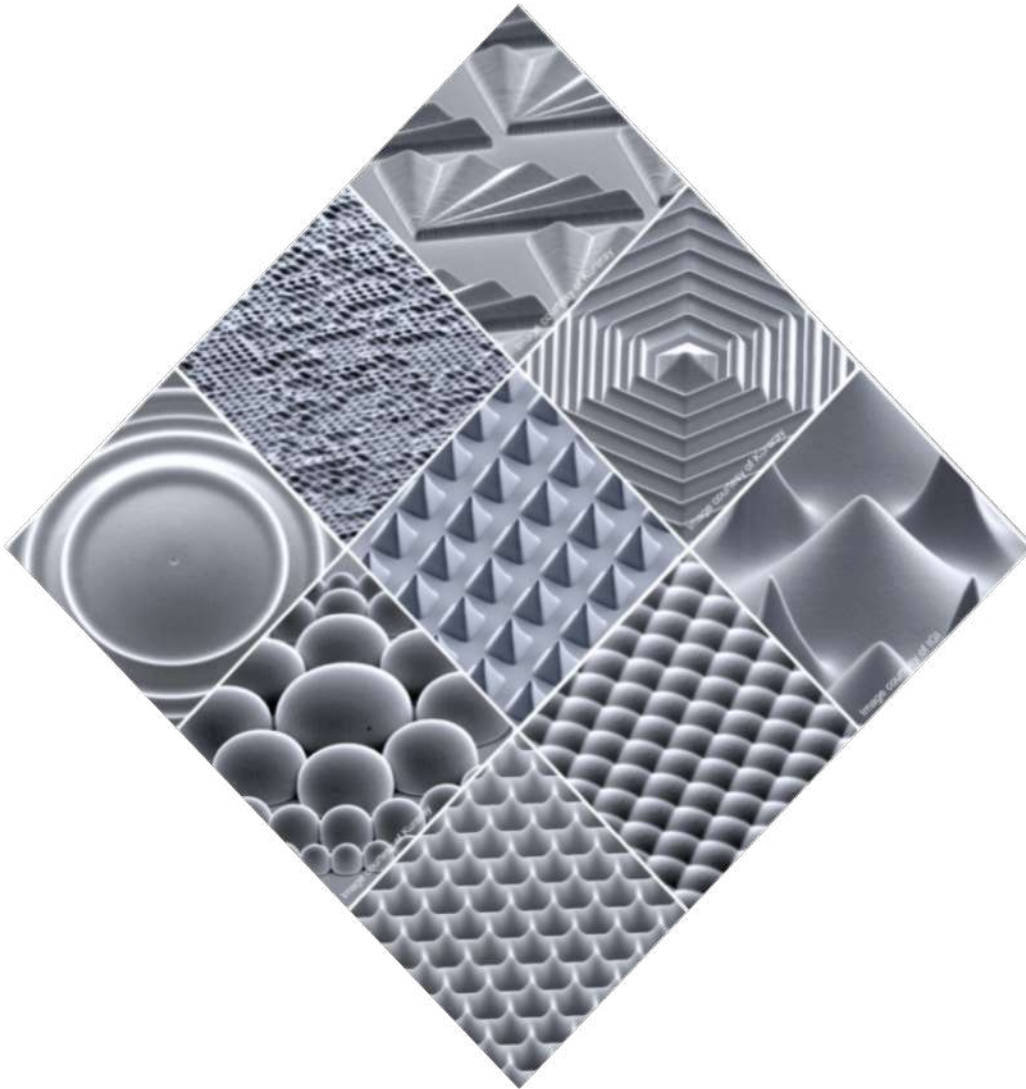


HEIDELBERG INSTRUMENTS

Grayscale Laser Lithography with Heidelberg Instruments DWL Series

Hideo Jotaki
Heidelberg Instruments KK

Product Overview

VPG+, ULTRA

Photomask Production

Advanced Packaging, Displays, Semiconductors, IC3D

NanoFrazor

Nanofabrication

Nanoelectronics, Nanofluidics, Nanoimprint Templates

The power of direct writing

DWL

Grayscale

Micro-Optics, Lenses, Reflectors, Surface Textures

MLA

Microfabrication

Electronic components, Sensors, MEMS, Microfluidics

Heidelberg Instruments Product Lines Overview

DWL Series

Beam
Modulator

DWL 2000/ 4000

VPG Series

Line
Modulator

VPG+ 800 / 1100 / 1400

MLA Series

Area
Modulator

MLA150

MLA300

Nano Frazor Series

Heat
Modulator

NanoFrazor Explore

HEIDELBERG INSTRUMENTS

DWL 2000 and 4000

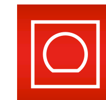
High Resolution Pattern Generators

Beam Modulator

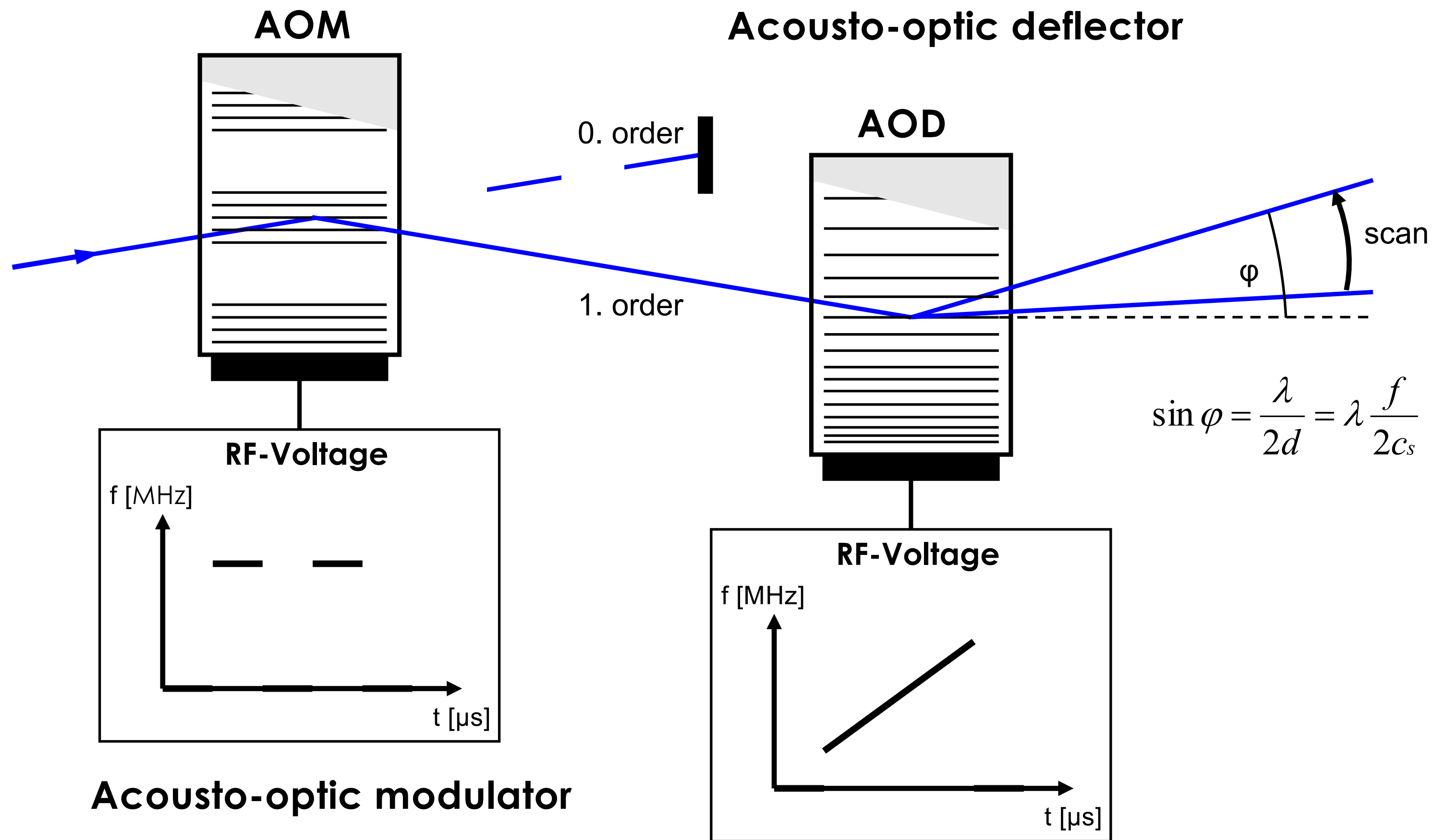
. 66+

graphy
ch Tool

Our systems for direct writing and low volume mask making – the DWL series

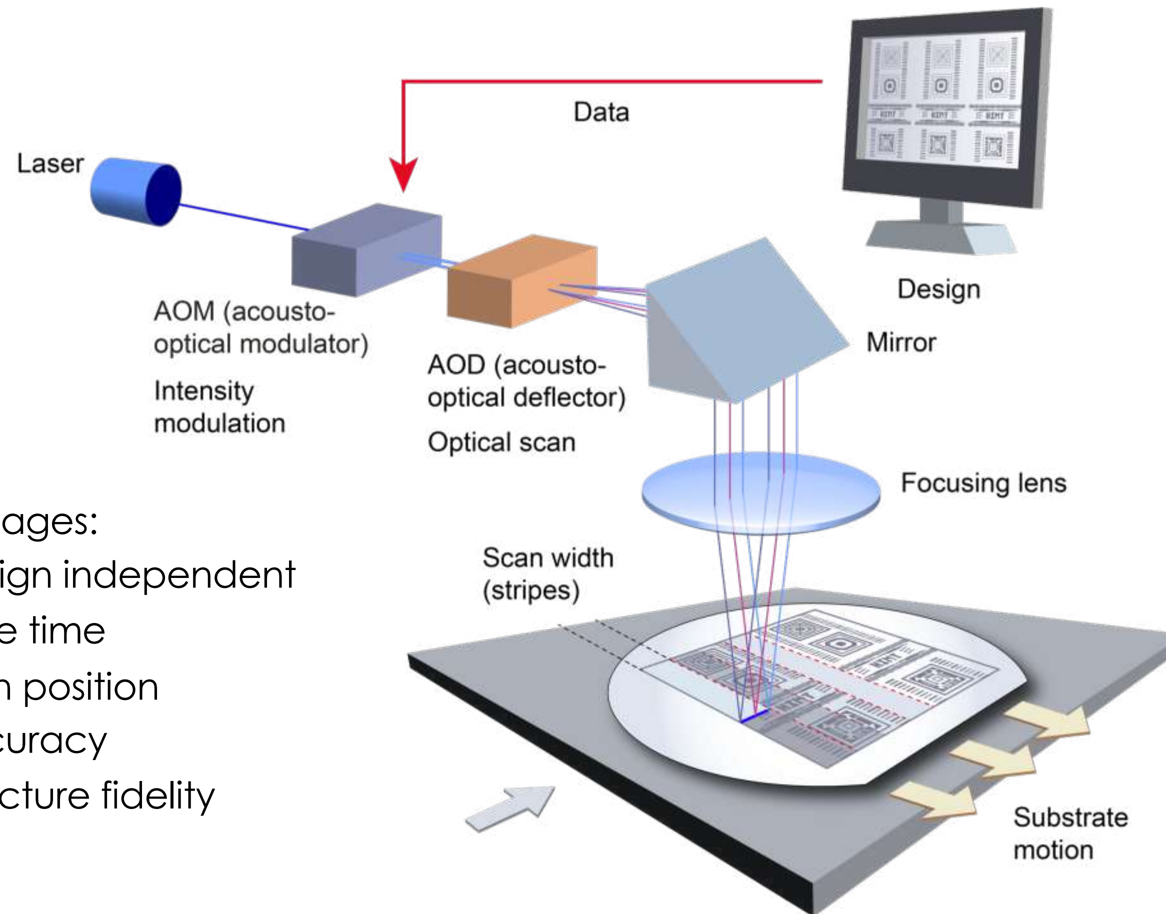


Acousto-optic modulator and deflector



Exposure strategy: The raster scan

HEIDELBERG INSTRUMENTS

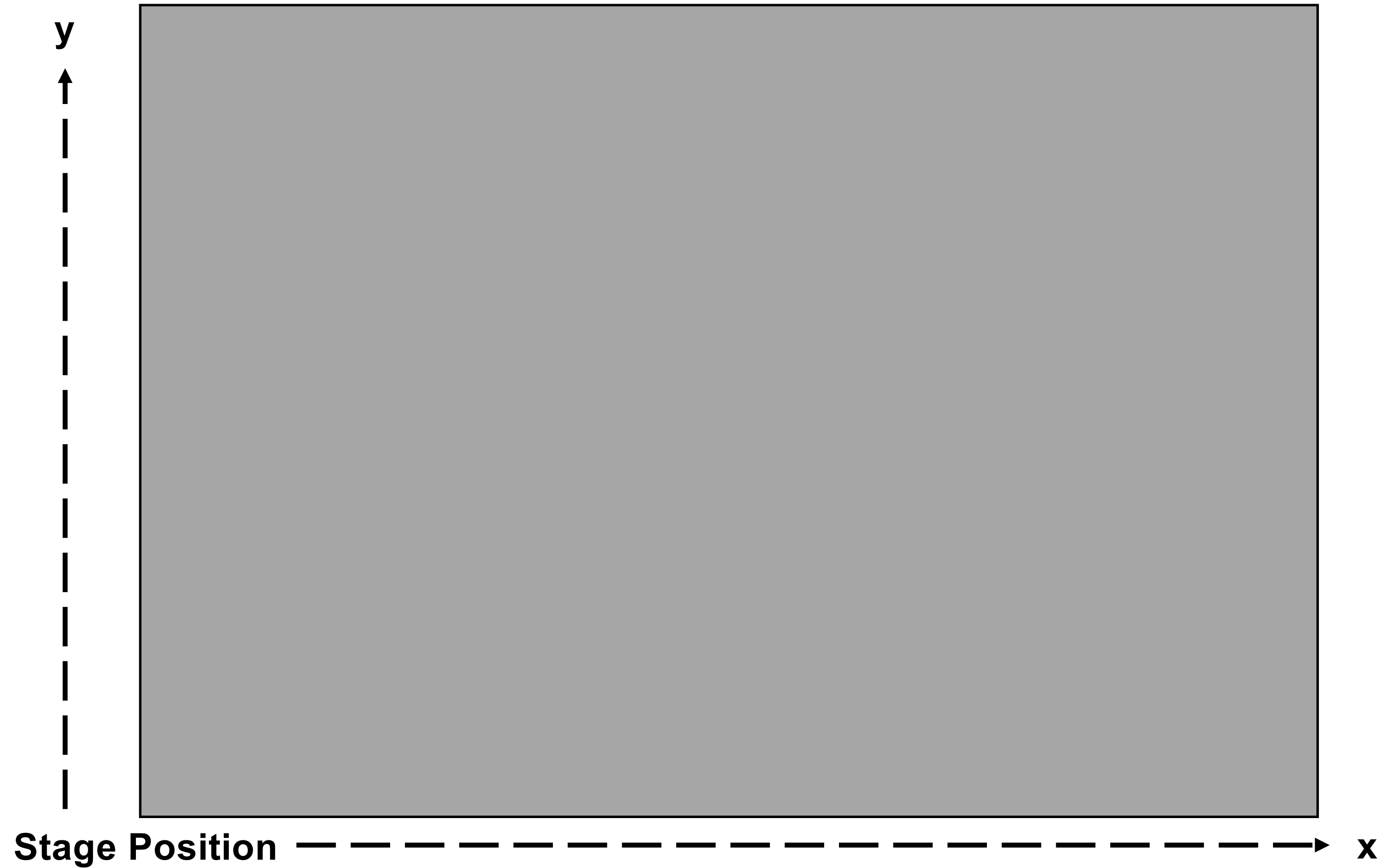


Advantages:

- Design independent write time
- High position accuracy
- Structure fidelity

Exposure strategy: The raster scan

HEIDELBERG INSTRUMENTS



ULTRA

Semiconductor Laser Mask Writer

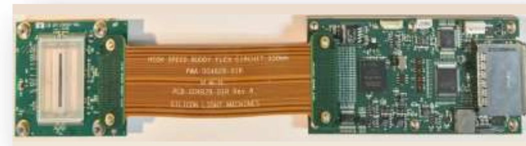
Line Modulator

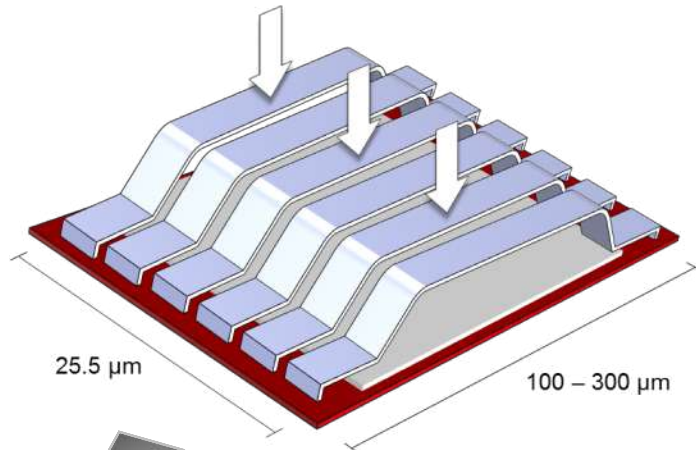
VPG+

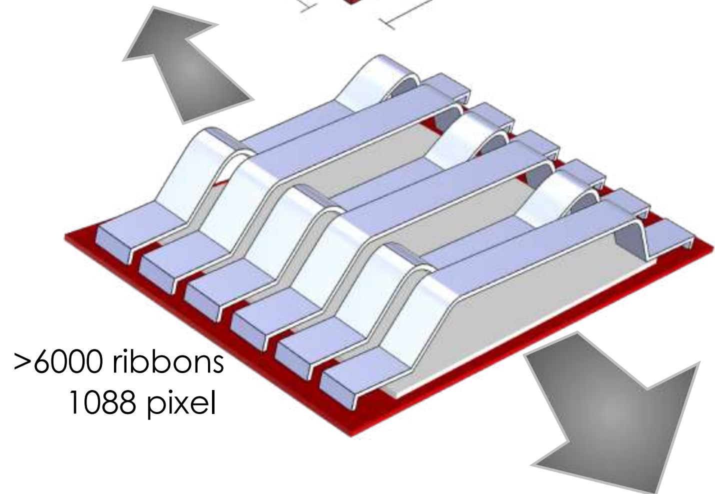
Small Area Volume Pattern Generators

Large Area Volume Pattern Generators

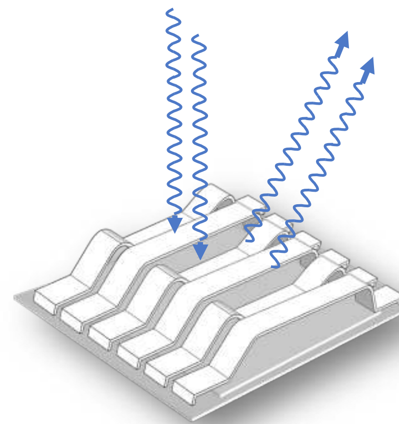
The Grating Light Valve

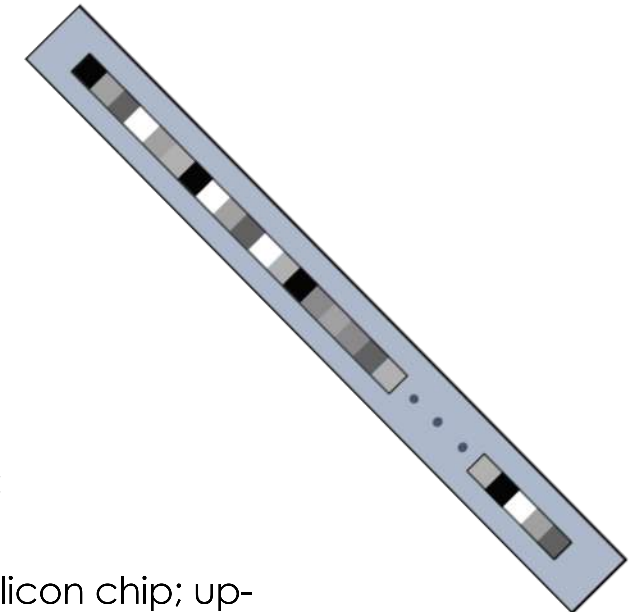






>6000 ribbons
1088 pixel





GLV: The **Grating Light Valve:**

A 1D-*spatial light modulator:*

Ribbons of silicon-nitride on silicon chip; up-and-down-position changed by voltage

→ Groups of ribbons form a diffractive **grating**

→ 3 variable and 3 fixed ribbons per pixel

→ Modulating laser light as per design data

Exposure strategy VPG⁺: Raster scan, continuous scrolling

Exposure strategy VPG$^+$:
Raster scan, continuous scrolling

HEIDELBERG INSTRUMENTS

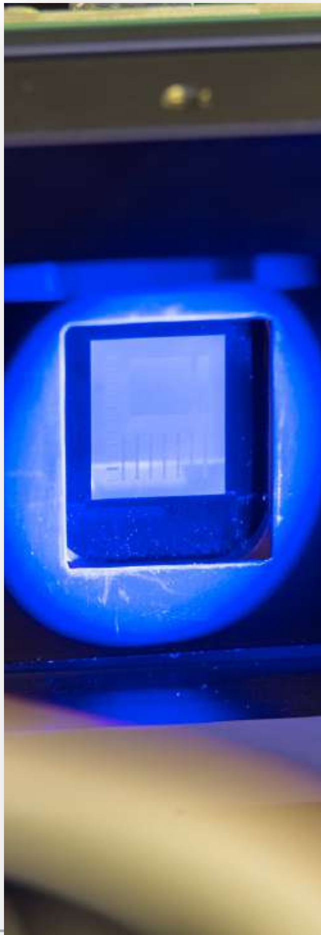
µMLA
MLA150
MLA300

Maskless Aligners

Area Modulator

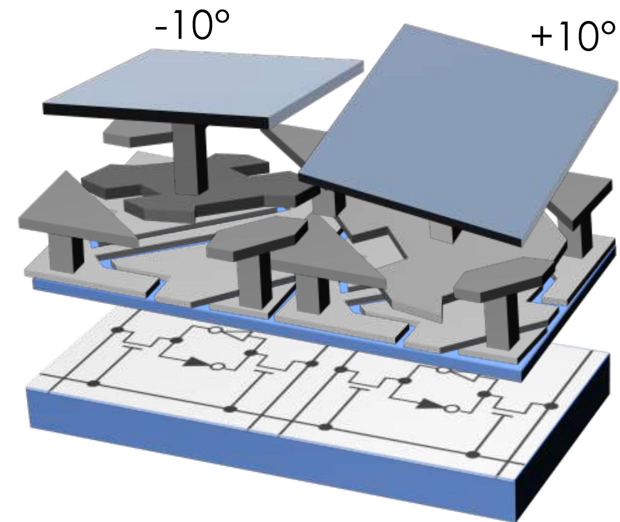
The DMD™

HEIDELBERG INSTRUMENTS



DMD™ = digital multimirror device

- MEMS device
- Each pixel consists of an aluminum micromirror
- Two bias electrodes tilt the mirror either to +10° or -10°
- ON (+10°): Mirror reflects light into lens, pixel is bright
- OFF (-10°): No reflection, pixel is dark
- DMD contains more than 442,000 micromirrors



Simplified representation of two tilted mirrors (i.e. two pixels) in a Texas Instruments DMD™

Schematic adapted from Marc J. Madou, Fundamentals of Microfabrication and Nanotechnology, Volume II, © CRC Press 2012

Exposure strategy MLA series

Laser light source

Data

Spatial Light Modulator

Mirror

Design

Focusing lens

Scan width (stripes)

Bidirectional writing process

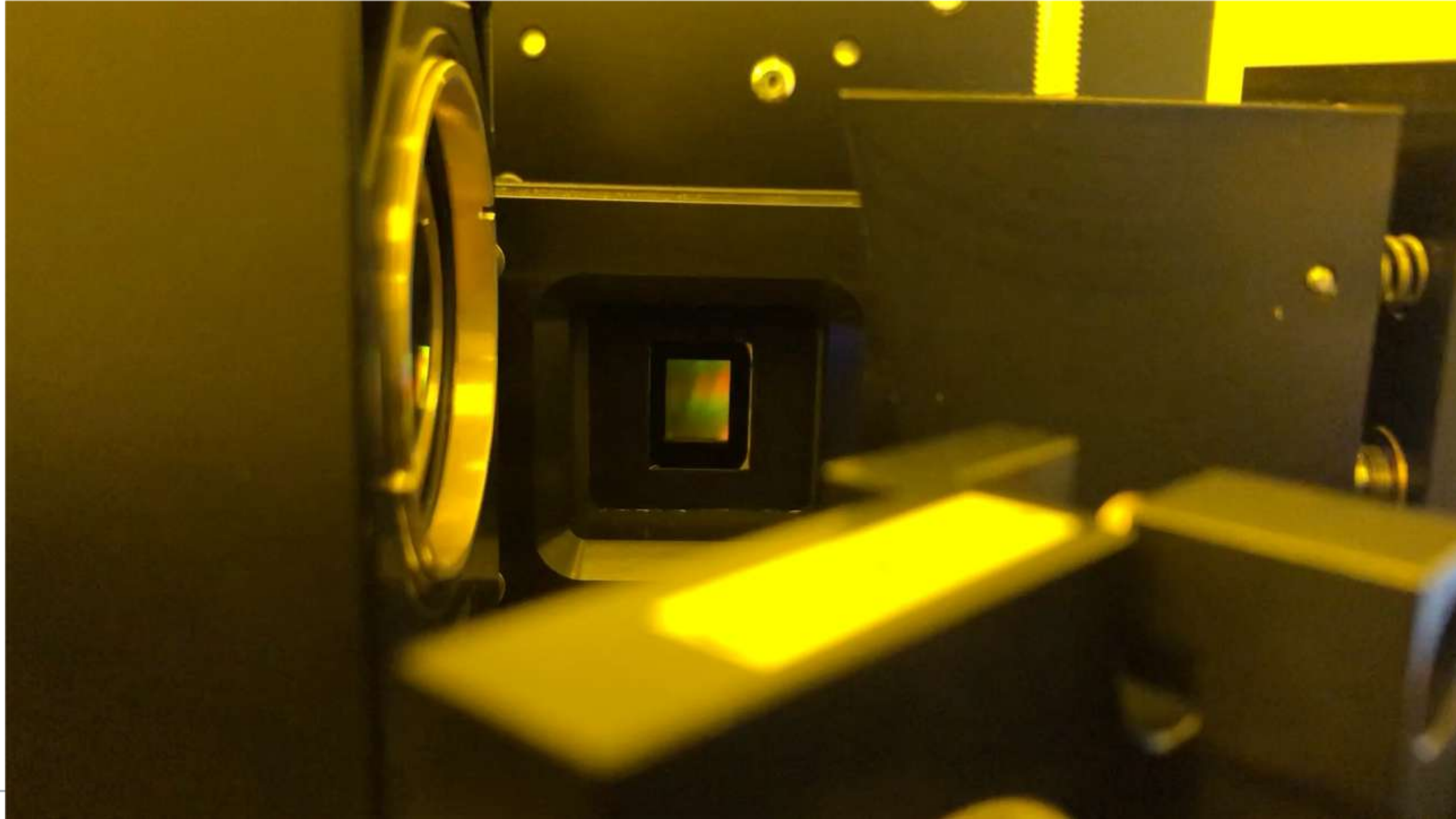
Write direction

Direction of stage travel

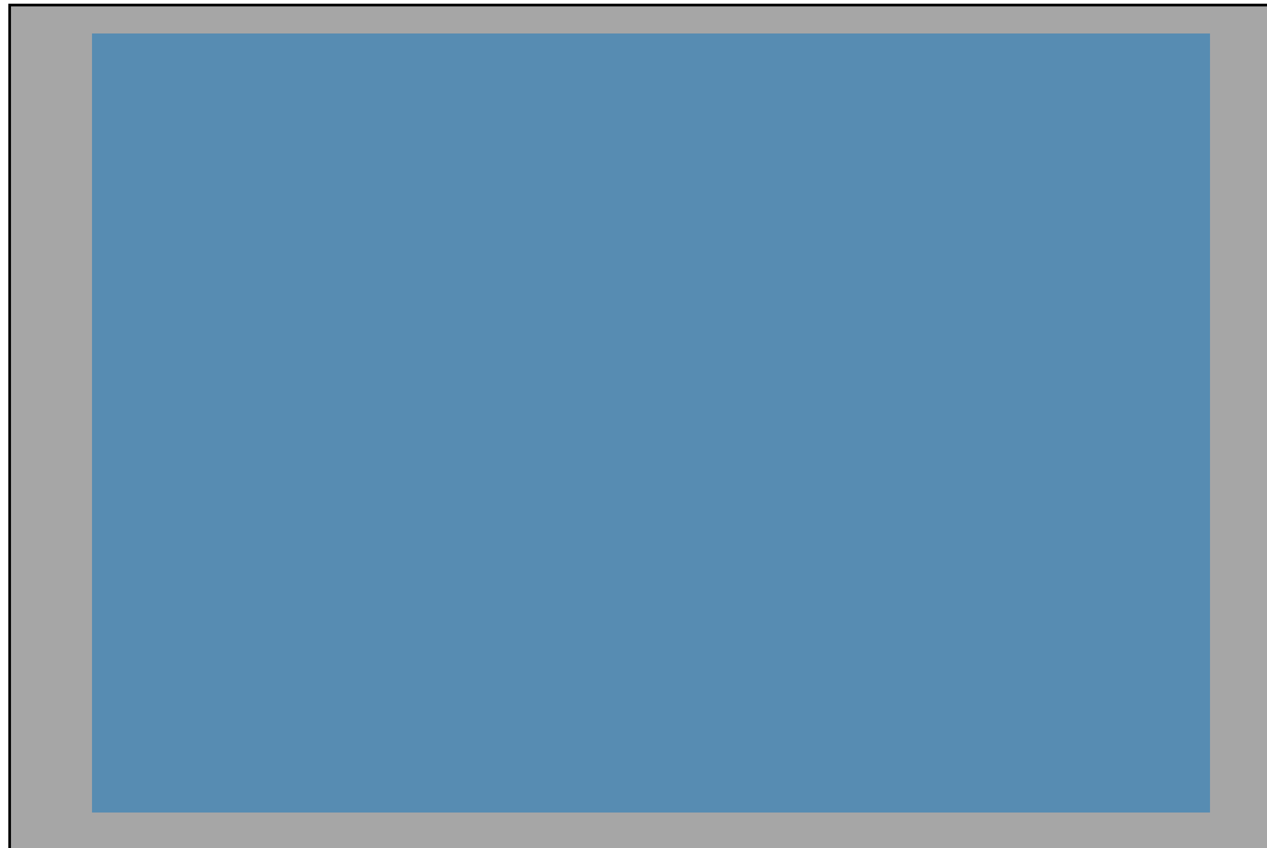
SPEED

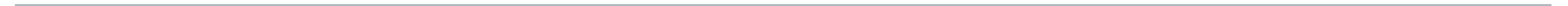
The DMD™

HEIDELBERG INSTRUMENTS



Exposure strategy MLA series





HEIDELBERG INSTRUMENTS
The power of direct writing

NanoFrazor lithography

16 February 2021

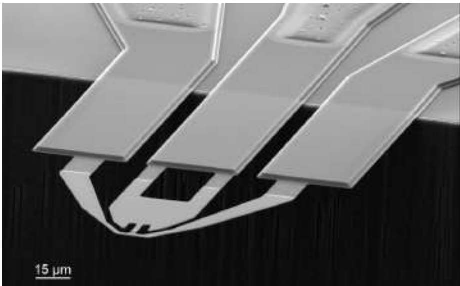
Heidelberg Instruments Nano
SwissLitho AG
Technoparkstrasse 1
8005 Zurich, Switzerland

NanoFrazor Thermal Cantilevers

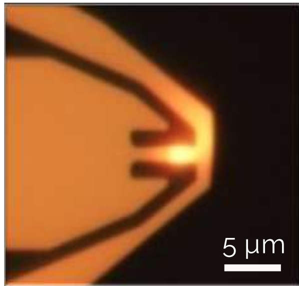
Key features

- **Ultra-sharp tip** (silicon)
- **Integrated tip heater** (resistive, up to 1100°C with 1 K resolution)
- **Integrated actuation** (electrostatic for fast and accurate deflection)
- **Integrated topography sensor** (unique AFM mode based on thermal distance sensor)

Smart cantilever holder
- Exchange within 1 min
- Access almost any sample

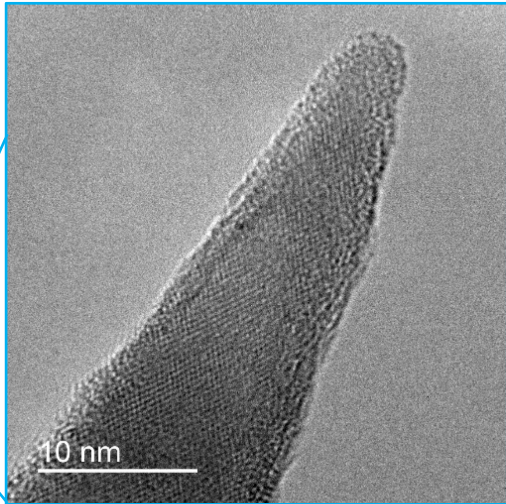


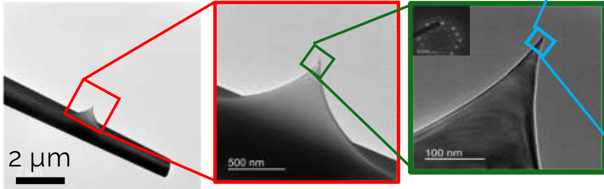
NanoFrazor Cantilever made of Si



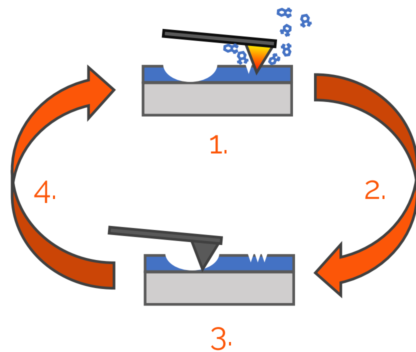
Glowing tip heater

Tip with < 2 nm radius



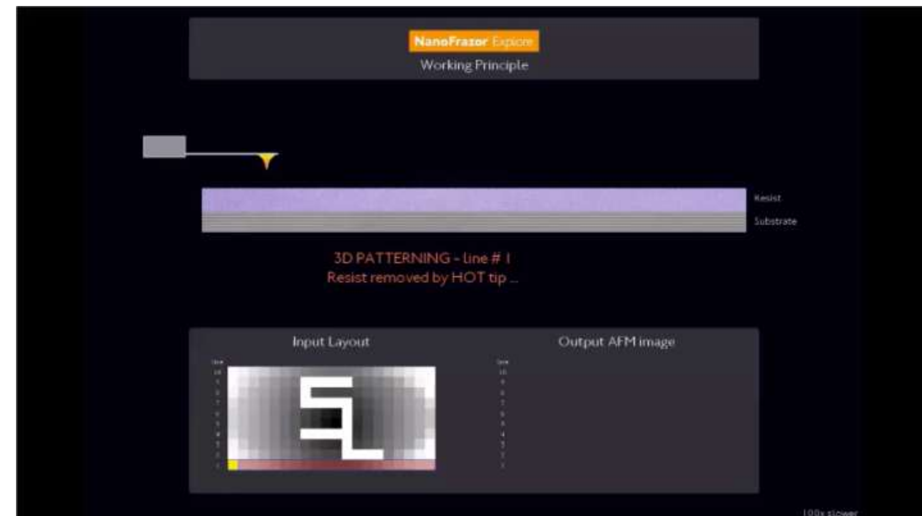


Closed-Loop Lithography: Patterning & Imaging



Every few milliseconds:

1. Patterning one line with hot tip
2. Cool down tip in few microseconds
3. Image topography of written line
4. Feedback algorithm to adapt patterning
5. Patterning of next line



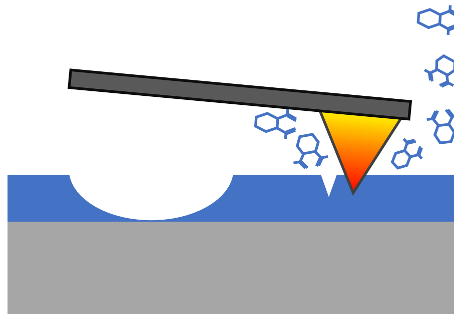
- "What You See Is What You Get"
- No separate metrology necessary after lithography
- Check and online adaption of patterning **every few ms**

⇒**Decrease total fabrication time**

⇒**Increase accuracy and reliability**

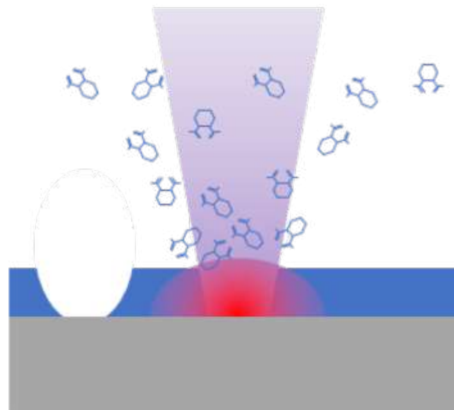
Principle of NanoFrazor

Writing



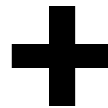
Thermal probe

- 10 nm sharp tip
- fast and accurate deflection



Laser sublimation

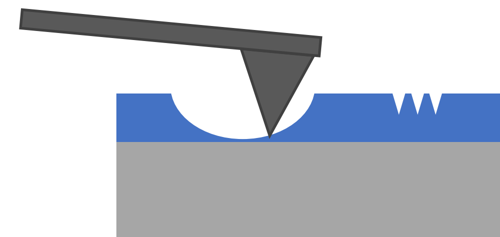
- micrometer resolution
- 100x faster



Reading

in-situ high-speed AFM

- Inspection
- Metrology
- Overlay & Stitching



unique distance sensor

- Level plane & Autofocus
- Drift corrections
- Other calibrations

Product Overview

VPG+, ULTRA

Photomask Production

Advanced Packaging, Displays, Semiconductors, IC3D

NanoFrazor

Nanofabrication

Nanoelectronics, Nanofluidics, Nanoimprint Templates

The power of direct writing

DWL

Grayscale

Micro-Optics, Lenses, Reflectors; Surface Textures

MLA

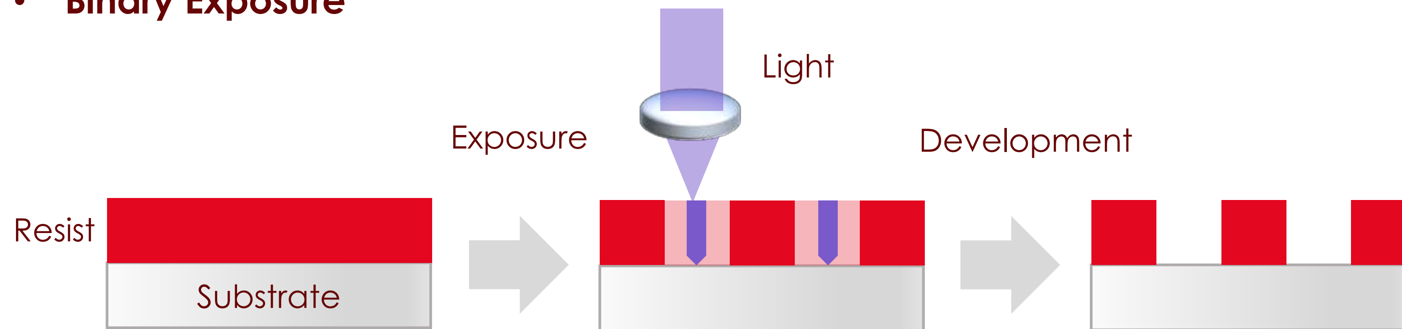
Microfabrication

Electronic components, Sensors, MEMS, Microfluidics

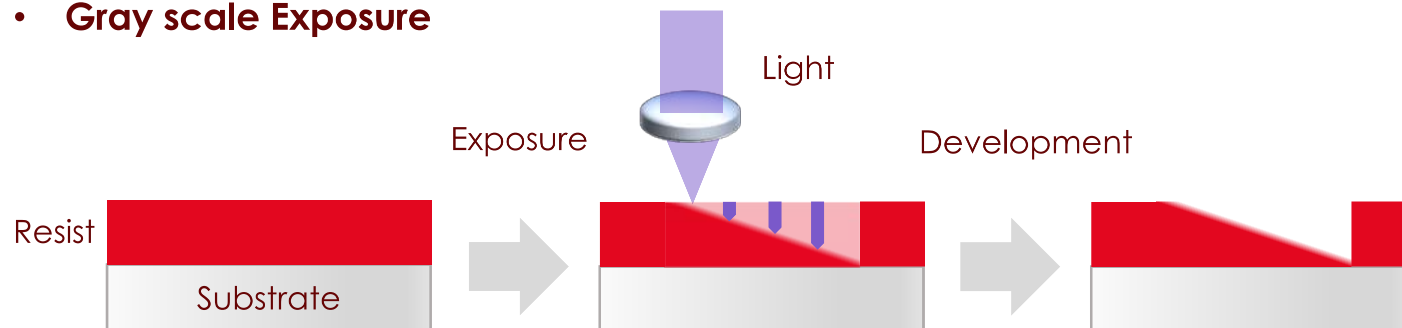
The Basic Principle

HEIDELBERG INSTRUMENTS

- **Binary Exposure**



- **Gray scale Exposure**



Exposure strategy in DWL systems

AOM
(acousto-optic
Modulator)

U ~ *Intensity*

f ~ Deflection angle

AOD
(acousto-optic
deflector)

Mirror

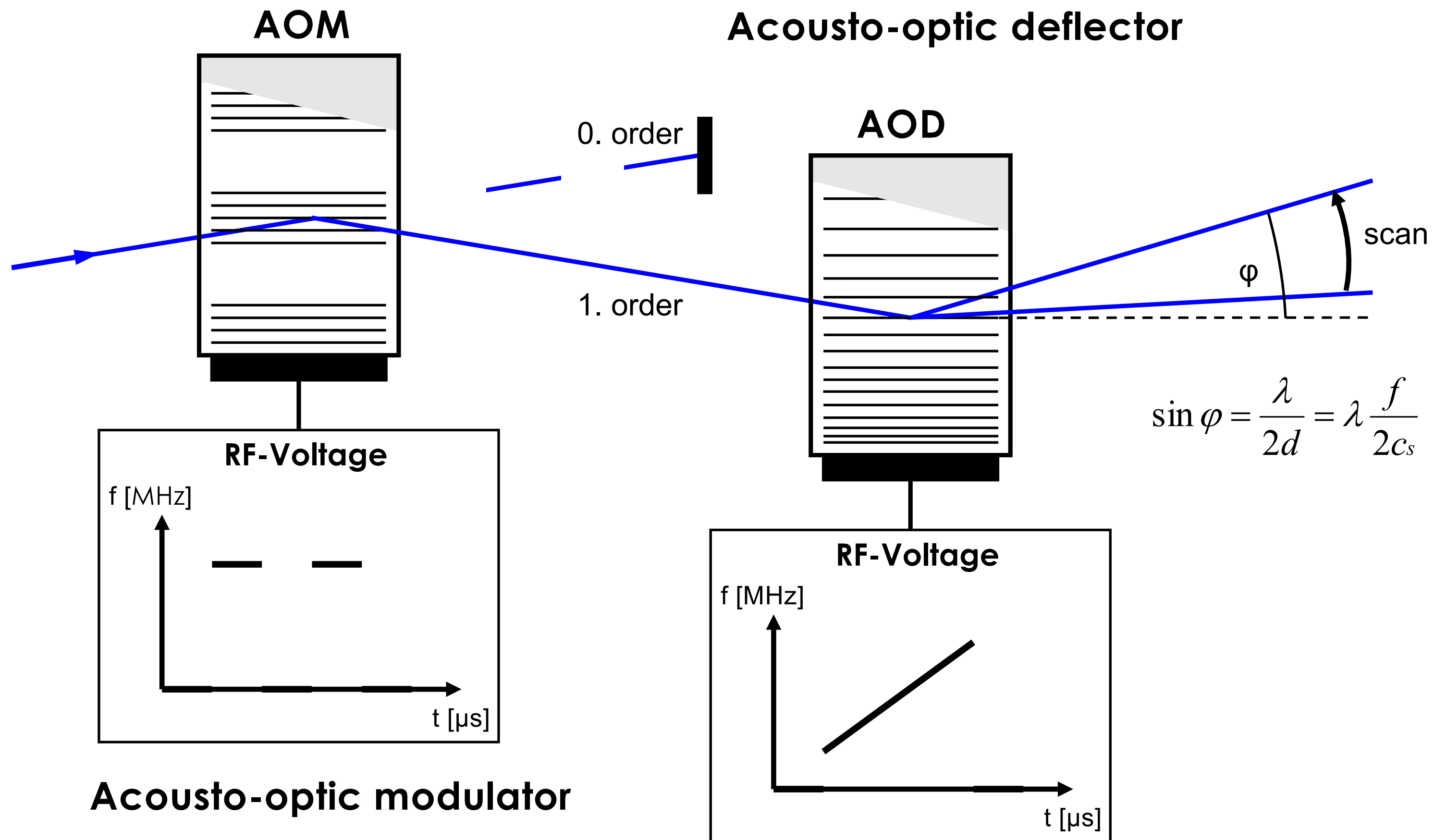
Focusing lens

Scan width

Substrate motion

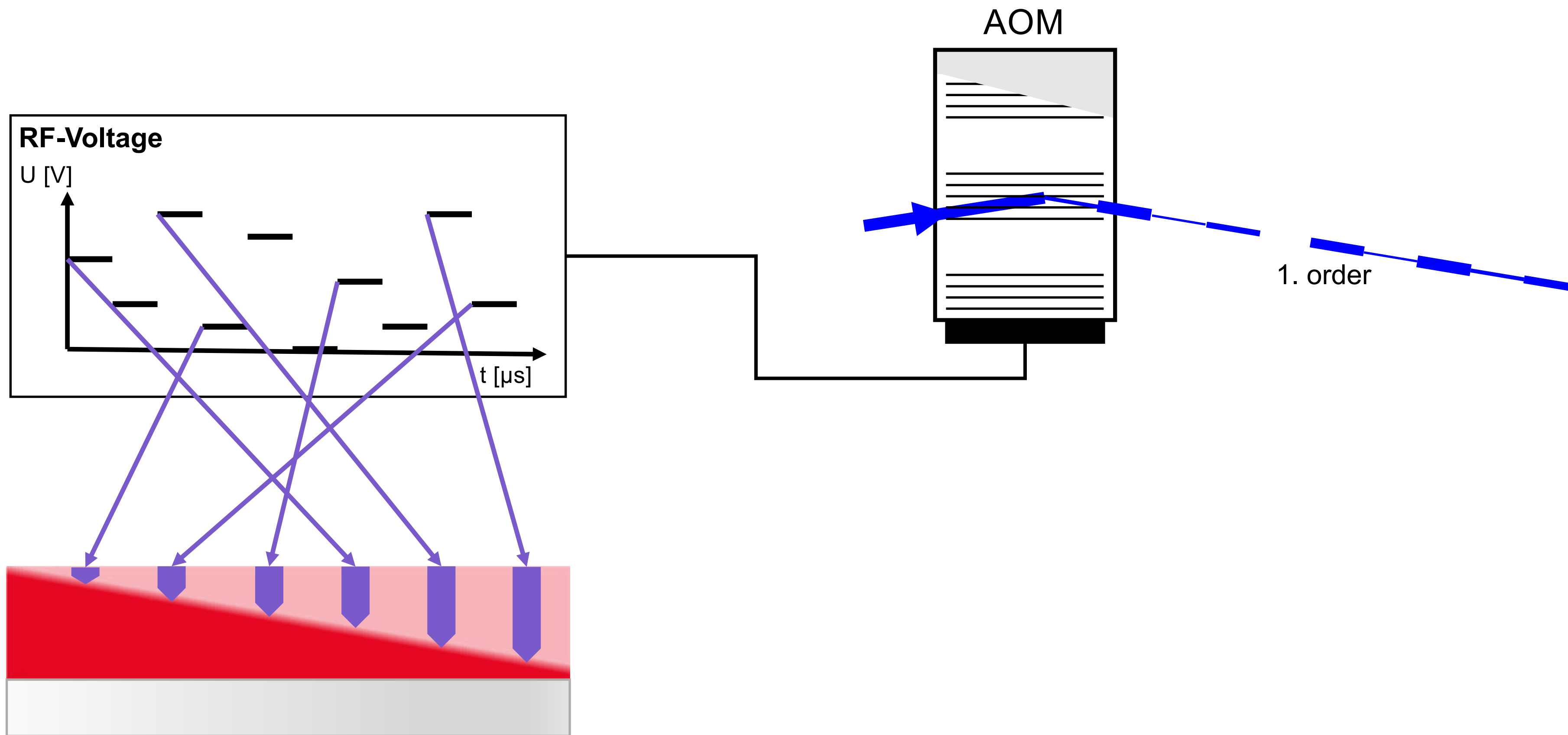
Acousto-optic modulator and deflector

HEIDELBERG INSTRUMENTS



$$\sin\varphi = \frac{\lambda}{2d} = \lambda\frac{f}{2c_s}$$

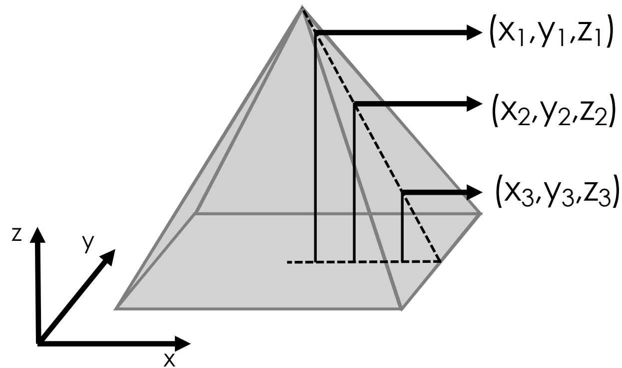
Exposure strategy in DWL systems



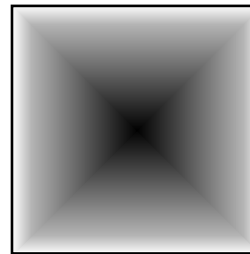
Pattern definition

HEIDELBERG INSTRUMENTS

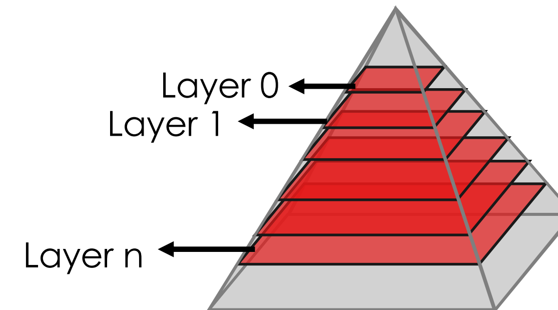
… in design coordinates
(STL, XYZ-ASCII)

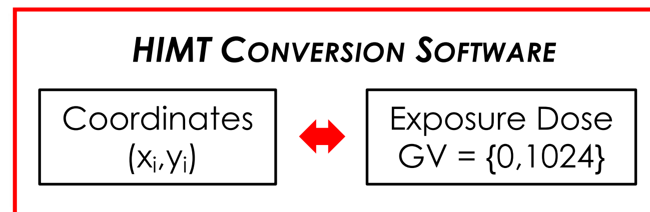


… in bitmap grayvalues
(BMP,PNG)



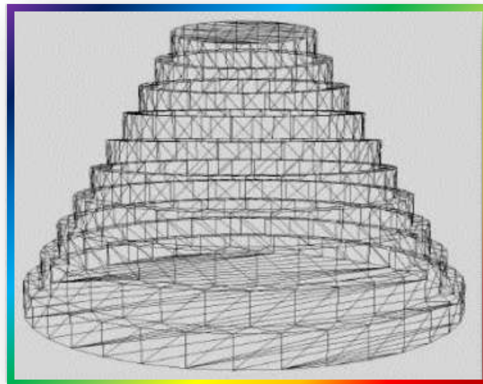
… in design layers
(DXF)

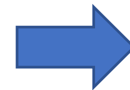




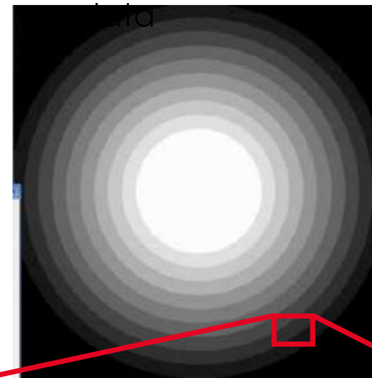
HEIDELBERG INSTRUMENTS

CAD data





Gray value



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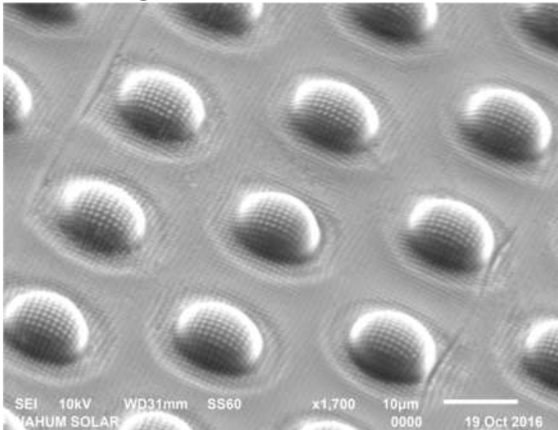
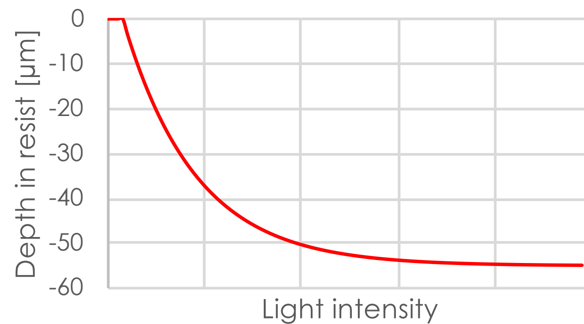
Challenges in grayscale lithography...

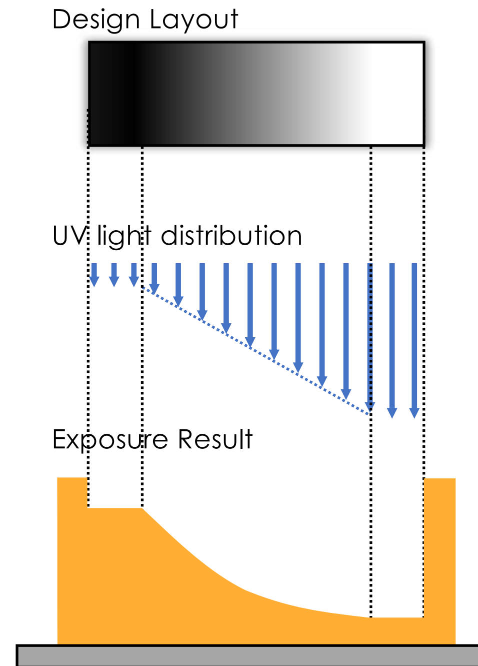
Stitching & other defects



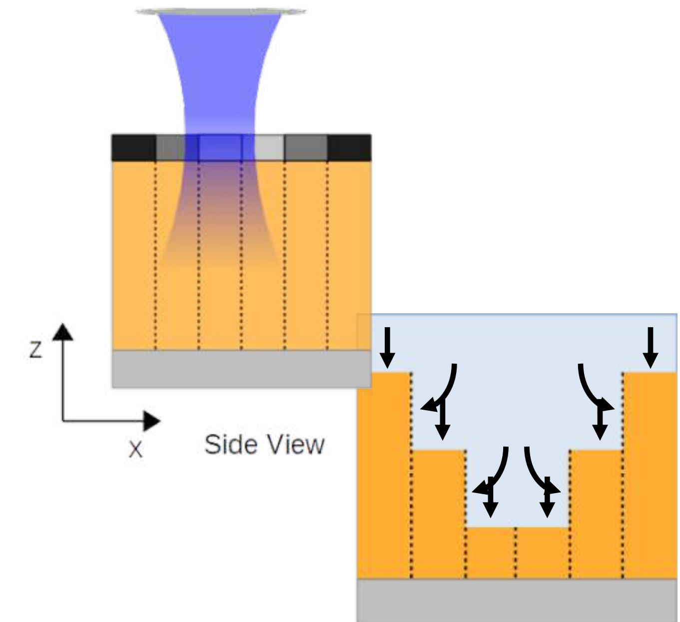
Maximum structure depth



Resist non-linearity



Proximity & process effects

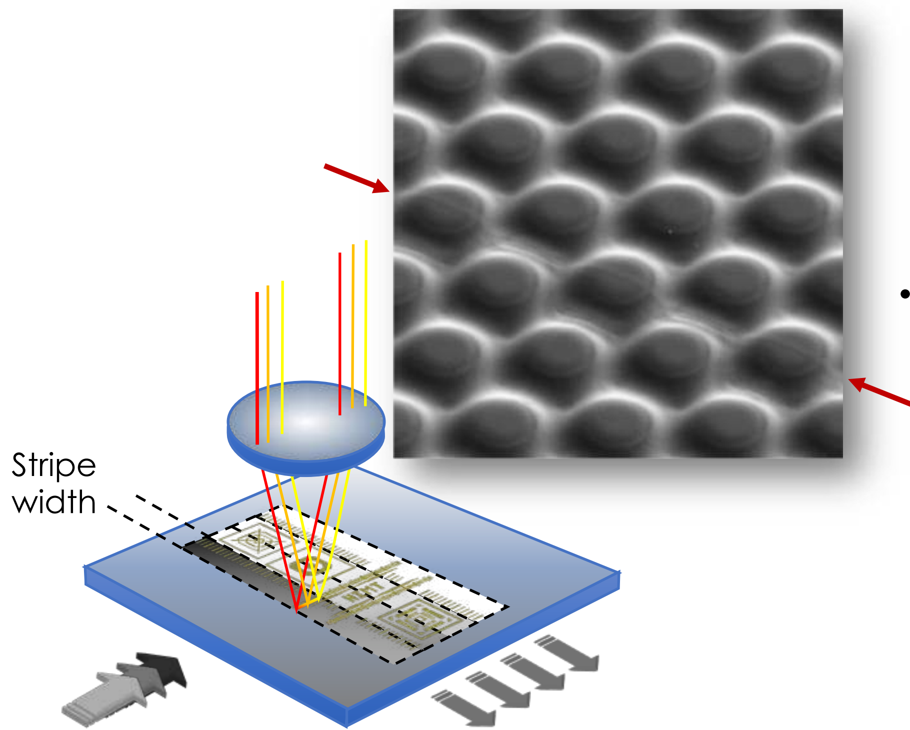


... and our solutions

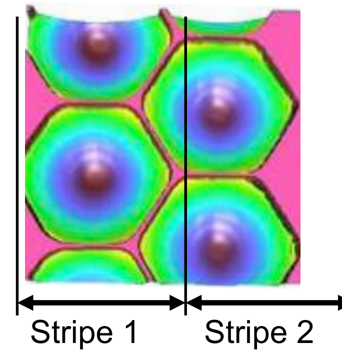
Stitching optimization

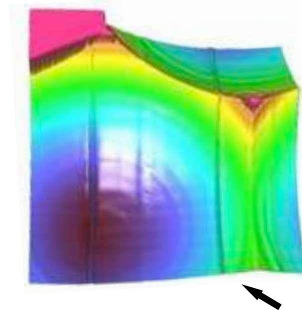
HEIDELBERG INSTRUMENTS

- Small intensity variations at the border between stripes
- Not visible in binary exposures

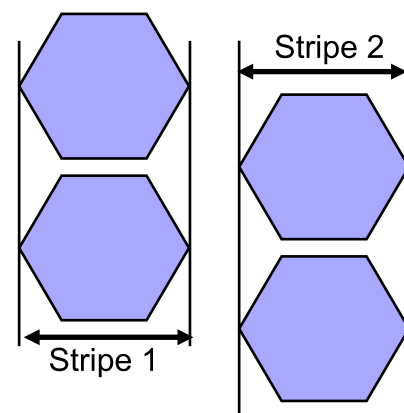


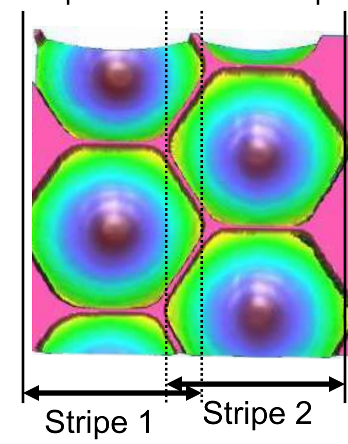
- Instead of spreading structures across multiple stripes…





- … place them inside a single stripe and optimize the stripe position

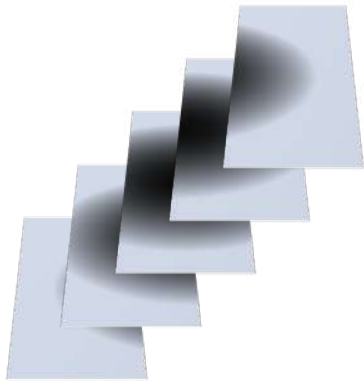




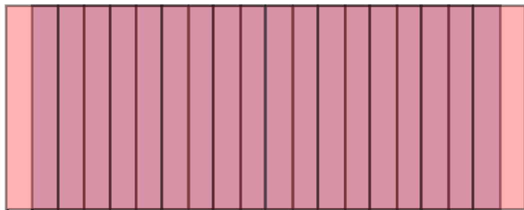
Stitching optimization

HEIDELBERG INSTRUMENTS

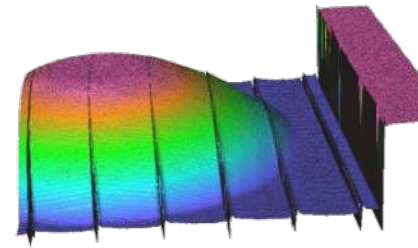
Idea: Smoothen stitching by averaging multiple exposures

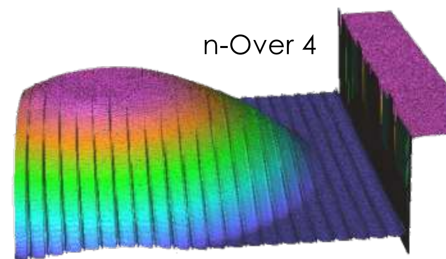


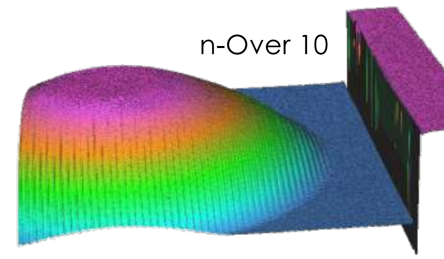
“n-Over:“ n-times overlapping

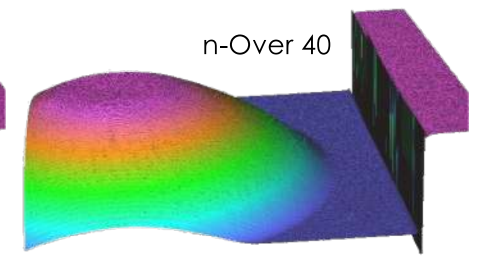


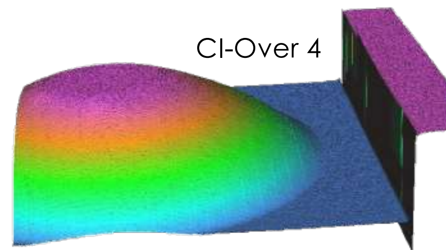
1/2 stripe width -> “n-Over 2“
Up to n-Over 40 possible

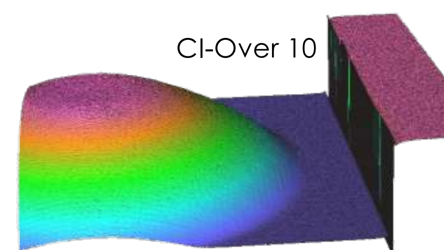


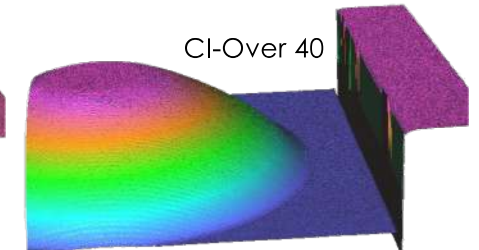






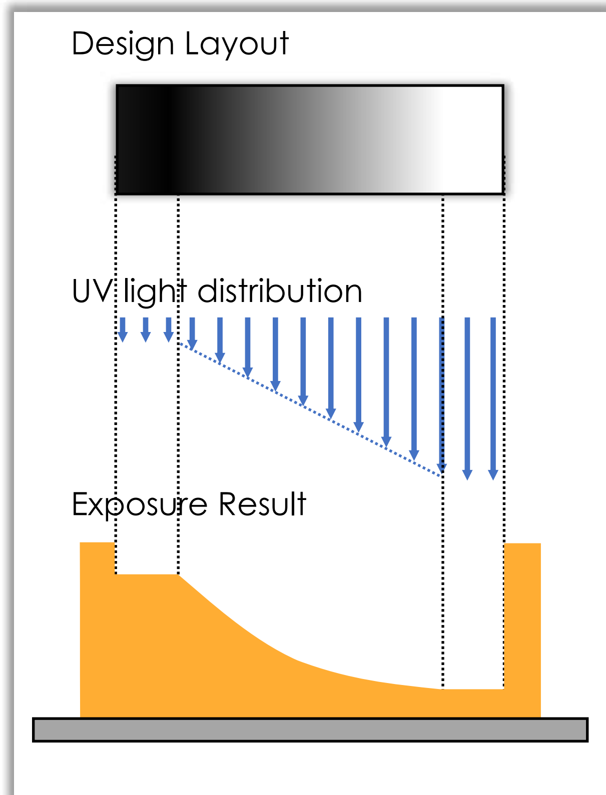


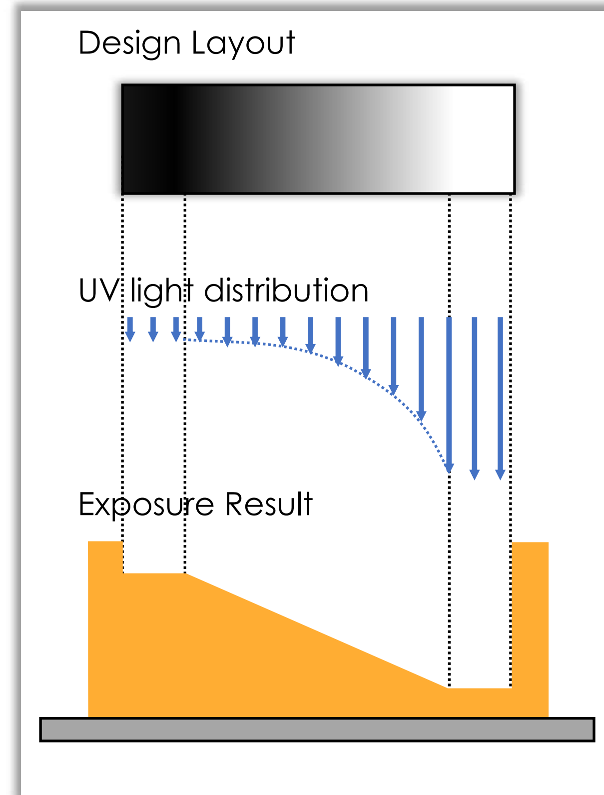




Non-linearity & proximity effects

HEIDELBERG INSTRUMENTS

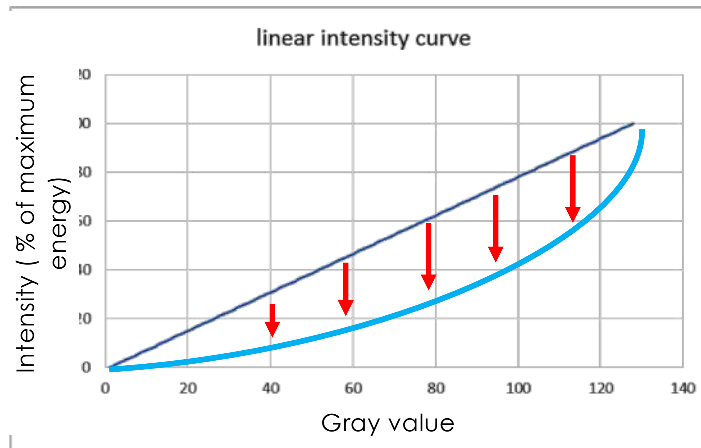


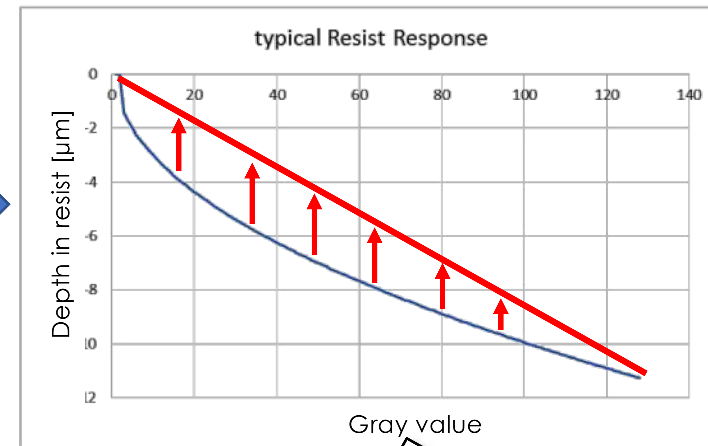


Creating linear topographies usually requires a non-linear light intensity distribution

Shape Optimization: Linearization

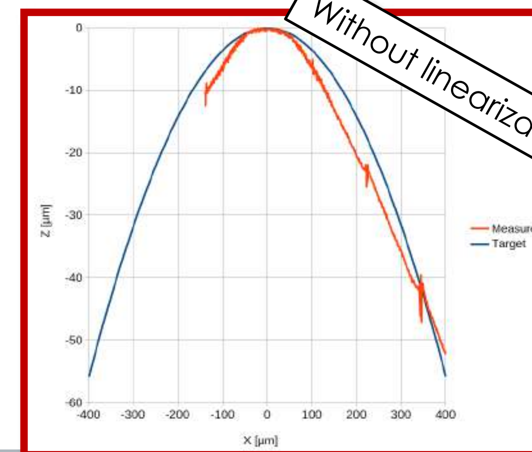
HEIDELBERG INSTRUMENTS





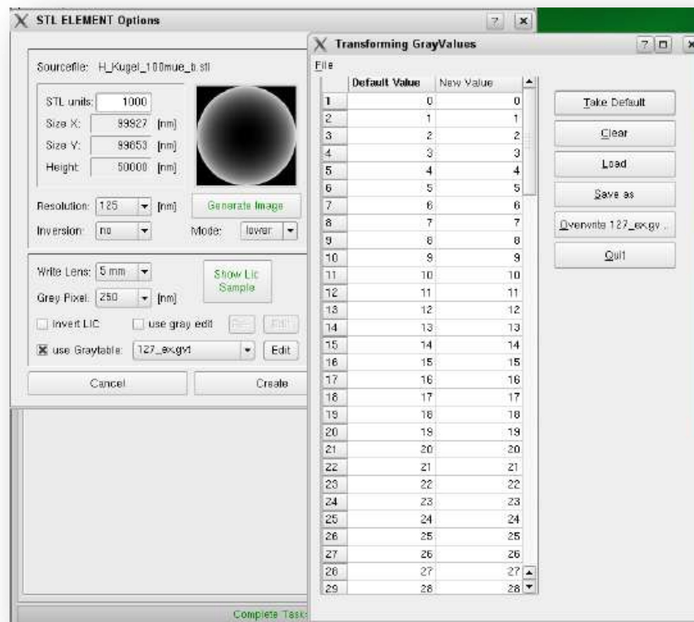
- Resist does not respond linearly
  - Minimum energy needed for photoreaction
  - Exposure proximity effect
  - Lateral development effect

→ Geometry dependent



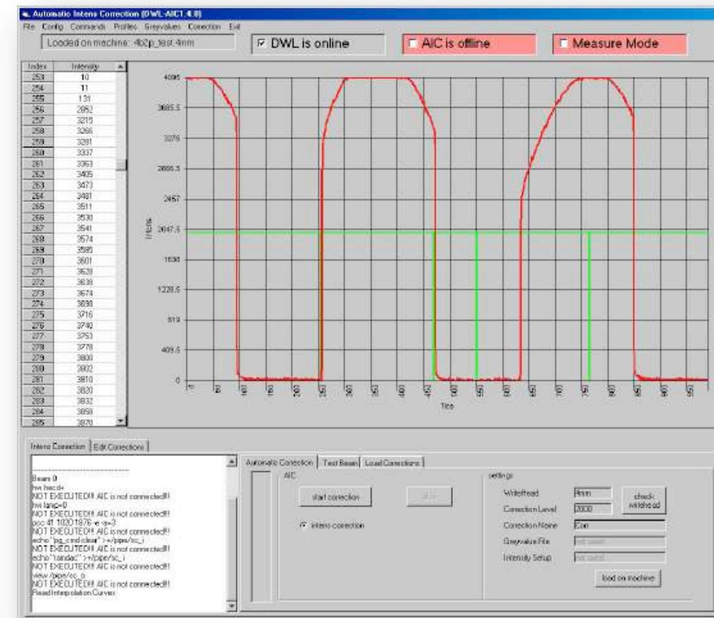
GRAY SCALE OPTIMIZATION METHODS

Gray Value Table (GVT)



- Maps design gray value to customized gray value
- Transformation at conversion level
- Decrease of gray level resolution

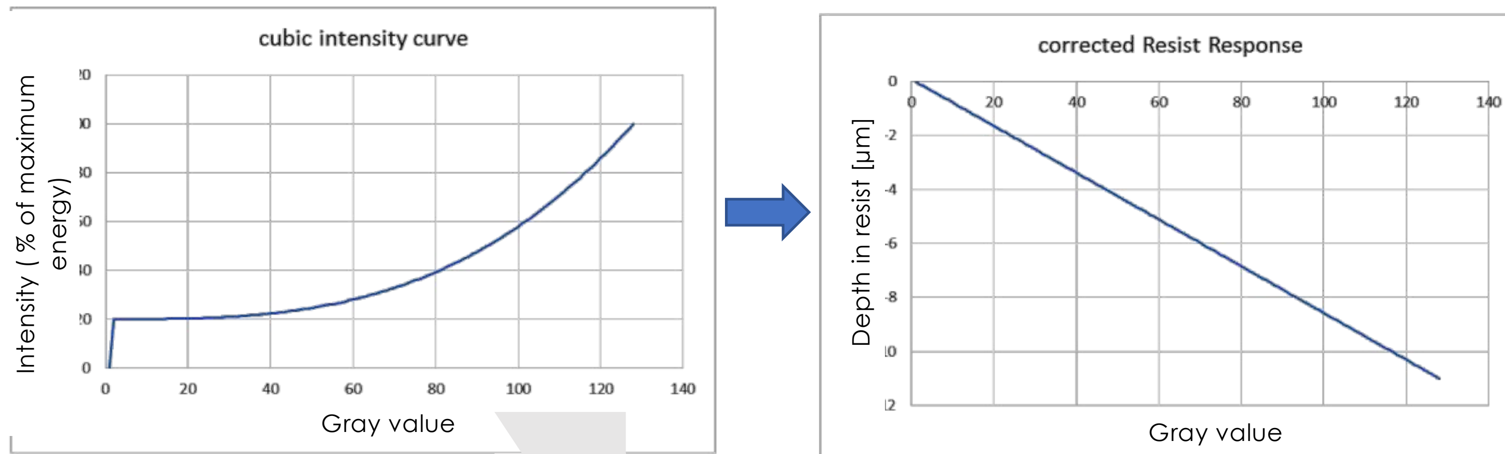
Automatic Intensity Correction(AIC)



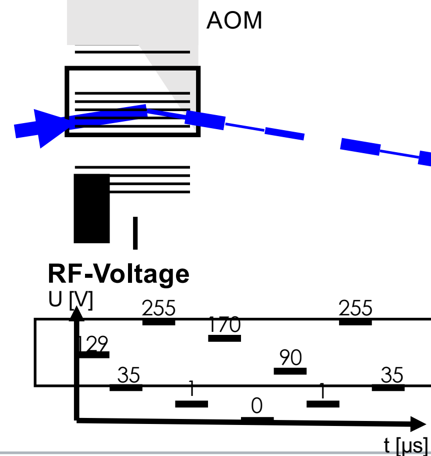
- Assigns design gray value to energy level
- Transformation at exposure level
- Keeps gray level resolution

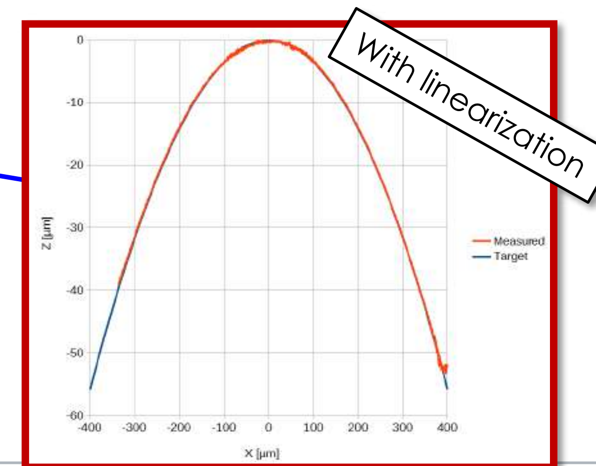
Shape Optimization: Linearization

HEIDELBERG INSTRUMENTS



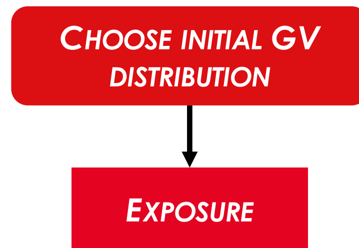
- Use of a non-linear relation between GV and energy:
  - One of 65000 energy levels can be assigned to each grayvalue

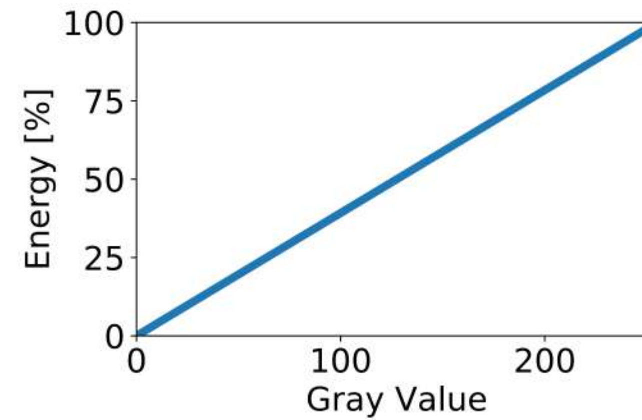




Non-linearity & proximity effects
GVD approach

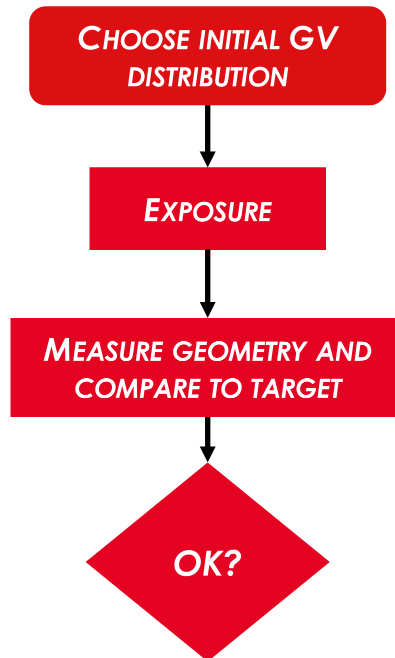
HEIDELBERG INSTRUMENTS

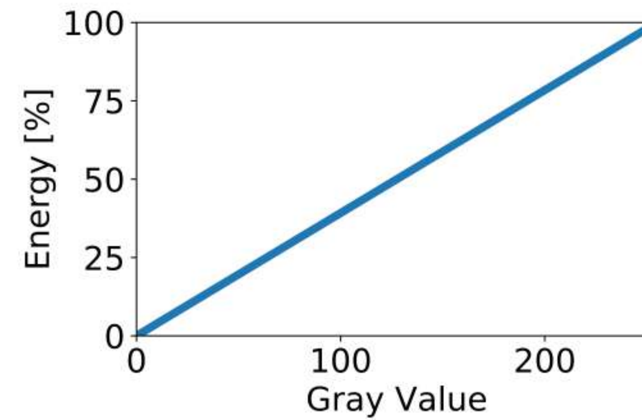


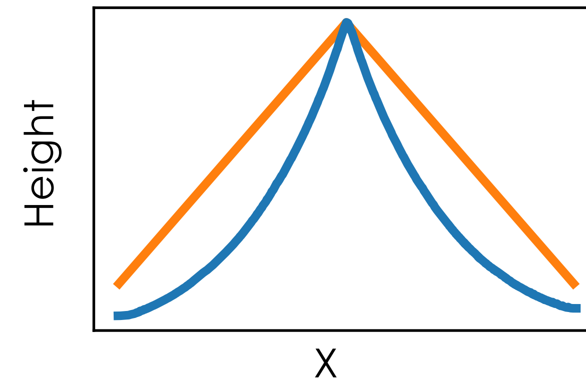


Non-linearity & proximity effects GVD approach

HEIDELBERG INSTRUMENTS

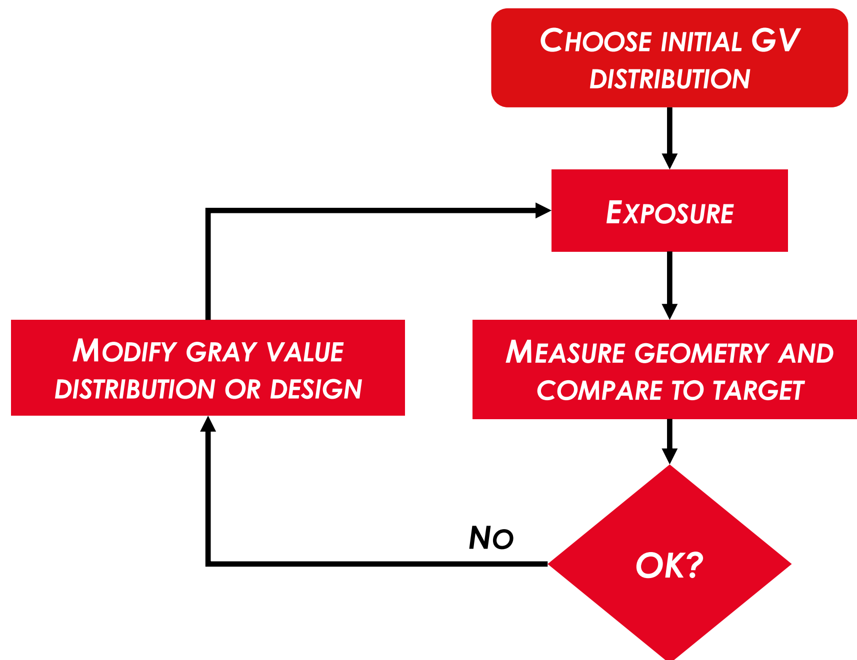


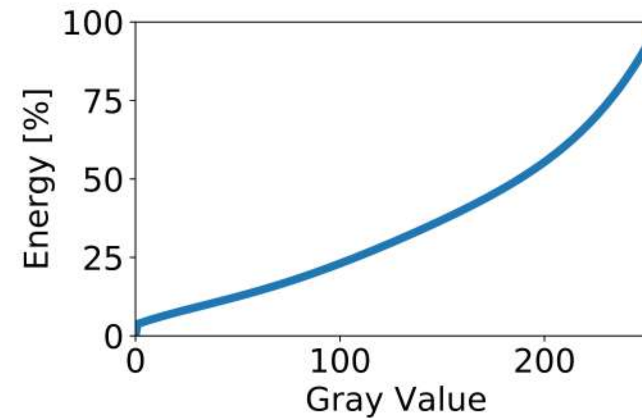


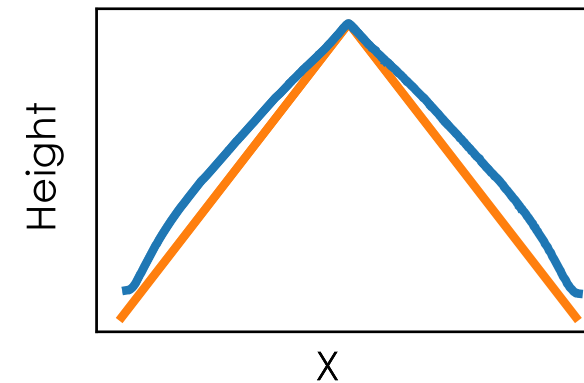


Non-linearity & proximity effects GVD approach

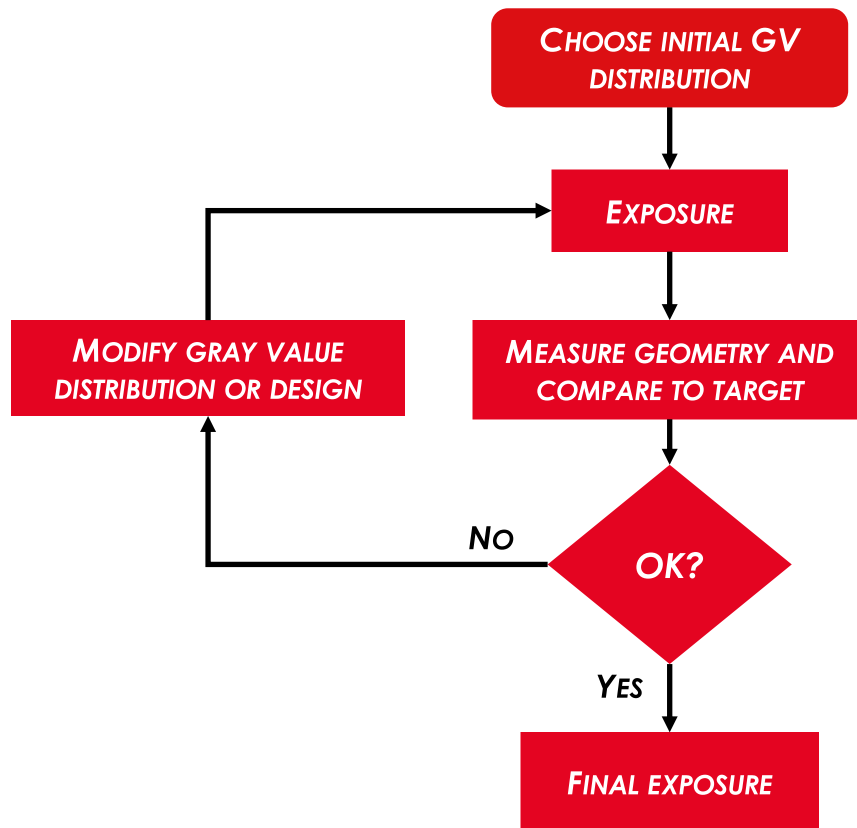
HEIDELBERG INSTRUMENTS

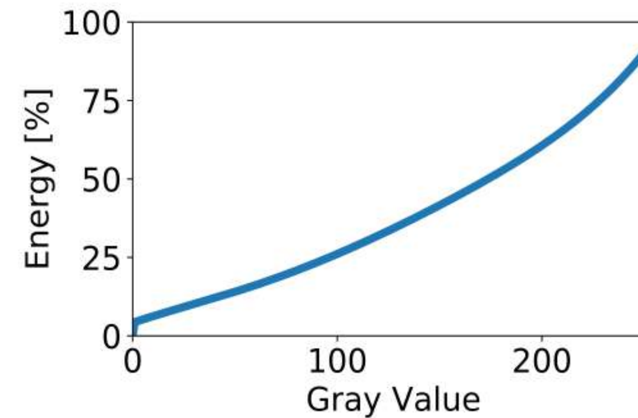


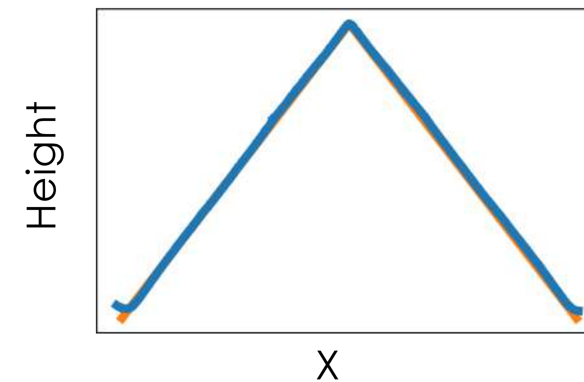




Non-linearity & proximity effects GVD approach

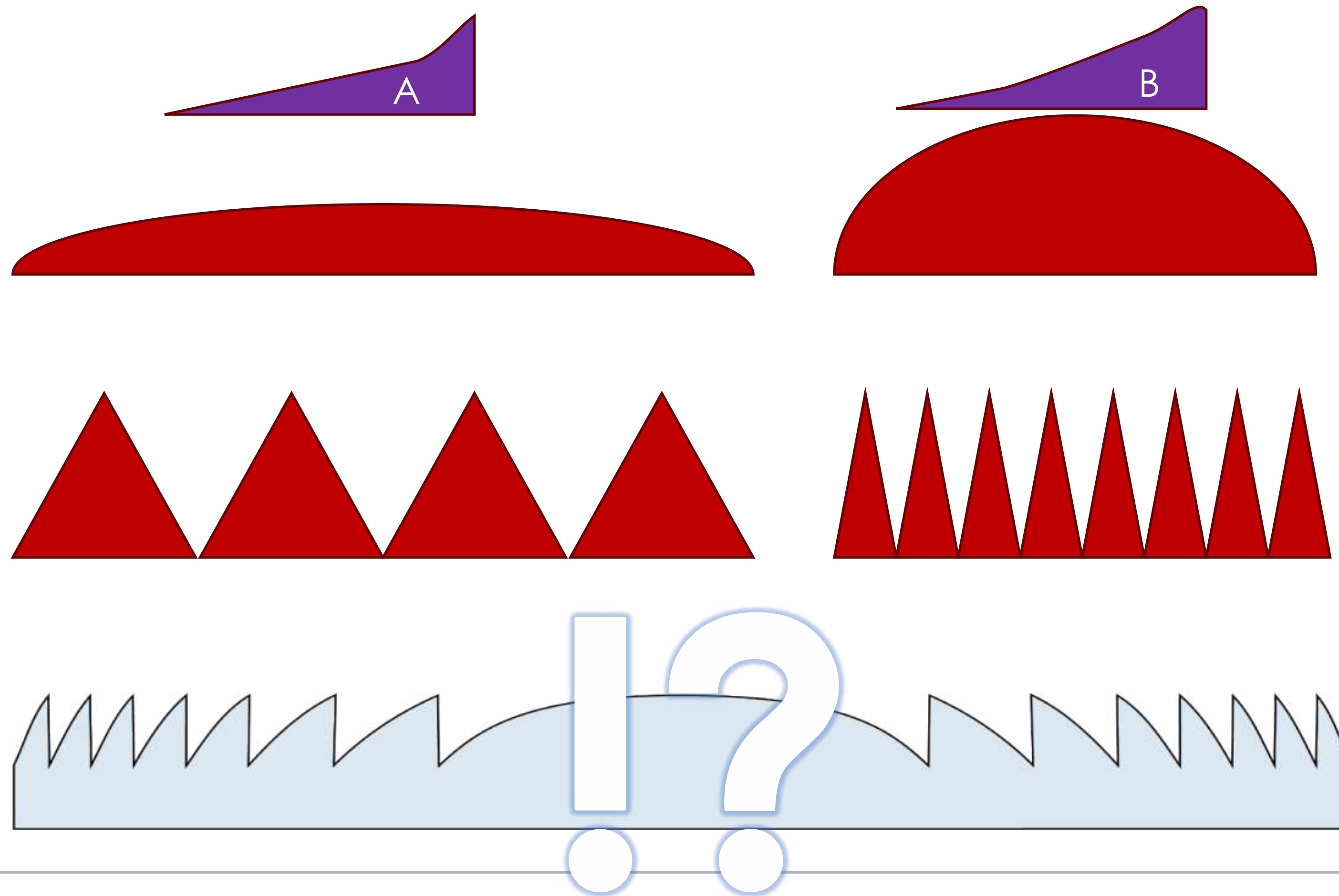






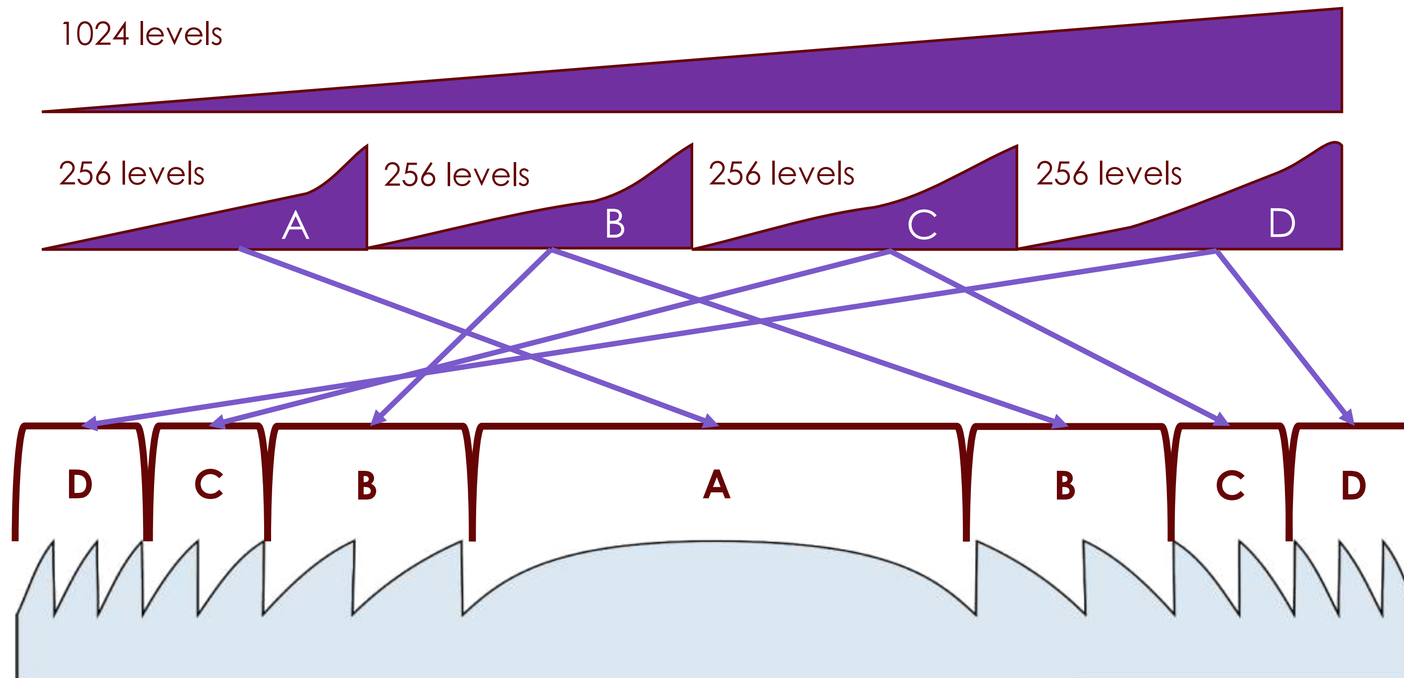
HEIDELBERG INSTRUMENTS

Why we need 1024 Grey Levels

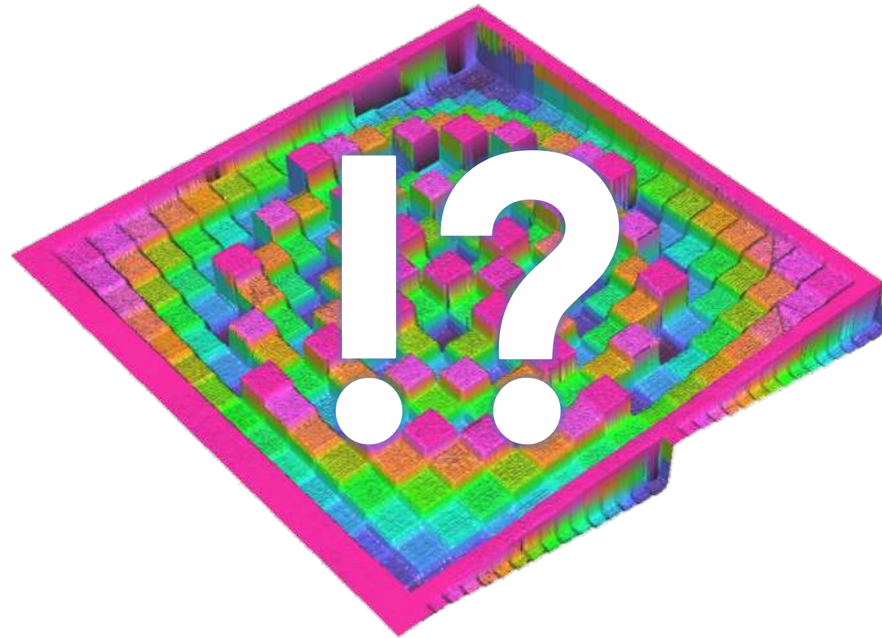


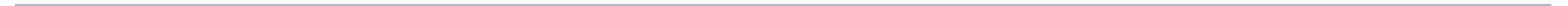
Why we need 1024 Grey Levels

HEIDELBERG INSTRUMENTS



!



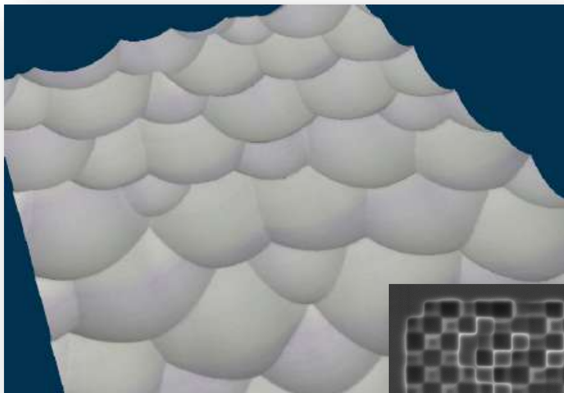


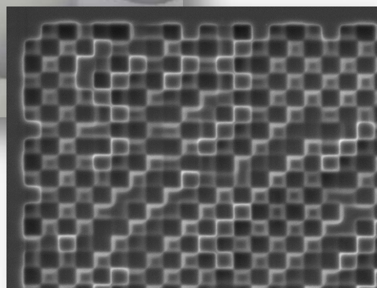
Non-linearity & proximity effects GVD approach

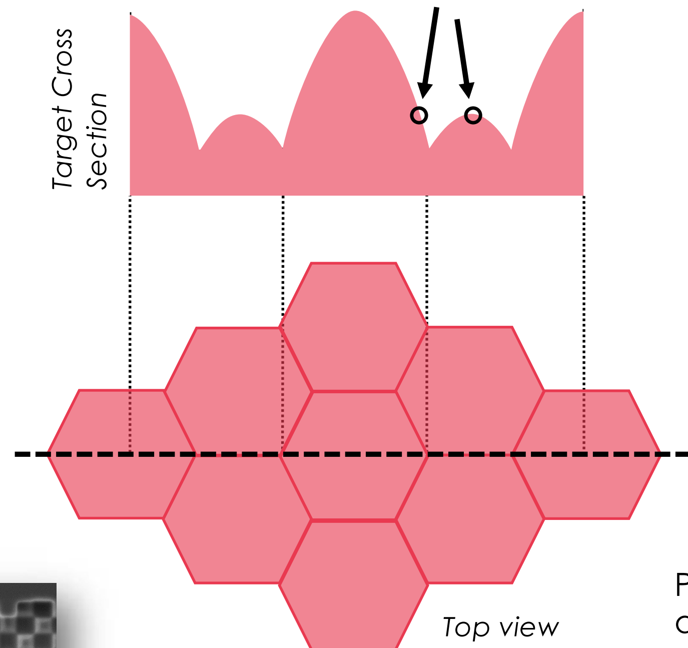
HEIDELBERG INSTRUMENTS

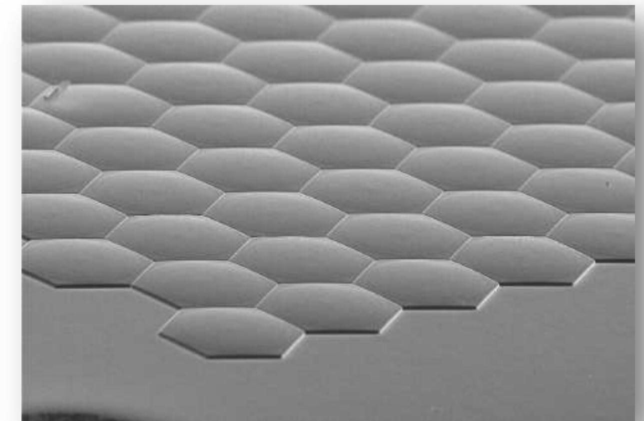
Works quite well, but...

- ... can be very time consuming
- ... requires compromises
- ... fails for irregular designs


Courtesy of IGI






Hexagonal microlens array

Positions with same theoretical depth, but different local environment

⇒ Same dose assignment leads to different resulting depth!

Non-linearity & proximity effects
BEAMER 3D-PEC

Layer Properties

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

Pattern data
gds, dxf, png, oasis, bmp

Tool
Spot size, gray values

Process
Resist data, contrast curve

BEAMER
3D-PEC

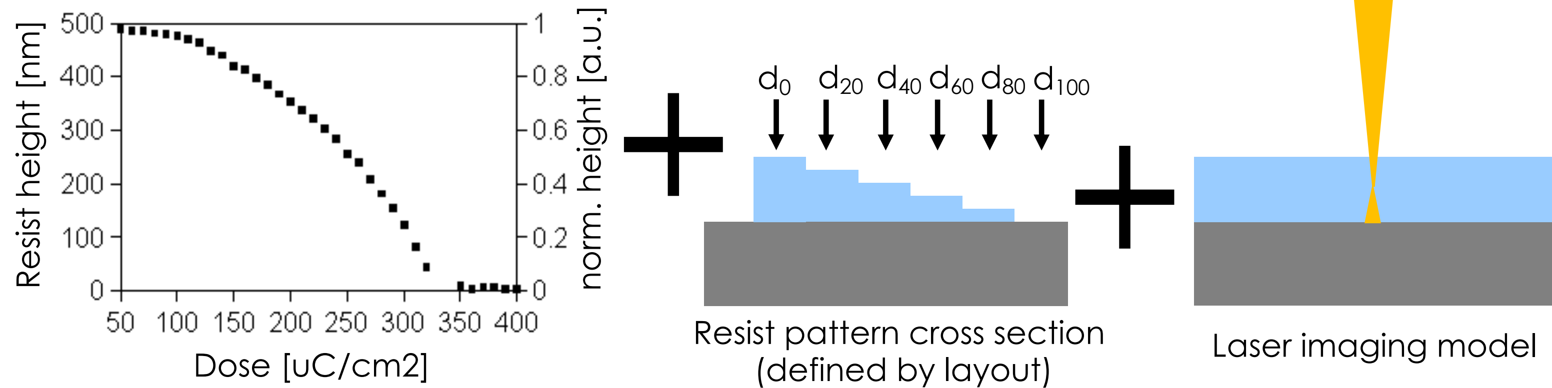
Exposure pattern
png, bmp, HIMT

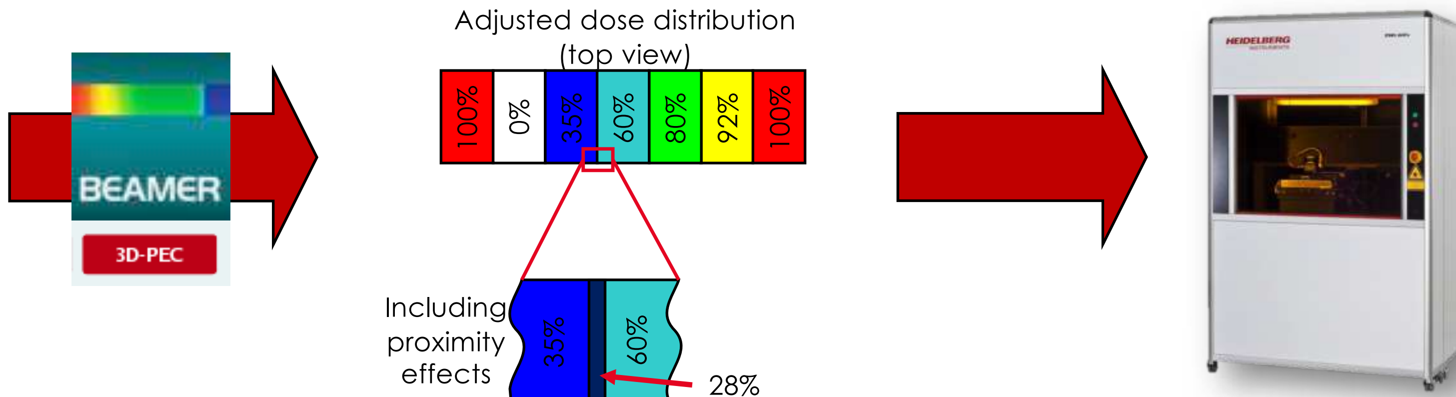
z
x
Side View

Remaining Resist Height [µm]
0 2 4 6 8 10
0 50 100 150 200 250
Gray Value

Shape Optimization: Genisys Beamer 3D PEC

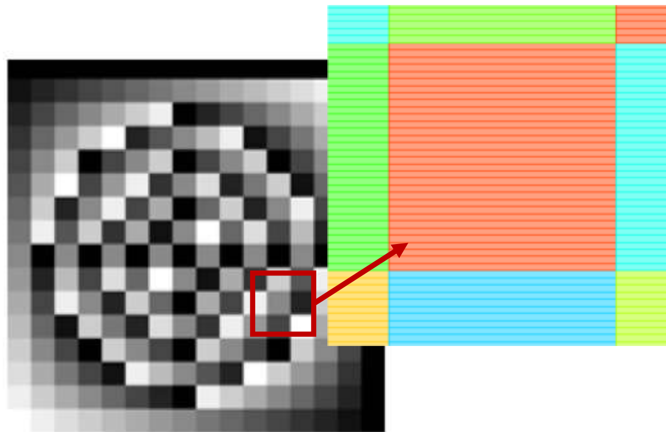
Process chain for multilevel resist pattern

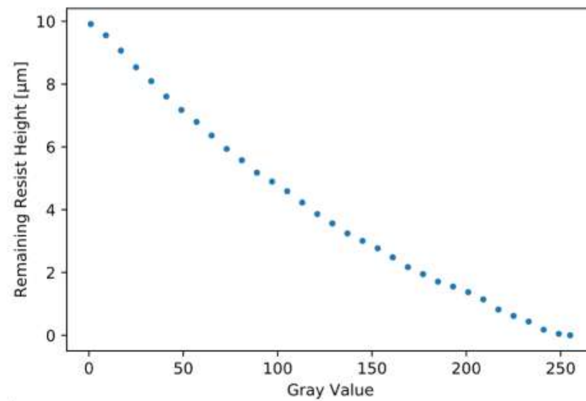


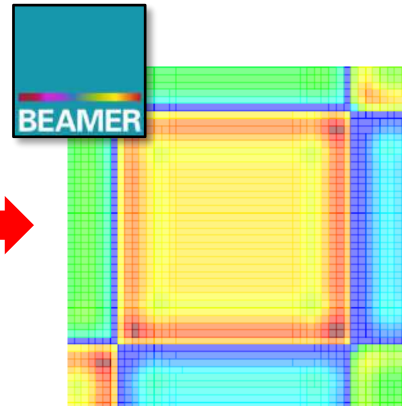


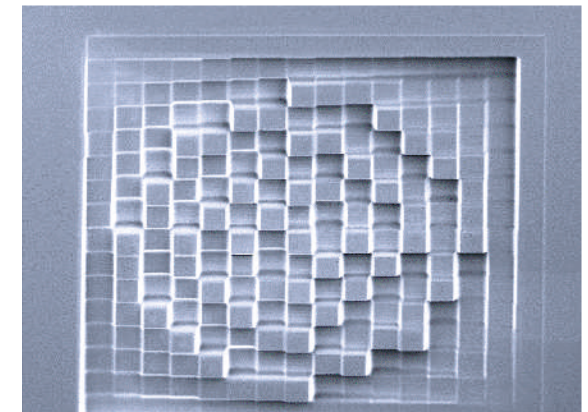
Non-linearity & proximity effects
BEAMER 3D-PEC

Example: DOE



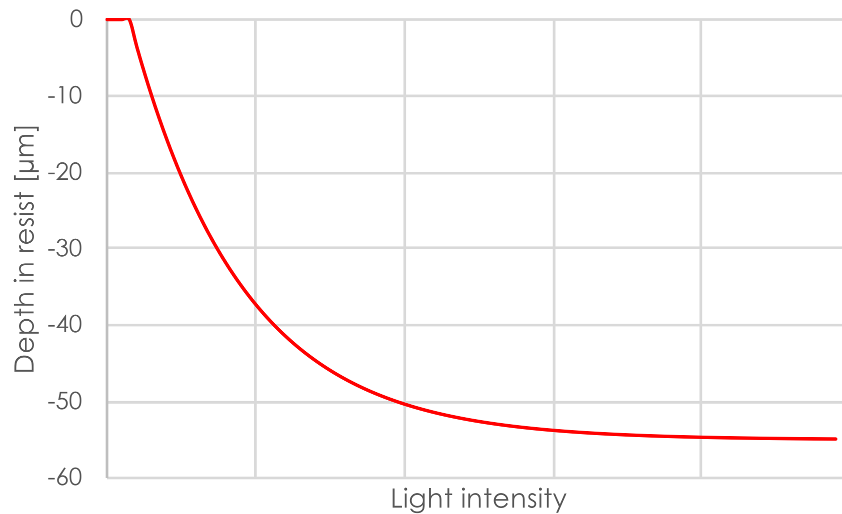




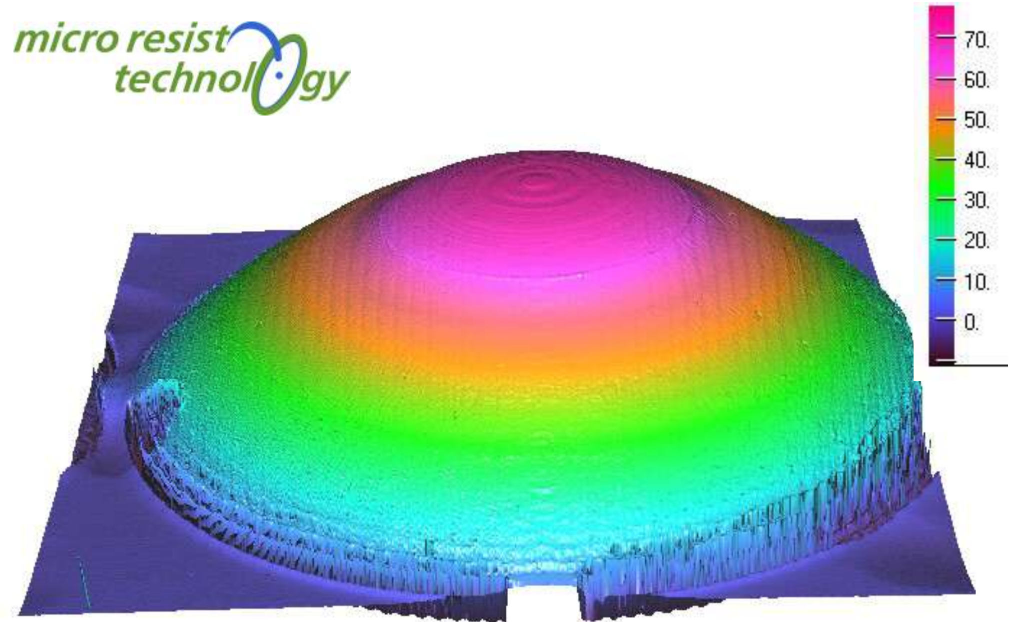


Maximum structure depth

So far: Limited to ~ 55 µm due to high absorption in upper resist layers

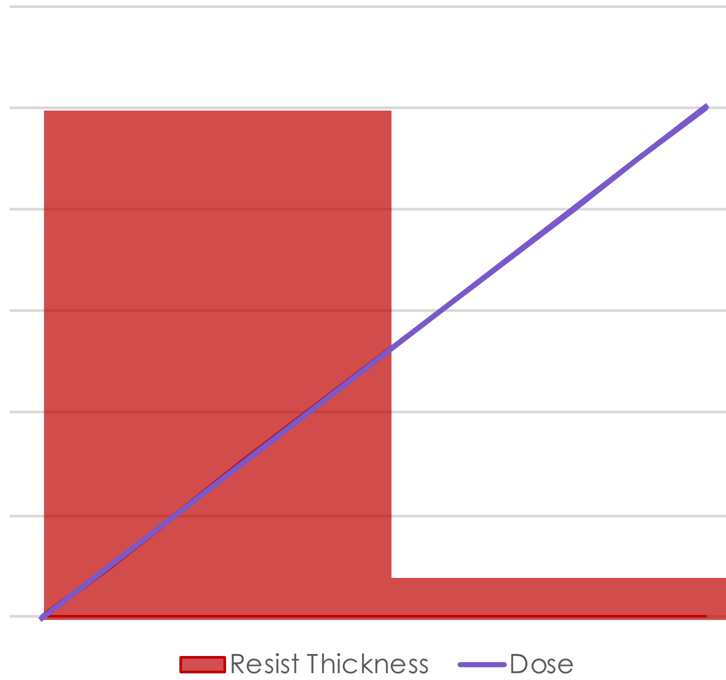


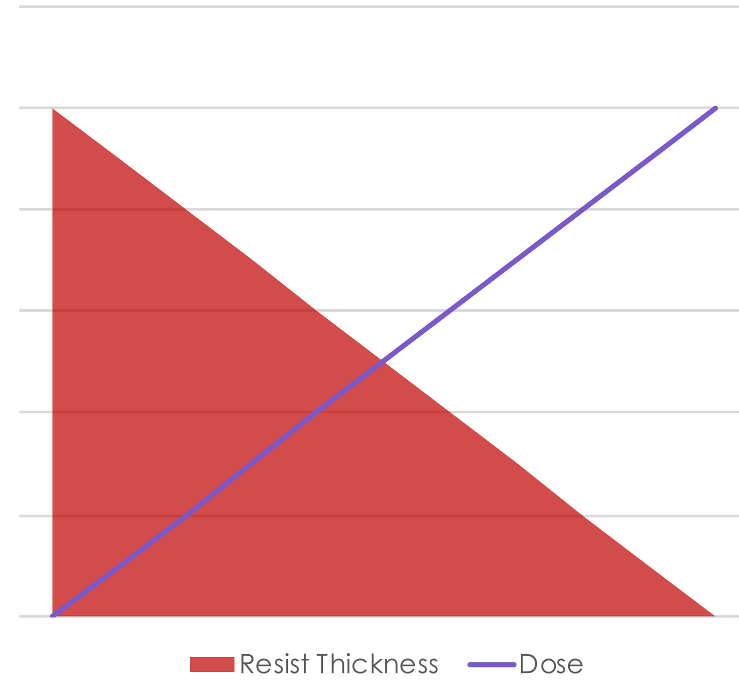
Now: Novel grayscale resist ma-P 1200 G



RESIST

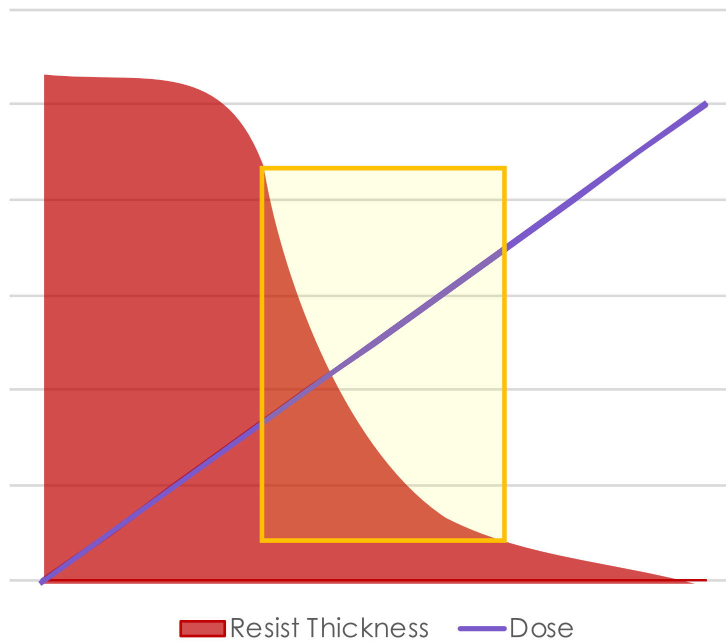
HEIDELBERG INSTRUMENTS

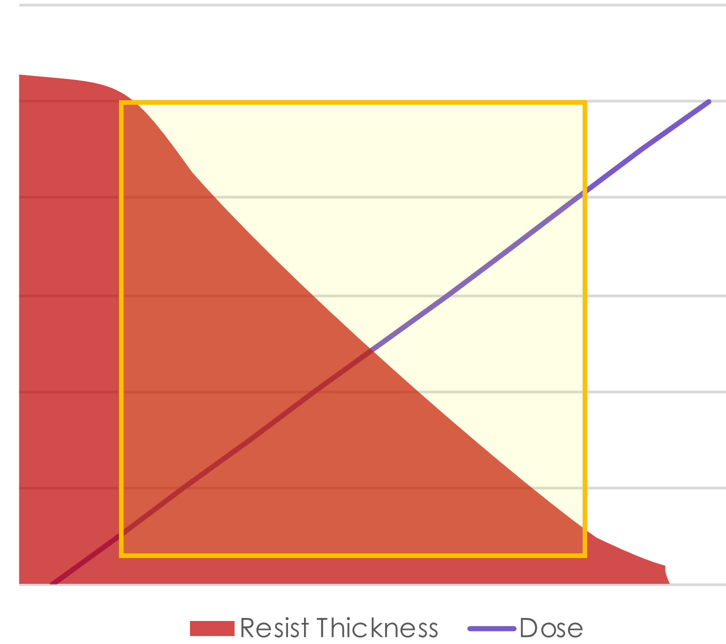




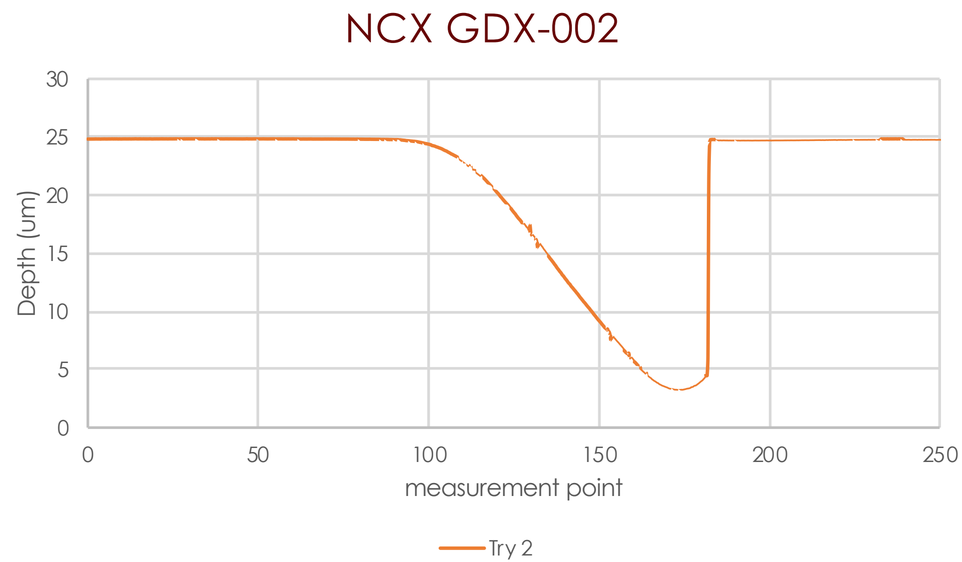
RESIST

HEIDELBERG INSTRUMENTS





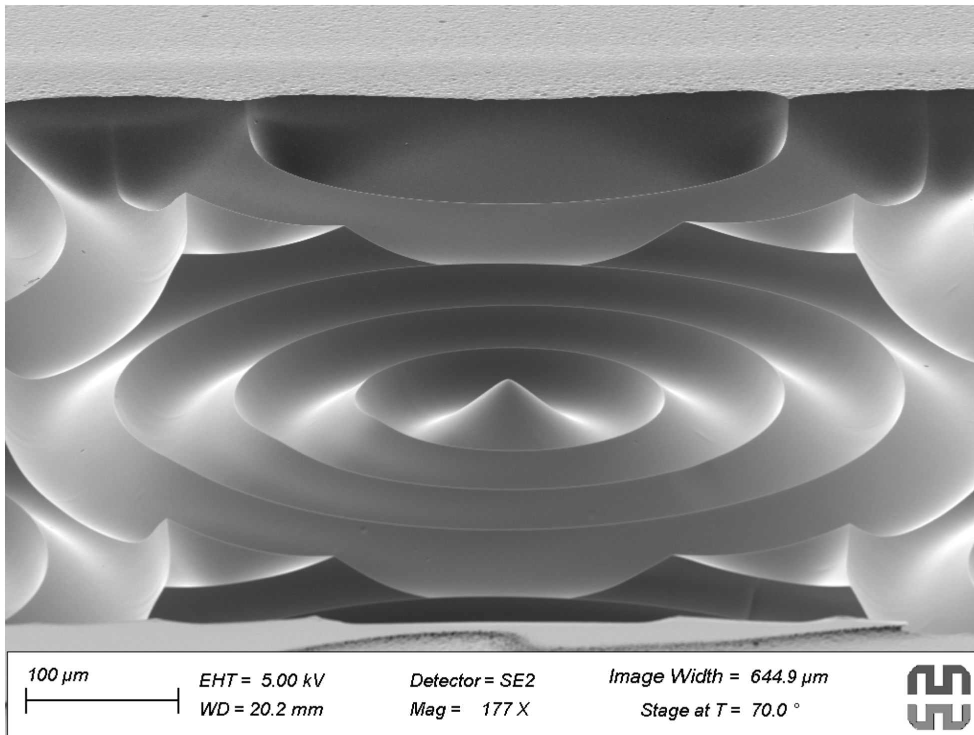
HEIDELBERG INSTRUMENTS

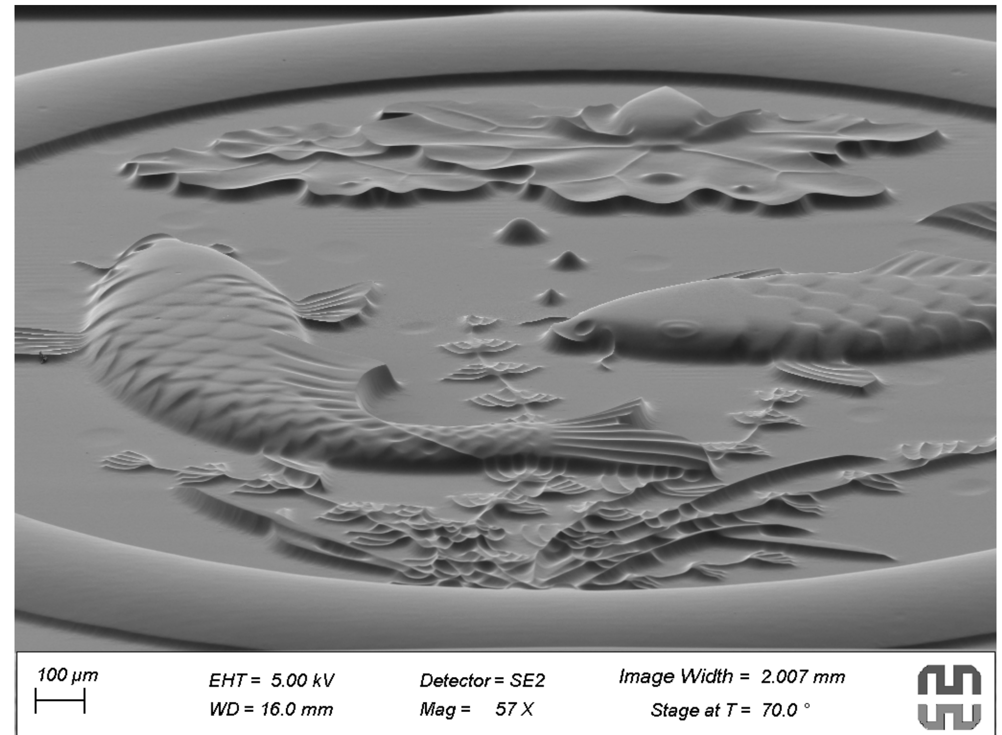


MATERIAL IS IMPORTANT!

Maximum structure depth

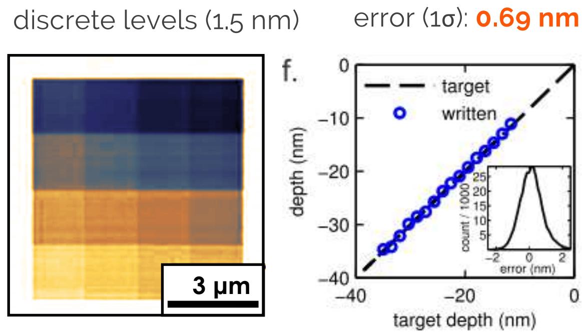
Very recent results:





Heidelberg Instruments Nano (SwissLitho AG)

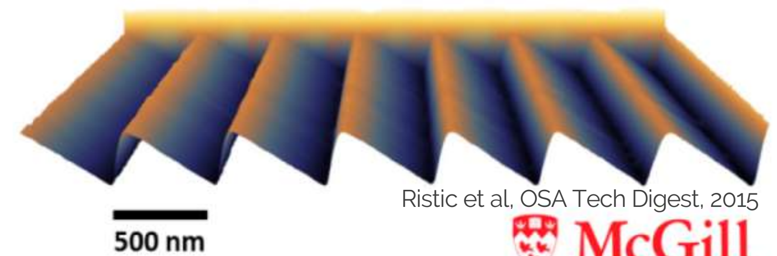
discrete levels (1.5 nm)   error (1σ): **0.69 nm**



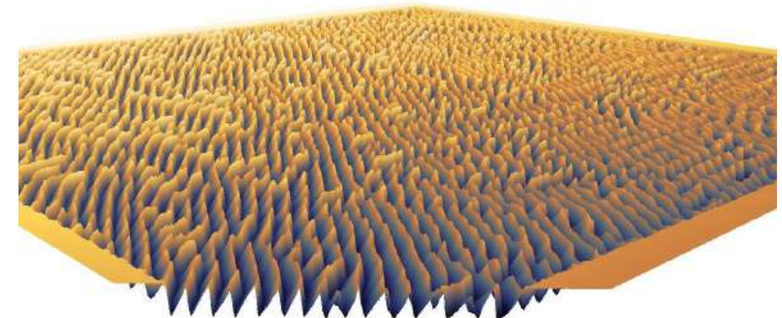
Rawlings et al, Sci. Rep., 2017

NanoFrazor Explore

NanoFrazor Scholar



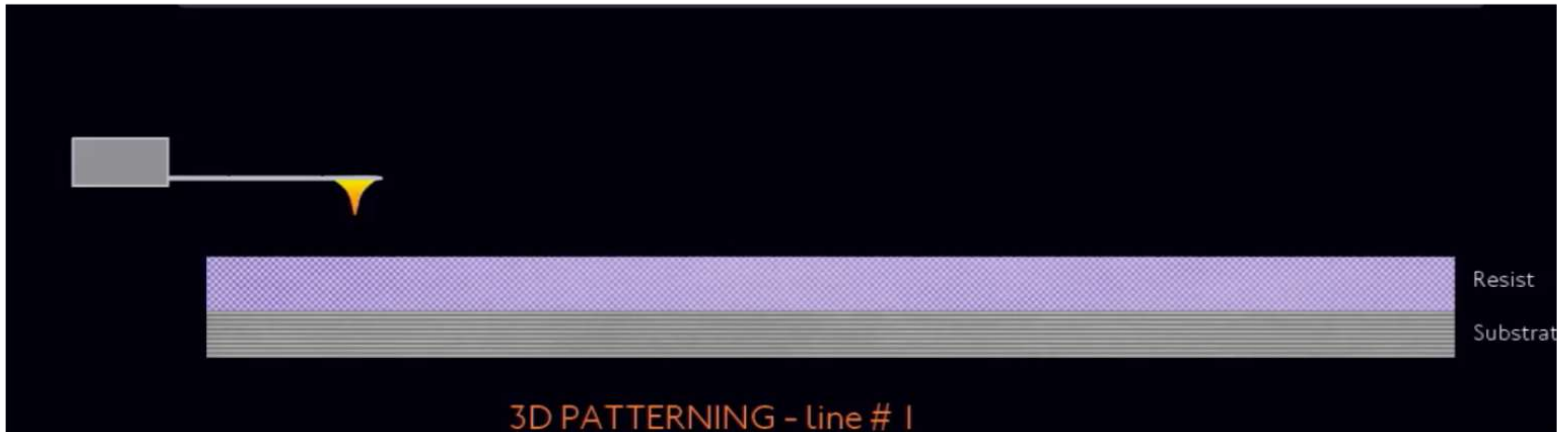
Ristic et al, OSA Tech Digest, 2015



Kulmala et al, SPIE Adv. Litho., 2018

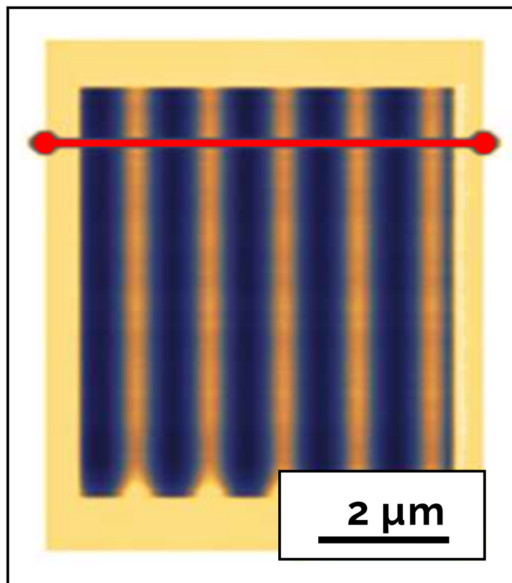
Heidelberg Instruments Nano (SwissLitho AG)

Thermal Scanning Probe Lithography

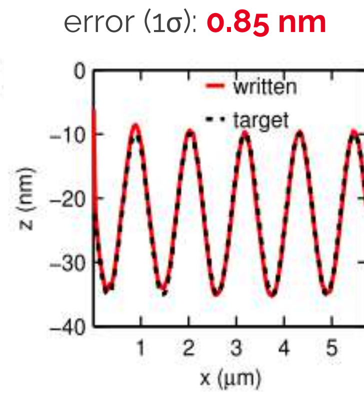


3D patterning with vertical resolution < 1 nm

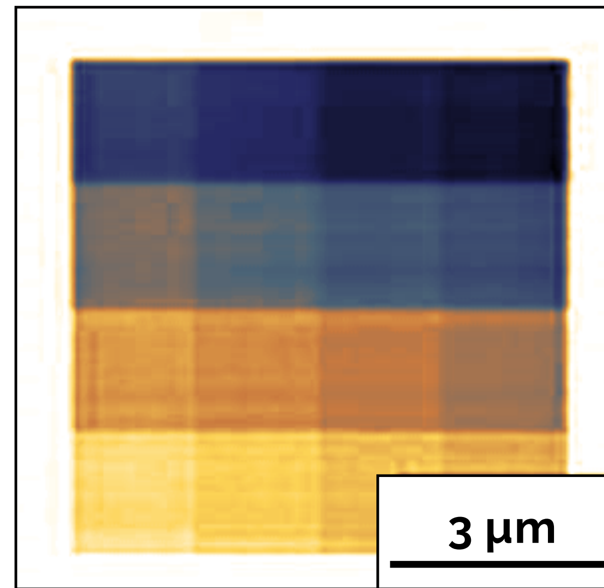
continous sine wave



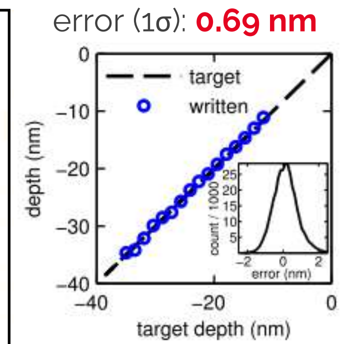
error (1σ): **0.85 nm**



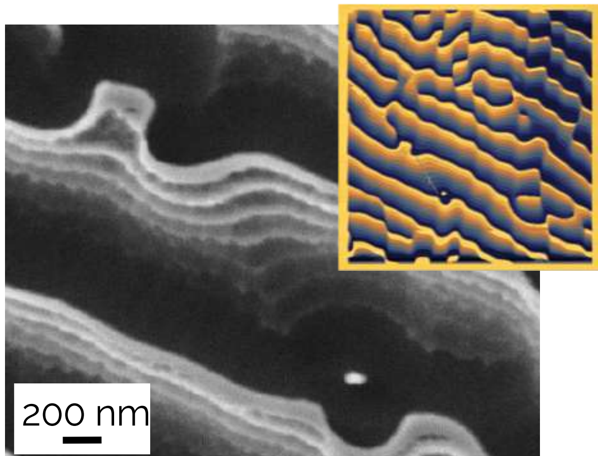
discrete levels (1.5 nm)



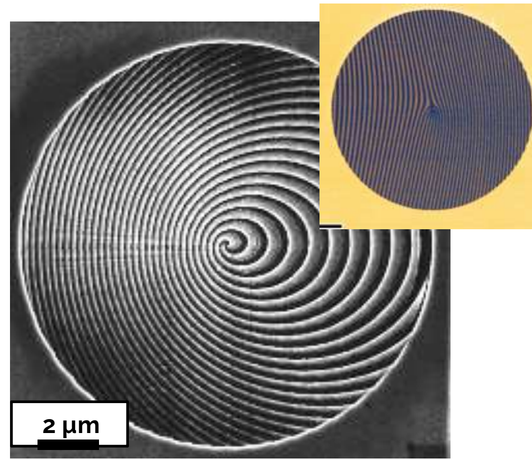
error (1σ): **0.69 nm**



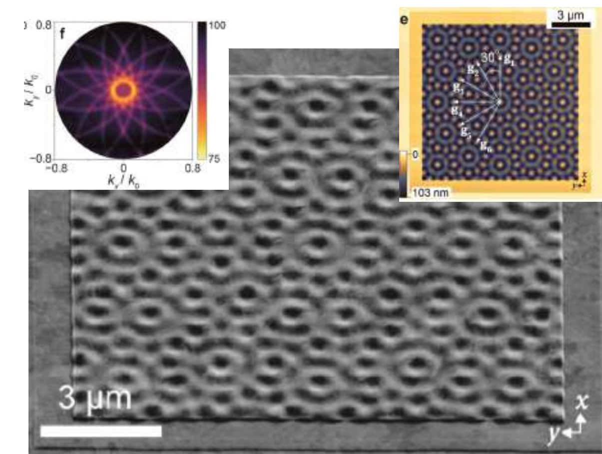
Published examples for 3D grayscale



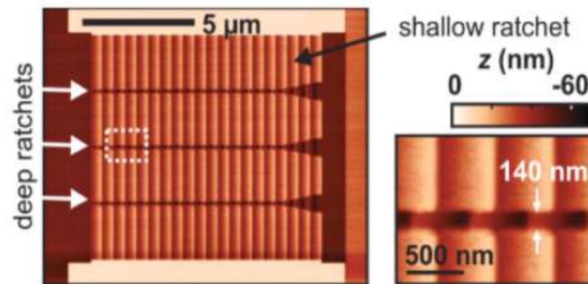
Hologram in Si (700 nm deep)
Kulmala *et al.*, SPIE, 2018



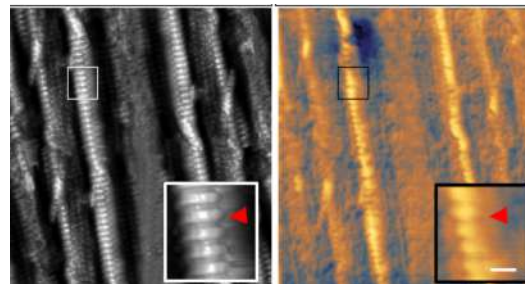
Phase Plates in SiN membranes
Hettler *et al.*, Micron, 2019



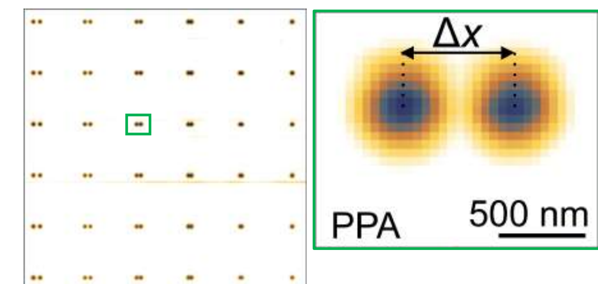
Optical Fourier Surfaces
Lassaline *et al.*, submitted to Nature, 2020



Nanofluidic Brownian Motors
Skaug *et al.*, **Science**, 2018



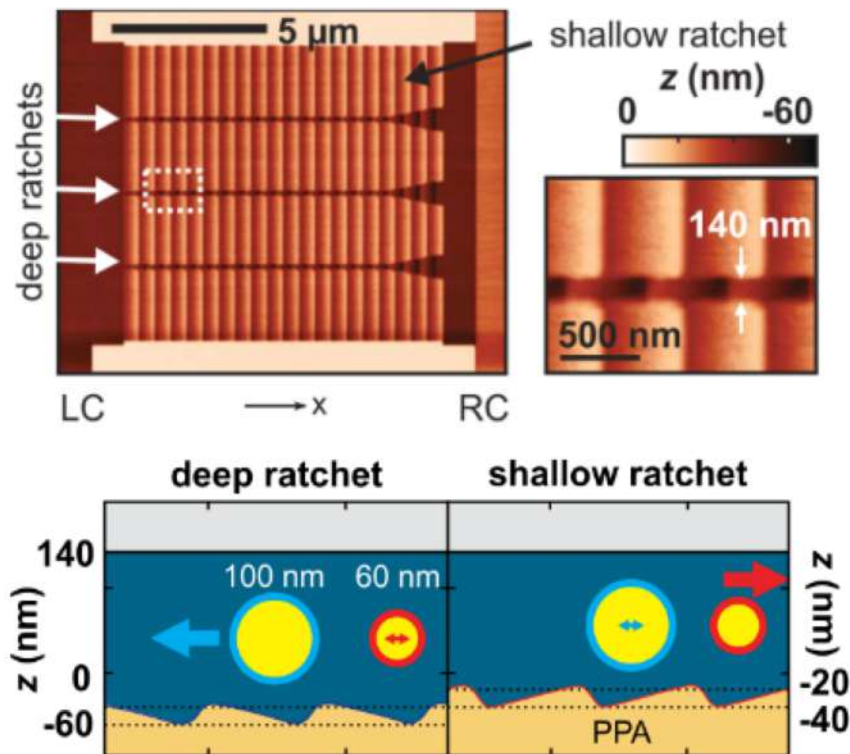
Topographies for stem cells
Tang *et al.*, ACS Appl. Mat., 2019



Photonic molecules
Rawlings et al., Scientific Reports, 2017

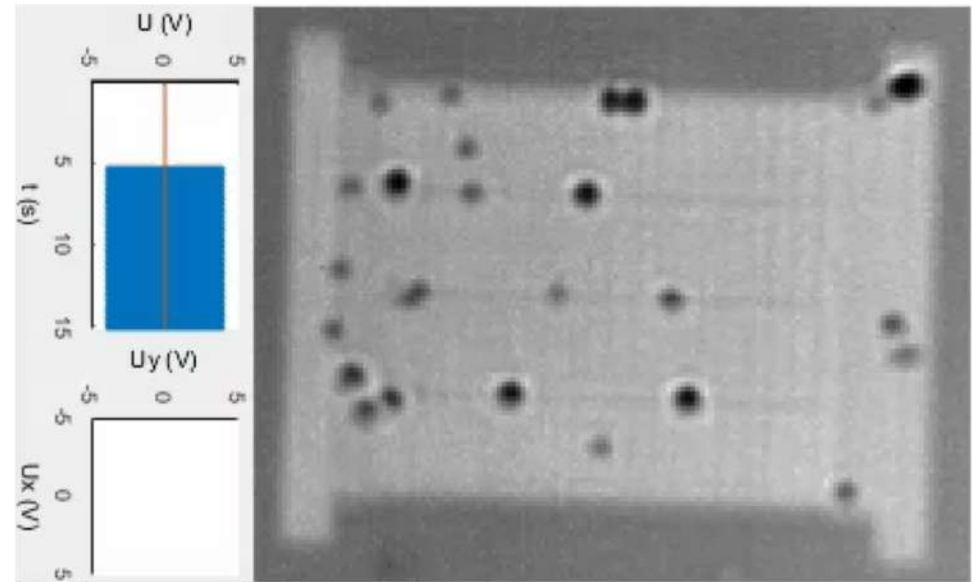
3D Nanofluidics

» Ratchets with nm accuracy



» Nanoparticles sorting using Brownian Motors

» Particles with 1 nm size difference move in opposite directions



Skaug *et al.*, **Science**, 2018

Thank you for
your attention!

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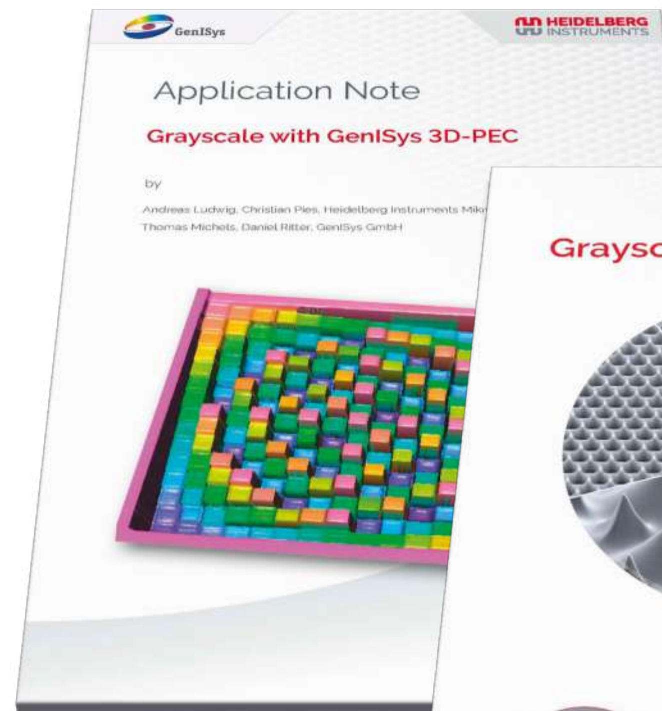
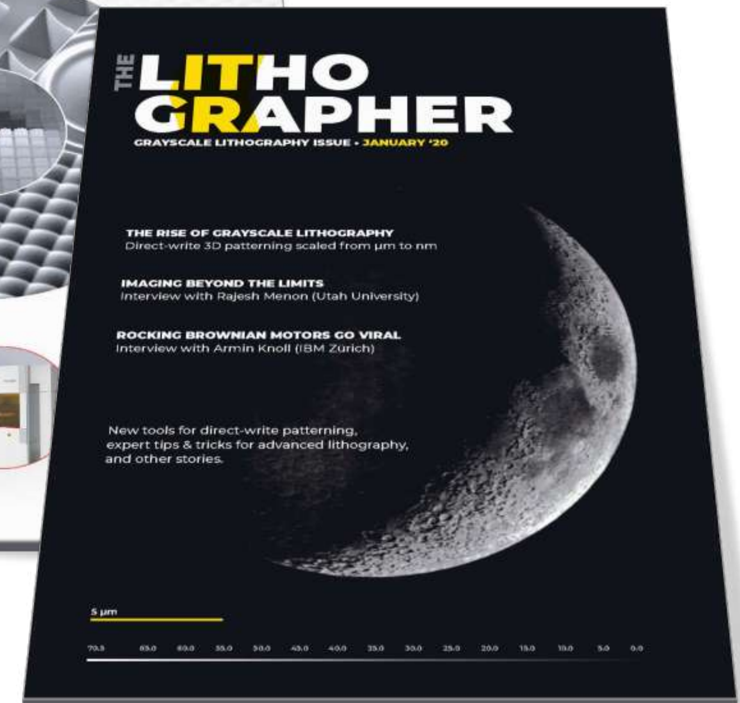
Phone +49 6221 3430-0
www.himt.de
www.thelithographer.com





The power of direct writing