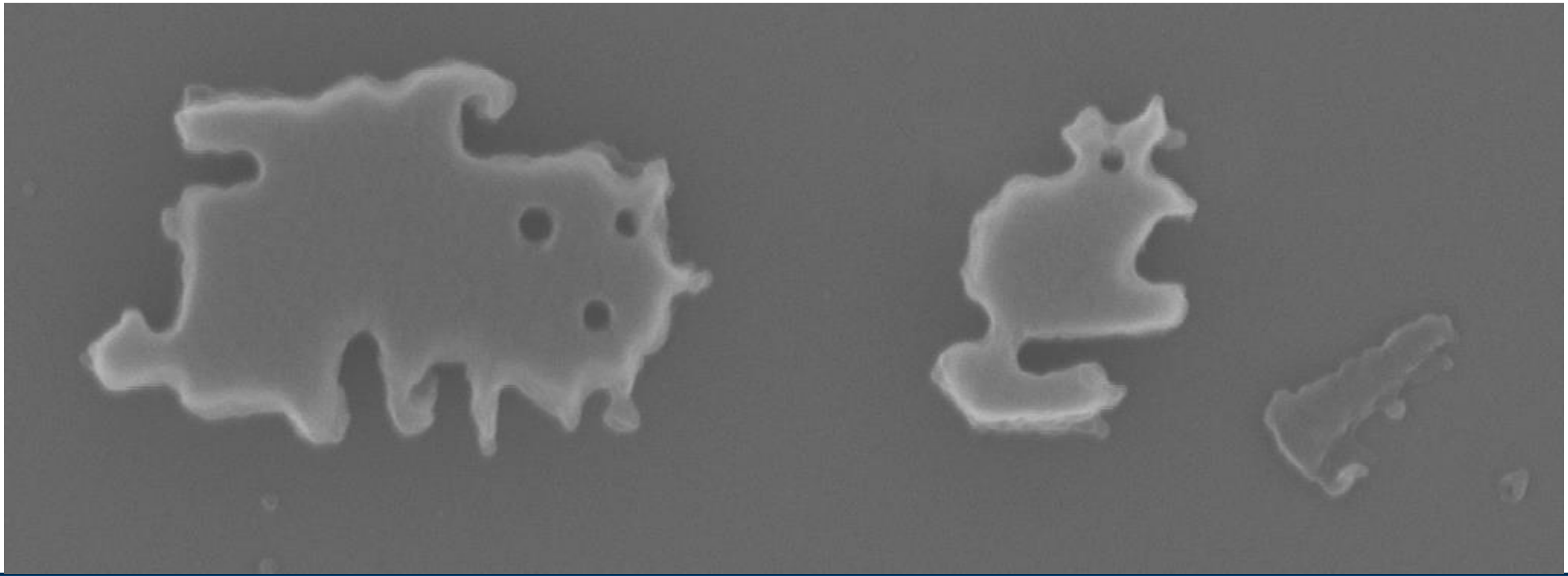


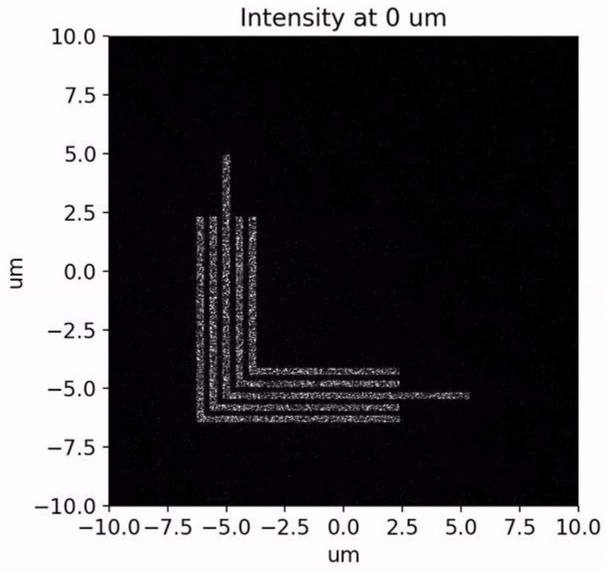
DESIGN, DEVELOPMENT AND EVALUATION OF HOLOGRAPHIC MASKS FOR PROXIMITY LITHOGRAPHY WITH EUV RADIATION

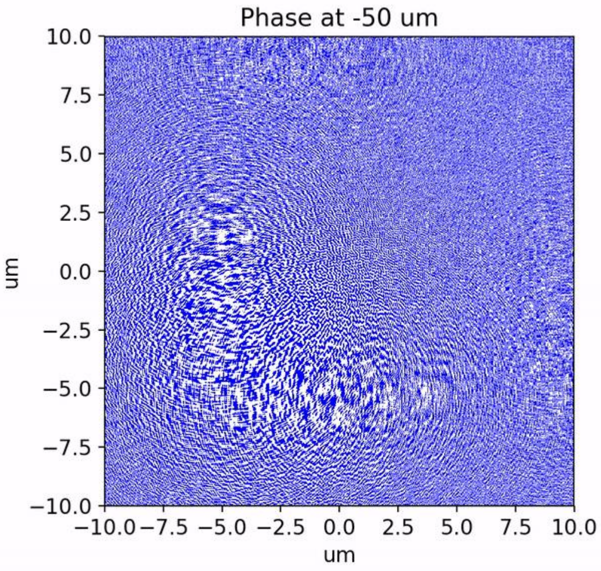
NOVEMBER 6TH 2019 I LARISSA JUSCHKIN

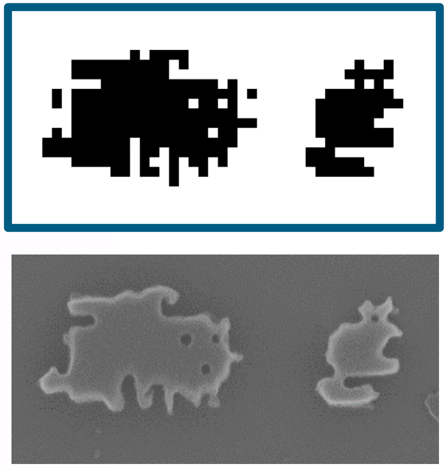
Valerie Deuter, Maciej Grochowicz, Sascha Brose, Jan Biller, Detlev Grützmacher

RWTH Aachen University and Forschungszentrum Jülich

COMPUTATIONAL PROXIMITY LITHOGRAPHY







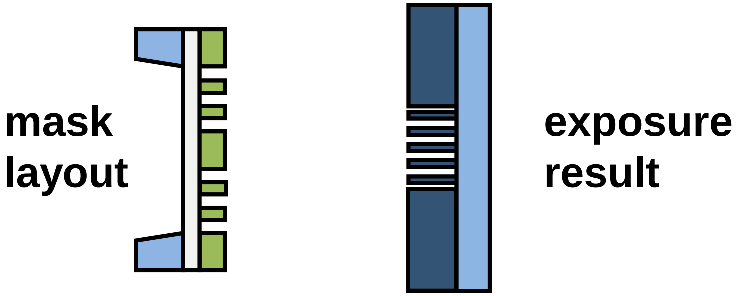
mask level

- Investigation of potential of EUV proximity lithography for producing arbitrary nano-scale pattern
  - Development of mask design (hologram)
  - Fabrication techniques
  - EUV lithography

MOTIVATION

Why interference / proximity lithography?

- Self-healing
  - Small defects on mask do not influence exposure result
- Lens-less
  - All materials are strongly absorbing EUV radiation → no refractive lenses
  - Simple setup
- Mask-wafer gap
  - Lower risk of mask/wafer damage



Why computational lithography?

- Optical proximity correction
  - Higher image contrast and resolution
- Designing of phase-shifting masks
  - More efficient masks

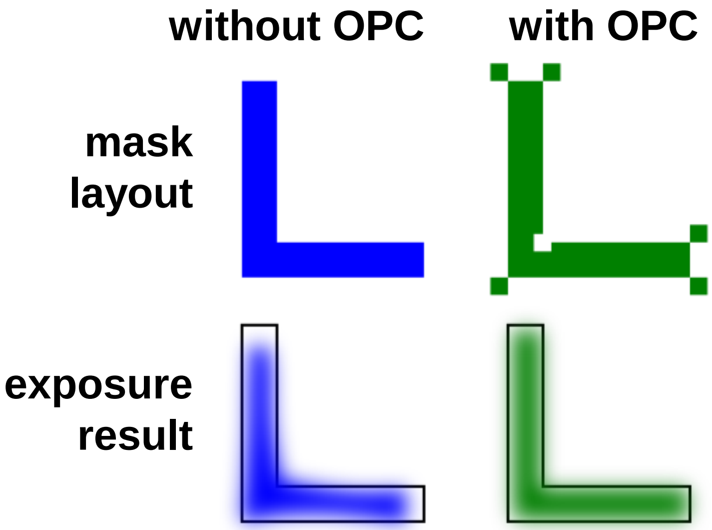


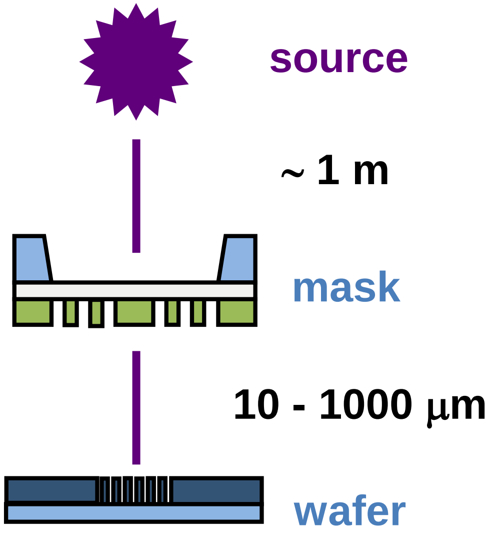
Image: https://de.wikipedia.org/wiki/Optical_proximity_correction

EUV PROXIMITY LITHOGRAPHY

- Small gap between mask and wafer for patterning
- Complex geometries when in Fresnel diffraction mode (N_F~1), e.g. for separate µm-scale features
  → mask layout ≠ resist pattern
- High resolution with specially designed masks
- Arbitrary structures

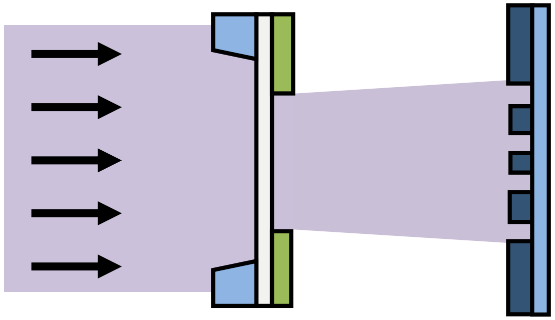
→ Negligible electron blur
→ No charging effects
} compared to eBeam

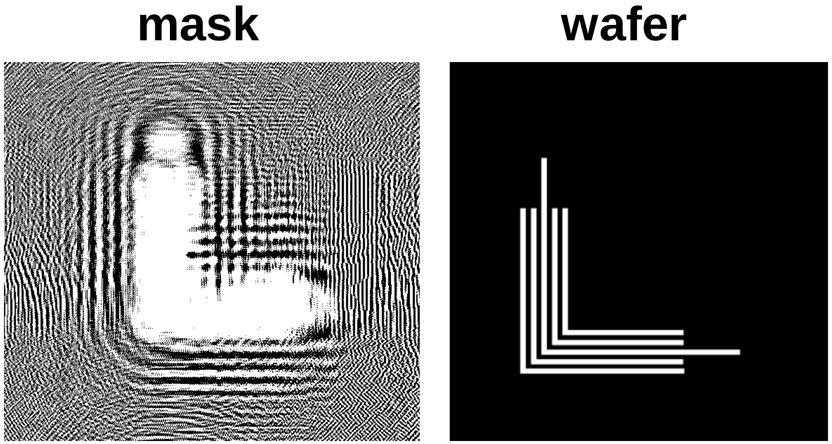
→ Simple optical system
→ Mask design is crucial



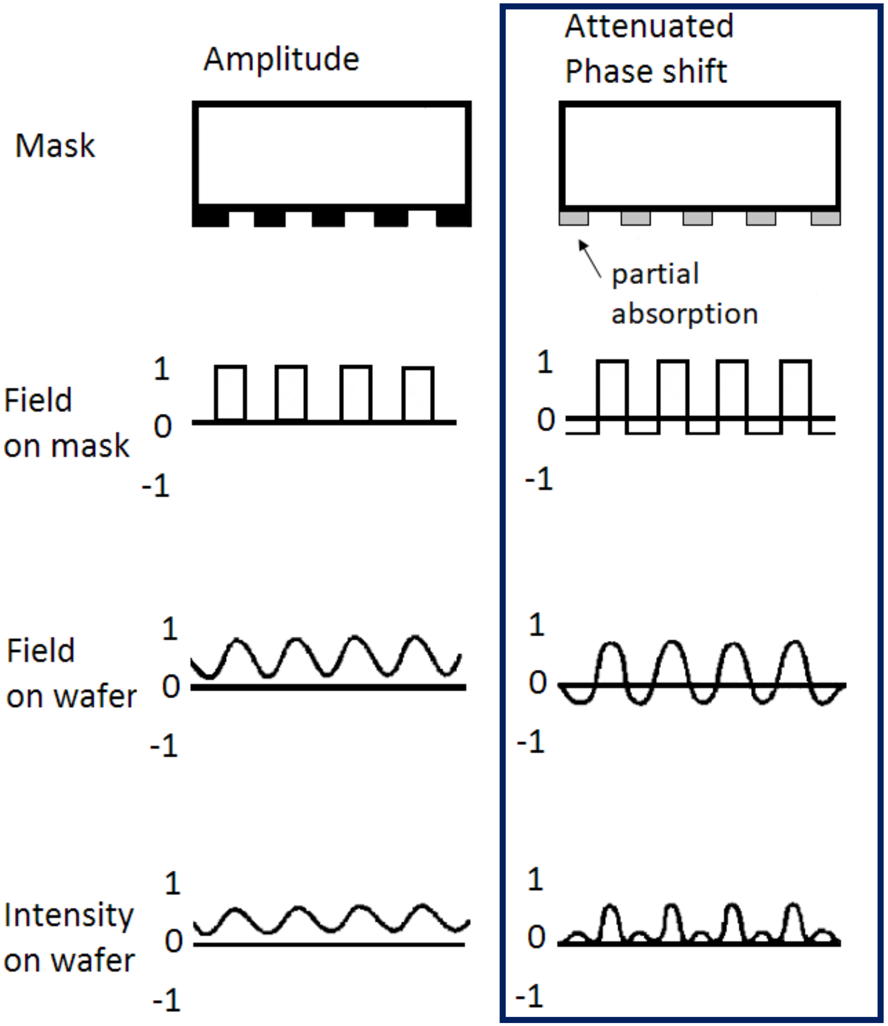
COMPUTATIONAL PROXIMITY LITHOGRAPHY

- Fabrication of µm-scale complicated / arbitrary structures without lens-based imaging systems
- Fresnel regime
- Elbow structure:
    - Prototype for lithography structures
    - High and low intensity regions
    - Sharp lines
    - Different line lengths





TYPES OF TRANSMISSION MASKS



- **Amplitude mask:**

  Absorber material: Ni, Cr, TaN

- **Phase mask:**

  Phase shifting materials: polymers, Zr, Mo, MoN, Nb

All materials are strongly absorbing EUV

→ Attenuated phase shifting mask

→ Phase shift of approx. π

→ Better diffraction efficiency of phase mask

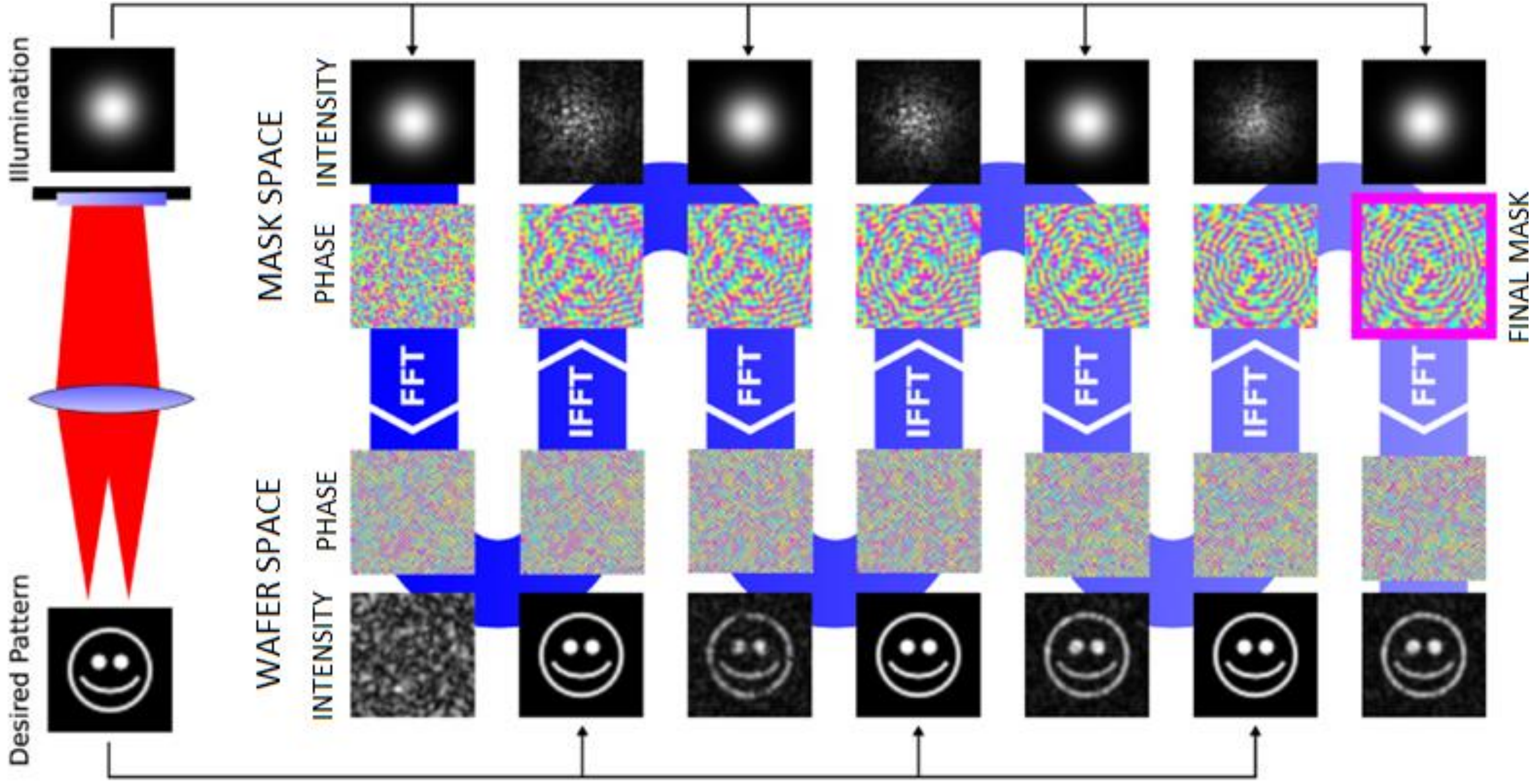
→ Fabrication of phase mask: no structure transfer needed with resist polymers

→ Phase shifting material: eBeam resist CSAR62

C. Pierrat et al., Appl. Opt. **34** (22), 4923-4928 (1995)

HOLOGRAPHIC MASK – COMPUTATIONAL PROXIMITY LITHOGRAPHY

Adapted Gerchberg-Saxton algorithm



http://cdn.iopscience.com/

HOLOGRAPHIC MASK – COMPUTATIONAL PROXIMITY LITHOGRAPHY

Start
$i = 0$

(WAFER)
$A_0 = A_{target}$
$\varphi_0 = \text{random}$

Propagation to mask

(MASK)
$A_i = discretize(A_i)$
$\varphi_i = discretize(\varphi_i)$

Propagation to wafer

(WAFER)
$i = i + 1$
$A_e = expose(A_i)$
$\varepsilon = l^2(A_e - A_{target})$
$A_i = A_{target}$
$\varphi_i = \varphi_{i-1}$

Propagation to mask

$\varepsilon_i < \varepsilon_{min}$
$\vee$
$i > i_{max}$

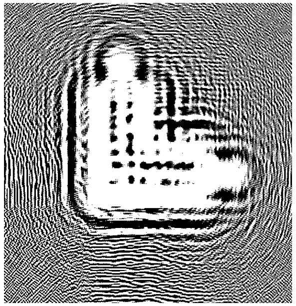
No

Yes

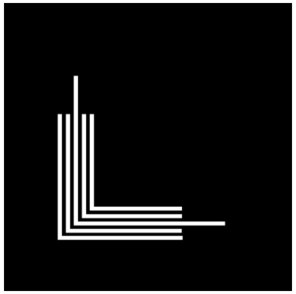
(MASK)
$A = discretize(A_i)$
$\varphi = discretize(\varphi_i)$

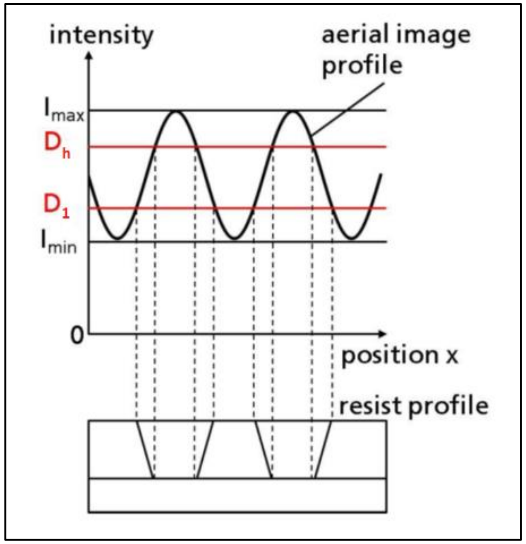
MASK READY
$U(x, y) = A\exp(i\varphi)$

Holographic mask



Intensity at wafer





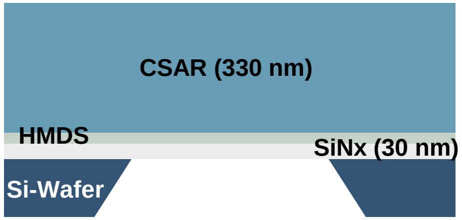
Constrains:

- Limited number of phase levels
- Discrete levels on mask
- Correlation between absorption and phase-shift properties of materials
- Minimal element size on mask due to fabrication process
- Resist response function
- Thresholding in resist

HOLOGRAPHIC MASK – LAYOUT AND FABRICATION

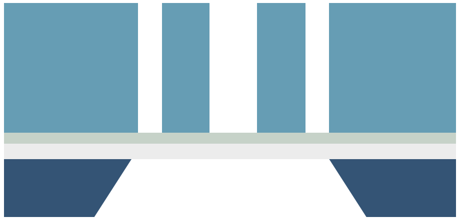
- 2 levels: CSAR resist / no resist
- No absorber → easier fabrication
- Design for one mask-wafer distance
- Small depth of focus

1-4) CSAR coating



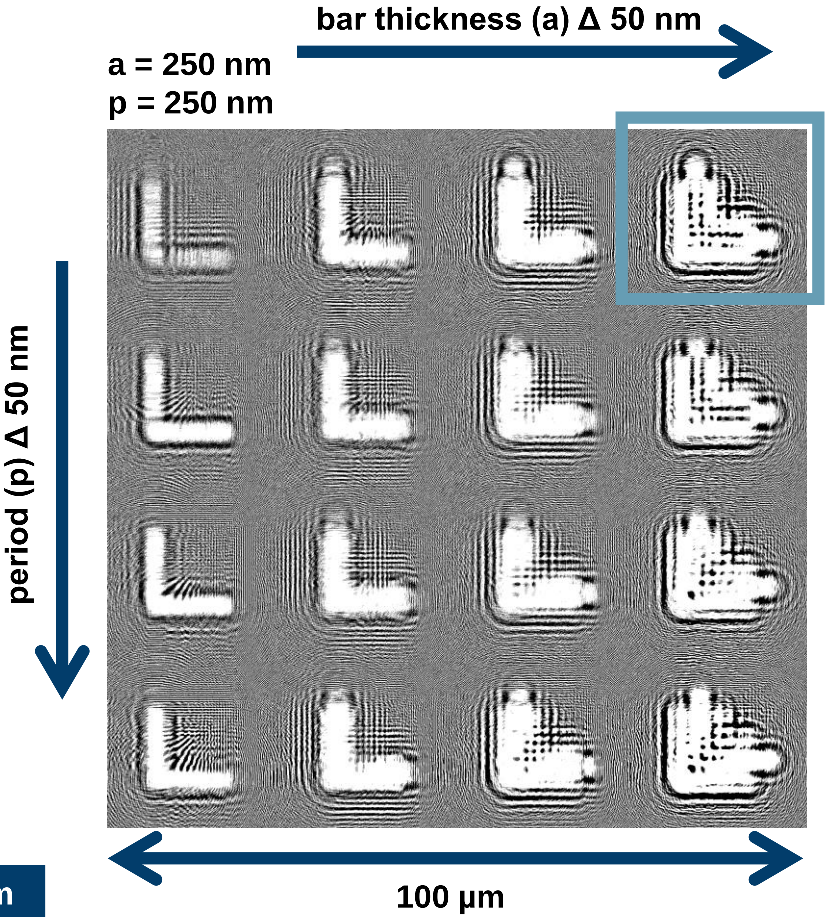
- ▨ CSAR resist
- ▨ HMDS
- ☐ SiNx-membrane
- ■ Si wafer

5-6) EBL / development



not to scale

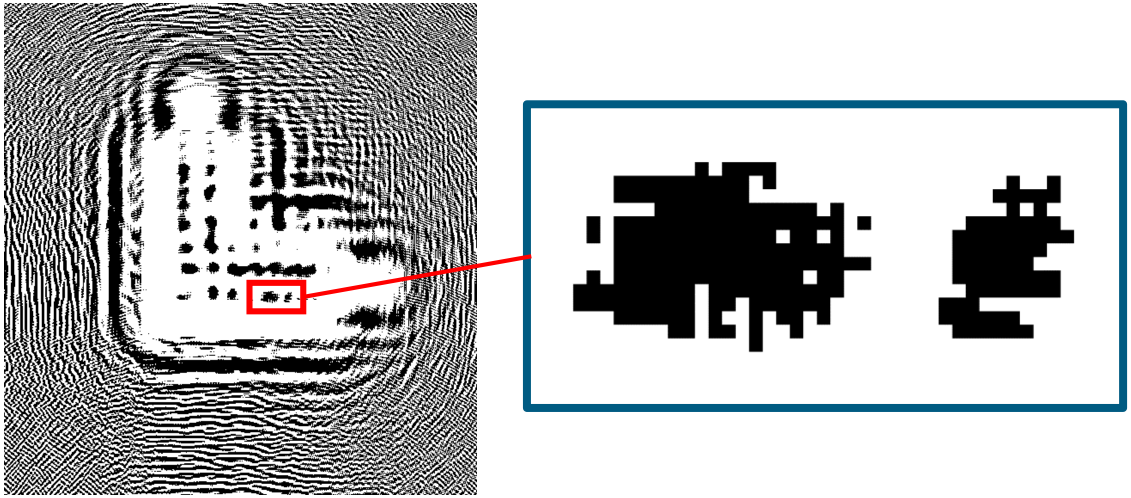
CSAR thickness	337 nm
Wavelength	13.5 nm
Mask-wafer distance	300 µm
Pixel size	50 nm



Black: phase shifting material
White: eBeam writing

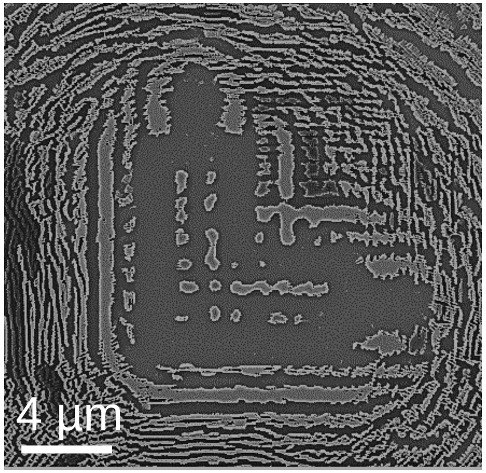
MASK FABRICATION

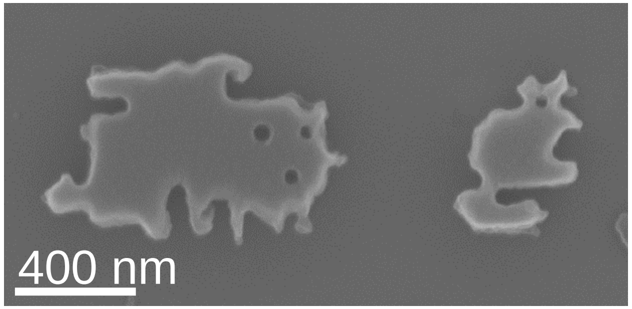
simulated mask layout



pixel size 50 nm

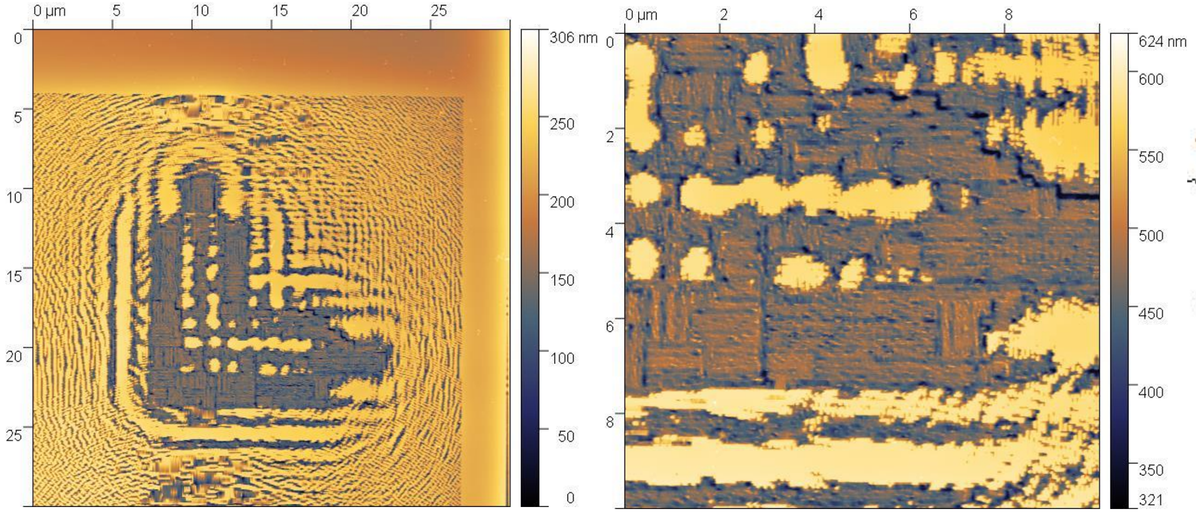
fabricated mask



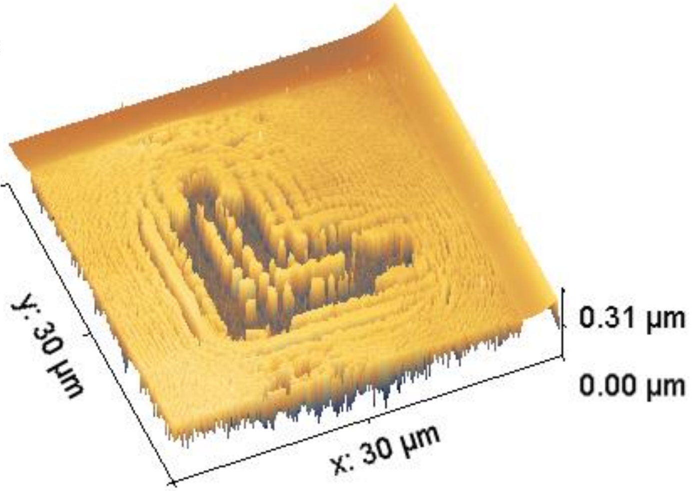


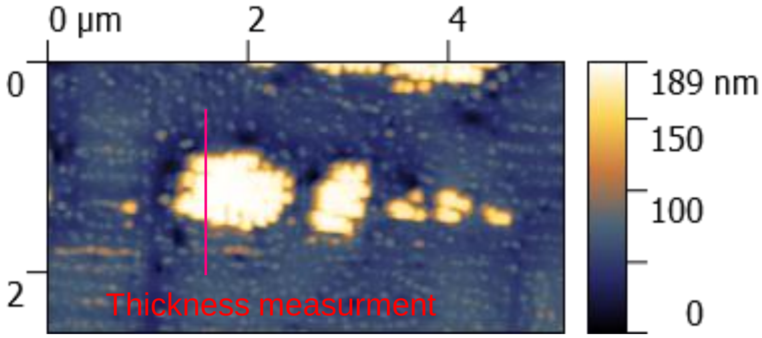
SEM image
3 nm Ir on CSAR

MASK FABRICATION – AFM



AFM Scans @ PSI



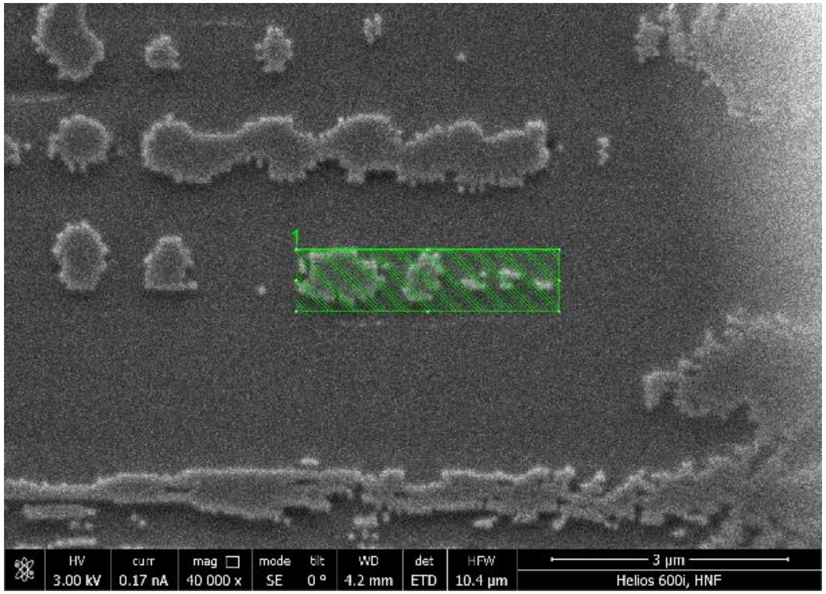


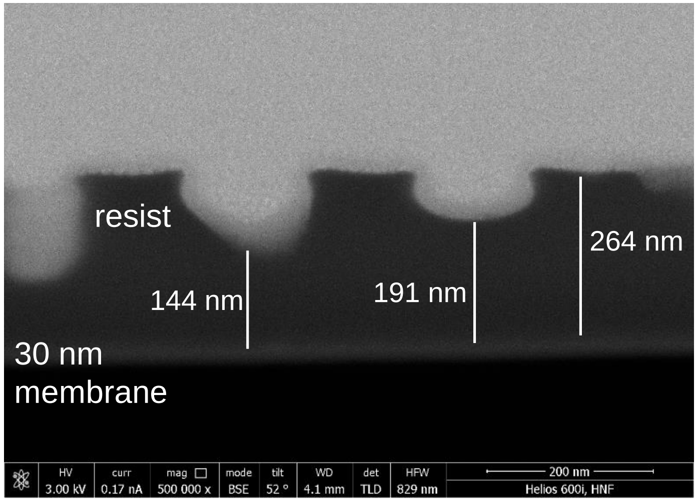
Ellipsometer [nm]	AFM [nm]
297	108
418	137

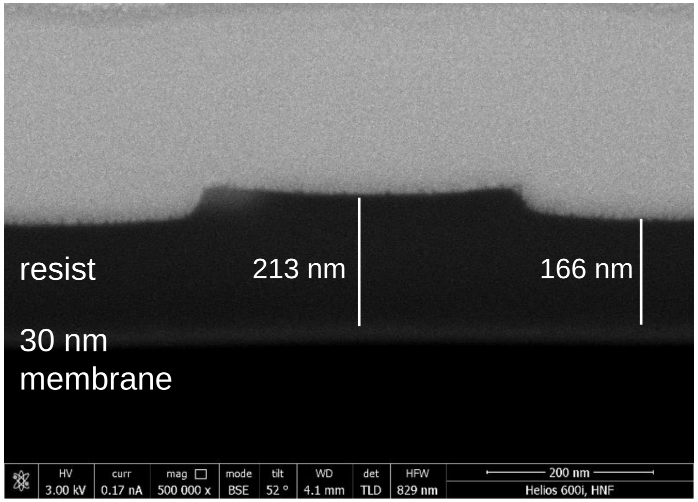
Resist thickness measurement:

- Goal: 330 nm
- Ellipsometer:
  outside structures
- AFM:
  inside structures (PSI)
- FIB cuts
  → check difference

MASK FABRICATION – FIB







Maks	Ellipsometer [nm]	FIB [nm]
F13	375	80

→ Resist is not fully developed

MASK FABRICATION – RESIST THICKNESS

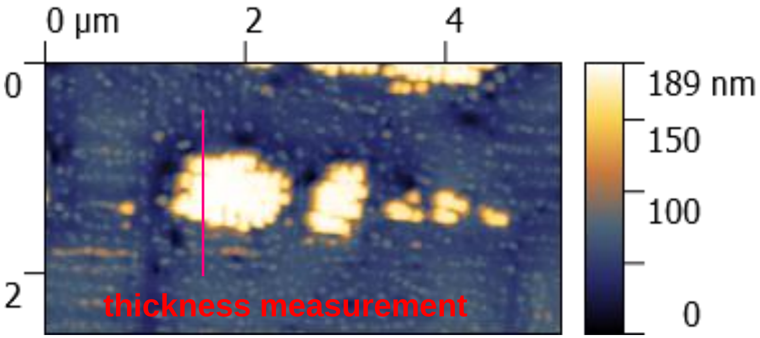
Maks	Ellipsometer [nm]	AFM / FIB [nm]
F8	297	108
F12	418	137
F13	375	80 (FIB)

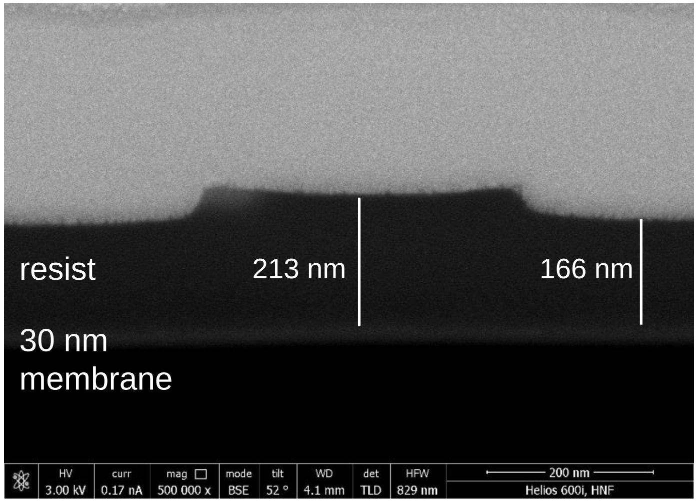
- AFM and FIB results are comparable

→ The resist is not fully developed

→ CSAR thickness too thin compared to design values

→ Different thicknesses within the mask





EXPOSURES AT PSI

- Synchrotron
- λ = 13.5 nm
- Resist: HSQ
  - Development: 25% TMAH
- Mask-wafer distance: 300 µm

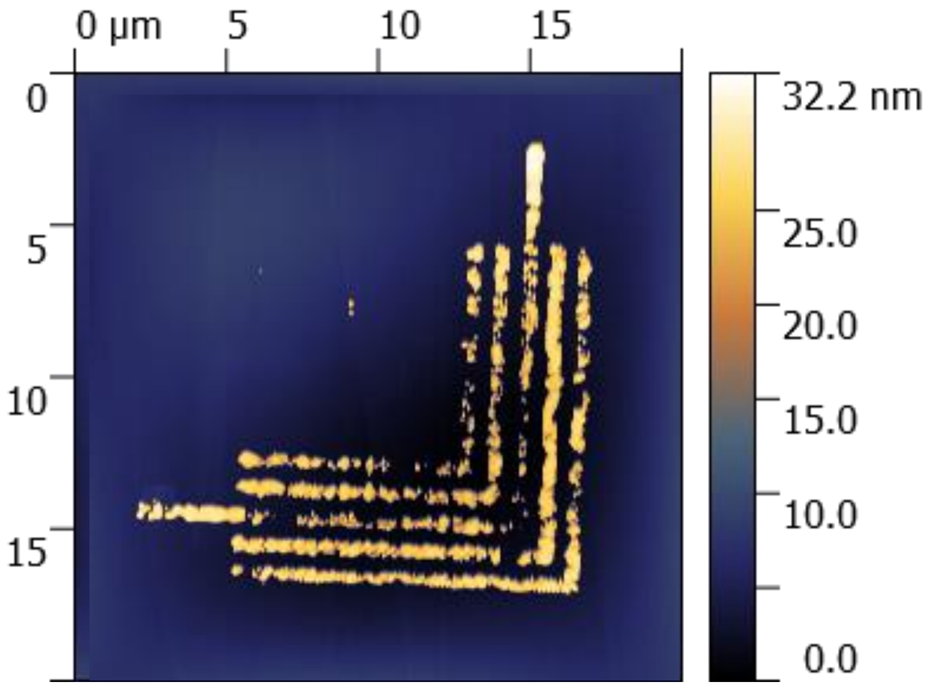
Investigated parameters:

- eBeam dose on mask
- EUV dose
- Resist thickness on mask
- EUV resist

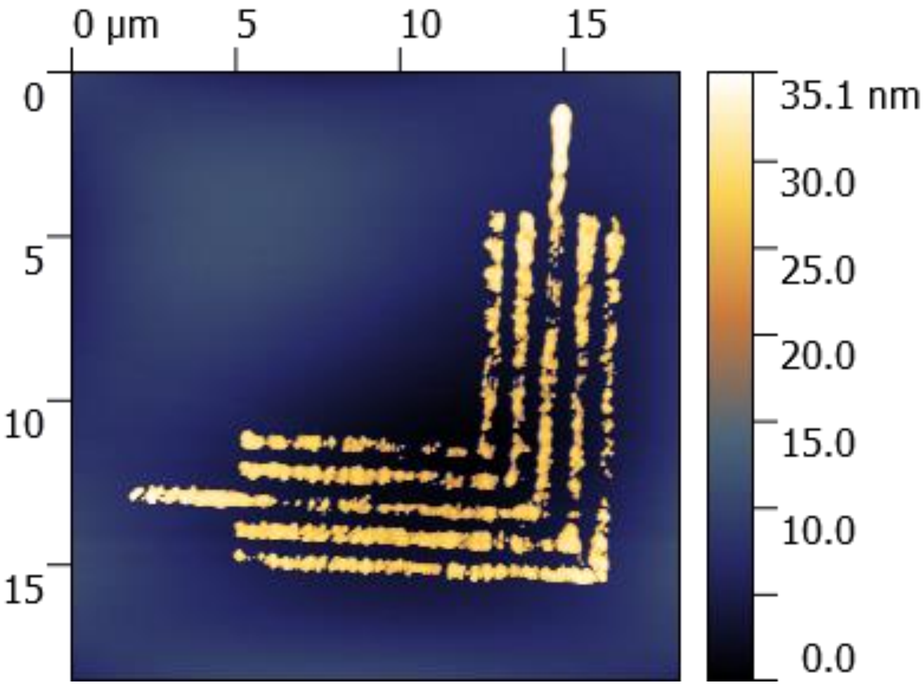
Mask wafer distance is critical but hard to control at this setup

BEST EXPOSURE RESULTS – AFM SCANS

normal mask (425 nm CSAR)



thick mask (555 nm CSAR)

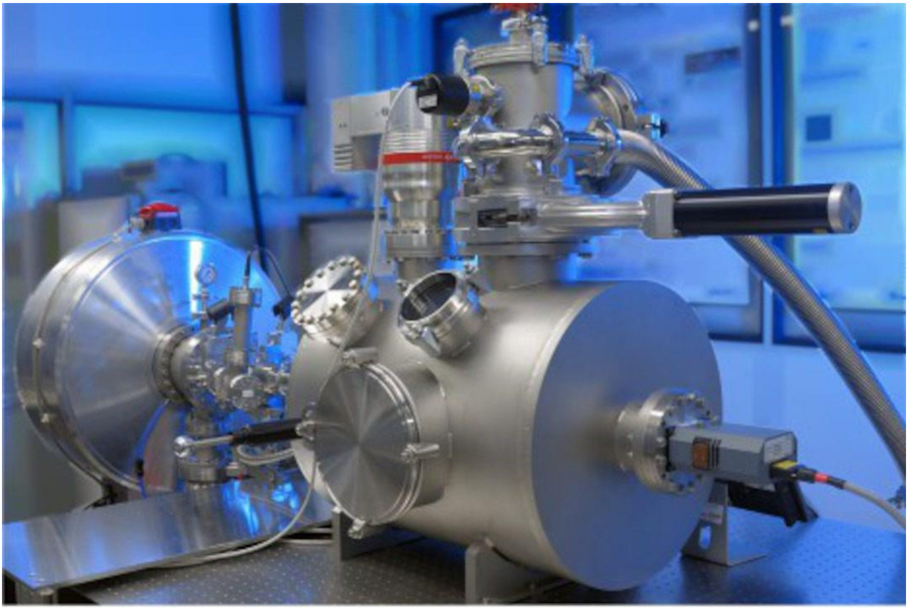


Mask-wafer distance: 289 µm

→ **Better results for mask with thicker CSAR resist**

→ **Closer to designed thickness and corresponding phase shift**

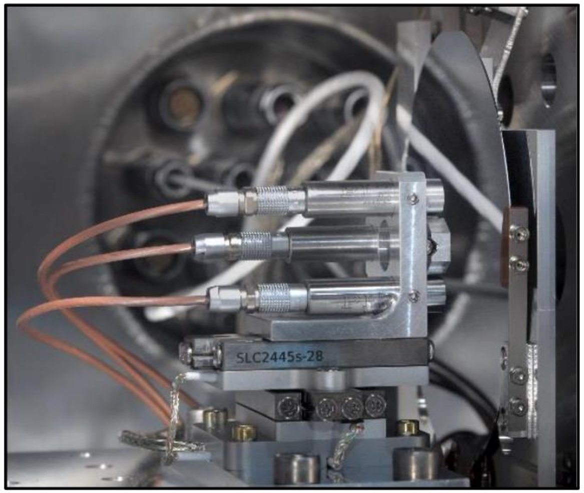
EXPOSURES AT ILT / RWTH-TOS



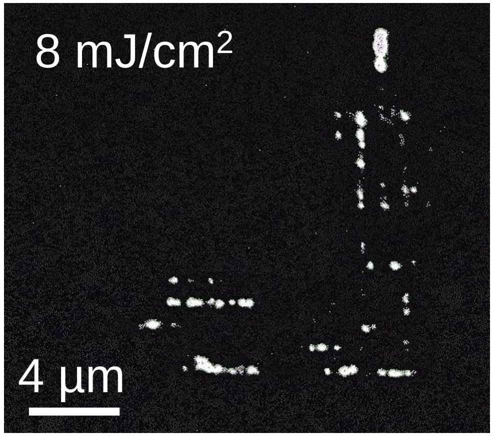
- Plasma source
- Limited coherence length (10 µm)
- λ = 13.5 nm
- Resist: SEVR (CAR resist)
  - Development: TMAH
- Mask-wafer distance: Scan 100-500 µm

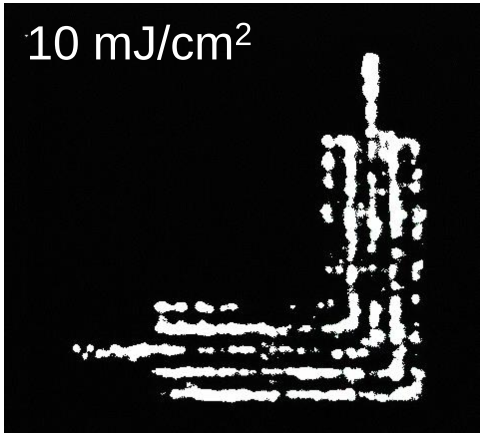
Investigated parameters

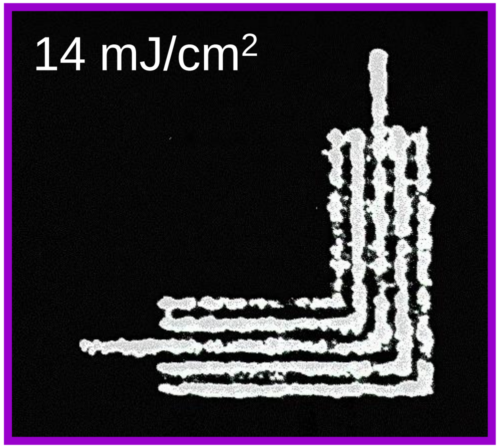
- eBeam dose on mask
- EUV dose
- Mask-wafer distance

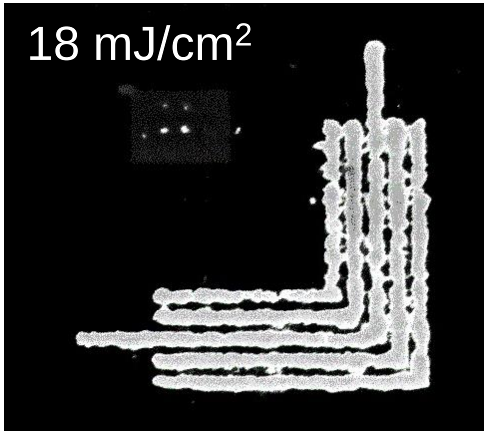


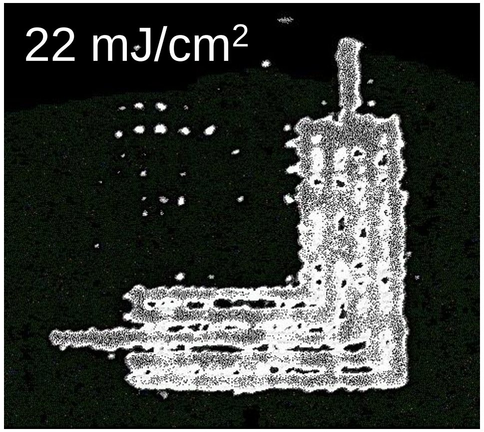
DOSE SCAN







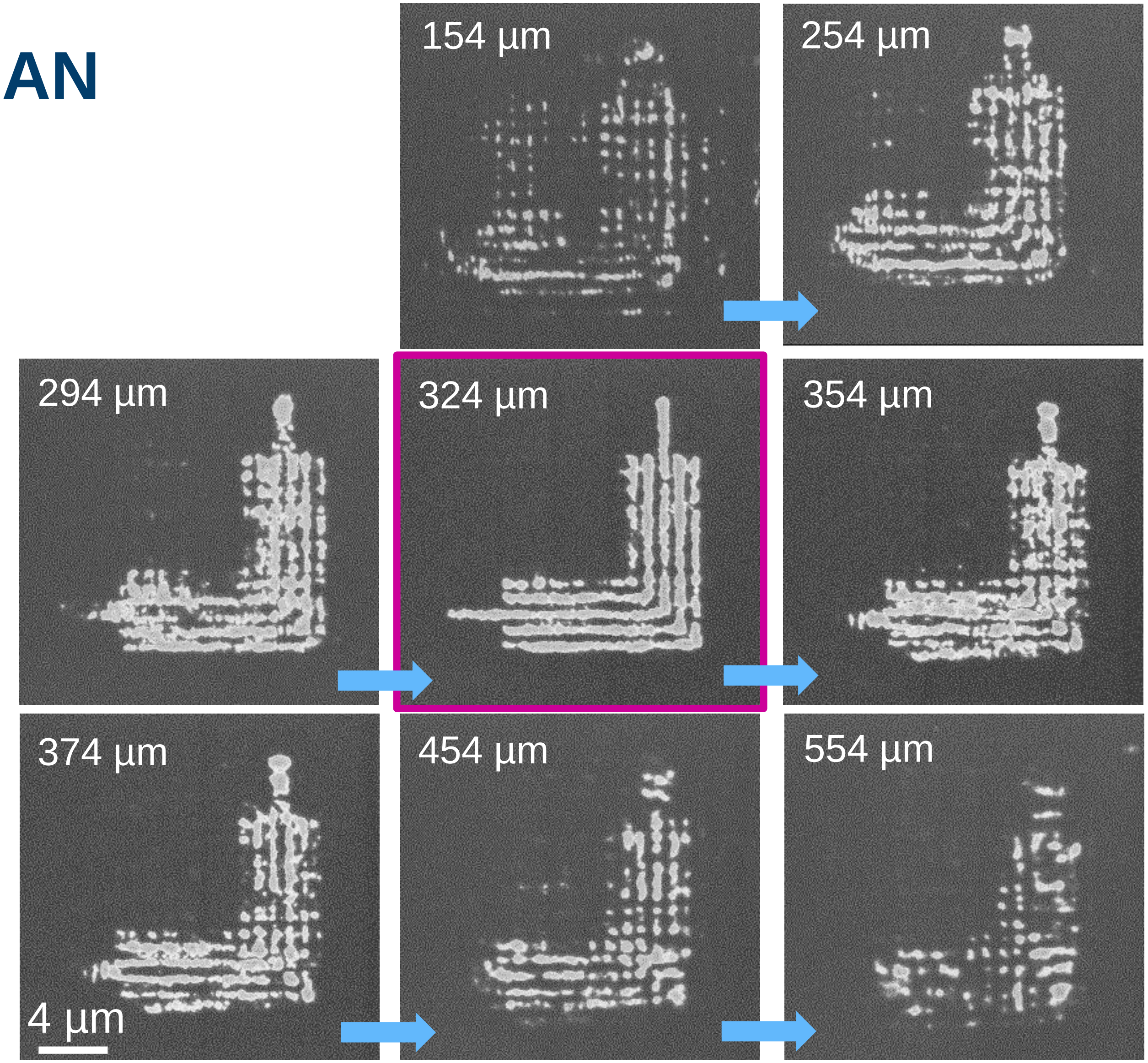




→best exposure result for EUV dose 14 mJ/cm^2

DISTANCE SCAN

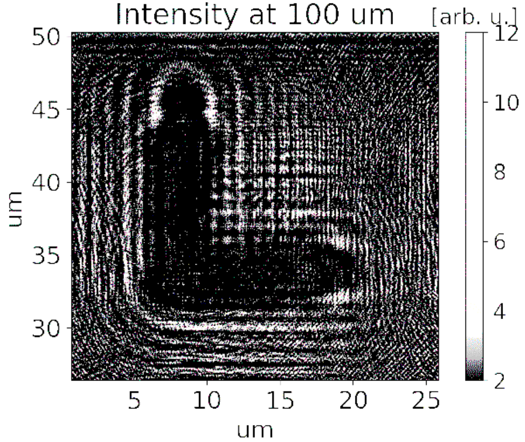
Mask: F22 (379 nm)

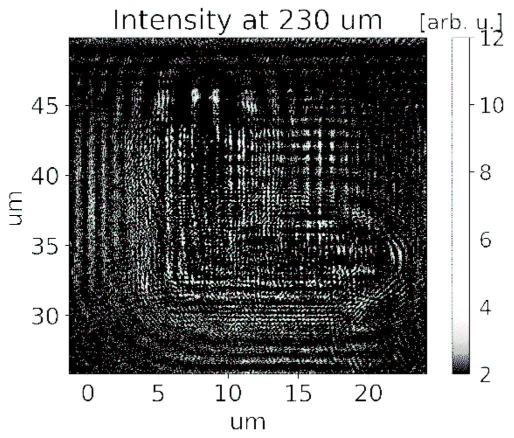


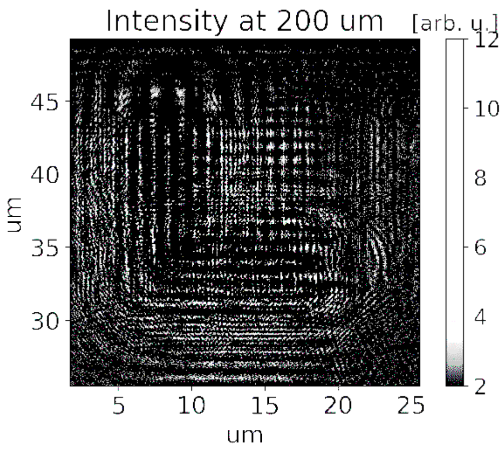
→ **mask-wafer distance 324 µm**

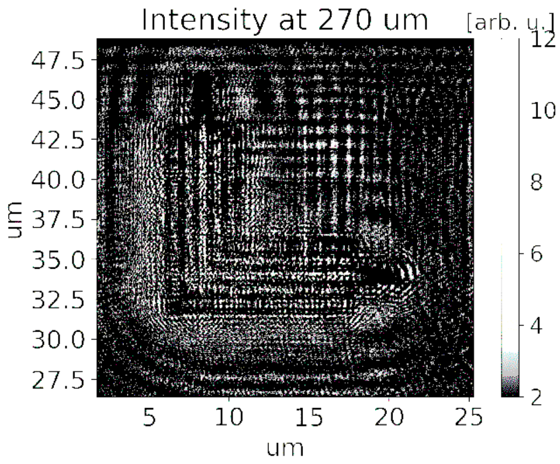
SIMULATIONS

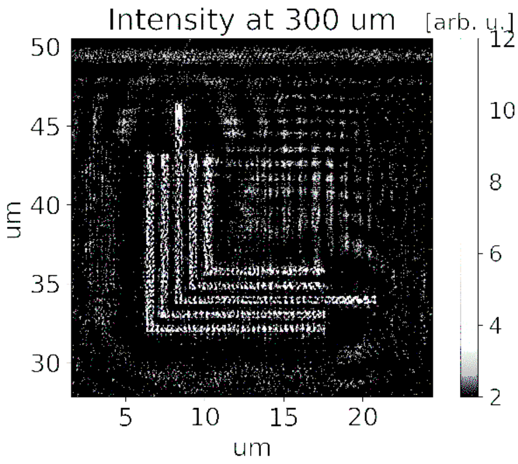
- Simulation of exposure results
- Ideal mask thickness 330 nm

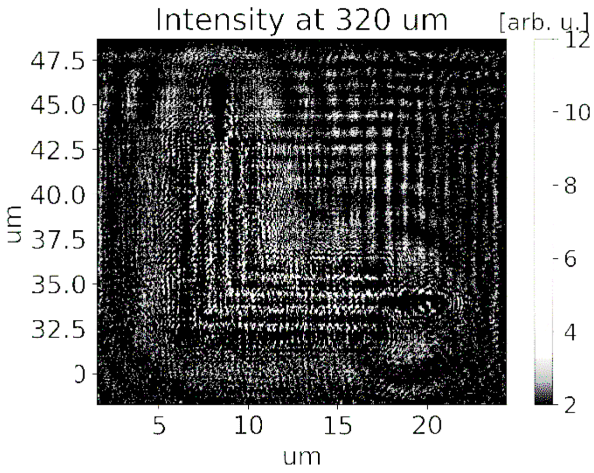

Intensity at 100 um

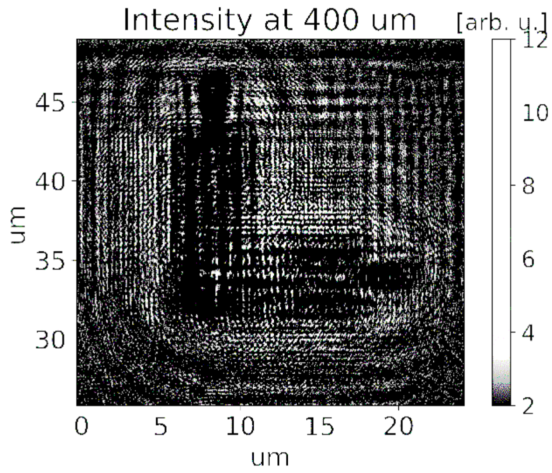

Intensity at 230 um

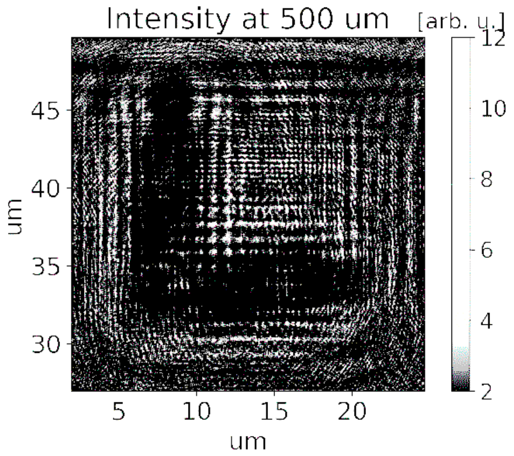

Intensity at 200 um


Intensity at 270 um

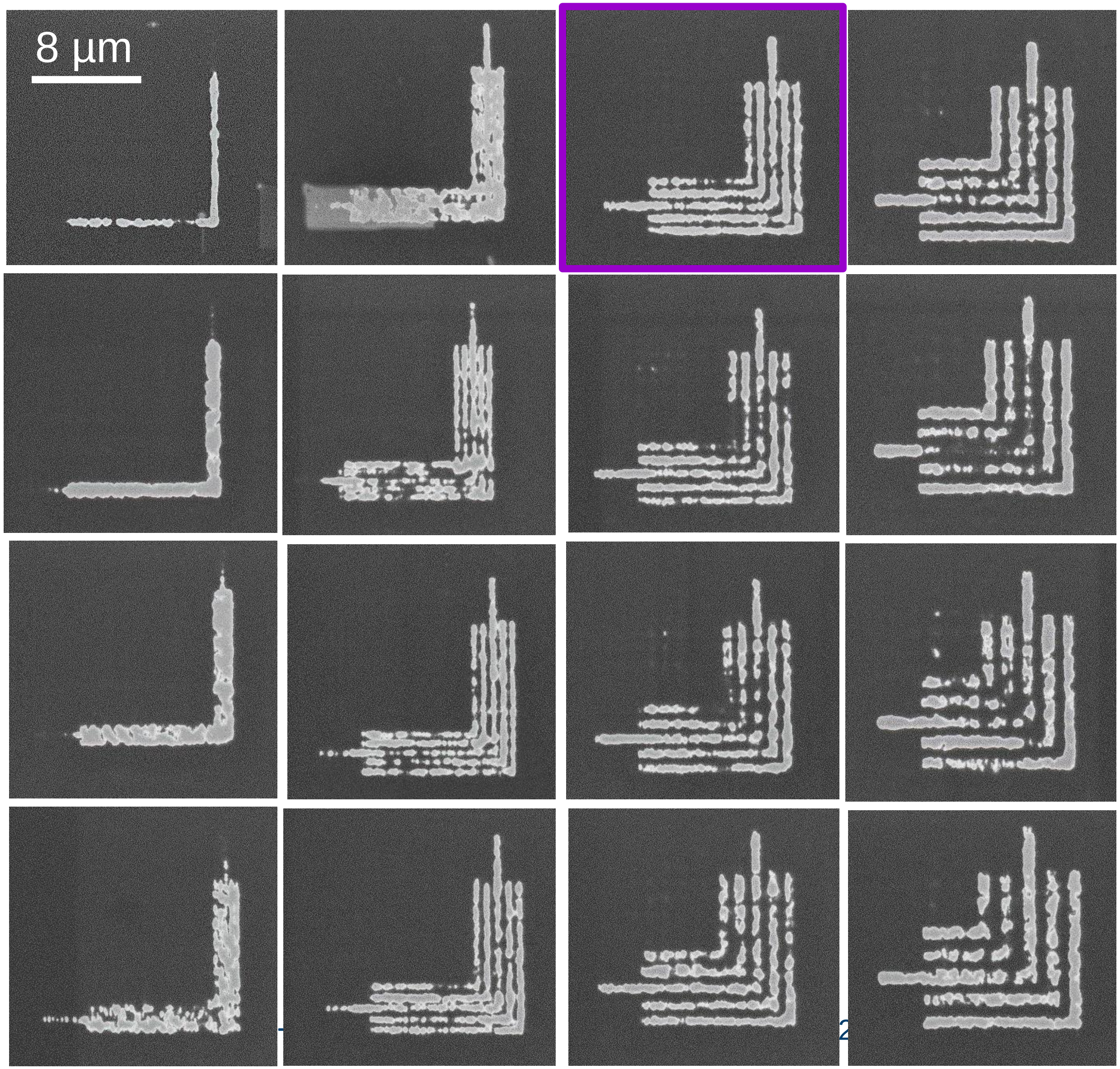

Intensity at 300 um


Intensity at 320 um


Intensity at 400 um


Intensity at 500 um

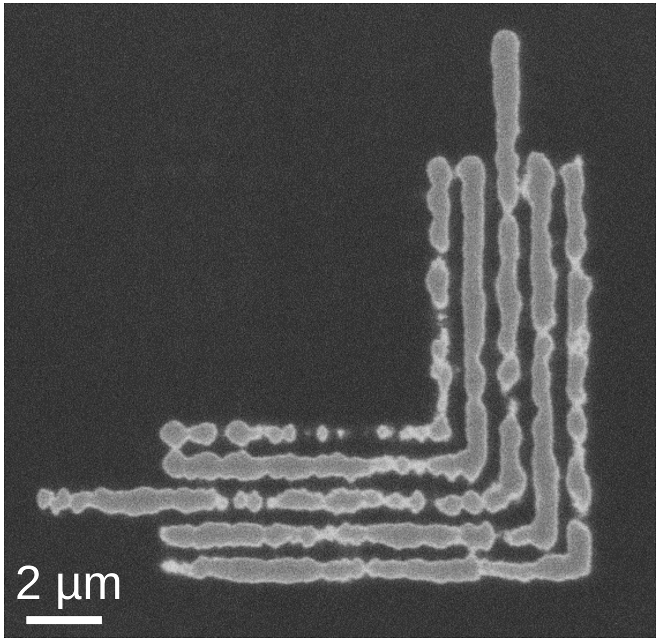
DIFFERENT ELBOWS



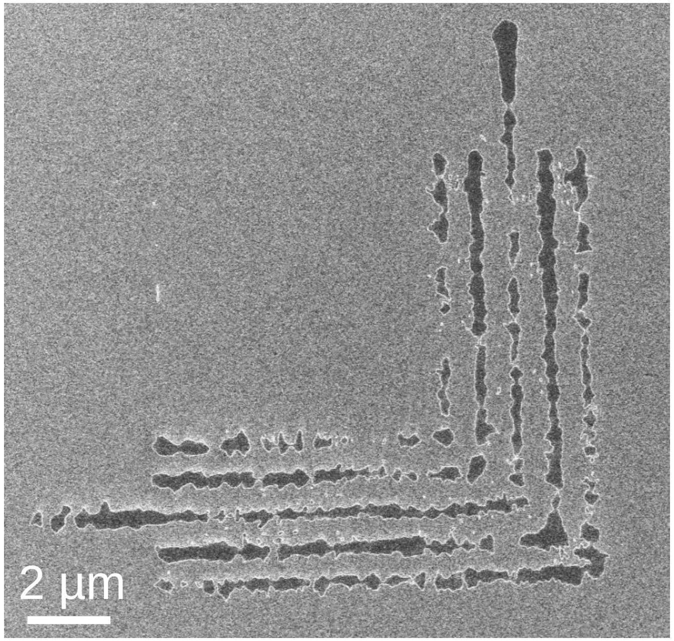
Mask-wafer distance 324 µm

PLASMA SOURCE VS. SYNCHROTRON

plasma source ILT



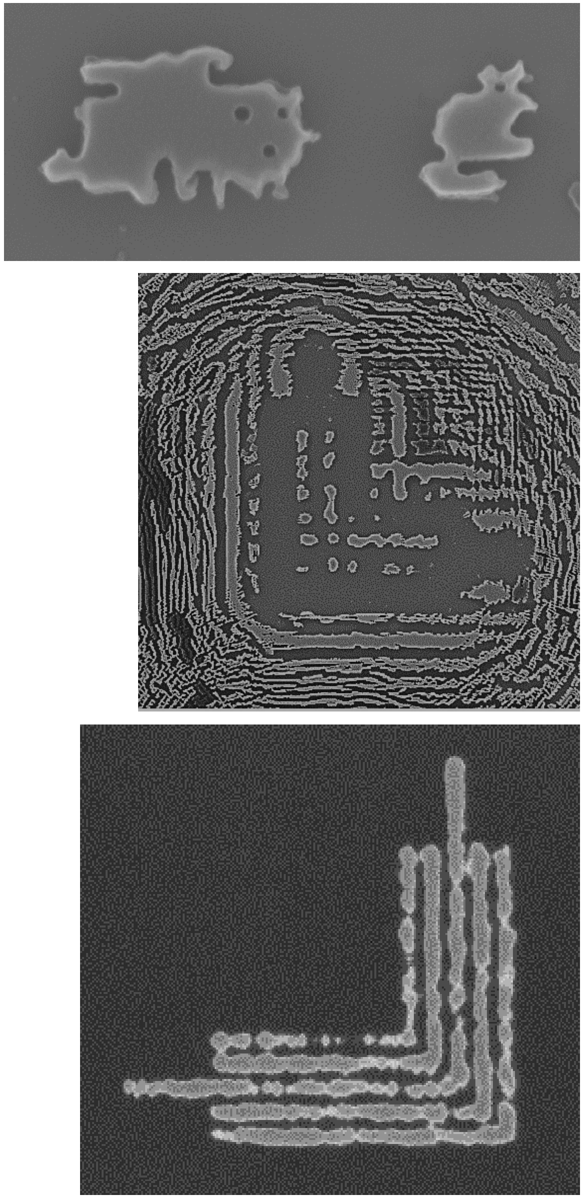
synchrotron PSI



→ Similar exposure results

SUMMARY

- Successful mask design and fabrication
- CSAR resist is suitable as phase shifting material
  - Optical properties as expected
  - Fabrication of needed thickness is challenging
- Exposures at PSI
  - Successful exposures
  - Difficult mask-wafer distance control
- Exposures at ILT / RWTH-TOS
  - Successful exposures
  - Distance scan matches simulations
- Similar results for PSI and ILT exposures
- The algorithm worked



Thank you for your attention!

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TOS Chair for Technology of Optical Systems | RWTH AACHEN UNIVERSITY

Fraunhofer ILT

JÜLICH Forschungszentrum

Outlook – open research questions

What are the resolution limits?
Can we generate nm-sized structures without having them on the mask?
Can we de-magnify the structures using appropriate illumination, e.g. in the Fresnel diffraction regime with a converging beam?

For hologram design, because of the thresholding nature of lithography, the solution is not unique, offering many advantages. But how to find optimal solution regarding mask manufacturability and pattern quality after lithography and structure transfer steps?

What are illumination and source requirements regarding spectral radiance and coherence? How to utilize “expensive” (difficult to generate) EUV photons in an efficient way?

At the mask technology side, can we create multi-phase-level holograms instead of binary masks used in lithography? How this can be achieved?