EUV Lithography Design Concepts using Diffraction Optics

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2020 EUVL Workshop P22 (euvlitho.com)

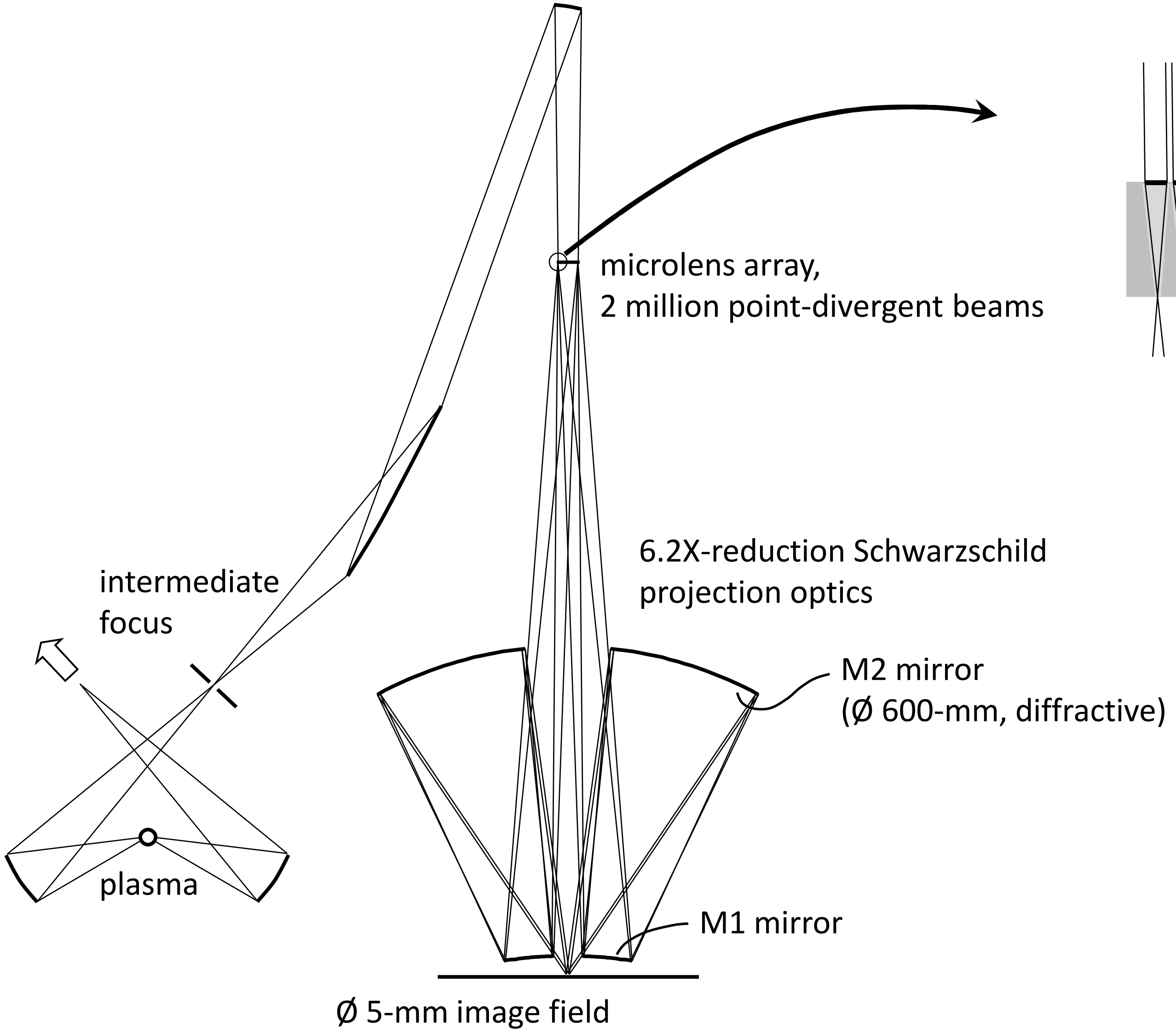
Abstract:
This presentation outlines design concepts for maskless and mask-projection (holographic) EUV lithography at wavelength 13.5 or 6.7 nm.

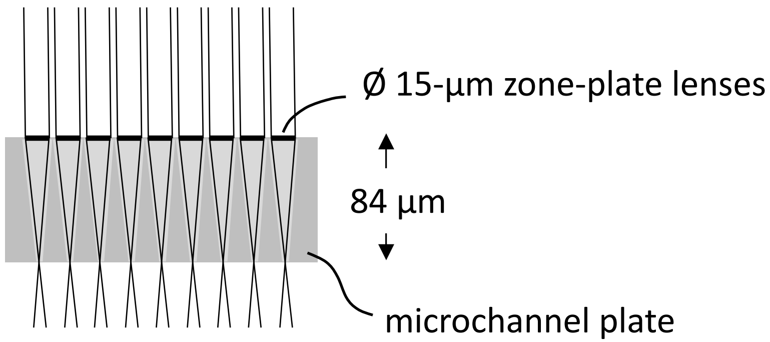
Presentation Outline

1. Review maskless EUVL design concept
2. Simplified chromatic correction with diffractive collection mirror
3. Extension from maskless to mask-projection, “holographic” EUVL

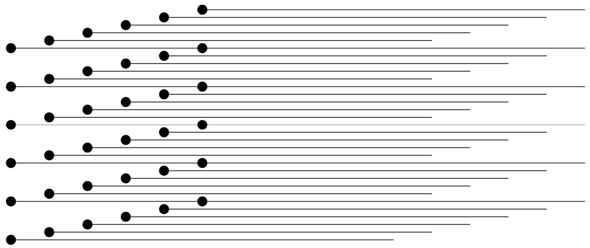
See slide notes, page 21.

Maskless Scanner Optics



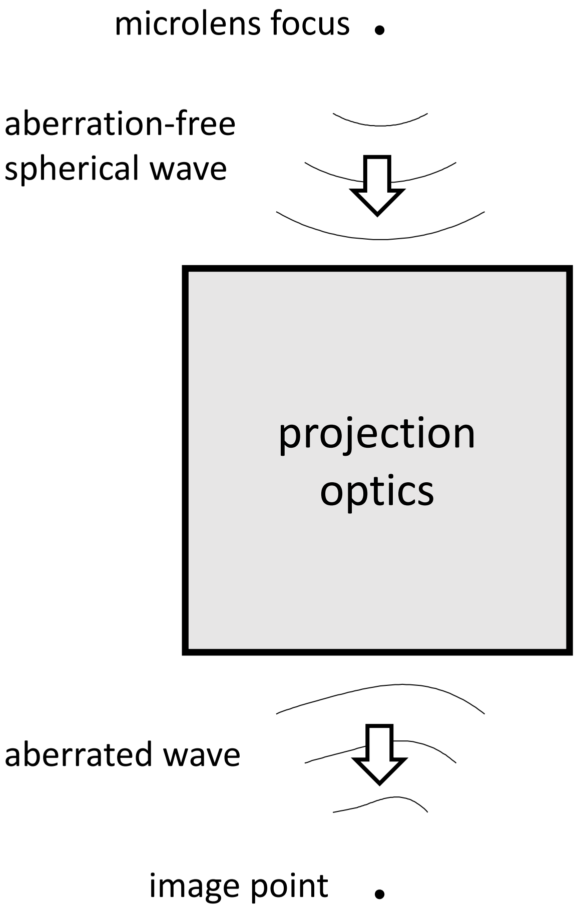


Raster-scanned focal point array:



Geometric Aberration Compensation

Without aberration compensation:



microlens focus

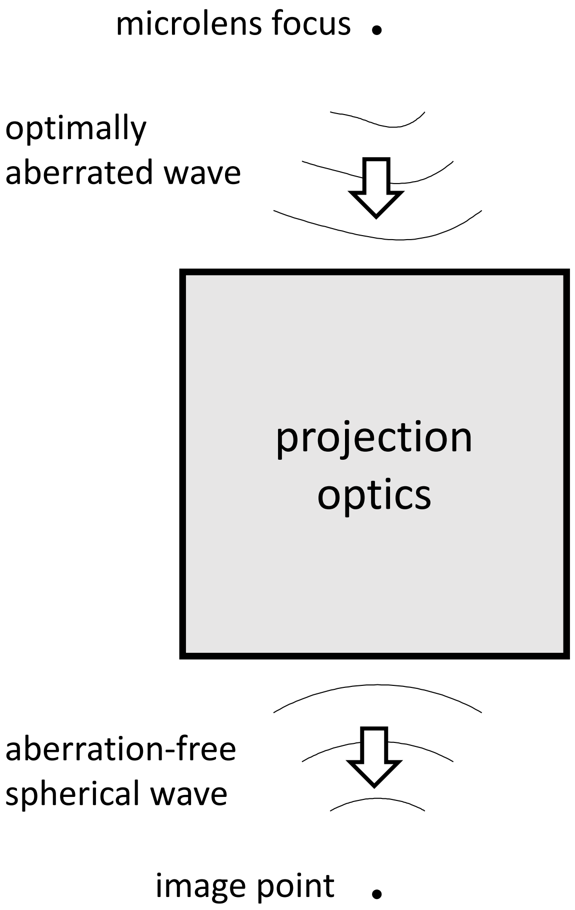
aberration-free
spherical wave

projection
optics

aberrated wave

image point

With aberration compensation:



microlens focus

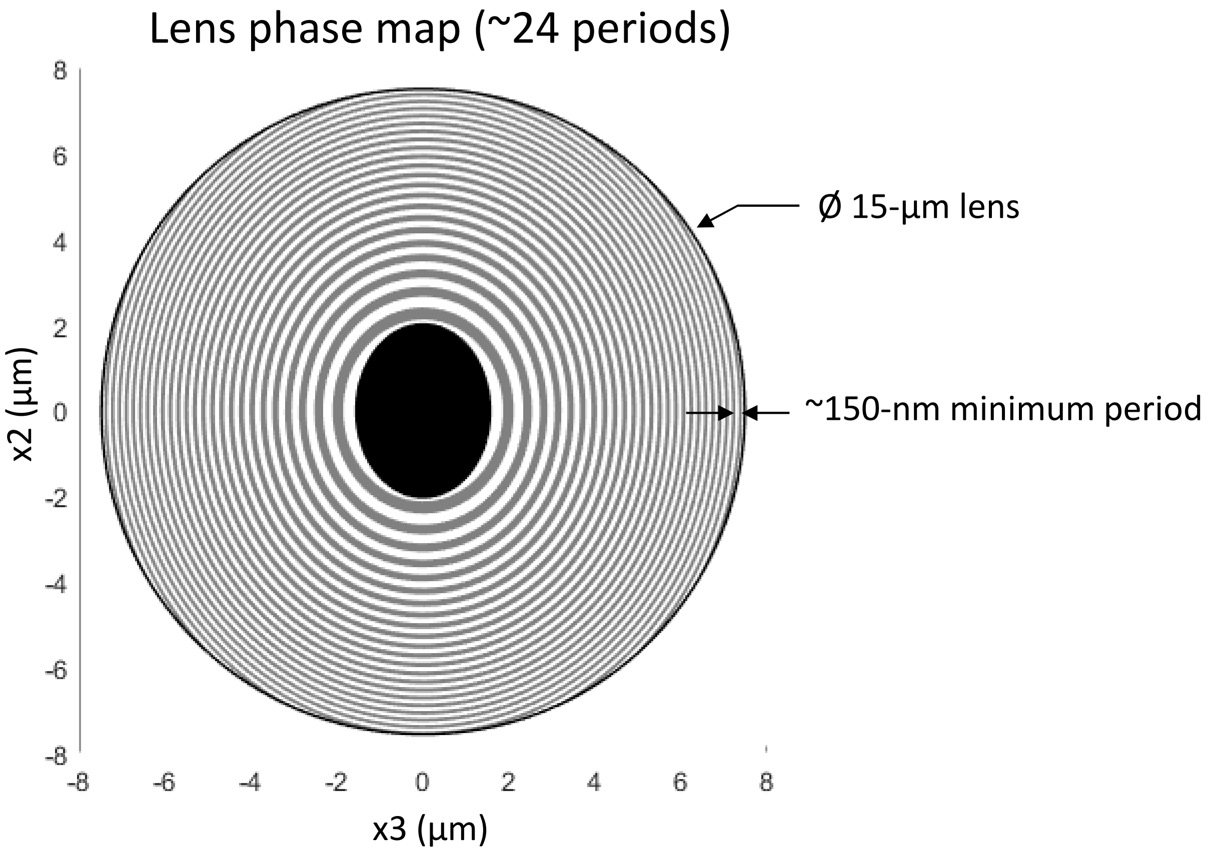
optimally
aberrated wave

projection
optics

aberration-free
spherical wave

image point

Lens zone pattern (at outermost field position)

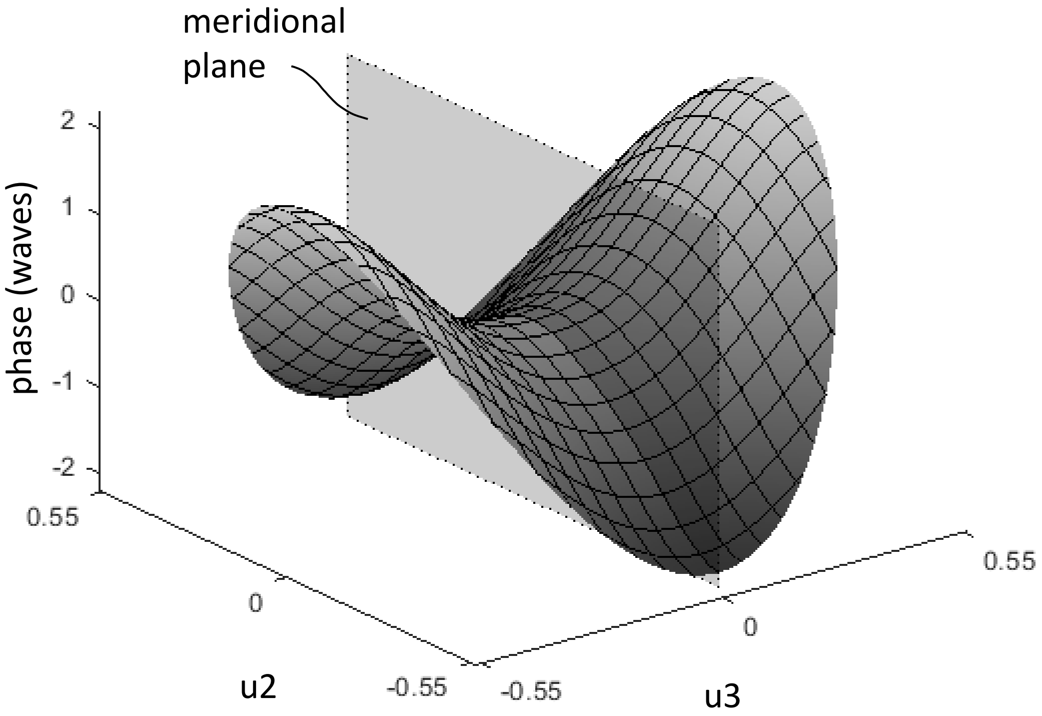

Lens phase map (~24 periods)

Ø 15-µm lens

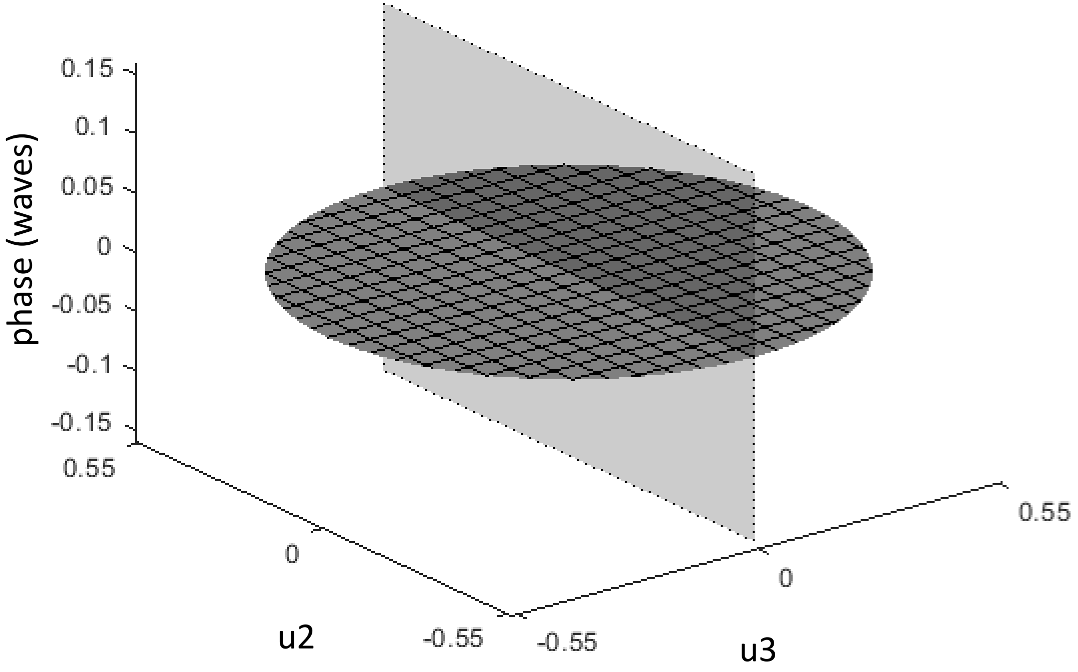
~150-nm minimum period

Phase aberration over exit pupil

uncorrected image phase error at λ=13.5nm
(1.0-wave RMS, 3.9-wave P-V)

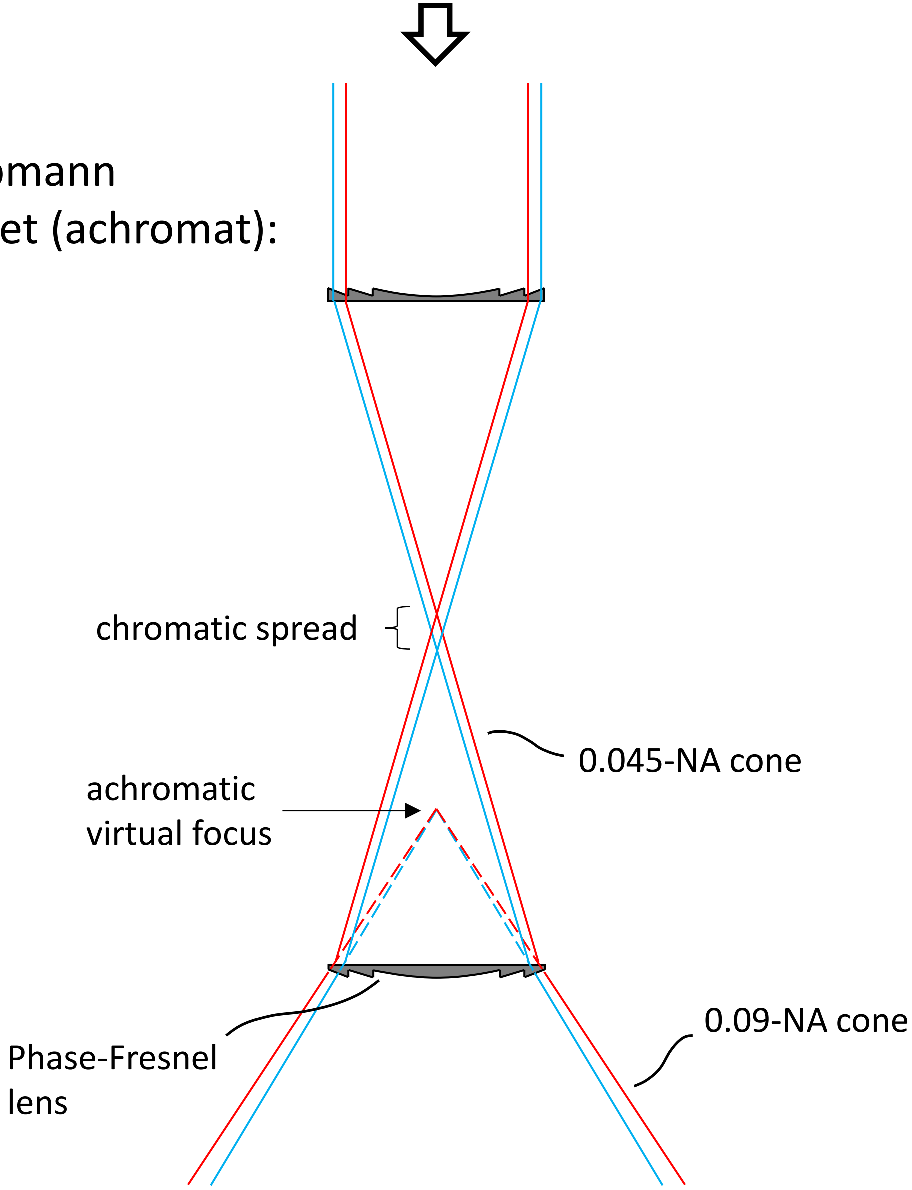


corrected image phase error at λ=13.5nm
(0-wave RMS, P-V)



Microlens Designs

Schupmann doublet (achromat):



chromatic spread

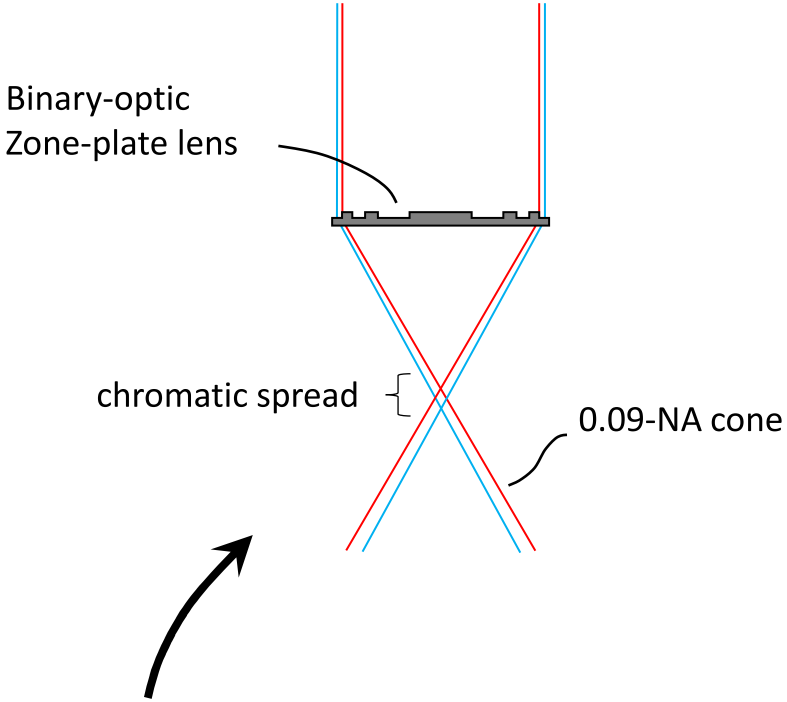
0.045-NA cone

achromatic virtual focus

Phase-Fresnel lens

0.09-NA cone

Zone-plate singlet:



Binary-optic Zone-plate lens

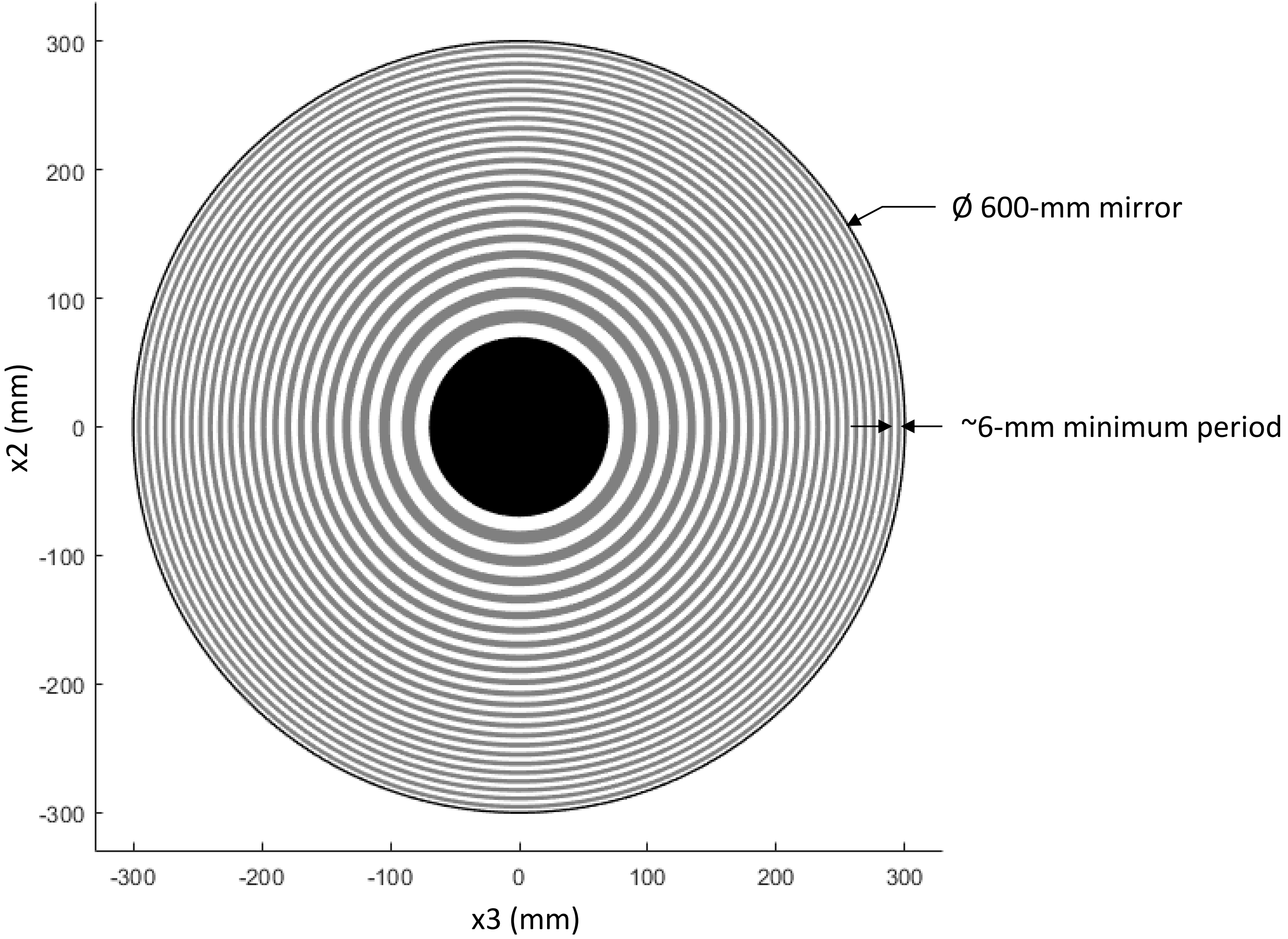
chromatic spread

0.09-NA cone

Much simpler!

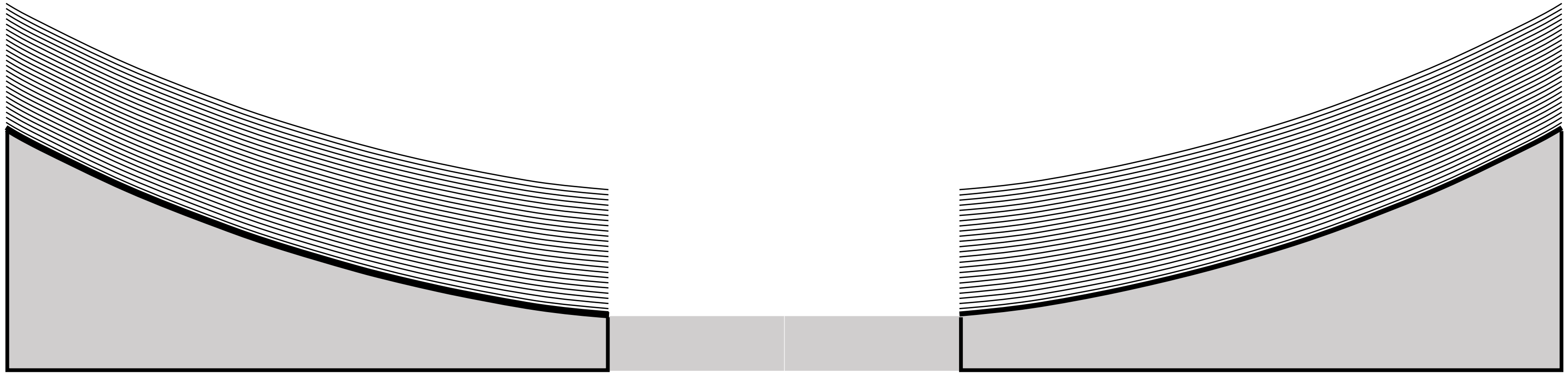
Diffractive Projection Optics

M2 mirror phase map (~24 periods)

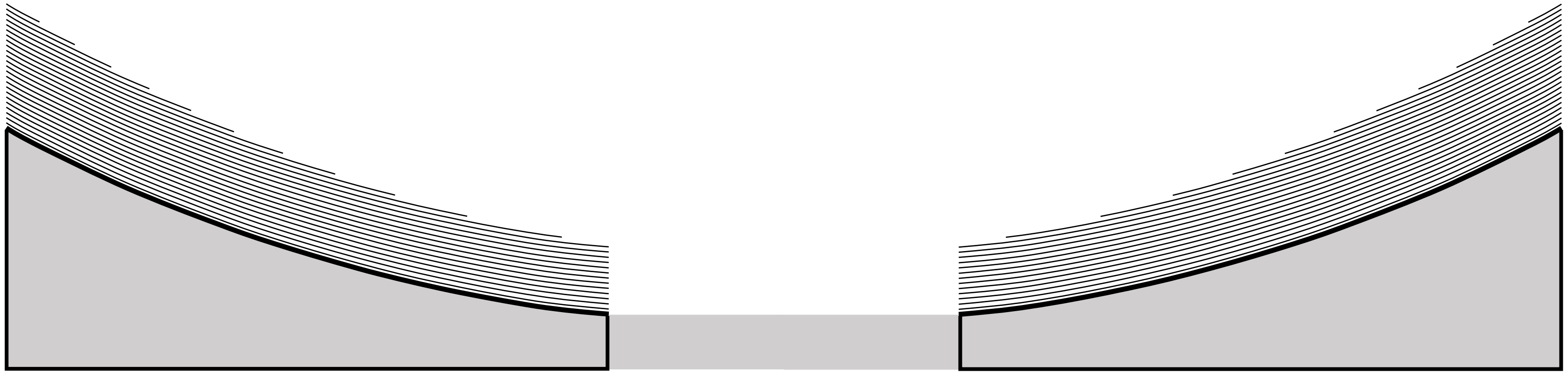


Diffractive Mirror Fabrication

Deposit ~70 Mo/Si bilayers for λ=13.5nm (or ~200 B/La for 6.7nm):

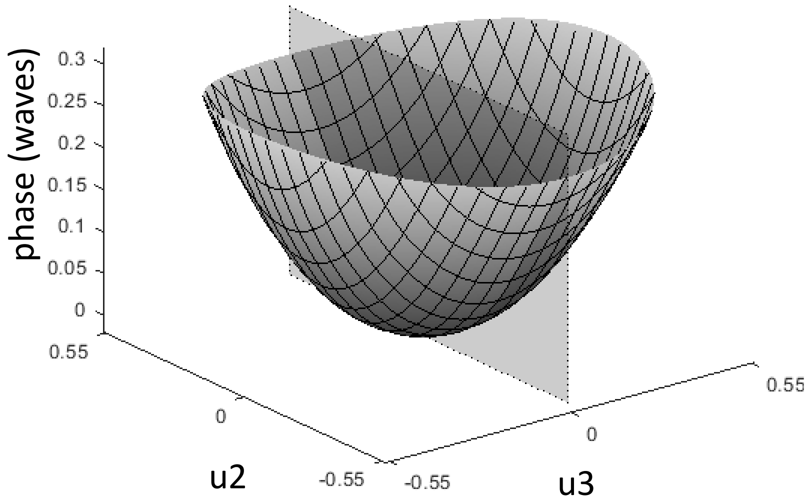


Form a quadratic bowl, ~24 bilayers center depth, via IBF processing:

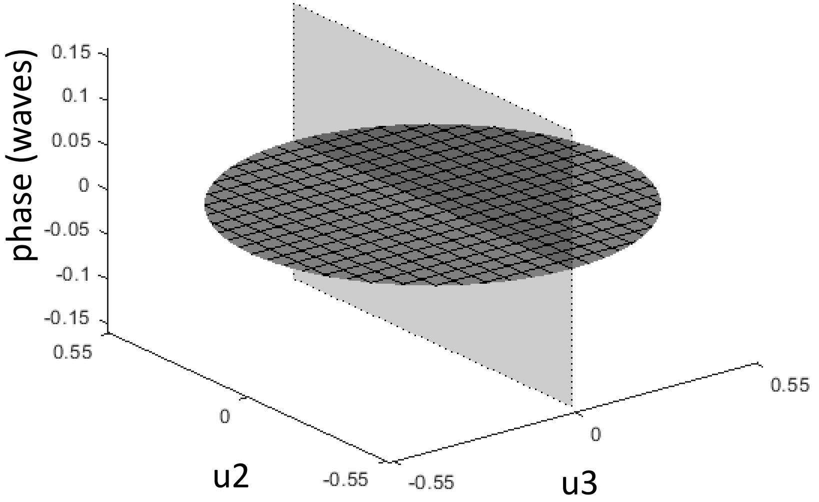


Chromatic aberration over exit pupil

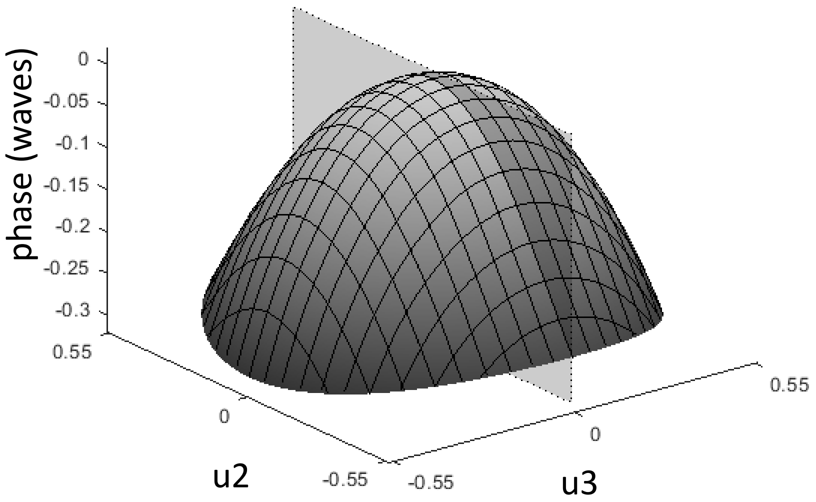
uncorrected image phase error at λ=13.35nm
(0.084-wave RMS, 0.29-wave P-V)



corrected image phase error at λ=13.5nm
(0-wave RMS, P-V)

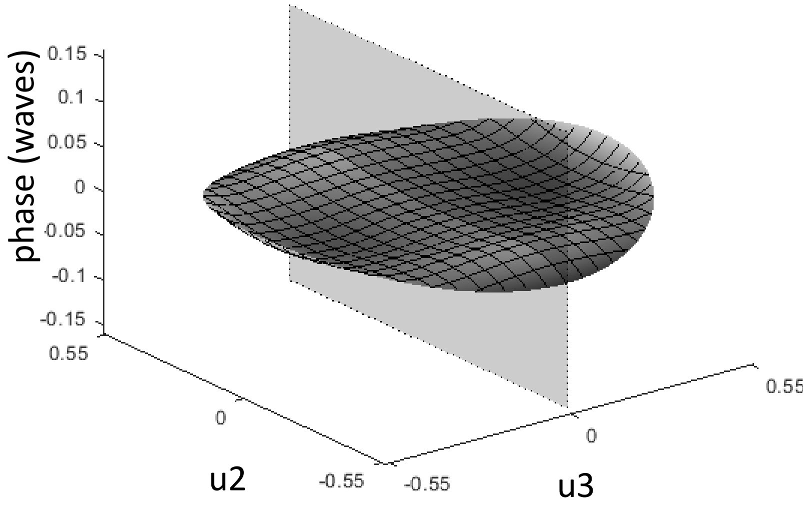


uncorrected image phase error at λ=13.65nm
(0.084-wave RMS , 0.30-wave P-V)

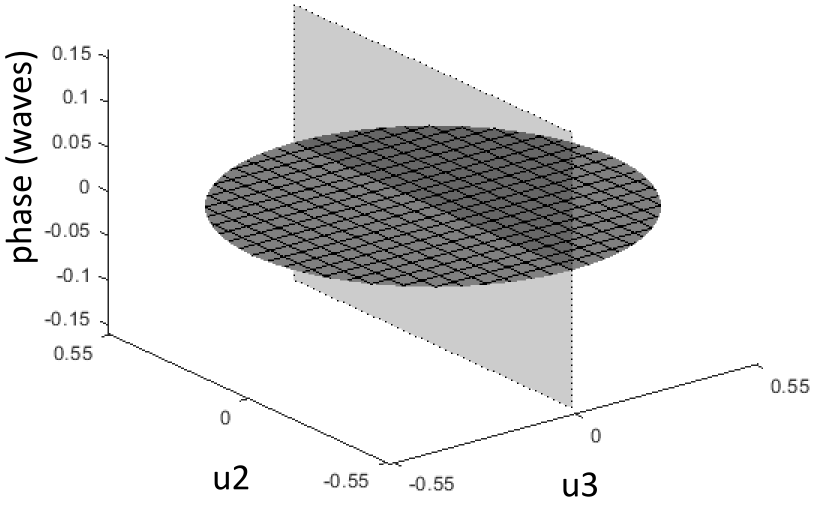


Chromatic aberration over exit pupil

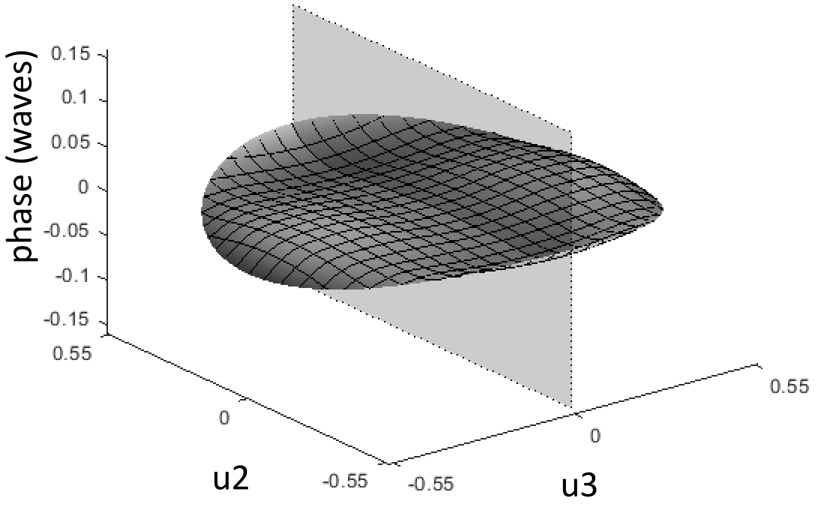
corrected image phase error at λ=13.35nm
(0.0067-wave RMS, 0.041-wave P-V)



corrected image phase error at λ=13.5nm
(0-wave RMS, P-V)

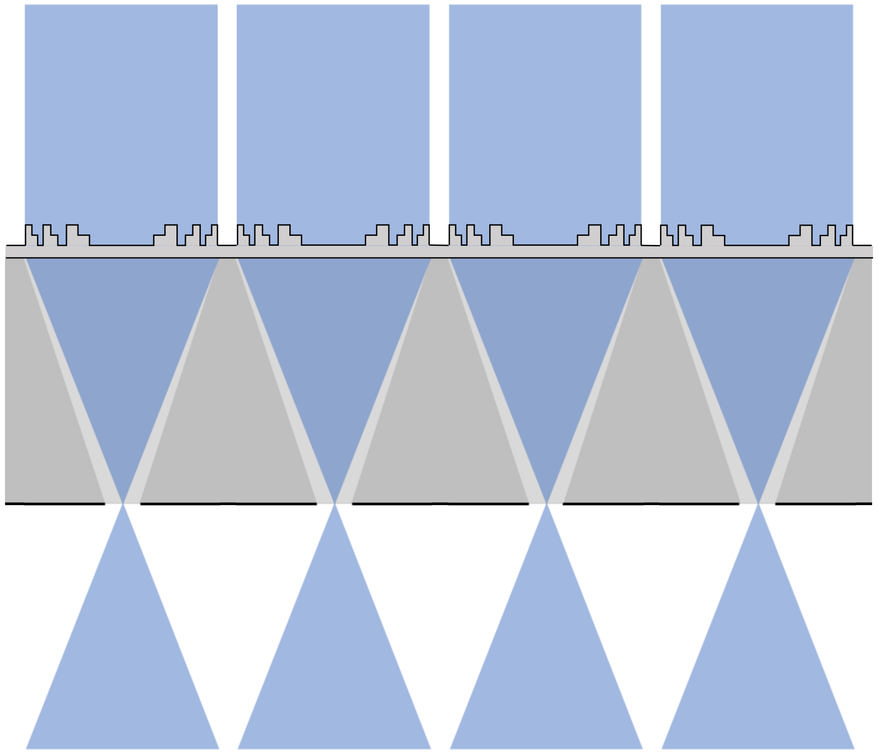


corrected image phase error at λ=13.65nm
(0.0067 wave RMS , 0.045-wave P-V)

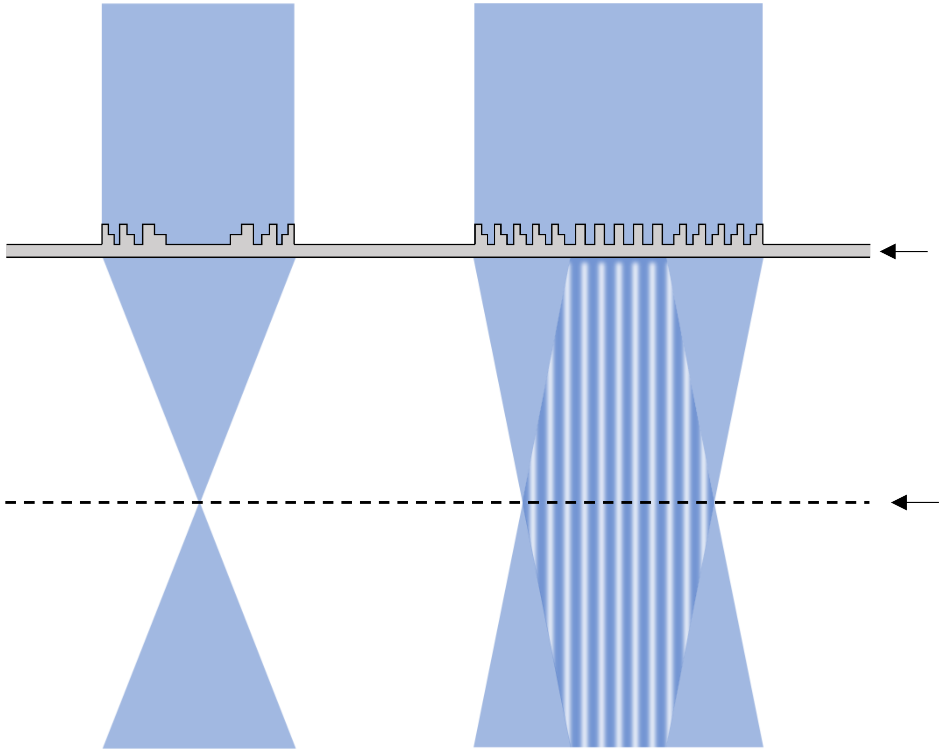


Holographic mask-projection EUV lithography

Maskless, spot-scanning



Mask-projection (field stepper)

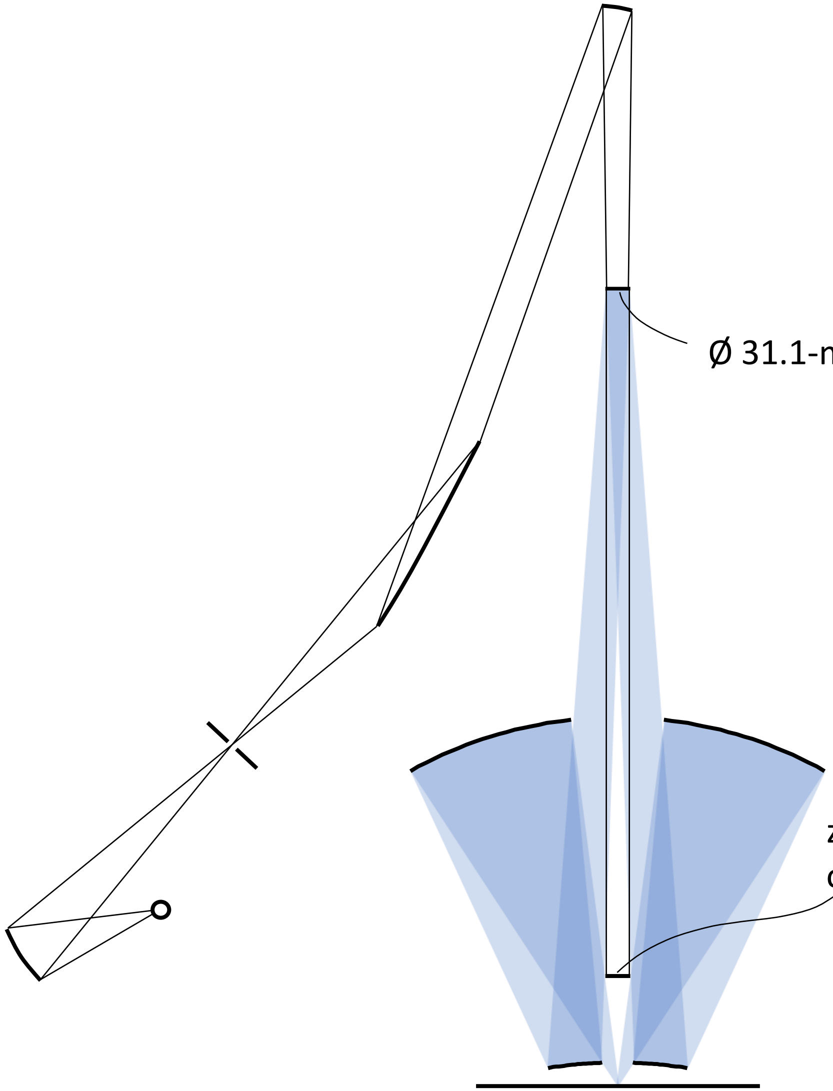


100 nm Si:
84% T @ λ=13.5 nm

200 nm B4C:
82% T @ λ=6.7 nm

focal plane

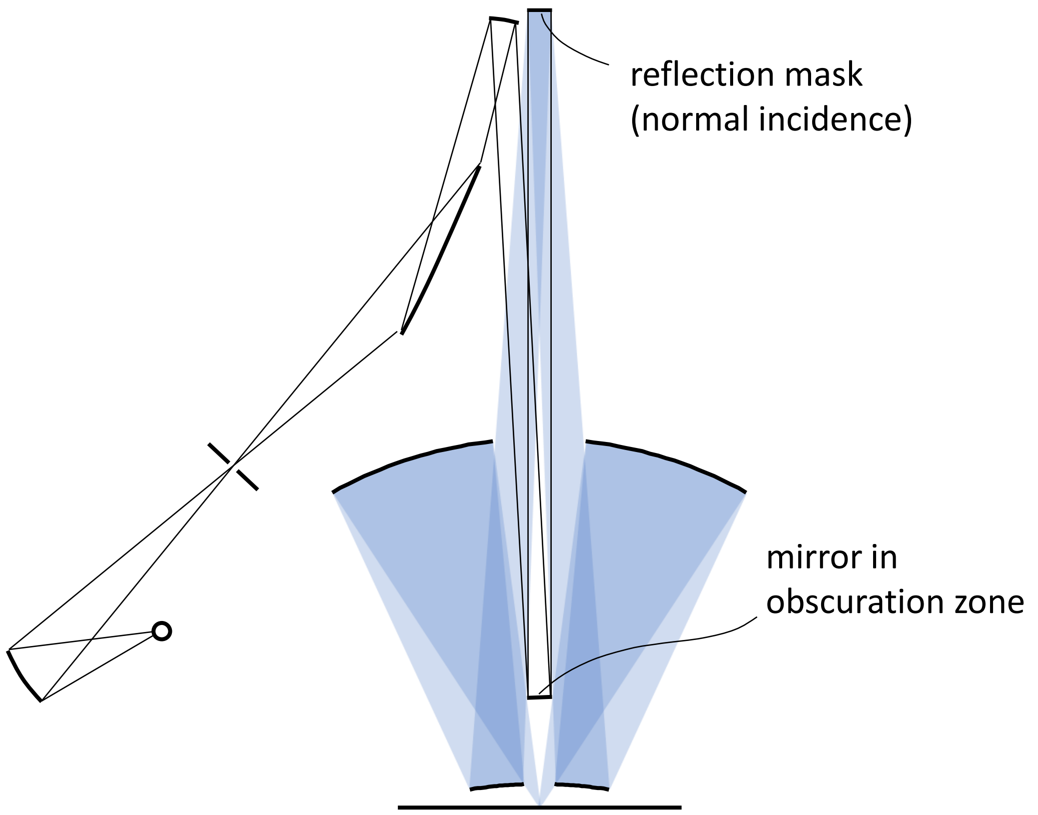
Mask projection with zero-order stop



Ø 31.1-mm object field

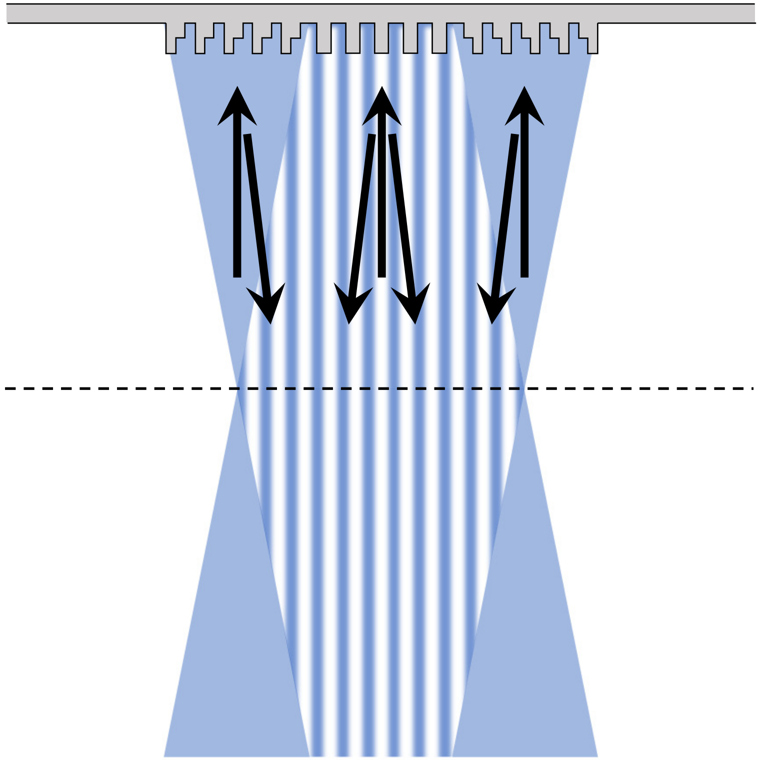
zero-order stop in
obscuration zone, Ø 37.7-mm

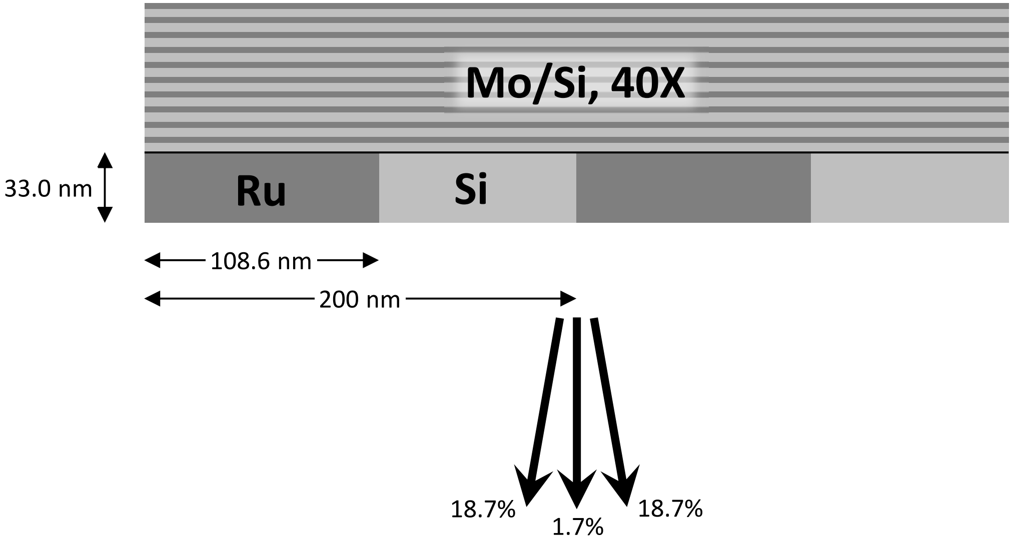
Reflection mask

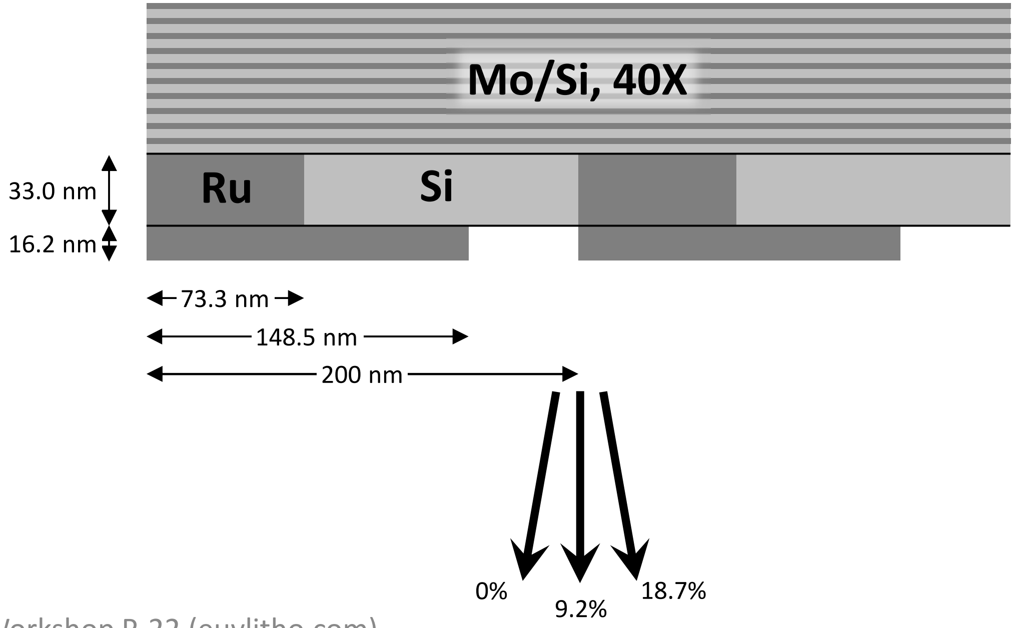


Holographic lithography

200-nm-pitch grating on reflection mask
→ 8-nm HP dense L/S on wafer

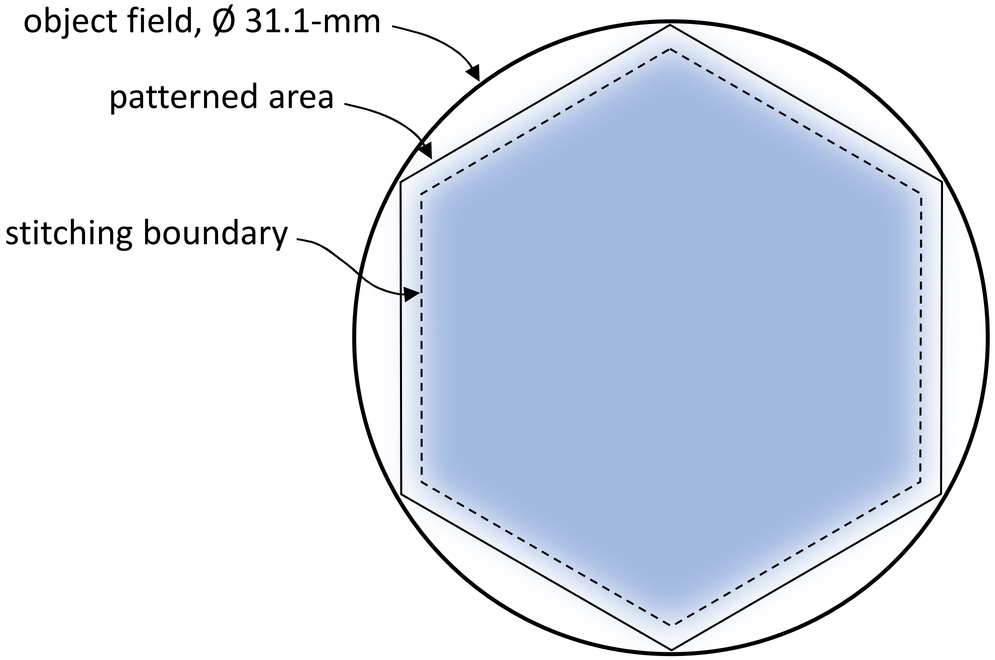




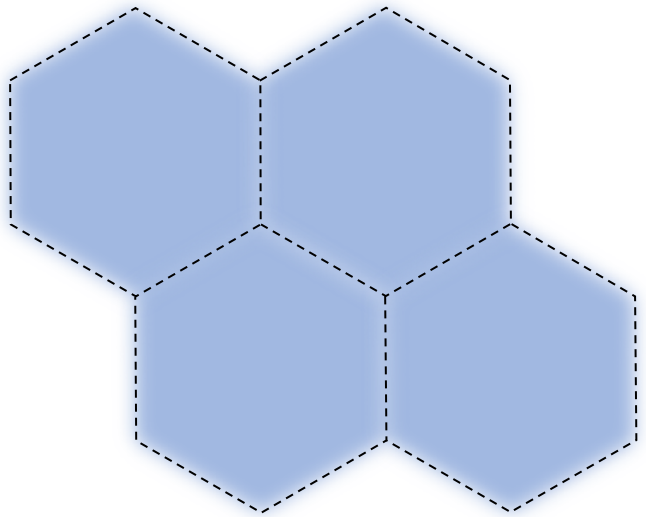


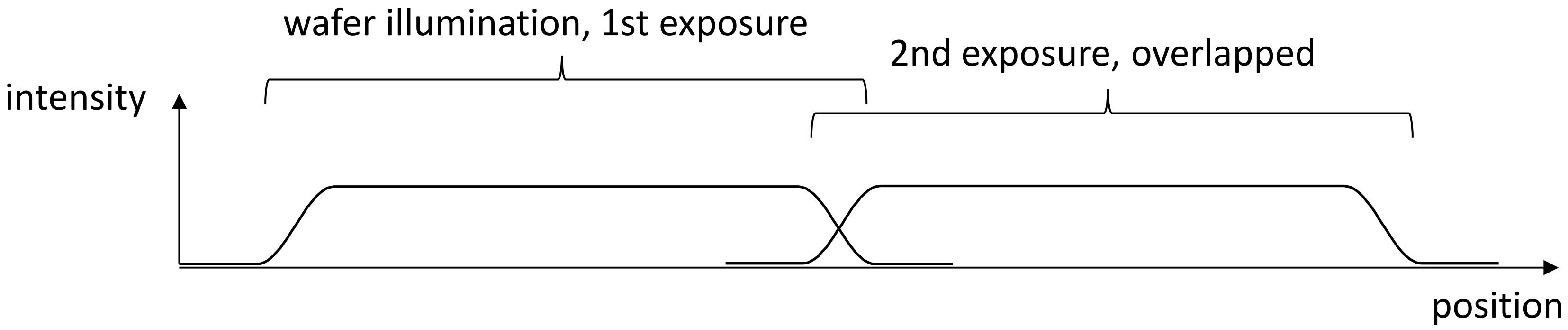
Apodized field stitching

mask geometry:



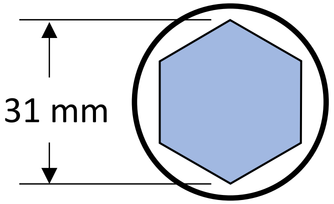
overlapped field stitching
(Apodization avoids edge diffraction effects.)



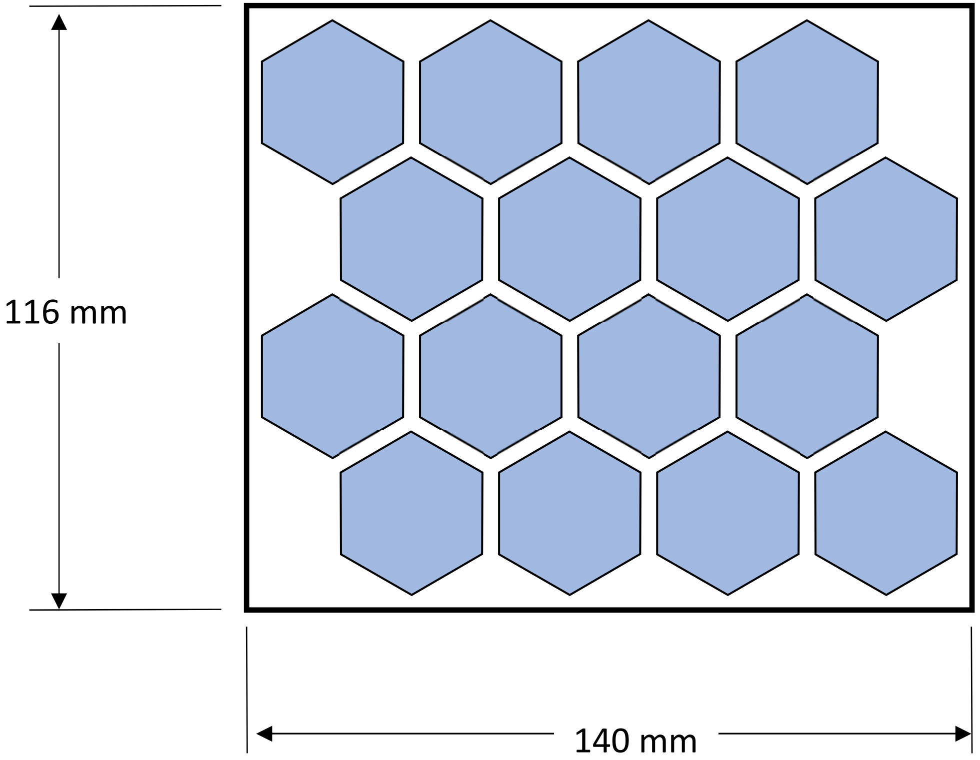


Mask layout options

1 exposure field per mask:

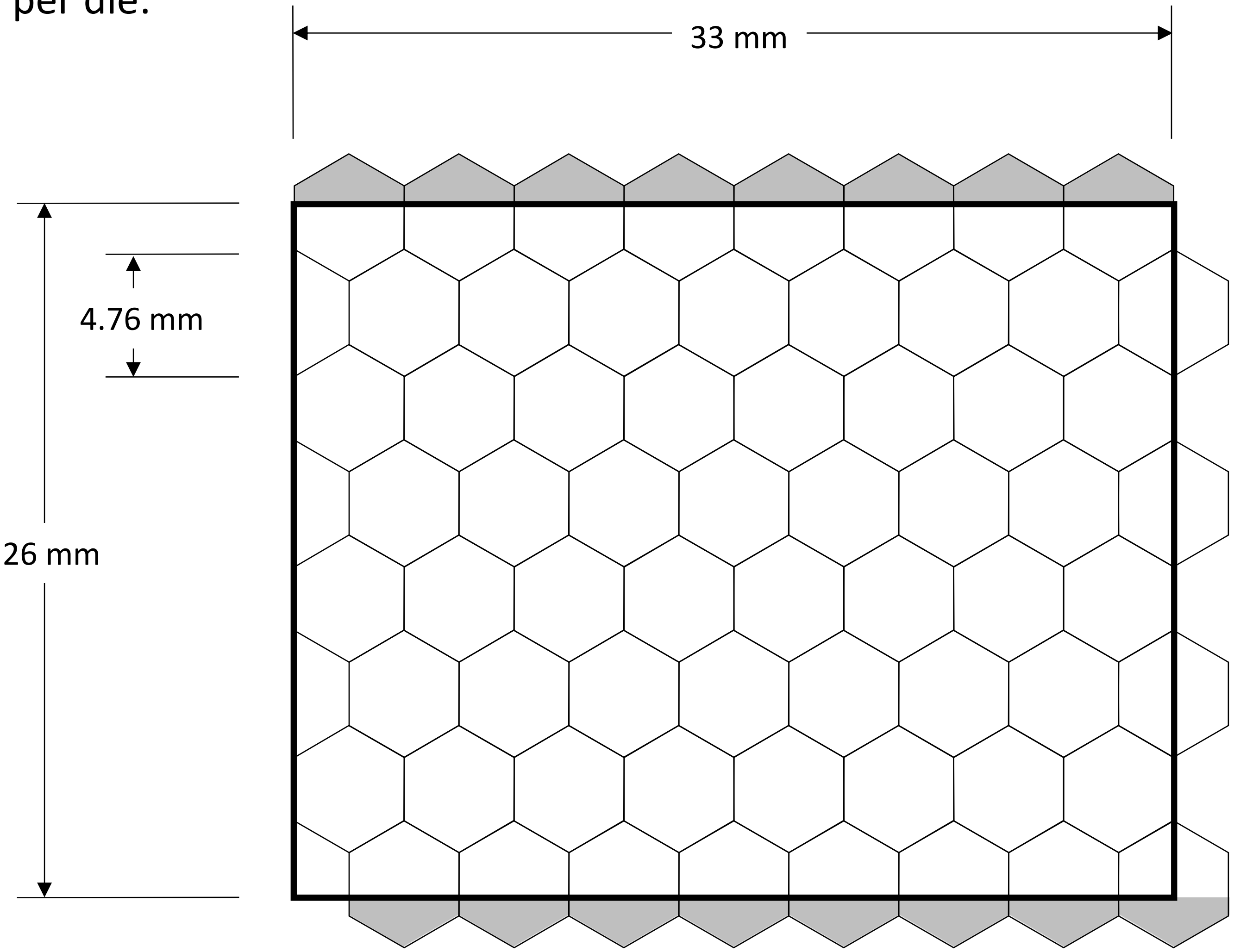


16 fields per mask:



Wafer tiling pattern

64 exposure fields per die:



Summary/Conclusions

Maskless EUVL can be implemented using conventional binary, zone-plate EUV lens technology, and conventional IBF mirror processing for achromatization.

If phase-Fresnel EUV lenses are feasible, maskless efficiency could be doubled, and holographic mask-projection EUVL (with much higher throughput) might also be possible.

Benefits of holographic EUVL (vs conventional mask imaging) include:

- High dose and/or throughput, especially for sparse patterns
- Full aberration correction with simple and efficient projection optics
- Minimal defect sensitivity
- Minimal 3-D mask effects

Maskless and/or holographic EUVL could work for Blue-X (λ=6.7nm).

Selected References

- Maskless EUVL
  - Maskless EUV lithography, an alternative to e-beam
    - https://doi.org/10.1117/1.JMM.18.4.043501 https://www.euvlitho.com/2019/P22.pdf
- EUV Microlenses
  - Fabrication and performance of transmission engineered molybdenum-rich phase structures in the EUV regime
    - https://doi.org/10.1117/12.2281487
  - X-ray Fresnel Zone Plate (NTT product specs)
    - https://www.ntt-at.com/product/x-ray_FZP/
  - Blazed X-ray Optics
    - https://www.psi.ch/en/lmn/blazed-x-ray-optics https://www.psi.ch/en/lmn/double-sided-zone-plates
- IBF-processed EUV mirror coatings
  - Homogenized ion milling over the whole area of EUV spherical multilayer mirrors for reflection phase error correction
    - https://iopscience.iop.org/article/10.1088/1742-6596/425/15/152009/pdf
  - High-efficiency spectral purity filter for EUV lithography
    - US Patent 7,050,237 https://patents.google.com/patent/US7050237B2/en
  - Ion Beam Figuring (Buhler)
    - https://www.buhlergroup.com/content/buhlergroup/global/en/products/leybold_optics_ibfseriesionbeamfiguringmachine.html
- Holographic/Phase-shift/Interference EUVL
  - Holographic mask for lithographic apparatus and device manufacturing method
    - US Patent 7,499,149 https://patents.google.com/patent/US7499149B2/en
  - Sub-Wavelength Holographic Lithography
    - https://nanotech-swhl.com/downloads.html
  - Holographic masks for computational proximity lithography with EUV radiation
    - https://doi.org/10.1117/12.2502879 https://www.euvlitho.com/2019/S34.pdf
  - Ultrahigh efficiency EUV contact-hole printing with chromeless phase shift mask
    - https://doi.org/10.1117/12.2243321 https://doi.org/10.1117/12.2260412
  - EUV Interference Lithography
    - https://www.psi.ch/en/lmn/euv-interference-lithography
- EUVL Aberration Correction
  - Single spherical mirror optic for extreme ultraviolet lithography enabled by inverse lithography technology
    - https://doi.org/10.1364/OE.22.025027

Presentation Notes:

Page 2
- This is a continuation of my presentation on maskless EUVL at the 2019 Workshop and my JM^3 paper. (See References, page 20.)

Page 3
- An LPP EUV source (e.g. Adlyte) can supply multiple scan modules.
- ~2 million microlenses focus EUV illumination through individual focal points, 0.09-NA convergence cones.
- The point array is imaged at 6X reduction onto the wafer at 0.55 NA (same NA as the EXE 5000).
- The wafer is raster-scanned while the points are modulated to sythesize a digital exposure image.
- The microlenses are supported by a microchannel plate with conical holes (TSV's) for beam transmission.
- MEMS shutters can be placed at the microlens foci (~1-micron travel range) to modulate each point.
- Alternatively, for printing periodic patterns (e.g. contact holes, DRAM cell arrays, etc.), a spatial light modulator might not be needed. Just modulate the source; all lens channels print identical patterns.
- The microlenses are binary-optic zone-plate elements, much simpler than what I proposed in 2019.
- The lenses are not achromatic; instead the system uses a diffractive M2 mirror to correct the chromatic aberration.

Page 4
- The system only needs two EUV projection mirrors because the microlenses can be designed to correct projection system aberrations.
- Zero-aberration imaging (at wavelength 13.5 nm) over wide image field, high NA.

Page 5
- Zone-plate lens illustration (at edge of object field), showing elliptically distorted phase zones to correct aberration.
- The black ellipse is the obscuration zone (distorted by aberration).
- Mo phase-shift rings (~85-nm thick) on Si substrate (50-100 nm), for wavelength 13.5-nm (or ~200 nm La on 100-200nm B4C for 6.7 nm)

Page 6
- Optical phase error over exit pupil, without and with aberration correction.
- u2 and u3 are ray direction cosines at the image, for an image point at the edge of the field.
- Without correction: 1-wave RMS (could be reduced to <0.2-wave RMS, but the phase slope would be very steep, more difficult to correct)
- The radial gradient of the phase error is zero on the pupil boundary, enables aberration correction without lens distortion or increased zone density.
- With correction: Zero phase error at 13.5 nm (but the lenses will exhibit chromatic aberration at other wavelengths).
- Lens zone widths control pupil illumination profile.

<u>Presentation Notes:</u>

Page 7
- Achromatic microlens system (left, proposed in 2019), simpler singlet lens (right, current design).
- The achromatic system requires:
    - 2 lenses in series, aligned on opposite sides of a microchannel plate
    - phase-Fresnel lenses (not easy to manufacture)
    - embedded MEMS shutters and data paths, if a spatial light modulator us used
- The singlet lenses can be simple binary-optic zone plates – single-layer litho processing, minimum half-pitch 75 nm (similar to lenses CXRO has been making for ~20 years, but needs to be scaled up to large arrays, ~2 million lenses).
- A binary-optic lens will have half the efficiency of a phase-Fresnel lens, but the beam goes through only one lens so efficiency is similar to the achromatic doublet.
- A binary-optic lens will generate a lot of optical scatter/flare in extraneous diffraction orders, but not a problem because the beam can be spatially filtered at the focal point.
- A singlet lens will exhibit significant chromatic aberration, but the projection system can correct the chromatic aberration.

Page 8
- Chromatic-correction diffraction structure on mirror M2
- Phase structure similar to microlens (~24 annular zones), but scaled up from 15-micron to 600-mm aperture.

Page 9
- Fabrication process for diffractive M2 mirror (can work for wavelength 13.5 nm or 6.7 nm)
- Apply Ion Beam Figuring (IBF) to carve out a quadratic bowl in an EUV multilayer mirror, center depth ~24 bilayers.
- IBF is a well established process for optics fabrication, has been used to process EUV mirror coatings (see References).
- The reflection layers act as a volume Bragg-diffraction grating. Efficiency in the first diffraction order is very similar to a standard EUV mirror, but the layer tilt relative to the boundary surface results in some chromatic aberration, which nullifies the microlens chromatic aberration.

Page 10
- Chromatic performance (phase aberration over exit pupil) without M2 correction, for 3 wavelengths: 13.5 nm (center) and 13.5+/-0.15 nm (right, left).
- 0.084-wave RMS (i.e. 1.1 nm @ 13.5-nm wavelength) chromatic focus change at the high/low wavelengths.

Presentation Notes:

Page 11

- Chromatic performance with IBF-processed M2 mirror: 0.0067-wave RMS (i.e., 0.090-nm) at edge of image field (worst-case, less near center of the field)
- The residual phase error is mainly due to mirror axial symmetry – it can only correct axially symmetric chromatic phase errors, but the peripheral microlenses are slightly asymmetric due to geometric aberration correction.
- This is for wavelength 13.5 nm. At 6.7 nm the residual chromatic phase error would be doubled (to 0.013 wave RMS).
- Reducing the projection optics scale by half (from 600-mm aperture to 300-mm aperture) would reduce the phase error by 2X, so similar performance at wavelength 6.7 nm should be achievable with a downsized projection system.

Page 12

- Next steps for future development:
- Replace the binary zone-plate lenses with phase-Fresnel lenses for doubled optical efficiency.
- If the phase-Fresnel lens quality is good enough (negligible scatter/flare), then the focal-plane spatial filter is not required and the filter and microchannel plate can be eliminated, leaving a free-standing thin film (“patterned pellicle”).
- Without the microchannel plate, any kind of diffraction pattern can be used (not just microlens patterns); can be used for mask-projection (not maskless) EUVL with transmission mask.
- "Holographic" EUVL: Mask is displaced from focal plane, is not imaged directly onto wafer.
- Microlens-type mask structures can be used for isolated point patterns, but with static imaging, not scanning – very high dose for isolated features (e.g. line cuts).
- Grating-type mask structures can be used to print dense line/space patterns via interference lithography; relatively high dose because there is no absorber.

Page 13

- Mask design can be simplified by putting a zero-order stop in the projection system (in the obscuration zone, supported by spider struts or pellicle).
- Dark-field imaging: To leave an area on the wafer unexposed, just don’t pattern the mask. No need for zero-order extinction.

Page 14

- Another design variant: Make the zero-order stop a mirror for directing illimitation onto a reflection mask.
- Normal incidence, minimal 3-D effects.
- Analogous to Lasertec actinic mask inspection system, which also has an axial fold mirror in the illumination optics.
- Use 45^{o}-incidence fold mirror for polarized illumination (could be useful for very high-NA interference lithography).

Presentation Notes:

Page 15

- Holographic reflection mask example: grating structure for printing dense line/space patterns at 8-nm half-pitch.
- Center region splits EUV illumination evenly into +1 and -1 orders for interference lithography.
- Side region generates only one first (+1 or -1) diffraction order; the other order is suppressed. Efficiency is matched to beam-splitter grating; lateral position controls phase matching.
- Zero order is no problem – it is masked in the projection optics. 2nd and higher orders are outside the NA limit.

Page 16

- Field size is ~30 mm on mask, 5 mm on wafer.
- Large-field coverage via field stitching (similar to EXE 5000).
- Use overlapped exposure fields (e.g. hexagonal) and apodized illumination to avoid diffraction effects on the stitch lines.

Page 17

- Mask layout options: single exposure field per mask (cookie-size), or 16 fields on a more standard mask size.

Page 18

- Field tiling on waver: 64 exposure fields per standard die (26 mm by 33 mm).

Page 19

- Re “Minimal defect sensitivity” for holographic EUVL: Mask defects are not in the focal plane, will be out of focus at the wafer.
- Re “Minimal 3-D mask effects”:
    - Important for Blue-X (6.7-nm wavelength) – reflection masks will require ~200 bilayers.
    - Transmission masks would probably have no significant 3-D effects.
    - Normal incidence illumination on reflection masks would minimize 3-D effects.
    - Holographic lithography might have sufficient degrees of freedom to nullify any 3-D effects.