate wafer.
Smart-NIL: Polymer stamp on a flexible foil, smaller structures are replicable.

The stamp is pressed into the liquid photoresist.
Soft-NIL: The stamp is vertically moved.
Smart-NIL: A roller moves on top of the stretched stamp foil.

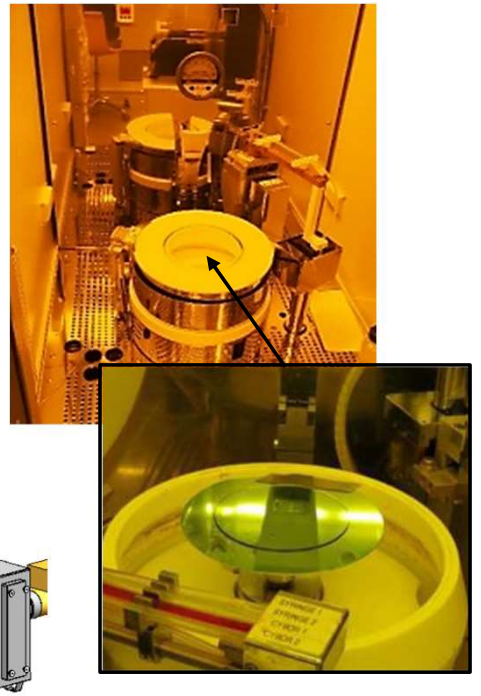
After the imprinting, the photoresist is exposed by UV light. The photoinitiators of the resist start the polymerization of the resist and the photoresist is cured.

The stamps are detached.

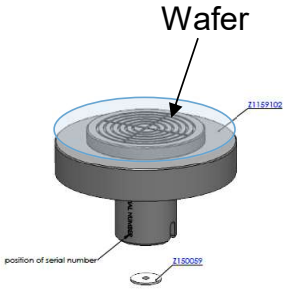
Replication

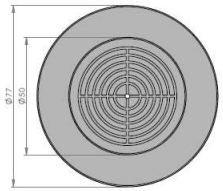
- Spin Coating
  - Hardware
    - Chemical cabinets
    - Dispensing of materials via syringes or dispensers
  - Software (recepies)
    - time
    - velocity [rpm]
    - acceleration
    - cycles
  - From 10nm to >50µm

EVG 101 200



Spin module (inside)





Chuck 4” / 6”

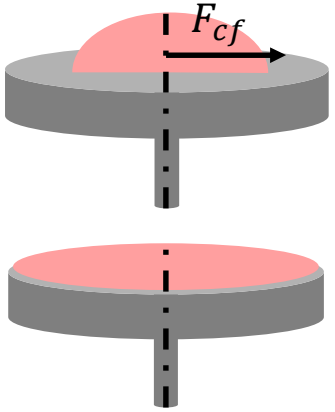
Replication

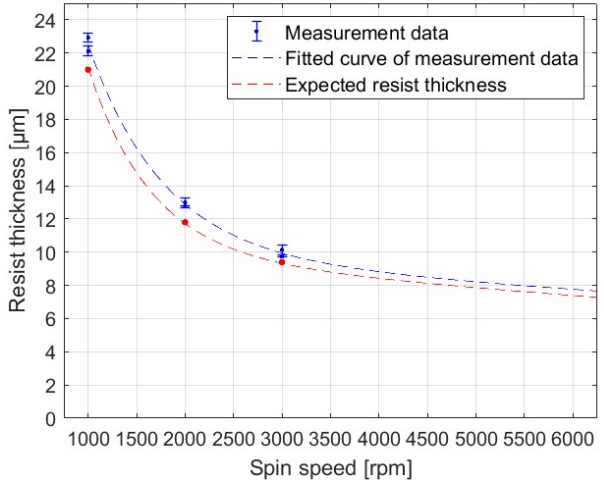
- Spin Coating
  - Goal: defined and thin layers
    - Thickness defined by rotation speed and time
    - Individuals curves
  - Impacts on the thickness
    - Temperature
    - Acceleration
    - Humidity
    - Spin time
    - Solvent (evaporates during post-bake)
    - …

Modell	Schichtdickenbereich*	Wellenlängenbereich
F20-UVX	1nm - 250µm	190-1700nm

$$F_{cf} = \frac{m \cdot v^2}{r}$$

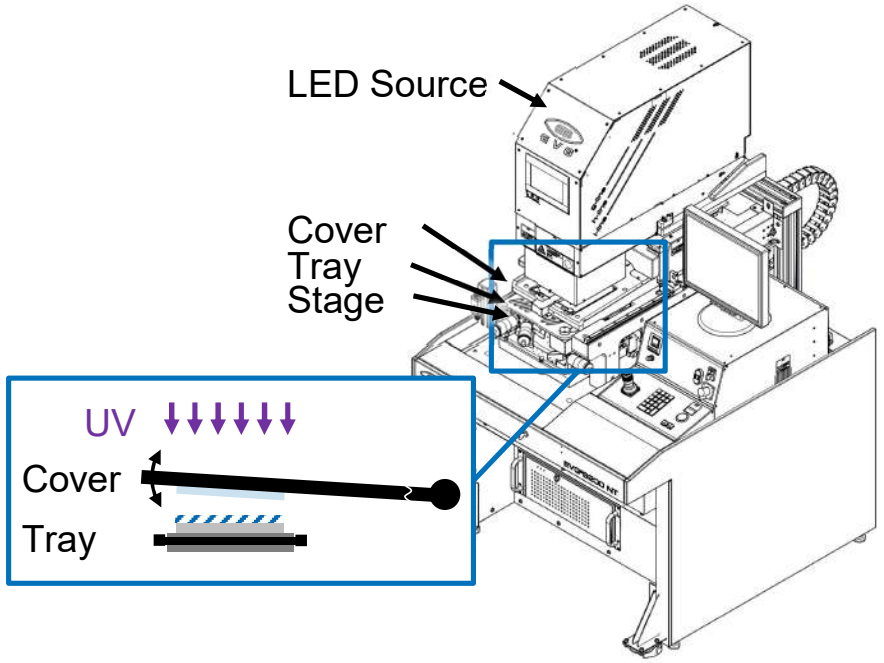
$$F_{cf} = F_{\eta}$$

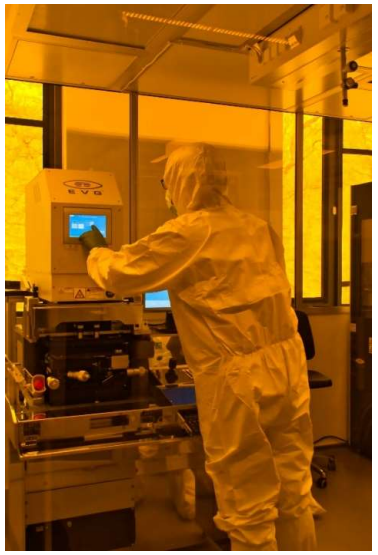




Replication

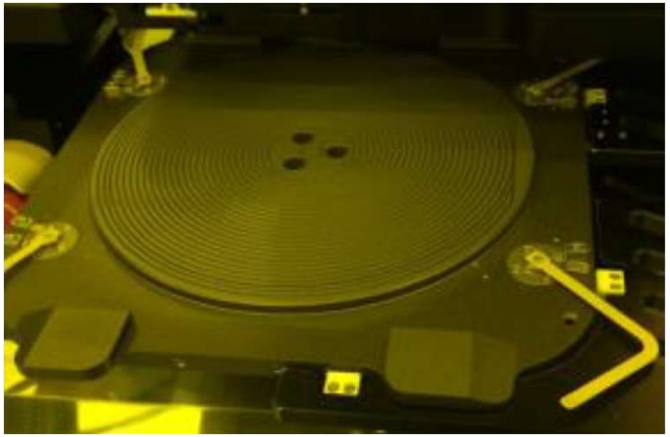
- Replication: EVG 620 NIL & Maskaligner
  - Hardware
    - LED unit
    - Cover (upper stamp unit)
    - Tray (loading tool)
    - Stage + optical alingment
    - Fixation via vacuum
  - Nanoimprint
    - Soft-NIL
    - Smart-NIL
  - Software (Recipes & Manual)
    - e.g. Exposure settings (Power, LED (g-, h-, i-line, Time)

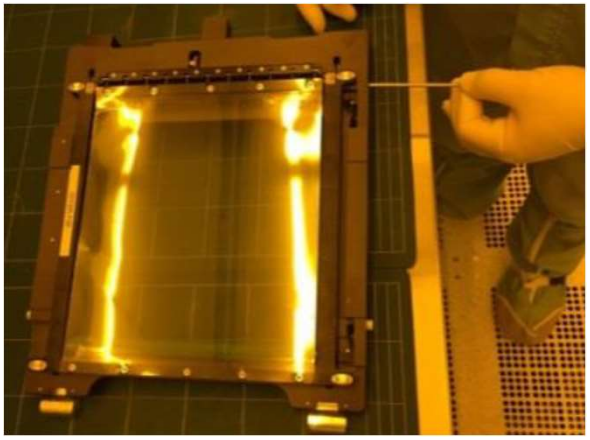


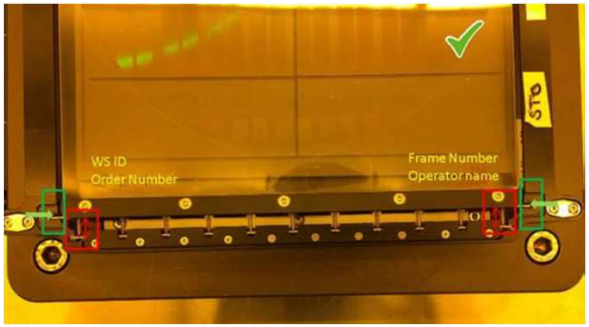


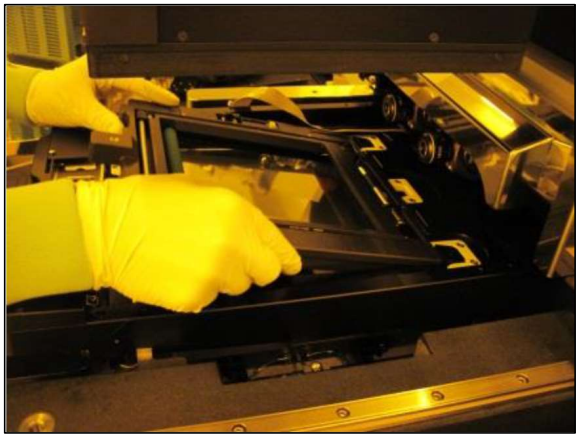
Replication

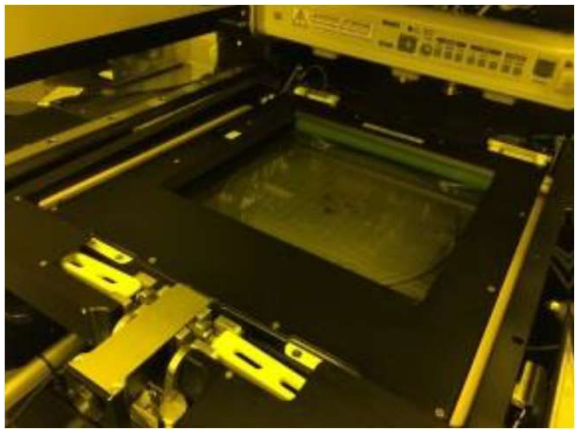
- Smart NIL: Tools





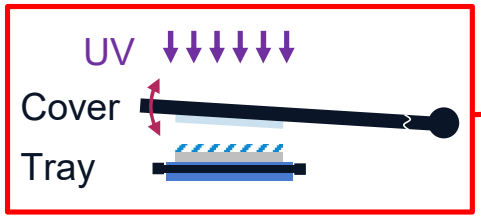


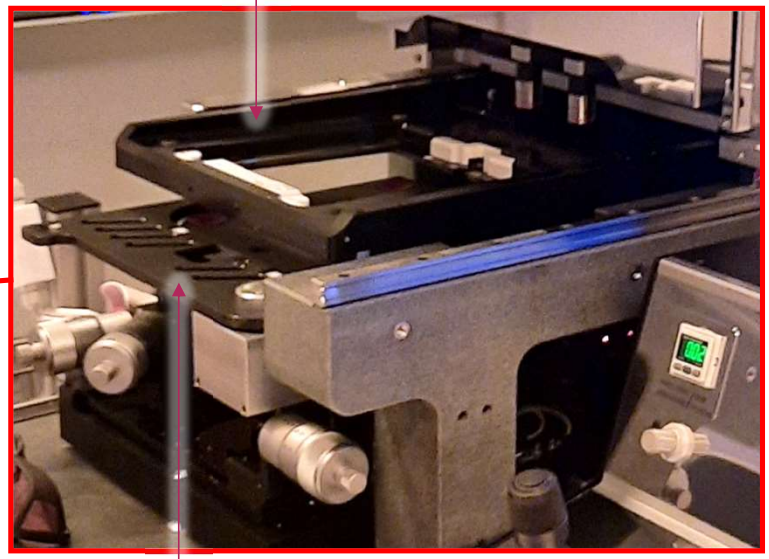




Replication

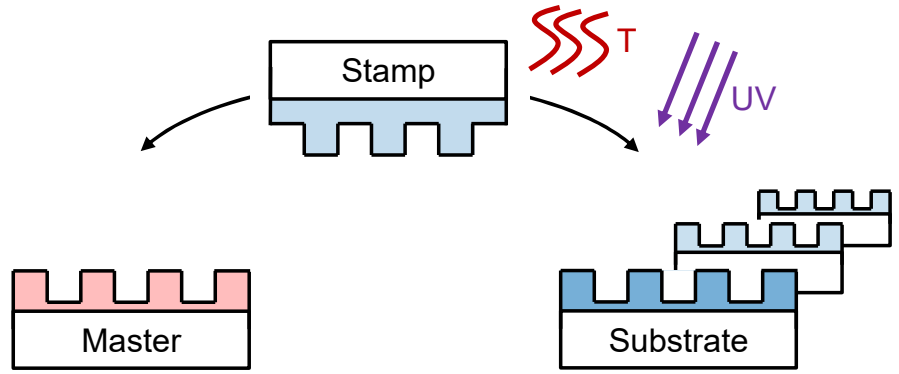
- Smart NIL: Tools





Side note: Resolution affecting parameters

- Master & Stamp
  - Individual resolution
  - Roughness
  - (Primer) and anti-sticking quality
- Process parameters
- Resin properties of stamp and replica
  - Absorption spectrum
  - Young‘s modulus [GPa]
  - Hardness [Mpa]
  - Optical properties e.g. refractive index for the application (Waveguide, diffractive optical element)
  - Shrinkage [%]
  - Viscosity



The materials used have a major impact on the resolution of the replicated NIL structure.
The master, the stamp, and the replica material must match.

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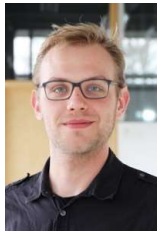
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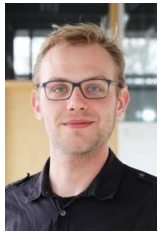
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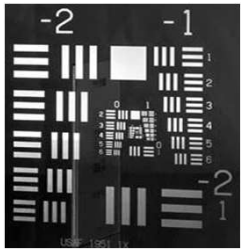
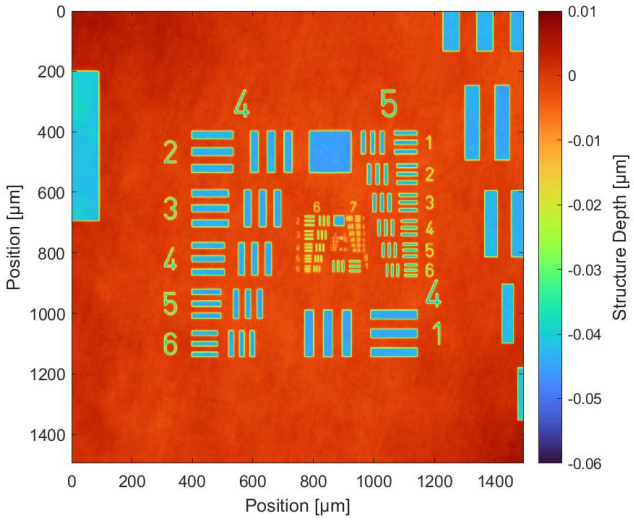
Examples – plane substrates

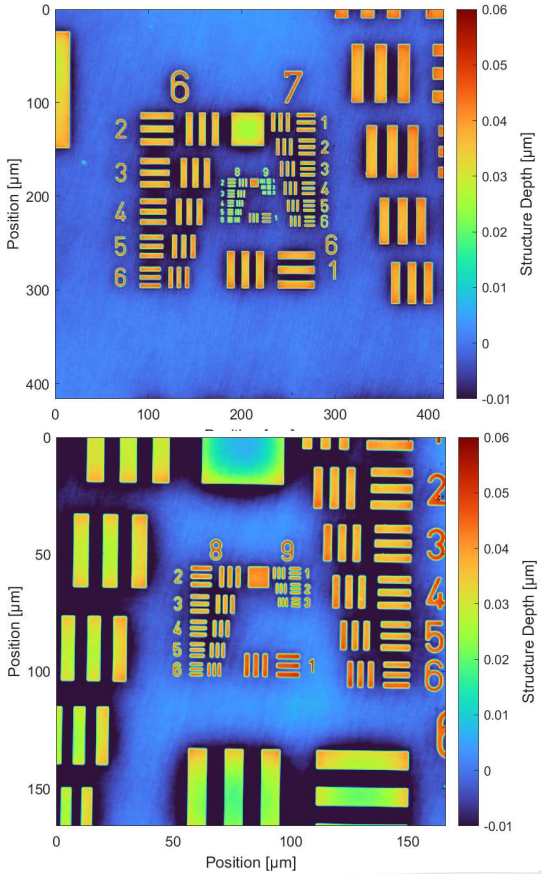
- USAF Target



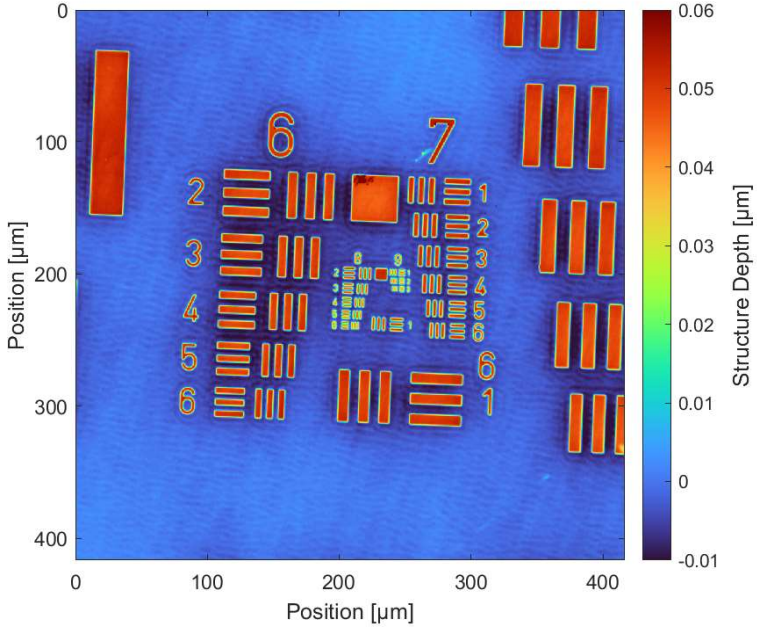
Master



Stamp

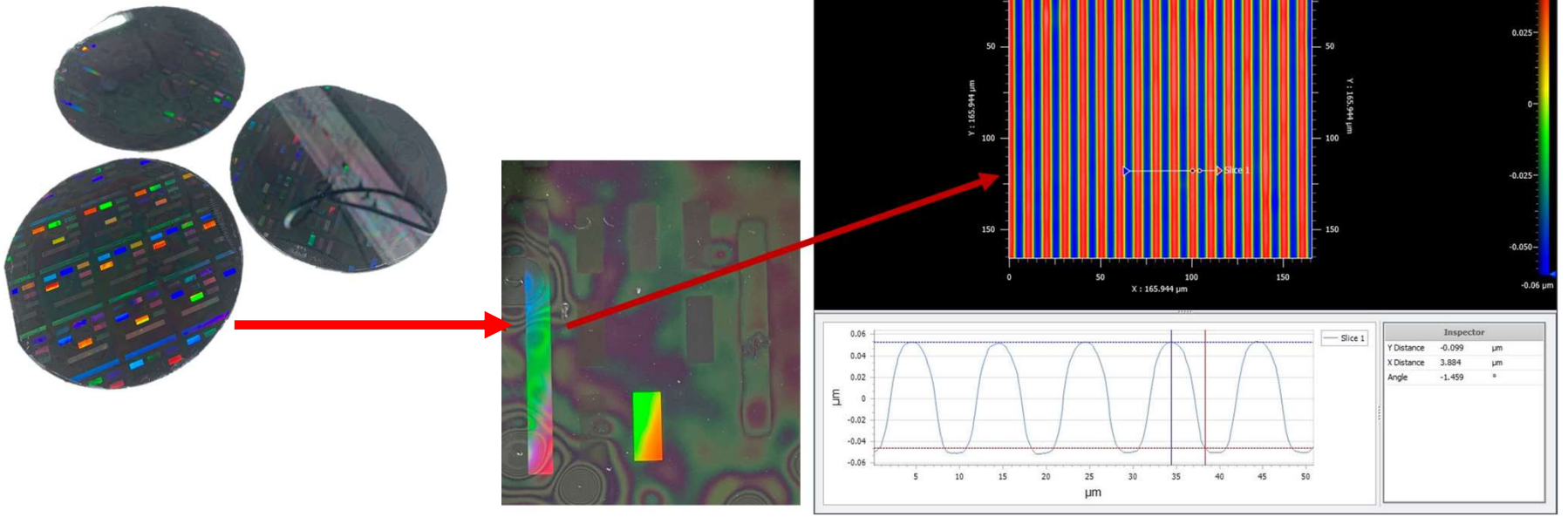


Replica



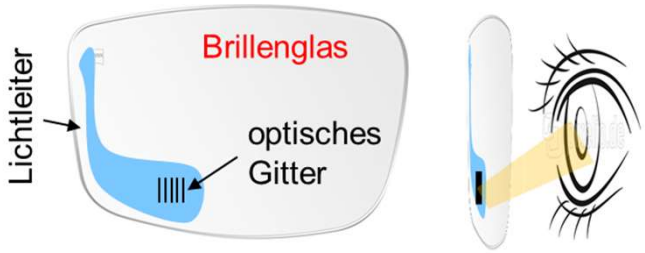
Examples – plane substrates

- grating
  - Line grating: 100 lp/mm
  - Structure height: 100 nm

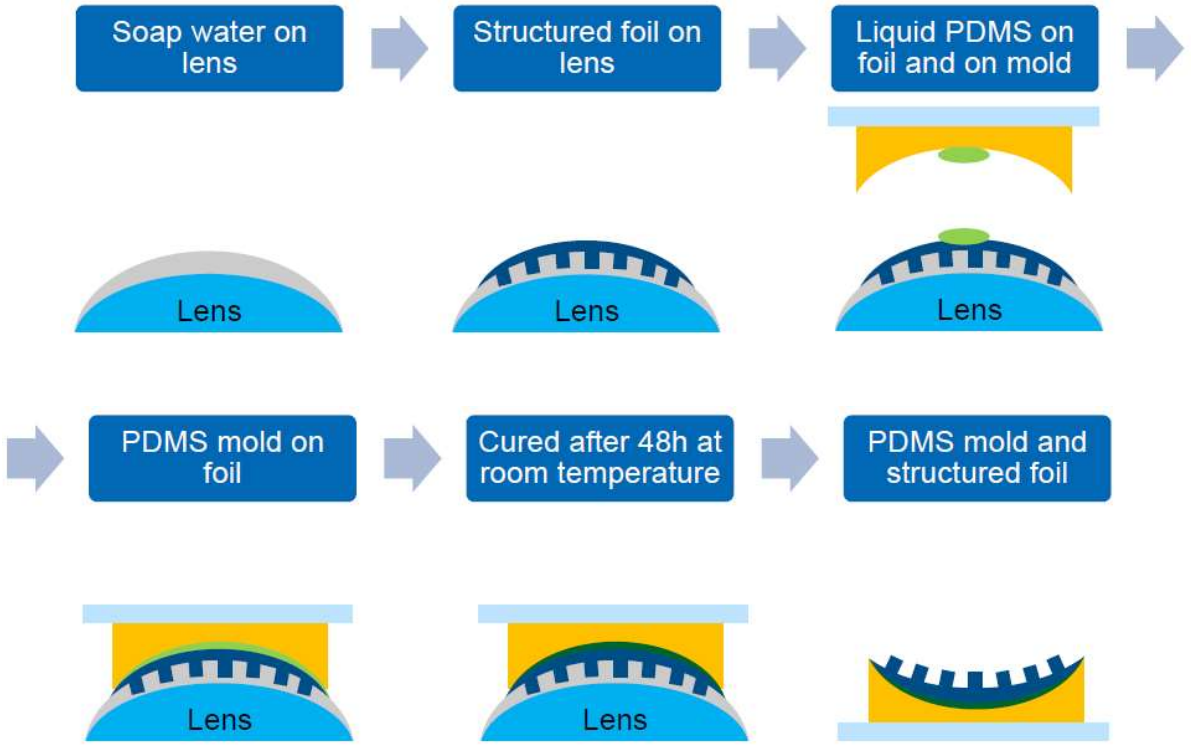


Examples – curved substrates

- Soft NIL
- grating
  - on lens for e.g. AR

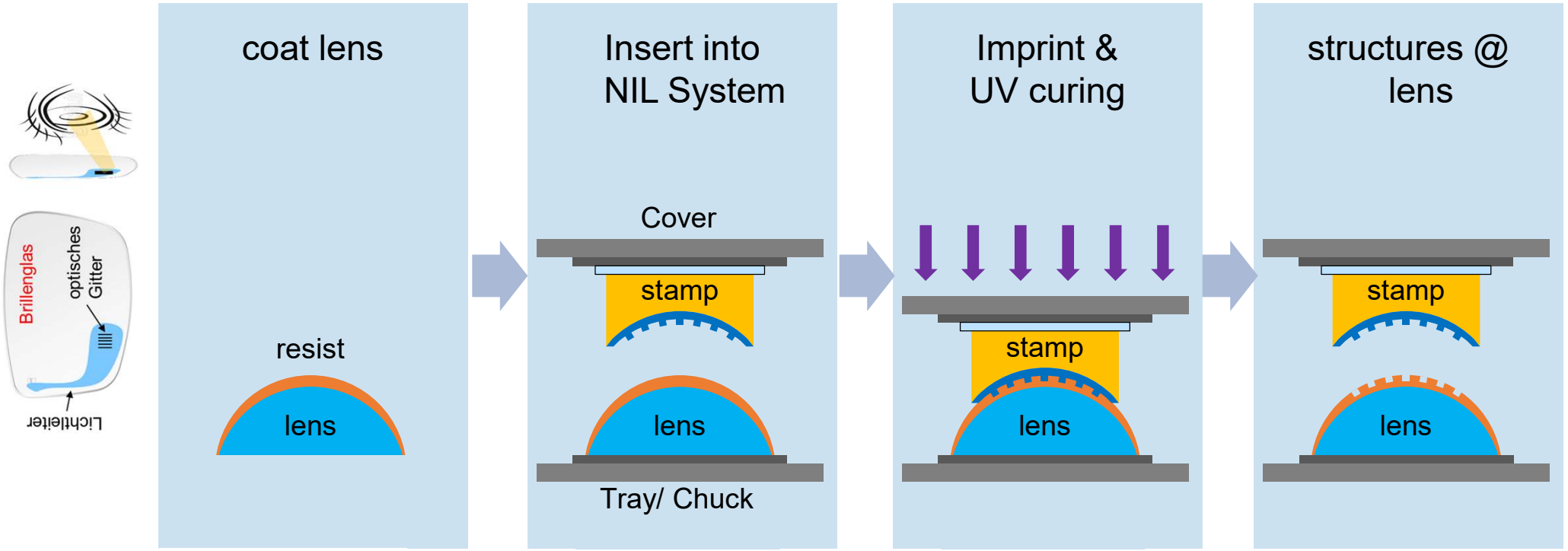


- Stamp preparation



Examples – curved substrates

- Soft NIL
- replication



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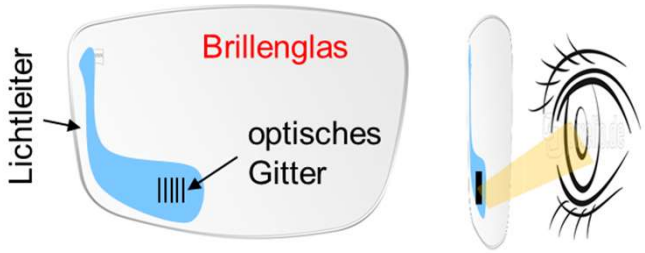
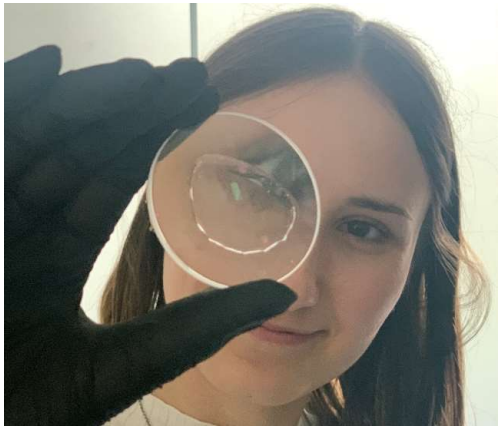
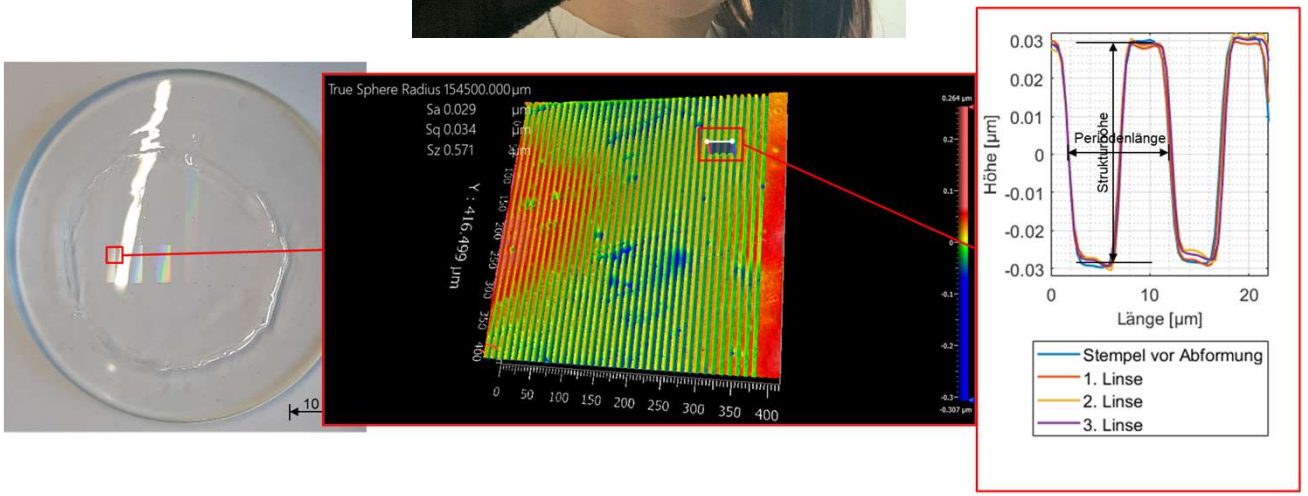
  - on lens for e.g. AR



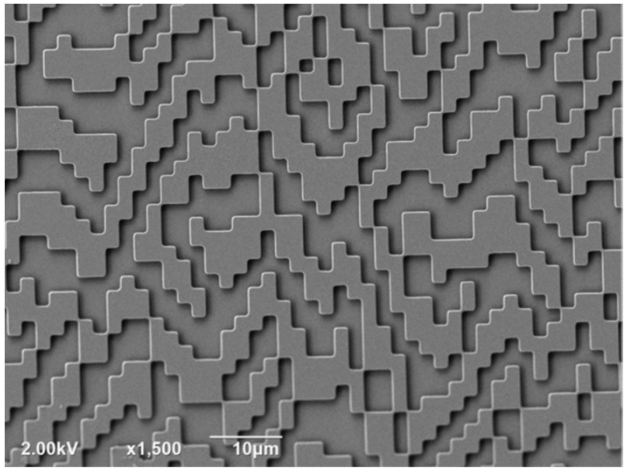
- result





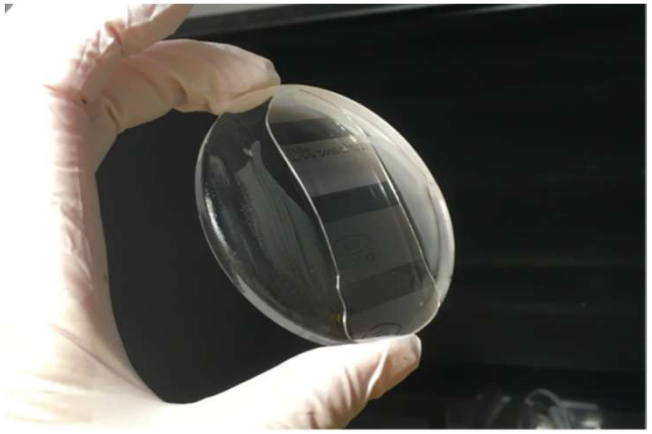
Examples – curved substrates

- Soft NIL
- Master CGH

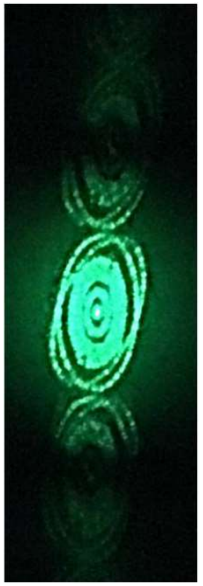


- result

NIL on lens



lens



CGH

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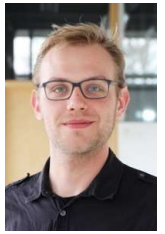
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Summary

NIL is fun ☺

Thank you for **your** Attention!

AASAP ZOT

Aalen School of Applied Photonics
Zentrum für Optische Technologien

Thanks a lot to the group …

Yannick Bauckhage
Selina Burkert
Annika Dehm
Mike Dohmen
Christian Eder
Arielle Koffi
Sangeetha Suresh
Sebastian Böhm
Julia Cikos
Marius Gubela
Roman Jungfer
Christos Karaptzakis
Samar Seyedeh
Antonio Torres
Cordelia Wittemann

… and to the sponsors

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