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Helmut Schift and Jan Erjawetz[1]

# Bend the line – shape optimization of microlenses made by laser-based direct write lithography

J. Erjawetz et al., Micro- and Nanoeng. 15 (2022) 100137

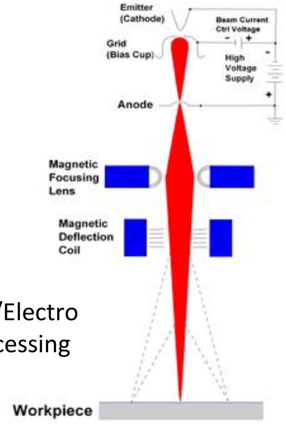
Swiss Photonics Workshop on Microoptics:: EPFL-Microcity in Neuchâtel :: 7 Nov 2022

# Outline

- The HIMT DWL 66+ – a direct (maskless) laser writer
- Contrast curve and and proximity effects in grayscale lithography
- 3D shape optimization by iterative and model-based approaches
- A single figure of merit as quantitative value for quality control
- … and **questions**…!

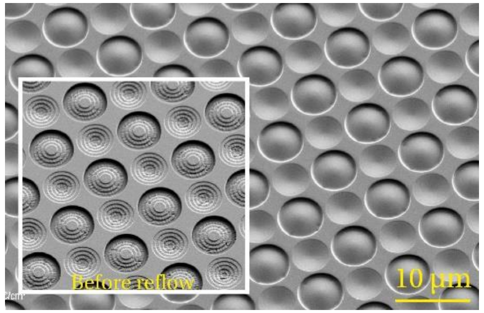
# Direct Write Lithography (DWL) techniques

## E-beam lithography



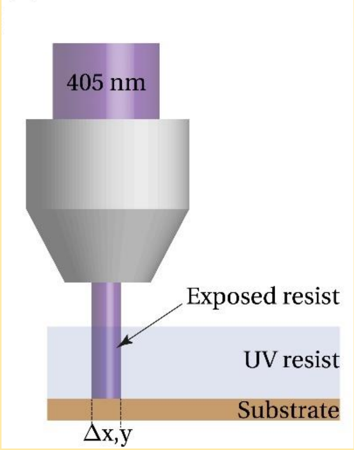

wikipedia.org/Electron_beam_processing

- Very high resolution
- Good stitching
- Long writing times
- 2.5D up to 4µm height
- Charging effects

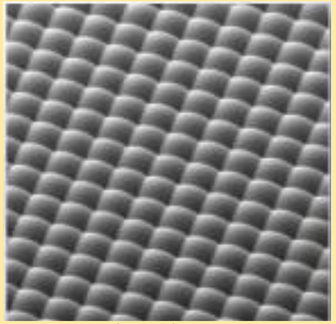



*Raith/Vistec EPBG5000 PLUS, A. Schleunitz 2014*

## Direct Laser Exposure



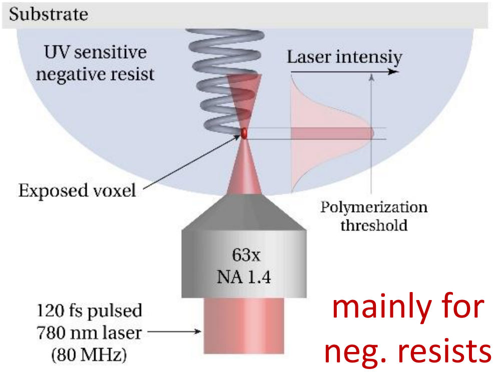

- OK resolution (write modes)
- Good stitching
- Fast writing times
- 2.5D up to 100µm height
- No substrate effect (BARC)



MLA, 20 µm height, 100 µm pitch

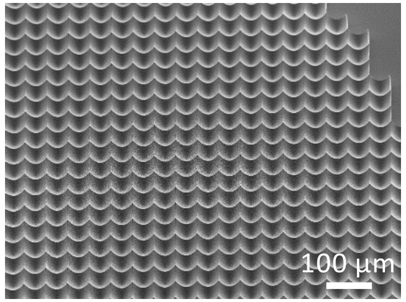
*Heidelberg Instruments, DWL66+ Series*

## 2 photon polymerization




mainly for neg. resists

- Good resolution
- Good stitching
- Very slow writing times
- Full 3D features possible
- No substrate effect



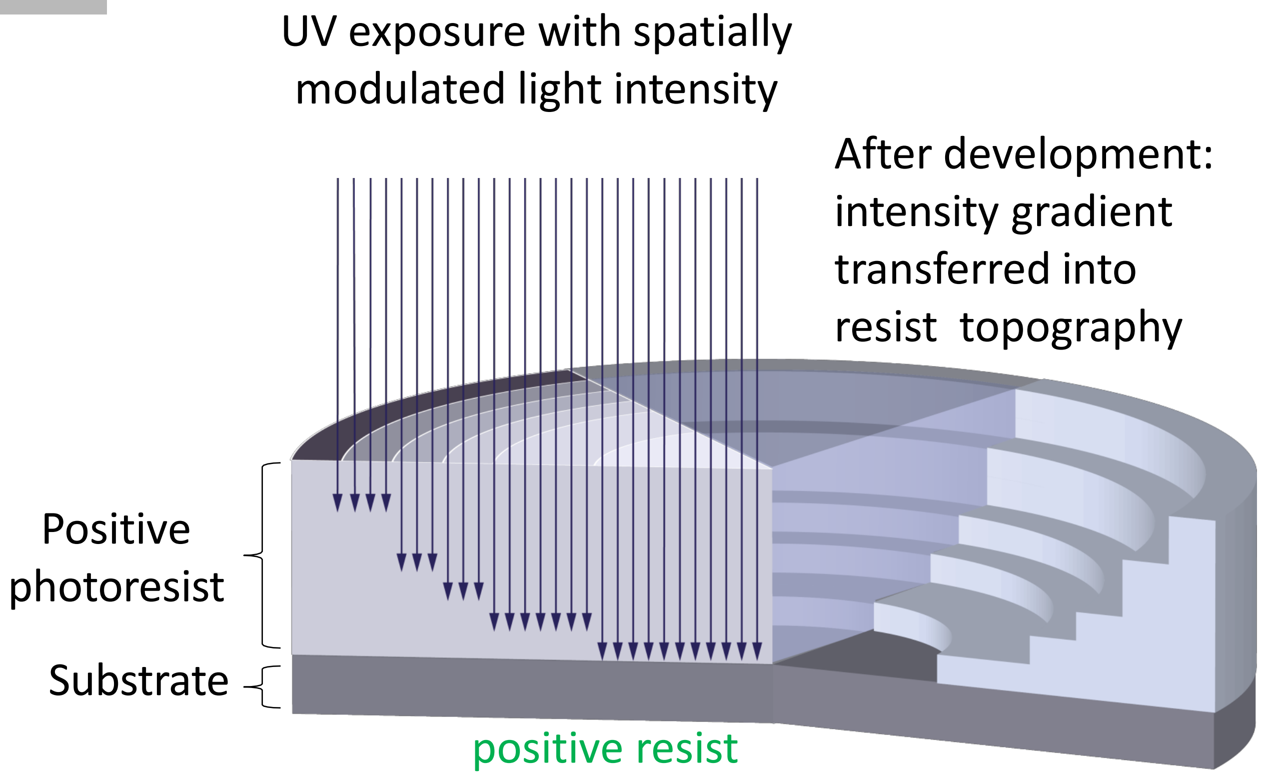

*NanoScribe, Photonics GT, Kirchner 2018*

# Grayscale lithography – Direct write lithography (DWL)

## The DWL 66+ : a lithography system for 2D and 3D patterning of photoresists

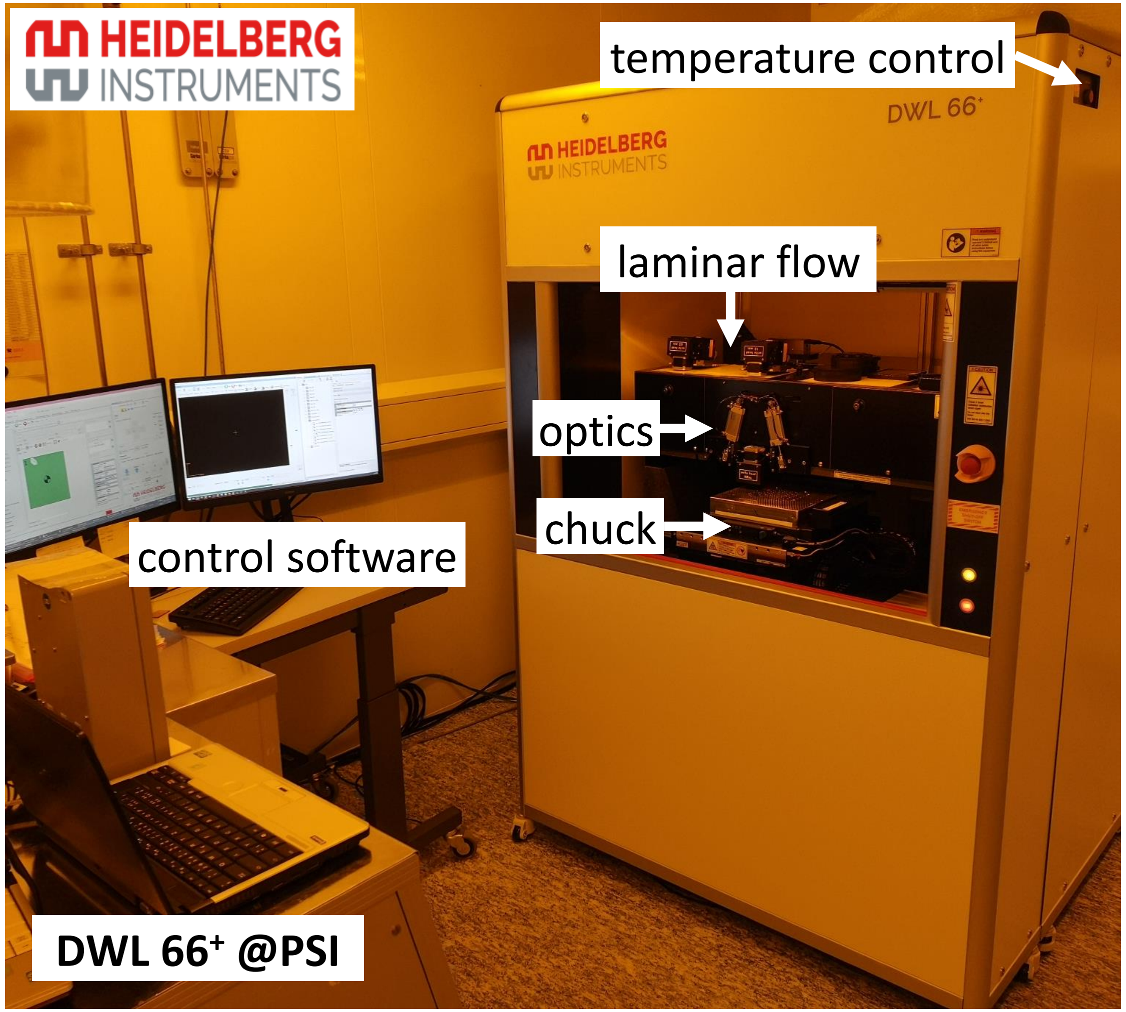
**Positive resist: becomes (more) soluable during exposure**

Negative resist: crosslinks upon exposure and postbake




positive resist

Image credit: Heidelberg Instruments Mikrotechnik GmbH



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# Laser Direct Write Lithography System

**The DWL 66+ is a lithography system for 2D and 3D patterning of photoresists**

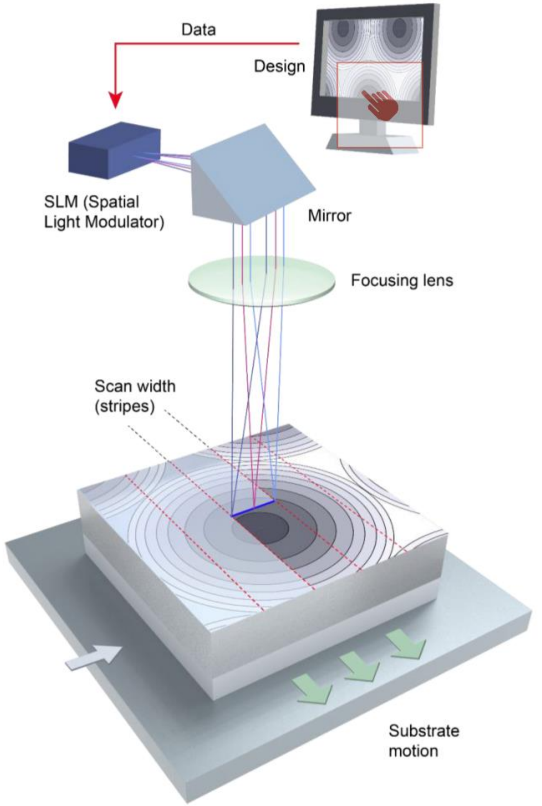
HEIDELBERG INSTRUMENTS

## DWL: Raster Scan Exposure

**Patterning of 100mm wafer:**

| different write modes: | | area per minute | min. resolution |
|---|---|---|---|
| | WM hi-res | 3.5 mm²/min | 0.3 µm |
| | WM I | 13 mm² | 0.6 µm |
| | WM III | 150 mm² | 1.0 µm |
| | WM V | 2000 mm | 4.0 µm |

- Spatial Light Modulator (SLM) : dynamic mask
- Ultra fast light modulation between each pixel.
- Up to 1000 gray levels are accessible for each pixel (minimum pixel size 50nm).
- SLM combined with focusing optic and XY stage motion enables fast writing of high resolution over large areas.
- The design is exposed stripe after stripe.




**Special capabilities**

Professional 3D mode for complex structures (micro + sub-µm)
Combination with Genisys 3D Beamer Software (3D proximity correction)
And with micro resist technology for the development of materials/processes

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- … and **questions**…!

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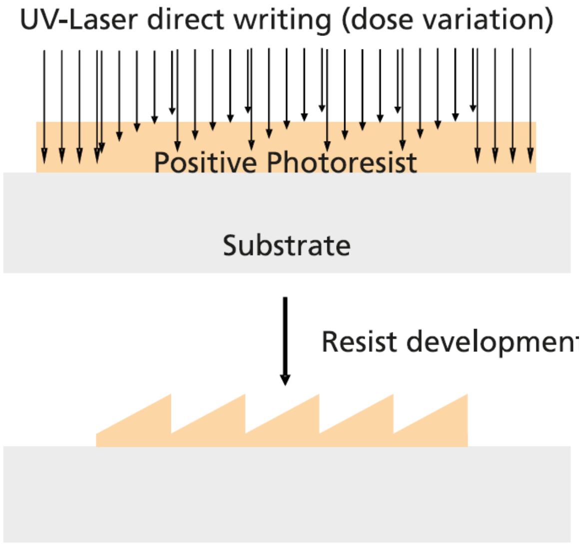
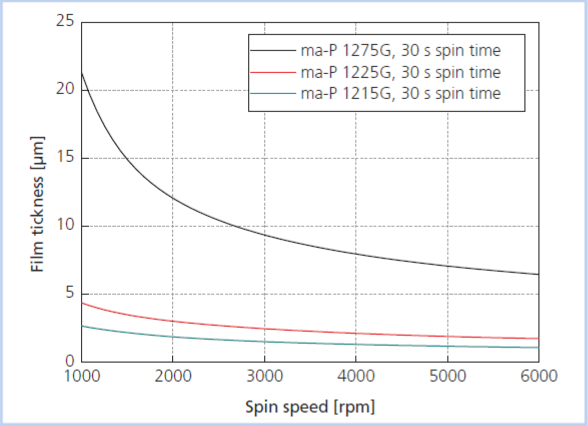
# DWL lithography with photoresists: Positive resists

micro resist technology

ma-P1200 G — Positive Tone Photoresist Series (Novolak-based)
for Laser Direct Write Lithography (DWL) @ 405 nm wavelength




## Unique features

– Reduced contrast (for G series)
– Film thickness up to 60 µm and higher
– 50 - 60 µm depth range of the patterns possible in greyscale lithography
– Spectral sensitivity 350…450 nm
– High intensity laser exposure possible without outgassing
– Aqueous alkaline development, for greyscale lithography with TMAH based developers, for standard binary lithography

## Film thickness

| Resist | ma-P | 1215G | 1225G | 1275G | | | |
|---|---|---|---|---|---|---|---|
| Film thickness | µm | 1.5 | 2.5 | 9.3 | 15 | 30 | 60 |
| Spin-coating | rpm | 3000 | 3000 | 3000 | 1500 | 500 | 1000 |
| Time | s | 30 | 30 | 30 | 30 | 60 | 4 |

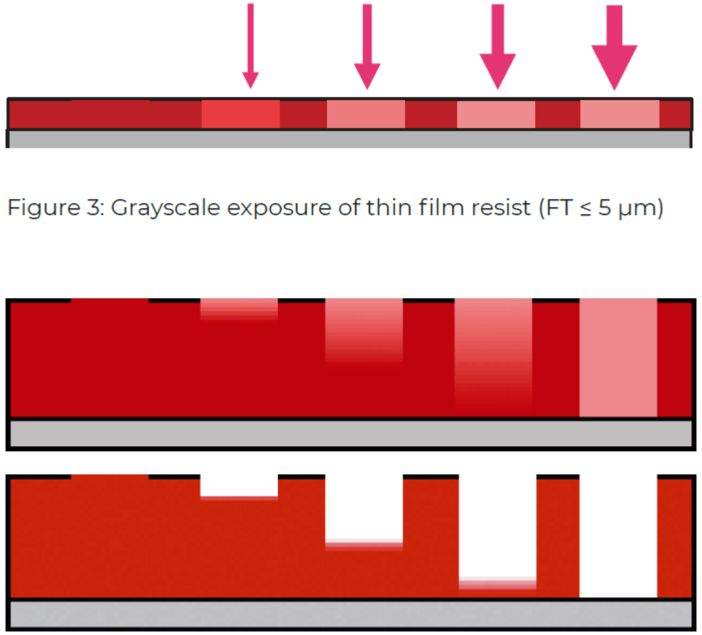
**1295G**
Up to 100 µm
high viscosity
HV for single
spincoating

**1202LIL**
200 nm
high contrast
for high
resolution

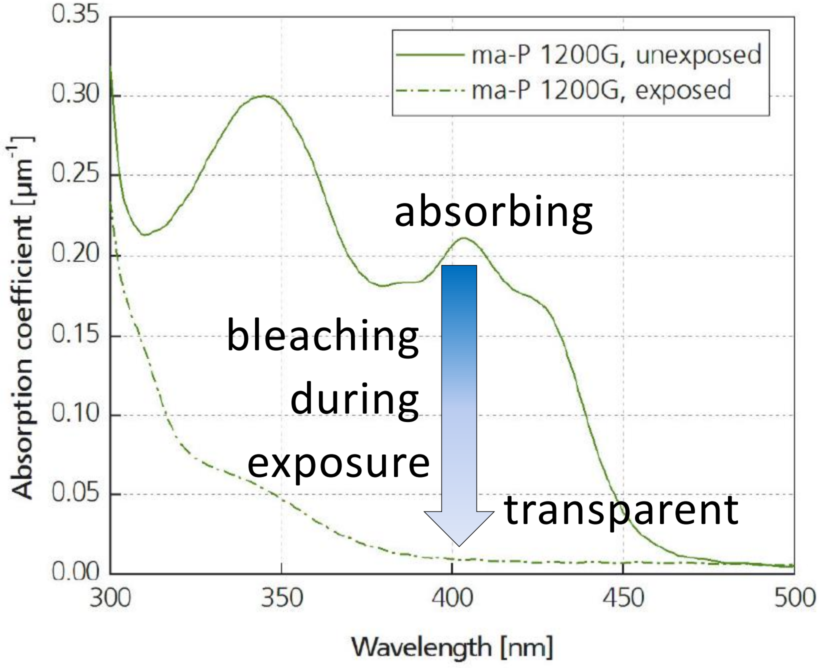
**Note:** This resist is specially designed for greyscale lithography but can also be used in standard binary lithography

# DWL lithography with photoresists: Positive resists

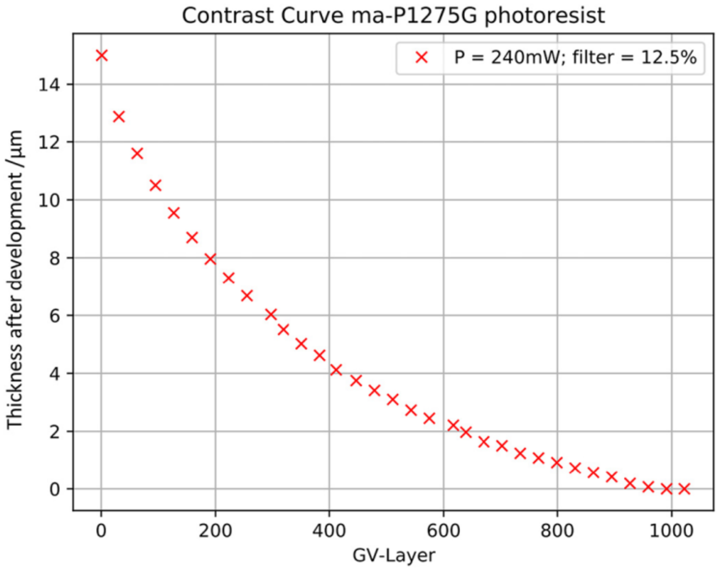
ma-P1200 G — Positive Tone Photoresist Series
for Direct Write Lithography (DLW) @ 405




Top: Grayscale exposure of thicker resist films (FT ≥ 5 μm); Bottom: resist pattern after development.




UV/vis absorption spectra of unexposed and exposed ma-P 1200G

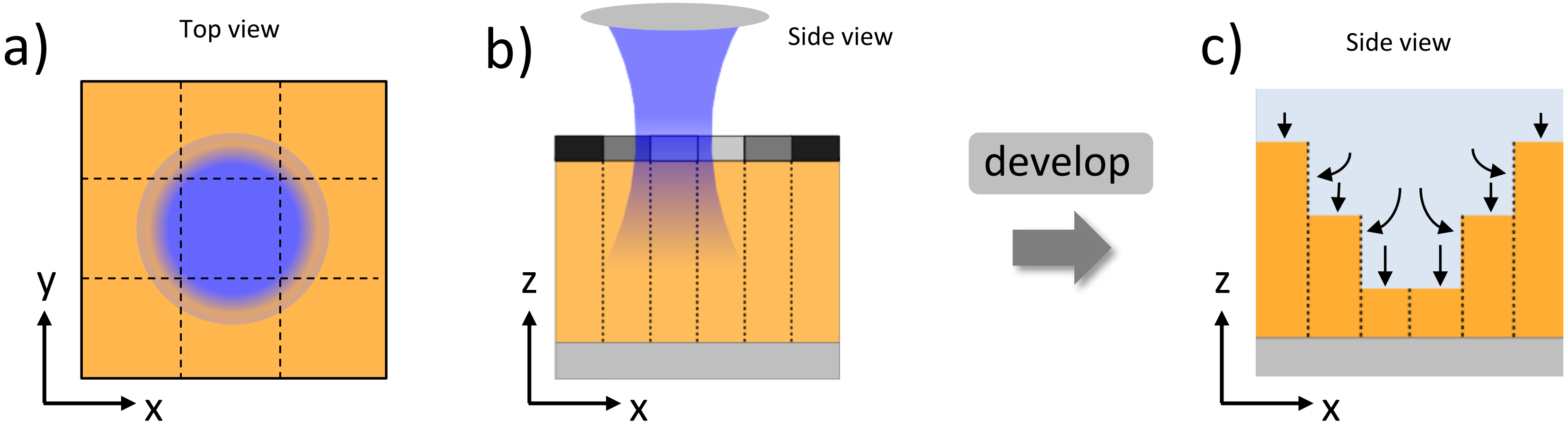



Contrast curve (in linear scale) of ma-P 1275G
(33 measurements for 32 exposure doses) from zero dose at 15 μm height down to dose-to-clear at 0 μm (thickness after development)

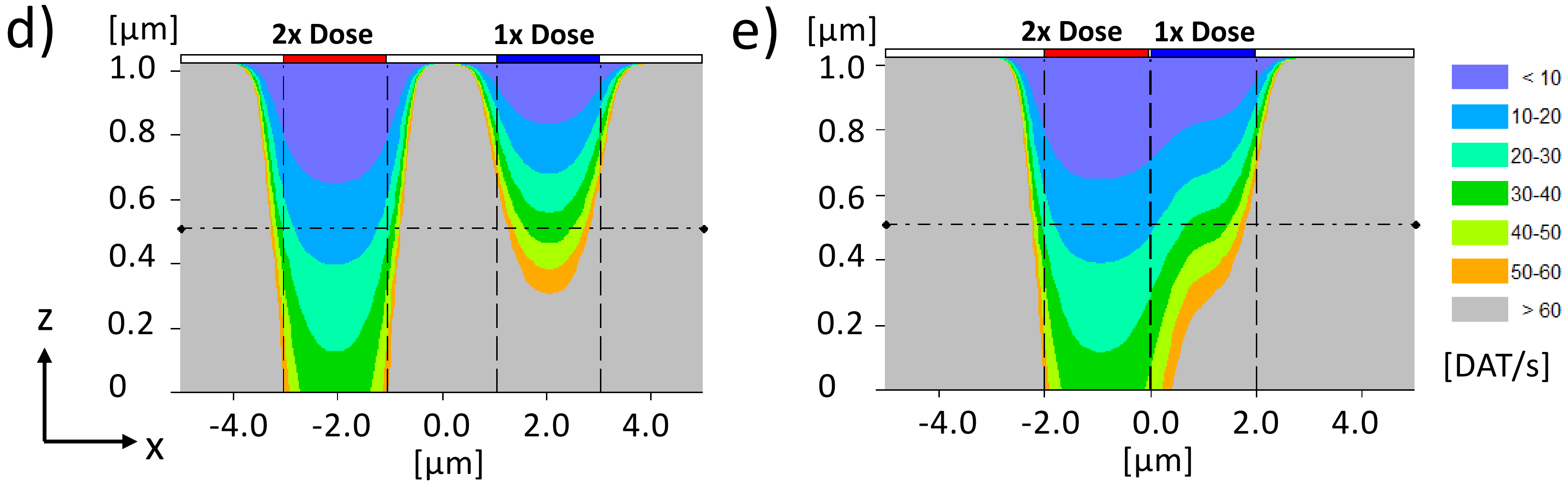
# Proximity & Process Effects

Beam characteristics (Gaussian beam + divergence)

Lateral erosion




Progression of development fronts into positive resist (3D resist simulation in LAB)



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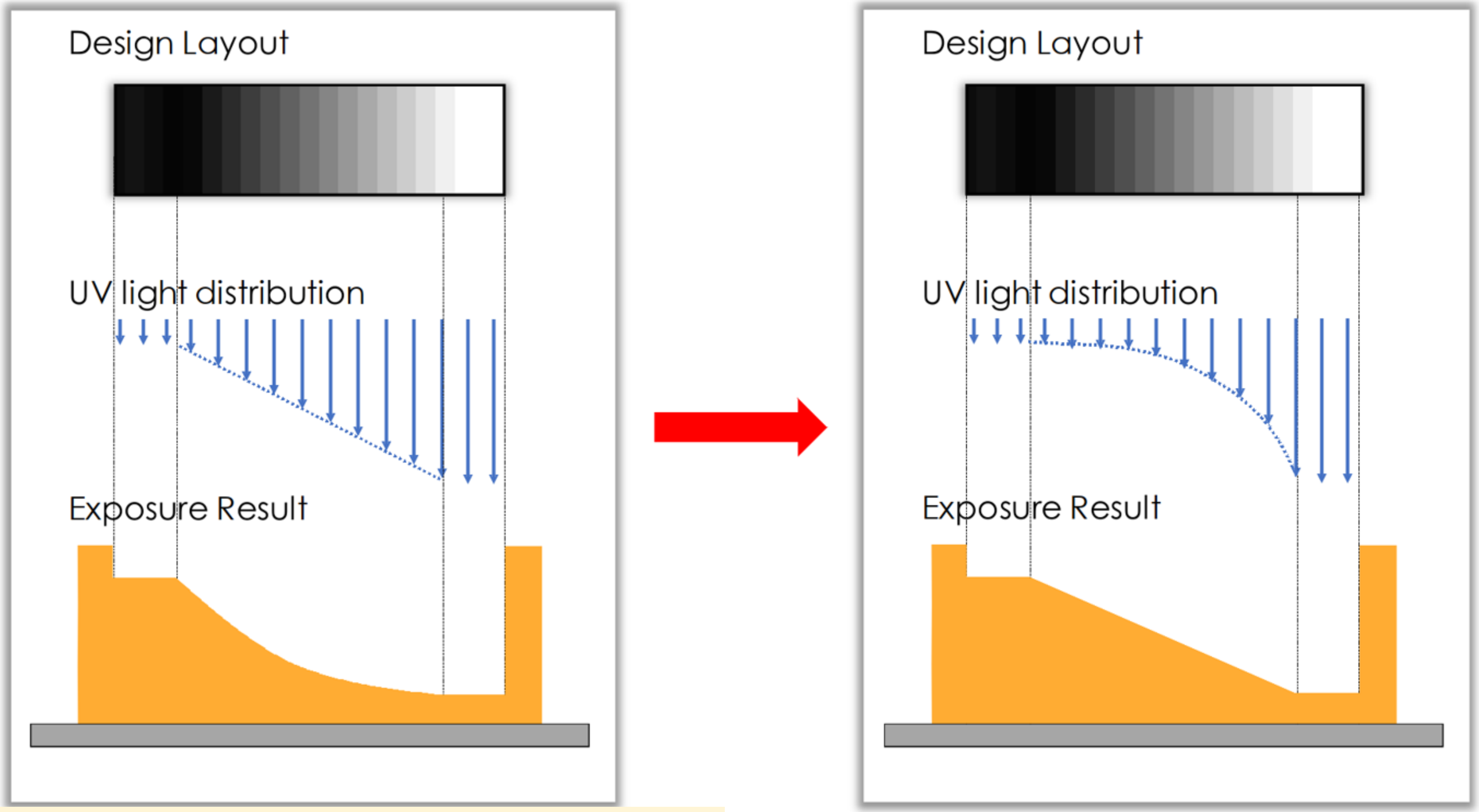
# Method 1: Iterative optimization of grayvalues

## GVD-based iterative approach (“GVD-iterative”)




An iterative optimization approach assigns initial intensity values to the gray value (GV) range used in a design, measuring the resulting profile of the exposure, and comparing it with the target profile defined by the design layout. The corrected intensity values assigned to the gray values defines a nonlinear GV distribution (GVD) that compensates the resist response.

An iterative optimization approach enables to find the desired linear behavior without further material and process knowledge

In case the result is not satisfying, or trade-offs for critical structural details have to be made, this procedure is repeated with the corrected GV distribution (GVD).

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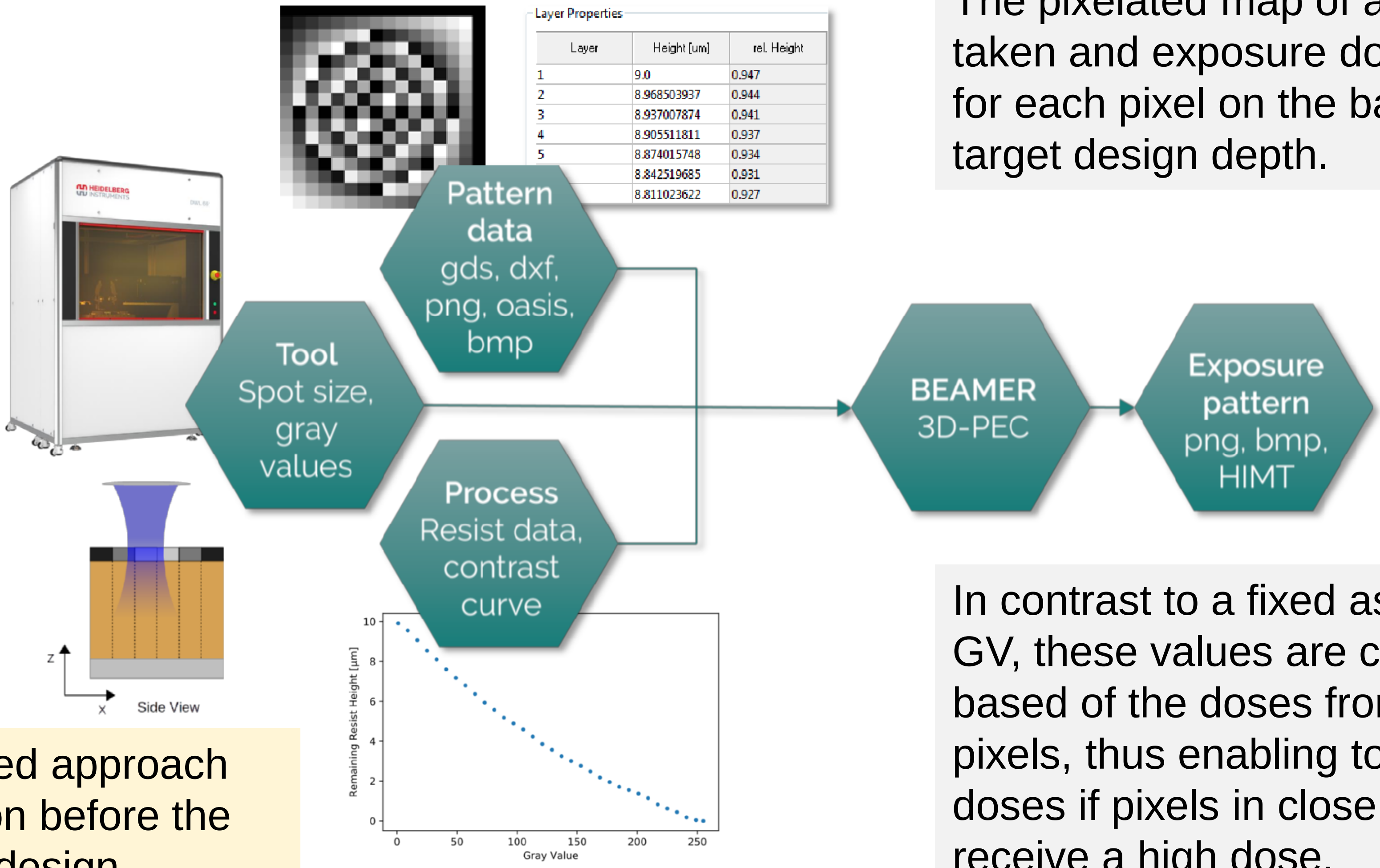
# Method 2: Model-based correction of design

## PEC model-based approach ("PEC-model")

using BEAMER 3D-PEC (Proximity Exposure Correction)




| Layer | Height [um] | rel. Height |
|---|---|---|
| 1 | 9.0 | 0.947 |
| 2 | 8.968503937 | 0.944 |
| 3 | 8.937007874 | 0.941 |
| 4 | 8.905511811 | 0.937 |
| 5 | 8.874015748 | 0.934 |
| | 8.842519685 | 0.931 |
| | 8.811023622 | 0.927 |

The pixelated map of a layout is taken and exposure doses assigned for each pixel on the basis of the target design depth.

In contrast to a fixed assignment of GV, these values are corrected based of the doses from neighboring pixels, thus enabling to assign lower doses if pixels in close vicinity receive a high dose.

The PEC model-based approach enables the correction before the first exposure of the design.

# Two methods for correction of „exposure effects“

## Comparison of the two methods:

Why should we / when do we need to switch to a model-based approach?

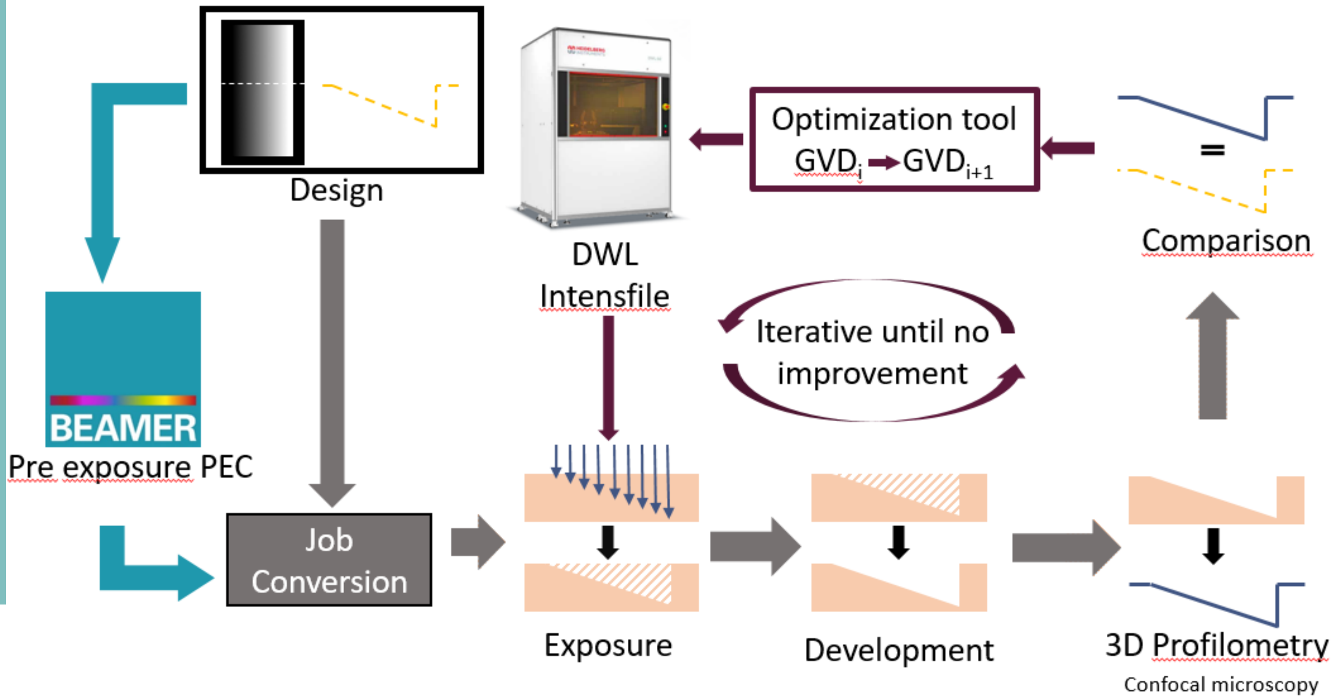
**PEC-model-based approach**

Parameters needed

Resist
- exact resist thickness
- contrast curve
- refractive index

DWL
- focus waist $w_0$
- focus location $z_0$
- Intensity

→ adapted topography




**GVD-iterative approach**

Information needed
- dose-grayvalue table
- measured topography
- dose-depth relation

Mathematical correlation
- dose correction
- adapted dose-grayvalue table

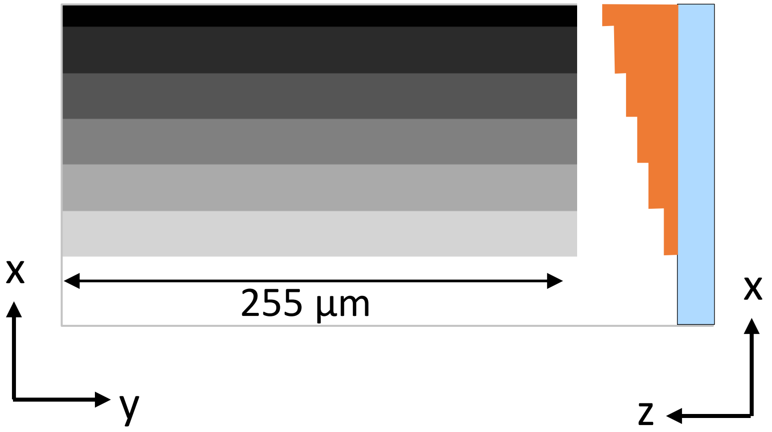
AIM: Find standard procedure for dose optimization in grayscale lithography

METHOD: quantitative method → optimal topography/quality (e.g. optical function)

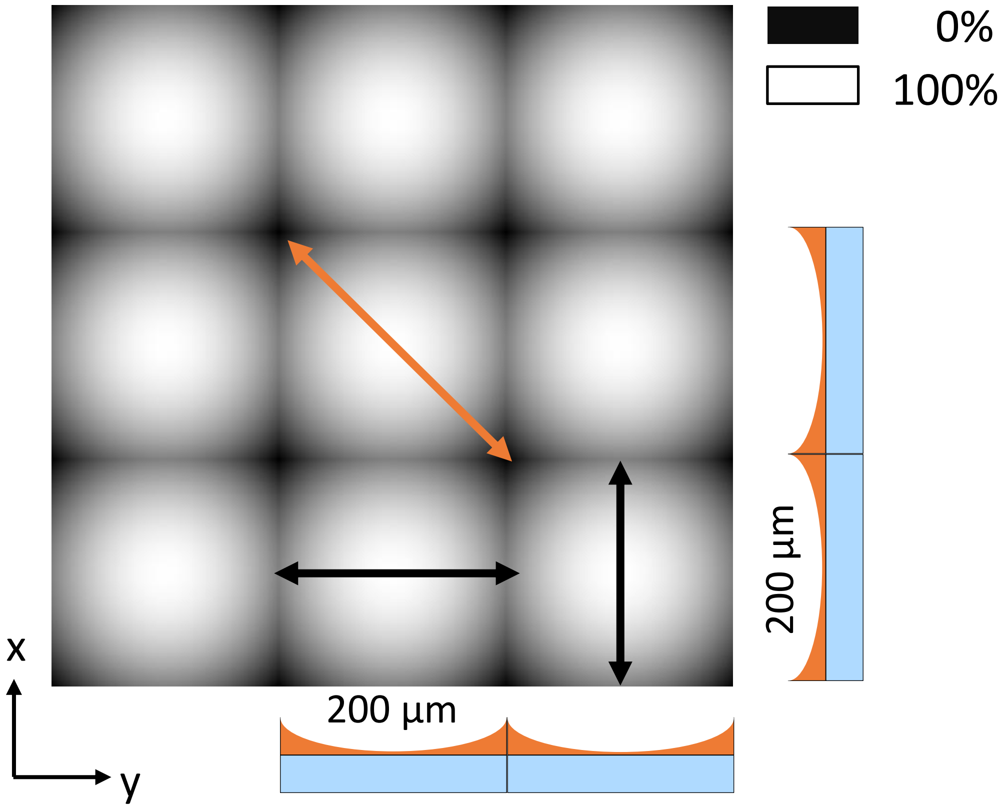
# Designs for experiment

## a) Continuous (linear slope)


## b) Staircase (equidistant steps)



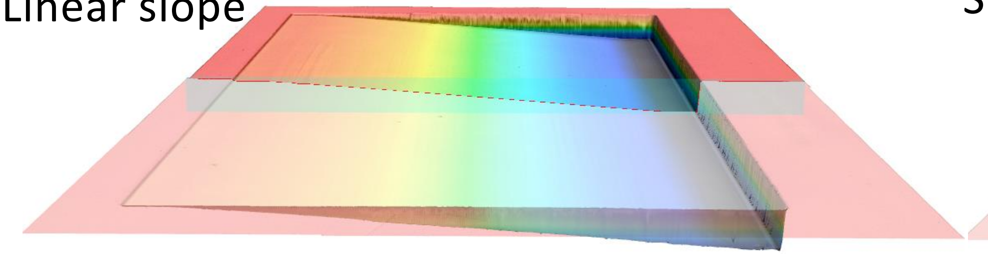

## c) 9x9 microlens array (concave)



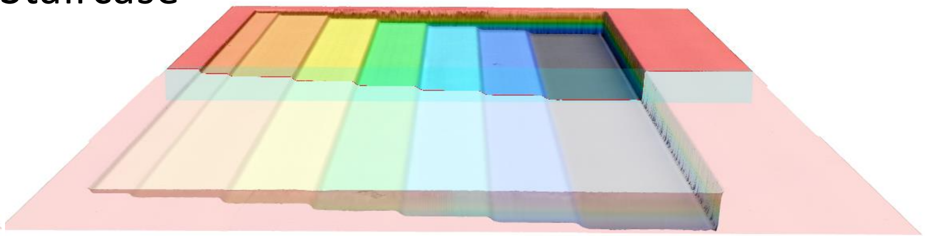

Designs for the experiment:
saved and processed as png-files

# Results after exposure and development

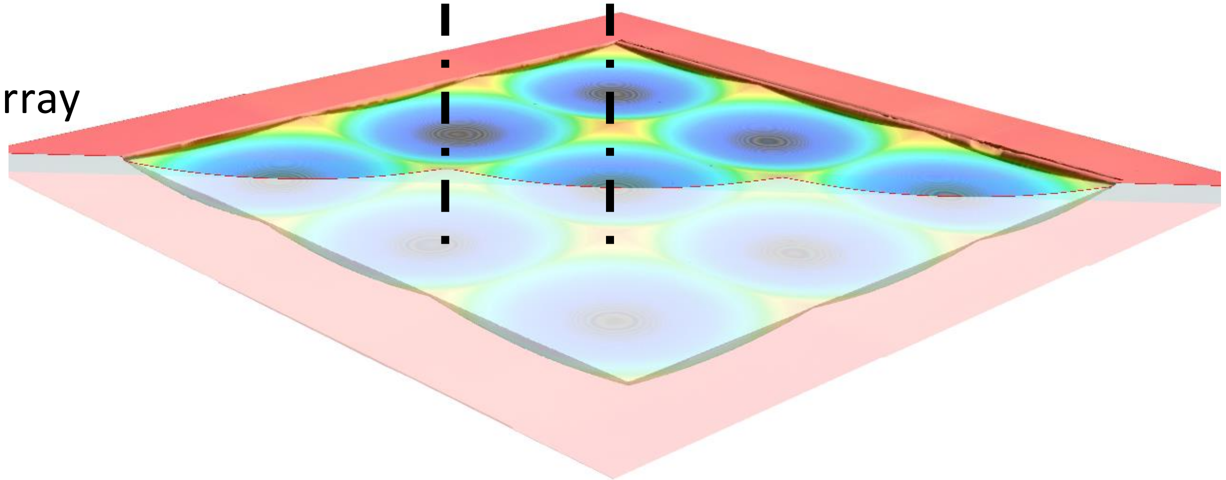
Linear slope



Staircase

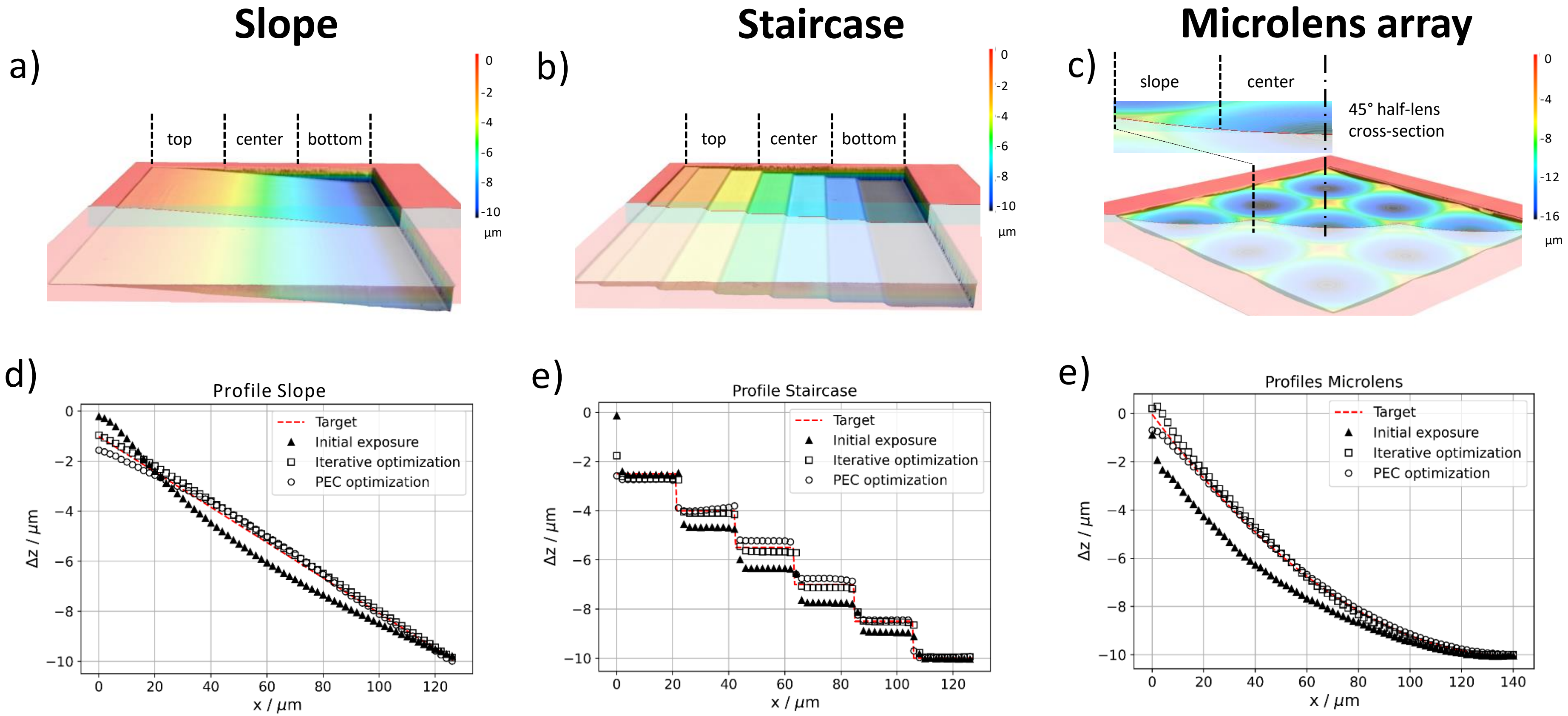


Microlens array



3D-Pictures acquired with a Keyence VK-X3100 laser scanning confocal microscope

# Comparison of shape optimization methods




profiles $z_i$ and $\hat{z}_i$

$z_i$ measured
$\hat{z}_i$ target

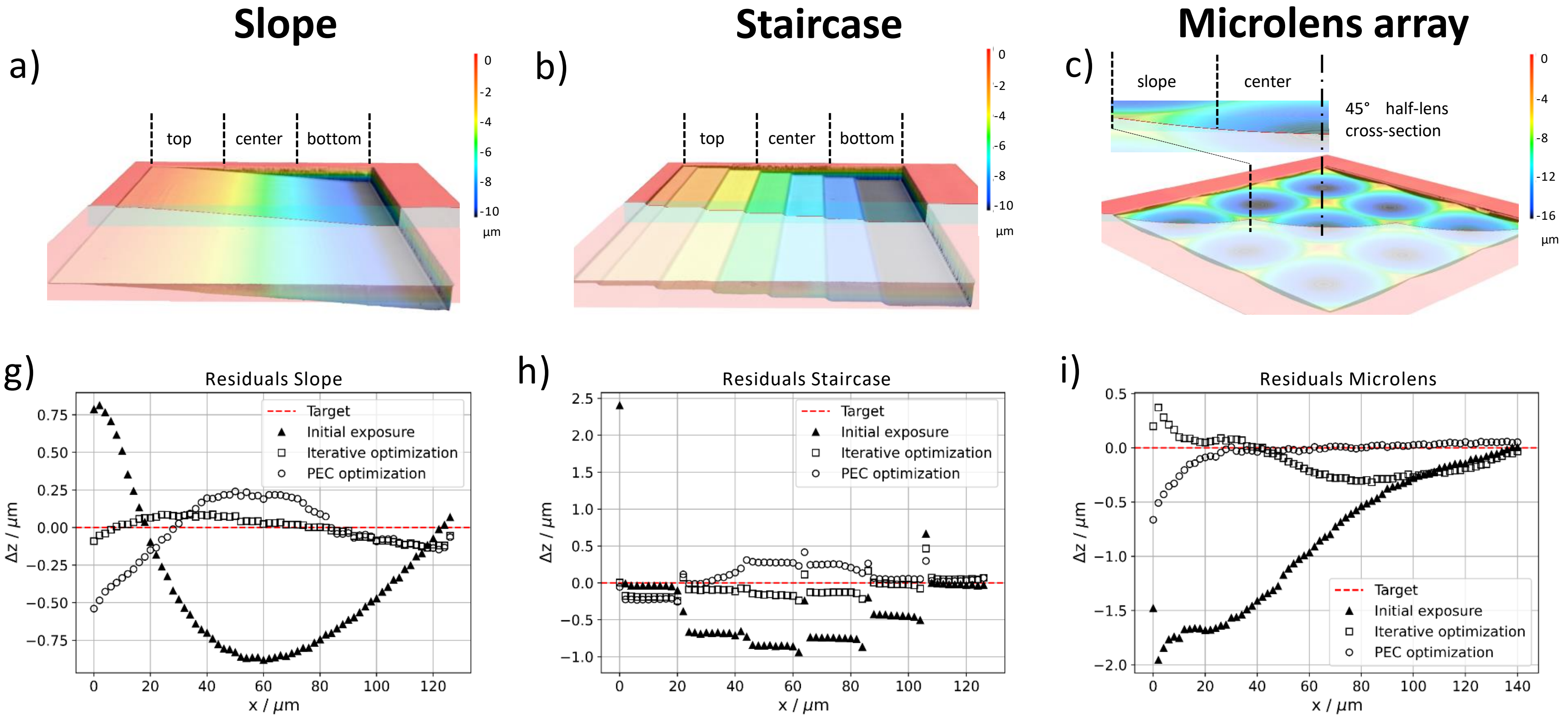
The non-linear contrast curve of photoresist requires correction based on measurements or model

- GVD iterative optimization methods enable correction of non-linear contrast curve
- PEC model software (GenISys BEAMER) allows optimization of more complex structures

BUT: All methods lead to a high appoximation of the target profile

J. Erjawetz et al., Micro- and Nanoeng. 15 (2022) 100137

# Comparison of shape optimization methods




residuals

$z_i - \hat{z}_i$

$z_i$ measured

$\hat{z}_i$ target

The residuals give a better idea about the deviations for the three test structures

- The initial exposures deviate strongly (because of the non-linear contrast curve)
- Deviations are often strong in the center of the structure, but often starting and end point are critical, too

BUT: Still a single figure of merit would be desired to give an indication of the „average“ deviation

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# Evaluation using $R^2$-values for the three test cases

Comparison for the initial, GVD-iterative, and PEC-model optimized structures. $R^2$ is given for the entire cross-section, and for the different segments of the cross-section (three equal segments for slope and staircase, and two equal segments for one microlens).

$$R^2 = \frac{\sum (z_i - \hat{z}_i)^2}{\sum (z_i - \bar{z})^2}$$

| Structure | w/ optimization | GVD-iterative | PEC-model |
|---|---|---|---|
| **Slope** | 0.956 | 0.999 | 0.994 |
| | | | |
| **Staircase** | 0.842 | 0.986 | 0.994 |
| | | | |
| **Microlens** | 0.842 | 0.996 | 0.998 |
| | | | |

* $R^2$ = coefficient of determination; statistic to evaluate goodness-of-fit between simulated (target) and observed (measurement) values. Used as figure of merit to determine quality of least-square-fitted datasets.
$R^2$ = 1.000 is perfect fit to target.

# Evaluation using RMS-values for the three test cases

Comparison for the initial, GVD-iterative, and PEC-model optimized structures. RMS is given for the entire cross-section, and for different segments of the cross-section (three equal segments for slope and staircase, and two equal segments for one microlens).

$$RMS = \sqrt{\frac{1}{N}\sum(z_i - \hat{z}_i)^2}$$

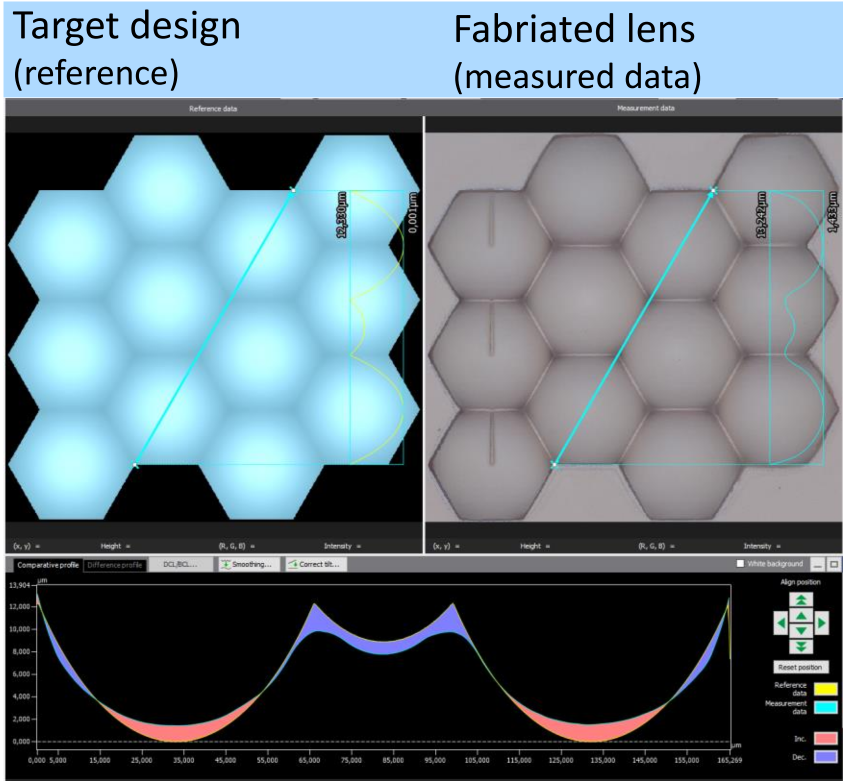
| Structure | w/ optimization in µm | GVD-iterative in µm | PEC-model in µm |
|---|---|---|---|
| Slope | 0.571 | 0.096 | 0.204 |
| | | | |
| Staircase | 0.629 | 0.297 | 0.189 |
| | | | |
| Microlens | 0.970 | 0.200 | 0.117 |
| | | | |

* RMS = root mean square; method to evaluate the deviations (sum of the squares of the residuals) between simulated (target) and observed (measurement) values. Used as figure of merit to determine the waviness or roughness of a surface quality.

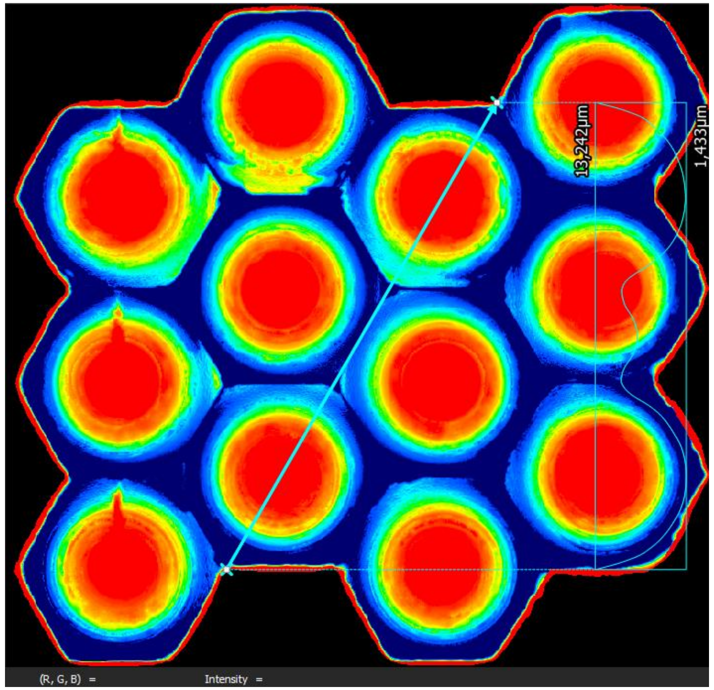
# Outlook – towards more complex structures

Both Keyence VK-X3100 and GenISys BEAMER offer volumetric analysis of the topography

- 2D analysis beyond cross-section, but comparison of fabricated with target topography
- Figures of merit for areas of interest (central lens, borders)




Direct comparison and subtraction with original design (STL)



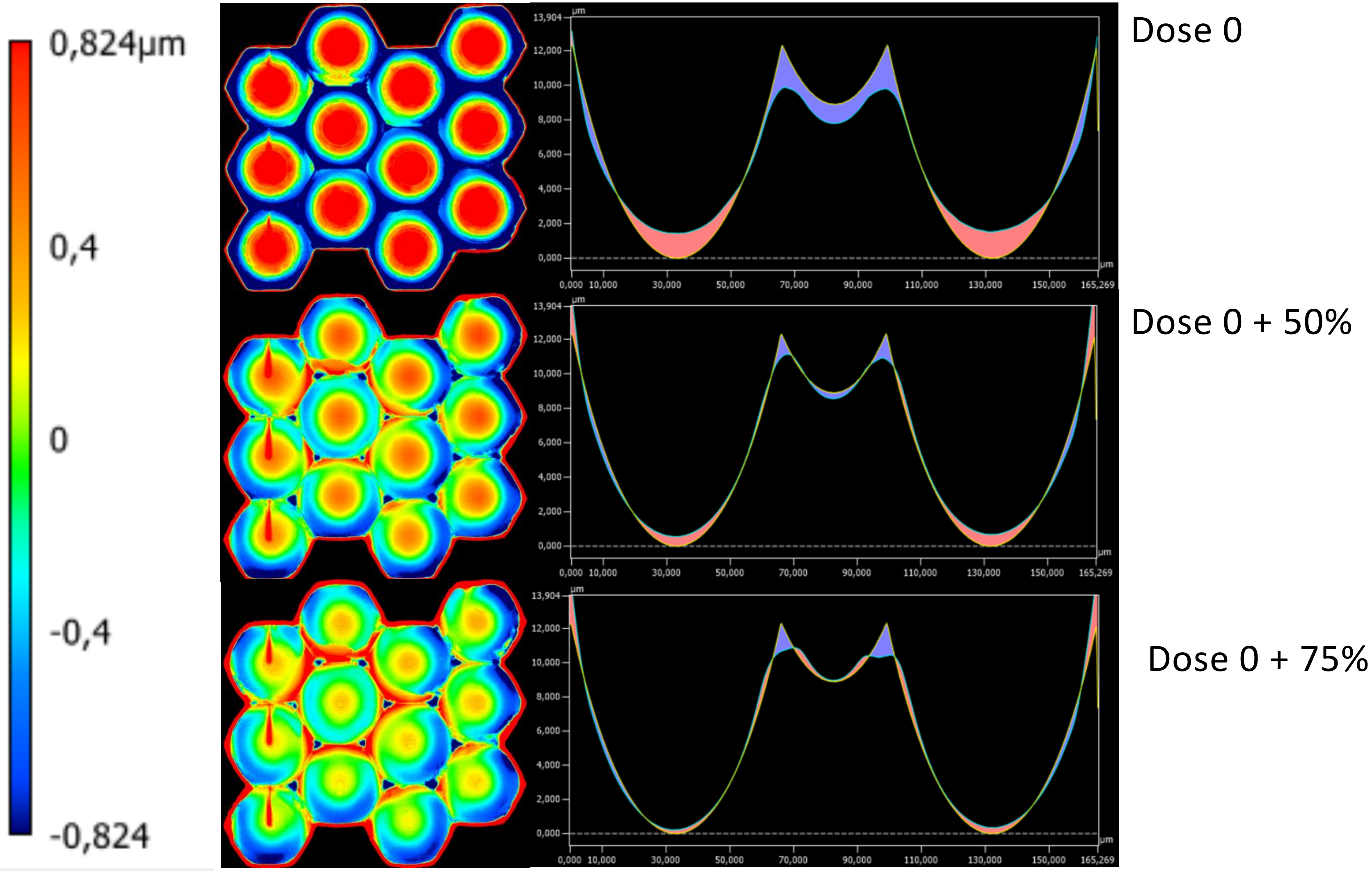

Pixelated map of the height differences of measurement to design

Hexagonal lens design
hexagon readius 33 µm
inner circle radius 28.6 µm
Target design 12 µm
Resist thickness 20µm

RED: target design deeper
BLUE: target design higher than fabricated lens

# Outlook – towards more complex structures

Variation of exposure dose for hexagonal lens array by up to +75%



# Conclusion

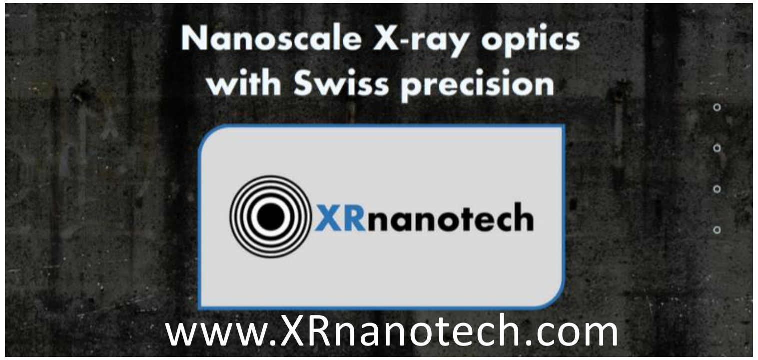
- Simple structures can be optimized with both methods with similar results

- Model-based optimization (BEAMER) can reach same or better results within less time and without extensive efforts (material consumption, microscopic analysis)
  - BUT: Only if preparation was precise enough
  - Tool, material and orocess parameters need to be known and stable!

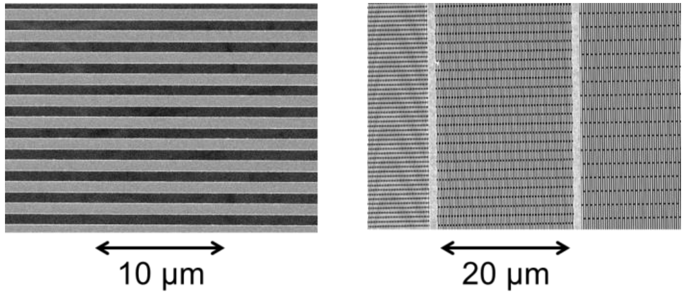
  → Additional task for tool and resist providers

- Iterative optimization will struggle with complex, non-symmetric structures
  - Only 1-dimensional (cross-sectional) optimization
  - No consideration of optical effects (beam shape, proximity effects etc.)

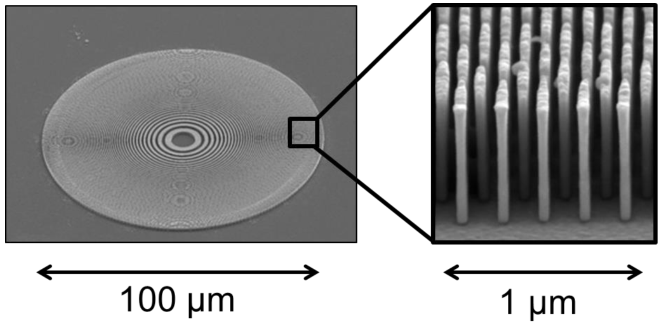
# **XRnanotech** origins: a PSI startup to commercialize X-ray optics …



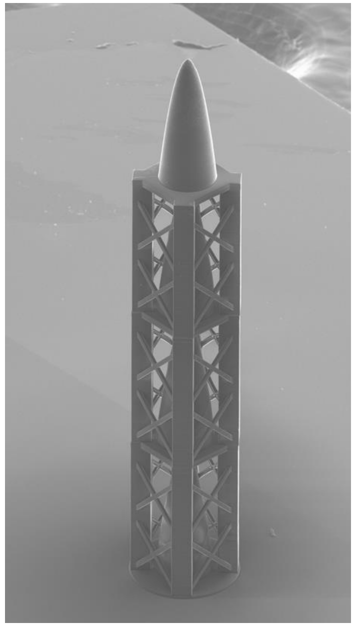

## Gratings and beam splitters



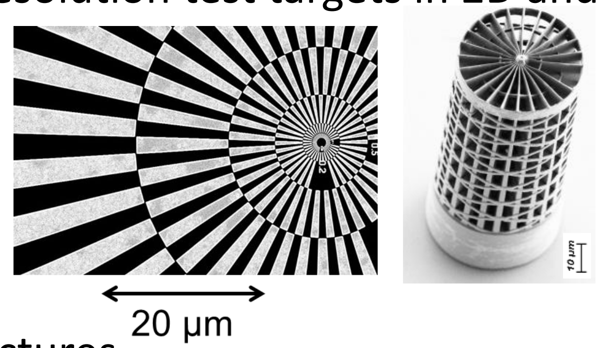

## Fresnel Zone Plates



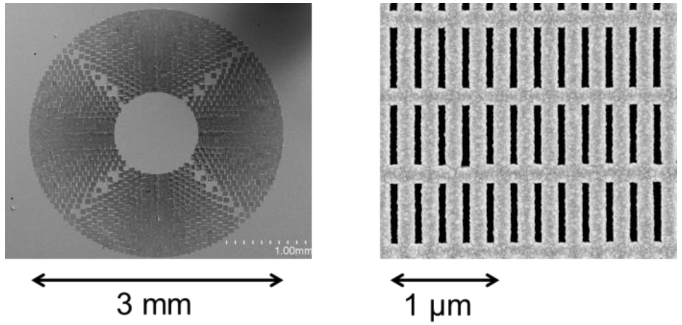

## X-ray Achromats



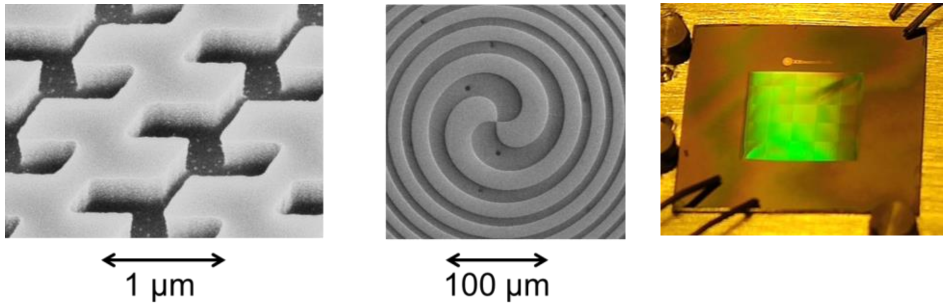
## Resolution test targets in 2D and 3D



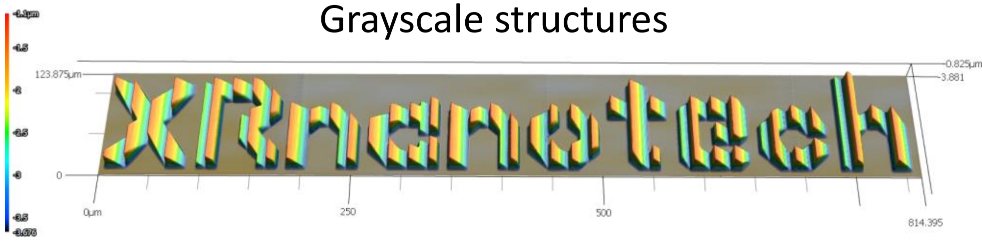

## Beam-shapers




## Custom structures




## Grayscale structures



**XRnanotech**

…and uses DWL knowledge for other customer services and projects, too

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# Wir schaffen Wissen – heute für morgen

XRnanotech

Thank you!

## Acknowledgement

@PSI

- Konrad Vogelsang

@Heidelberg instruments

- Dominique Collé

HEIDELBERG INSTRUMENTS

@micro resist technology

- Christine Schuster

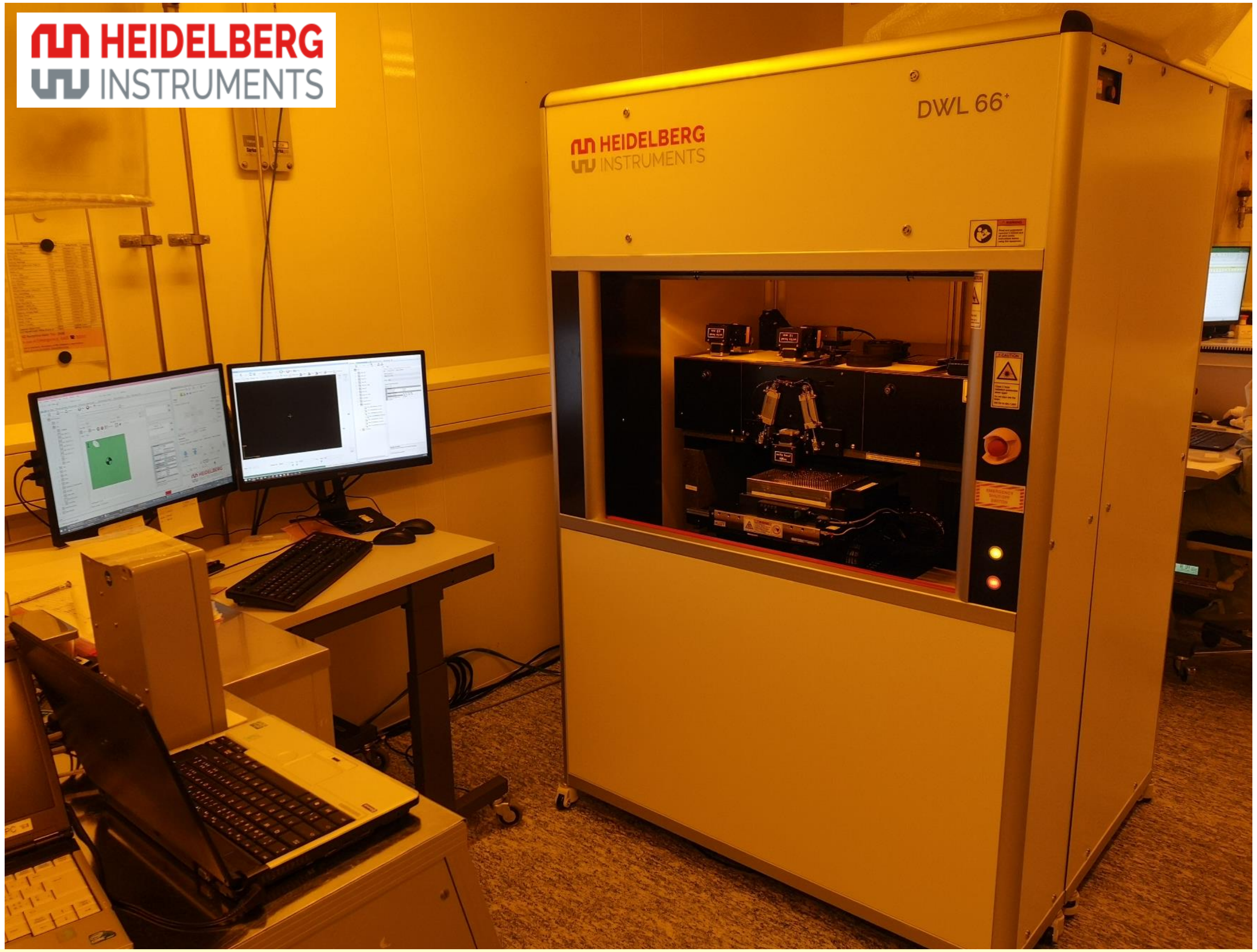
micro resist technology

@GenISys

- Aditya Reddy

GenISys Advancing the Standard

# DWL 66$^+$: Direct Laser Write tool for 405 nm exposure




**h-line exposure** (405 nm)

positive/negative resists (up to 50-100 µm)

max. power 300 mW

**Substrate size**

min. 10x10 mm$^2$, max. 227x227 mm$^2$

max. writing field 200x200 mm$^2$

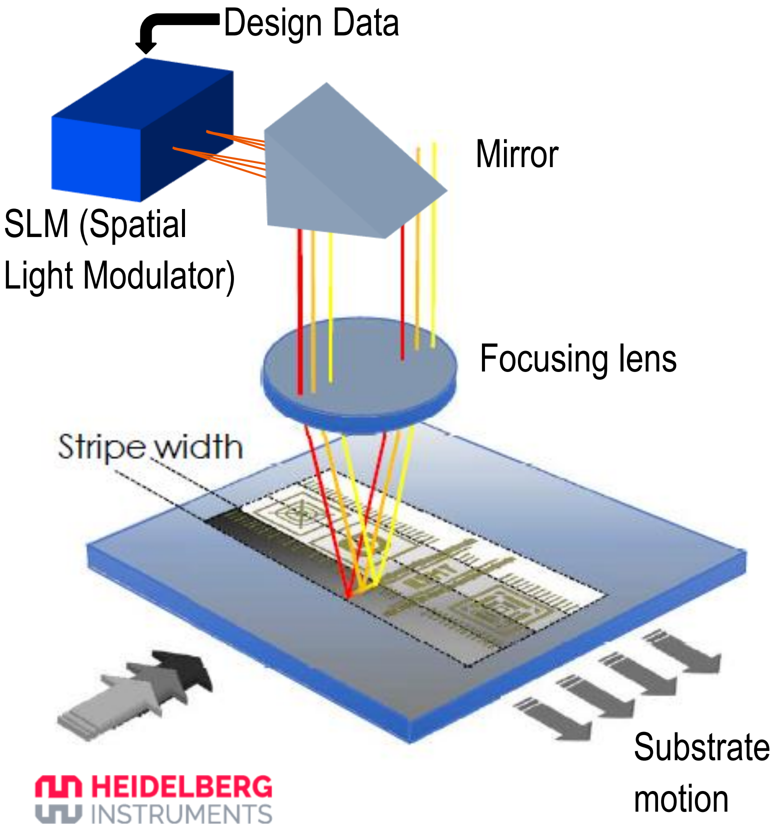
**Patterning of 100 mm wafer:**

| | min. resolution | time |
|---|---|---|
| hi-res | 0.3 µm | 45 h |
| mode I | 0.6 µm | 8 h |
| mode III | 1.0 µm | 1 h |
| mode V | 4.0 µm | 4 min |

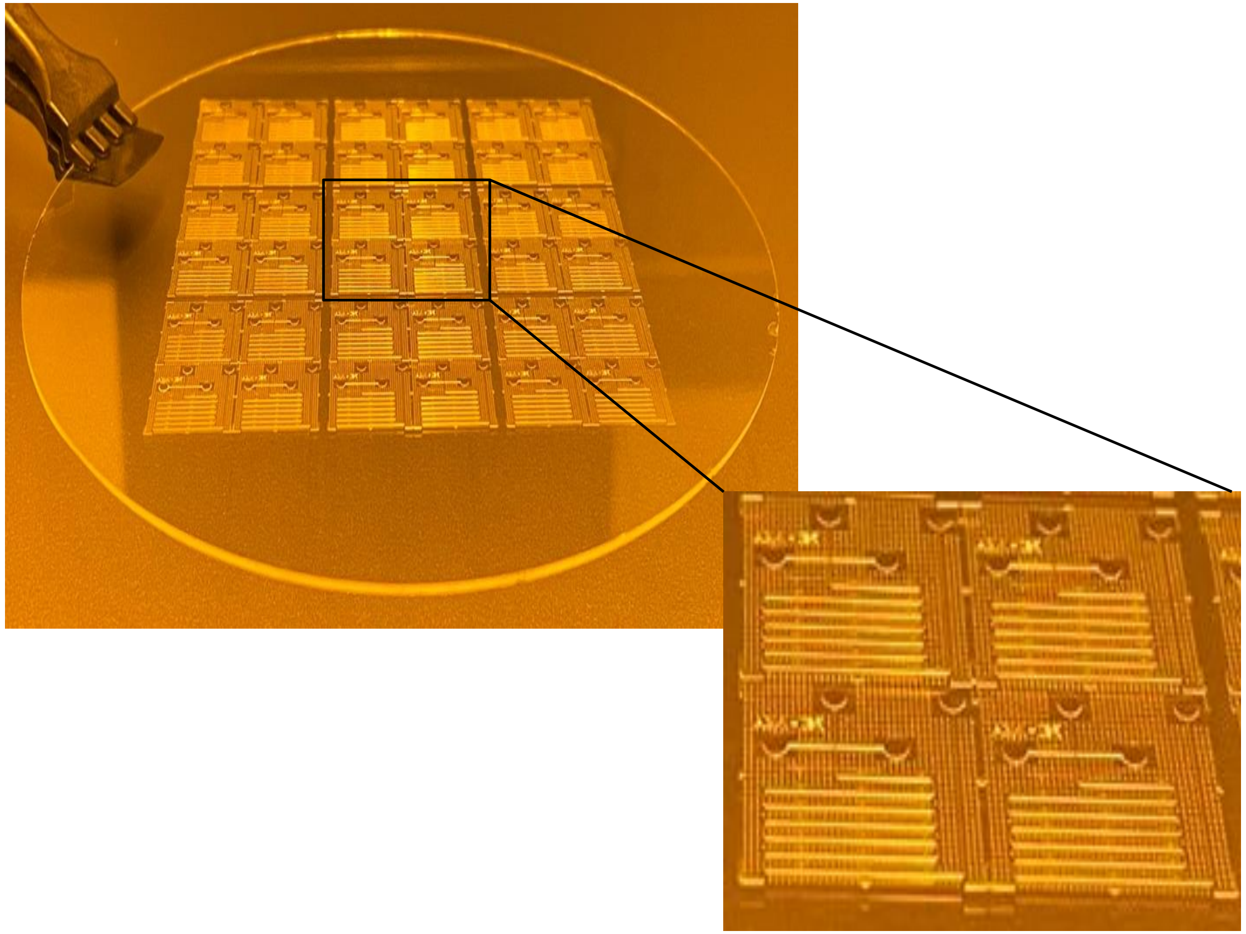
DWL is well suited for flexible patterning of 3D structures for research and industrial projects (XRnanotech @ PSI)

**Note:** A direct laser writer will replace a maskaligner and you can write your own masks – but it can do more

# Fabricated microfluidic structure (mr-DWL40)




- Direct exposure by DWL 66⁺



- Microfluidic test structure (microfluidic mixer with 3 inlets and meander) on Ø100 mm wafer after development with 67 µm thickness

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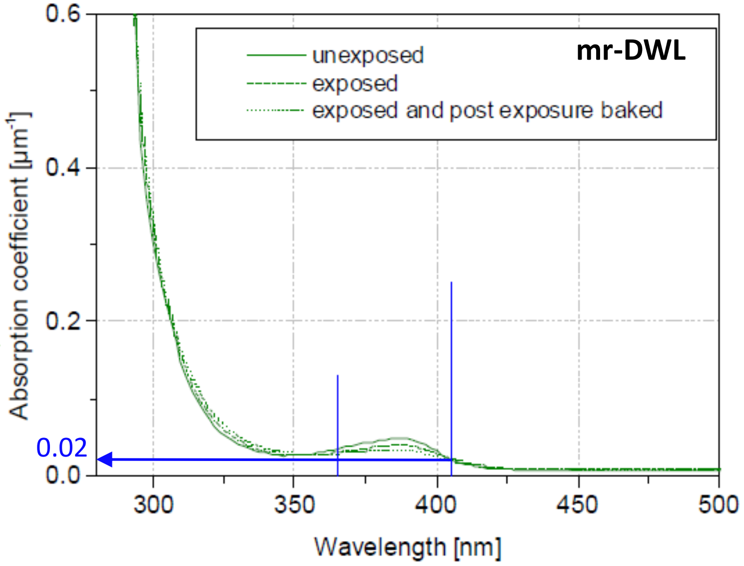
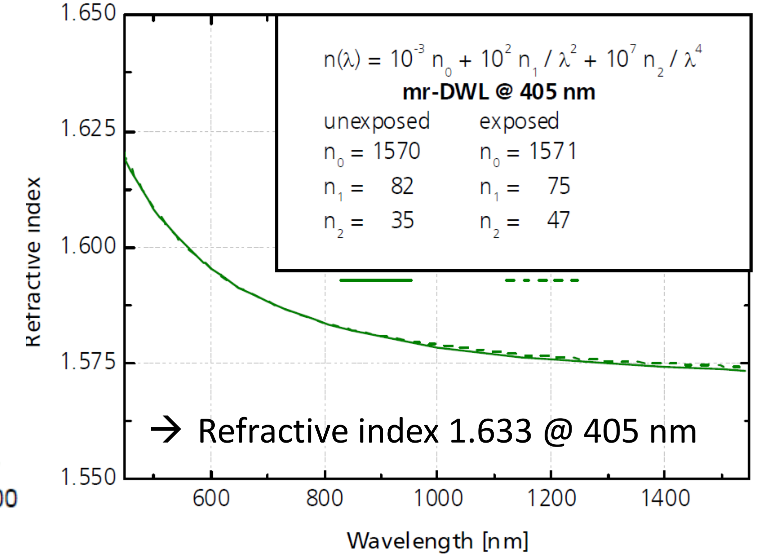
# Characteristics of the resists

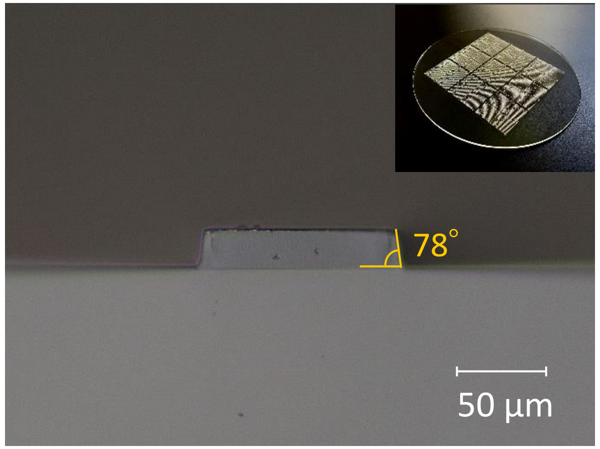
## Negative resist

mr-DWL
(epoxy)

micro resist technology



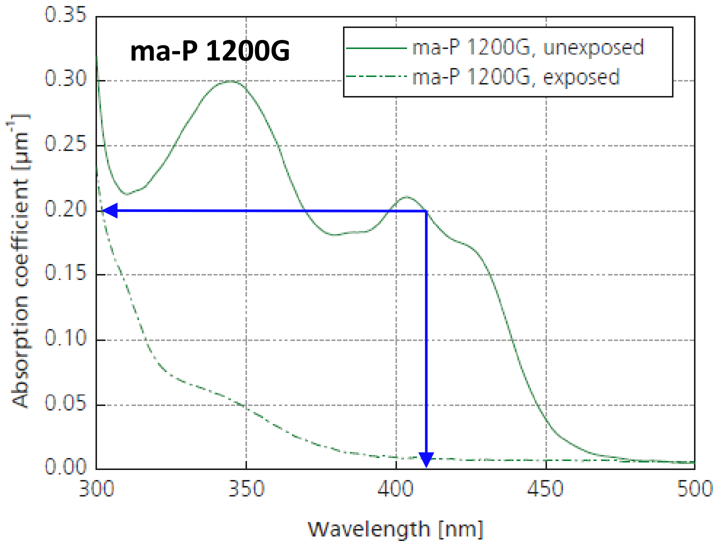



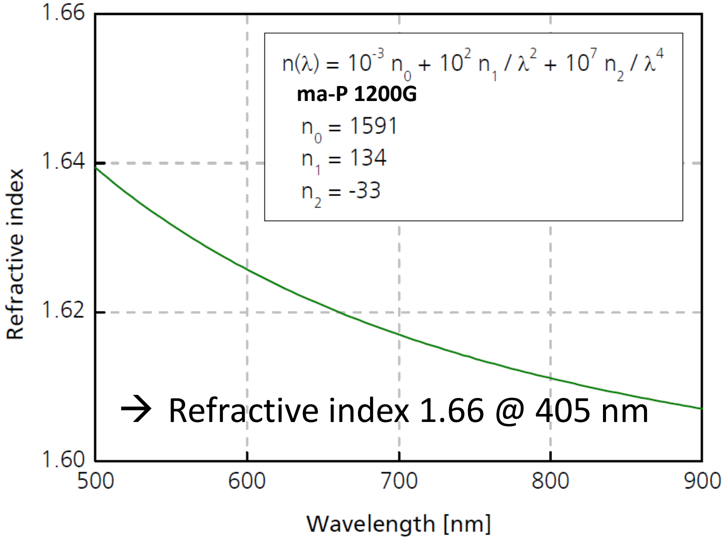

WM I, 329 mJ/cm²
100mW, 0% Focus, 12.5% filter

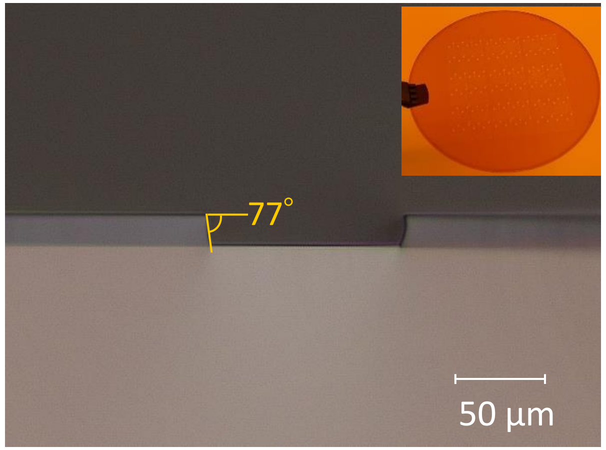
## Positive resist

ma-P1275G
(novolak)

micro resist technology




→ Side wall angle of ma-P1275G and mr-DWL40 for 20 µm thickness are almost similar (78° )

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# The impact of thermal processing on resist

micro resist technology

**Resist: ma-P1275G** – DNQ based positive resist (on novolak-basis)

DNQ $\xrightarrow{+h\nu}$ Ketene $\xrightarrow{+H_2O}$ ICA ⇨ solubility ↑

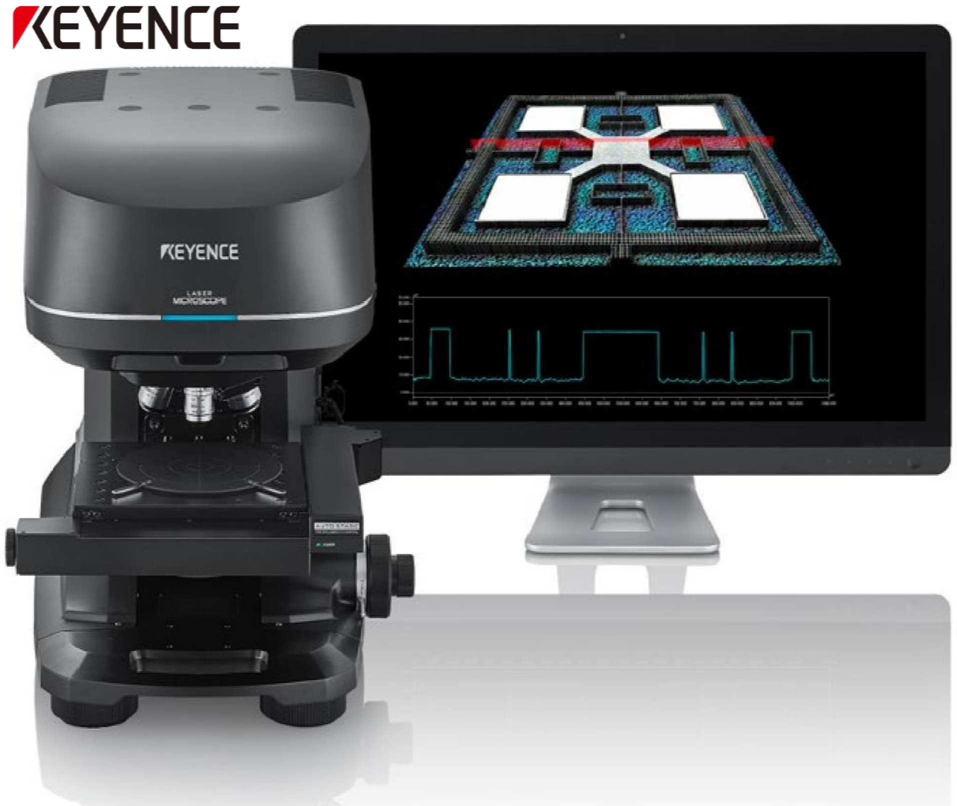
| | | | |
|---|---|---|---|
| **Process** | Prebake | Cooling | Rehydration |
| **Aim** | • Dry the film | • Reduce internal stress | • Ensure chemical reaction |
| **Parameters** | Additional vacuum: reduces baking time & temperature | Extreme long cooling: damages contrast | Water diffuses in resist: <20 µm: 1 µm/min >20 µm: a few hours to overnight |

Working thickness up to 60 µm; more critical for thickness >20 µm

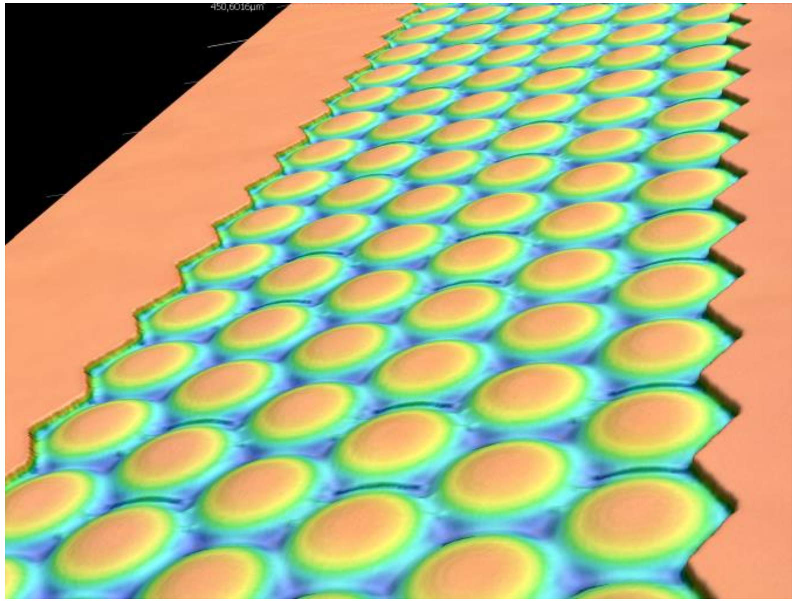
*DNQ: diazonaphthoquinone based photoactive compound (PAC); ICA: indene carboxylic acid is soluble in aqueous-alkaline developer*

# Confocal microscopy – Keyence VK-X 3100

(laser 404 nm)




Konfokales 3D Laserscanning-Mikroskop der **Modellreihe VK-X**

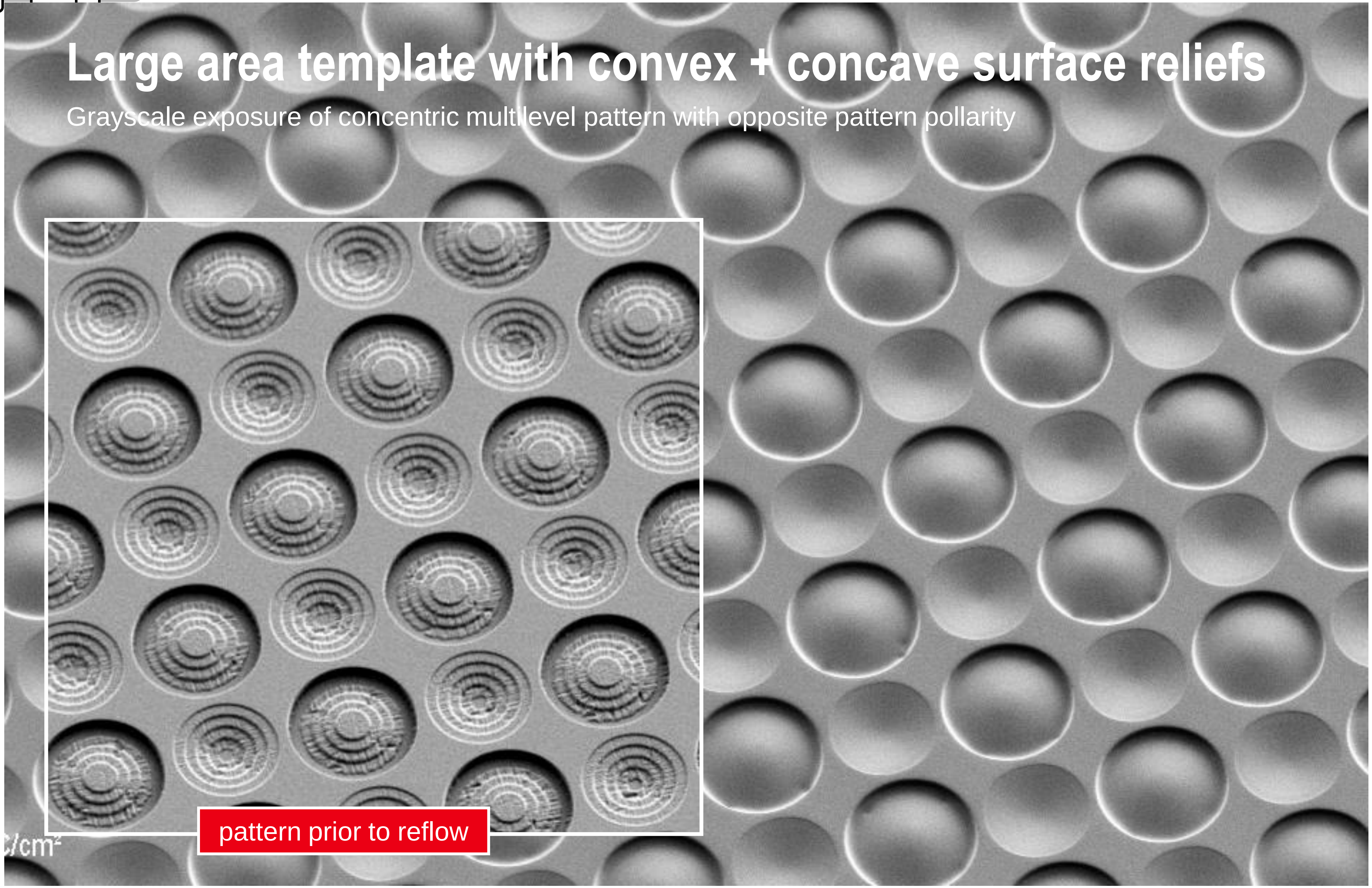


Acquired with AM-SFA investment money
+ 300x300 mm$^2$ stage for large substrates

A Laser scanning confocal microcope (LSCM) is for fast acquisition of 3D profiles of resist structures.

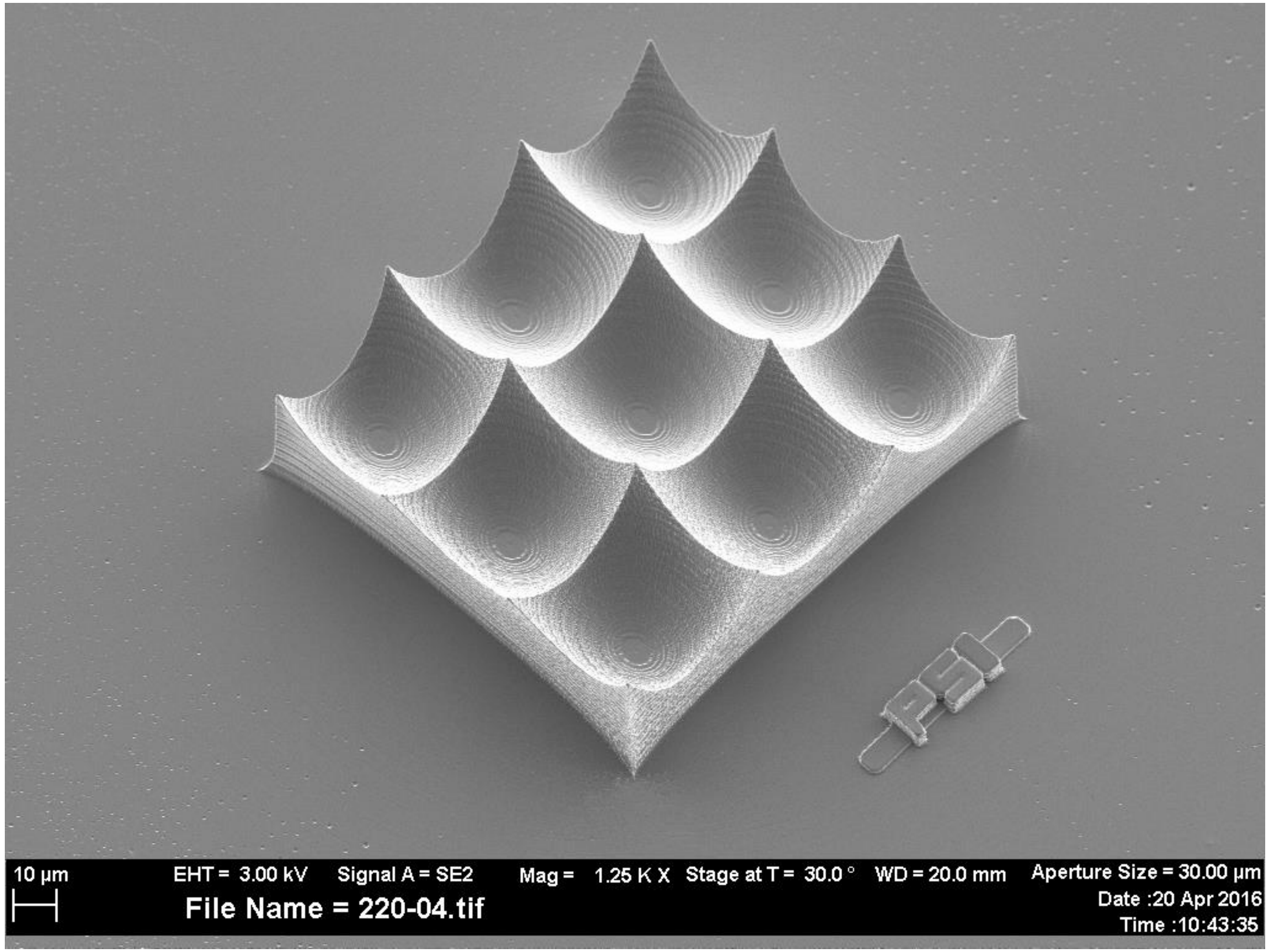
Since the confocal microscope is at 404 nm laser wavelength, the same «fake» effects might happen during writing AND examination, e.g., interference effects in the resist that cause wrong exposures/measurement. THEREFORE: control with SEM/profilometer is still needed!

# 3D E-Beam Lithography + Thermal Reflow



# Motivation

Surfaces of microstructures are typically «rough» in different dimensions

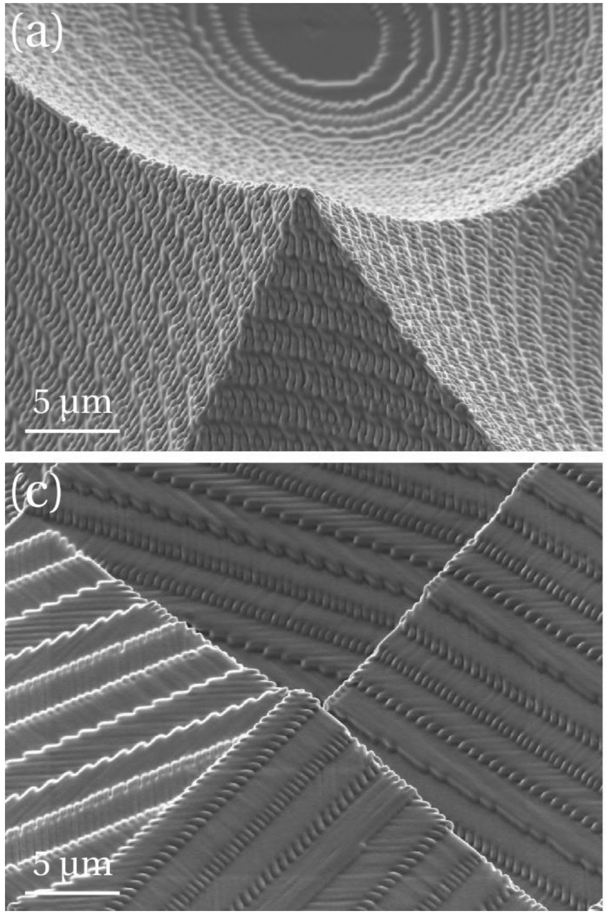



**Test structure:** Micro-lens array (3x3) concave 50 μm x 50 μm x 50 μm (each)

# Motivation

## Distinction between structural details and unwanted «nano»roughness

Rough surface



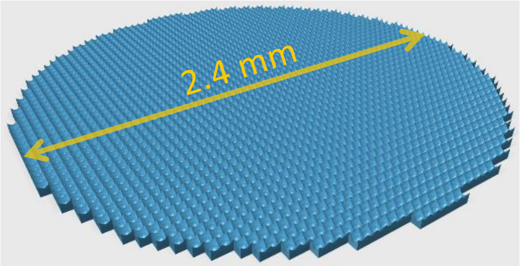

Concave lenses

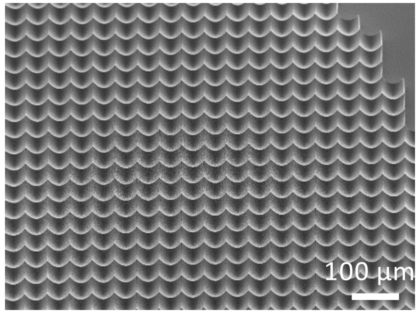
Tiled slopes

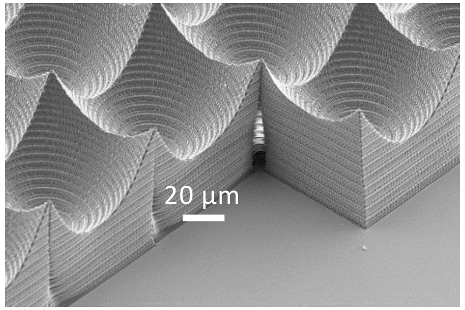
**Segments intersection:** sharp <1 µm tips («high aspect ratio»)

# Device (48 hours writing)

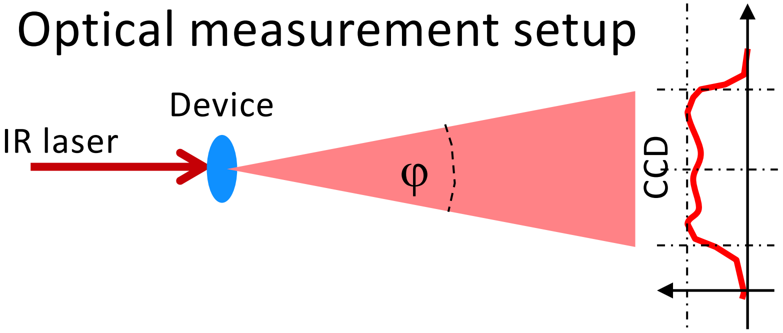
## Master fabrication



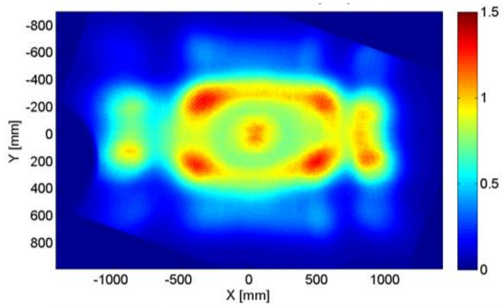




## Optical measurement setup




**FOI:** Field of illumination given by angle $\varphi_x$

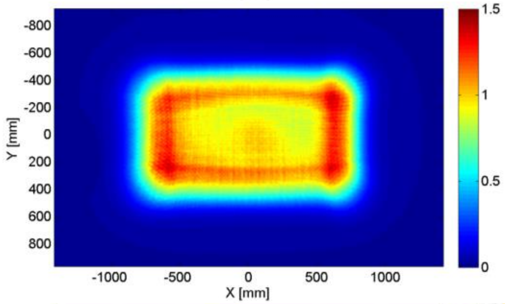
**Intensity variation:** standard deviation by Sigma




**IpDip Master**

x-FOI (75%) = 61.5°

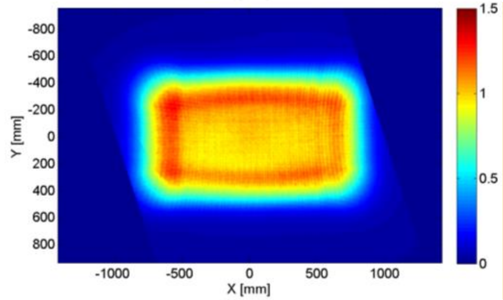
Sigma = 10%




**PMMA as embossed**

x-FOI (75%) = 75°

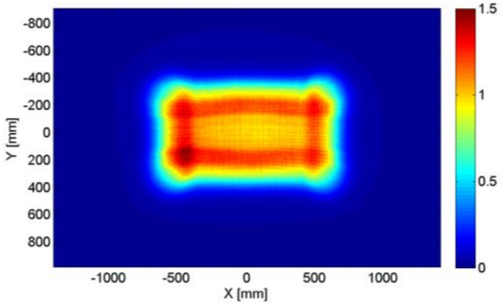
Sigma = 10%




**PMMA exp+reflow**

x-FOI (75%) = 74.5°

Sigma = 5%

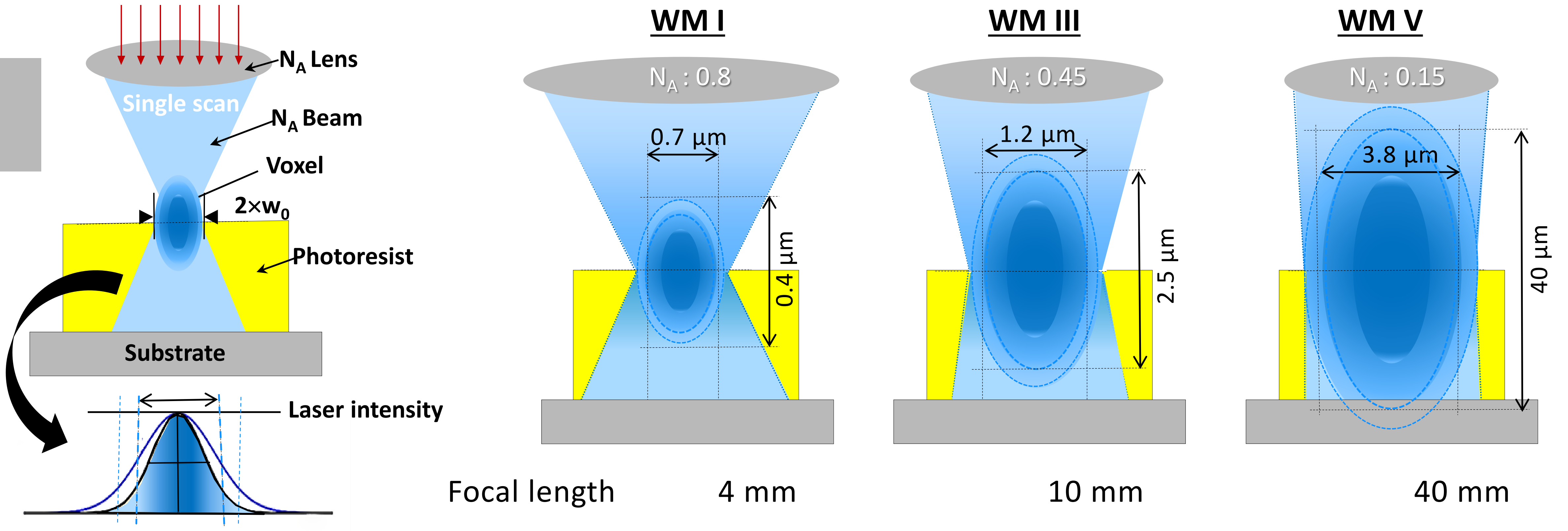



**PMMA no exp reflow**

x-FOI (75%) = 63.2°

Sigma = 7%

# HIMT DWL 66$^{+}$ with different Write Modes (WM)

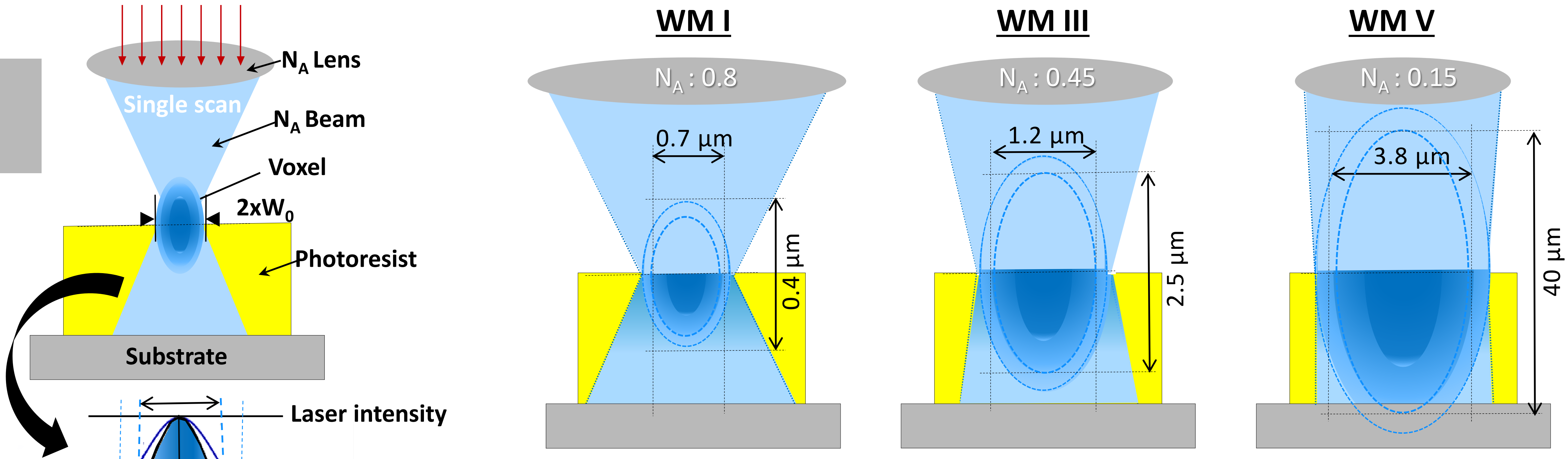



Gaussian beam

| | WM I | WM III | WM V |
|---|---|---|---|
| Focal length | 4 mm | 10 mm | 40 mm |
| Writing speed | 13 mm$^2$/min | 160 mm$^2$/min | 2060 mm$^2$/min |

- The write modes use focusing lenses with different $N_A$ and resolution for throughputs
- 405 nm (h-line) exposure for positive/negative photoresists with maximum power 300 mW
- 3 types of write modes (WM) used to investigate the structure

# HIMT DWL 66⁺ with different Write Modes (WM)

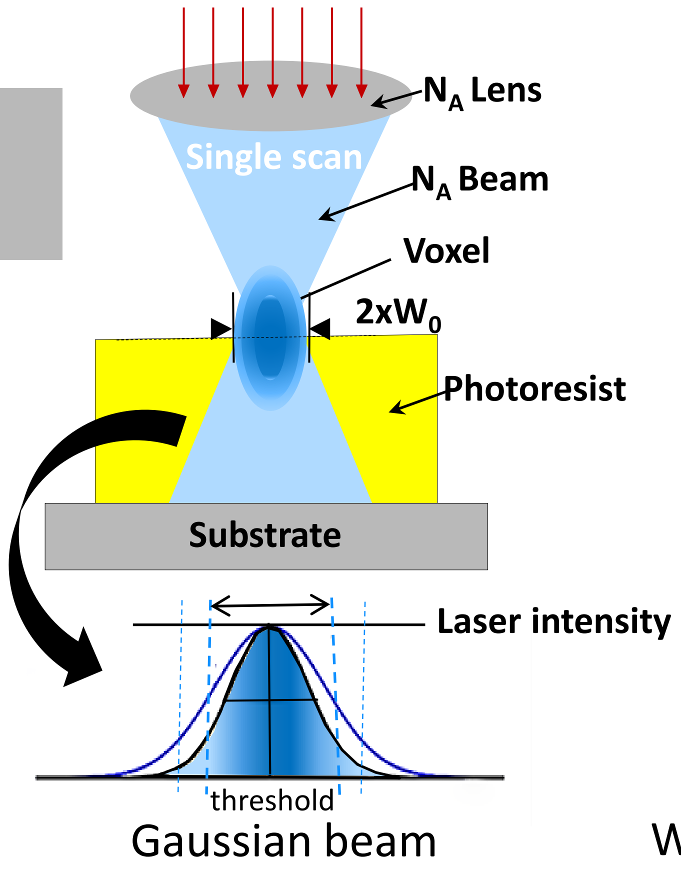


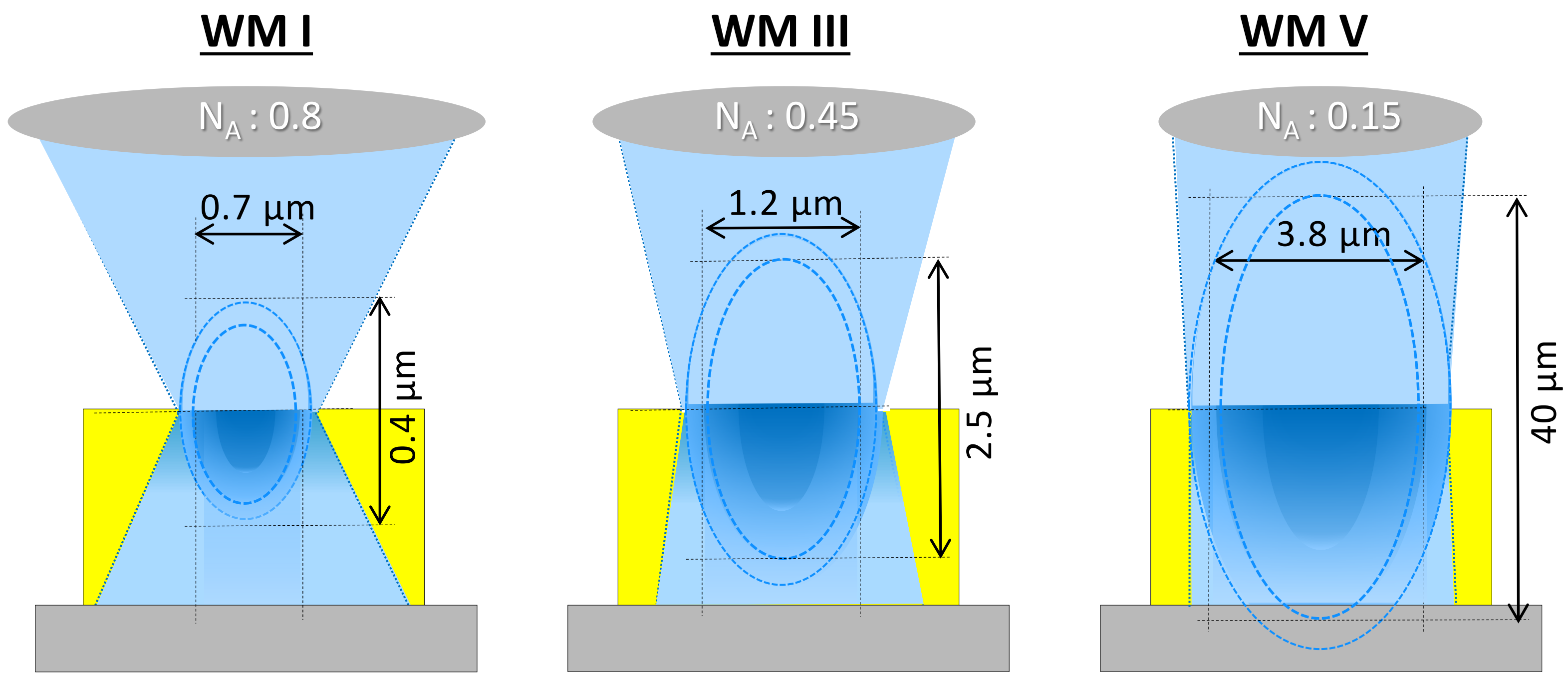

Gaussian beam

| | WM I | WM III | WM V |
|---|---|---|---|
| Focal length | 4 mm | 10 mm | 40 mm |
| Writing speed | 13 $mm^2$/min | 160 $mm^2$/min | 2060 $mm^2$/min |

- The write modes use focusing lenses with different $N_A$ and resolution for throughputs
- 405 nm (h-line) exposure for positive/negative photoresists with maximum power 300 mW
- 3 types of write modes (WM) used to investigate the structure

# HIMT DWL 66+ with different Write Modes (WM)




| | WM I | WM III | WM V |
|---|---|---|---|
| Focal length | 4 mm | 10 mm | 40 mm |
| Writing speed | 13 $mm^2$/min | 160 $mm^2$/min | 2060 $mm^2$/min |

- The write modes use focusing lenses with different $N_A$ and resolution for throughputs
- 405 nm (h-line) exposure for positive/negative photoresists with maximum power 300 mW
- 3 types of write modes (WM) used to investigate the structure

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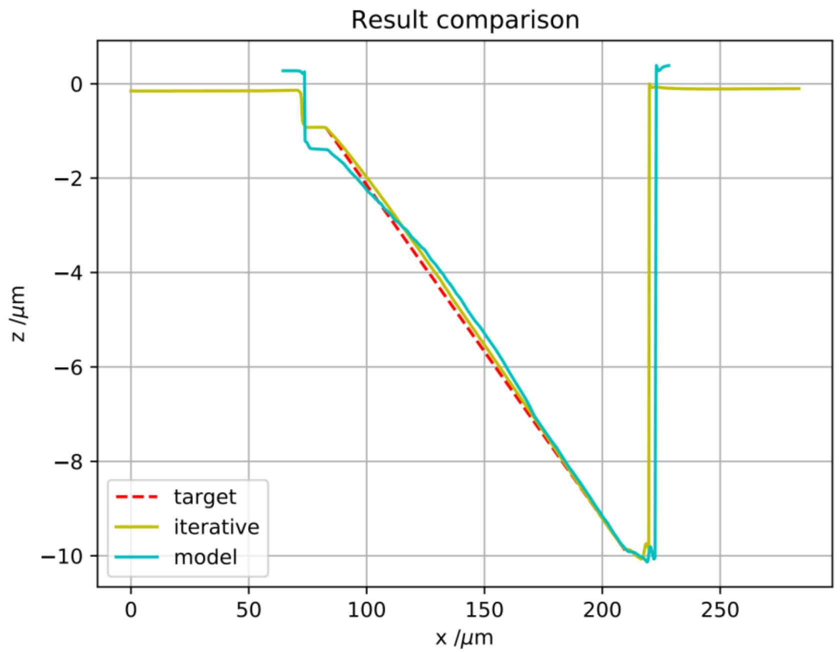
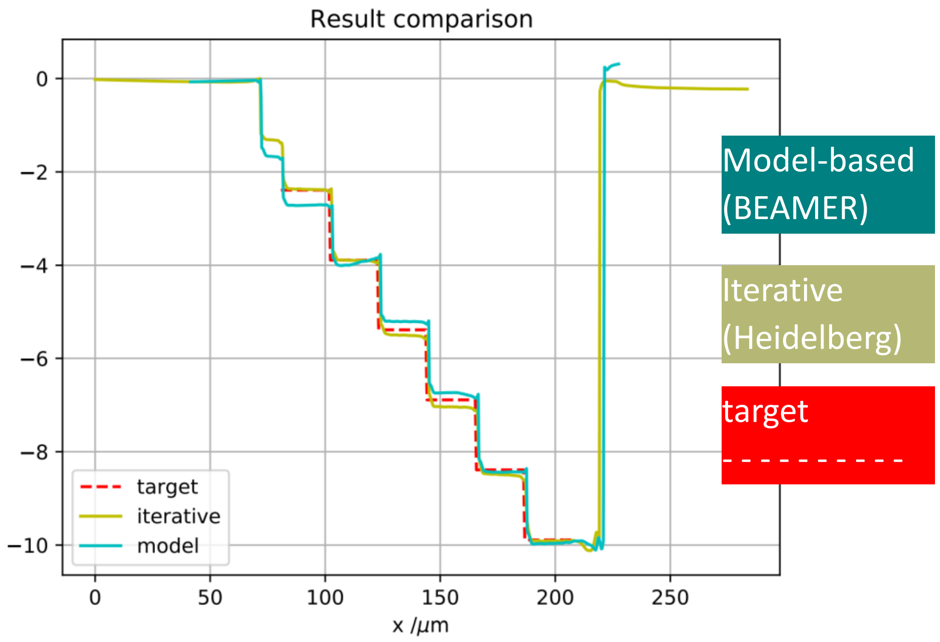
# Results (slope and staircase)




Deviations are quite difficult to judge

Both methods show abilities but also shortcomings

- GVD-iterative: stairs with many almost identical GVs
- PEC-model: beginning of curve and overshoots