Lithography 1: General concepts

I. Introduction to lithography

Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

Lithography

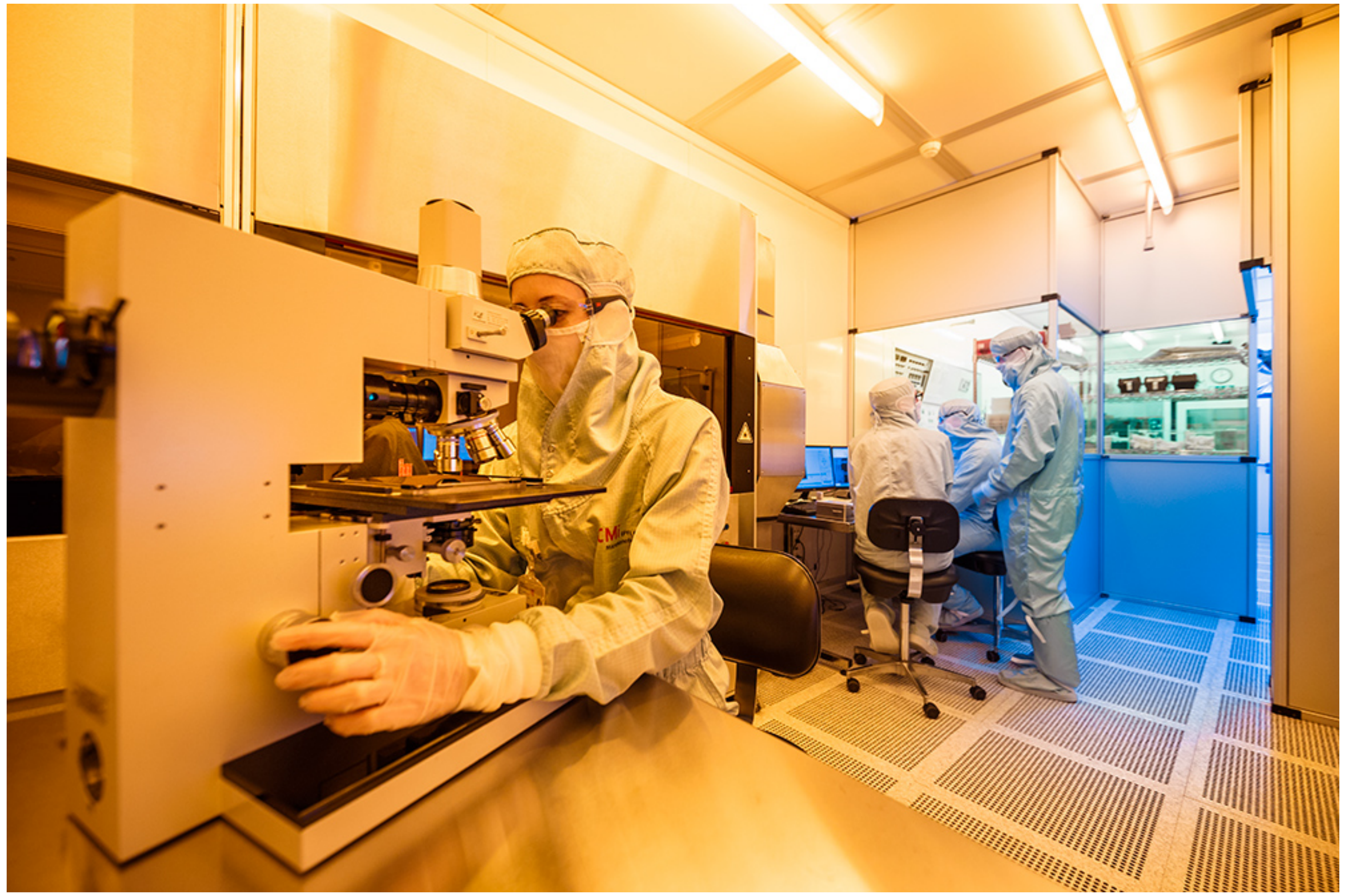
- General concepts
- Mask writing and Direct Write Laser
- UV lithography
- Electron Beam Lithography (EBL)
- Alternative lithographies

General concepts

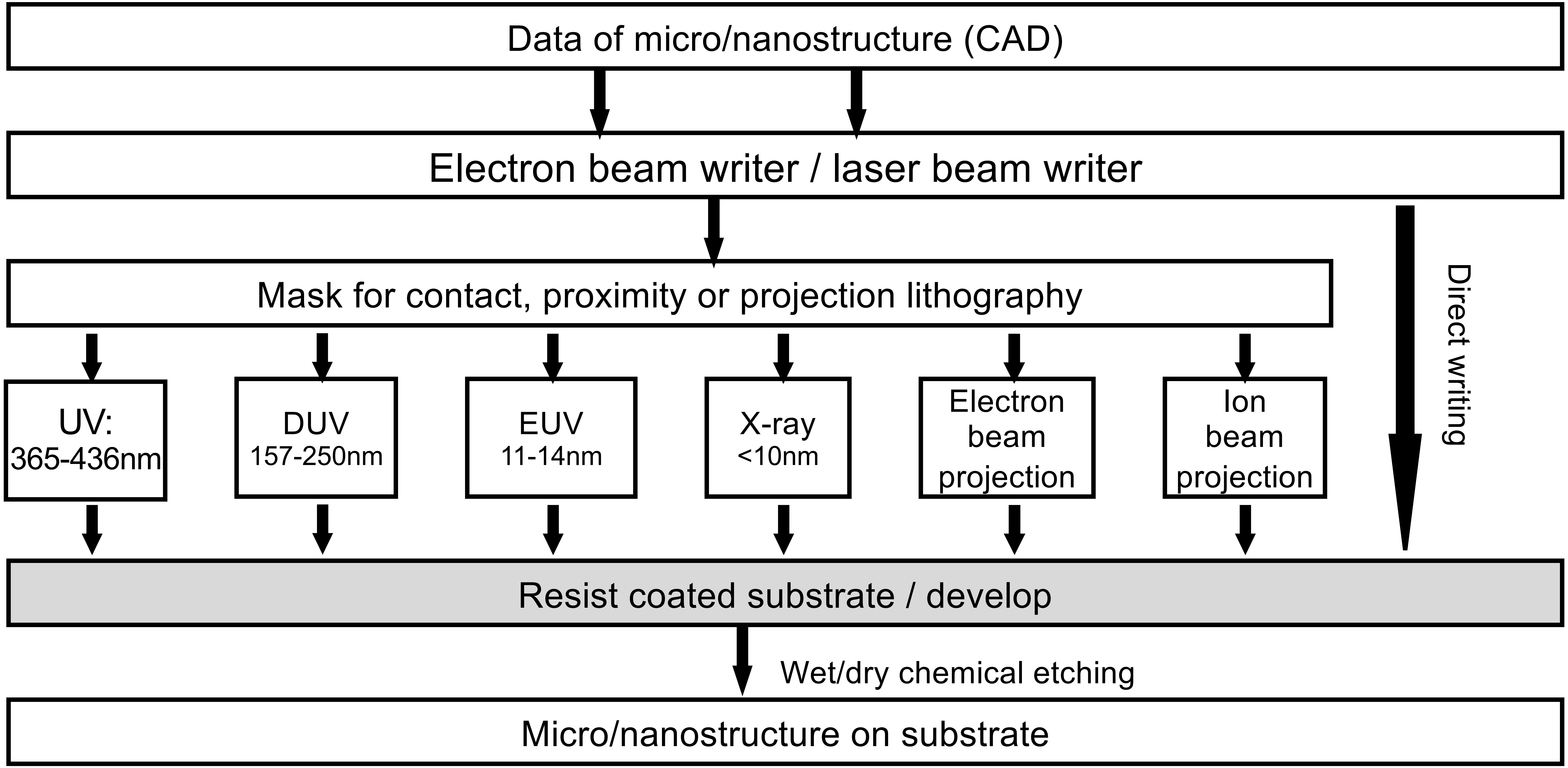
- Lithography process flow
- Exposure methods
- Photoresist
- Pattern transfer

General concepts in lithography

- Fundamental step in microfabrication
  - From design to physical patterning
  - Enabling step for local dry etching or metal deposition
- The lithography step is based on
  - Electromagnetic interaction and modification of a resist via photons or electrons, followed by development
- In a cleanroom & under yellow light



From design to a micro/nanodevice



Concept of lithography

- Processes involved
  - Radiation generation and shaping by an exposure tool to tune the intensity, wavelength and surface where the resist is exposed.
  - A chemical reaction involving both the resist and developer
  - Mechanical control over the relative position of substrate and exposure tool for alignment of possibly multiple layers

Lithography process flow

- Substrate preparation
- Resist coating and pre-baking
- Resist exposure
- Resist development
- Pattern transfer (etching, lift-off)
- Resist stripping

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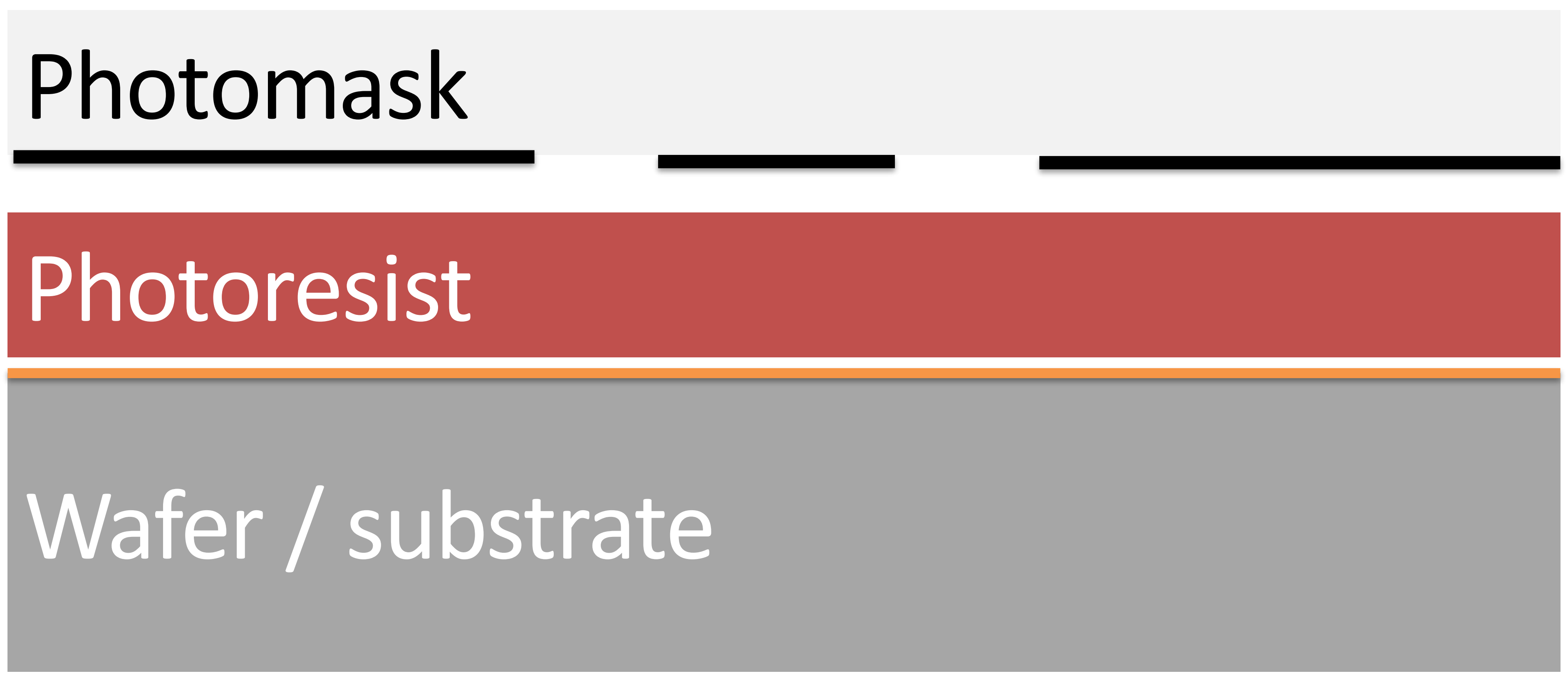

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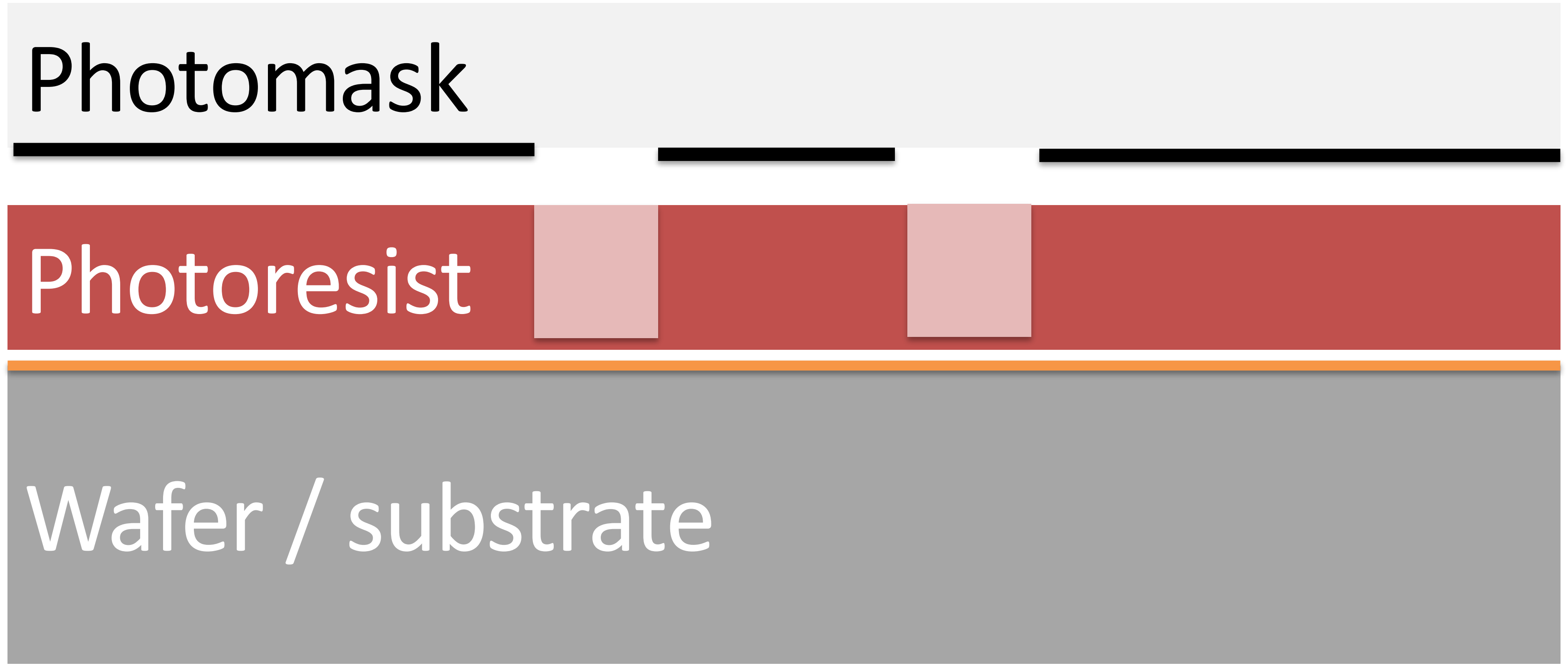

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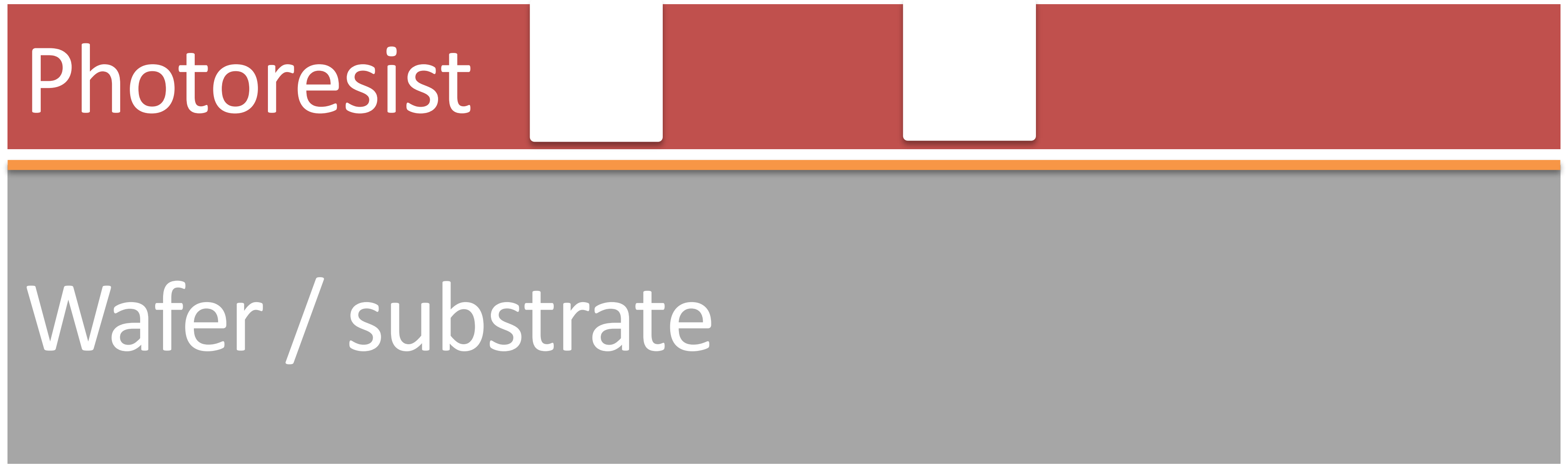

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Lithography 1: General concepts

II. Resist properties and exposure methods

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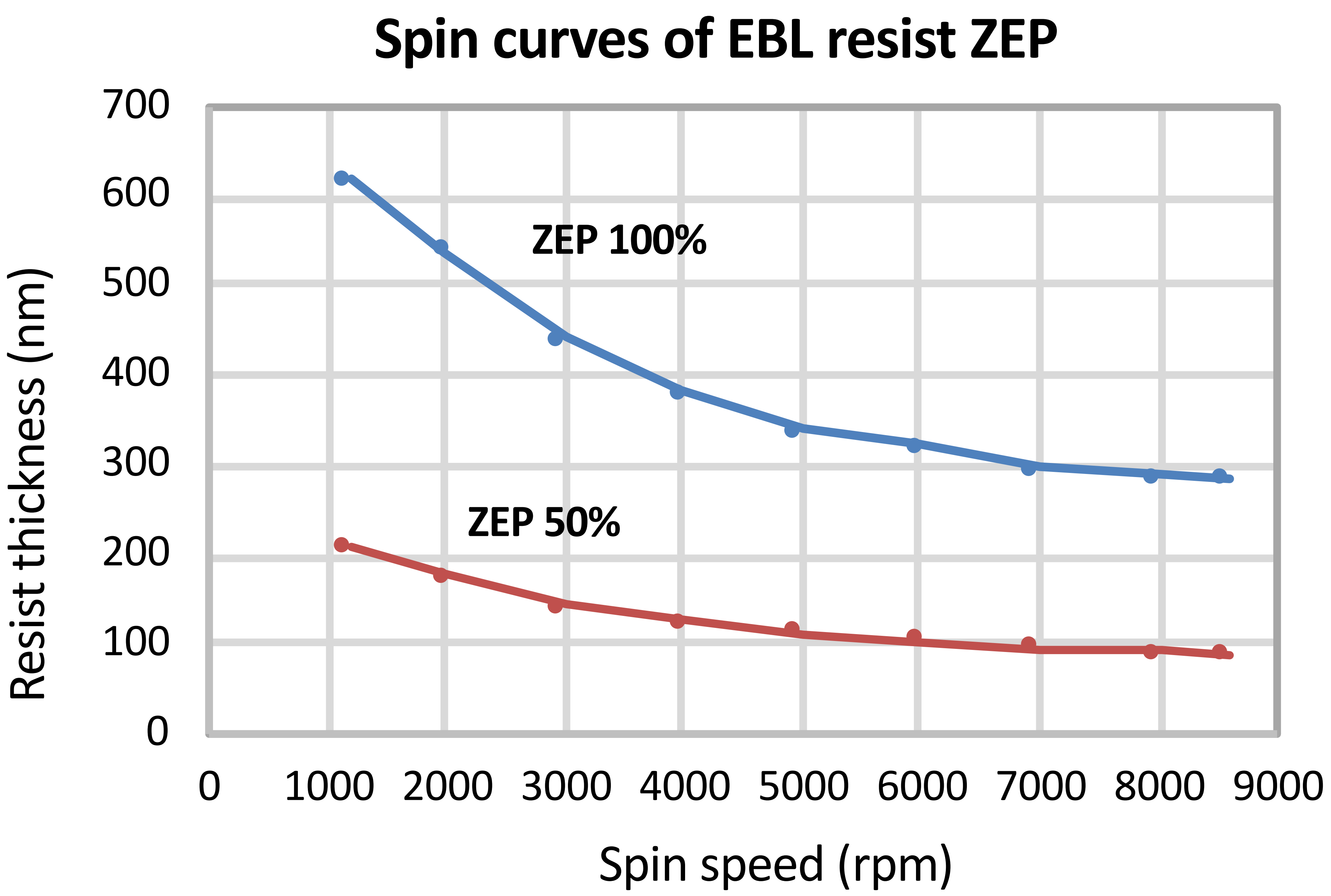
Resist coating

- Substrate preparation
  - Surface cleaning
  - Resist adhesion
- Resist coating
  - Spin coating
  - Spray coating
  - Casting
  - Lamination

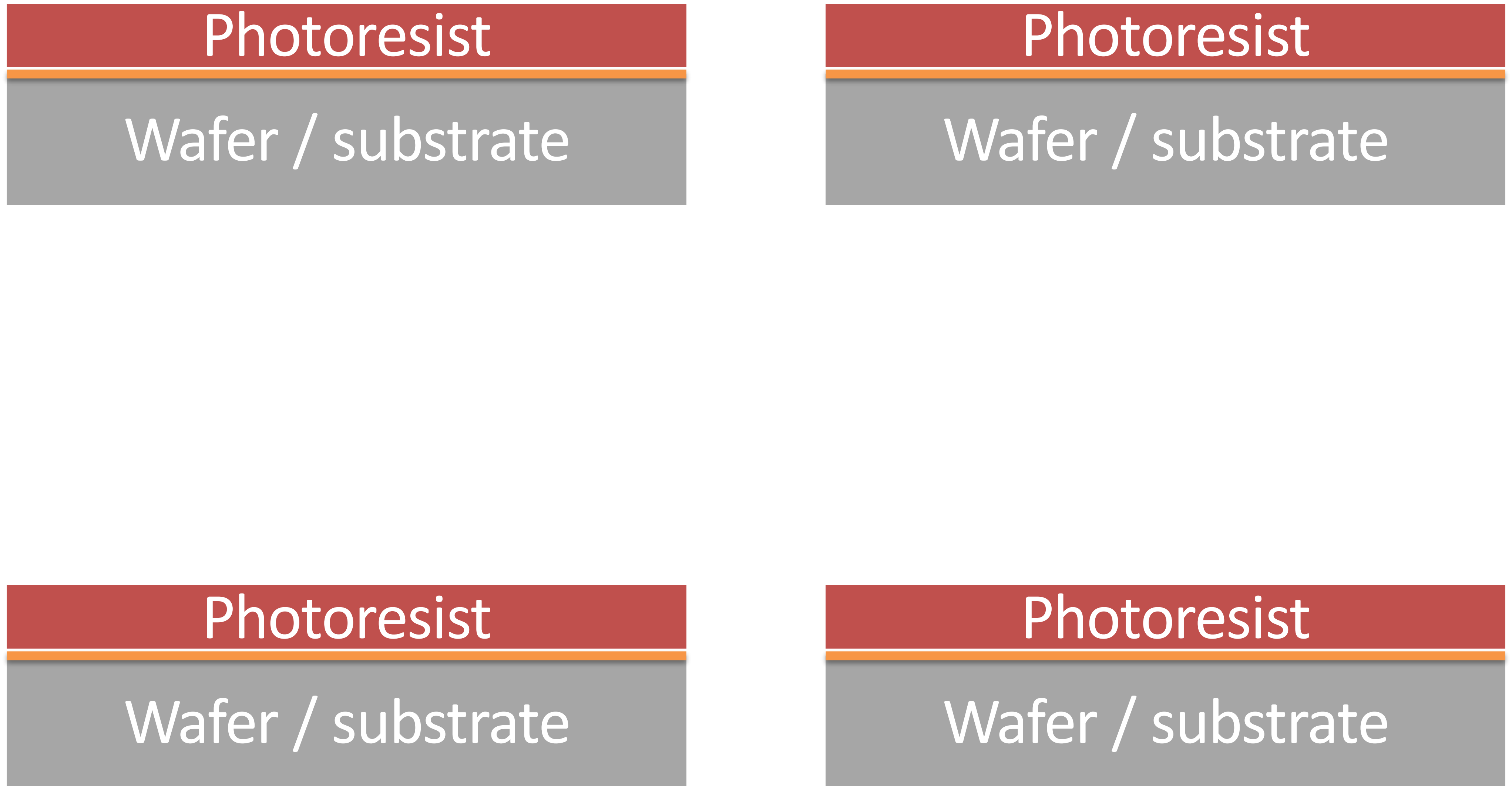
$$T = K\, C^{\beta}\, \eta^{\gamma} / \omega^{\alpha}$$

Resist thickness T
K = overall calibration constant
C = polymer concentration in g/100 mL solution
η = intrinsic viscosity
ω = rotations per minute

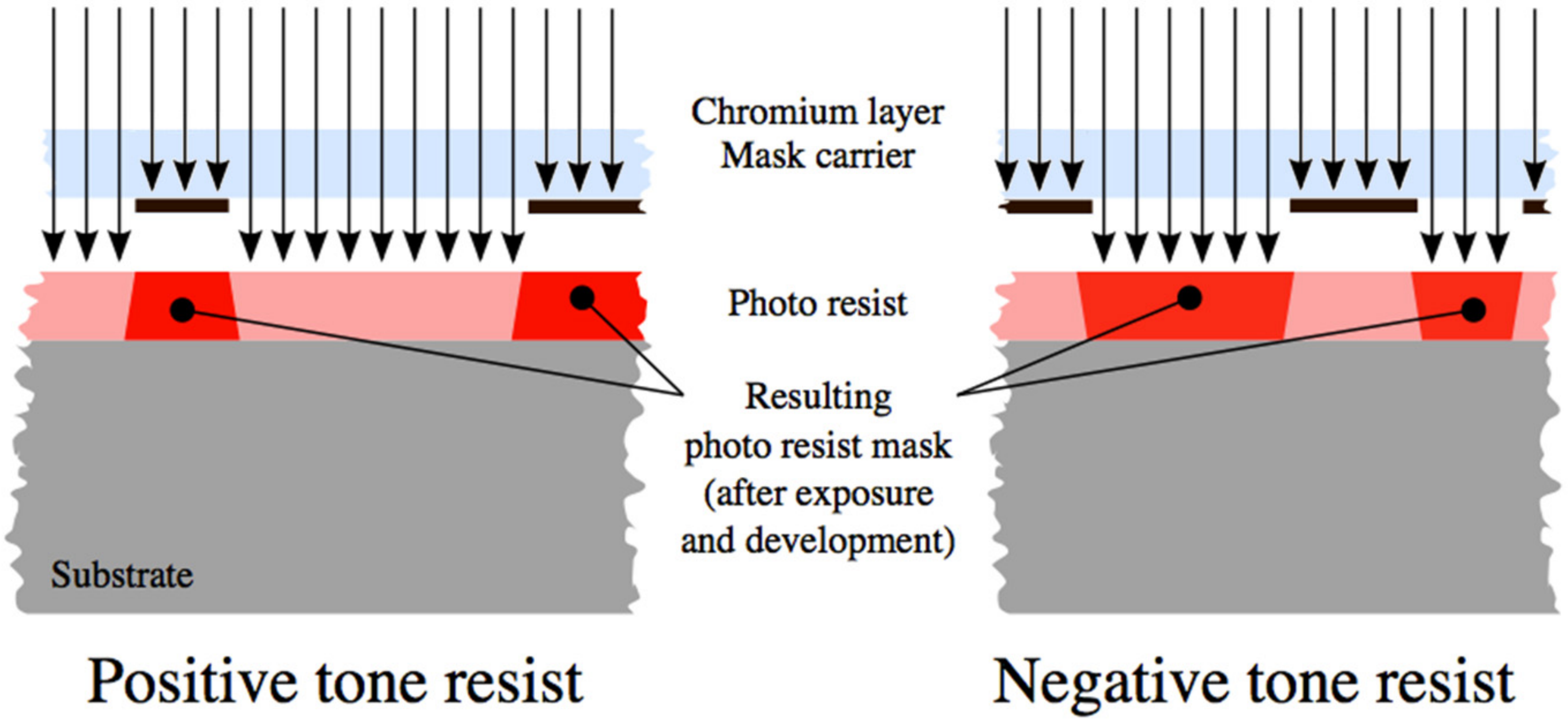


Exposure methods and resolution

- **Exposure** brings localized energy in the form of photons, electrons or ions
- Resist is **sensitive** to the energy used
- Optical lithography uses photons (resolution limited by diffraction ~ wavelength/2)
- Electron beam lithography uses electrons (limited by scattering)
- X-ray lithography (complicated mask)
- Ion beam lithography (complicated tool)



Photoresist tones



- Base resin
- Photosensitizer
- Organic solvent

→ **breaking bonds**

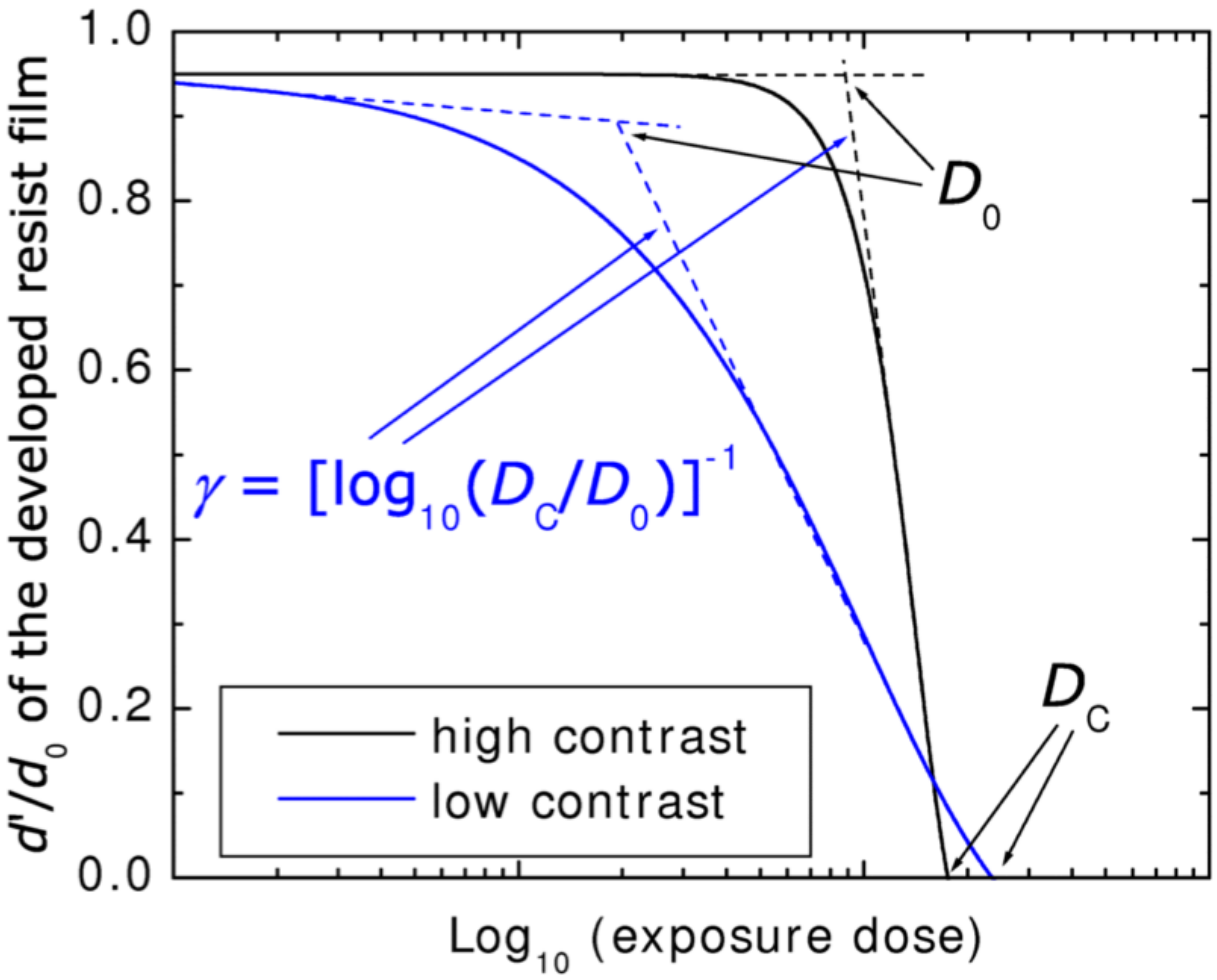
- Polymers
- Photosensitizer

→ **creating bonds**

- Dose: energy/surface
- Dose-to-clear
- Dose to fully cross-link
- Over exposure
- Under exposure
- Processing speed

Photoresist contrast

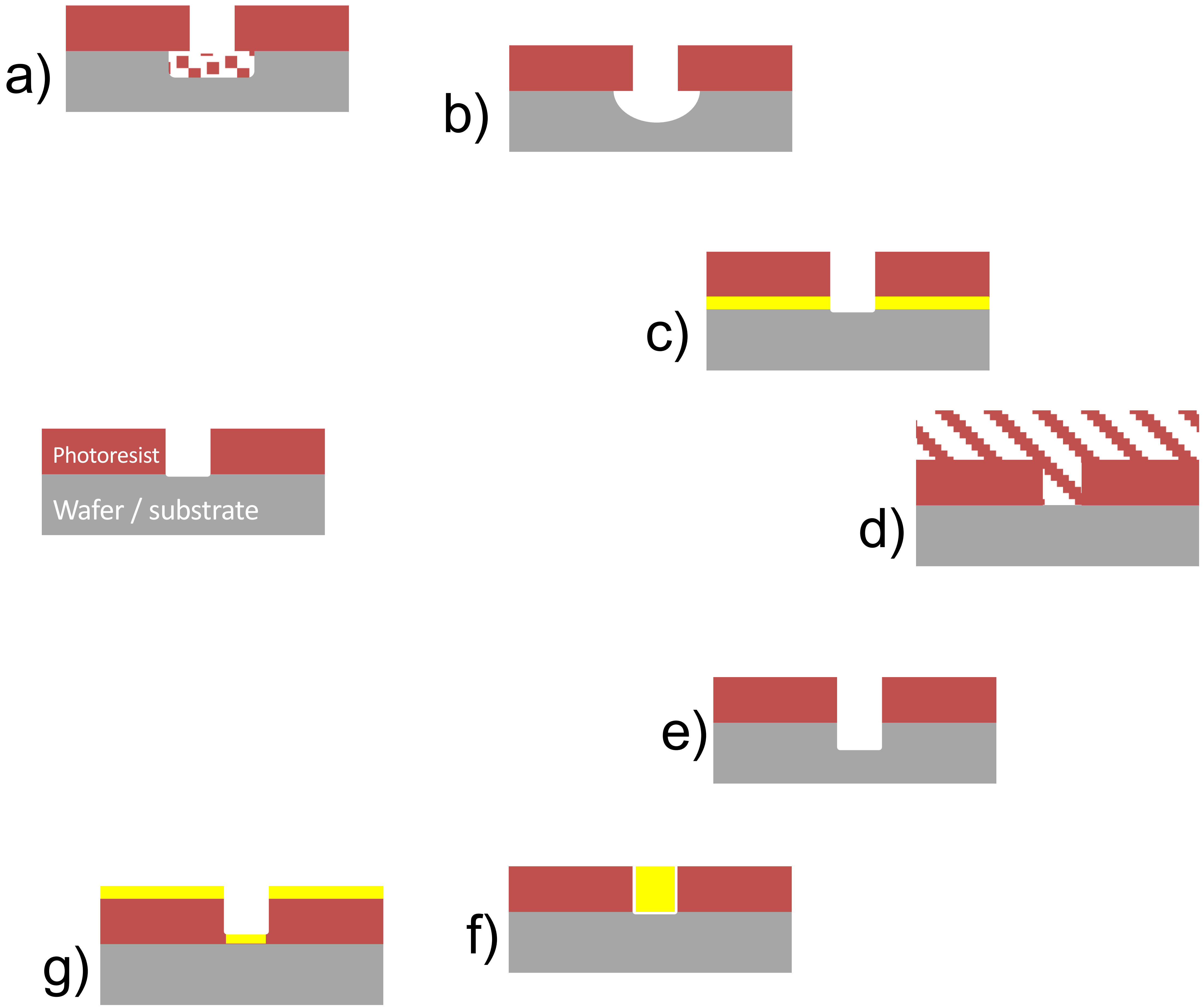
- Contrast is an intrinsic parameter that defines from which dose a reaction starts and at which dose it is completed
- Determines the critical dose for a lithography process
- High contrast gives steeper sidewalls
- Low contrast allows for gray scale lithography



Photoresist contrast, "Exposure of Photoresist", MicroChemicals, http://www.microchemicals.com/technical_information/exposure_photoresist.pdf

Pattern transfer

a) Ion Implantation
b) Isotropic etching (wet and dry)
c) Thin film etching
d) Moulding
e) Anisotropic etching (wet and dry)
f) Electro-plating
g) PVD thin film coating (lift-off)



General concepts

- Lithography process flow
- Exposure methods
- Photoresist
- Pattern transfer

Supplementary

Lithography 1: General concepts

III. Photoresist sensitivity and modulation transfer function

Micro and Nanofabrication (MEMS)

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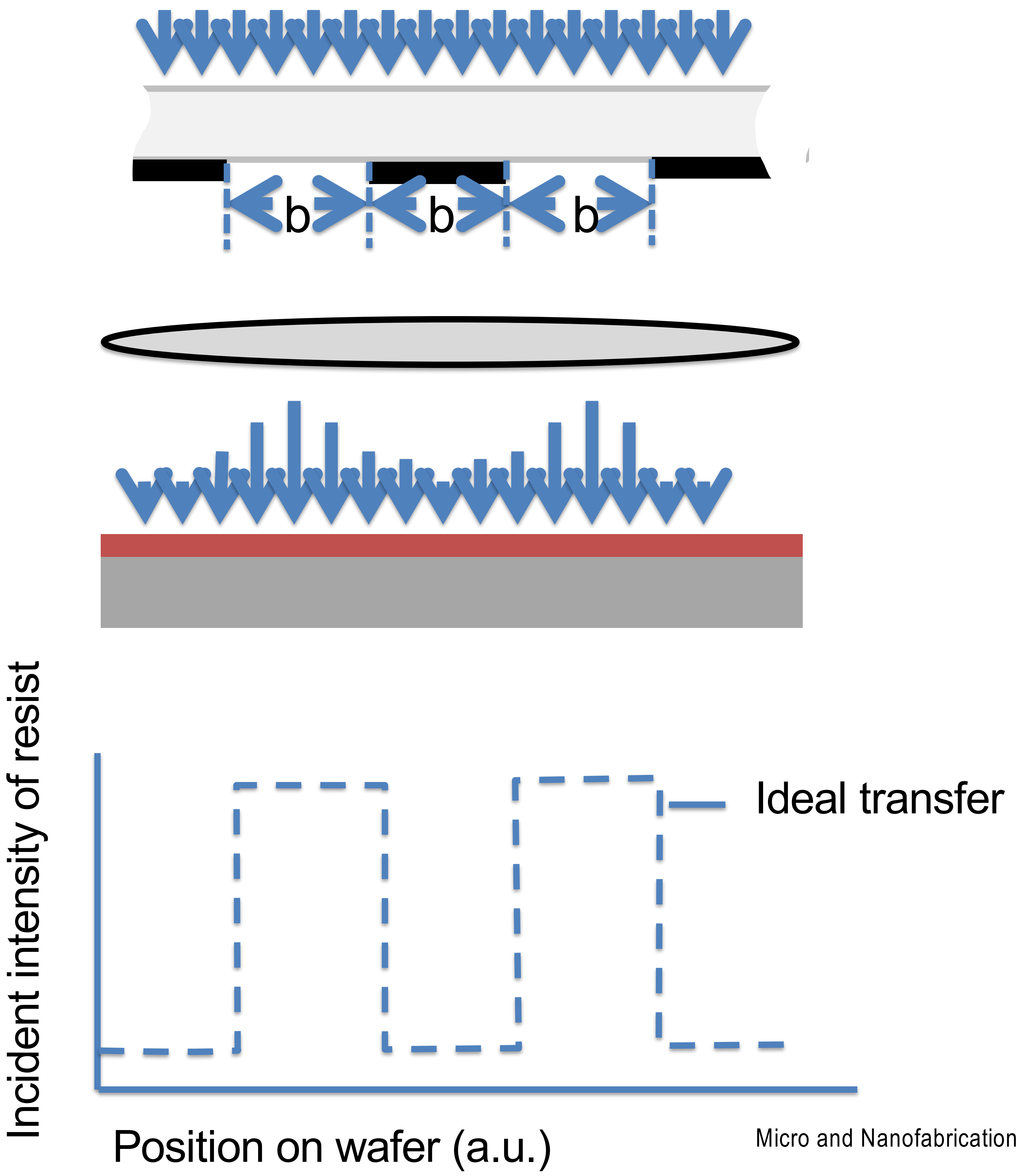
Photoresist sensitivity

- Intrinsic sensitivity Φ = necessary incident energy needed to produce photochemical reaction
- single component resist ~ quantum yield
- # photon-induced events / # photons absorbed
- $\Phi_{PMMA} = 0.02$
- $\Phi_{DQN} = 0.2 – 0.3$

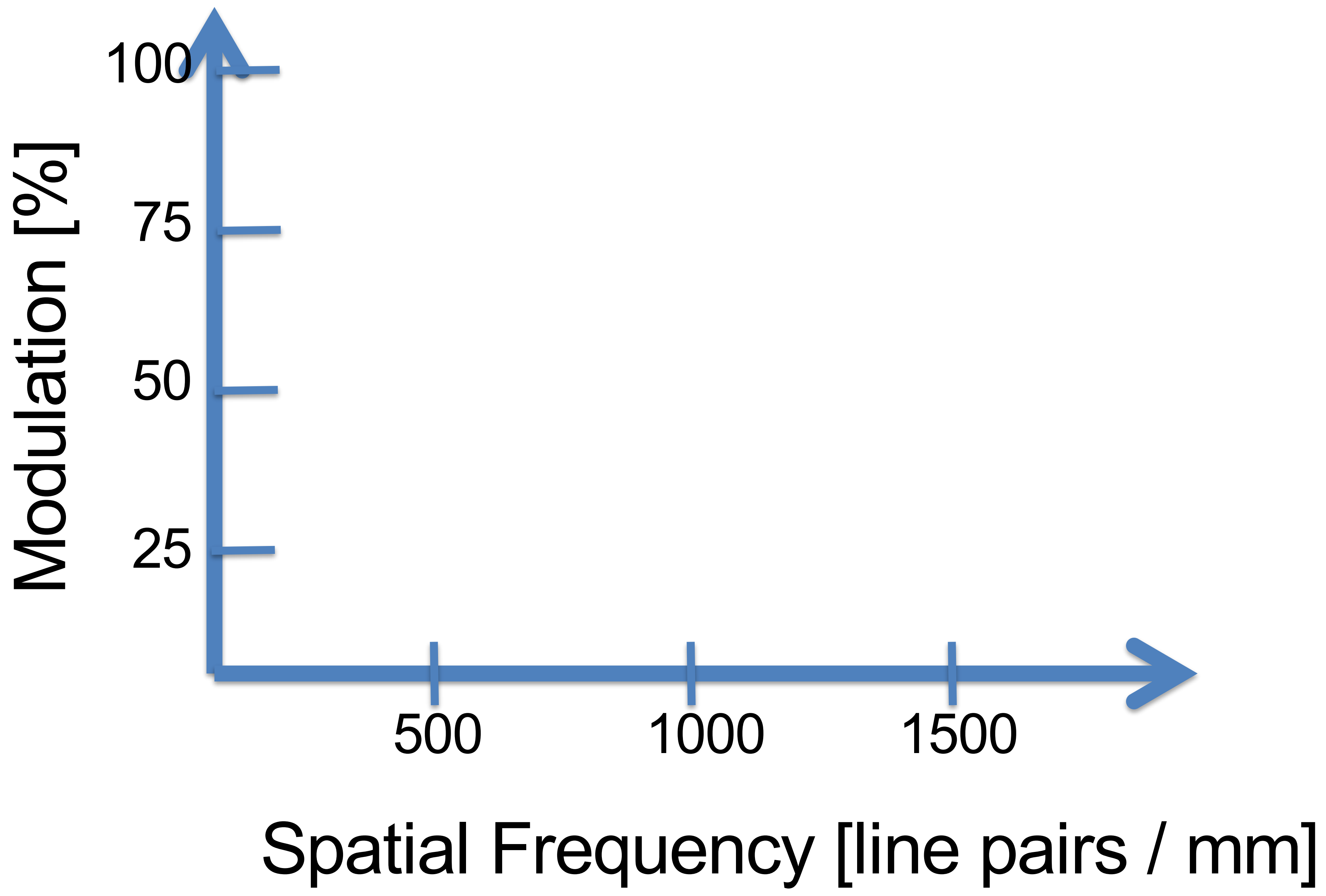
Modulation transfer function

- MTF is a measure of the optical contrast in the areal image by the exposure system.
- The higher the MTF the better the optical contrast.
- MTF of an image is defined as:



Modulation transfer function

- MTF increases with decreasing λ
- MTF = 1 for larger features
- MTF → 0 for closely spaced features



Lithography 2: UV Lithography

Direct writing and mask writing

Micro and Nanofabrication (MEMS)

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Mask making and Direct Laser Writer

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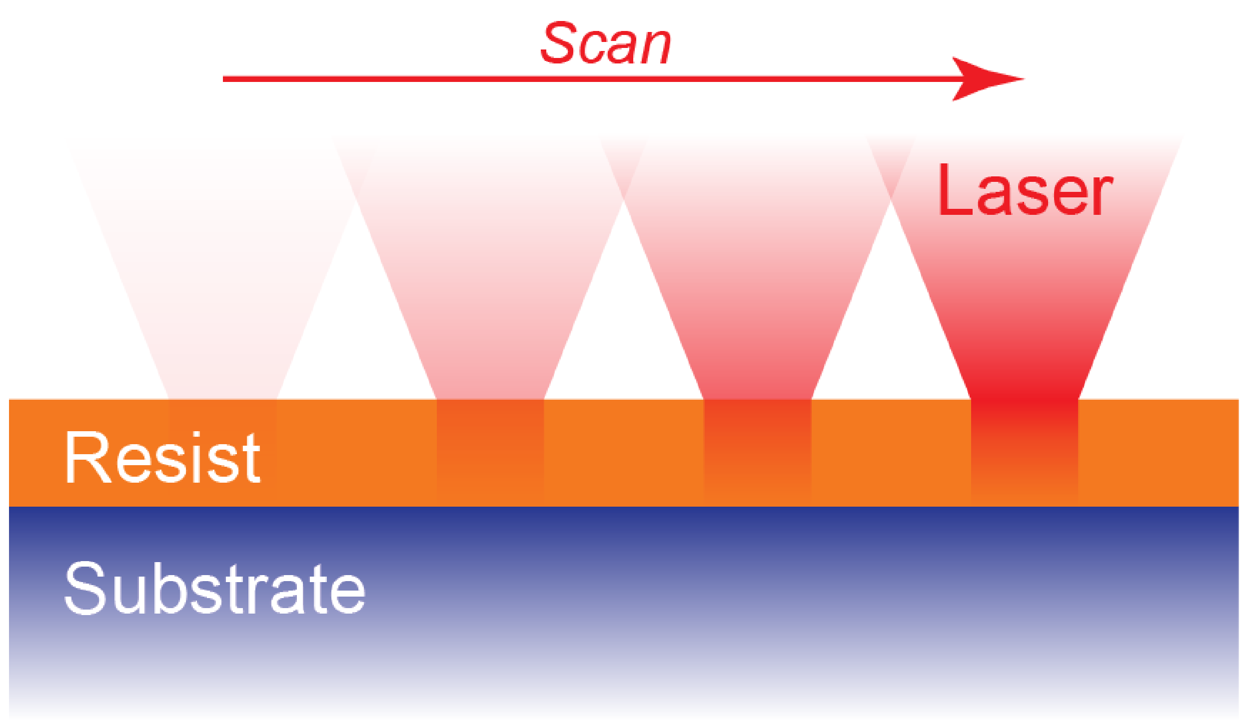
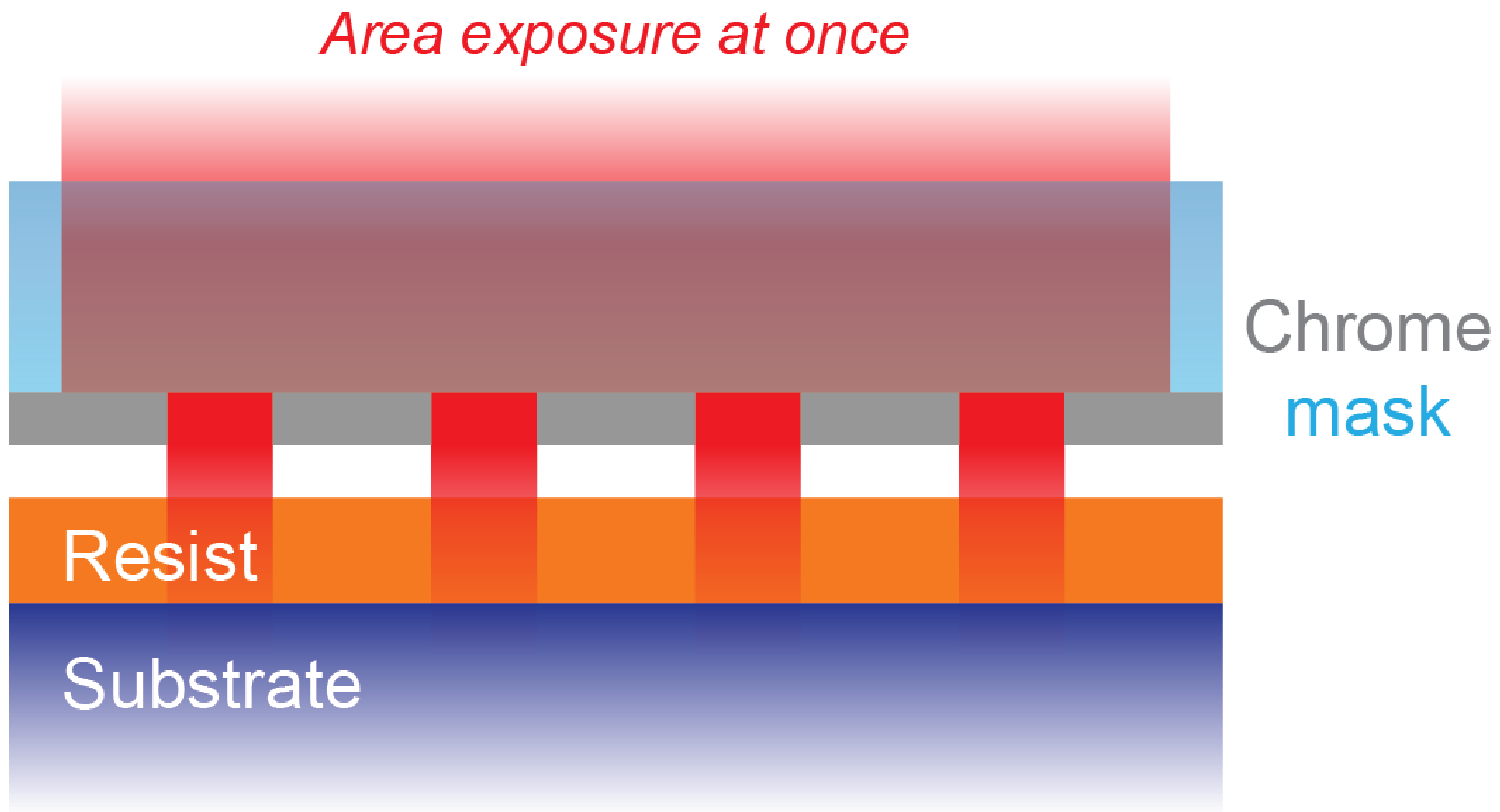
- Photo mask process flow
- Direct Laser Writer
- From the CAD file to the mask
- Cleanroom videos
- Examples

Serial vs parallel exposure

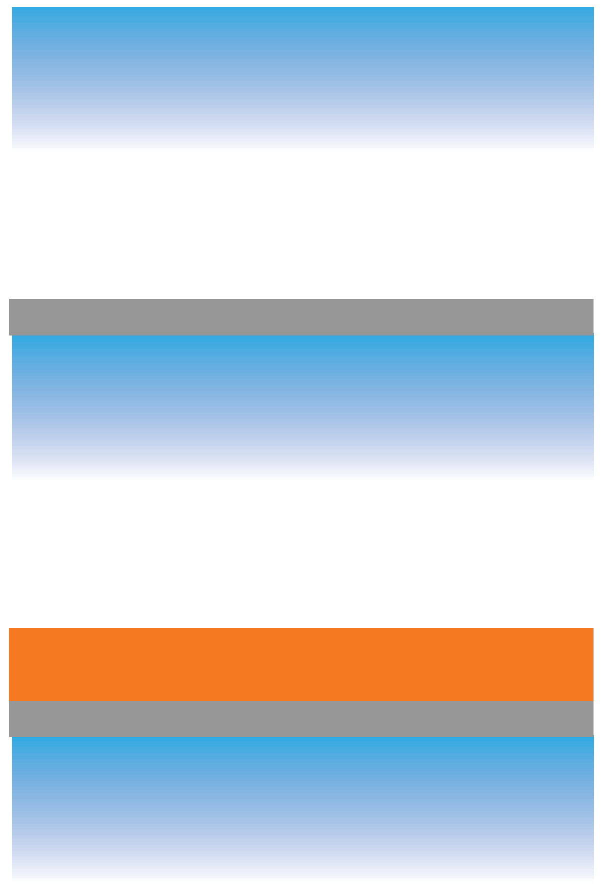
- Two approaches in photolithography
  - *serial laser writing* vs *parallel using photomasks*
- Single serial writing of a photomask
  - Exposure from minutes to hours
  - High resolution without contact
  - Single wavelength
- Exposure through mask for pattern replication
  - Exposure time in seconds
  - High throughput
  - Laser writing required for the original mask

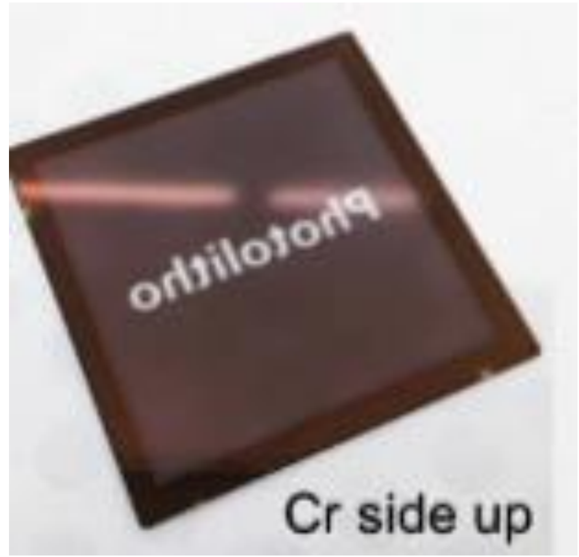




Photomask: process flow

- Photomask:
  1) Quartz or soda-lime square substrate
  2) Opaque chromium layer ~100nm
  3) Positive photoresist

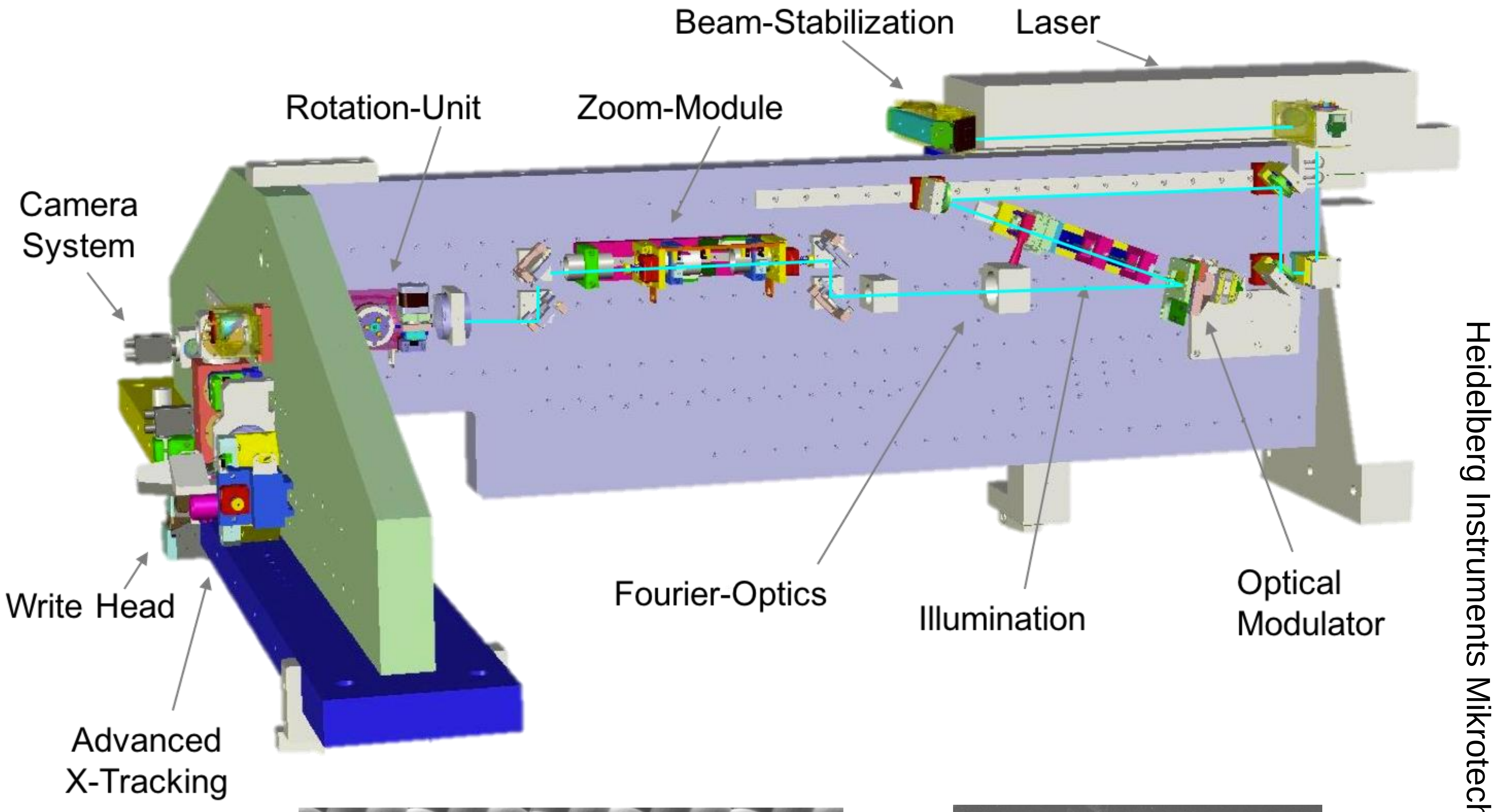




- Serial laser exposure
- Resist development
- Wet etching of chromium
- Resist stripping
- Mask drying
- Use in mask aligner

Direct laser writer

- Direct writing of resist with a laser beam
  - Point by point, single pixel raster scan
  - Partial area exposure with an SLM or DMD
    - Projection of a multi-pixel area at once
    - Semi-parallel approach improve throughput
- Stage based displacement
  - High resolution interferometers
- Tunable dose and focus during exposure
  - Greyscale lithography
- High power density
  - Thick and absorbing layers



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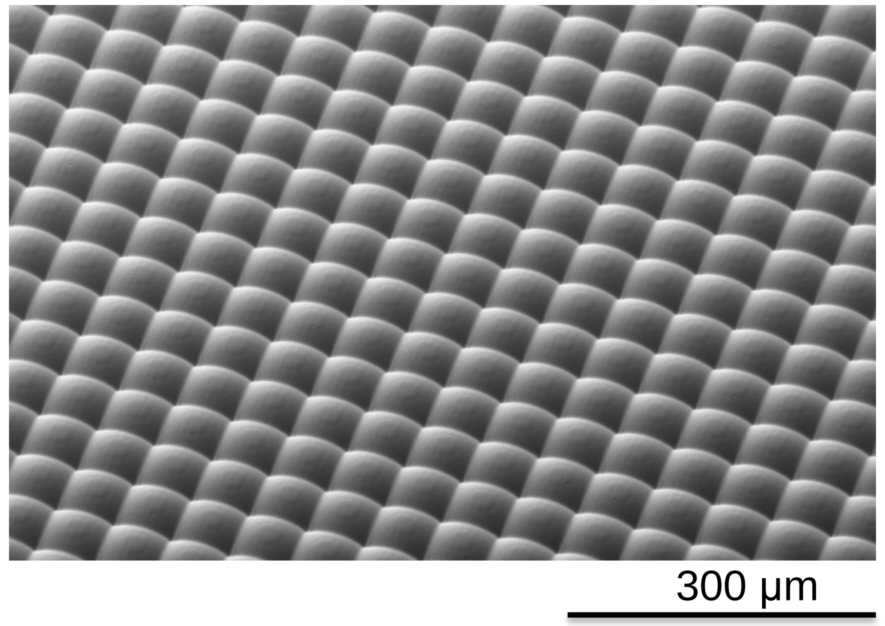
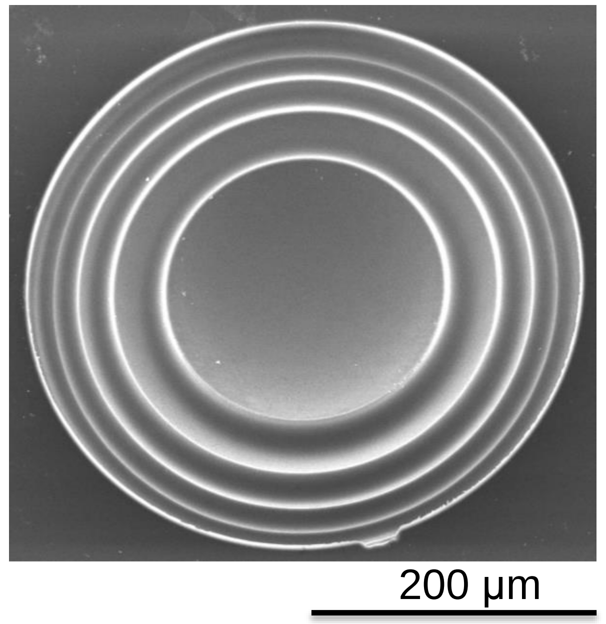
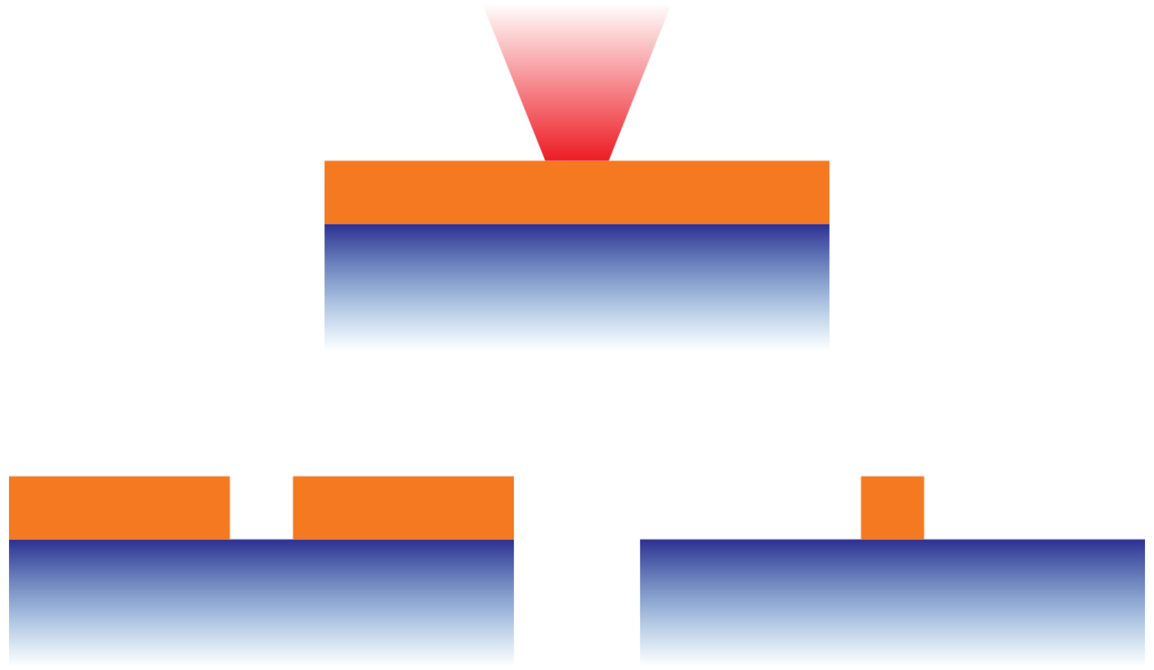


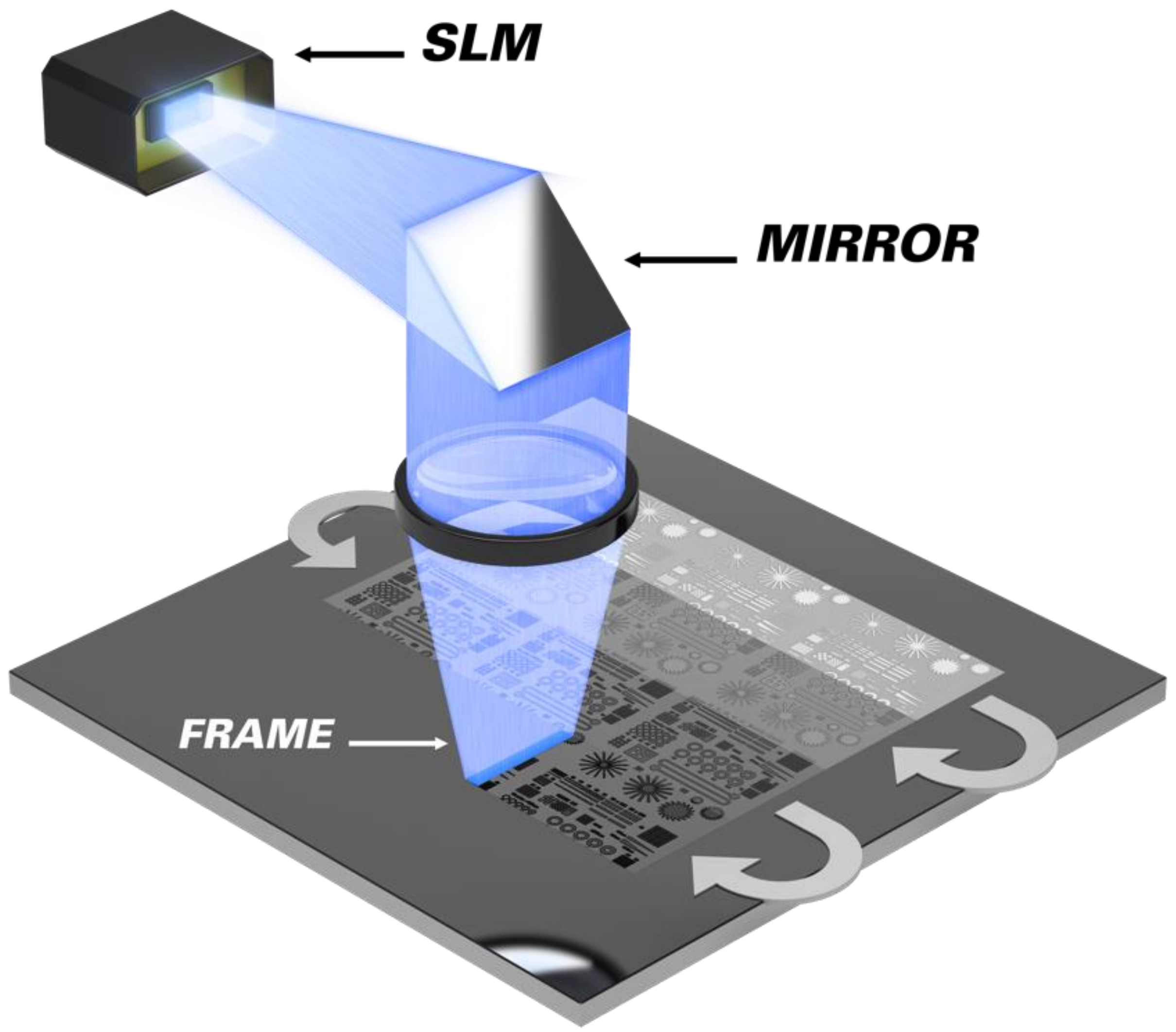


Resolution in DWL

- Physical limit: lens numerical aperture
  - Rayleigh criterion and process window
- Practical choice: lens write head magnification
  - Different lens magnifications or write heads allow varying physical field sizes
  - Low magnifications allow for large area writing at once with large physical pixel size
- Number of pixels on the SLM/DMD
  - Associated to the lens magnification, the number of pixels on the source elements defines the physical pixel size

600 – 800 nm resolution





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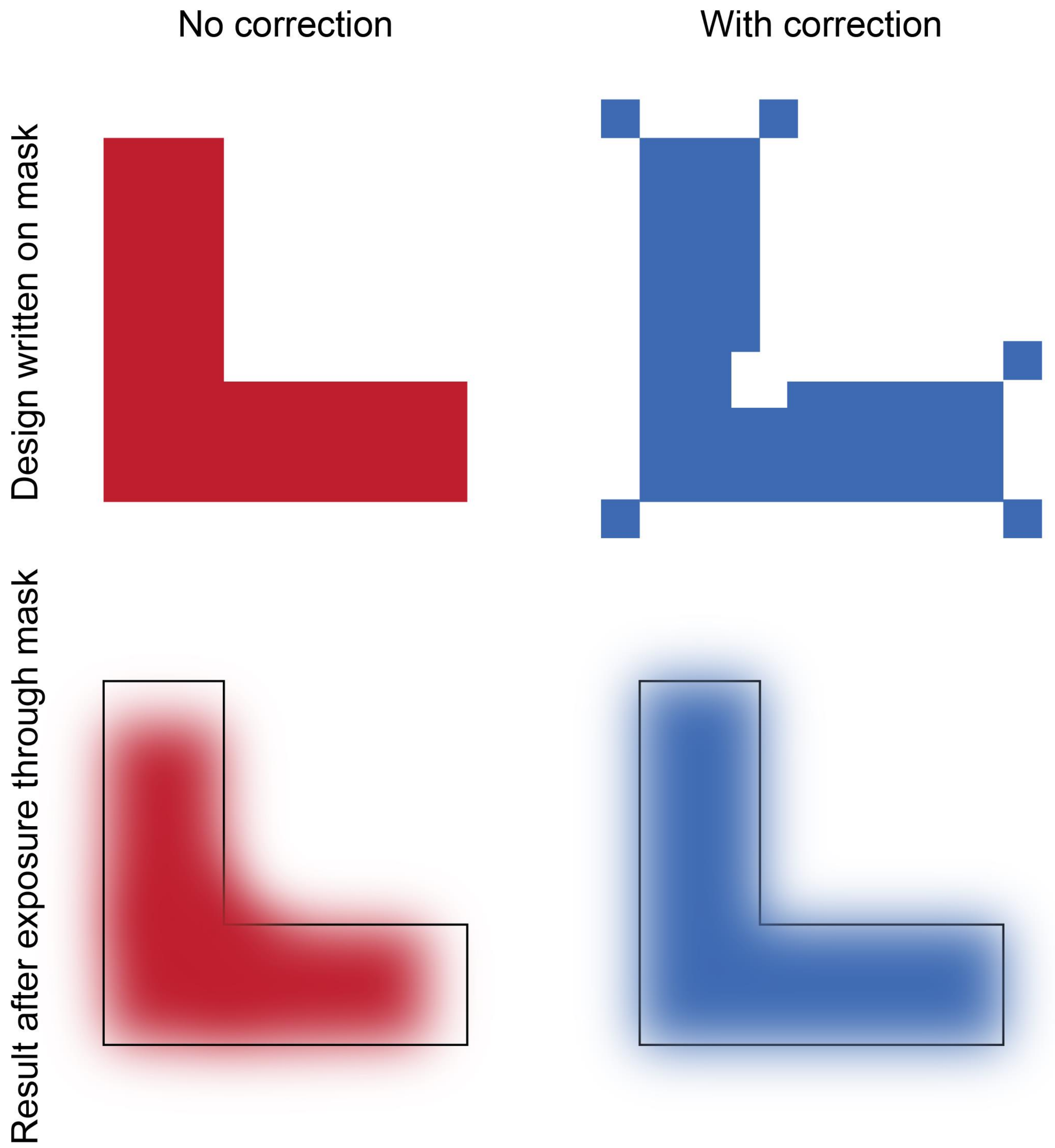
From the CAD file to the mask

- Typical CAD files .CIF or .GDS
  - Repetition of base cells
  - Multiple layers
- Mask writing: design mirroring
- Choice of resolution
  - Design discretized on a grid: affects speed and resolution
- Shape corrections
  - Serif: compensate corner smoothing
  - Bias: compensate for finite beam size
  - Axial bias: compensate for beam shape/ asymmetry

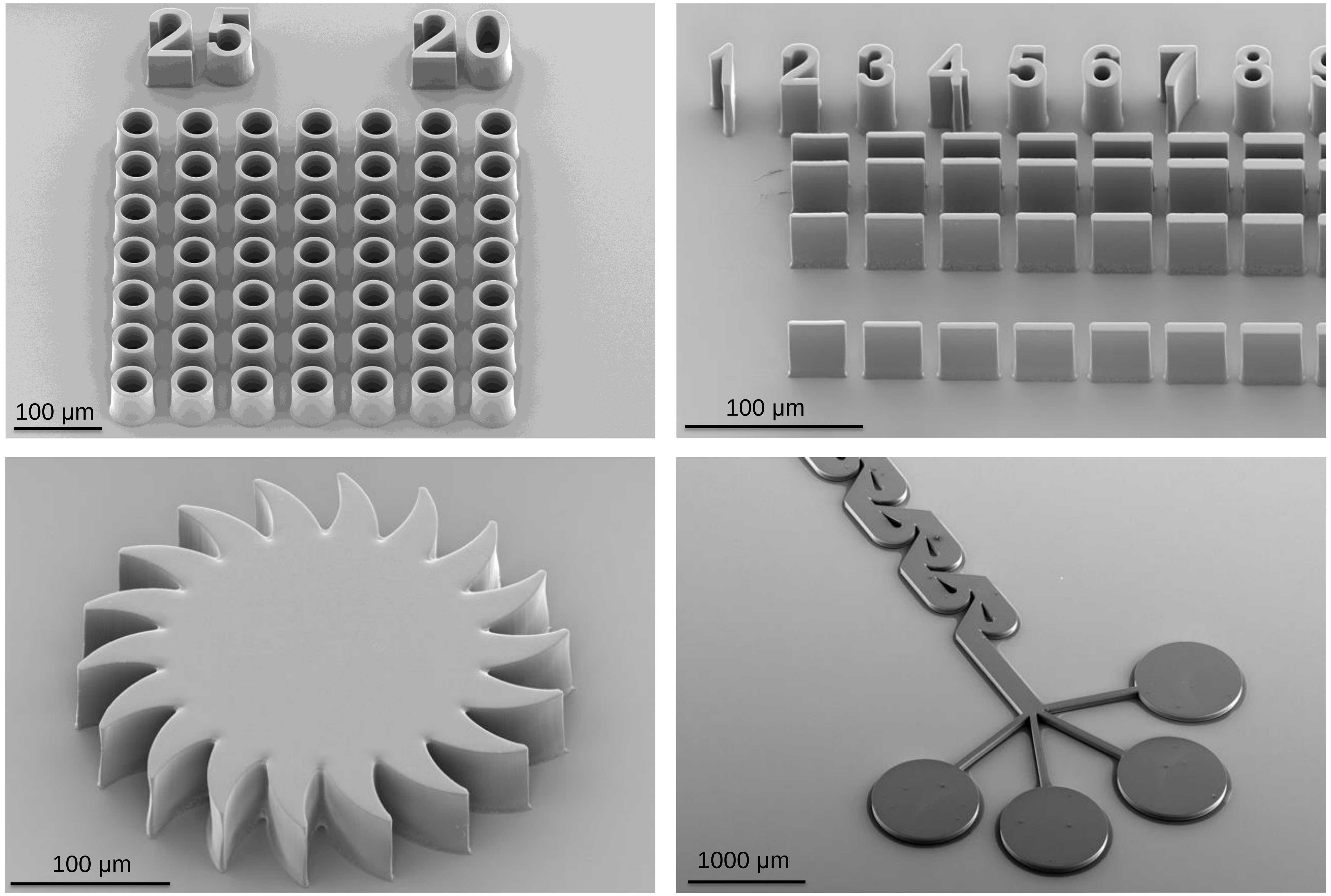


Development and etching

- Resist development
  - Positive resist type (e.g. AZ1512)
  - Resist thickness 0.6 um for high resolution
  - Development in MP 351 (water diluted 1:5)
    - NaOH aqueous alkaline solution
  - Dissolution of exposed resist
  - Chromium wet etching
    - $HClO_4$ + Ce $(NH_4)_2(NO_3)_6$ + H_2O
    - 90 second etching
  - Resist strip in solvent and water rinse

Example: direct writing of SU-8

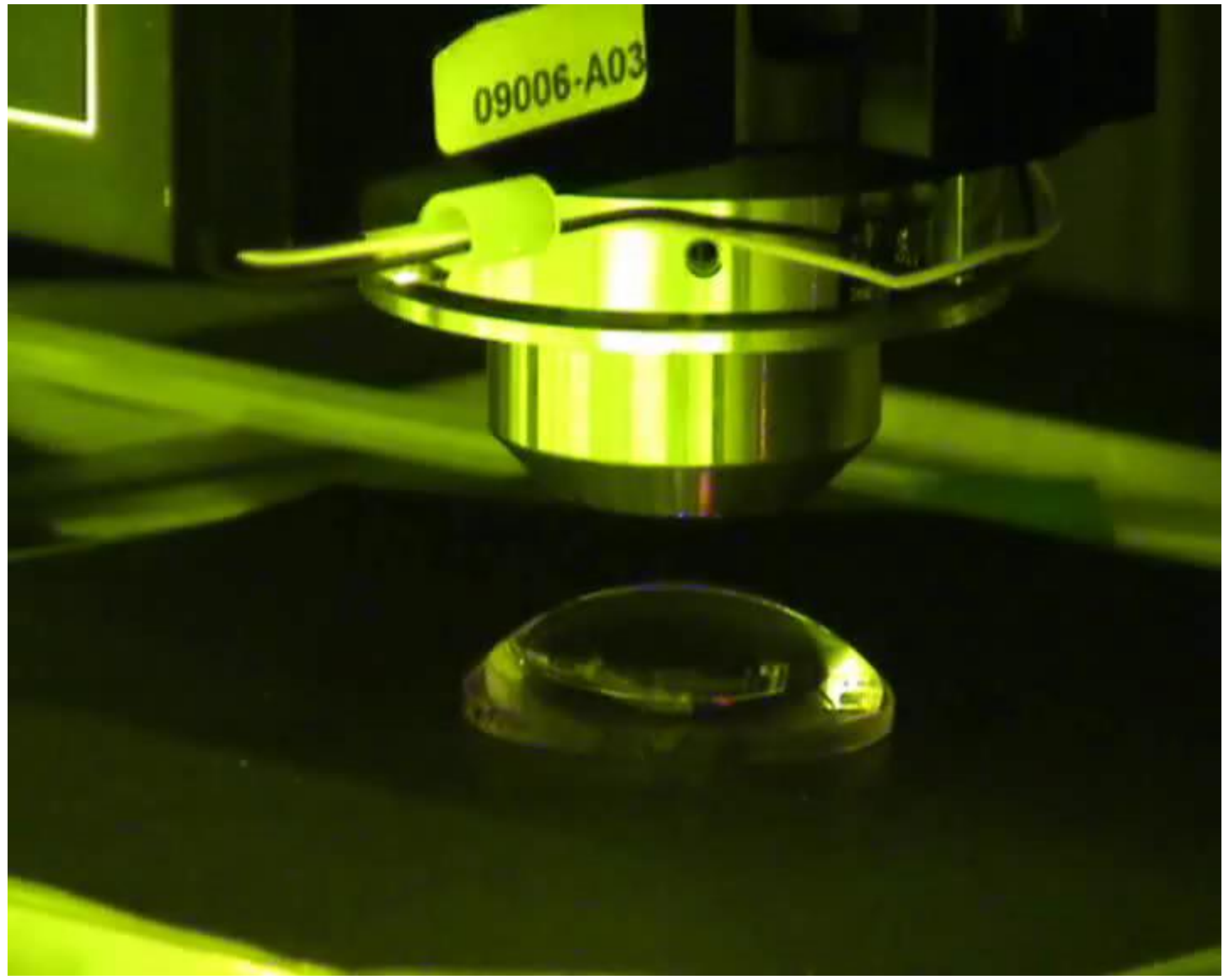
- SU-8: negative-tone resist
  - Epoxy-like functional material
  - Large thickness range from µm to mm
- Applications:
  - Optical elements
  - MEMS and cantilevers
  - Molds for post-processing
- Unique property:
  - Self focussing via refractive index change during exposure: high aspect ratio



T. Besson - Heidelberg Instruments Mikrotechnik GmbH

Example: special surfaces

- Lithography on a lens



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Example: special surfaces

- Large scale masks
  - Over 1400x1400mm writing area
  - Source output up to 10W

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Mask making and Direct Laser Writer

- Photo mask process flow
- Direct Laser Writer
- From the CAD file to the mask
- Cleanroom videos
- Examples

Lithography 3: UV Lithography

Mask based lithography

Micro and Nanofabrication (MEMS)

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UV lithography

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- Alignment and exposure tool
- Contact, proximity and projection
- Resolution limit and enhancement
- UV resists
- Post processing
- Examples

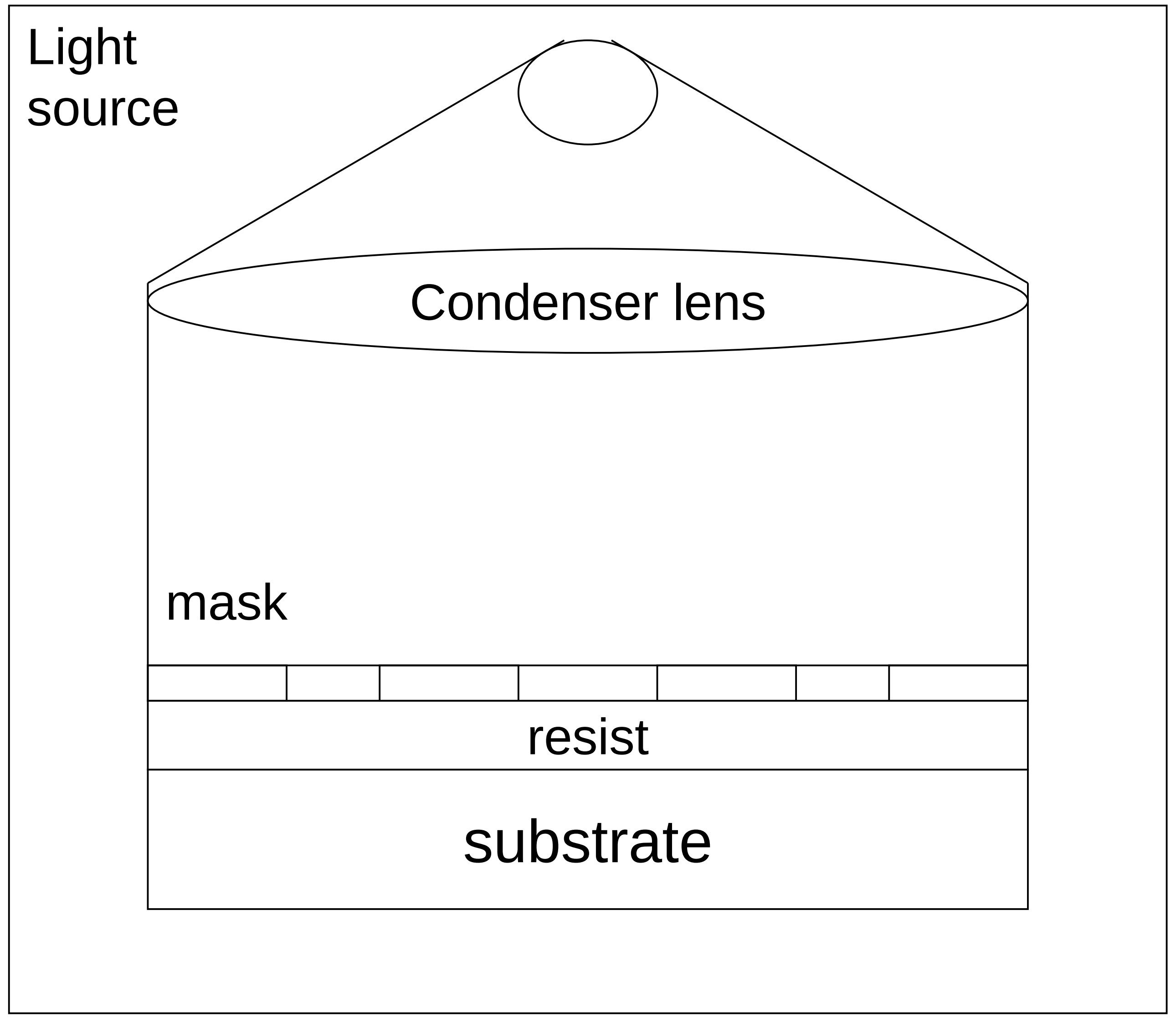
Alignment and exposure tool

- Mechatronic equipment
- X, Y, Theta control of Chrom mask w/r to resist coated wafer
- Alignment marks (double-side optics, or Infra-red)
- Control of mask – wafer distance
- Control of exposure intensity and dose (time)
- One of the most used equipment in any cleanroom

Contact and proximity

- Contact exposure:
  - Mask is in physical contact with substrate
  - Best resolution (diffraction limited)
  - Risk of contamination
- Proximity exposure:
  - Mask is a few micrometers above the substrate
  - Loss in resolution
  - No risk of contamination

contact

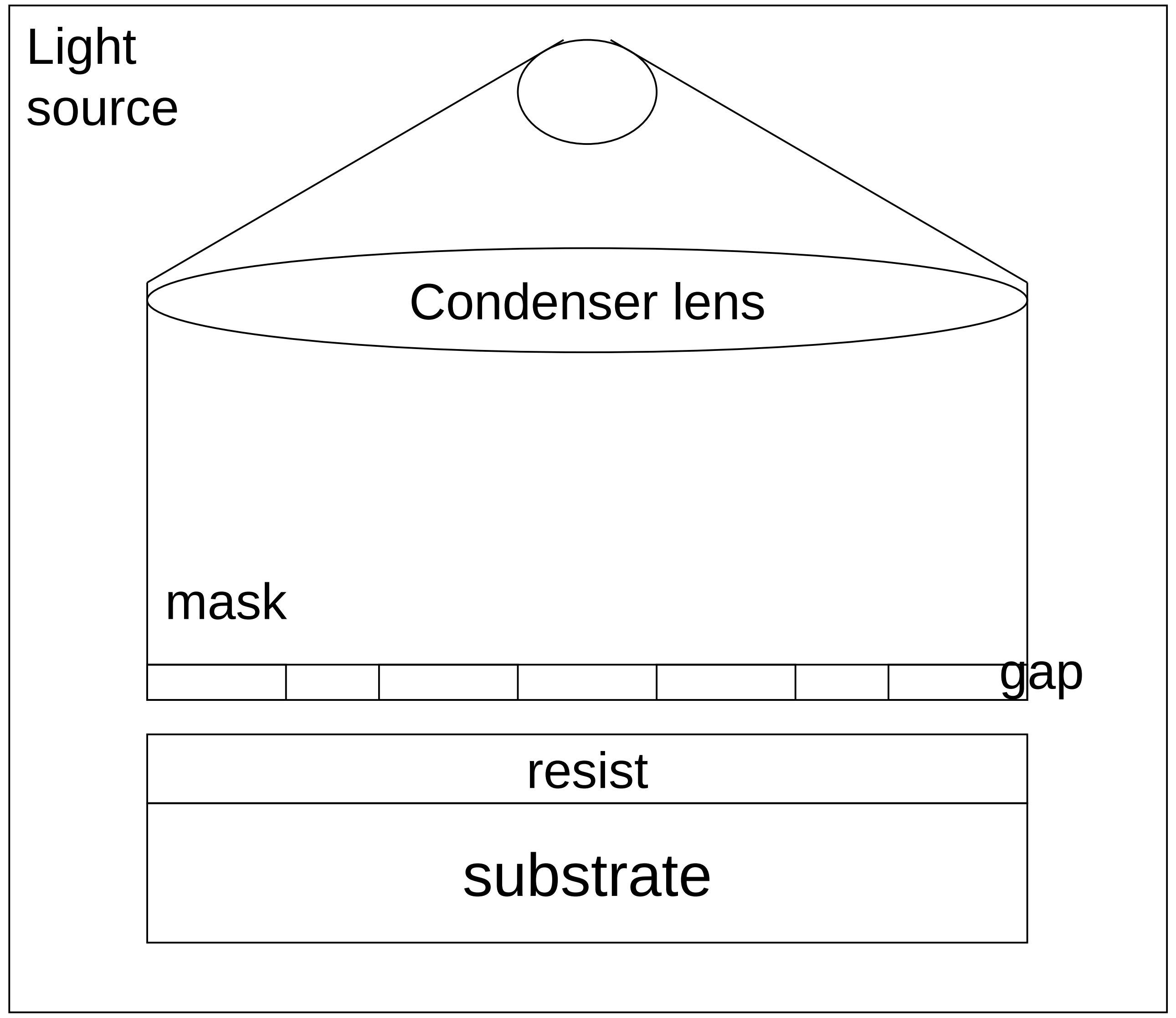


$$MFS = \sqrt{d \cdot \lambda}$$

$$d = thickness(resist)$$

$$\lambda = wavelength$$

proximity



$$MFS \approx \sqrt{(d+g) \cdot \lambda}$$

$$d = thickness(resist)$$

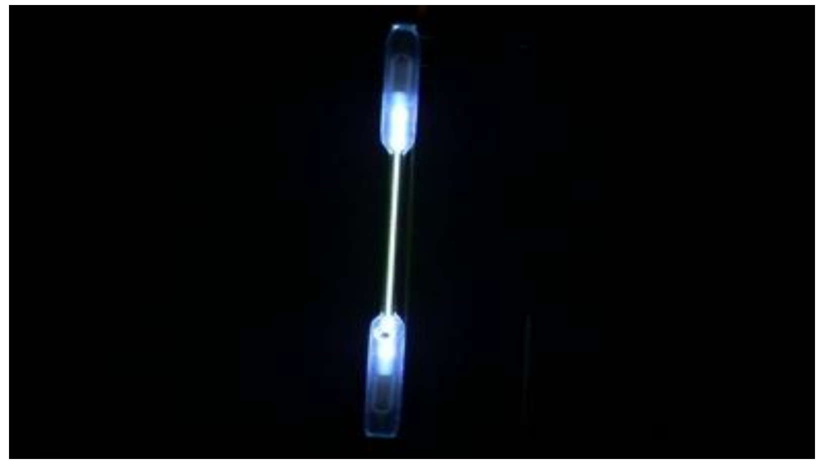
$$g = gap$$

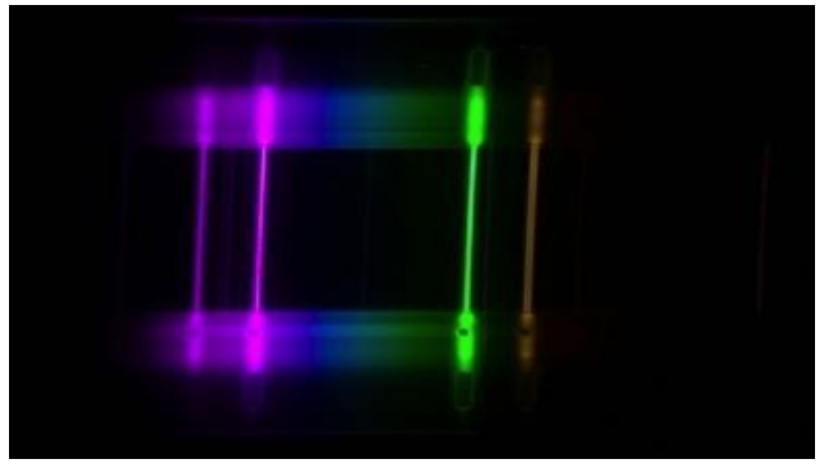
$$\lambda = wavelength$$

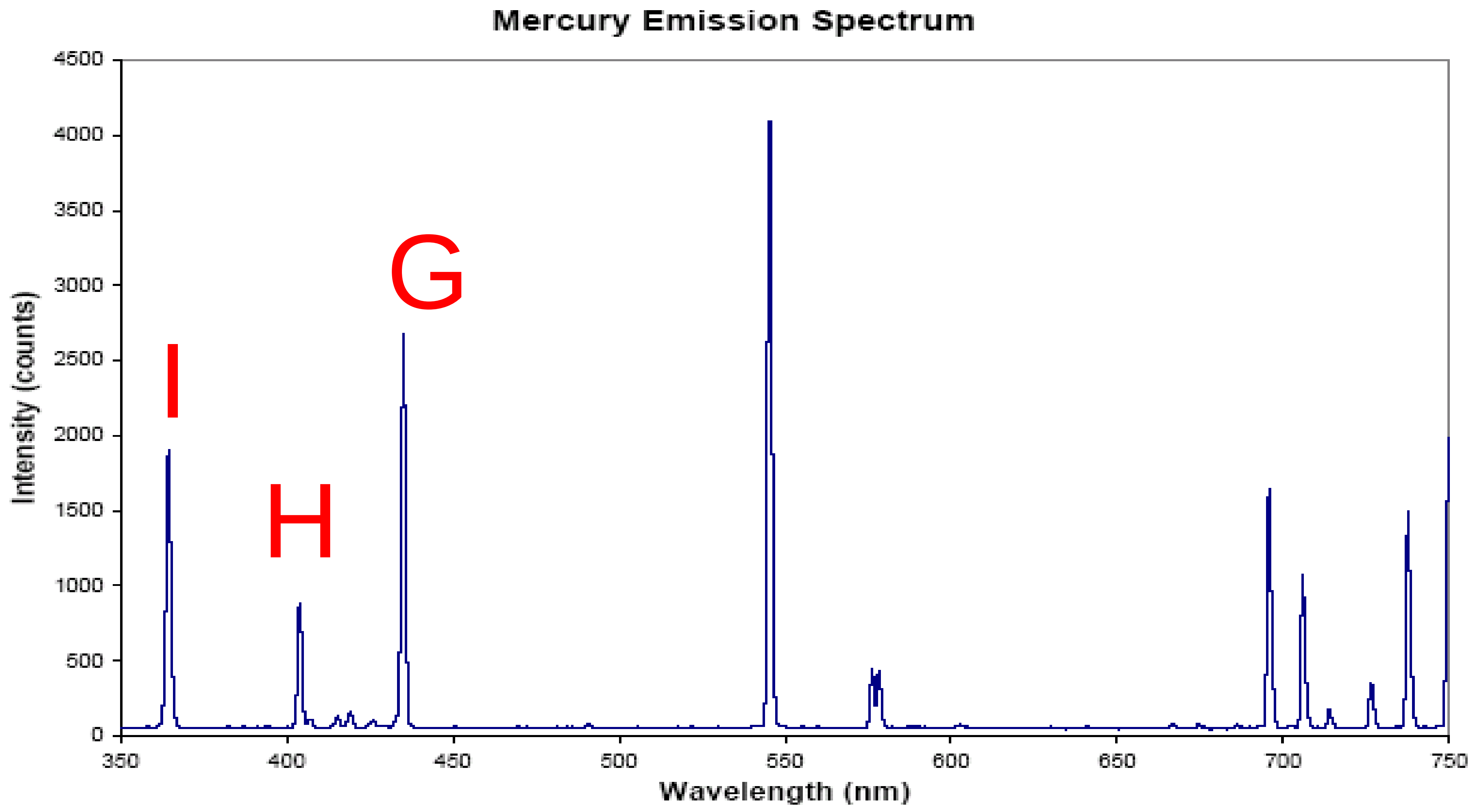
* MFS = Minimum Feature Size

Exposure wavelength and light sources

Wavelength [nm]	Source	Range
436	Hg arc lamp	G-line
405	Hg arc lamp	H-line
365	Hg arc lamp	I-line
248	Hg/Xe arc lamp, KrF excimer laser	Deep UV (DUV)
193	ArF excimer laser	DUV
157	F2 laser	Vacuum UV (VUV)
~ 10	Laser-produces plasma sources	Extreme UV (EUV)
~ 1	X-ray tube, syncrotonon	X-Ray



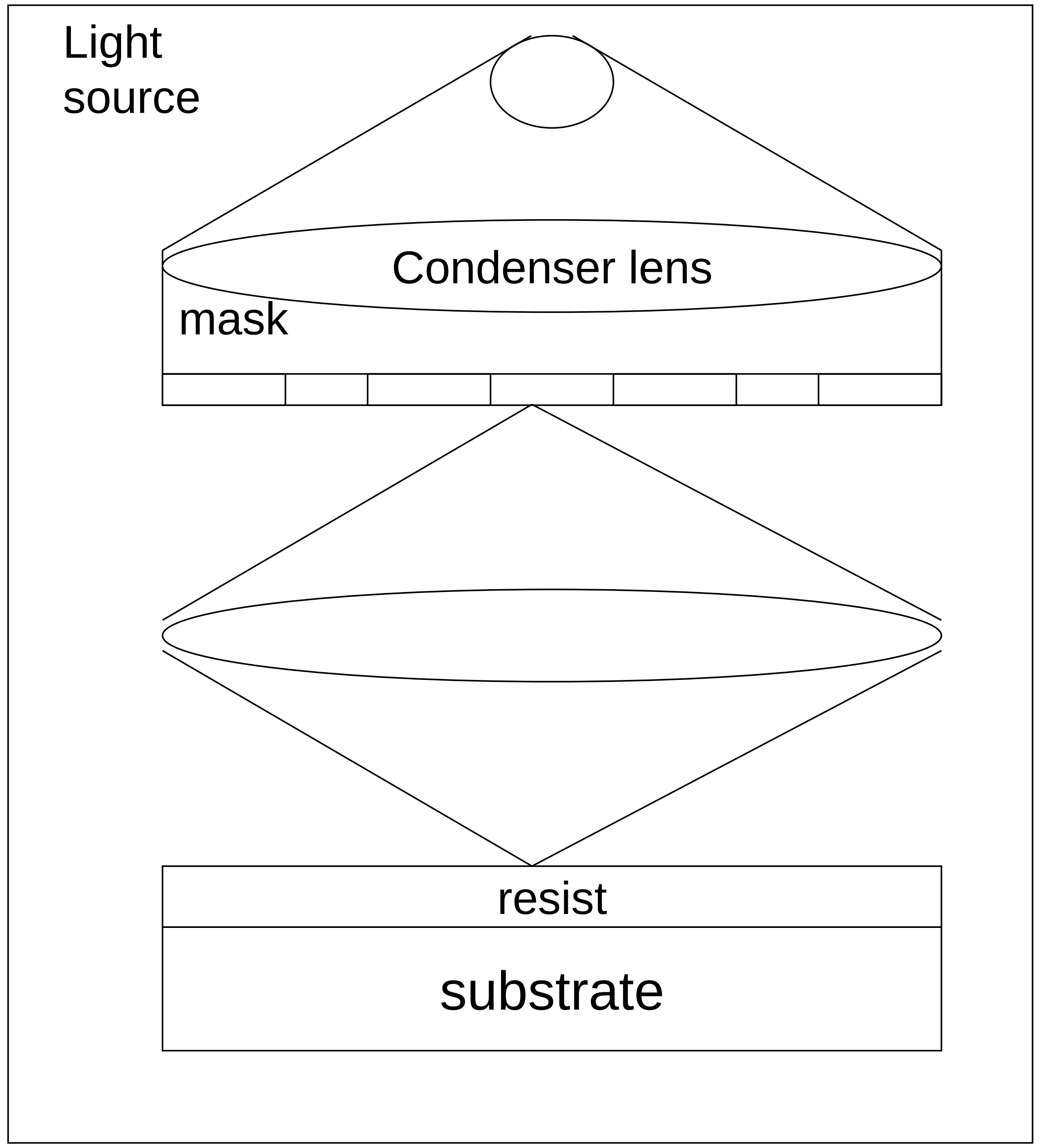




Projection lithography

- Mainly used today for IC industry
- Picture of the mask is projected
- No contact
- No deterioration
- Excellent resolution (reduction e.g. 4x, 5x)
- Reduction of errors
- Stepper, x-y movement, from field to field

projection



Rayleigh criterion says:
MFS=0.61*λ/NA

In microlithography:
$MFS=k_1*\lambda/NA$
k_1=technology cte (0.5-0.9)
Non-ideal behavior of equipment
Lens error
Resist processing, shape, etc.

$$MFS = \sqrt{d \cdot \lambda}$$
$$d = thickness(resist)$$
$$\lambda = wavelength$$

- MFS = Minimum Feature Size
  NA = Numerical Aperture

Resolution enhancement of Optical Lithography

- Resolution R:
- Depth of Focus DOF:

$$R = k_1 \frac{\lambda}{NA} \qquad DOF = k_2 \frac{\lambda}{NA^2}$$

* NA = Numerical Aperture, λ = wavelength

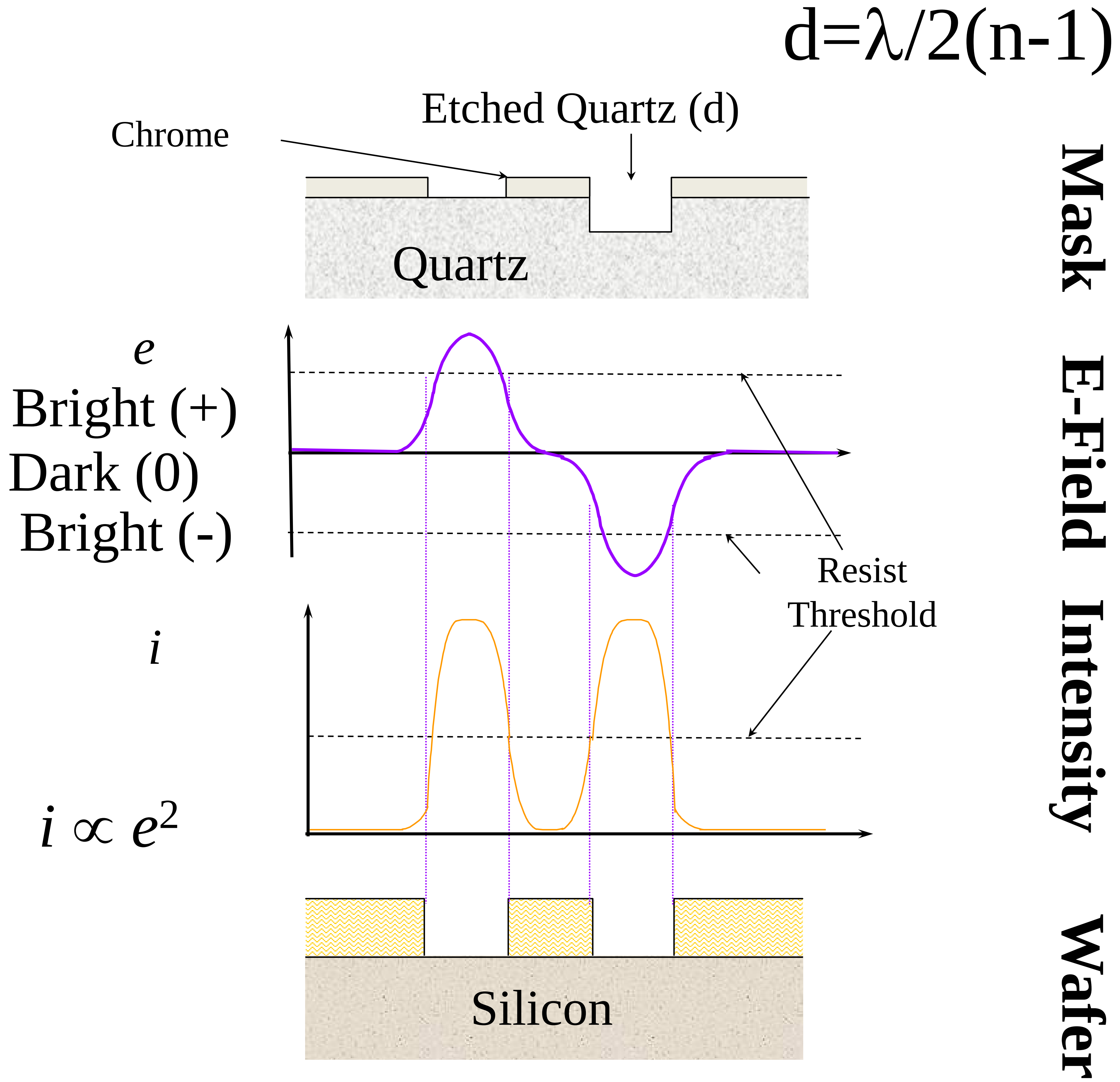
- To decrease R: → need to decrease λ and increase NA (stepper)
- But: DOF decreases too

- → need to decrease k_1
- k_1 = optical engineering = f(resist, mask , illumination)

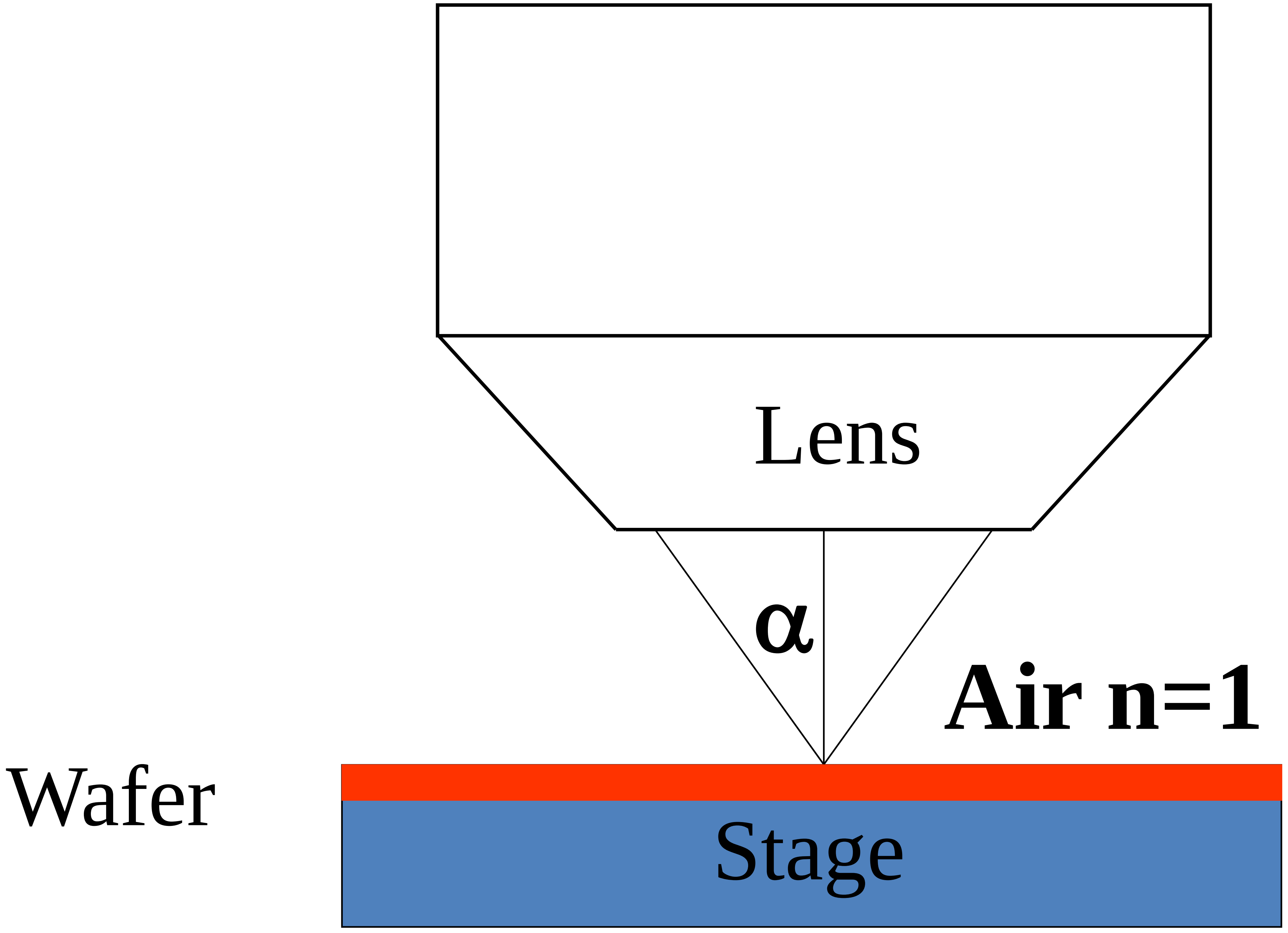
- Examples: Optical Proximity correction (OPC), Phase shift mask (PSM), Off-axis illumination (OAI)

Phase shift mask

- Normal masks are called binary
- PSMs transmit with a phase shift
- Semi-transparent structures that produce a 180 deg phase shift
- Either removed quartz parts, or added
- Creates destructive interference
- Enhances intensity profile
- Sharper image
- Higher resolution



Immersion lithography

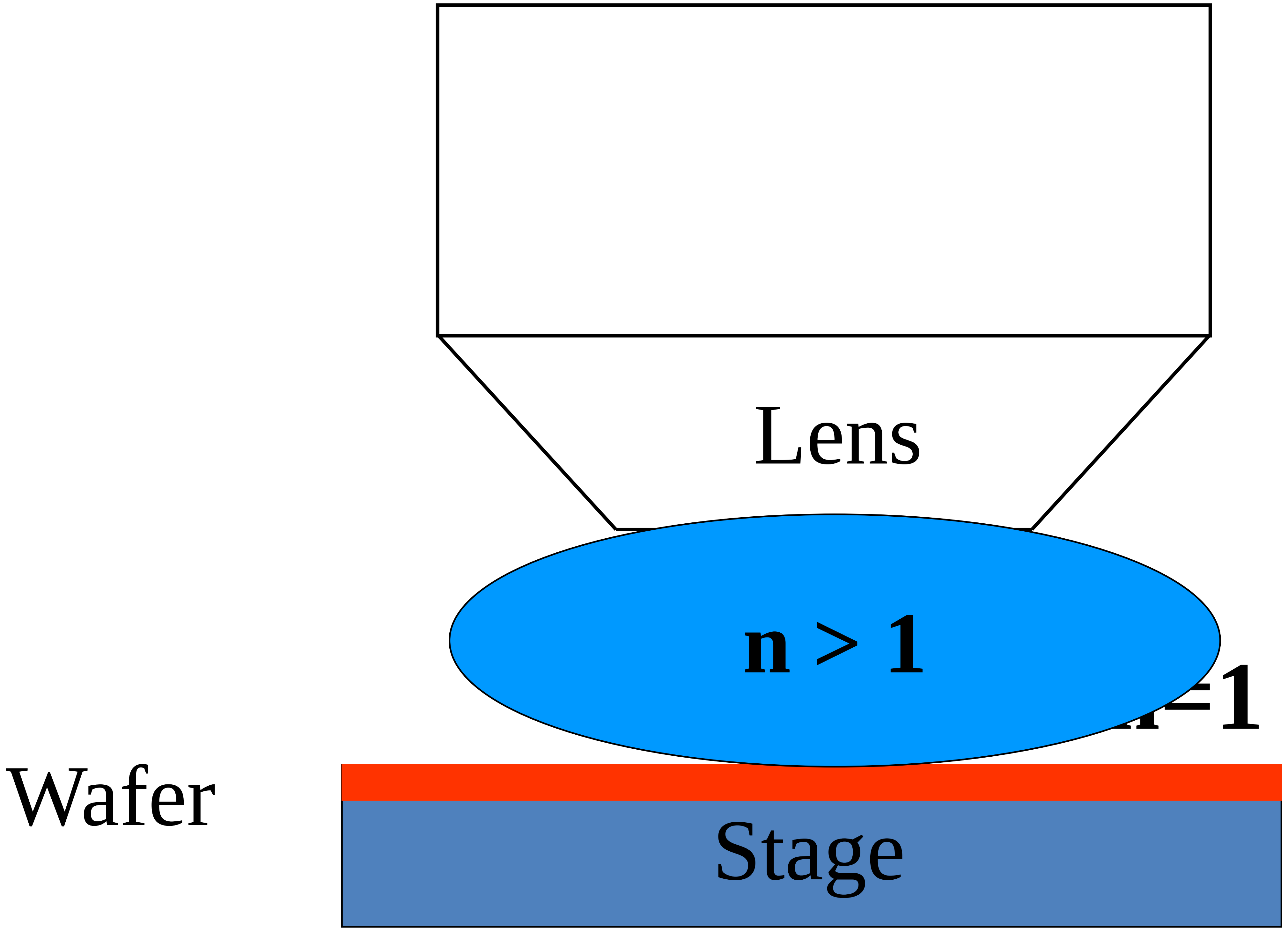


$NA = n \sin \alpha$

$R = k_1 \lambda / NA$

$DOF = k_2 \lambda / NA^2$

Immersion lithography



	Medium	n	λ/n
193 nm dry	Air	1.0	193 nm
193 nm immersion	H_2O	1.44	134 nm
157 nm dry	N_2	1.0	157 nm
157 nm immersion	PFPE	1.37	115 nm

$NA = n \sin \alpha$

$R = k_1 \lambda / NA$

$DOF = k_2 \lambda / NA^2$

$R = k_1 (\lambda/n) / \sin \alpha$

$DOF = k_2\, n\lambda / NA^2$

Lithography 4: Electron beam lithography

I. Tool overview

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Lithography

- General concepts
- Mask writing and Direct Write Laser
- UV lithography
- Electron Beam Lithography (EBL)
  - Tool
  - Process
- Alternative lithographies

Electron beam lithography (EBL): tool

- System overview
- Vacuum levels
- Electron guns
- Electron lenses
- Lens aberrations
- Beam deflection and writing
- Typical tools

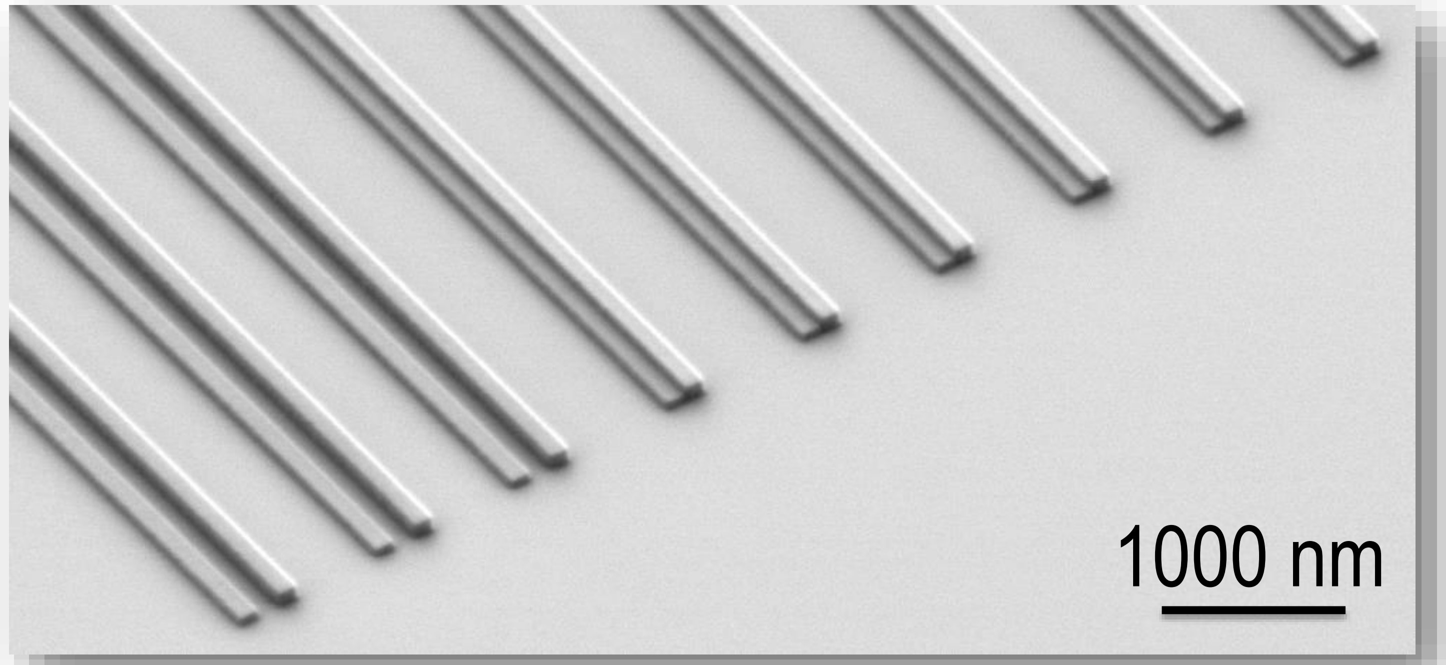
EBL: basic concepts

- Why use electrons instead of photons?
  - Overcome the optical diffraction limit
  - Electron wavelength, De Broglie equation

kV	1	10	100
nm	0.038	0.012	0.0038

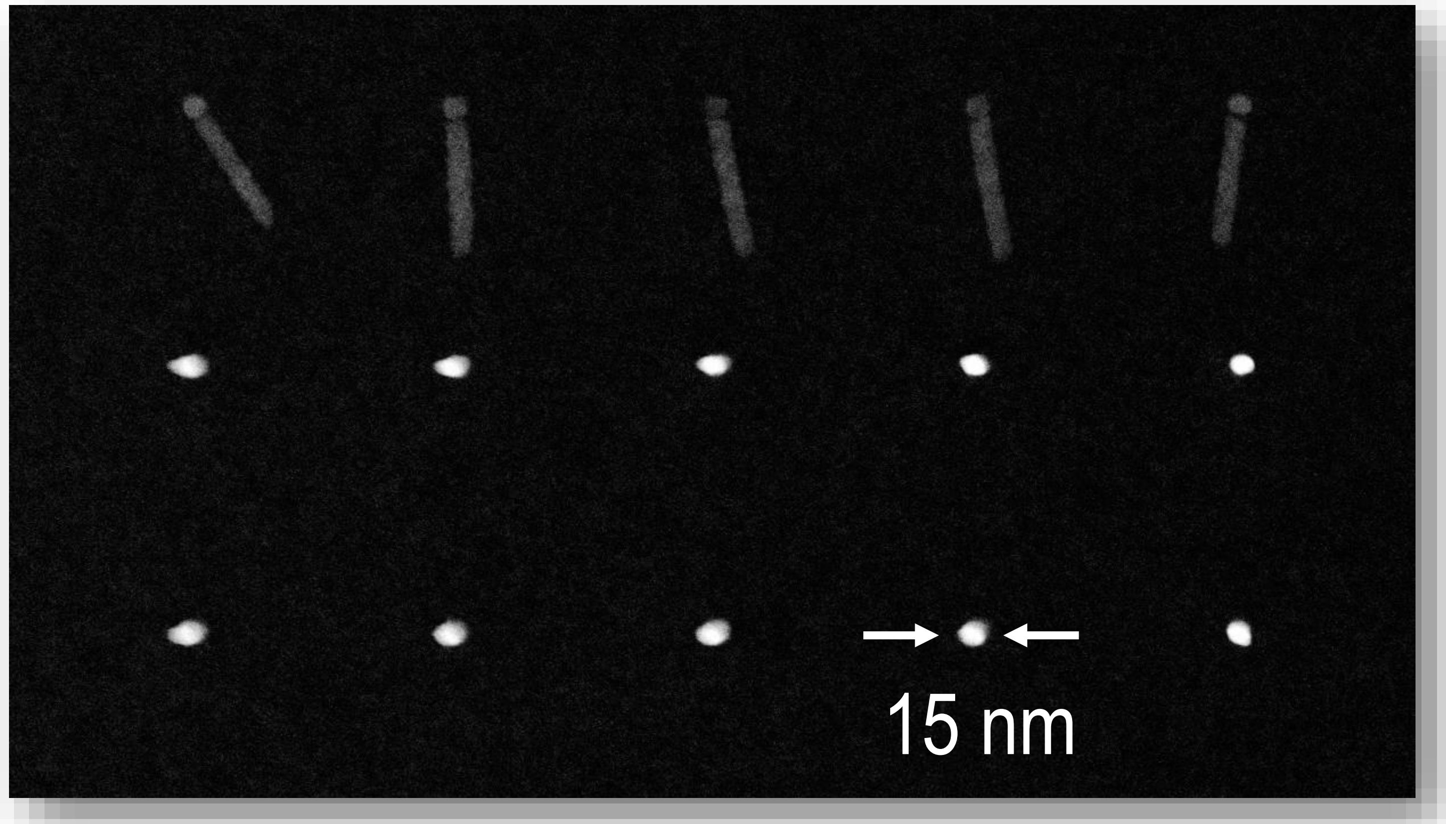
  - sub-20 nm features feasible
  - Writing tool for UV/DUV masks
- What are the «cons»?
  - Expensive
  - Slow when compared to projection lithography systems

SEM image of two layer lithography with negative resist (HSQ)



V. Flauraud - EPFL

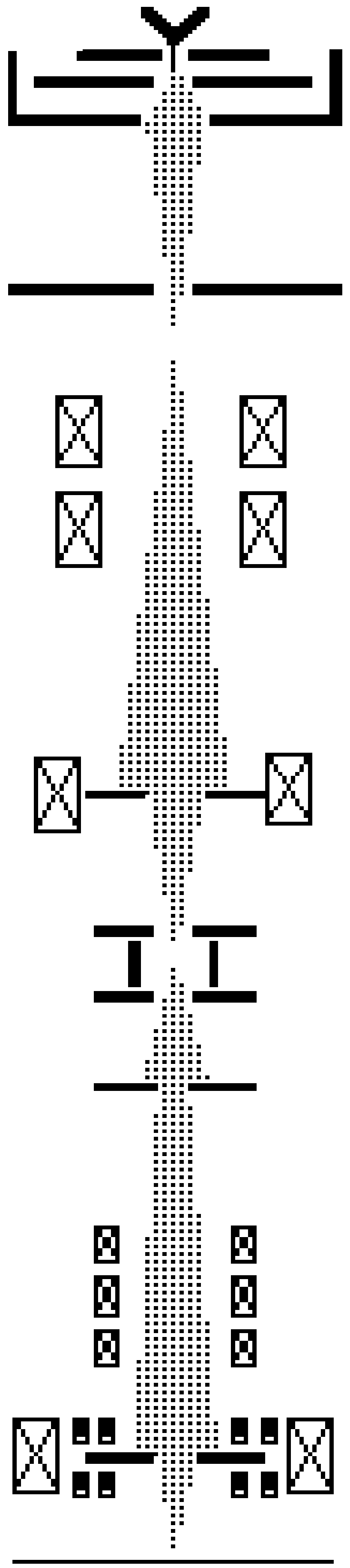
Negative resist (HSQ) pillars 15 nm diameter, 150nm height

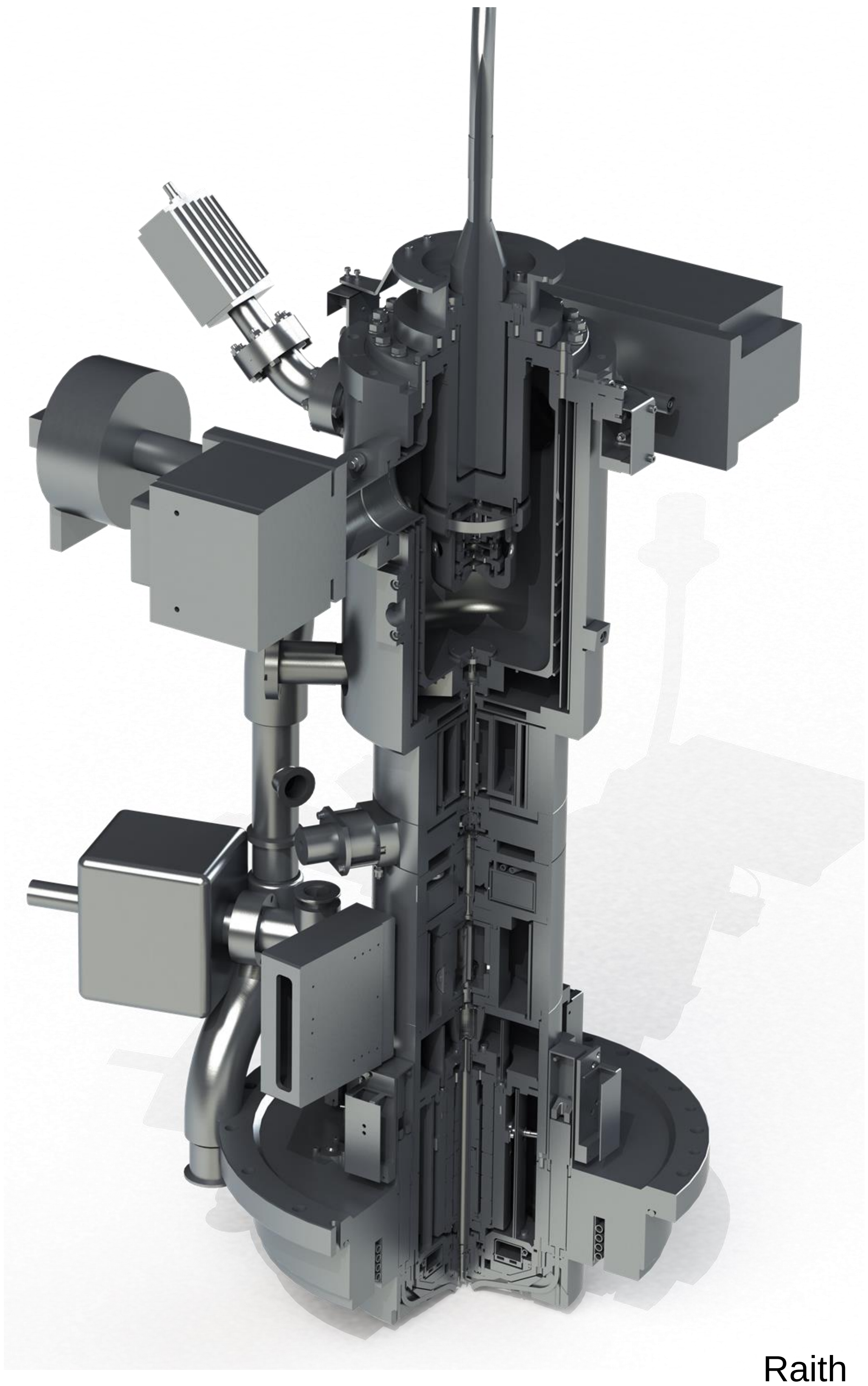


V. Flauraud - EPFL

EBL: tool overview

- Key components:
  - An electron gun
  - Electron optics and blankers
  - A pattern generator
  - A load-lock as the system operates in vacuum
  - A high resolution interferometric stage
  - An interferometric height measurement





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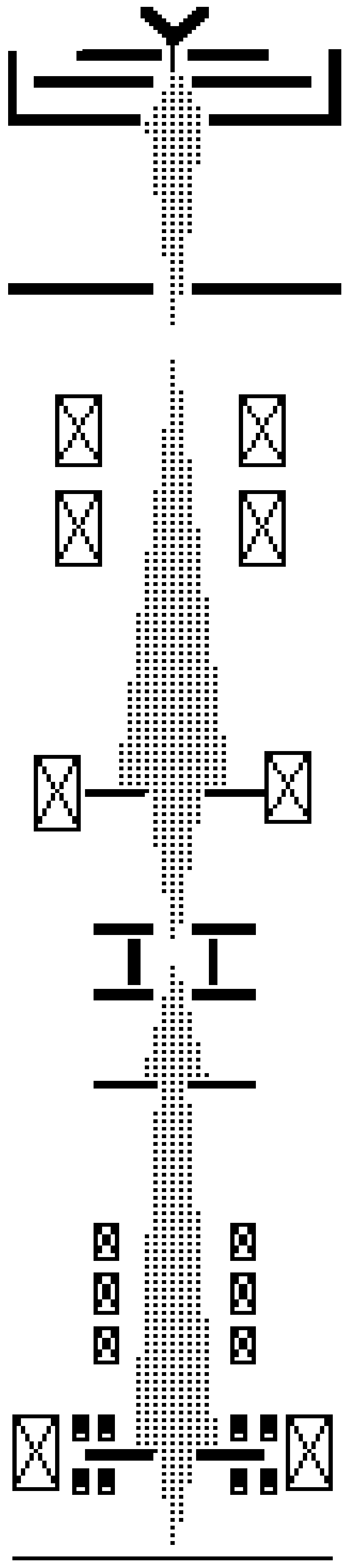
EBL: vacuum levels

- Electron source
  - 1.10^{-10} mbar
  - Ion pump
- Electron optics column
  - 1.10^{-8} mbar
  - Ion pump
- Substrate transfer and stage
  - 5.10^{-7} mbar
  - Turbomolecular pumps



EBL: electron source / « electron gun »

- 2 types of sources:
  - Thermionic
  - Field Emitter
- High voltage
- Maximum beam current
- Electron virtual source size
- Electron energy spread
- Lifetime and stability

EBL: electron guns

- Field emitters
  - electric-field driven tunelling
  - Schottky field emitter
    - High current density
    - 1800° C
    - Energy spread 0.9 eV
    - Source size 20nm
  - Cold field emitter
    - Low current stability
    - 20° C
    - Energy spread 0.22 eV
    - Source Size 5nm

- Thermionic
  - Work function overcome by heat
  - Large source size >20um
  - Low cost

Schottky FEG with ZrO2 revervoir and tip close-up

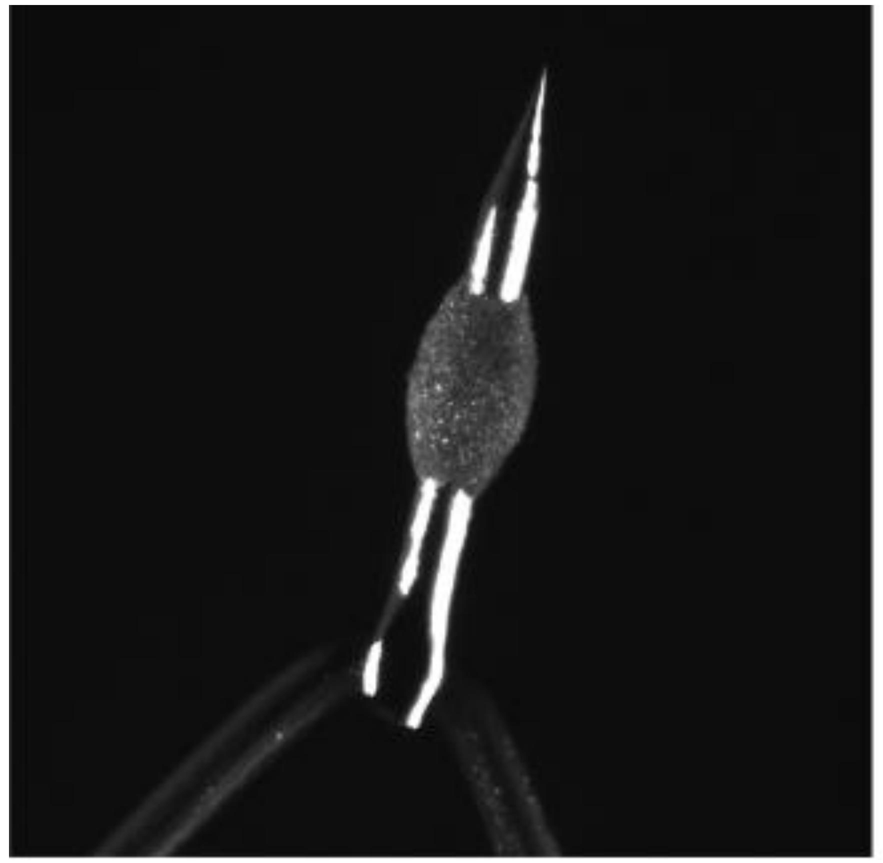


Image: 1.25x1.25 mm

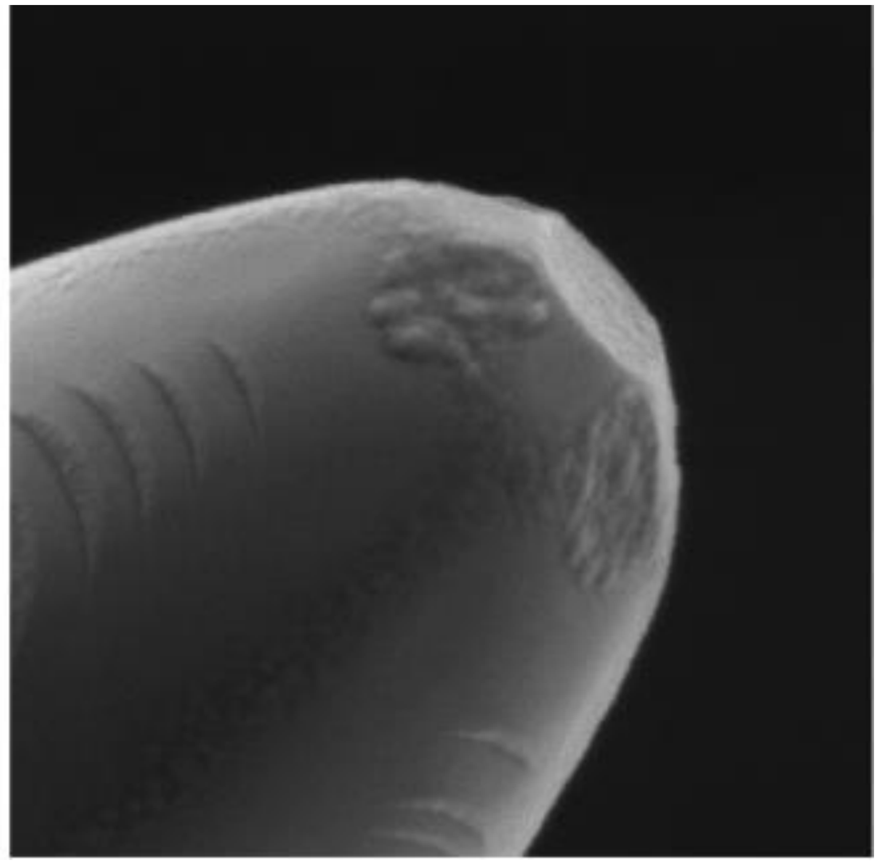
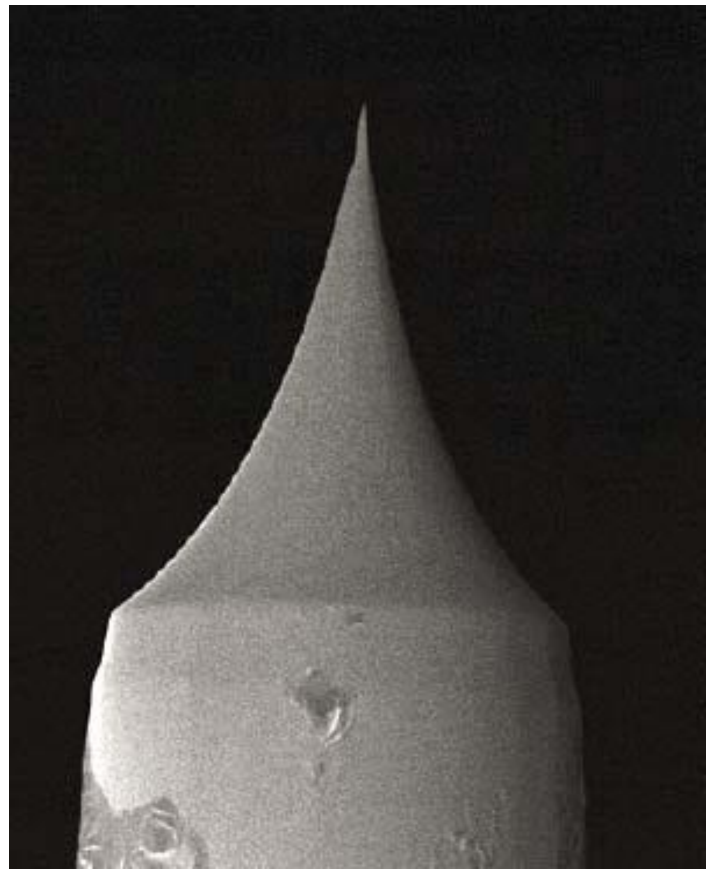
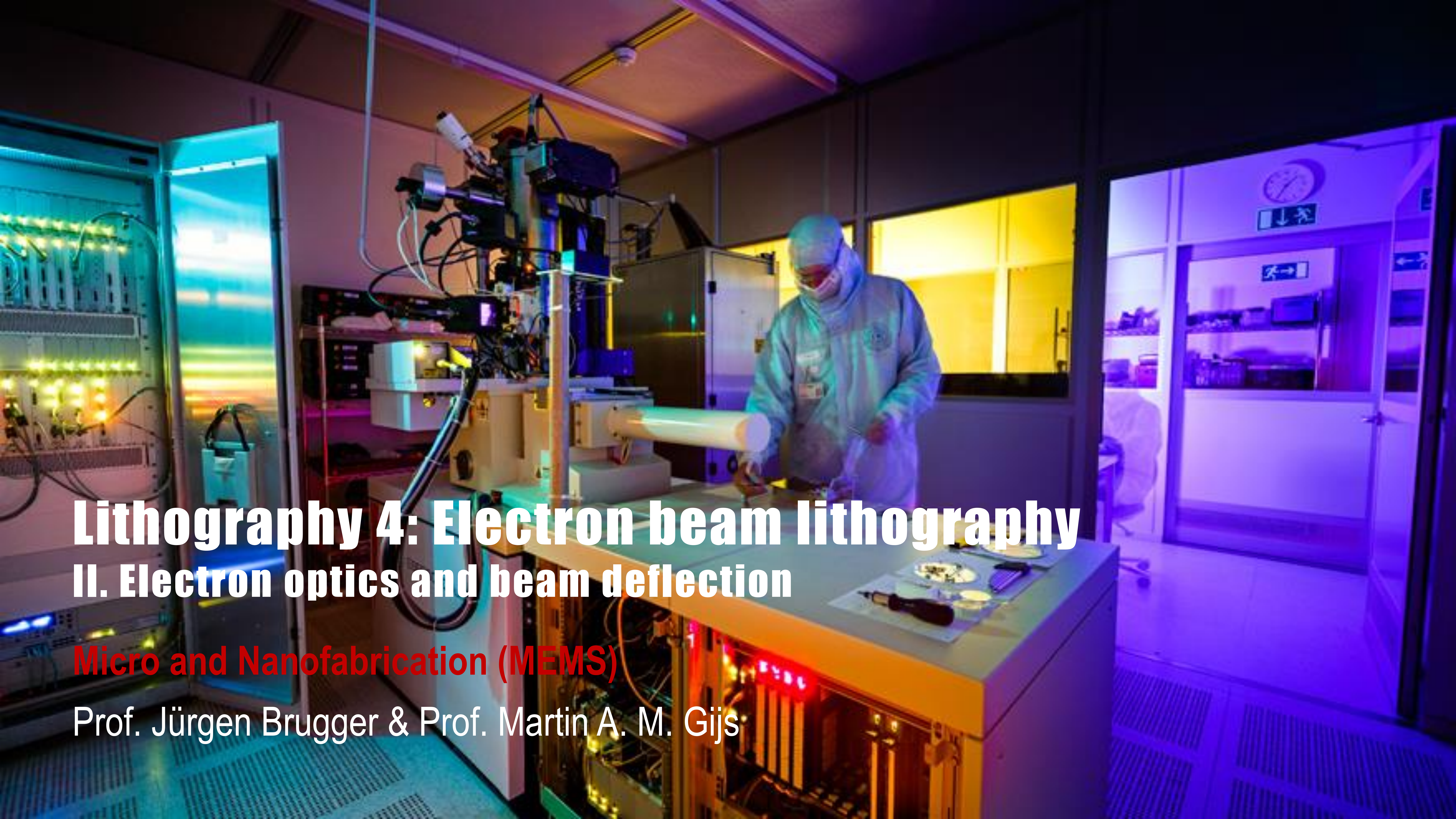


Image: 1.45x1.45 µm

I. Liska – Brno University of Technology

Sharp W tip (CFEG)





Lithography 4: Electron beam lithography

II. Electron optics and beam deflection

Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

EBL: electron optics / lenses

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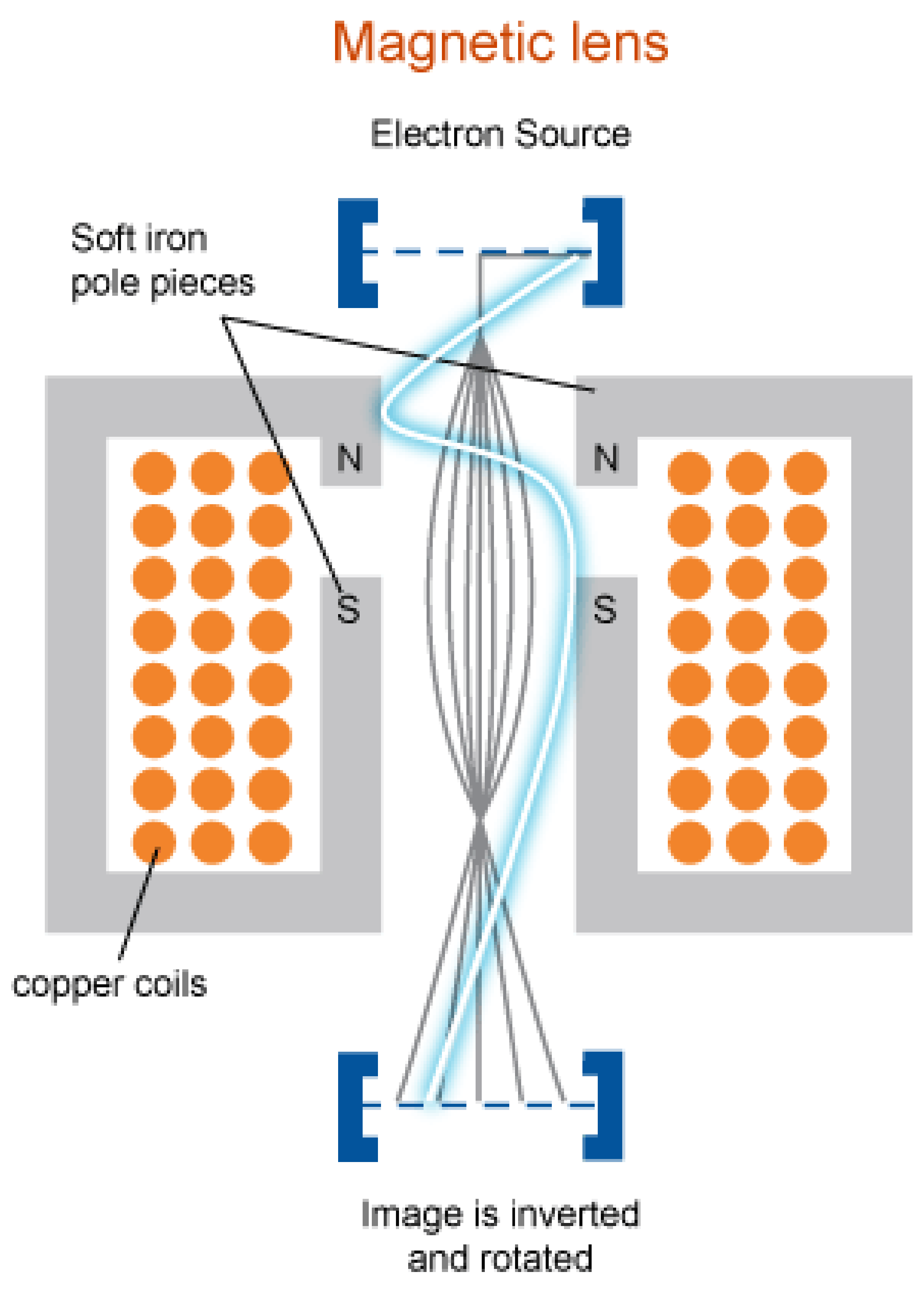
- $F = q(E + v \times B)$

F = Lorentz force
q = charge
E = electric field
v = velocity
B = magnetic field

- Electrostatic vs electro-magnetic

- Electrostatic
  - Fast but large aberrations
  - Ideal for the beam blanker

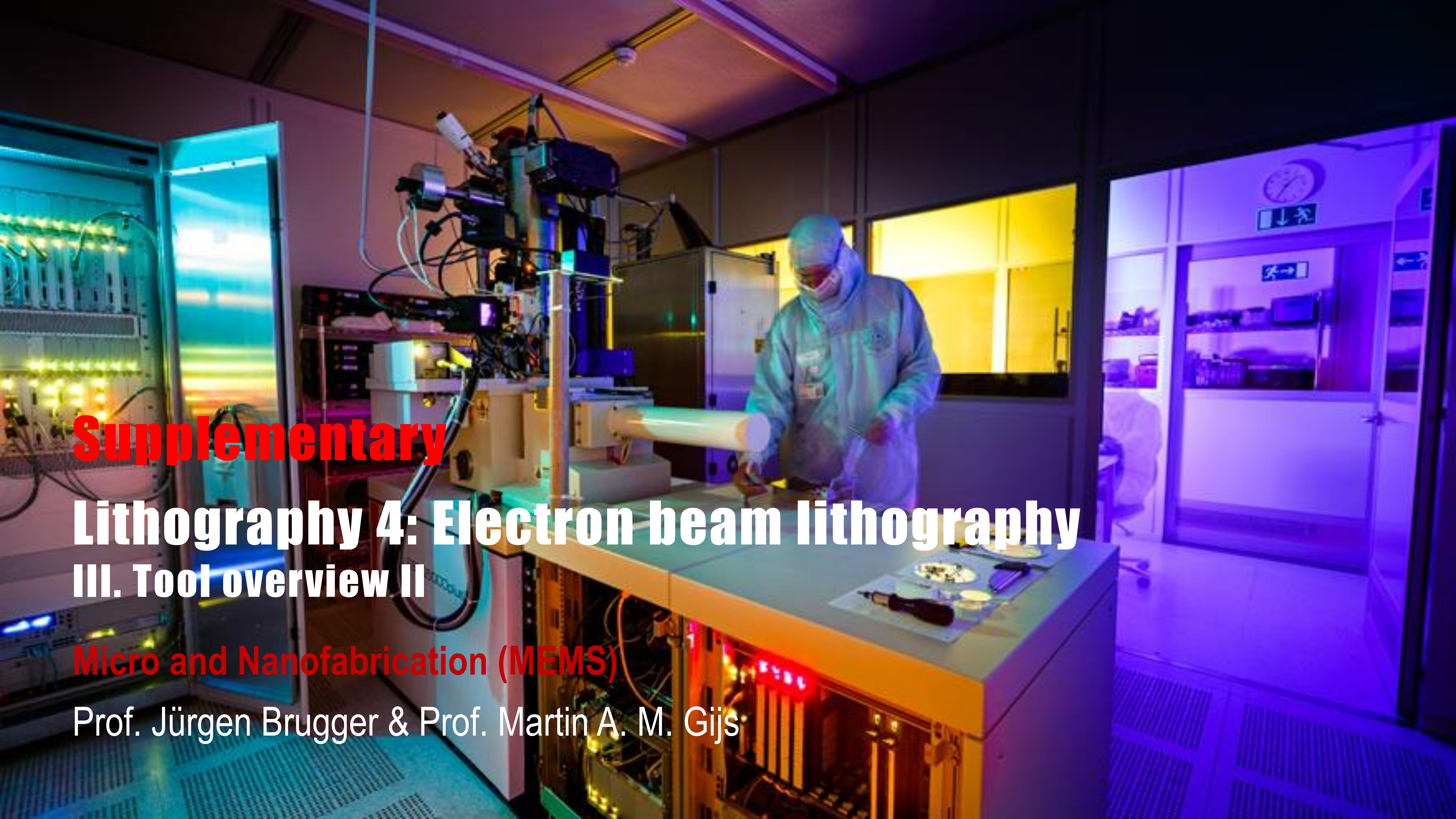
- Electro-magnetic
  - Aberration correction possible
  - Electrons spiral through the lens
  - Inductance of the magnetic coils limits their frequency response



Australian Microscopy & Microanalysis Research Facility

EBL: beam deflection and stages

- Typical beam deflections
  - up to 1x1mm at best
  - The pattern must be split into fields to write at wafer scale
- Fields are devided in sub-fields
  - Approximately 10x10μm in order to avoid large deflections that would be slow
- Beyond one write field the stage is physically moved at the wafer scale
- Field stitching
- Raster or vector scan



Supplementary

Lithography 4: Electron beam lithography

III. Tool overview II

Micro and Nanofabrication (MEMS)

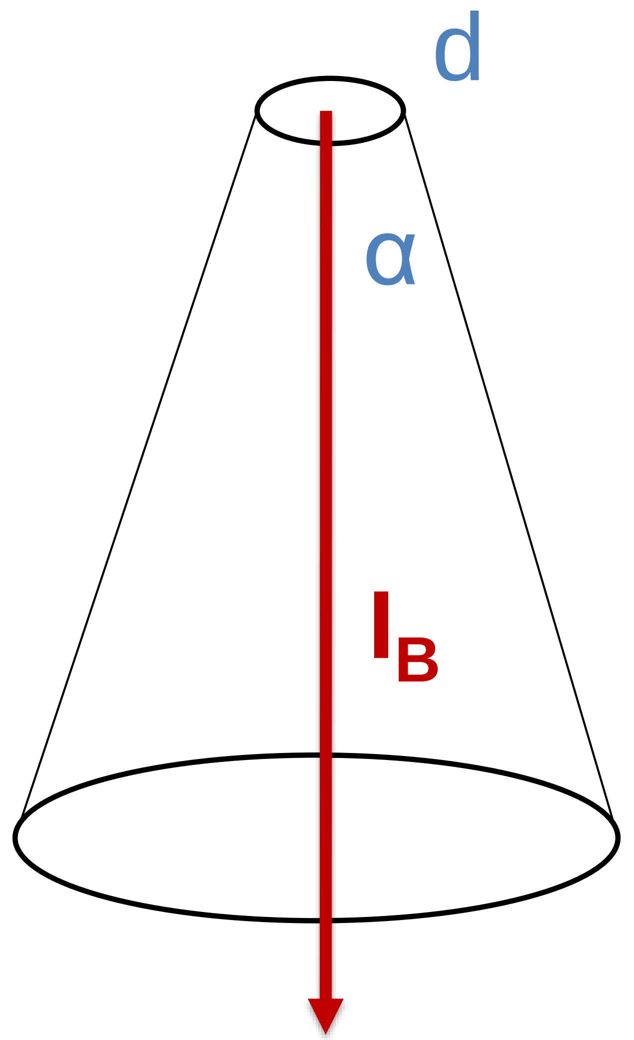
Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

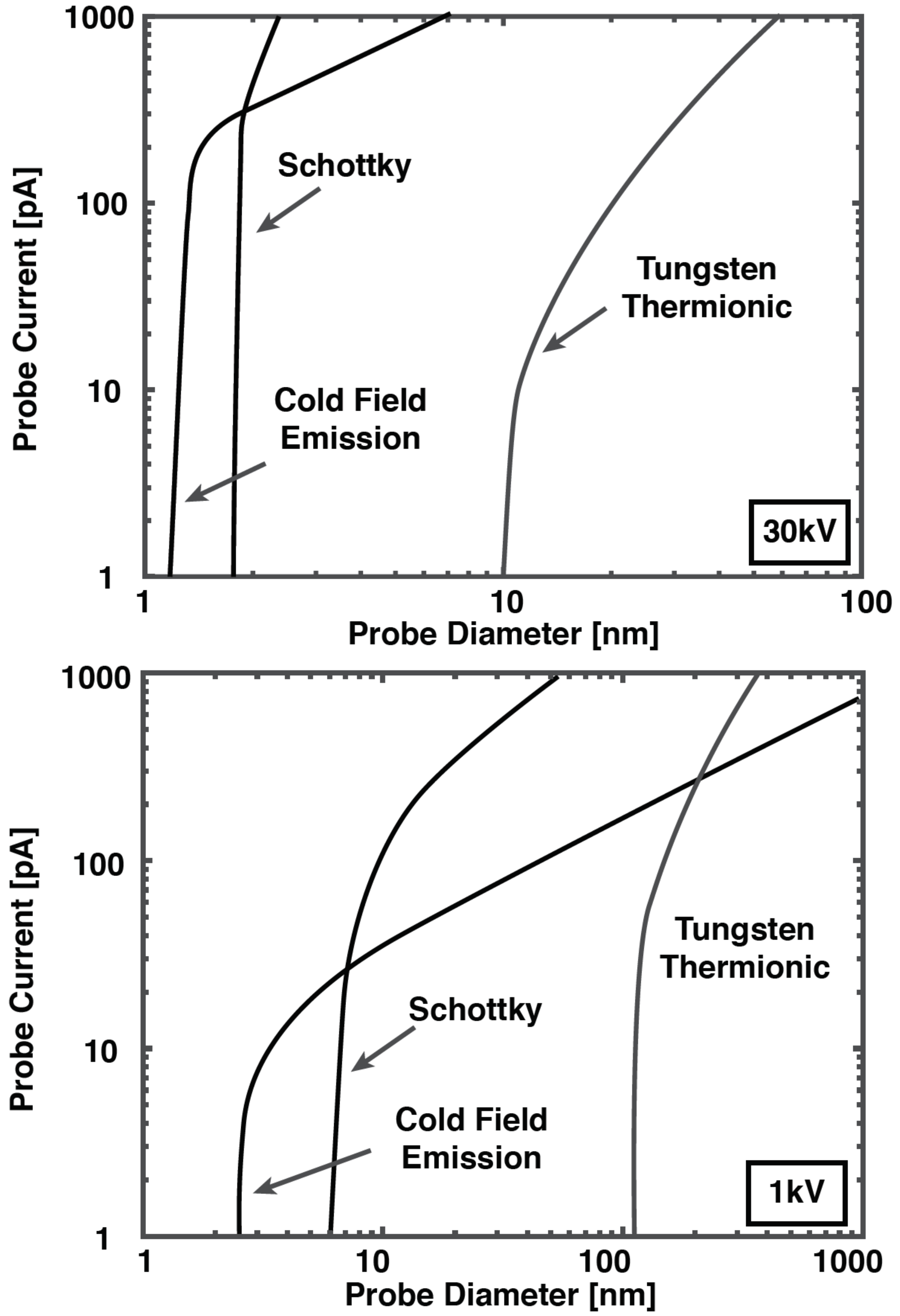
EBL: electron gun brightness

- Probe size depends on
  - Gun type
  - Acceleration voltage
  - Extraction current
- Gun brightness β
- EBL writing speed: varying beam properties for different features

$$\beta = \frac{beam\ current}{area \cdot solid\ angle}$$

$$\beta = \frac{4\, I_B}{\pi^2\, d^2 \alpha^2}$$

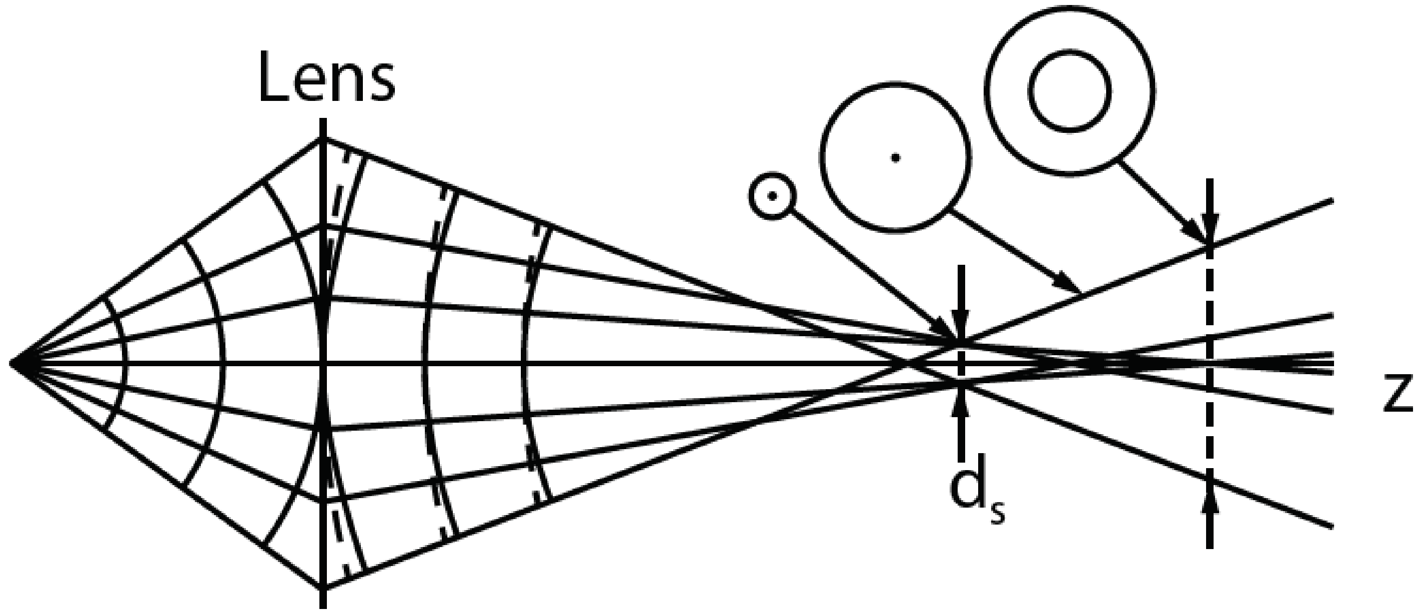




EBL: electron lens aberrations

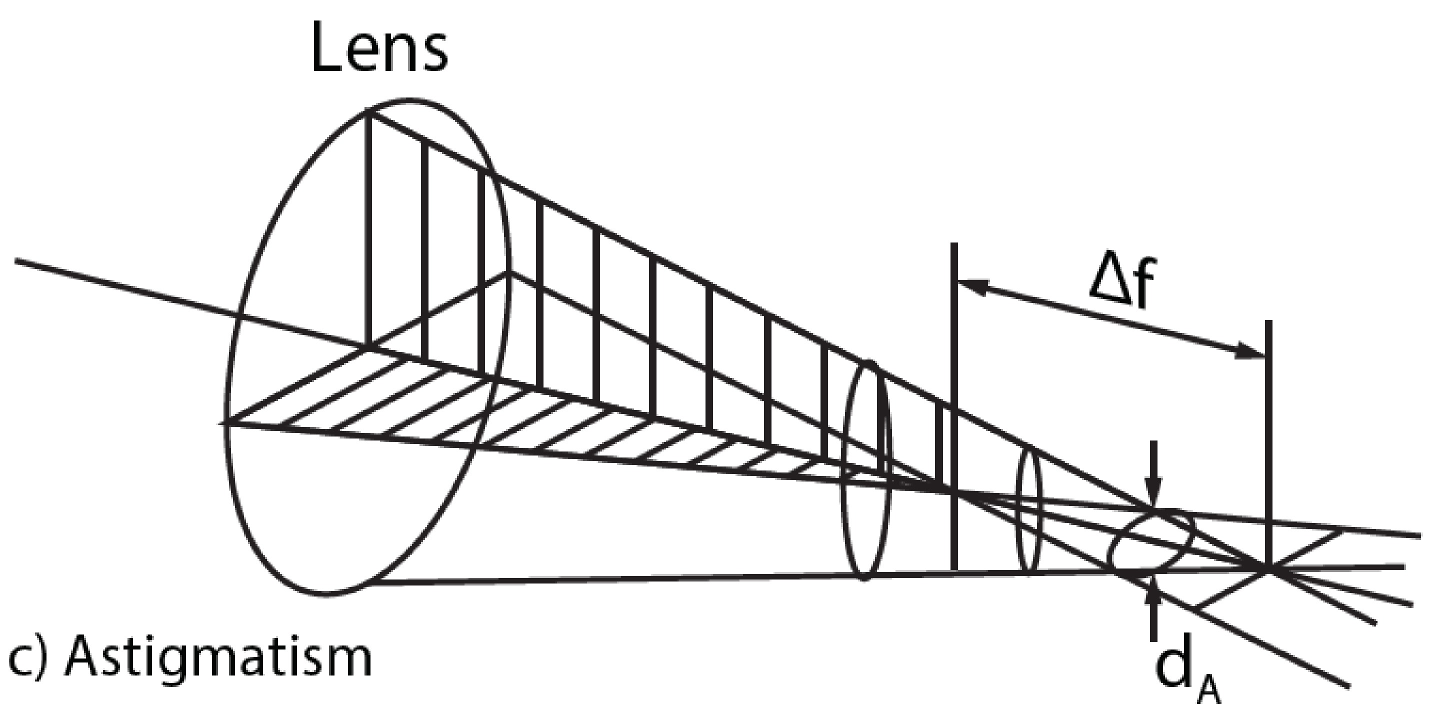
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

(a) Spherical aberration, (b) Chromatic aberration, (c) Diffraction, (d) Astigmatism

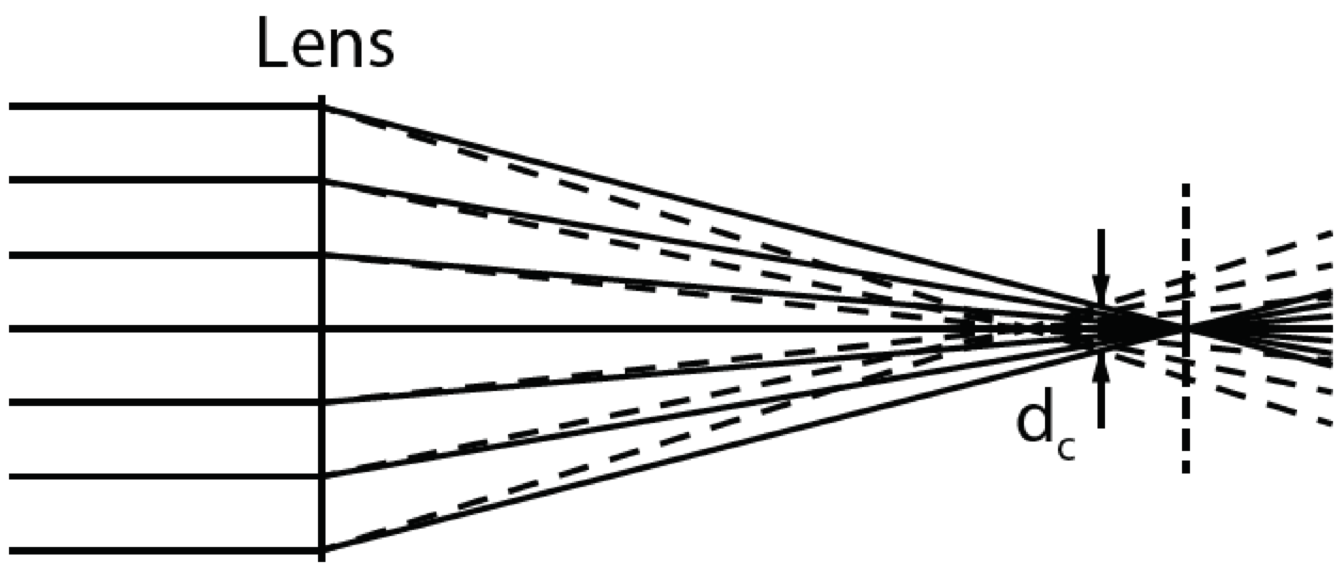


a) Spherical aberration

- - - Wavefront without spherical aberration
—— Wavefront with spherical aberration

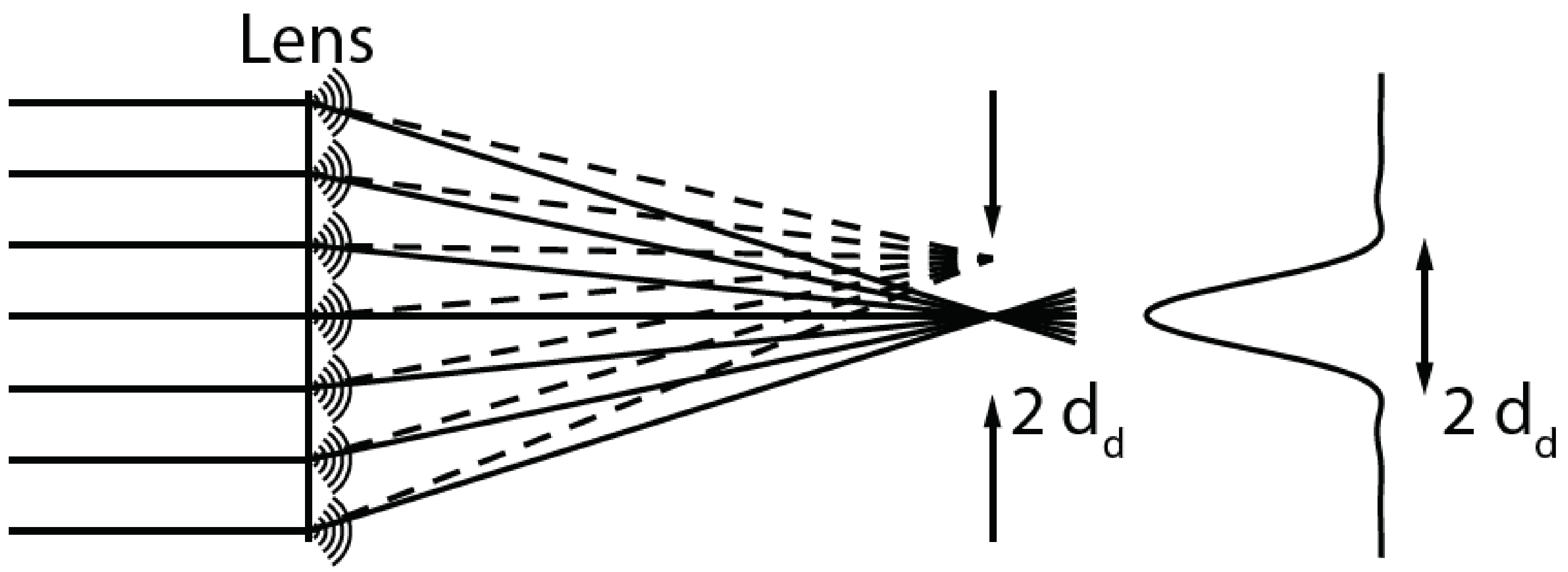


c) Astigmatism



b) Chromatic aberration

- - - U_0-ΔU
—— U_0



d) Diffraction

EBL: effective beam diameter

Effective beam diameter

$$d = \sqrt{d_g^2 + d_s^2 + d_c^2 + d_d^2}$$

d_v: virtual source diameter
M (>1): demagnification

$$d_g = \frac{d_v}{M}$$

Spherical aberration

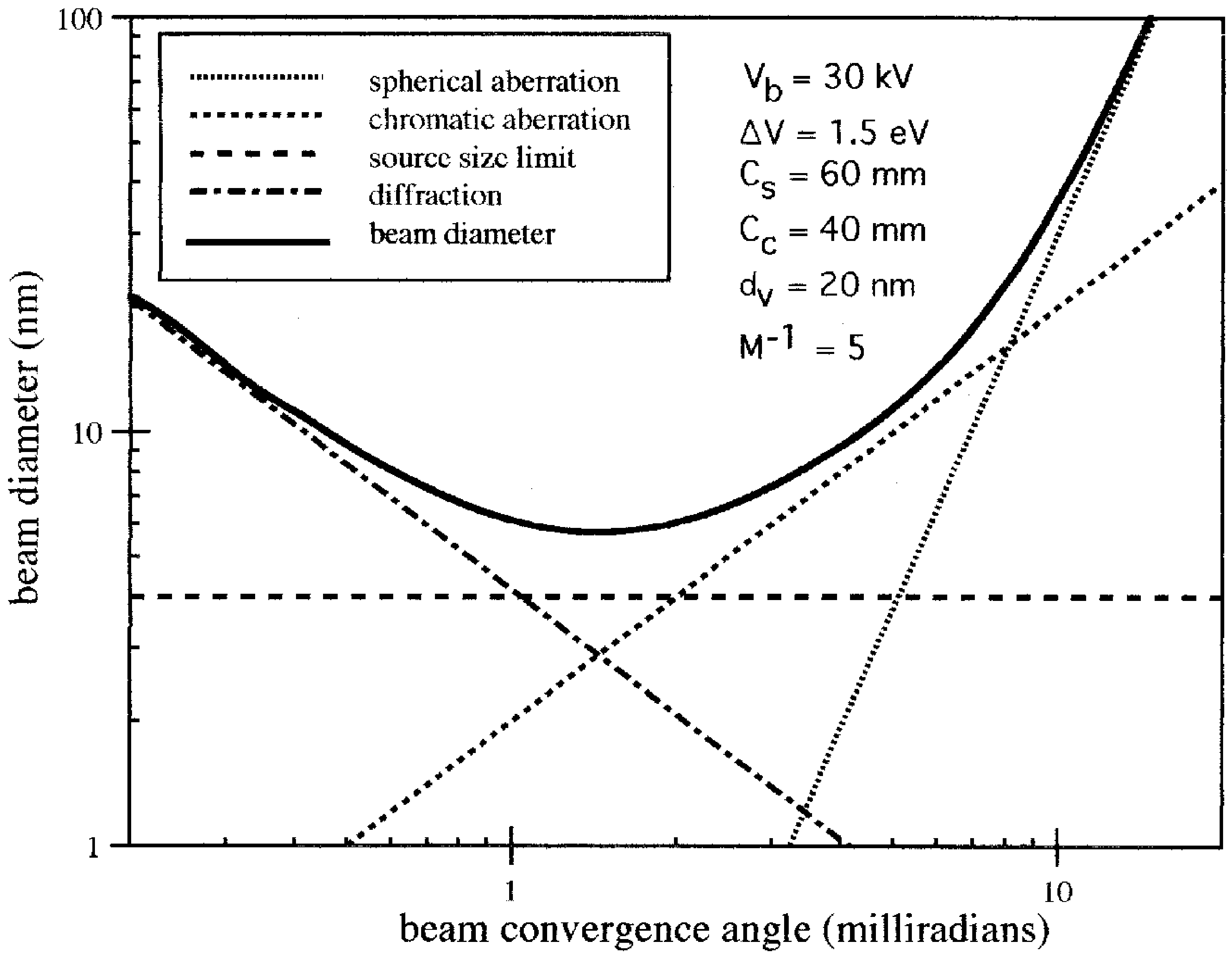
$$d_s = \frac{1}{2} C_s \alpha^3$$

Chromatic aberration

$$d_c = C_c \alpha \frac{\Delta V}{V}$$

Diffraction

$$d_d = 0.61 \frac{\lambda}{\alpha}, \lambda = \frac{1.2}{\sqrt{V}} nm$$



SPIE Handbook of Microlithography, Micromachining and Microfabrication
Mark A. McCord, Michael J. Rooks, 1997
Reproduced by permission of the Institution of Engineering & Technology

EBL: classical implementation

- Converted SEM*
  - Conventional SEM column (30kV)
  - Almost no SEM modification
  - Add beam blanker
  - Add hardware controller and software
  - SEM + extra $100K
- Dedicated EBL
  - High energy column (100kV)
  - Dedicated electron optics
  - High reproducibility
  - Automatic and continuous (over few days) writing
  - >$5M

*SEM: scanning electron microscope

Supplementary

Lithography 5: Electron beam lithography

Design preparation and fracture

Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

Lithography

- General concepts
- Mask writing and Direct Write Laser
- UV lithography
- Electron Beam Lithography (EBL)
  - Tool
  - Process (design and writing)
- Alternative lithographies

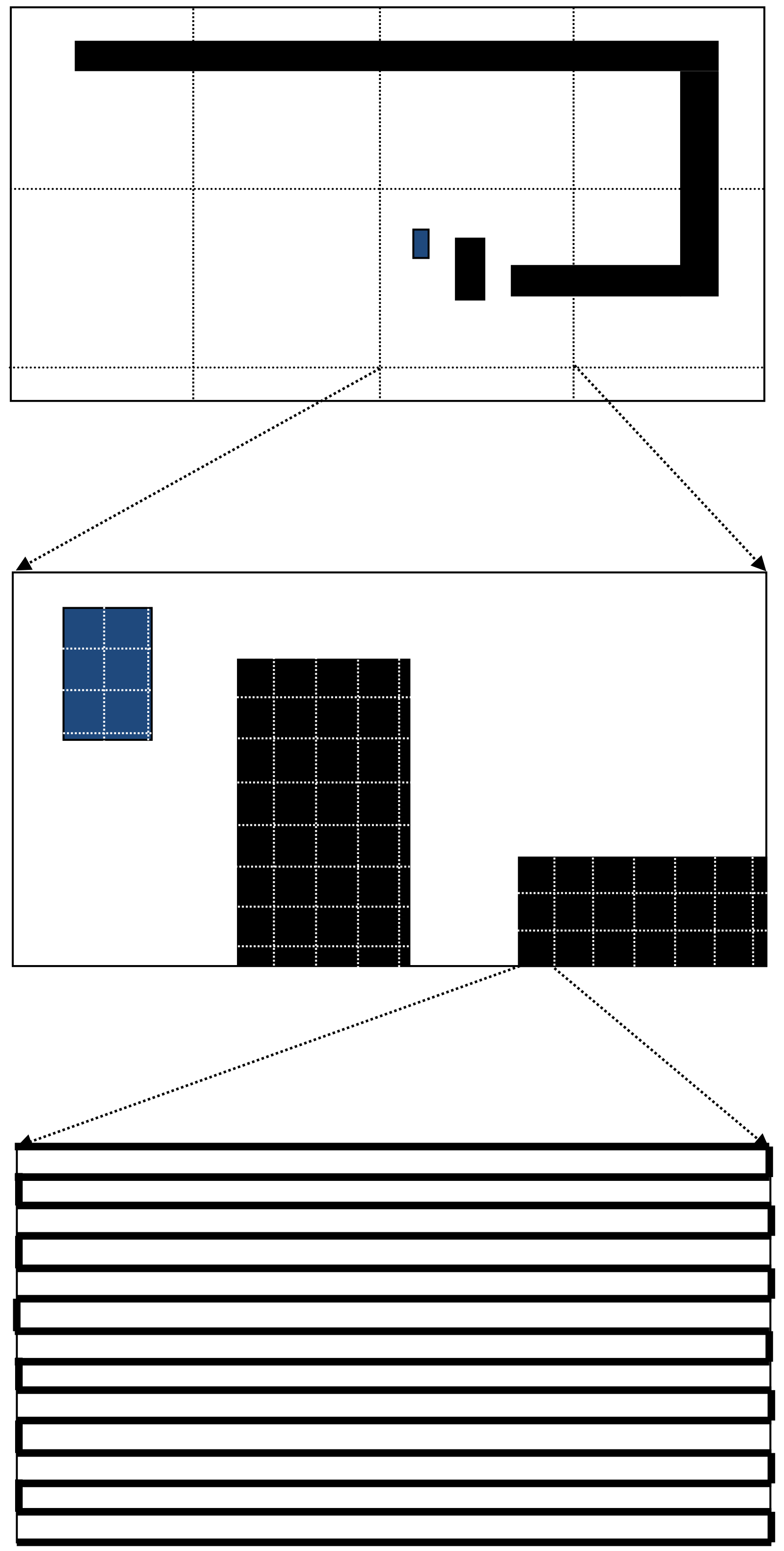
Overview

- Design preparation and fracture
- Electron sample (resist) interaction
- Resist contrast
- Positive and negative resists
- Proximity effects
- Alignment process
- Examples

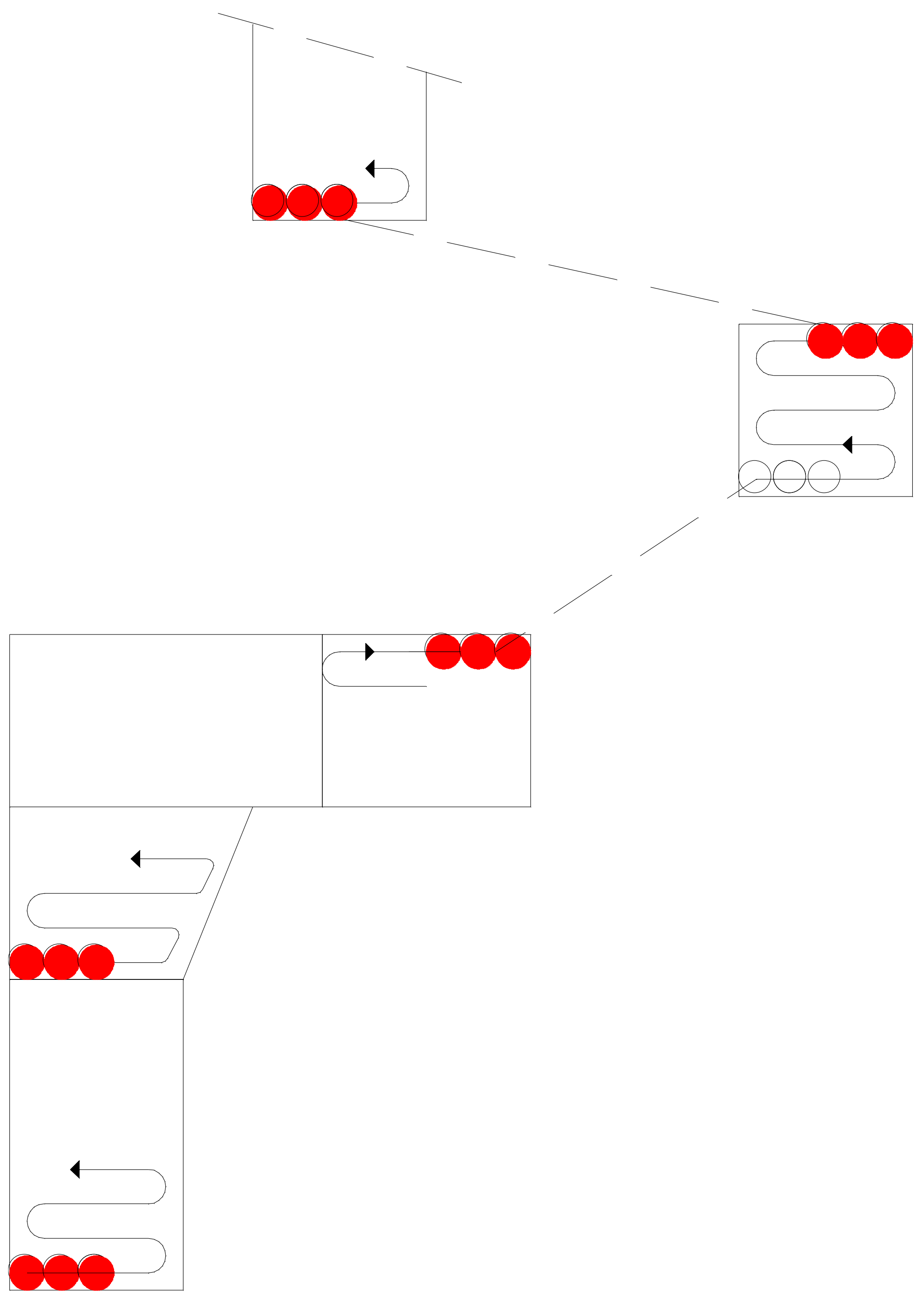
Design preparation: fracture

- Fracture
  - Conversion from shape to «shots»
- Fracture influences
  - Resolution
  - Line edge roughness
  - Aliasing and discretisation
- Beyond beam step size (BSS)
  - Fracture scheme
  - Shape specific fracture
  - Example: optimise for circles

Field fracture



Shape fracture

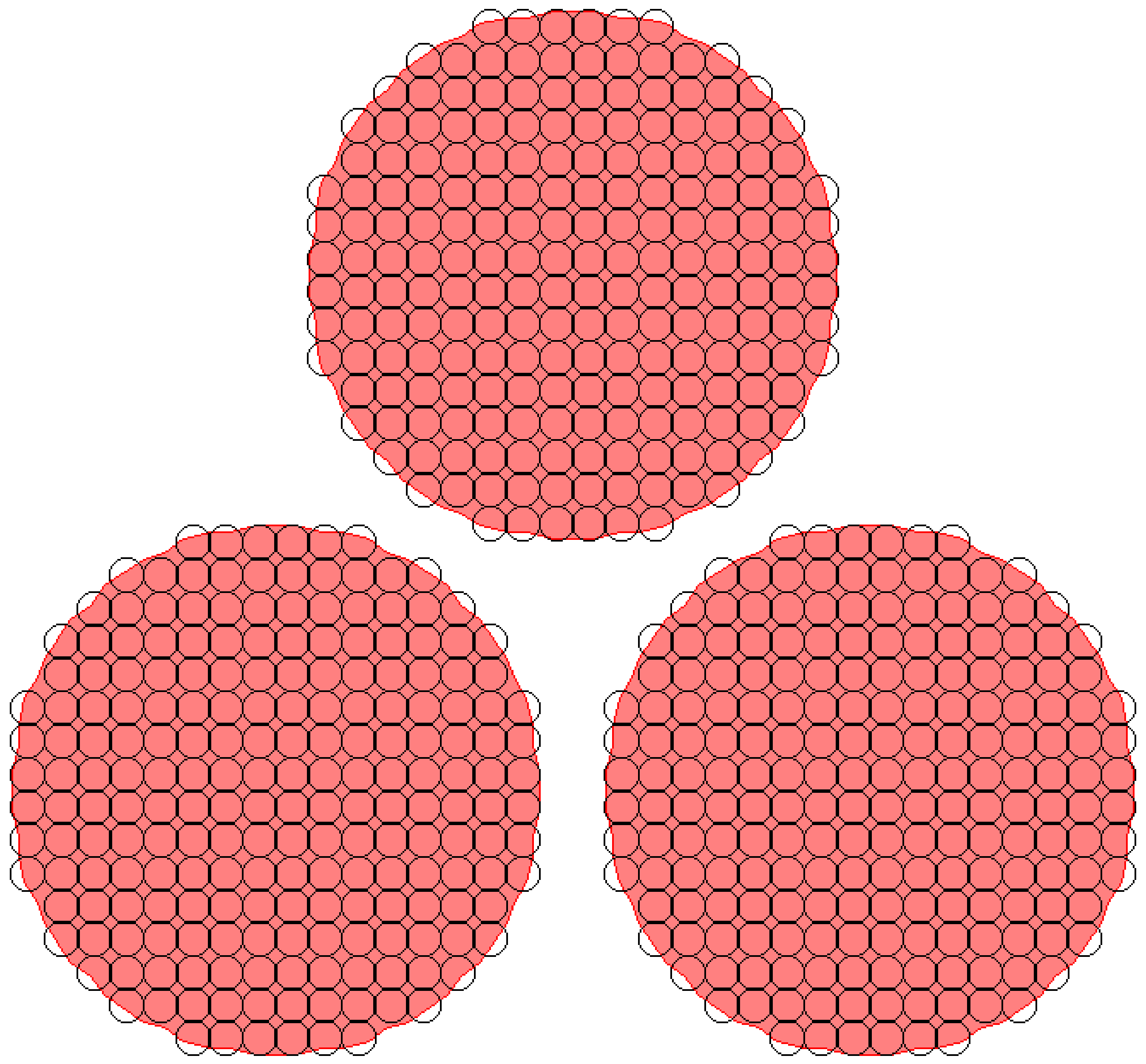


Raith

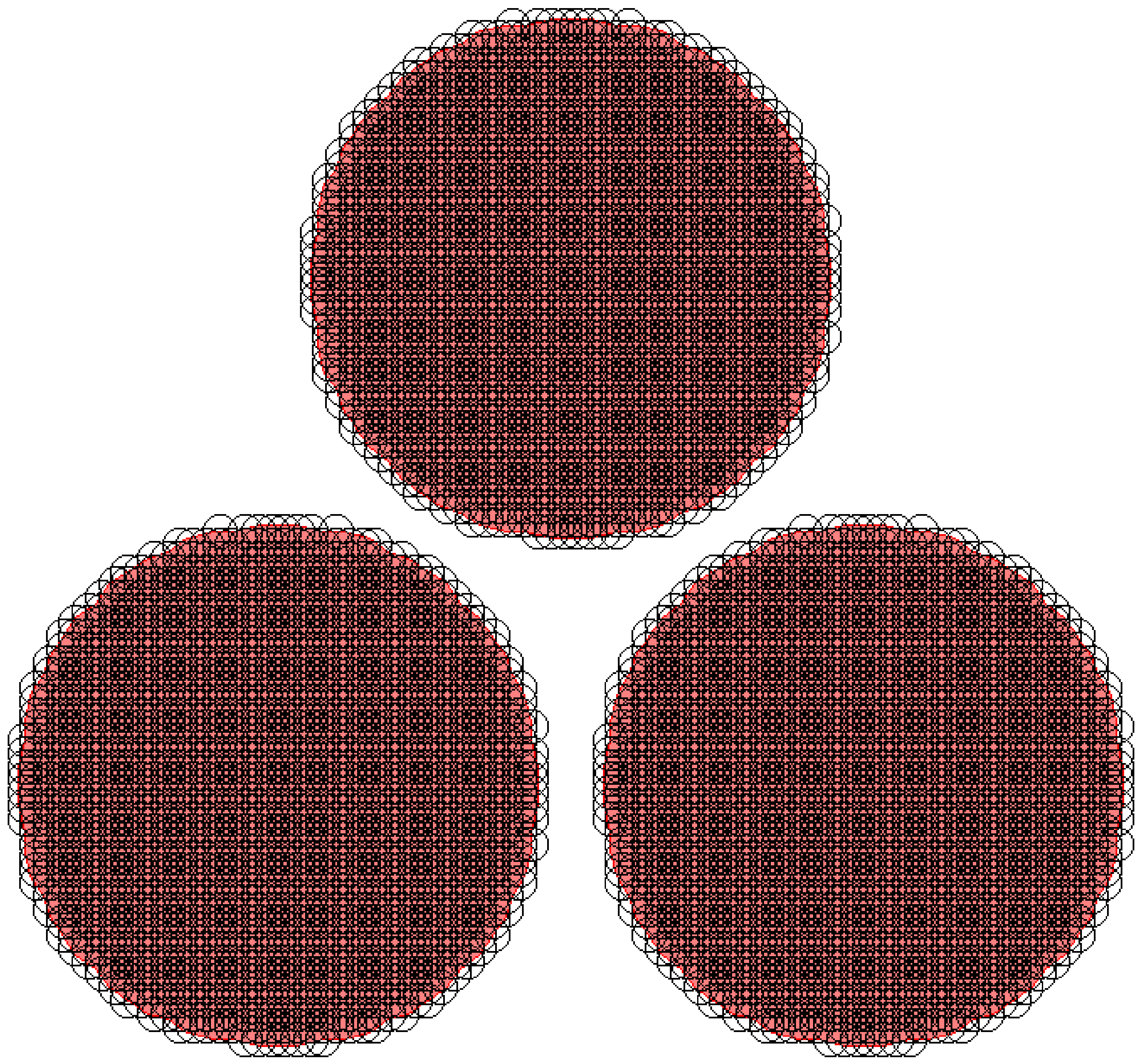
Design preparation: fracture

- Beam step size

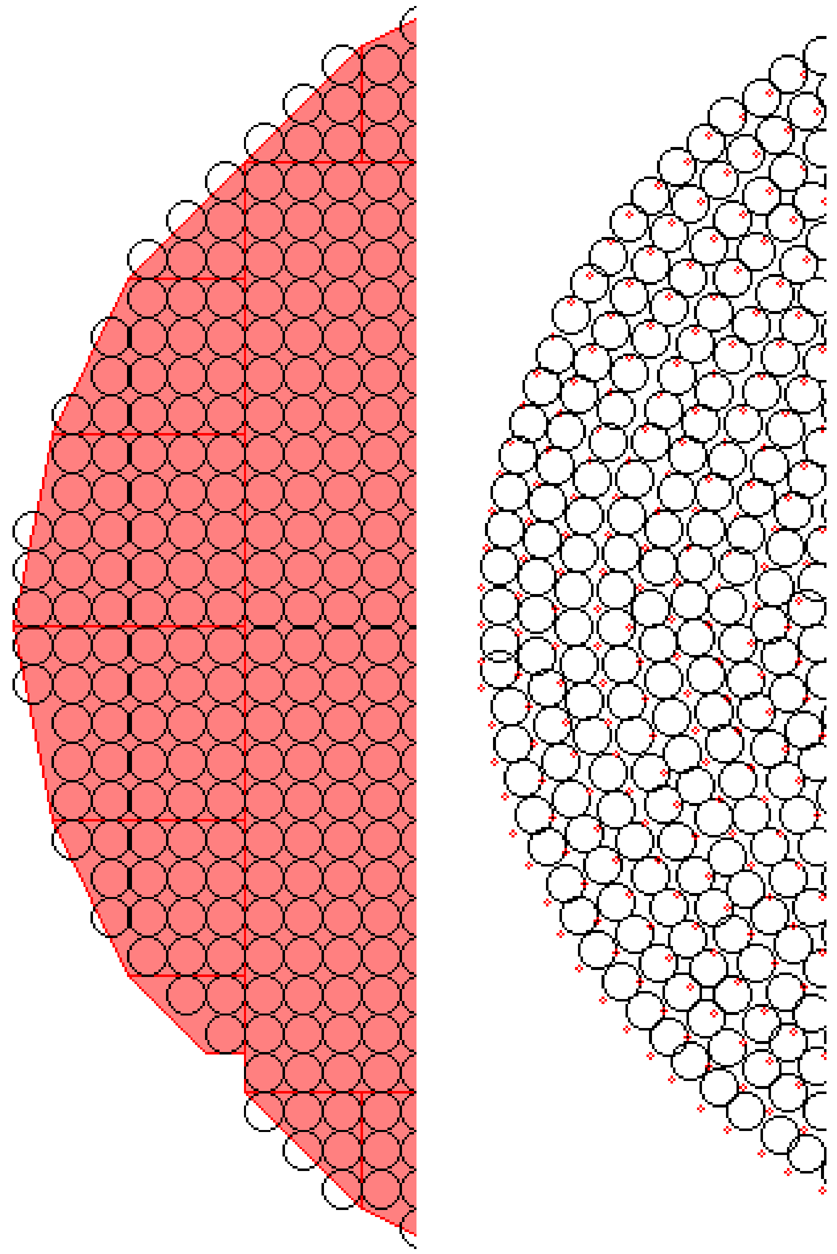
Shots: 5nm beam 5nm grid



Shots: 5nm beam 2nm grid

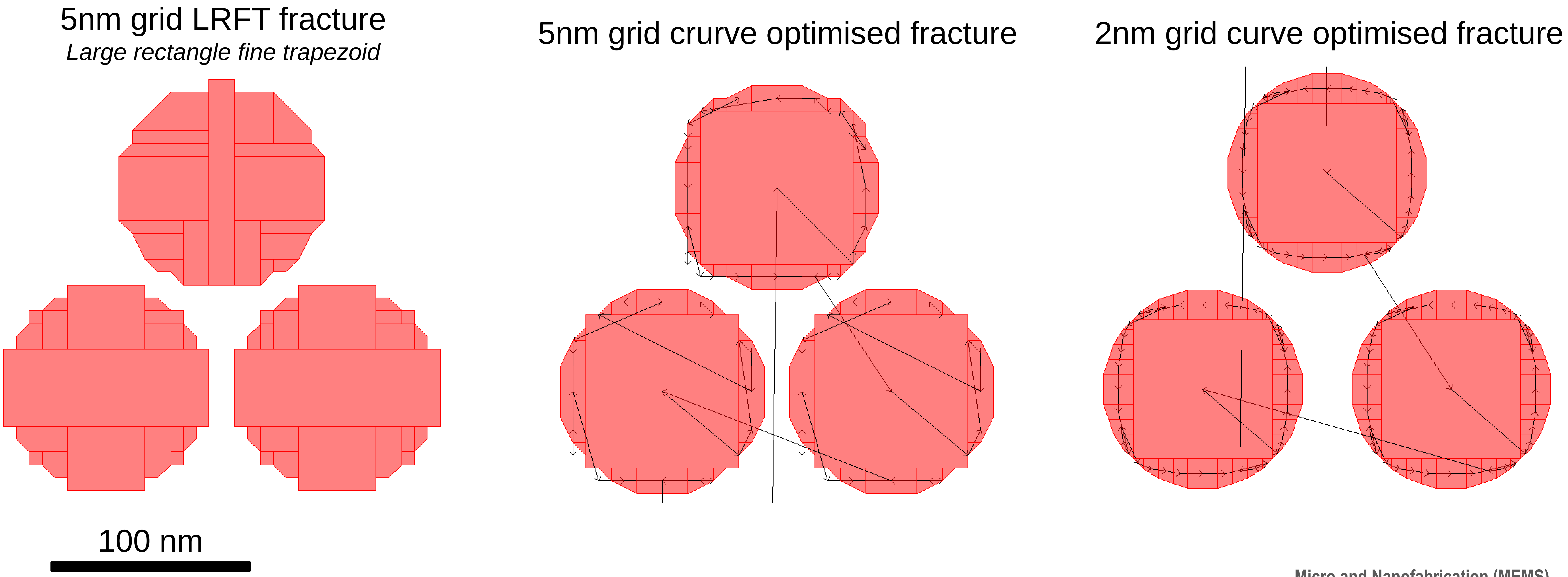


Advanced shot placement



Design preparation: fracture

- Shape discretisation and fracture optimisation

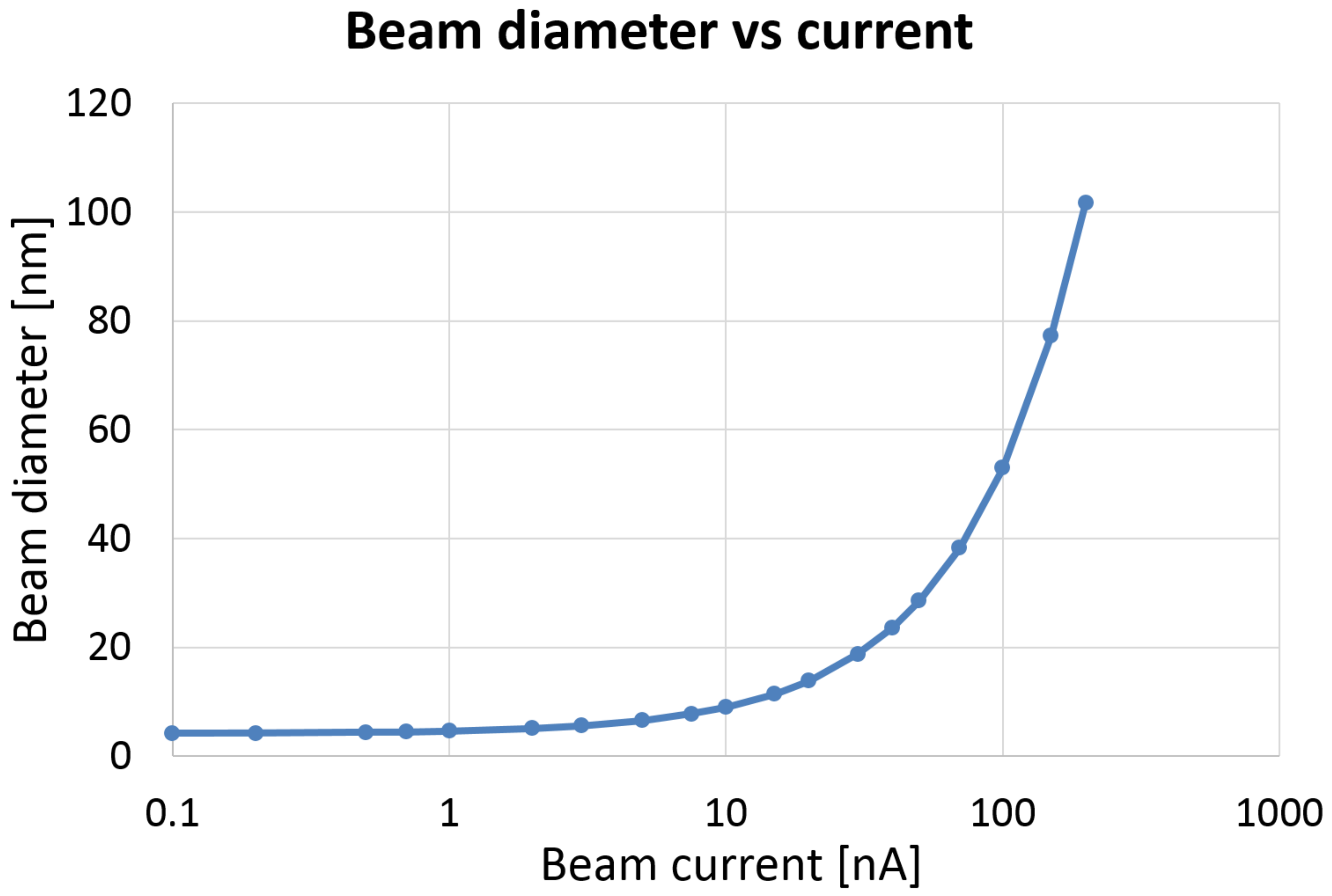


Design preparation: write time

- Beam step size (BSS) and beam diameter (beam current) influence writing time
- Beam diameter/current should be scaled according to BSS chosen when fracturing
- Bandwidth limit for tool (MHz)
  - Minimal exposure time/shot
  - Limits writing speed
  - For small grids time/shot may be too low

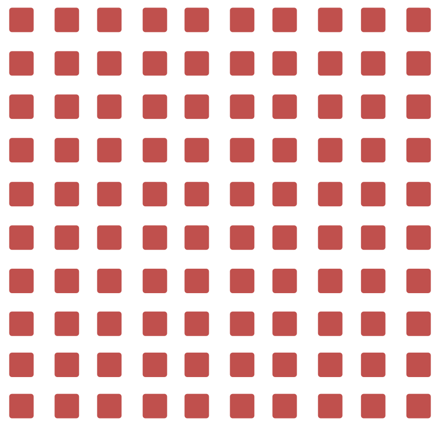
$$t = \frac{D \cdot A}{I} \qquad f = \frac{I}{D \cdot BSS^2}$$

t = writing time
D = desired dose
A = writing area
I = beam current
BSS = beam step size



Design preparation: write time

- Example: how long does it take to write the following matrix?



100 squares of 50x50 nm^2

Choosing the optimum parameters for this design:

- Grid size: BSS = 5 nm
- Current: I = 3 nA, 5.6 nm diameter
- Bandwidth limit of our tool: f = 50 MHz
- Dose: D = 160 µC/cm^2 (resist dependent)

$$t = \frac{D\left[\frac{C}{cm^2}\right] \cdot A[cm^2]}{I\,[A]} = \frac{160 \cdot\ 10^{-6}\frac{C}{cm^2} \cdot (100 \cdot 2.5 \cdot 10^{-11})\ cm^2}{3 \cdot 10^{-9} A} = 1.33 \cdot 10^{-4}\ \ s$$

Design preparation: write time

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$$\mathrm{f}\,[\mathrm{MHz}] = 0.1\,\frac{I\,[nA]}{D\left[\frac{\mu C}{cm^2}\right]\cdot BSS^2\,[\mu m]} = 0.1\,\frac{3\,nA}{160\,\frac{\mu C}{cm^2}\cdot(5\cdot 10^{-3})^2\,\mu m} = 75\,MHz$$

Over tool capabilities

- Adjust new current: I = 2 nA, to obtain a 5 nm beam

$$t = \frac{D\left[\frac{C}{cm^2}\right]\cdot A[cm^2]}{I\,[A]} = \frac{160\cdot\ 10^{-6}\,\frac{C}{cm^2}\cdot(100\cdot 2.5\cdot 10^{-11})\,cm^2}{2\cdot 10^{-9}A} = 2\cdot 10^{-4}\ s$$

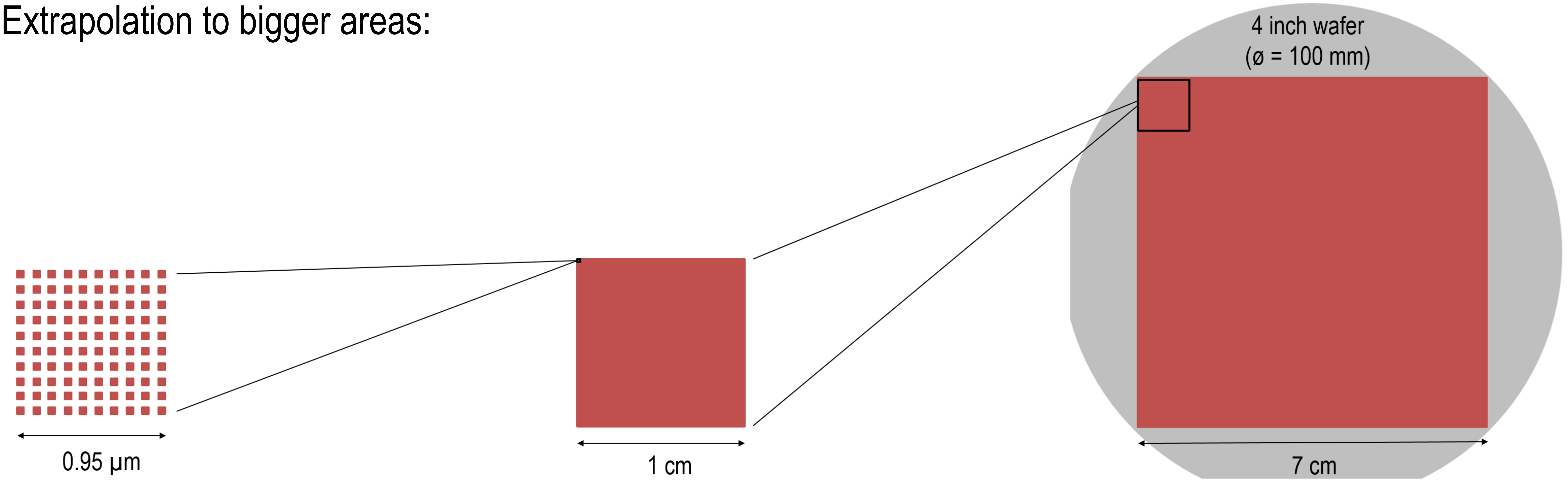
$$\mathrm{f}\,[\mathrm{MHz}] = 0.1\,\frac{I\,[nA]}{D\left[\frac{\mu C}{cm^2}\right]\cdot BSS^2\,[\mu m]} = 0.1\,\frac{2\,nA}{160\,\frac{\mu C}{cm^2}\cdot(5\cdot 10^{-3})^2\,\mu m} = 50\,MHz$$

Max tool bandwidth

Design preparation: write time

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- Extrapolation to bigger areas:



100 squares of 50x50 nm^2

$$t = 2 \cdot 10^{-4}\ s$$

11080341274 squares of 50x50 nm^2

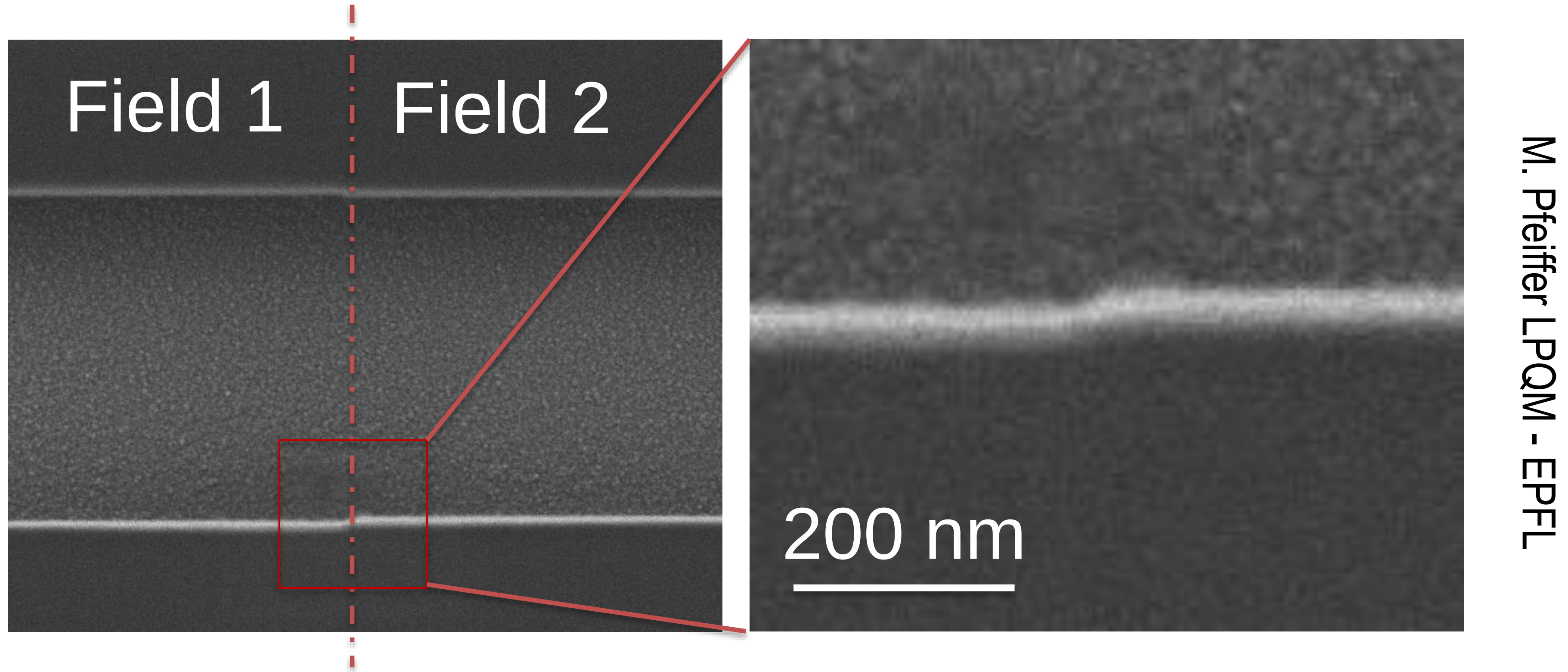
$$t = 6.16\ h$$

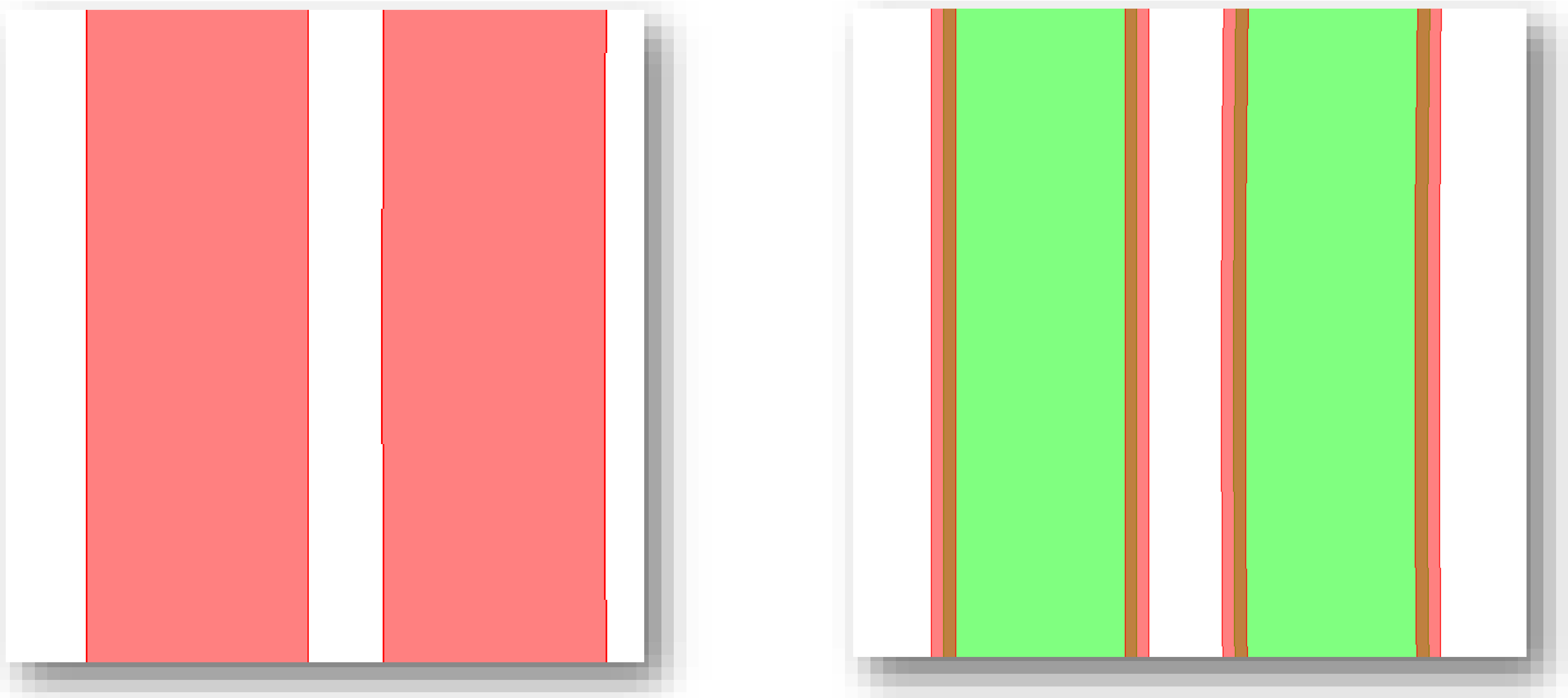
542936722426 squares of 50x50 nm^2

$$t = 12.57\ days$$

Design preparation: additional considerations

- Writing schemes
  - Field positioning
    - Avoid field boundary in pattern
  - Multiple pass
    - Smooth out drifts and field boundaries
  - Bulk sleeve
    - Variable grid or beam size
  - Writing order
    - Speed, short range accuracy

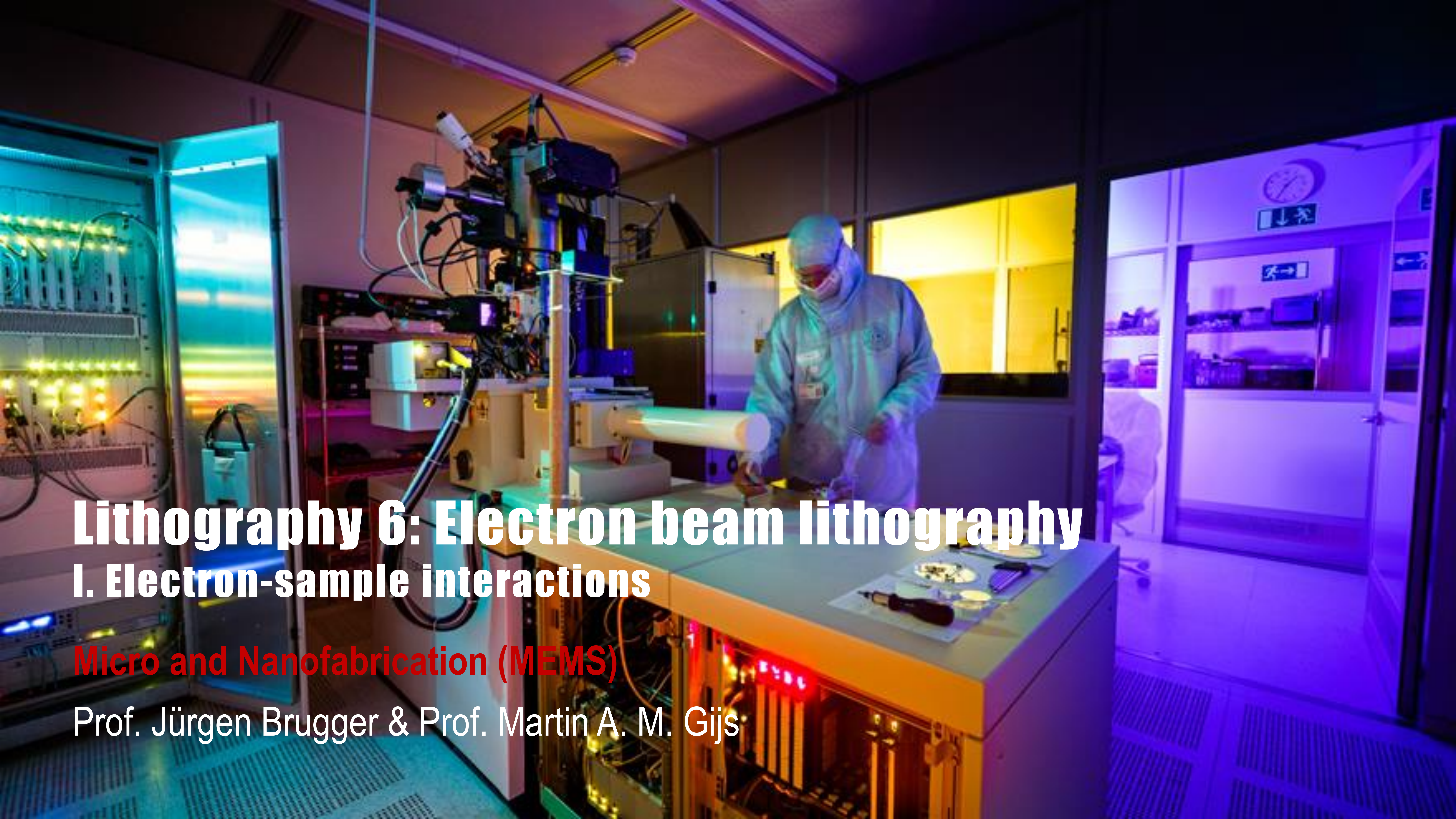




Overview

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- ✓ Design preparation and fracture
- Electron sample (resist) interaction
- Resist contrast
- Positive and negative resists
- Proximity effects
- Alignment process
- Examples



Lithography 6: Electron beam lithography

I. Electron-sample interactions

Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

Overview

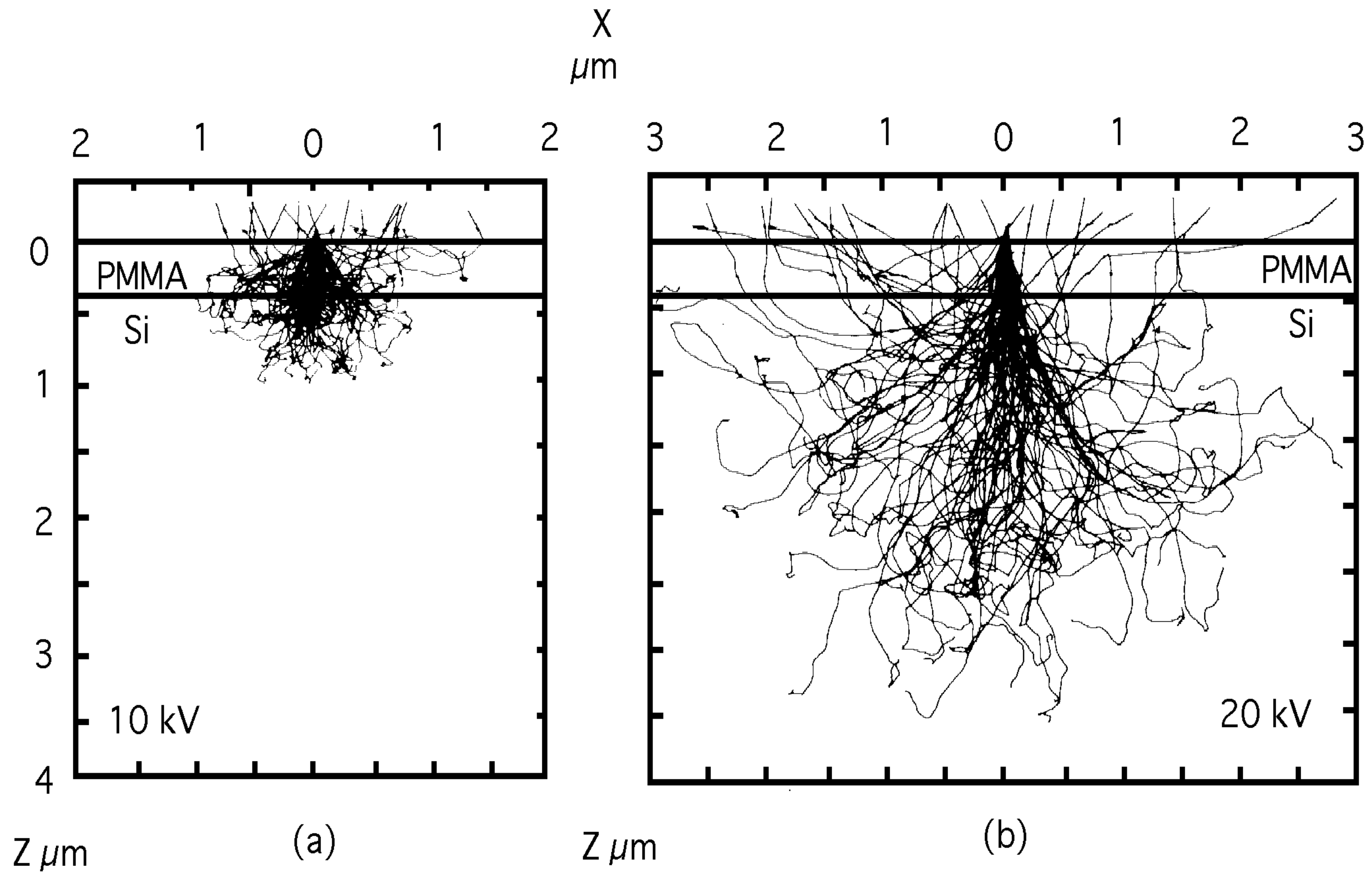
- ✓ Design preparation and fracture
- Electron sample (resist) interaction
- Resist contrast
- Positive and negative resists
- Proximity effects
- Alignment process
- Examples

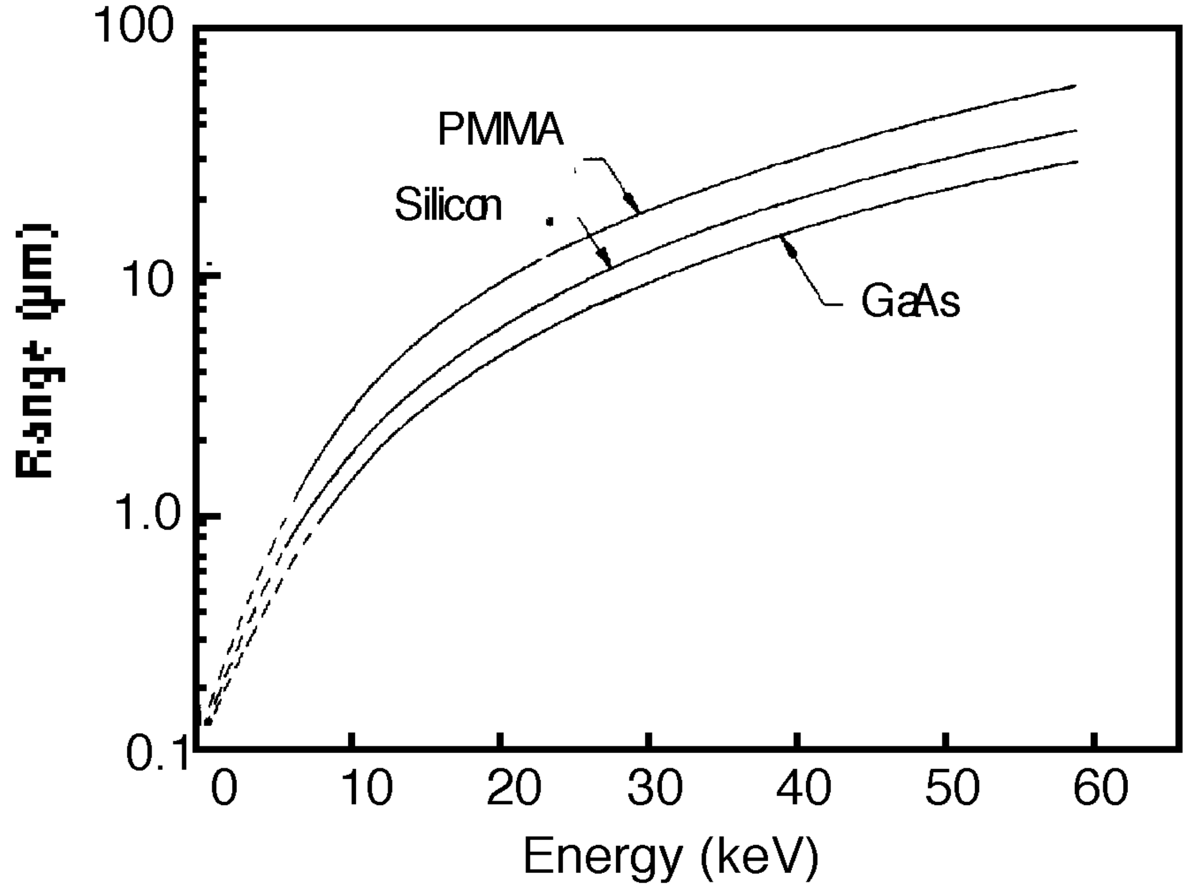
Electron-sample (resist) interactions

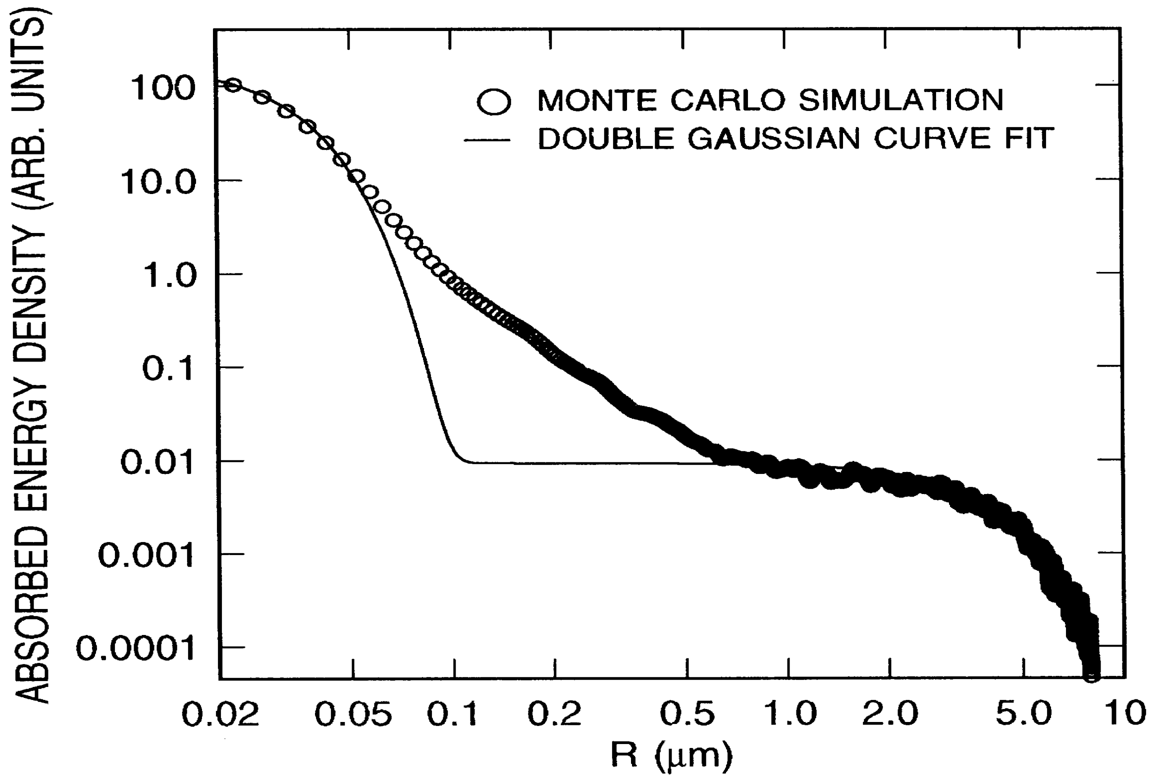
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- The electron beam scatters into the resist and substrate
- Beam penetration/range increases with beam energy
- Electron range decreases with substrate atomic mass

- Effectively two main contributions:
  - Forward scattering
  - Backscattering



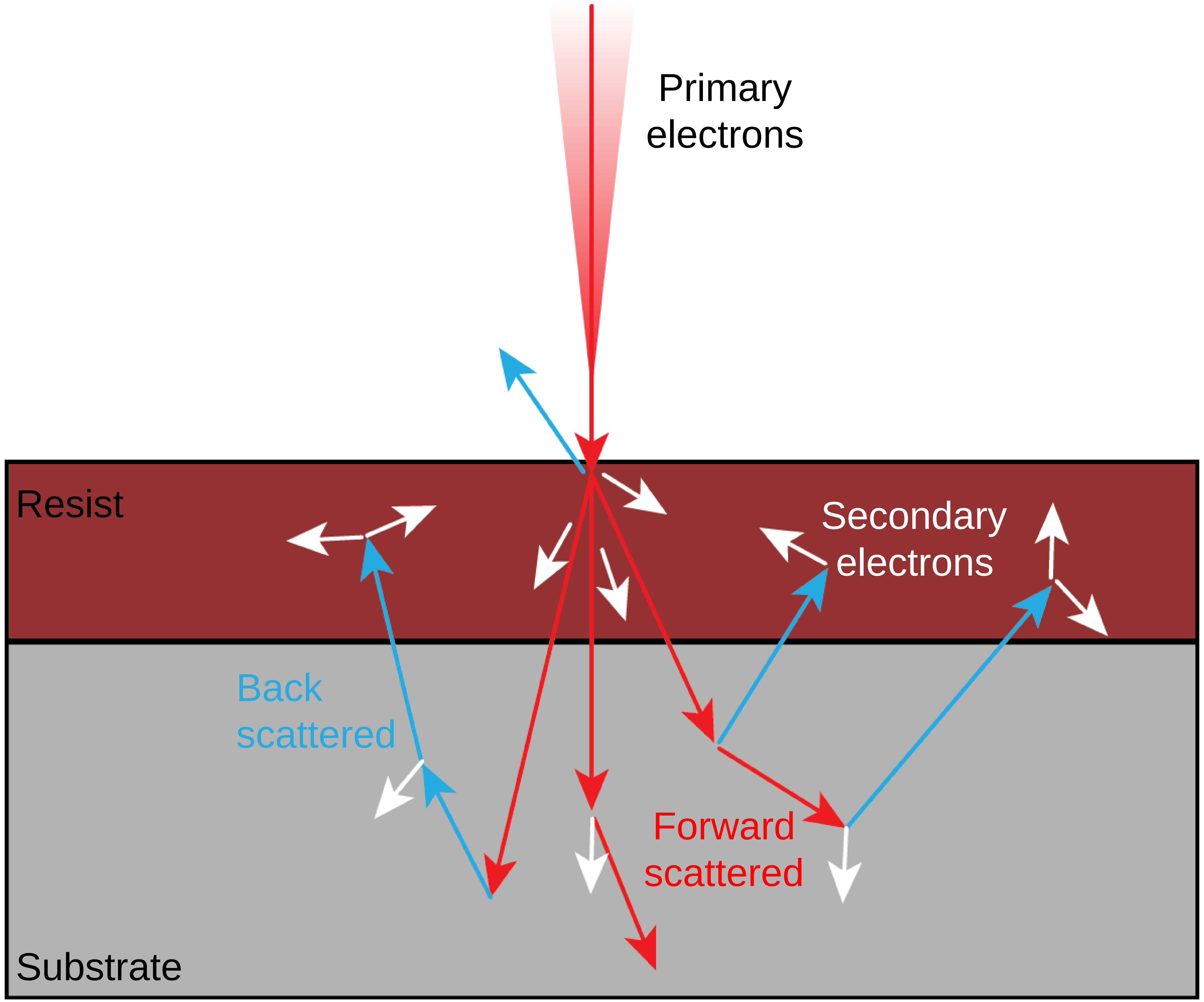




SPIE Handbook of Microlithography, Micromachining and Microfabrication
Mark A. McCord, Michael J. Rooks, 1997

Electron-sample (resist) interactions

- Primary electrons hit the sample
- Forward scattered
  - Small angles
  - Affects most electrons
  - Travel through the resist with high energy
- Some electrons are back-scattered
  - Large angles and high energy, thus large range
- Secondary electrons
  - Ionisation products
  - Have lower energy and penetration
  - Responsible for the broadening of resist exposure



Electron-sample (resist) interactions

- Scattering implies
  - Beam energy affects interaction volume
  - The dose to clear depends on beam energy
  - Forward scattering affects the resist profile

1400nm PMMA (positive resist), 30 kV, line width: 300 nm
development with MIBK:IPA = 1:3

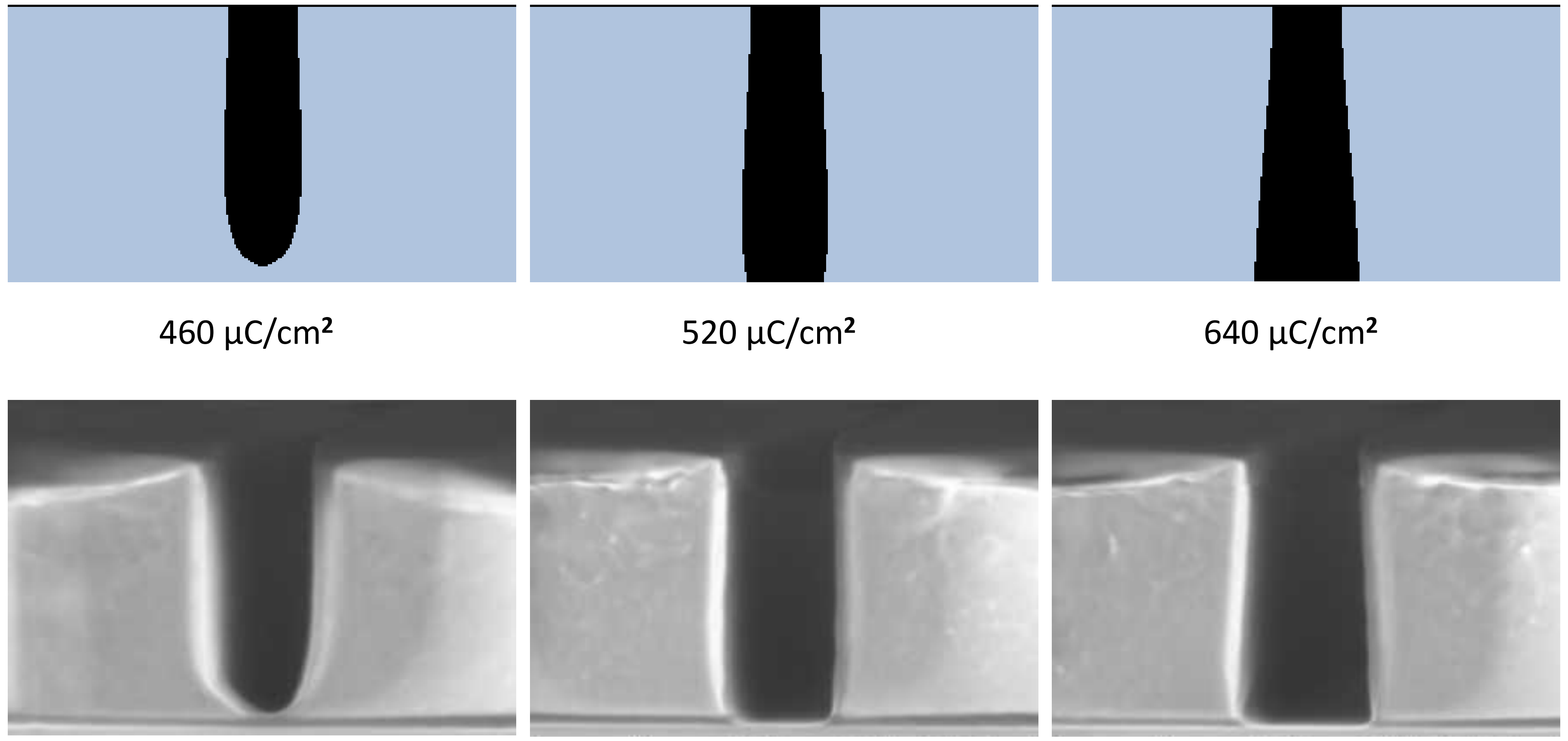


Image: Raith

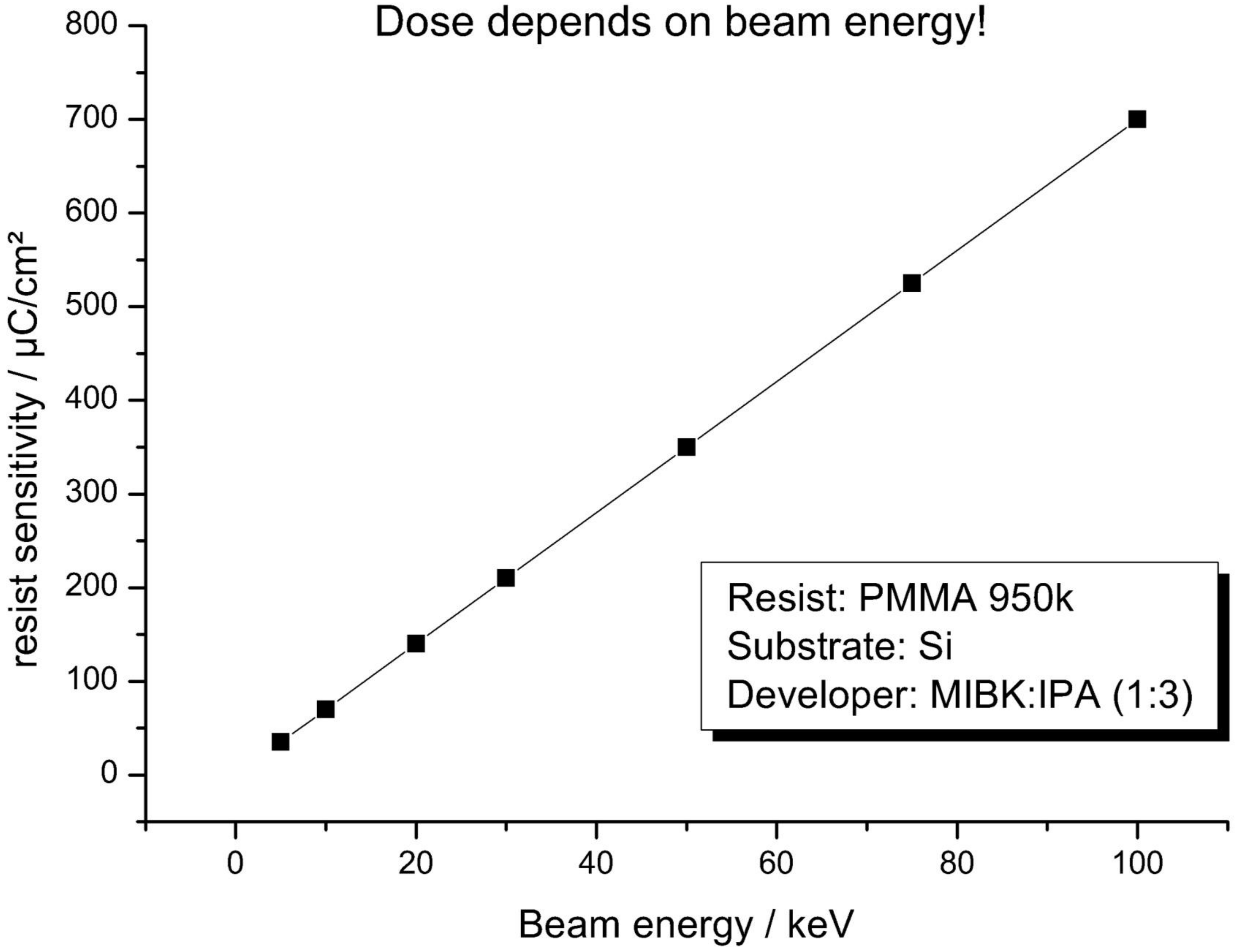


Image: Raith

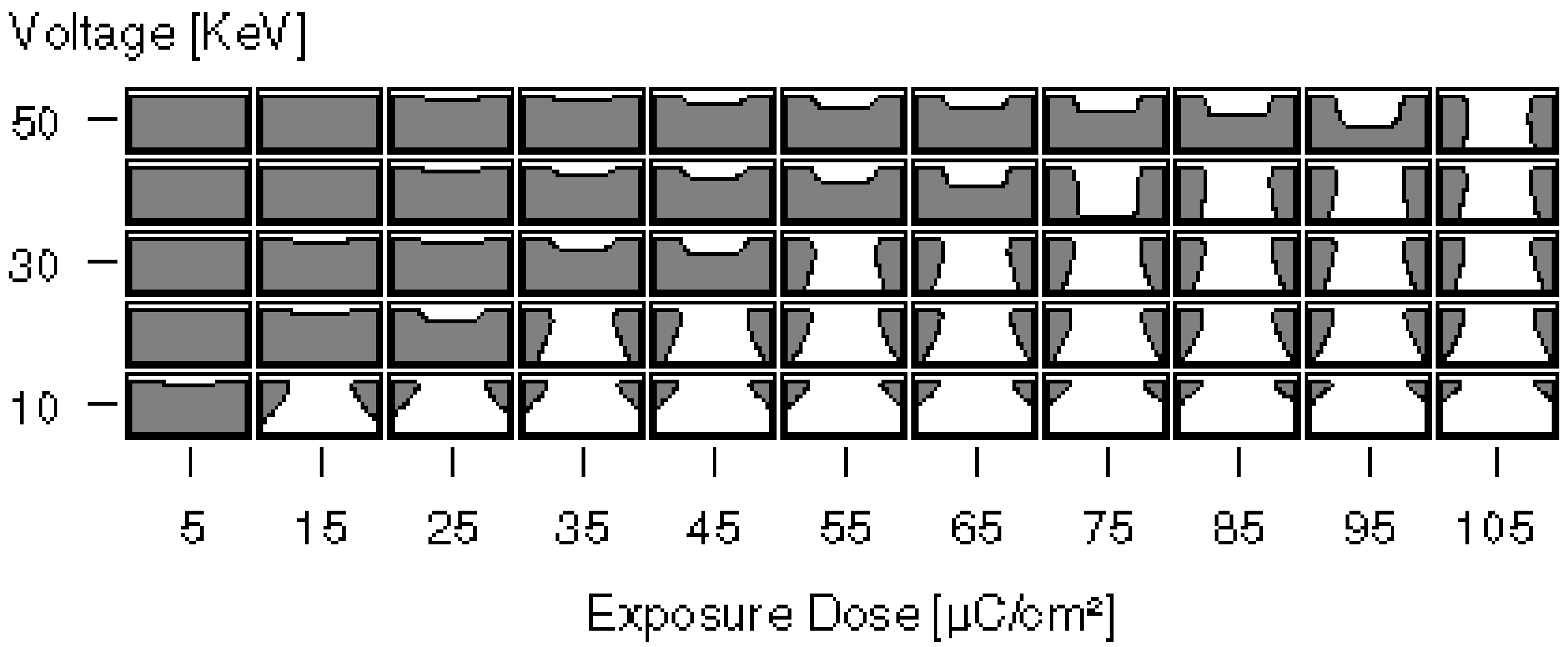


Image: Raith

Contrast curve

- Sensitivity: dose to clear positive or cross-link negative resist
  - High sensitivity – fast writing
  - Moderate sensitivity – high resolution

$$\gamma = \frac{1}{\log_{10}\frac{D_{100}}{D_0}}$$

γ = positive resist contrast
D_{100} = dose for 100% resist removal
D_0 = threshold dose

- Contrast: slope of thickness to dose variation
  - High contrast – high resolution
  - Low contrast – grayscale lithography

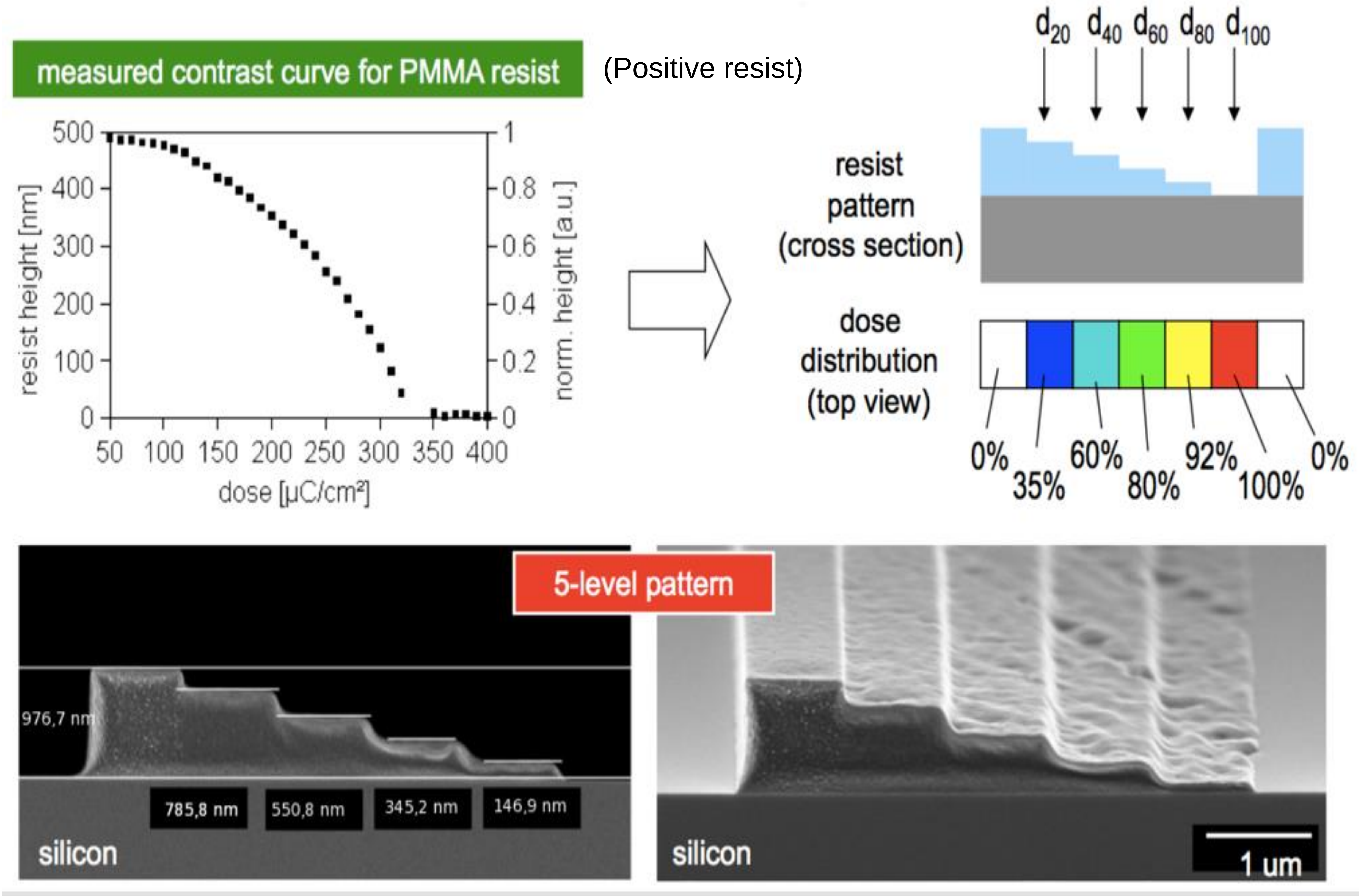


Image: Courtesy PSI, Switzerland

Lithography 6: Electron beam lithography

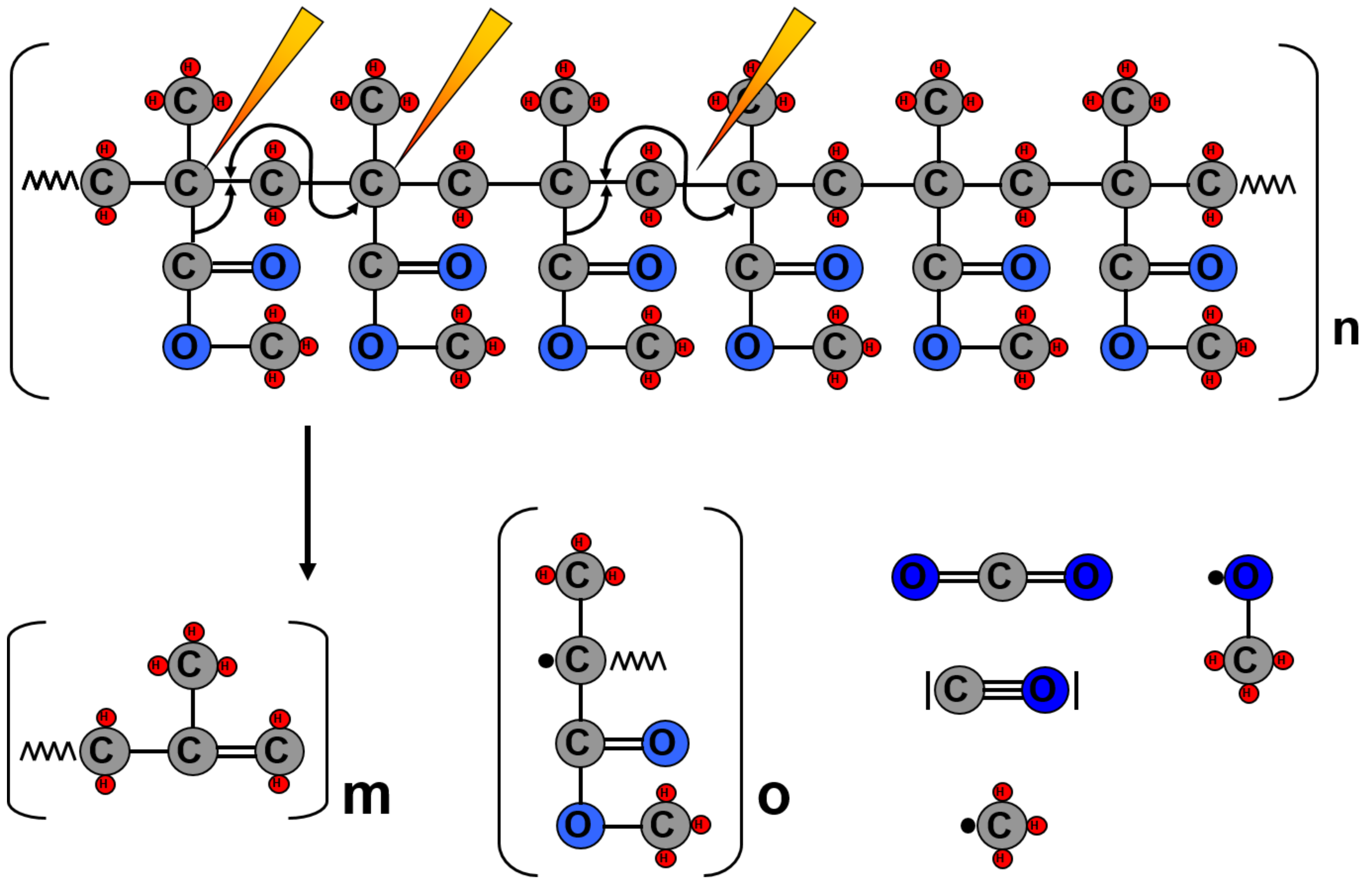
II. Resists

Micro and Nanofabrication (MEMS)

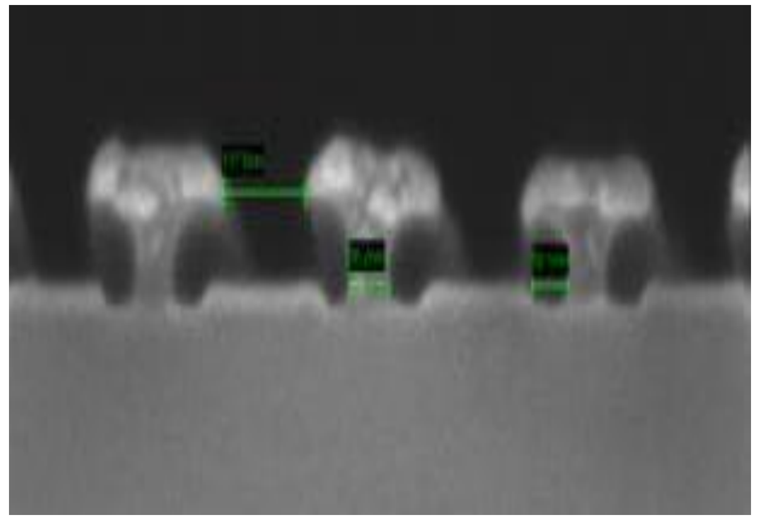
Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

Positive resist: PMMA

- PMMA (polymethyl methacrylate)
  - High resolution positive resist
  - Various molecular weight
    - Higher dissolution / sensitivity at low weight
    - Bi-layer process for undercut
- Reaction
  - Chain scission upon exposure
- Alternative resist:
  - ZEP, CSAR better mask for dry etching



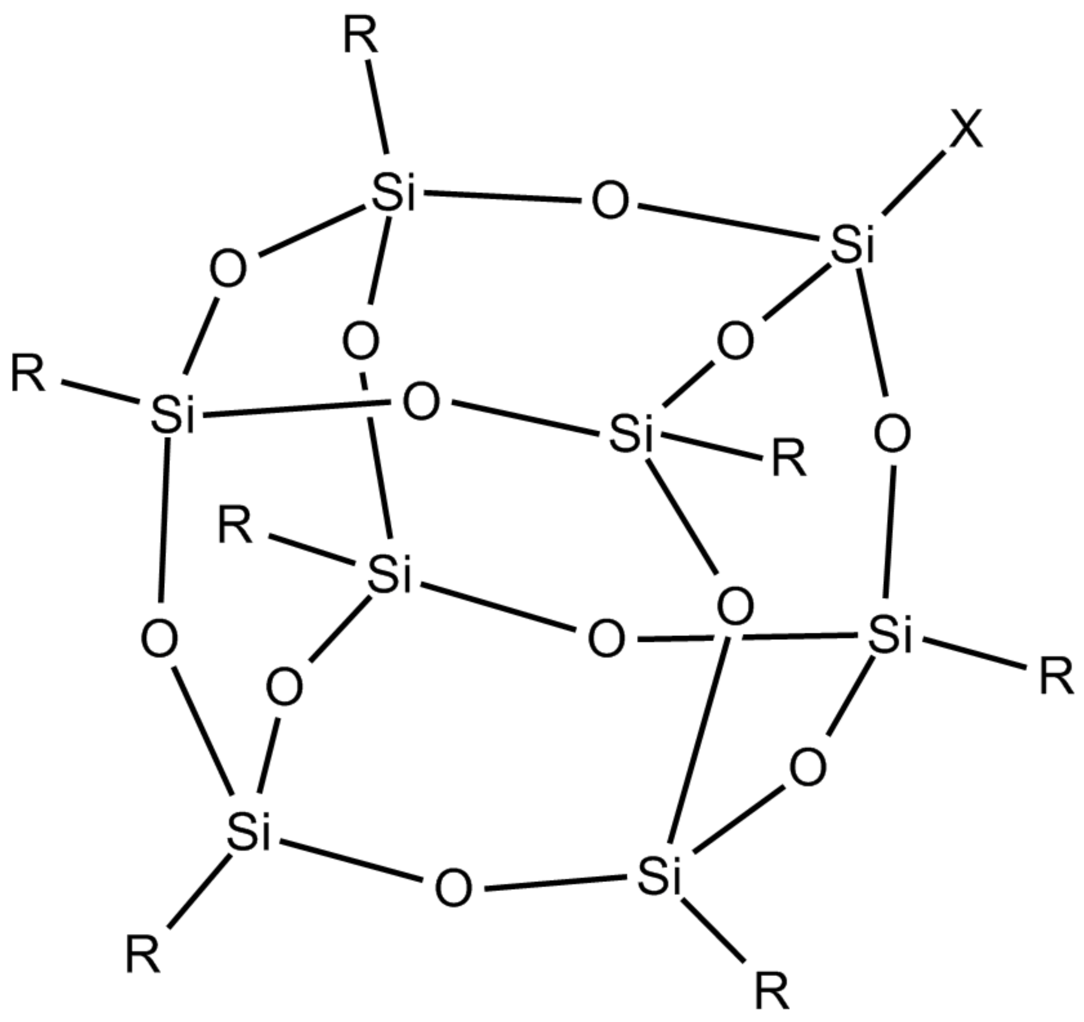
Schematic: Raith

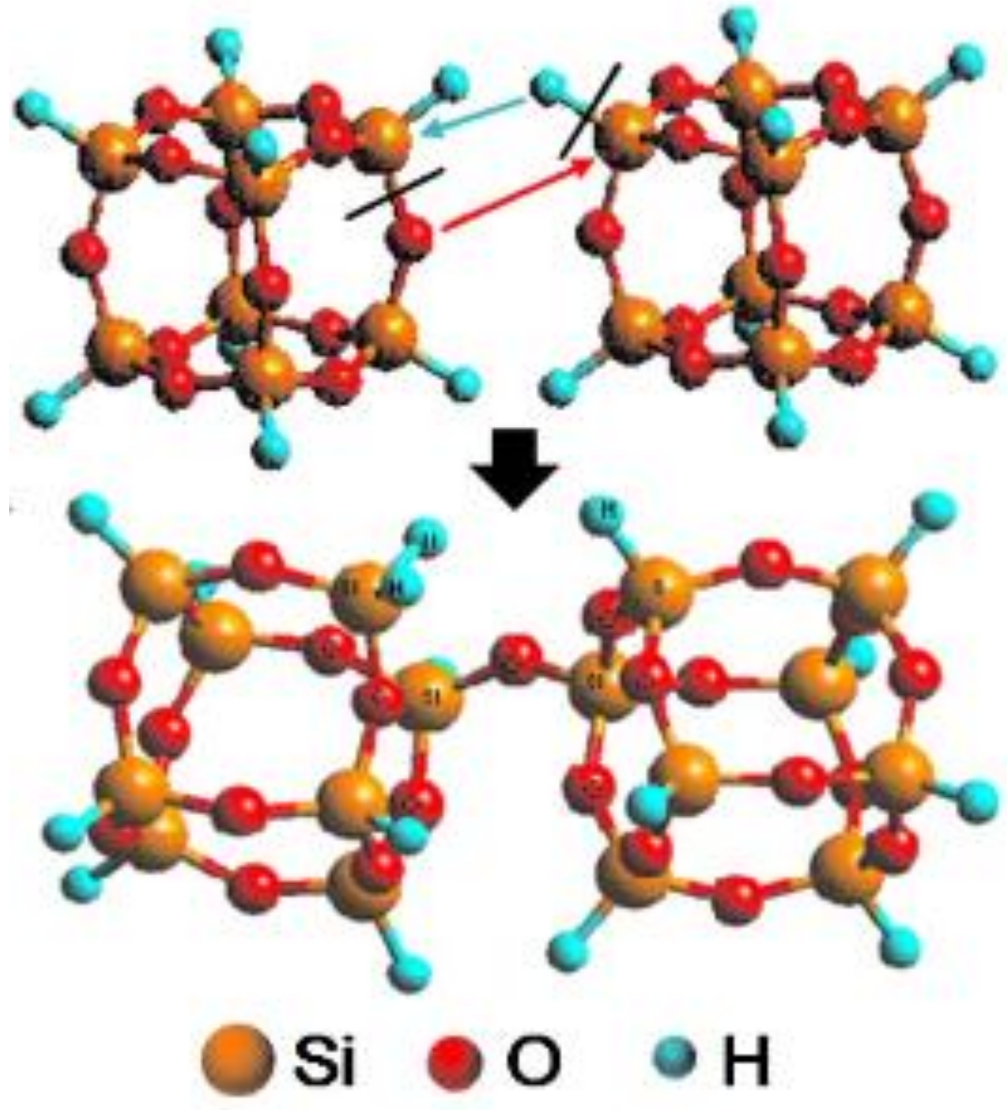


Molecular weight: PMMA1 < PMMA2

Negative resist: HSQ

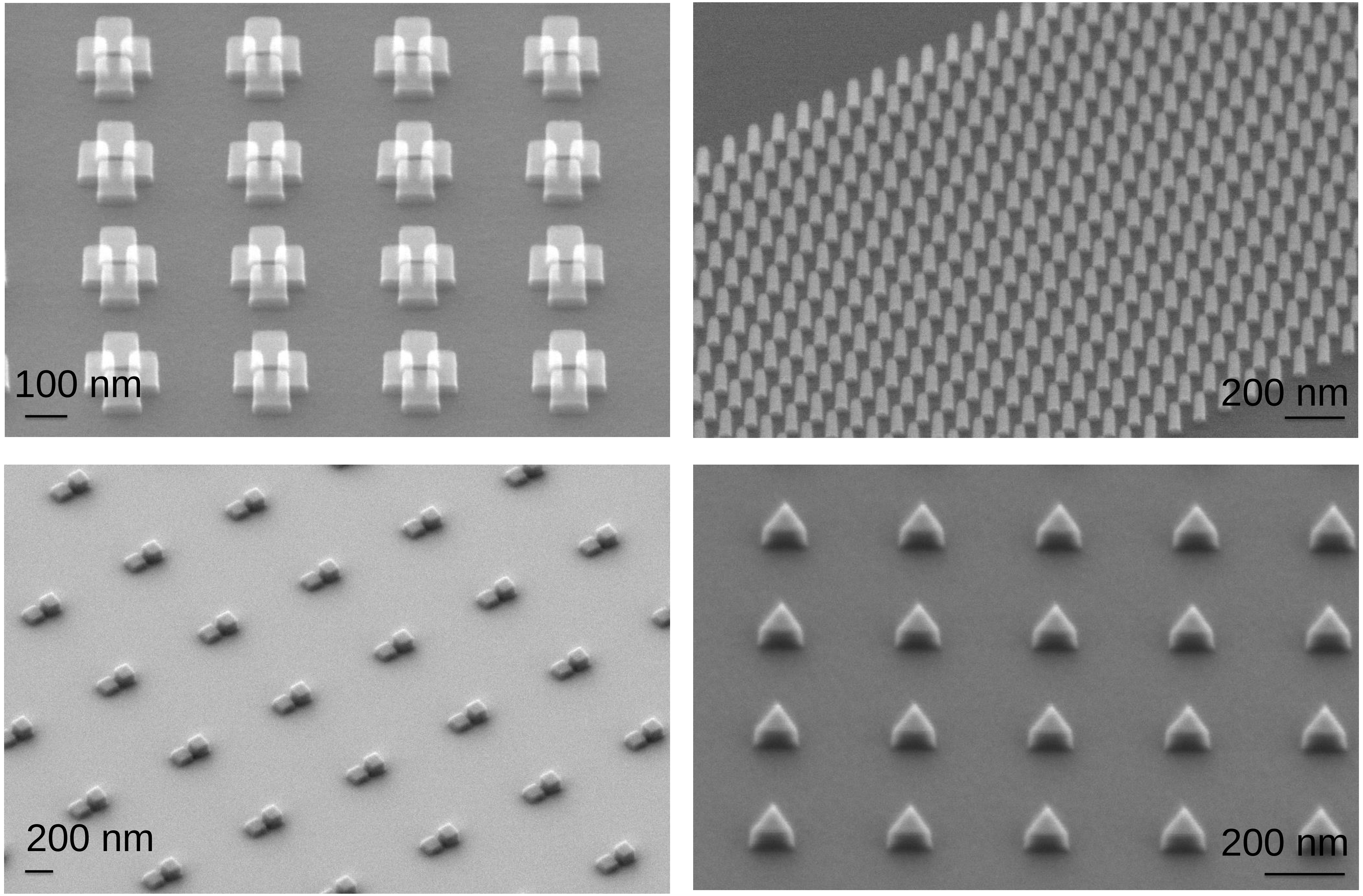
- Hydrogen silsesquioxane (HSQ)
  - Very high resolution negative resist (few nm)
  - Inorganic material ($H_8Si_8O_{12}$)
  - Resistant to solvents and O_2 plasma after exposure
  - Well suited as mask for dry etching
- Cross-linking upon exposure
- Developed in base solutions
  - Chemical reaction with NH_4OH or NaOH that produces H_2, not dissolution.
  - Ultimate contrast in salty developers
- Removed in HF solutions





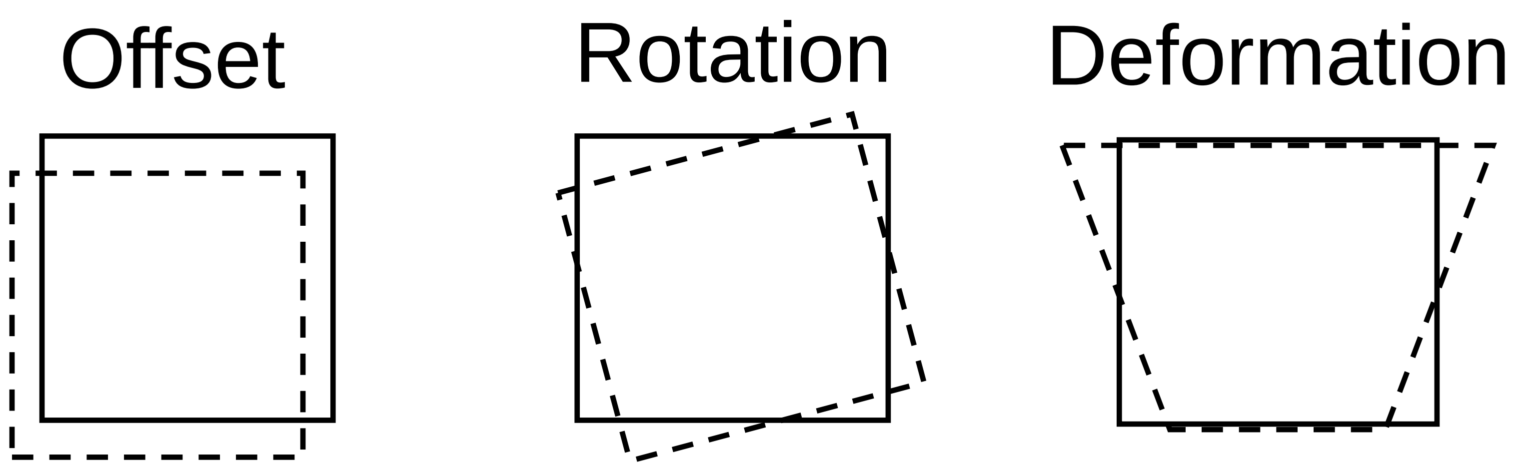
D.L. Olynick & Al - J. Vac. Sci. Technol. B 28 (3), May/Jun 2010

Examples with HSQ

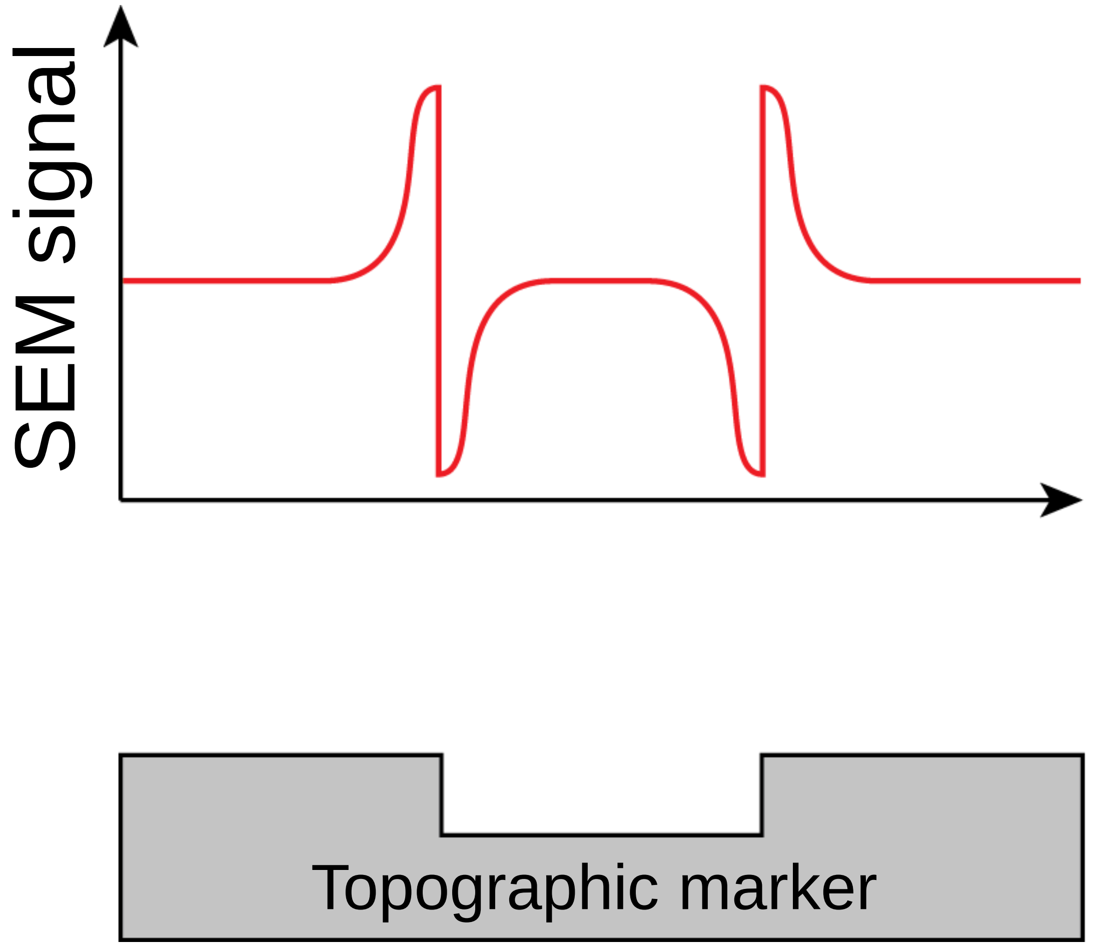


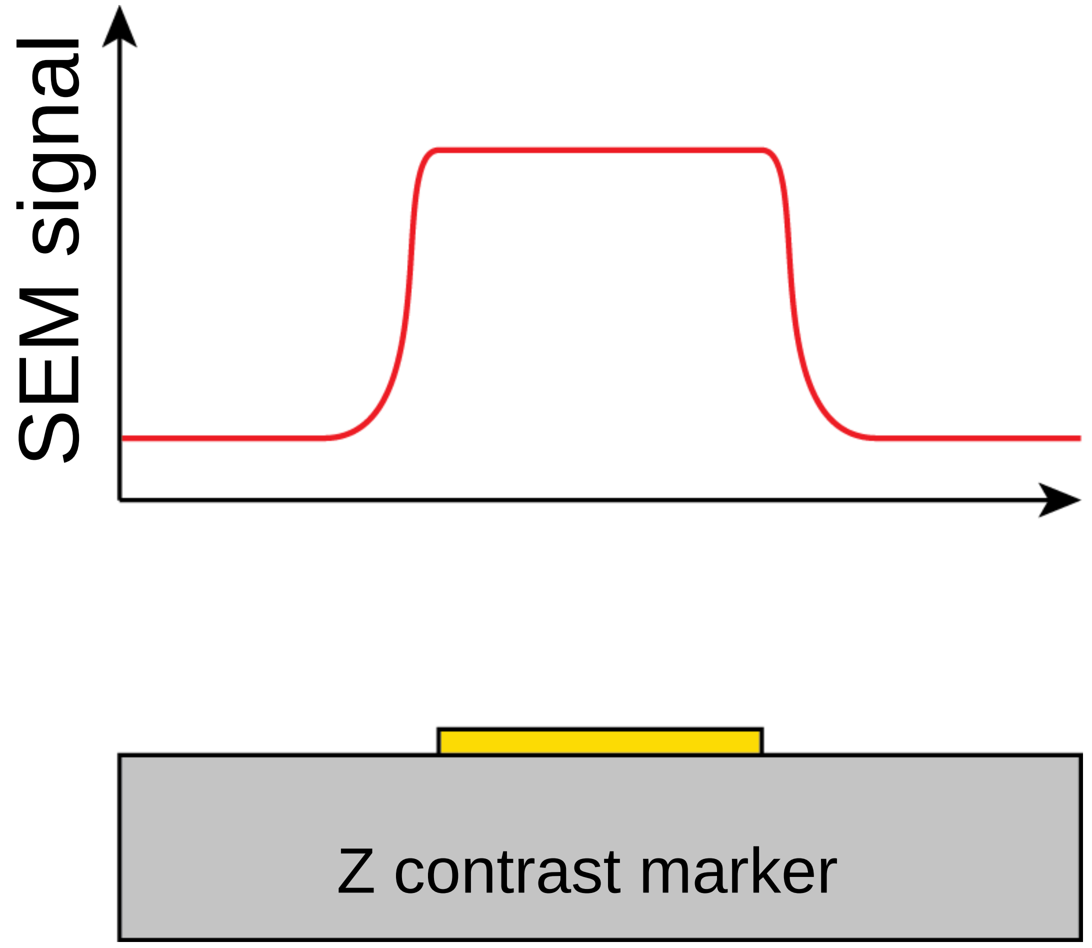
Multi-layer processes and alignment

- Processes are inherently multi-layer
  - Reference markers
  - Imaging methods



- EBL as an SEM
  - Markers should provide contrast
  - High topography: etched
  - High Z contrast: metal markers





- EBL alignment corrects
  - Position and rotation
  - Stretches and deformation

Conclusion

- ✓ Design preparation and fracture
- ✓ Electron sample (resist) interaction
- ✓ Resist contrast
- ✓ Positive and negative resists
- ✓ Proximity effects
- ✓ Alignment process
- ✓ Examples

Supplementary

Lithography 6: Electron beam lithography

III. Proximity effect

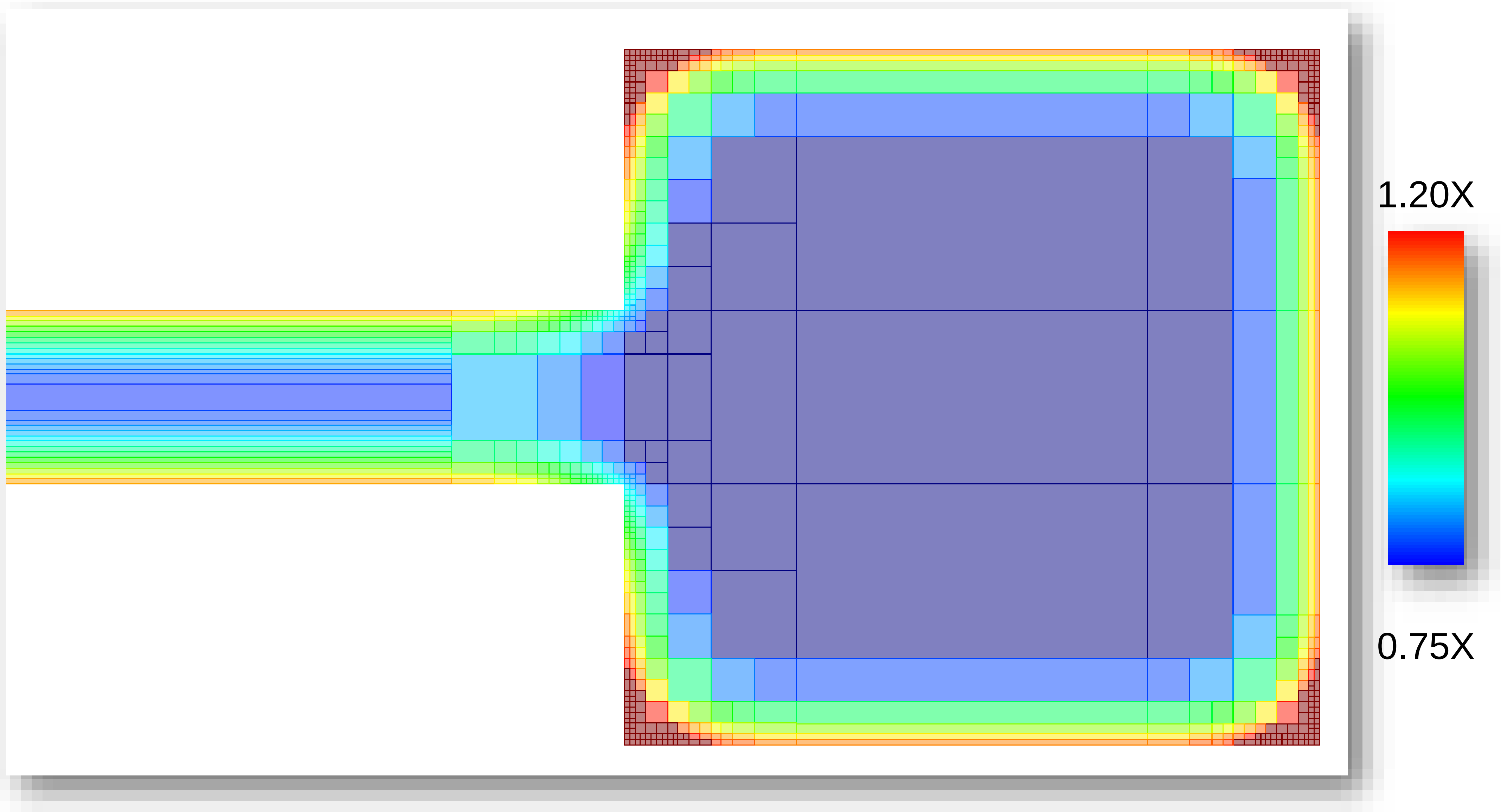
Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

Proximity effect corrections (PEC)

- Exposure beyond beam diameter
- The dose outside of the pattern may increase enough to expose the resist
- Small patterns of uniform density
  - PEC by adjusting dose uniformly
- Large and inhomogeneous features
  - Requires a pixel per pixel dose correction
  - A model of the beam point spread function is needed

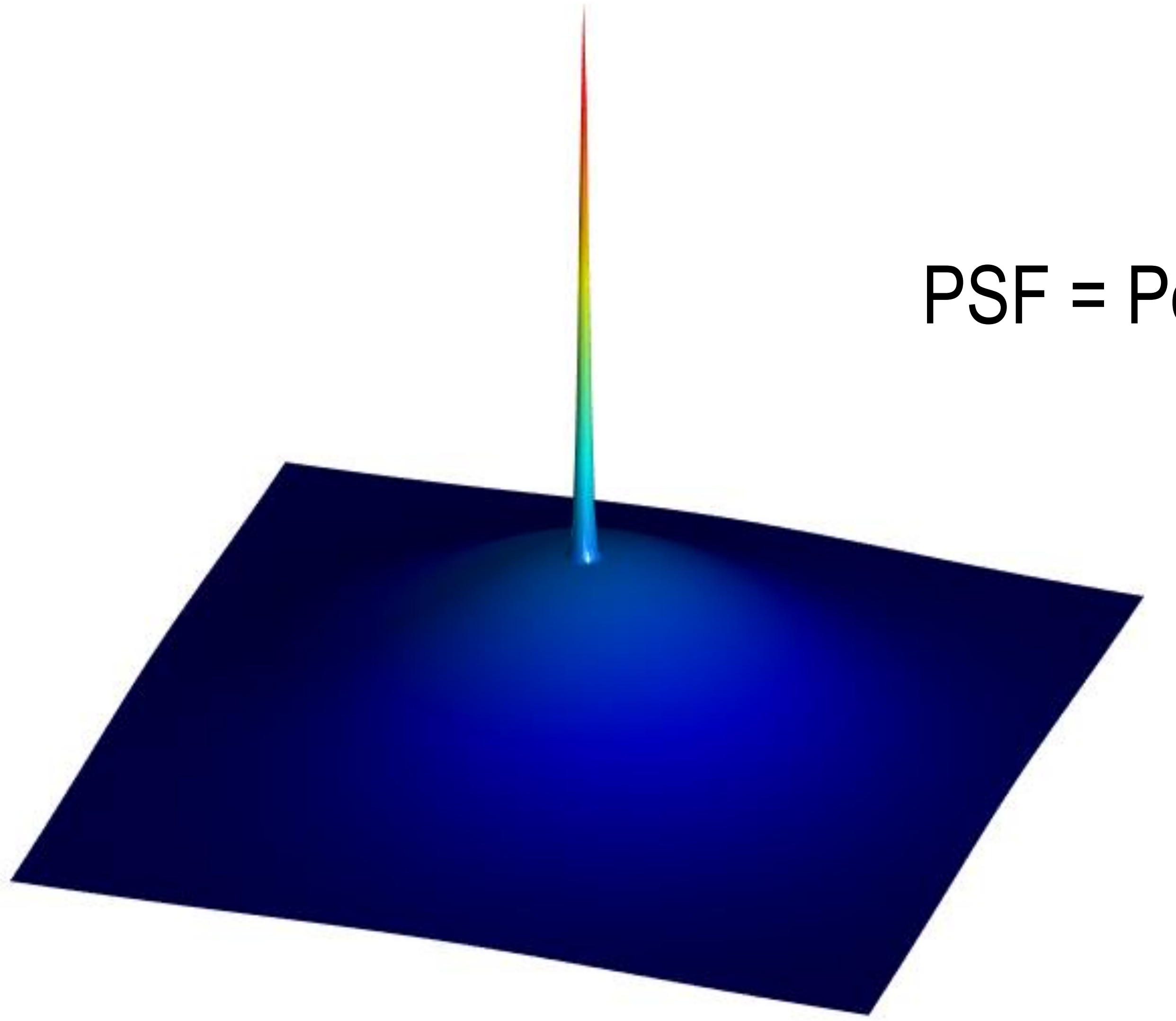
The color scale is the ratio to 50% nominal dose



Proximity effect corrections (PEC)

- Input parameters: beam model
  - Double Gaussian approximation: forward and backscattering
    - **α**: forward scattering parameter
      - Lowered with higher acceleration voltage
      - Dependent on resist thickness
    - **β**: backscattering parameter
      - Reduced with low Z substrate
      - Increased with higher acceleration voltage
    - **η**: forward/backscattered energy ratio

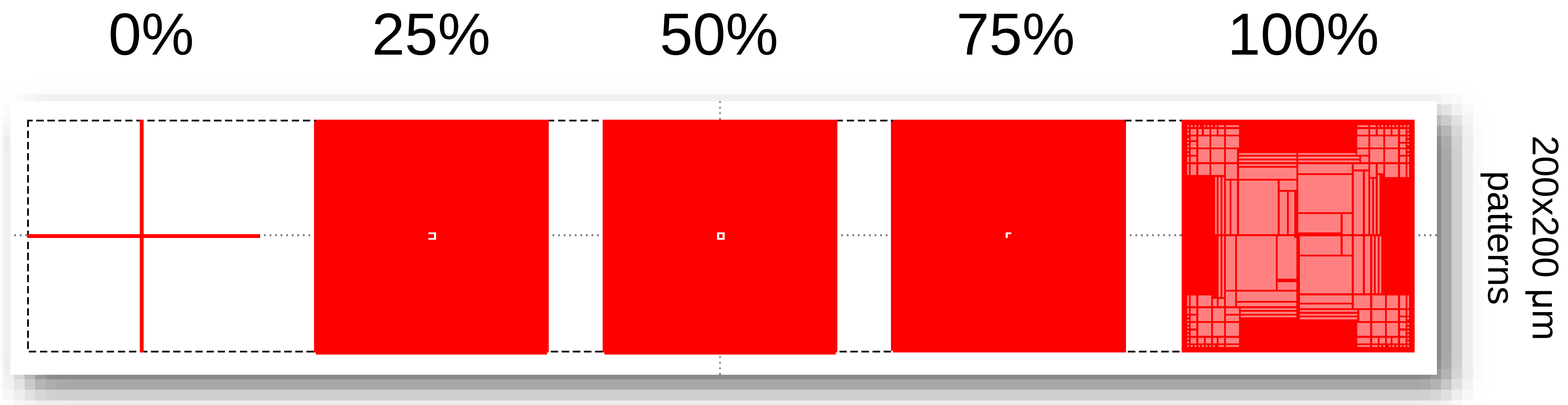
$$I(r) = \frac{1}{\pi(1+\eta)}\left(\underbrace{\frac{1}{\alpha^2}e^{-\frac{r^2}{\alpha^2}}}_{\text{Forward scattering}} + \underbrace{\frac{\eta}{\beta^2}e^{-\frac{r^2}{\beta^2}}}_{\text{Backscattering}}\right)$$

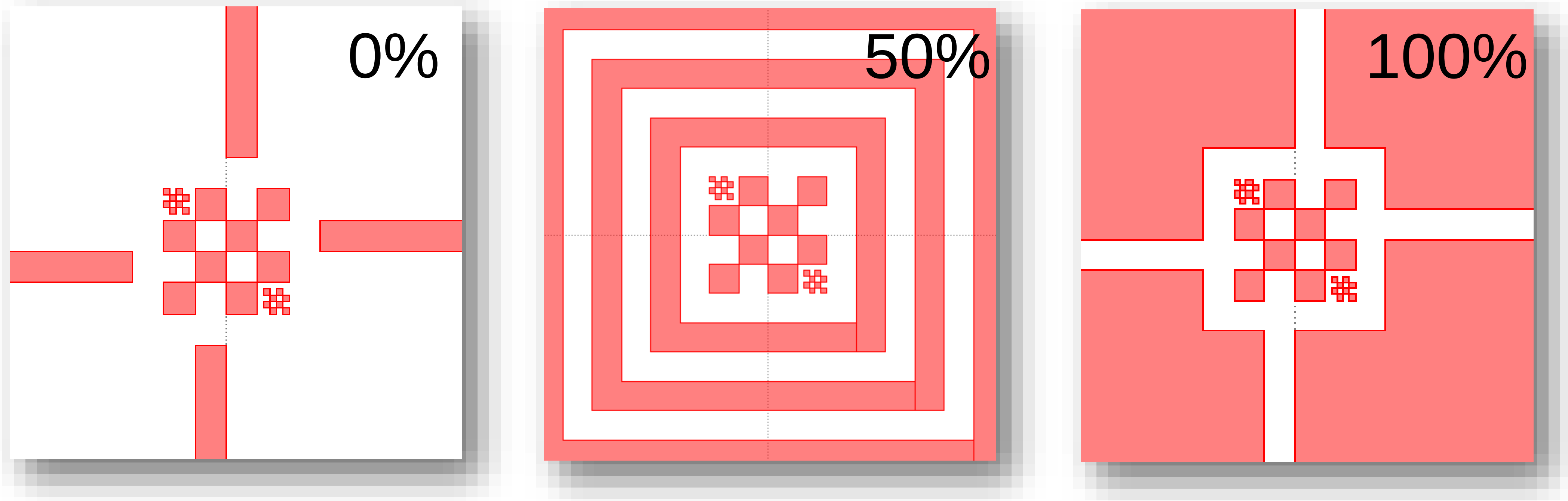


PSF = Point Spread Function

Proximity effects

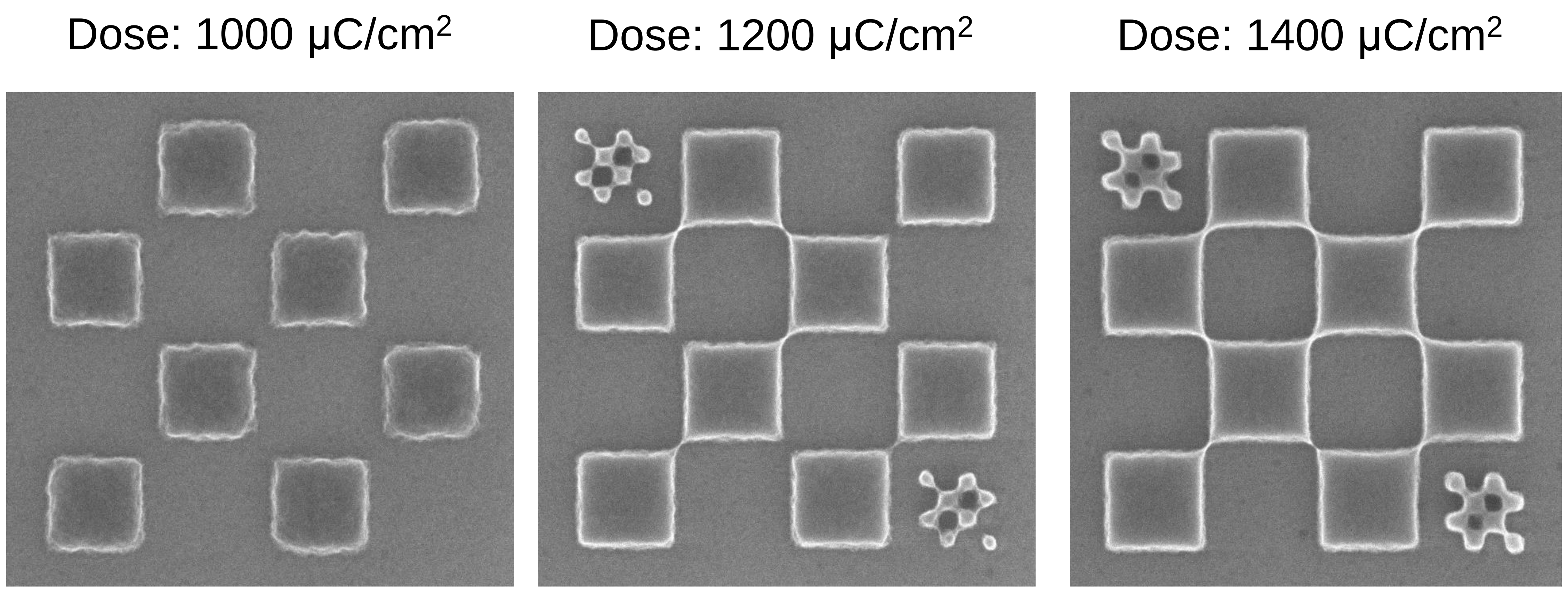
- Experimental approach
  - Nested patterns
    - Uniform density variations
    - Decorrelate multiple parameters
  - Dose sweep
    - 50% loading dose
    - Does not depend on Eta
  - Eta sweep
    - Check dose scaling vs density
  - Convenient metrology
    - 250 nm & 50 nm checkerboard



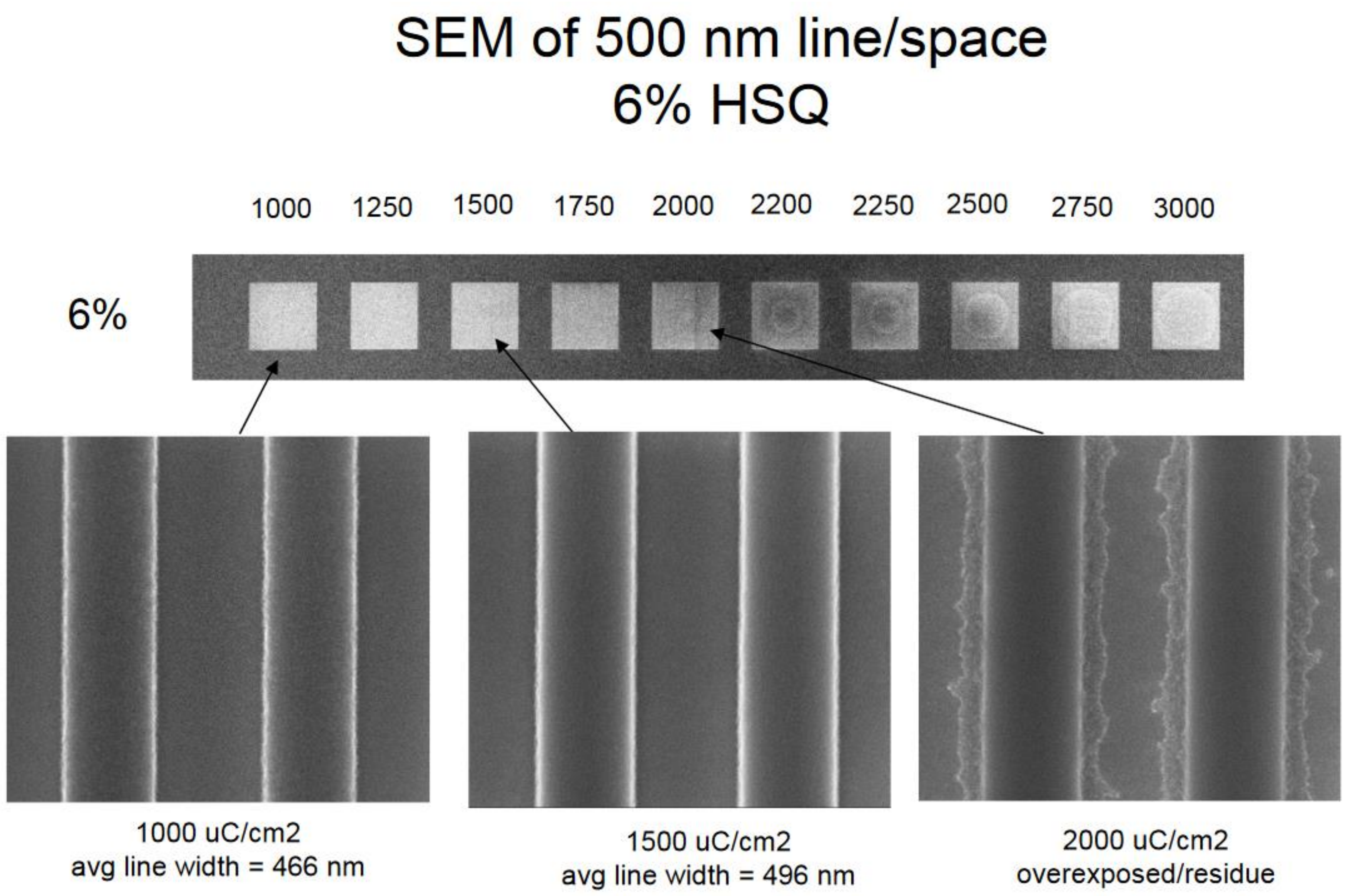


Proximity effects: base dose

- HSQ 6% (negative resist) 150nm thick
  - 50% density base dose
  - Loading pattern line width
  - Fine features: checkerboard



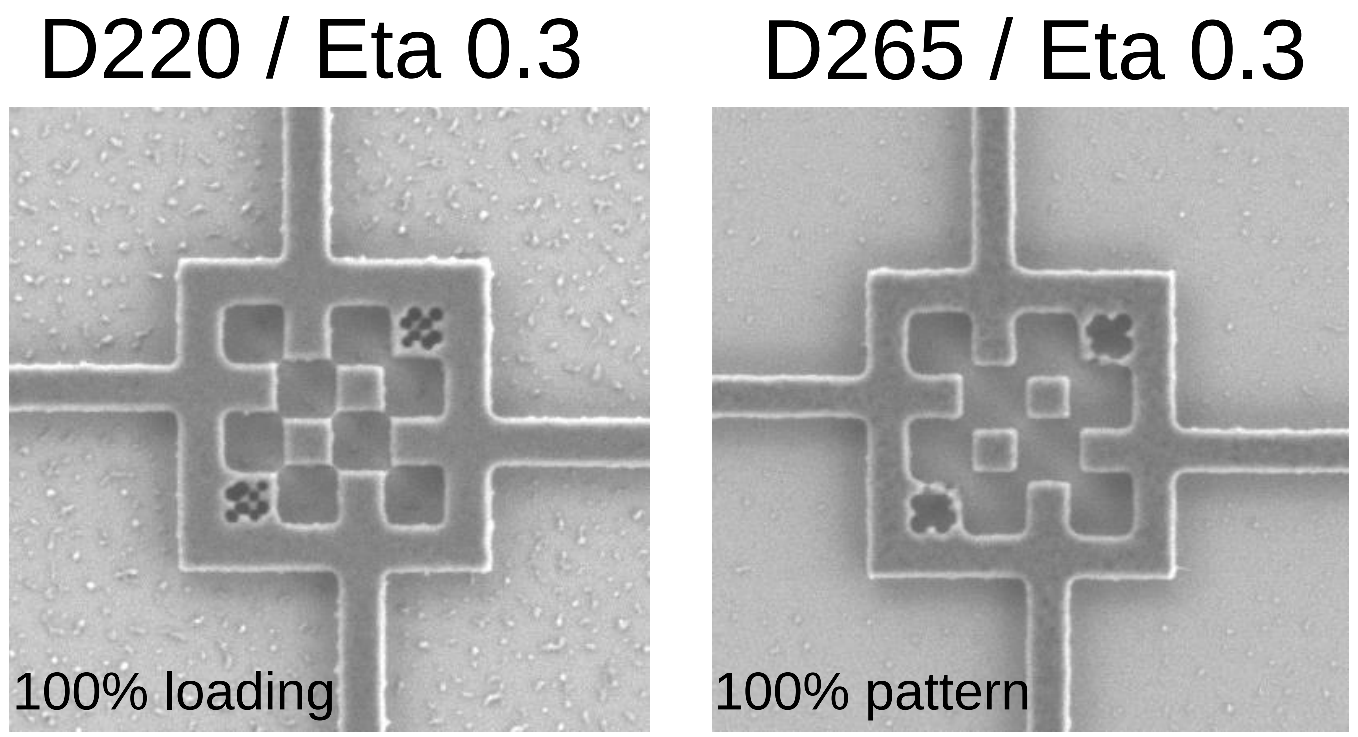
Z. Benes - EPFL

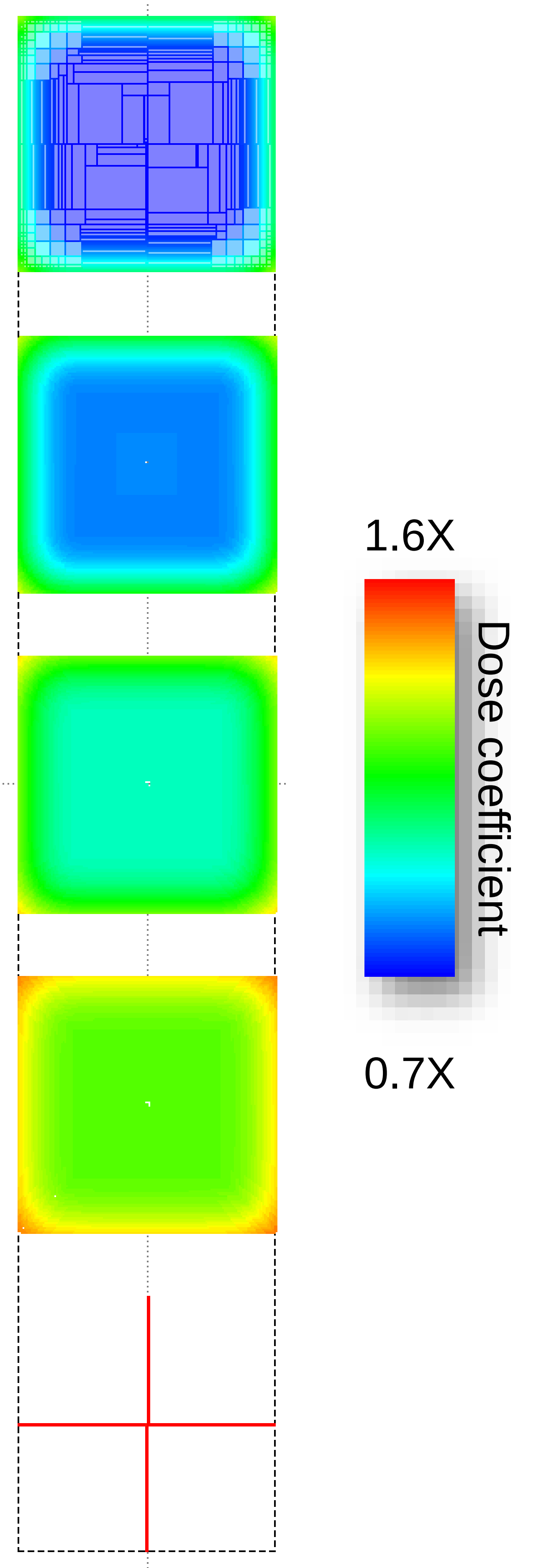


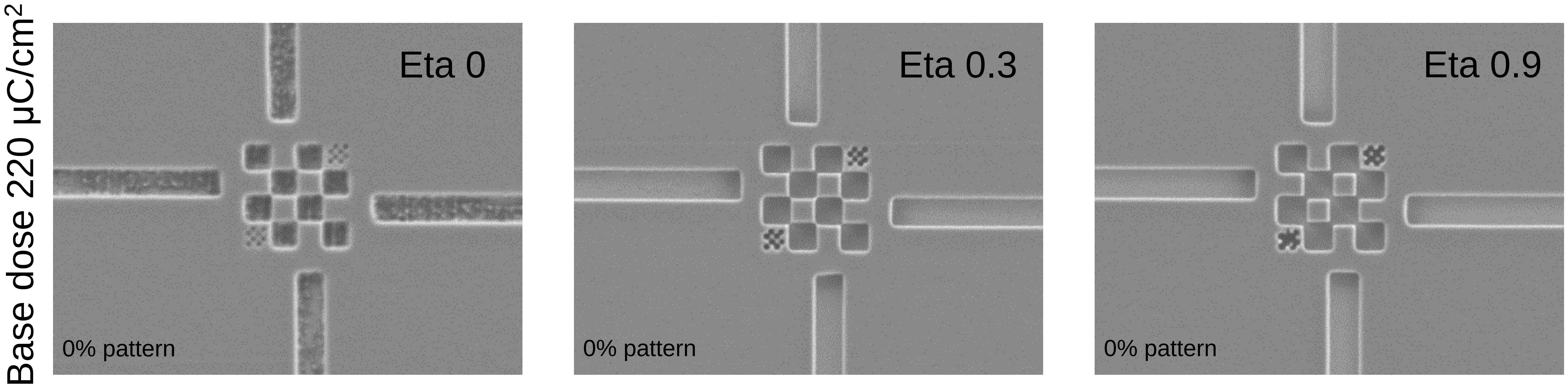
Devin K. Brown – Georgia tech

Proximity effects: Eta

- CSAR (positive resist)
  - 50% density base dose: 220 μC/cm^2
  - Inspection of 0 %, 25 %, 75 % and 100% loading
  - Process window limits







Lithography 7: Alternative patterning methods

I. Scanning probe lithography

Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

Alternative lithography methods

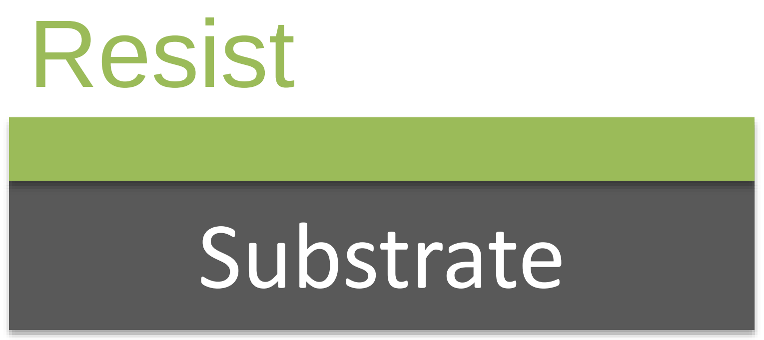
- Scanning probe lithography
- Nanoimprint lithography
- Soft-lithography
- Stencil lithography

Microscopy versus lithography

Optical
Microscopy
Lithography

Scanning Electron
Microscopy
Lithography

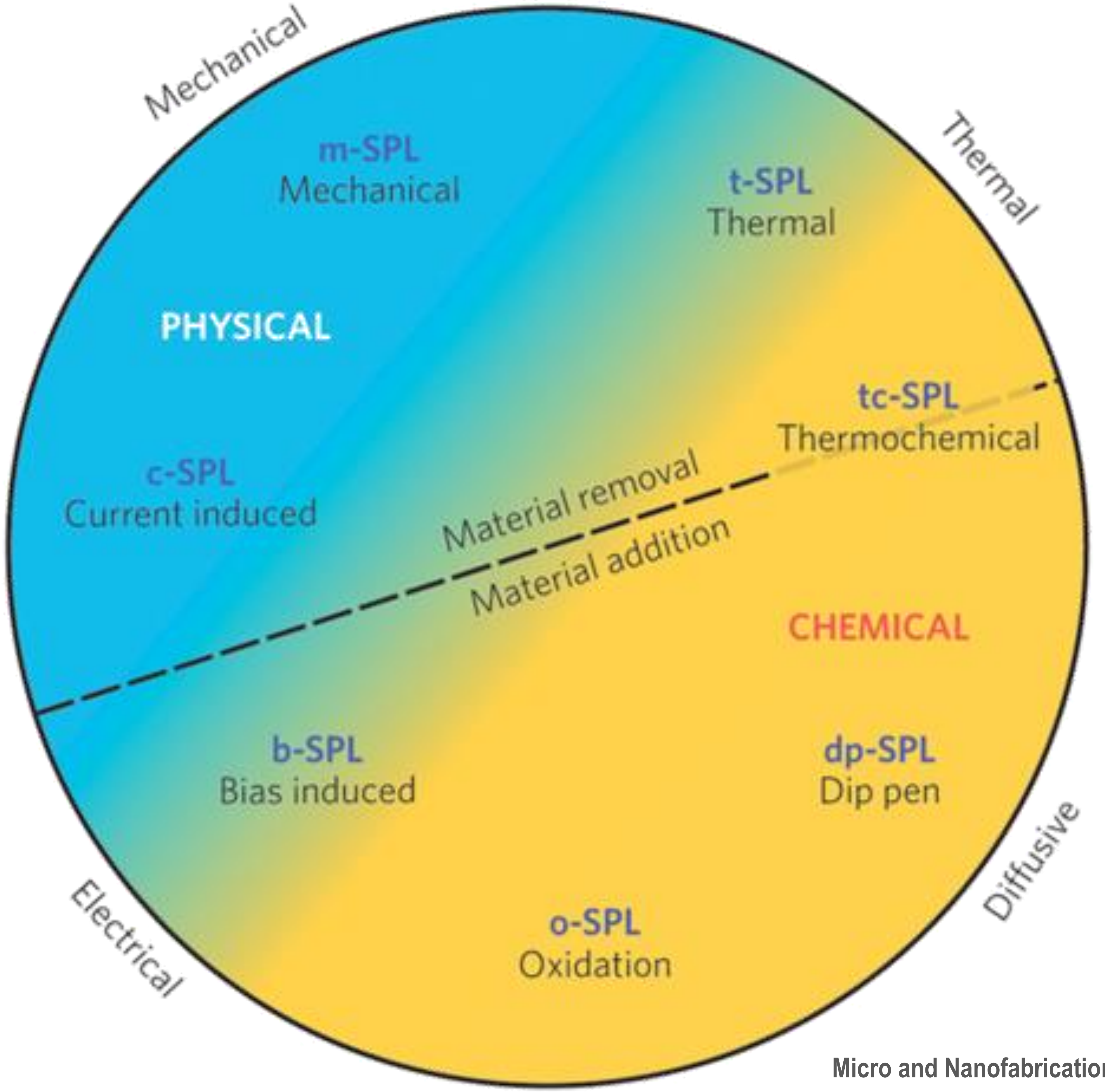
Scanning Probe
Microscopy
Lithography



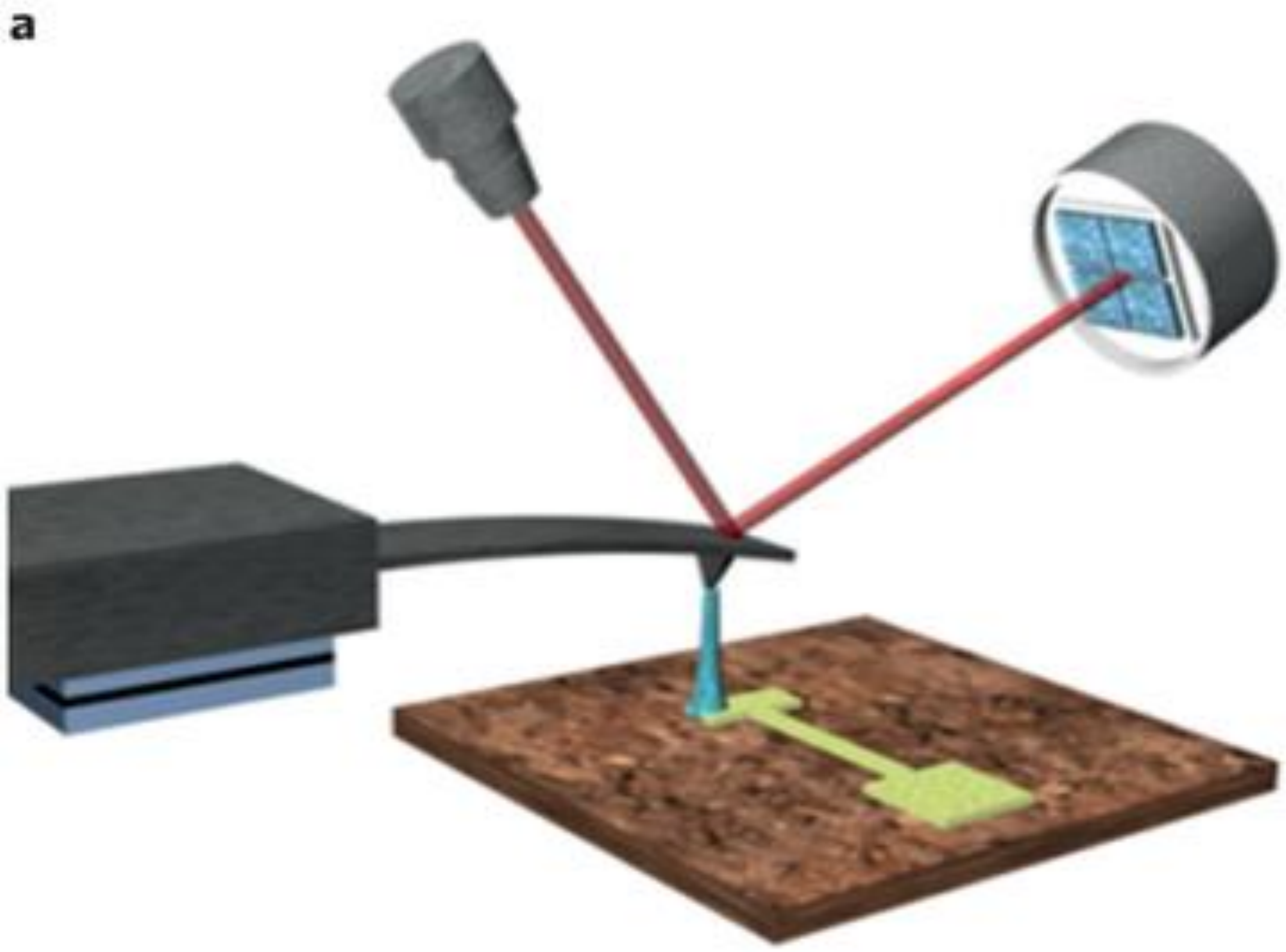
Far-field

Near-field

Scanning probe lithography

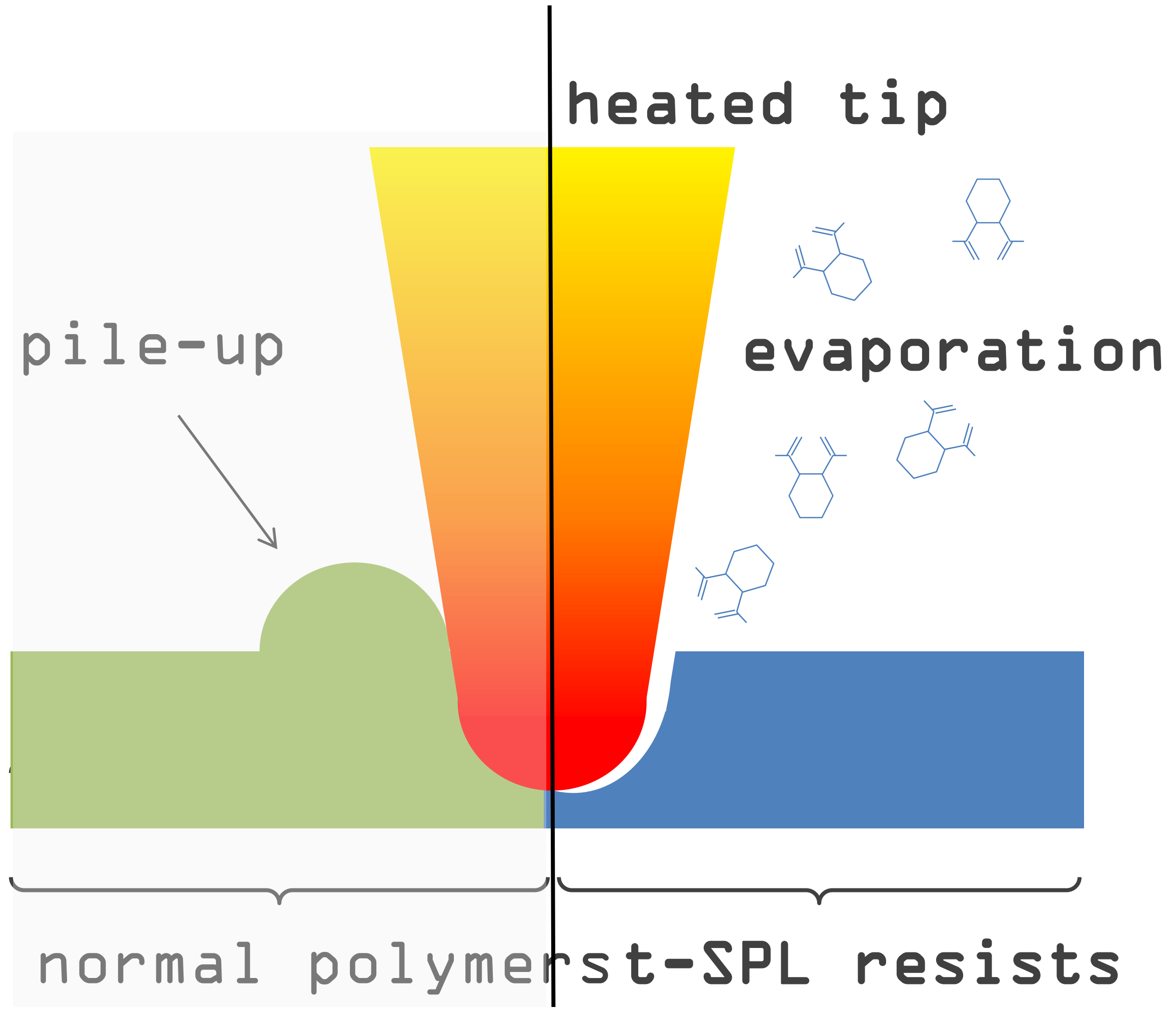


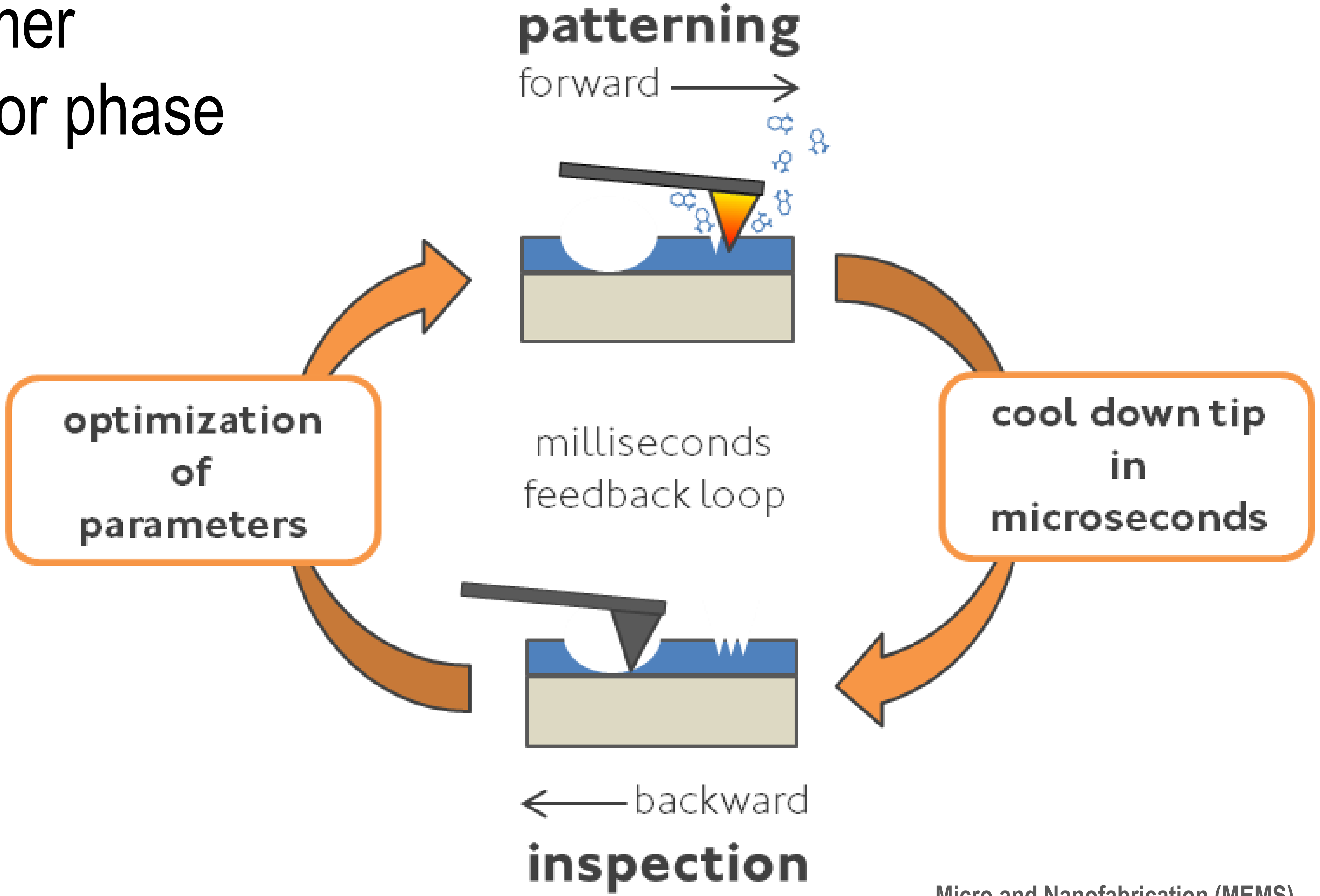
Scanning probe lithography



Thermal scanning probe lithography

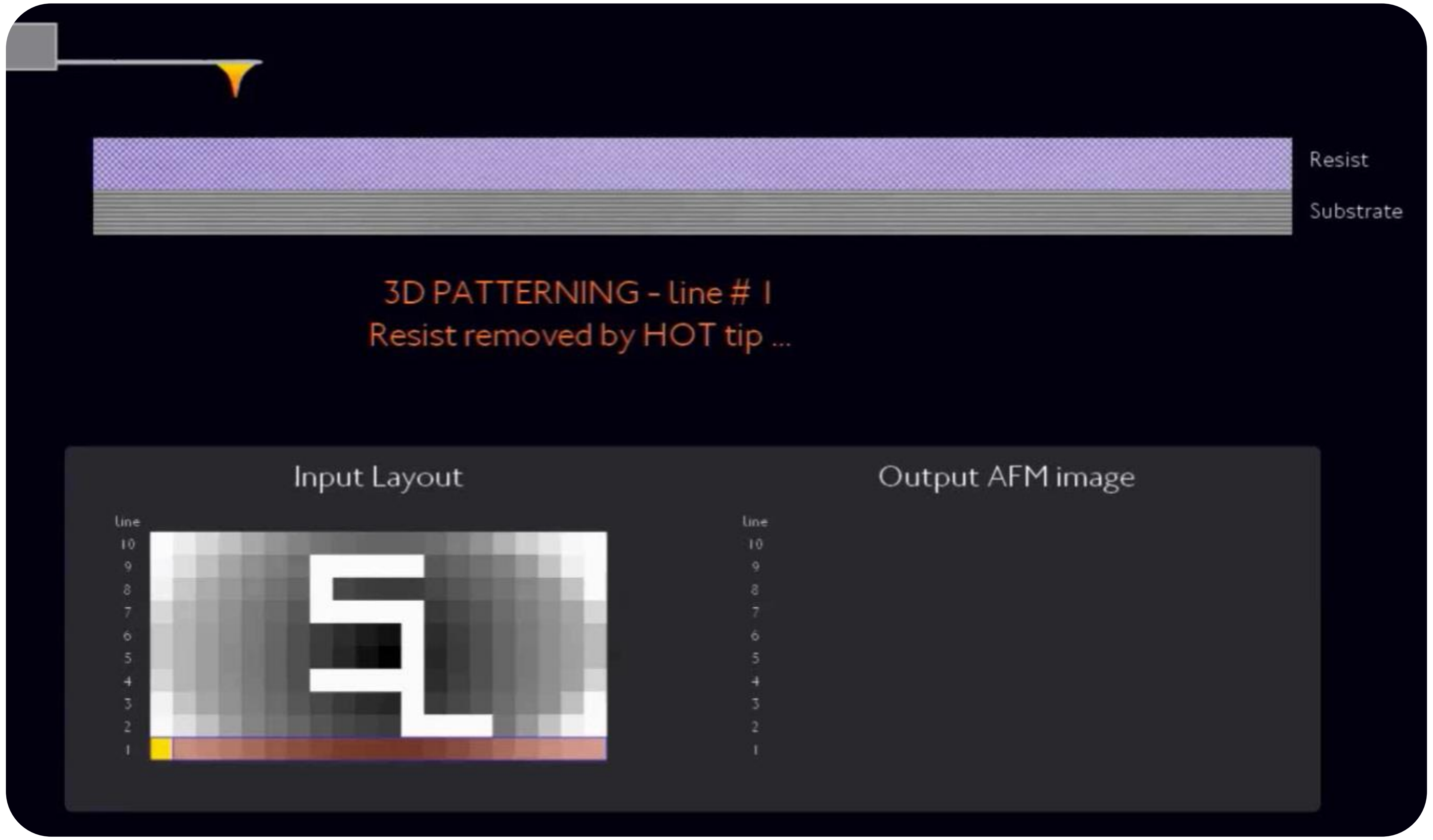
- Resist requirement (when heated):
- Not 'flowing' like normal polymer
- Completely removed into vapor phase
- "see what you get"
- In-situ metrology





Courtesy: Swisslitho GmbH

Thermal scanning probe lithography



Courtesy: Swisslitho GmbH

Supplementary

Lithography 7: Alternative patterning methods

II. Replication methods

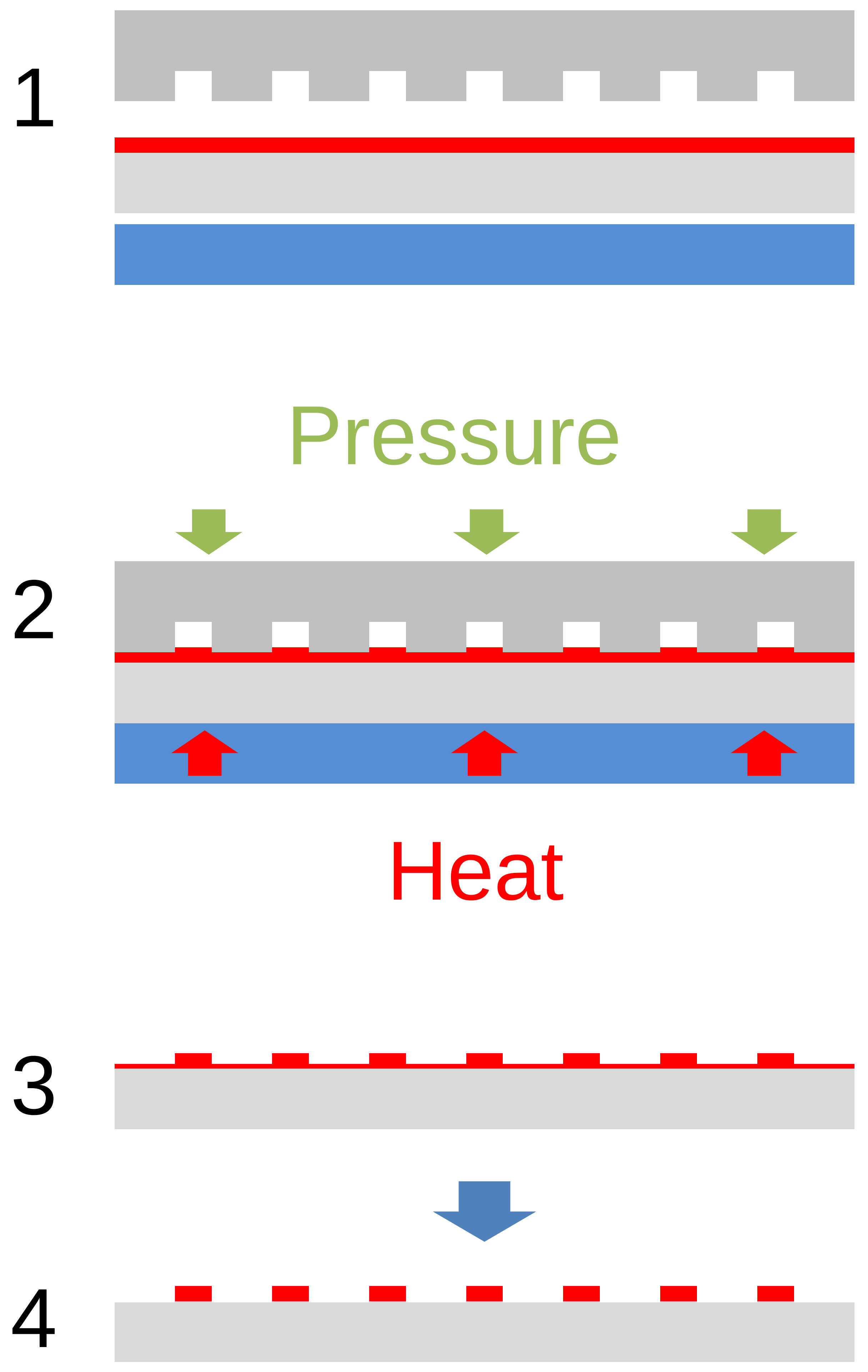
Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

Alternative lithography methods

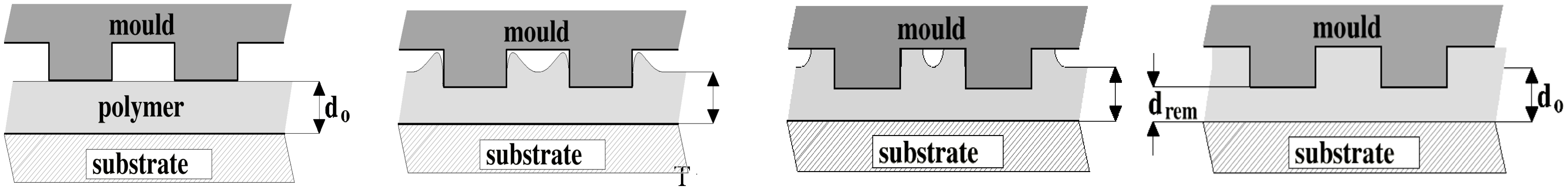
- Scanning probe lithography
- Nanoimprint lithography
- Soft-lithography
- Stencil lithography

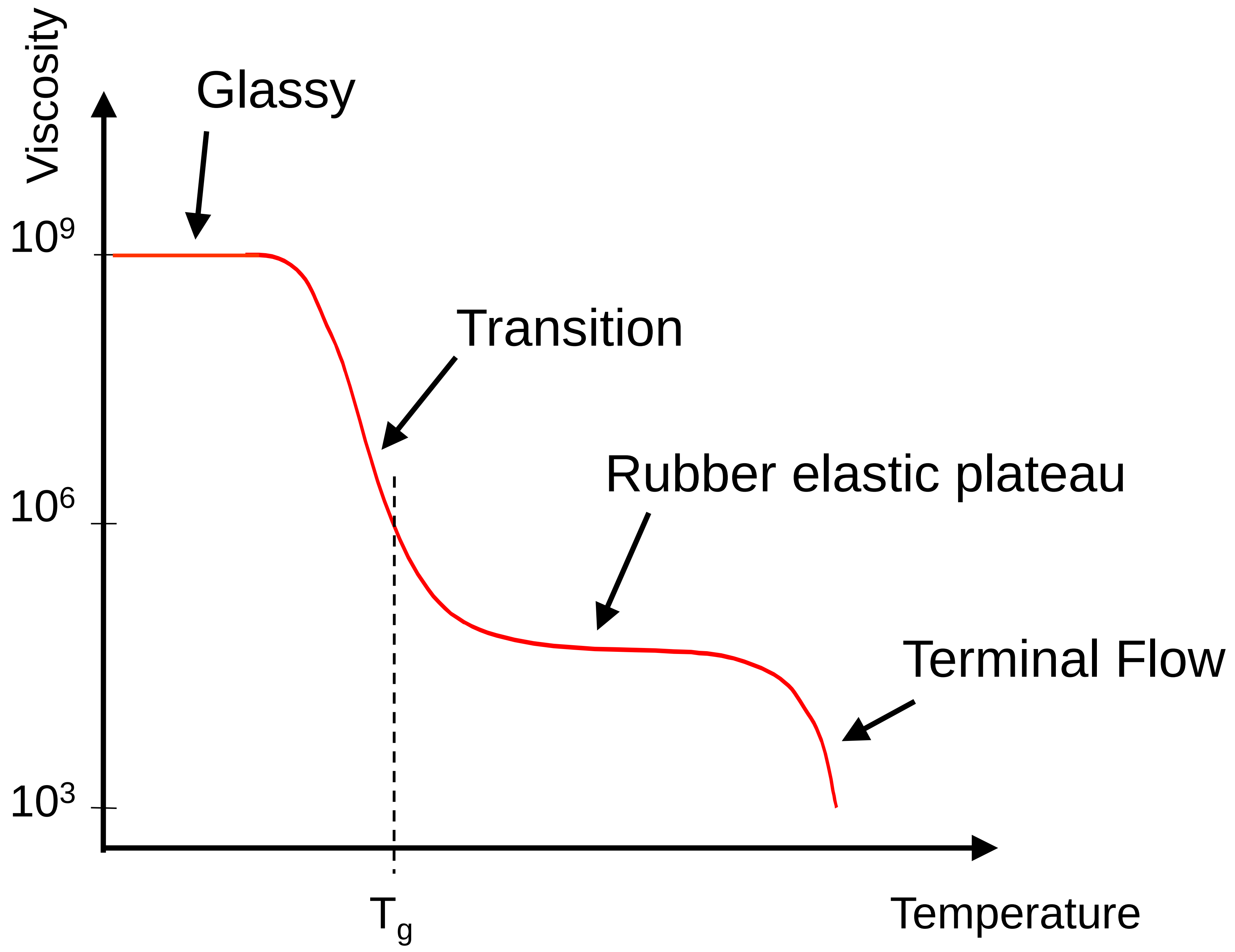
Nanoimprint lithography (NIL)

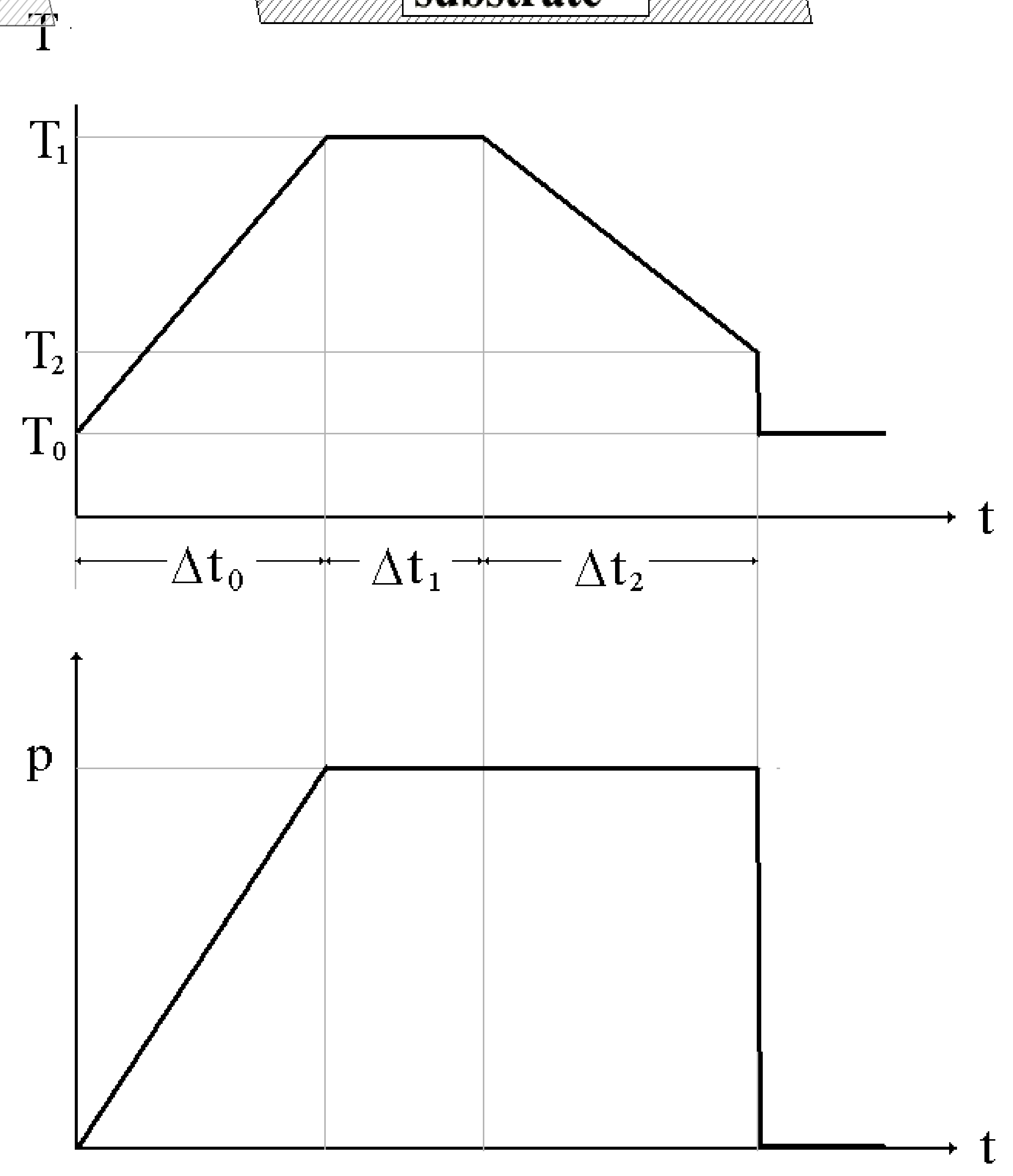


1. Imprint stack preparation
   - Stamp (or mold), Resist, Substrate, Chuck
2. Imprinting
   - Pressure / temperature / time profile
3. Separation
   - Temp control
4. Residual layer etch
   - Remove thin resist layer by O2 plasma

Nanoimprint lithography (NIL)







Temp / pressure profile

T_1 (ºC)	~	185
T_2 (ºC)	~	95
P (bar)	~	30
Δt_1 (s)	~	60
Δt_2 (s)	~	160

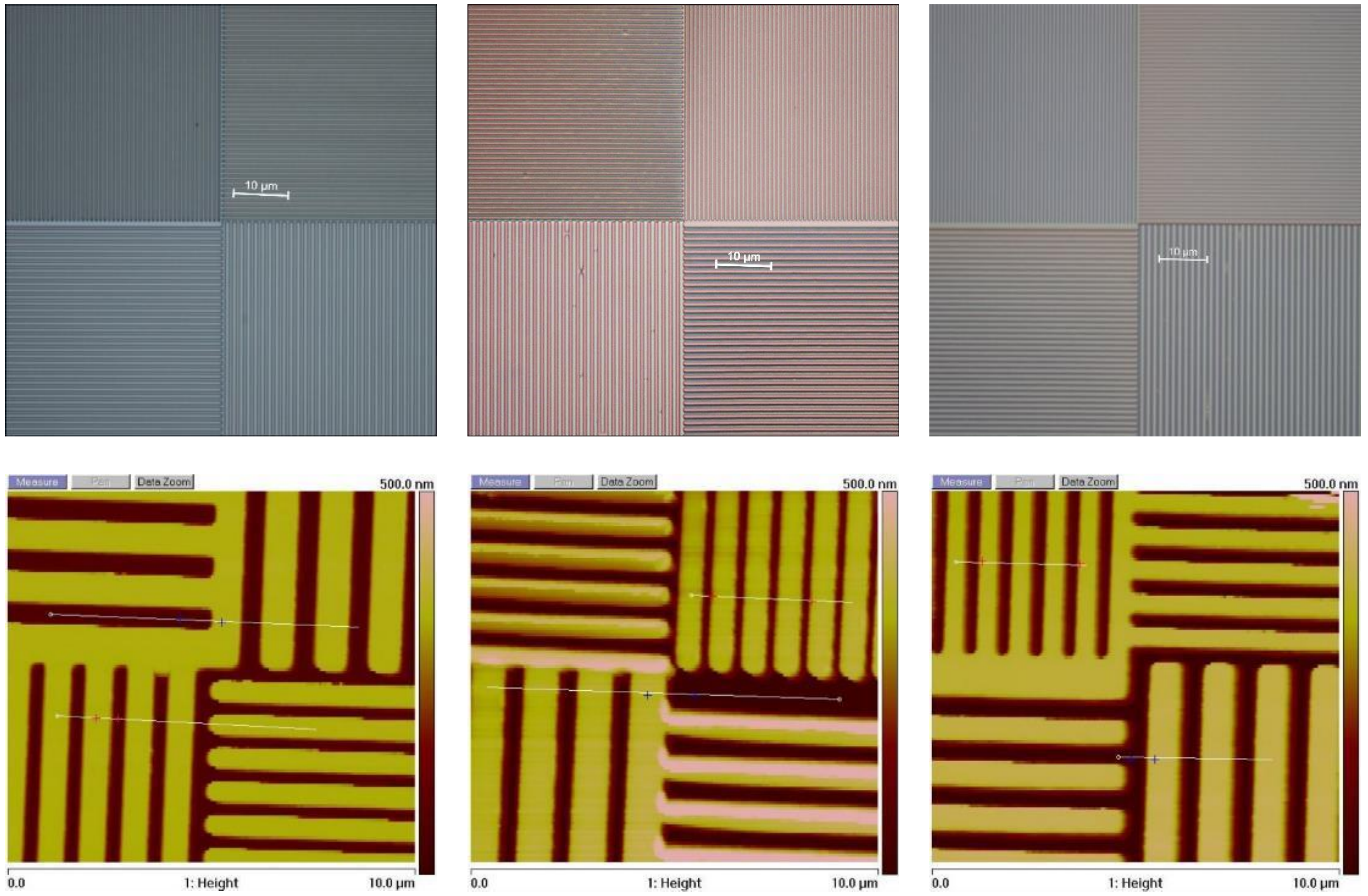
Nanoimprint lithography

- Master stamp is costly
- Replicate master in working stamp
- Use working stamp for substrate imprinting and for mass fabrication
- Working stamp can be Nickel, Polymer, etc.

Master | Working stamp | Substrate

Optical Microscope 100x

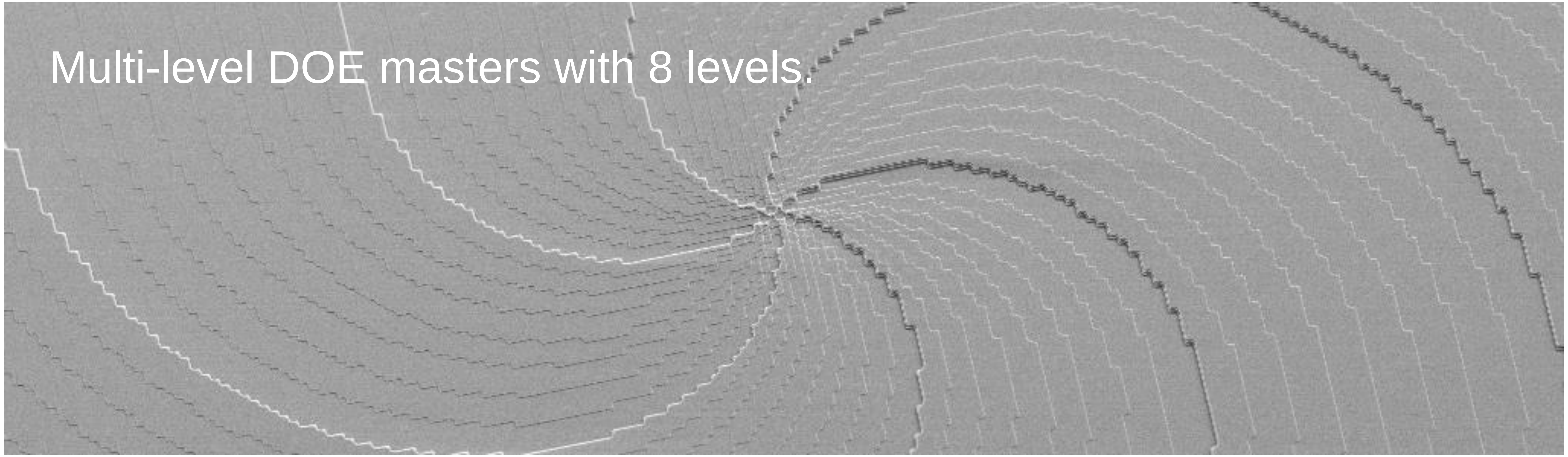
AFM



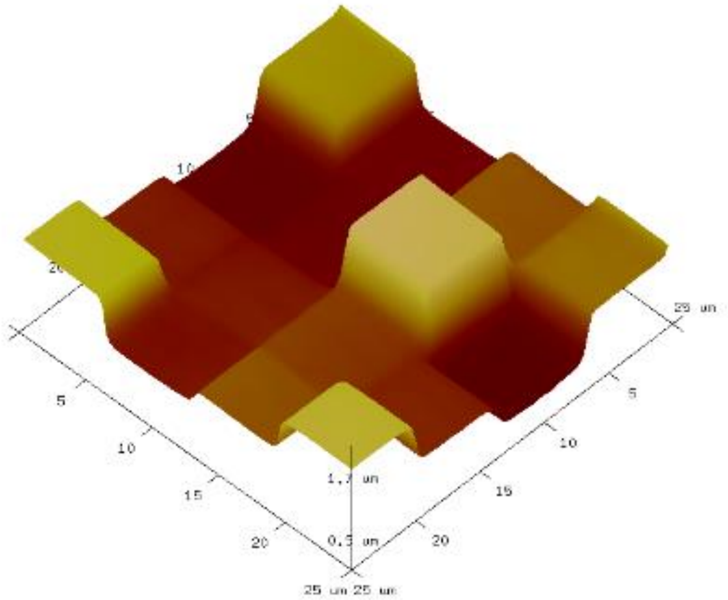
Master depth is 514 nm, imprint depth is 503 nm.
Master to substrate replication
Residual layer thickness < 20 nm

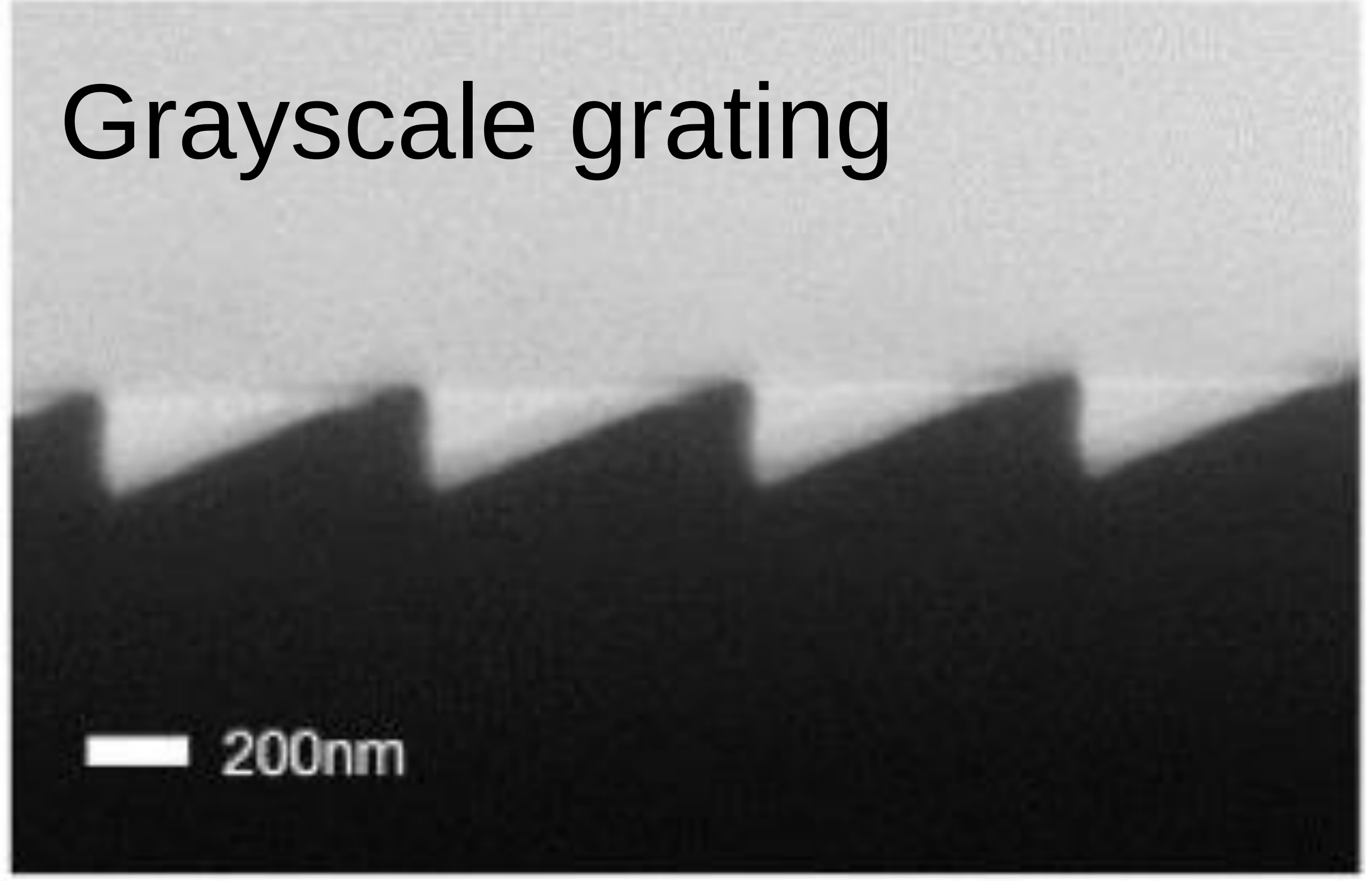
Courtesy: NILT

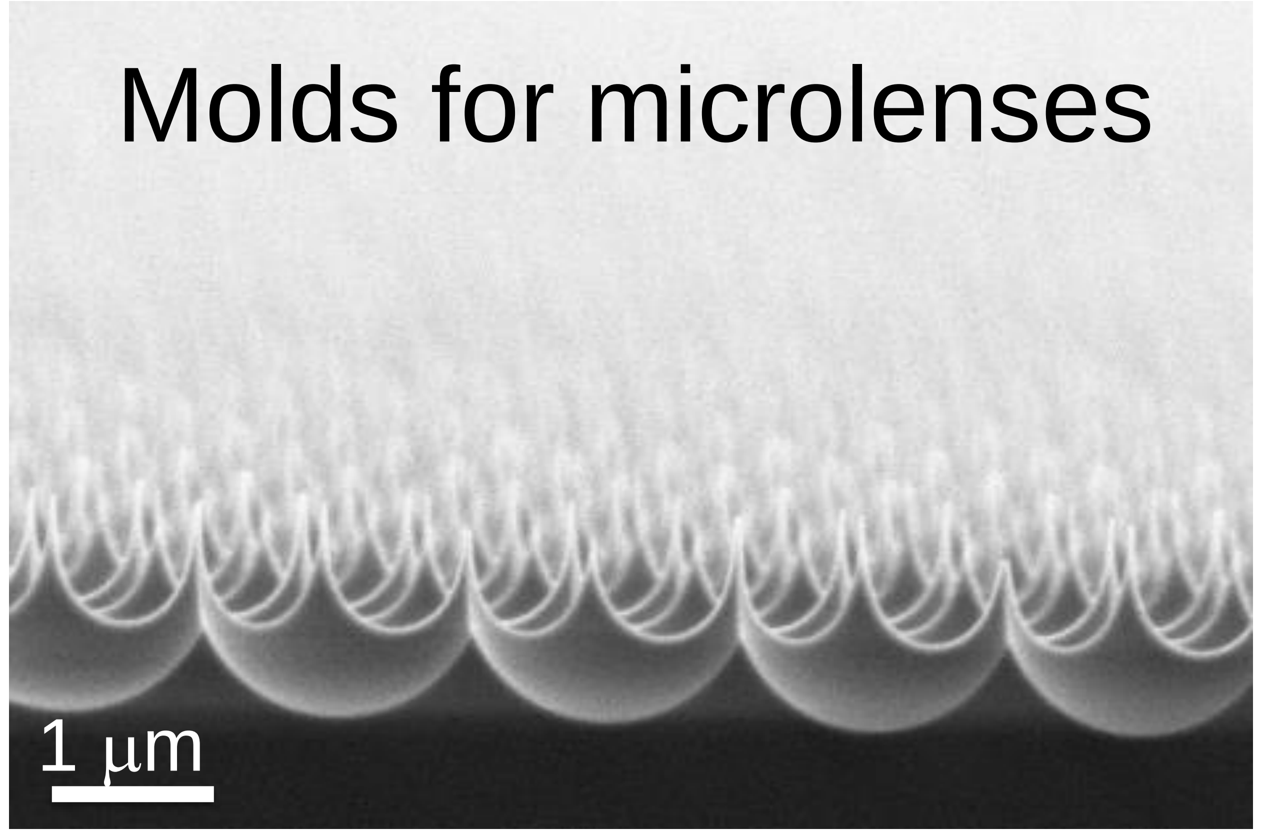
Nanoimprint lithography

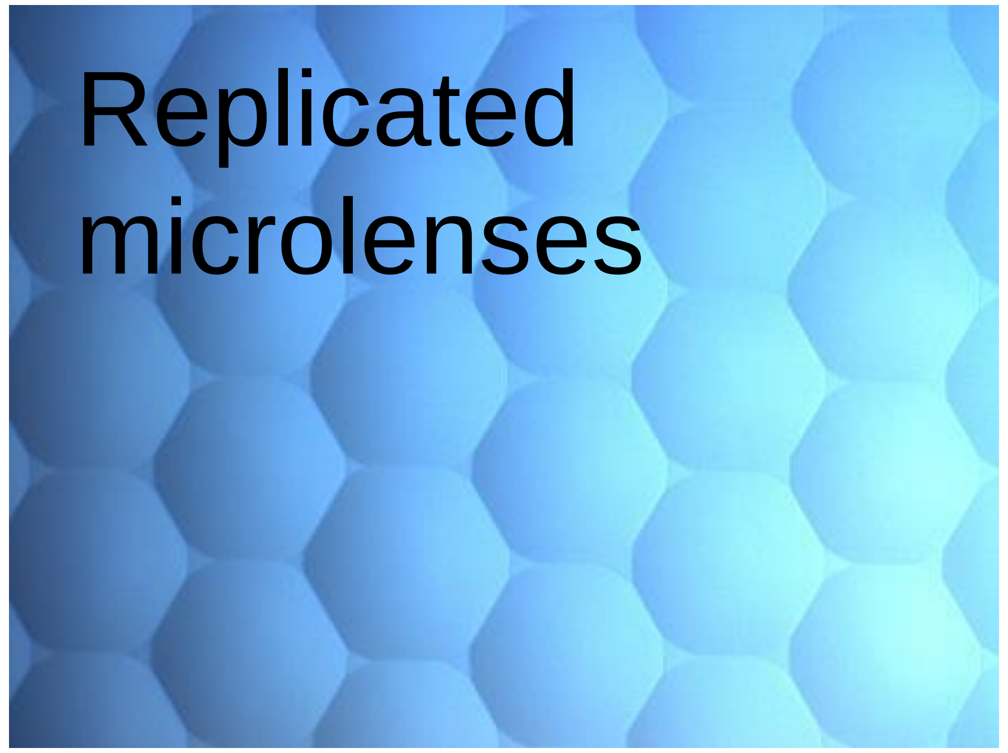


Courtesy: NILT



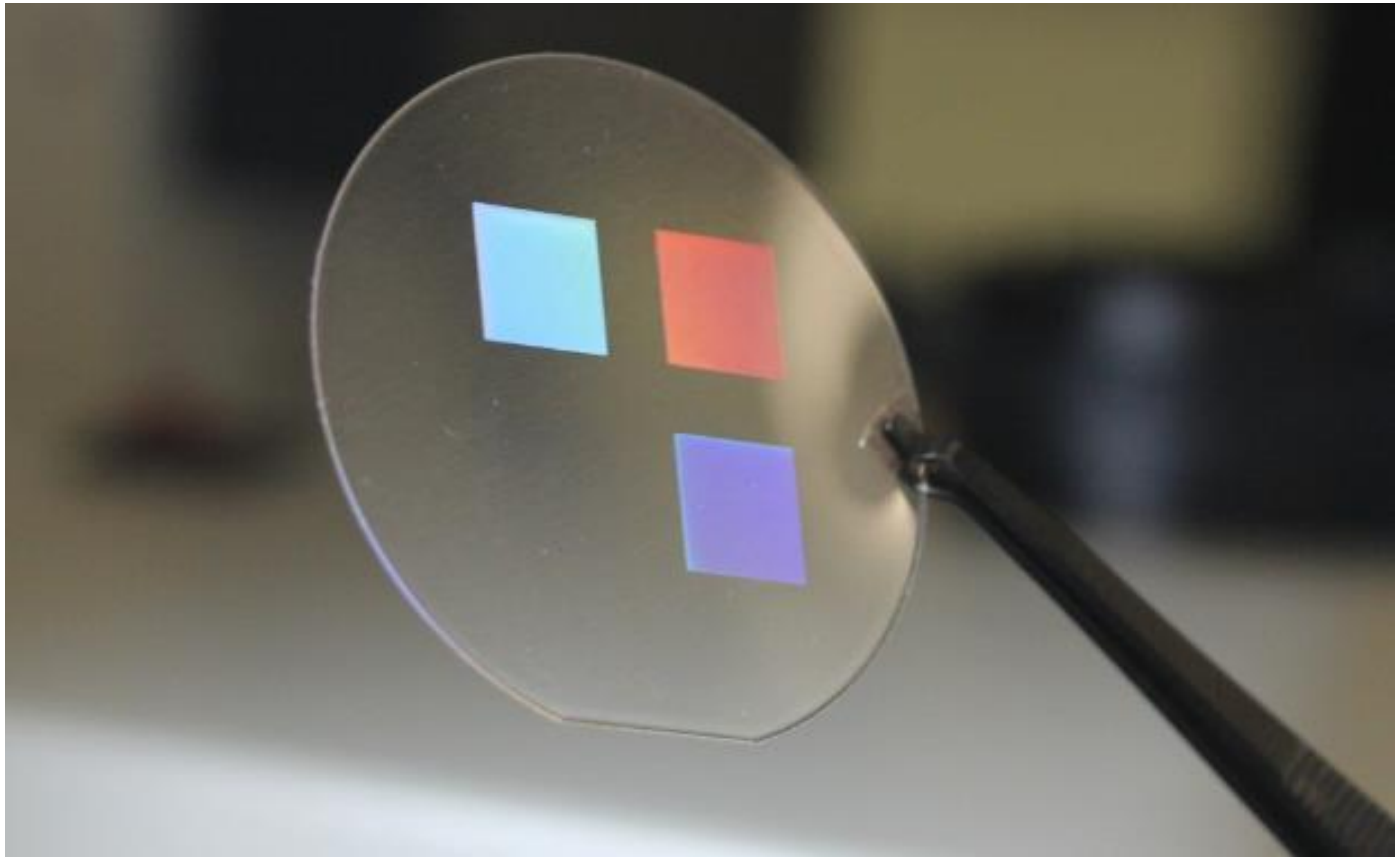






Nanoimprint lithography

Courtesy: NILT



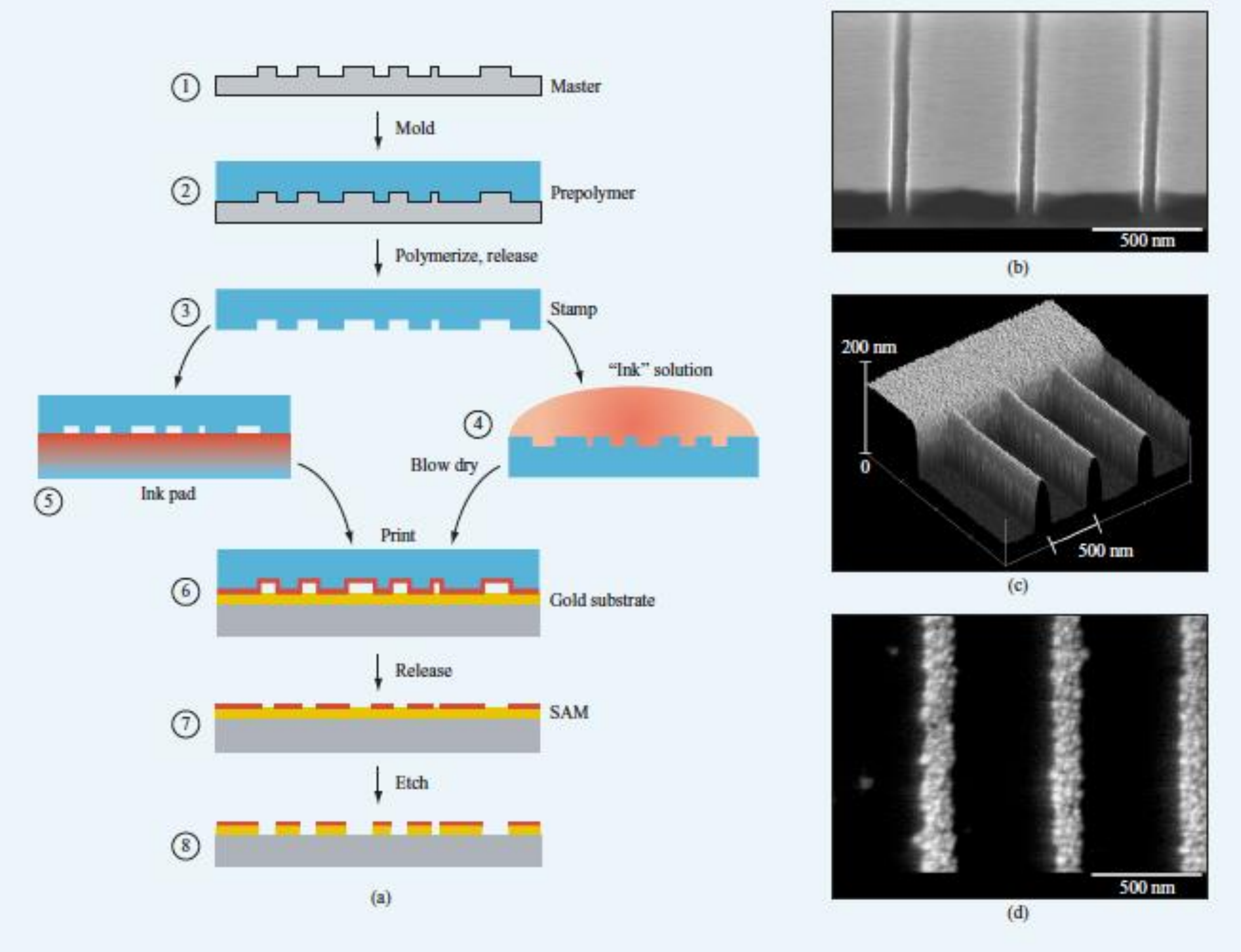
Large area standard pillar stamp insert.

Alternative lithography methods

- Scanning probe lithography
- Nanoimprint lithography
- Soft-lithography
- Stencil lithography

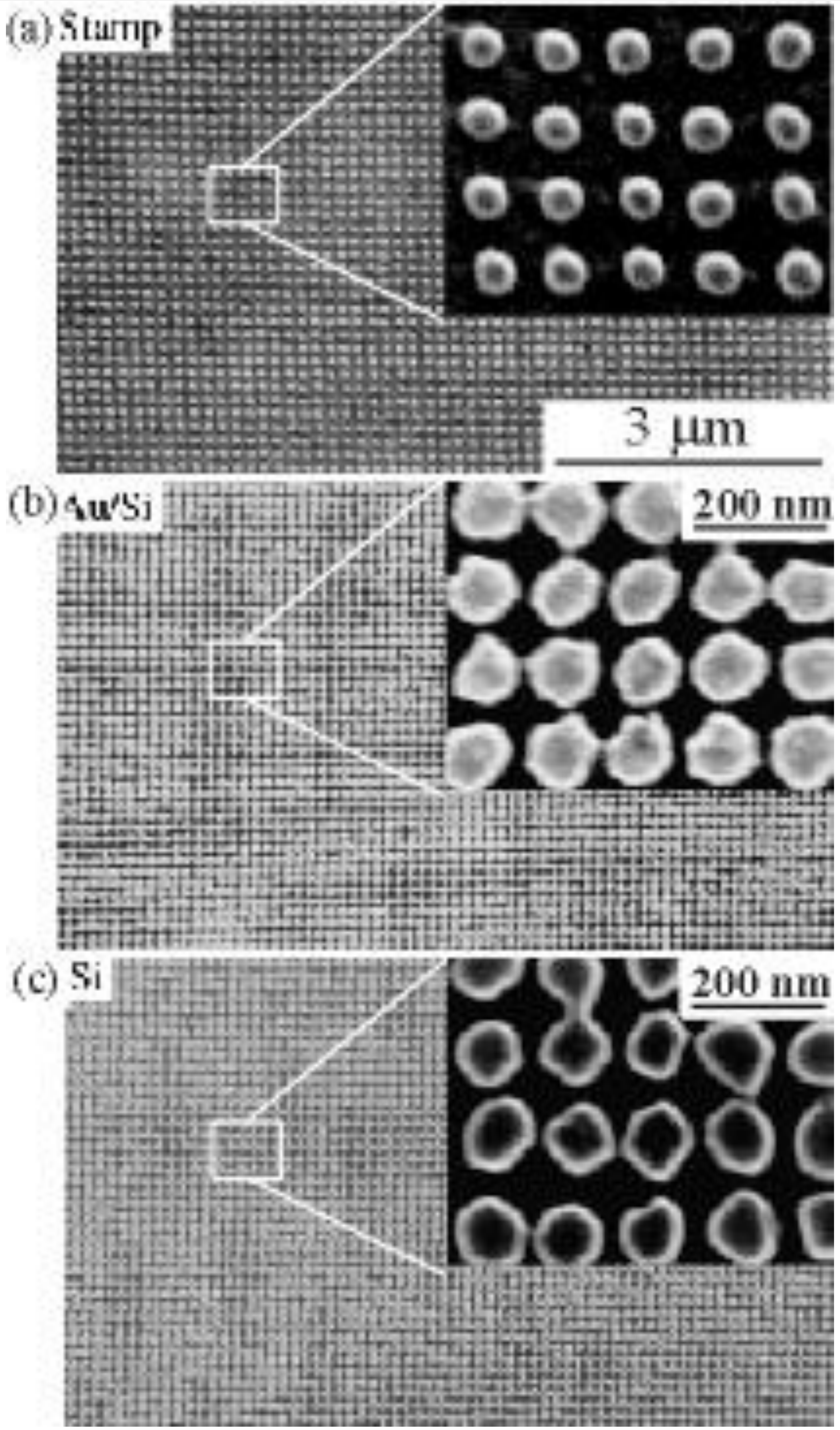
Soft-lithography, micro-contact printing

1. Master
2. Pre-polymer
3. Demolded stamp
4. Stamp inking by pad
5. Stamp inking by immersion
6. Printing on the substrate
7. Forming a SAM
8. Selective etching into layer



With permission:
IBM J. RES. & DEV. VOL. 45 NO. 5 SEPTEMBER 2001

Soft-lithography, micro-contact printing

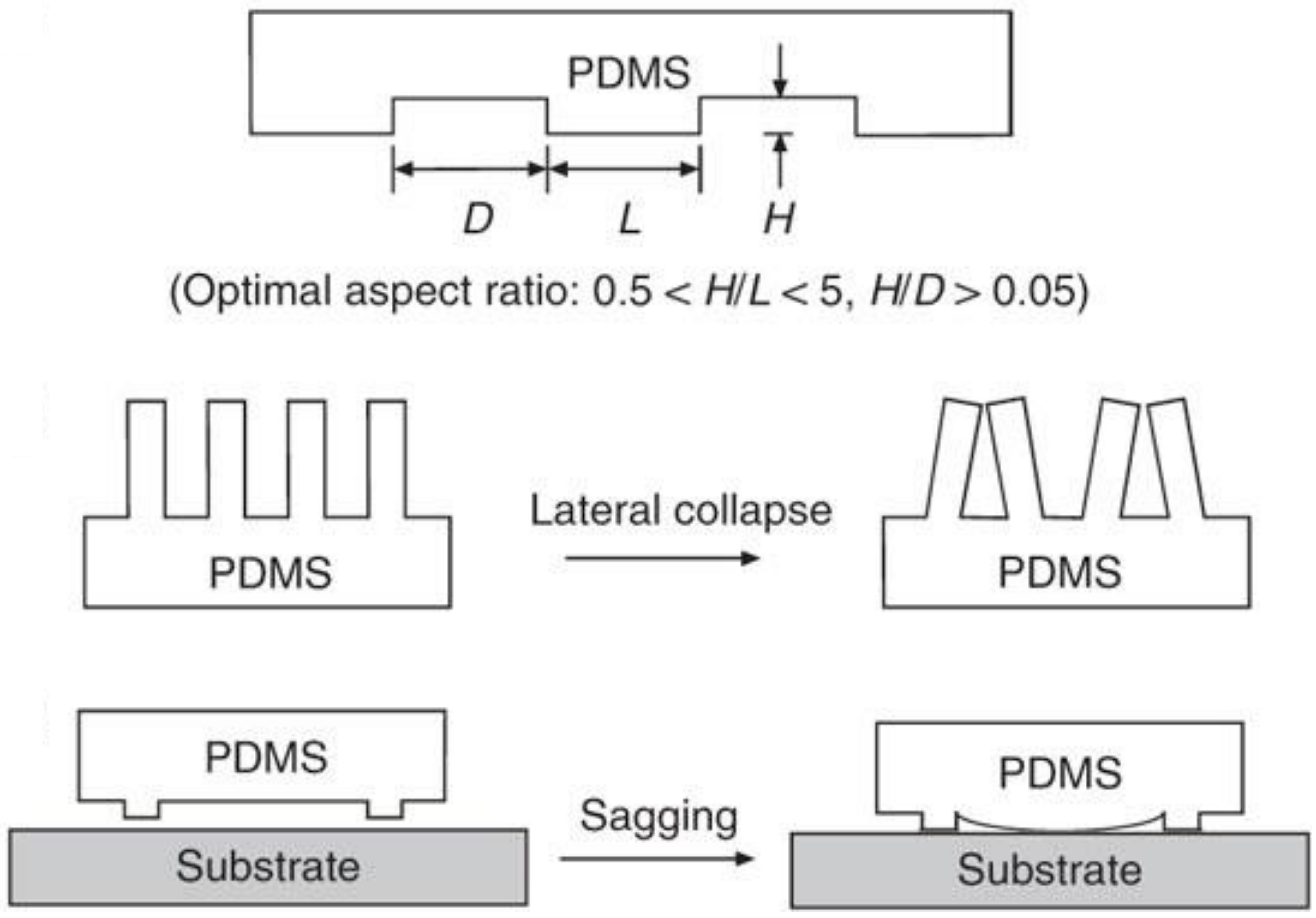


- High-resolution µCP:
- Scanning electron micrograph of a stamp with 60 nm dots.
- The corresponding gold dots fabricated by printing and etching were slightly broadened due to ink diffusion and substrate roughness.
- The gold pattern served as a mask to etch the bare regions 250 nm deep into the underlying silicon by reactive ion etching.

Soft-lithography, micro-contact printing

- Possible problems and limitations

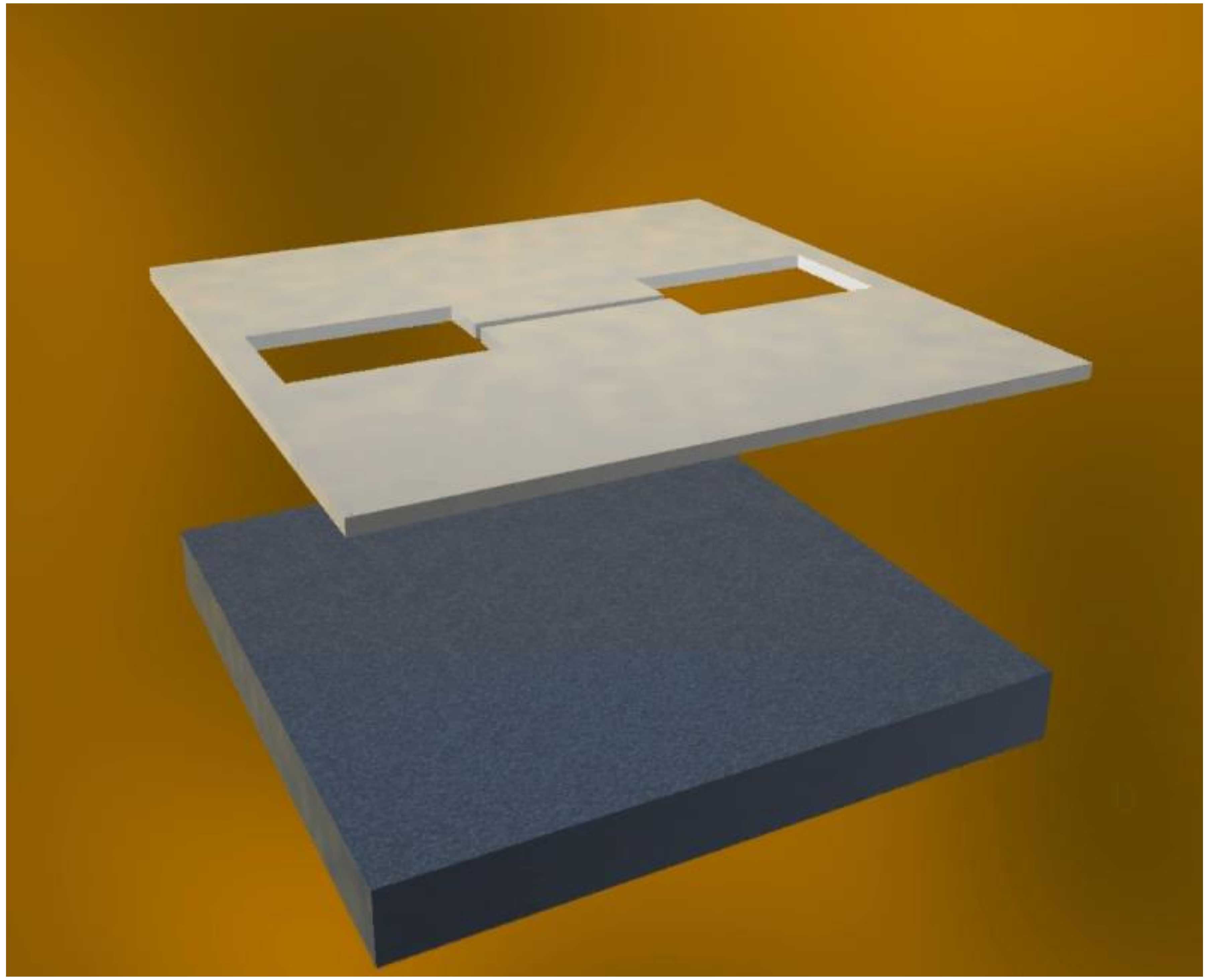
  Aspect ratio of stamp features
- Lateral collapse
- Sagging



Alternative lithography methods

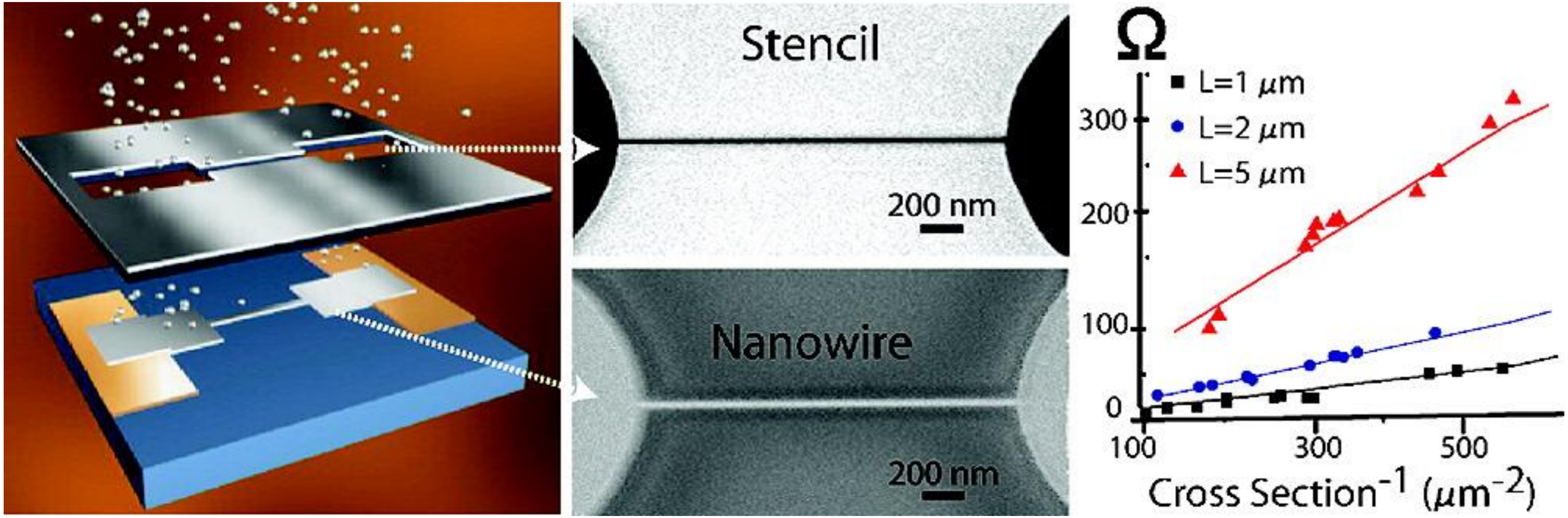
- Scanning probe lithography
- Nanoimprint lithography
- Soft-lithography
- Stencil lithography

Stencil lithography



Direct fabrication of nanostructures without resist.

Stencil lithography nanowire fabrication



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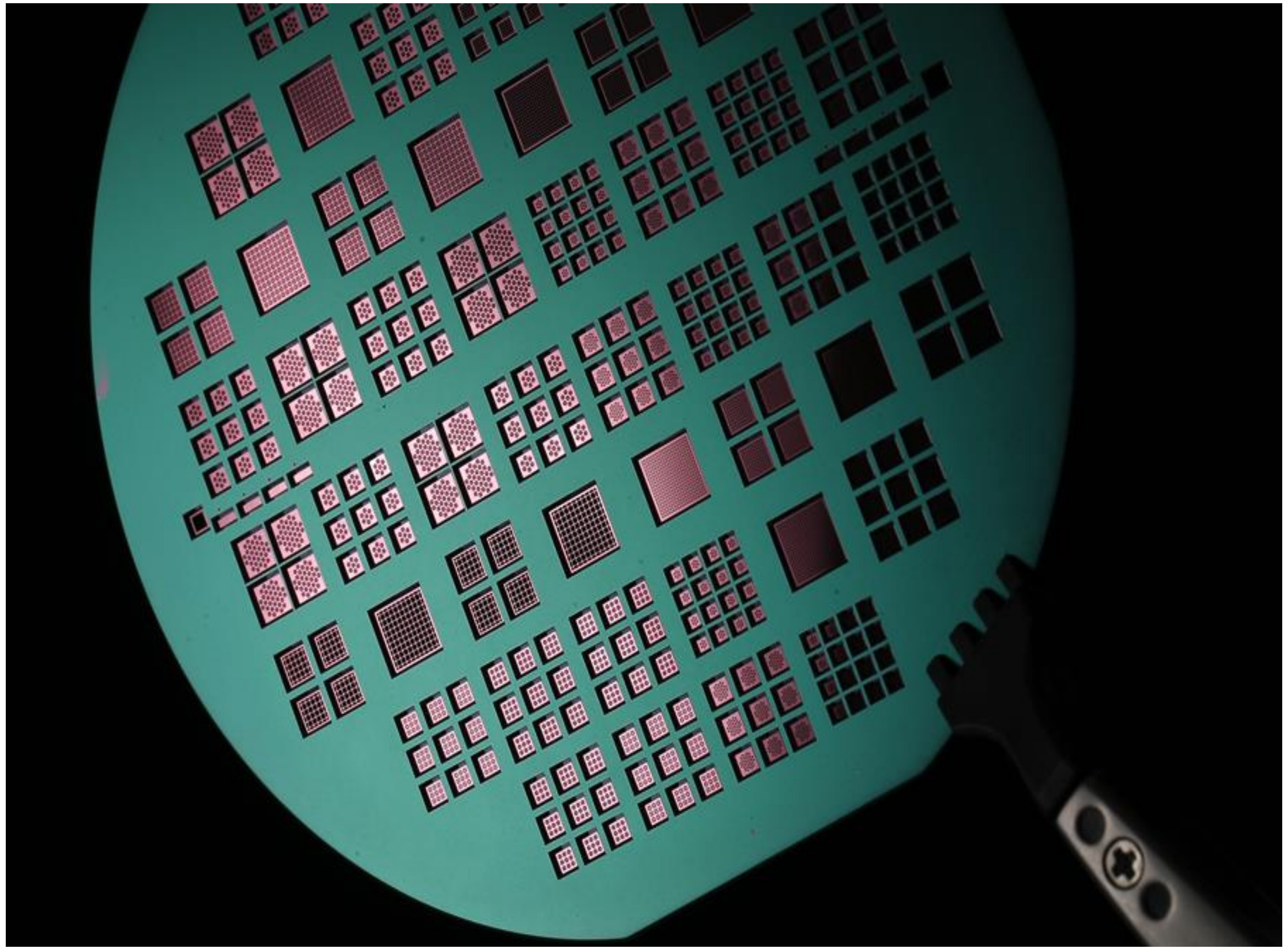
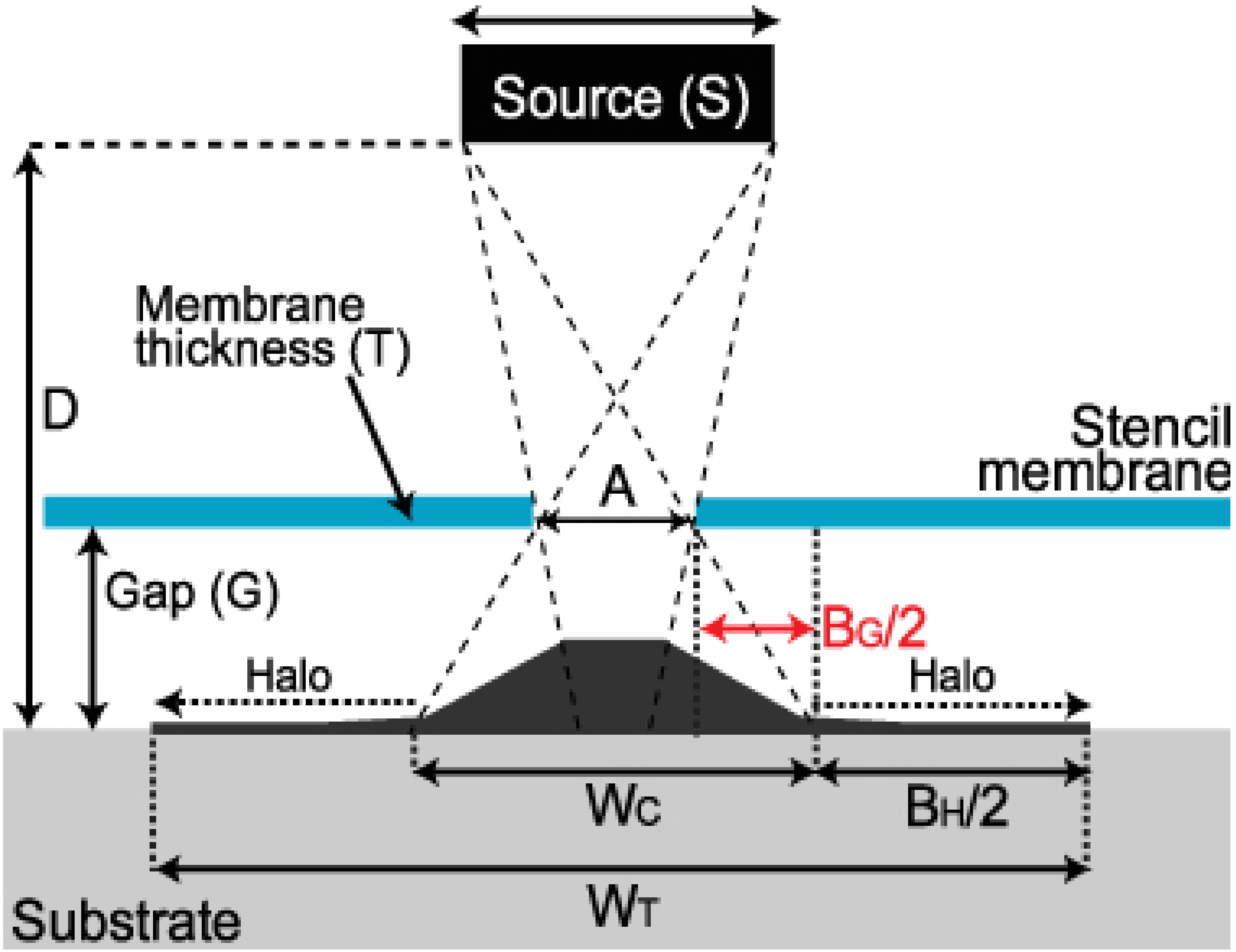
O. Vazquez et al. Nano Lett., 2008, 8 (11), pp 3675–3682

Stencil lithography full wafer



- 100mm size wafer stencil for high-resolution shadow-mask technique
- Aperture resolution down to ~ 50 nm

Stencil lithography details



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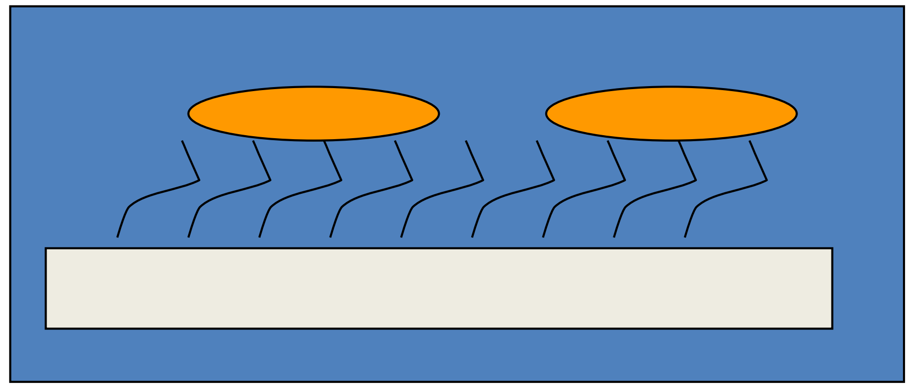
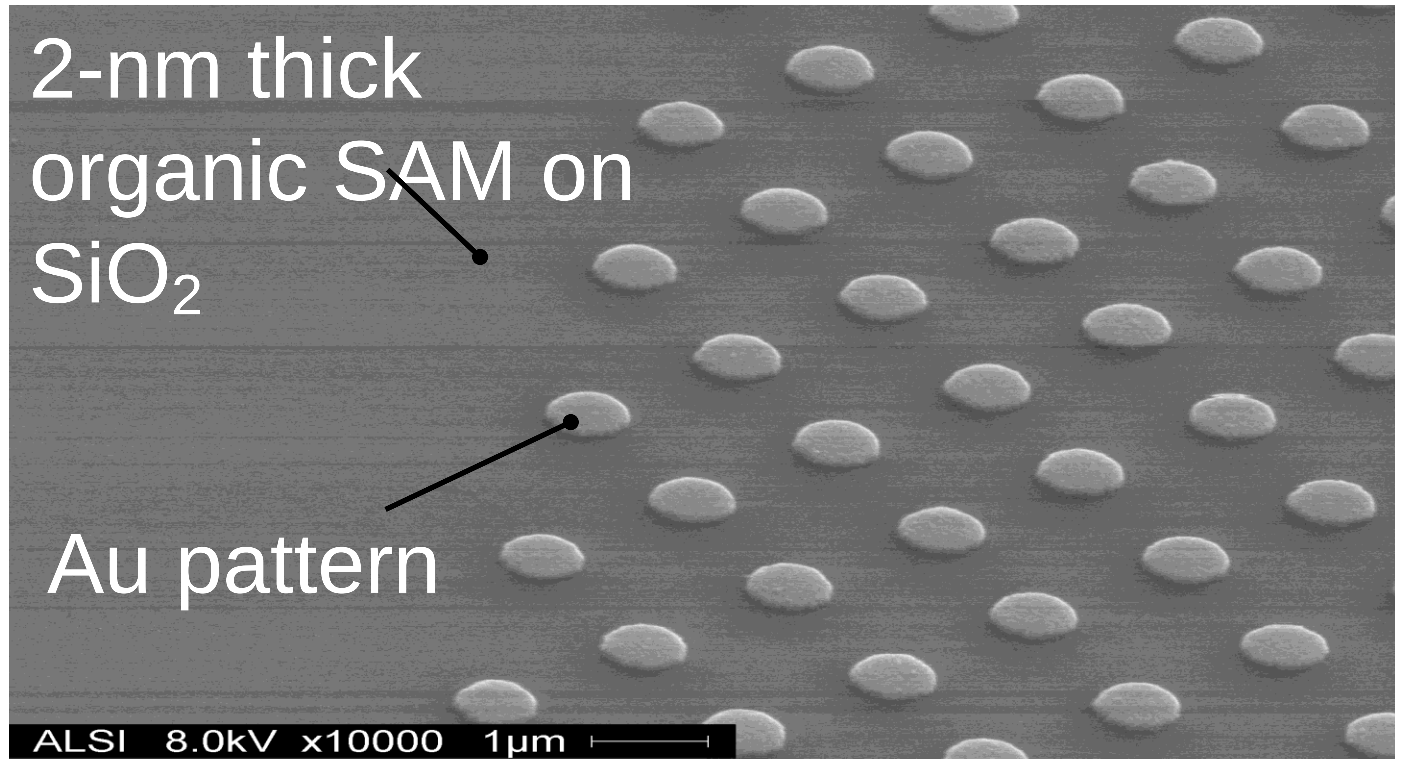
O. Vazquez et al. Nanotechnology, Volume 20, Number 41

Nanostencil lithography on ‘exotic’ surfaces

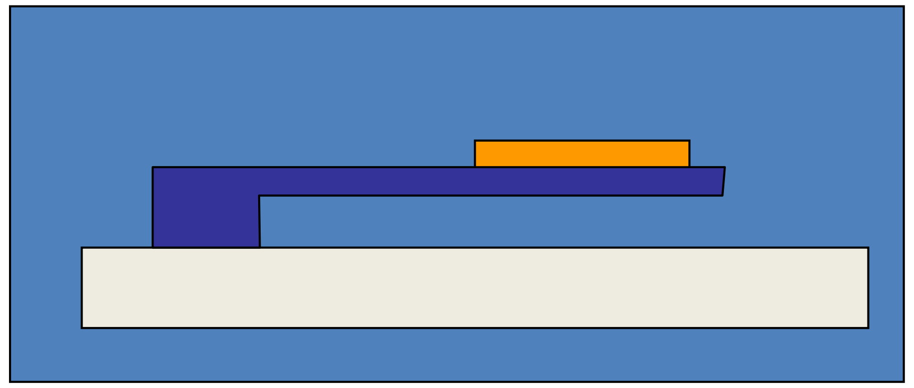
On SAM

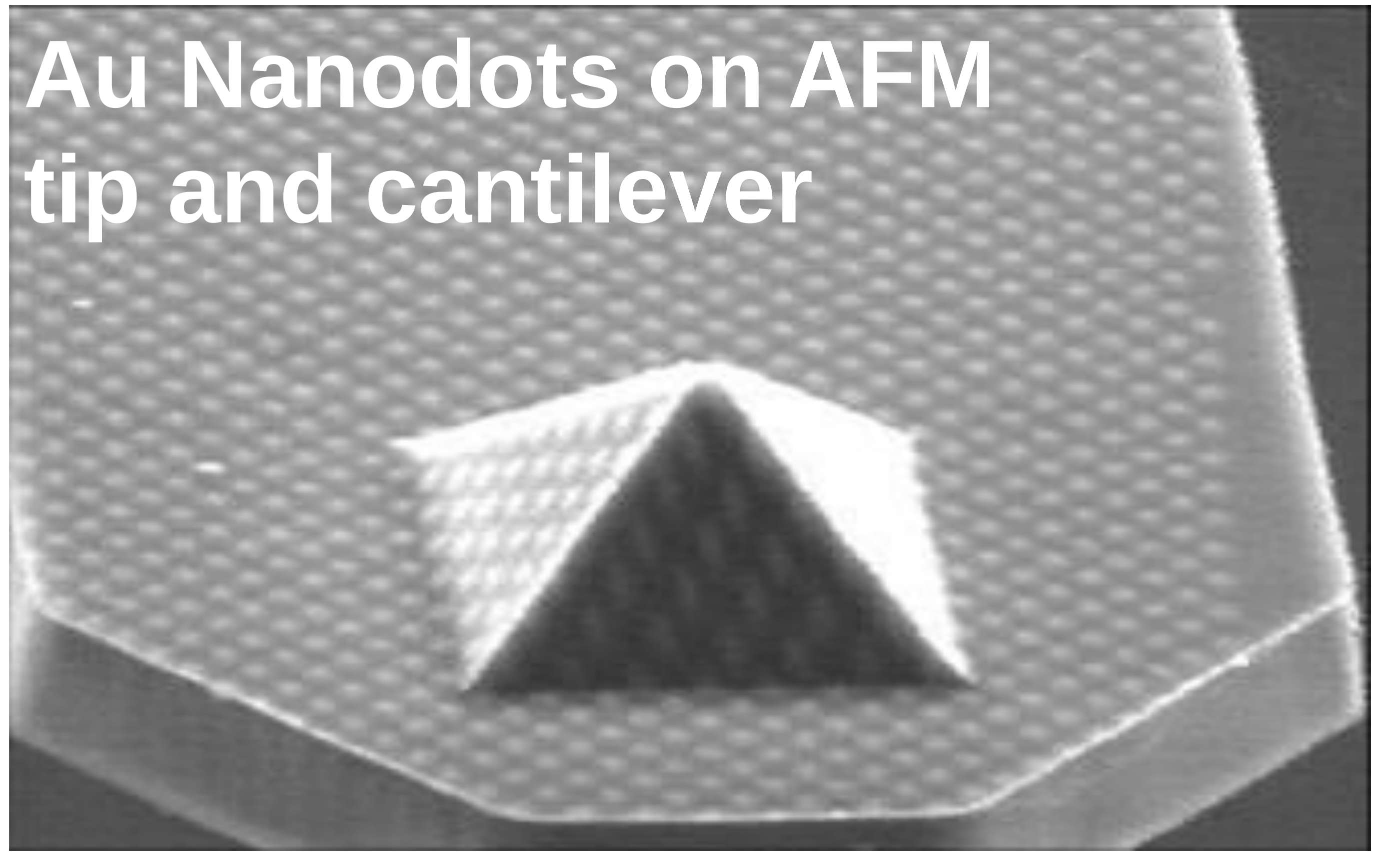




E.A. Speets et al., Twente University (2004)

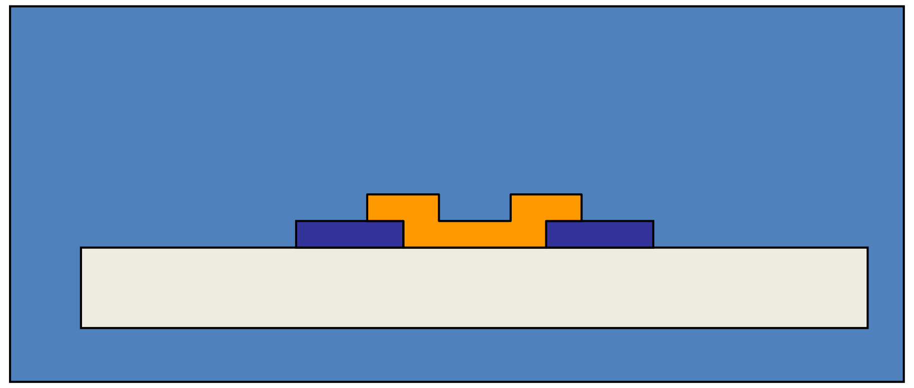
Freestanding MEMS

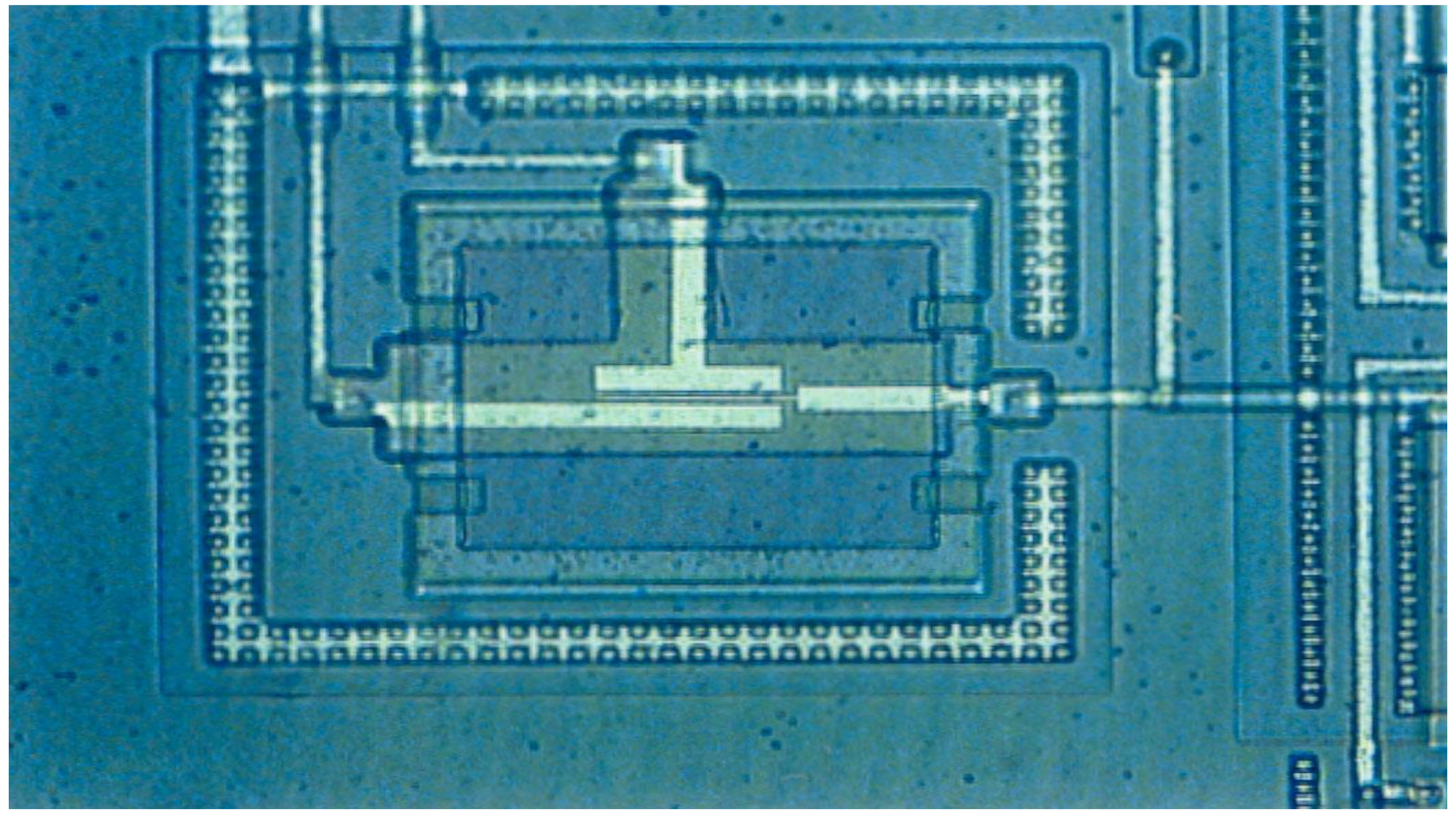




Brugger et al., Twente University (2000)

Post CMOS

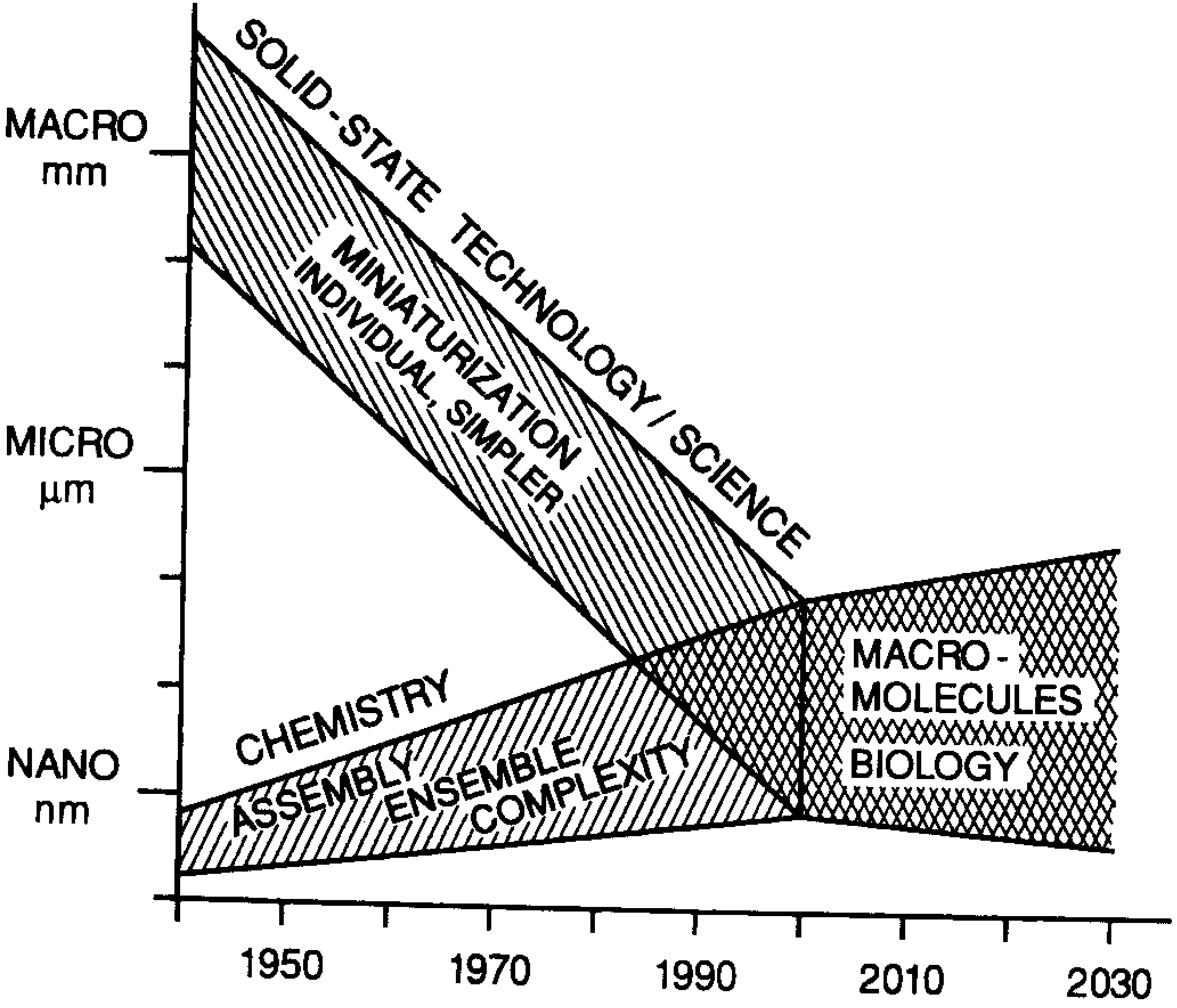




Arcamone et al., CNM Barcelona (2009)

Alternative lithography methods

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



- Scanning probe lithography
- Nanoimprint lithography
- Soft-lithography
- Stencil lithography

- Bottom-up Self Assembly