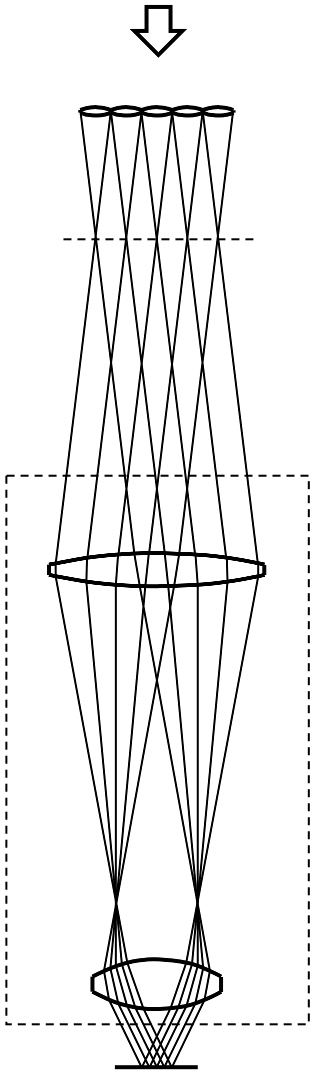
Diffraction Optics for EUV Microscopy and Lithography

- Actinic Inspection/Metrology/Defect-review/Alignment
- Maskless EUV Lithography
- Holographic Mask-Projection EUV Lithography

Spot-Array Imaging*: Schematic Concept



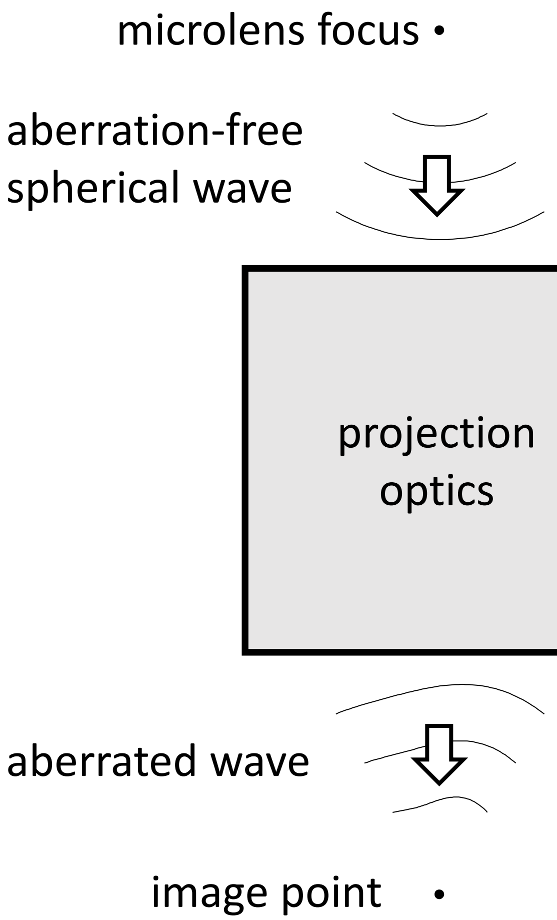
Advantages:

- Simple microlenses (large, low-NA)
- Accessible focal plane
  - Spatial filtering of stray light, flare
  - MEMS shutter modulators
- Aberration compensation

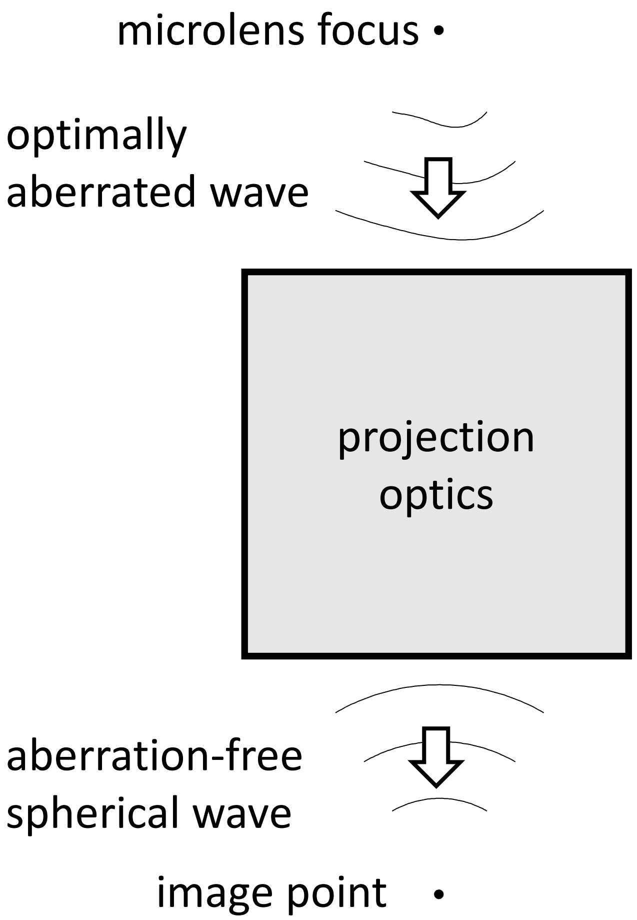
* "Maskless EUV lithography, an alternative to e-beam" (JM3 2019)
"Maskless EUV Lithography" (2019 EUVL Workshop)
"Application of EUV Diffraction Optics for Actinic Mask Inspection and Metrology" (2018 EUVL Workshop)

Aberration Compensation

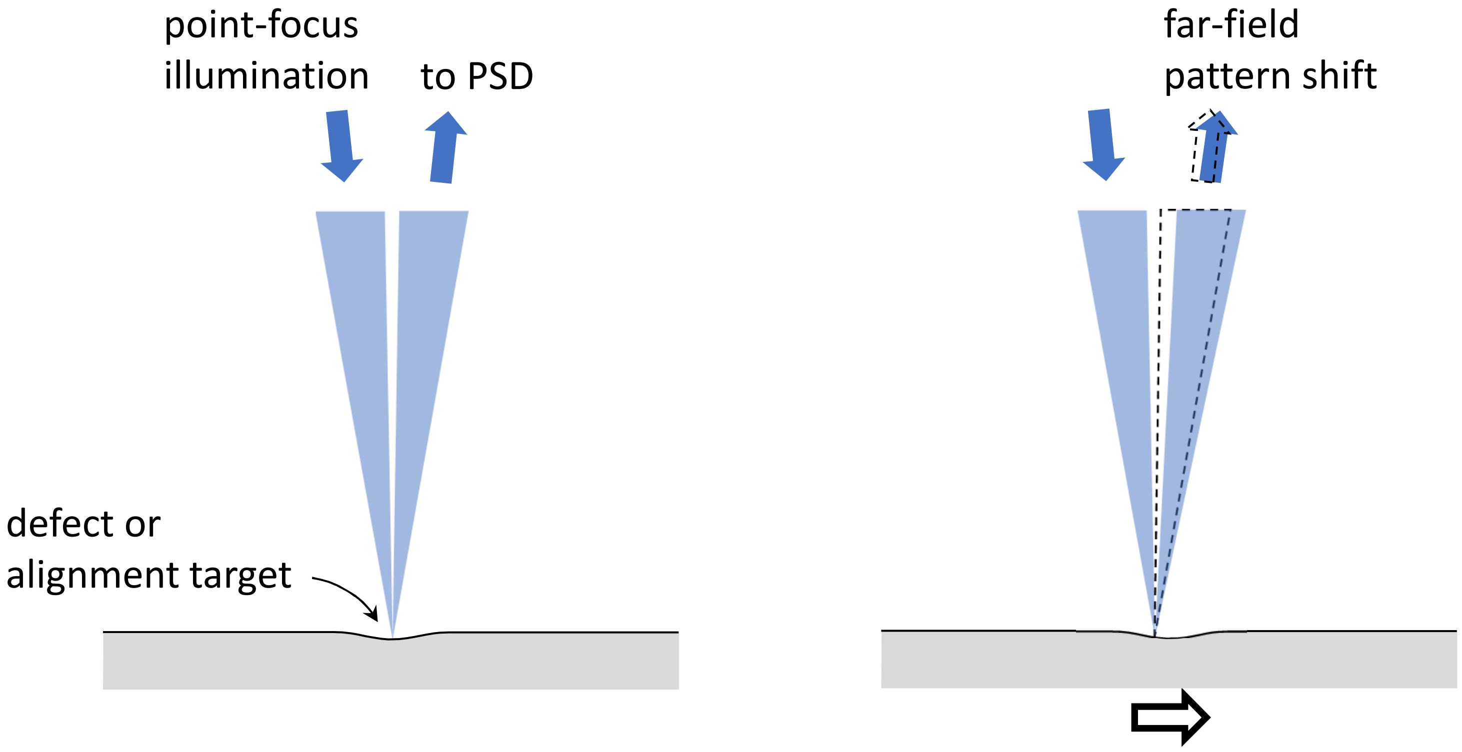
Without aberration compensation:



Aberration-compensated:



Spot-Scanning Microscopy (e.g. inspection, alignment)

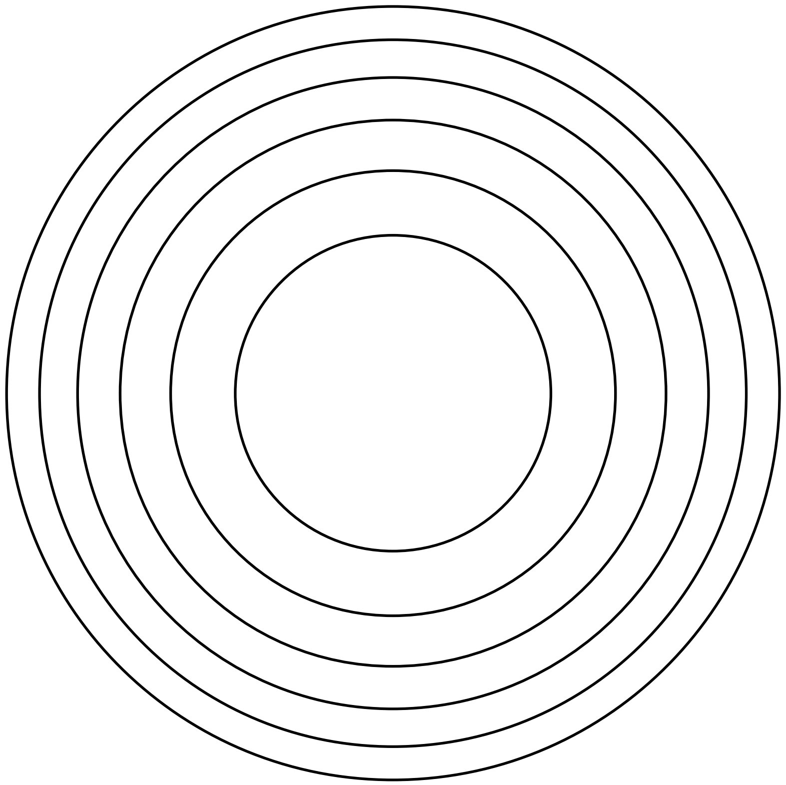


Apps:

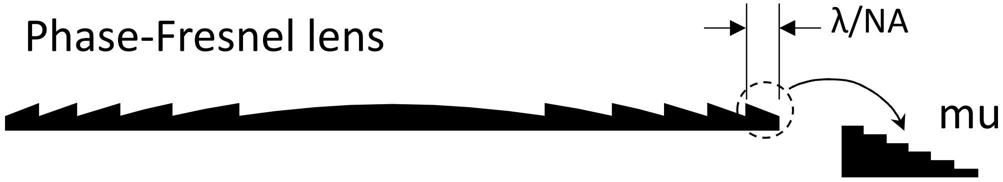
- Mask inspection (ABMI/APMI): potential order-of-magnitude improvement in phase sensitivity over darkfield, focus scan
- Alignment: alternative to imaging, grating diffraction; potentially smaller alignment targets

EUV Diffractive Microlenses*

Lens zone pattern



Phase-Fresnel lens



e.g., 6-level:
λ=13.5nm: ~150 nm Mo (pattern depth) / 50 nm Si (substrate)
λ=6.7nm: ~340 nm La (pattern depth) / 50 nm B4C (substrate)
~50% efficiency

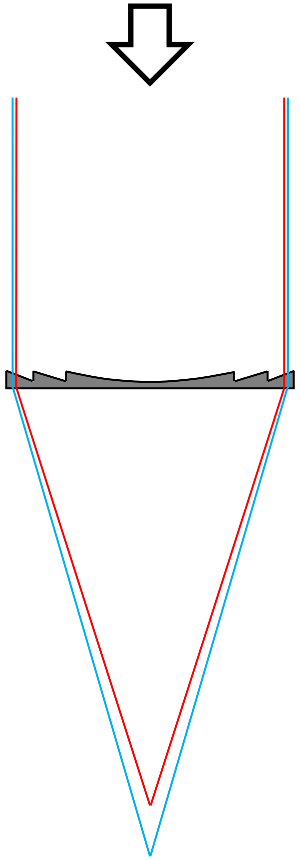
Binary-optic zone-plate lens (2-level)

λ=13.5nm: ~89 nm Mo (pattern) / 50 nm Si (substrate)
λ=6.7nm: ~210 nm La (pattern) / 50 nm B4C (substrate)
~30% efficiency

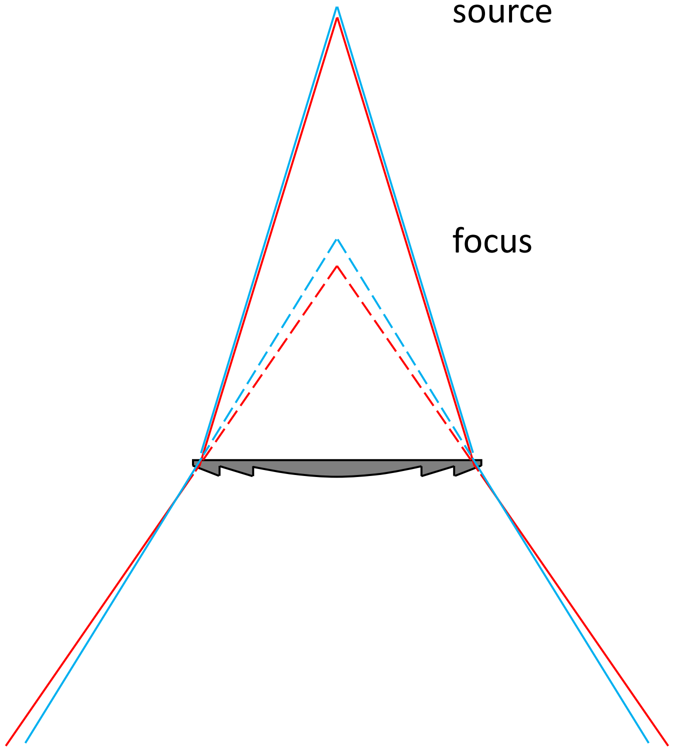
* Fabrication and performance of transmission engineered molybdenum-rich phase structures in the EUV regime (CXRO 2017);
X-ray Fresnel Zone Plate (NTT product specs);
Blazed X-ray Optics (Paul Scherrer Inst.);
Double-sided zone plates (Paul Scherrer Inst.)

EUV Diffractive Lenses: Chromatic Aberration

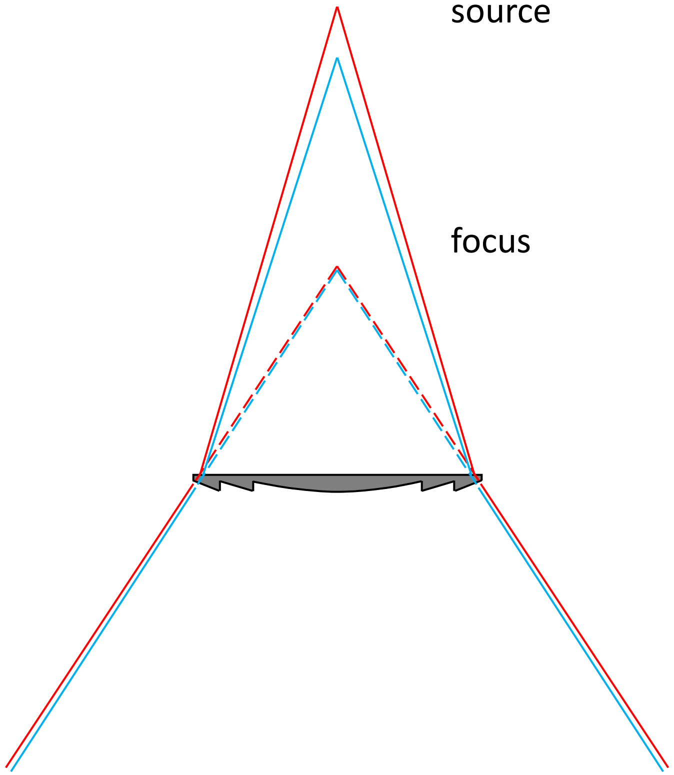
Point-focus lens: Longer wavelengths are more strongly diffracted.



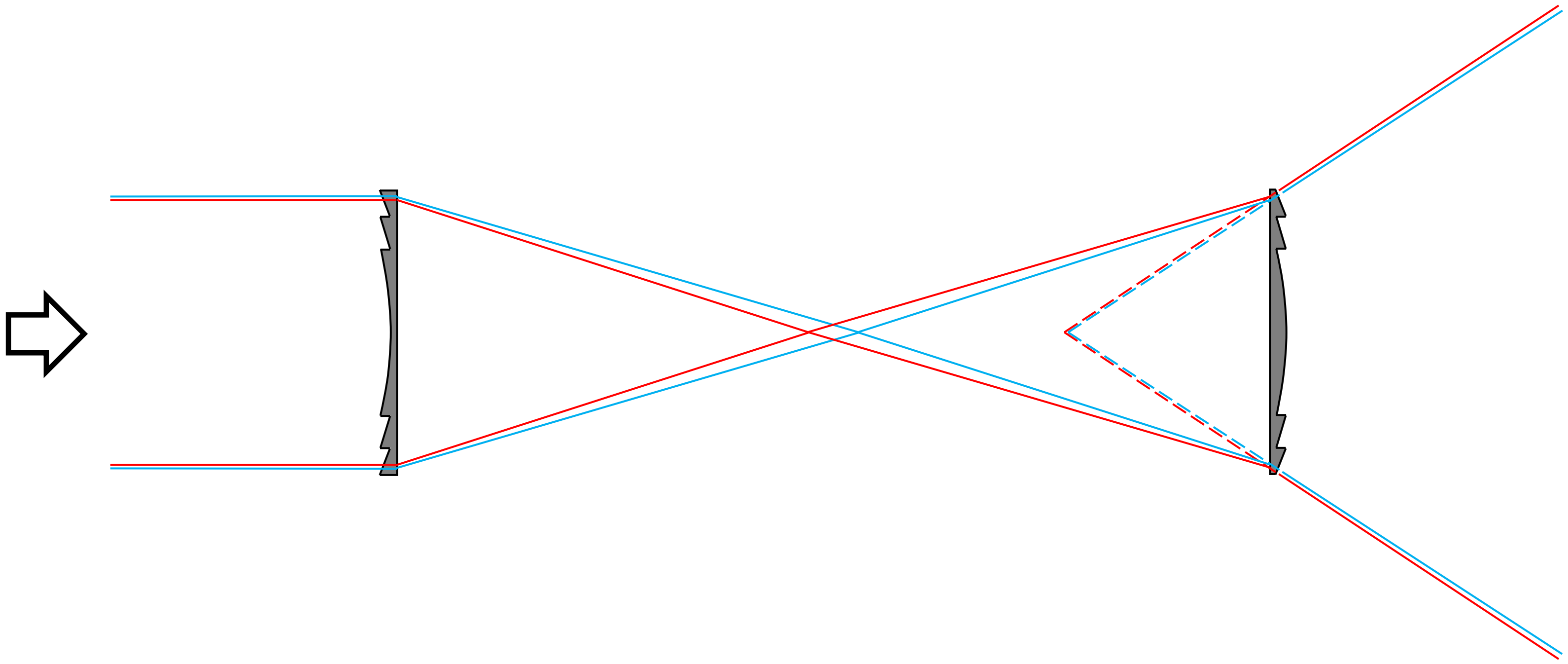
Divergent lens, point source, dispersed virtual focus.



Divergent lens, pre-dispersed source, resolved virtual focus.

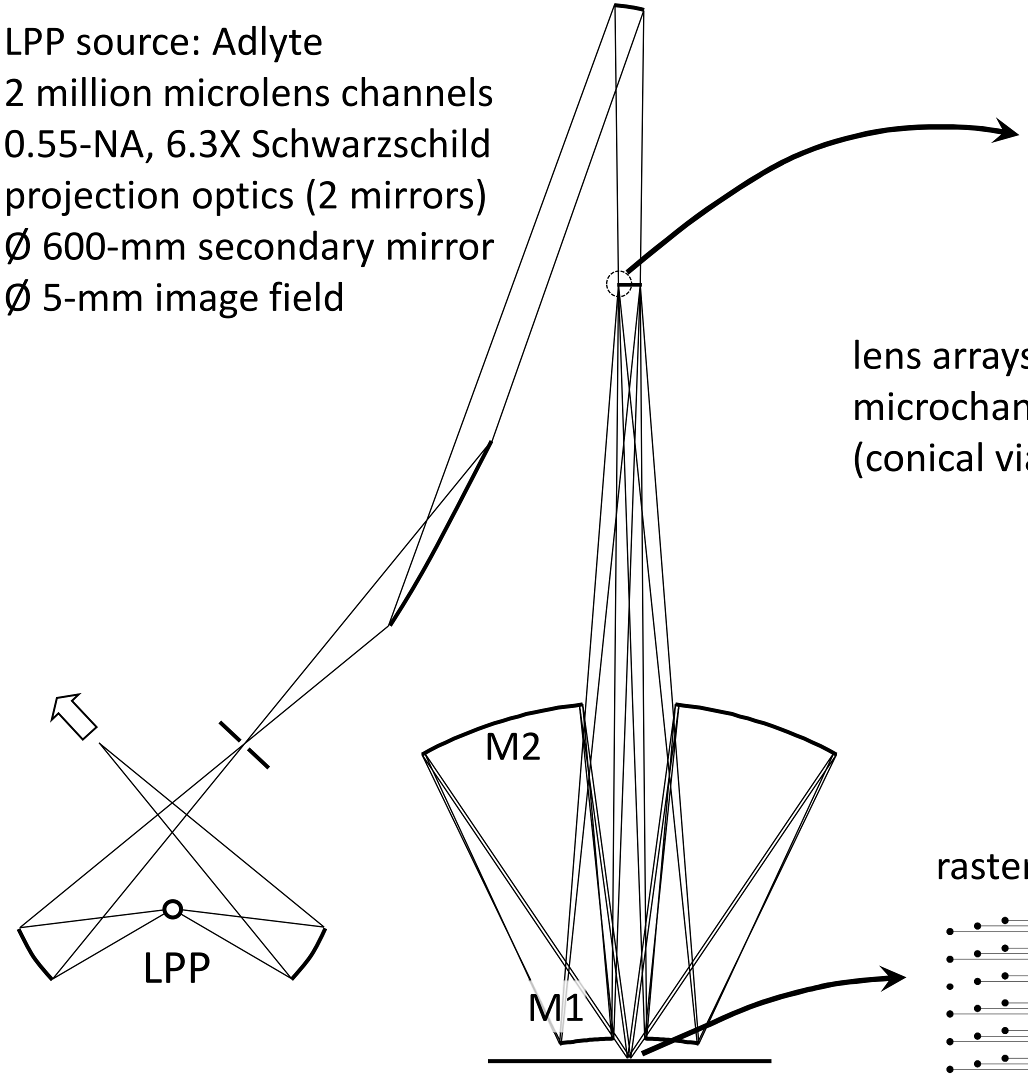


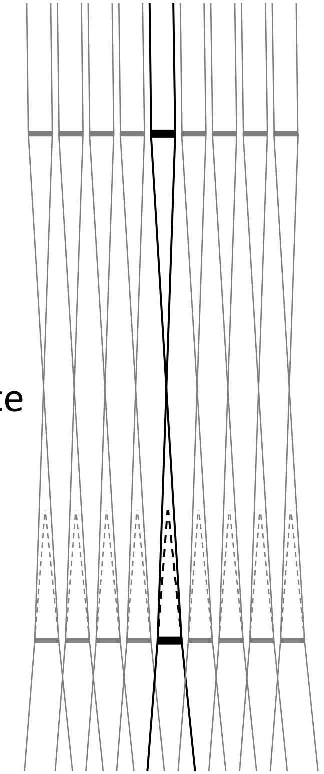
Achromatic EUV lens (Schupmann doublet)

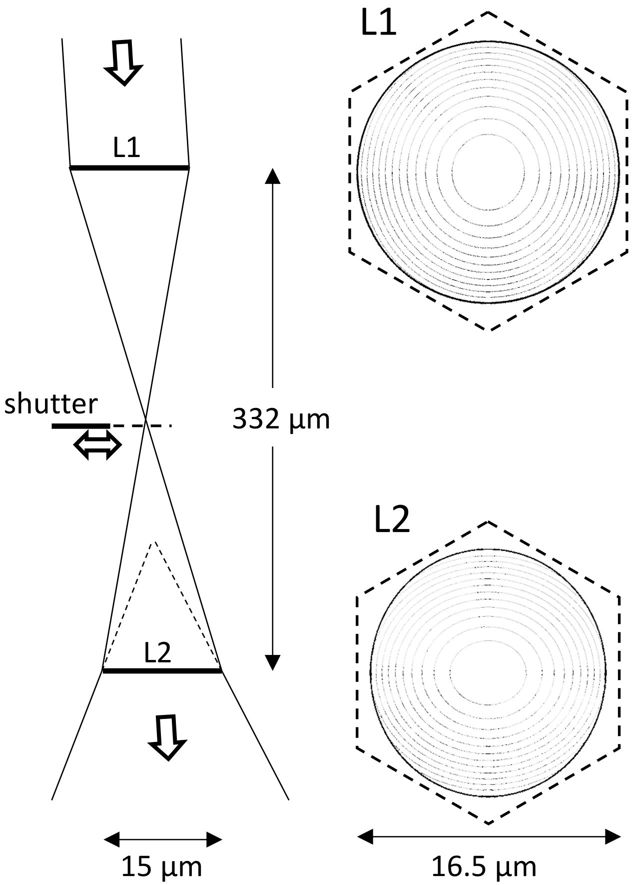


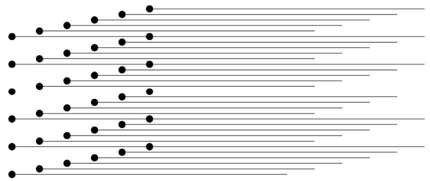
EUV Maskless Scanner (13.5 nm, 0.55 NA)

- LPP source: Adlyte
- 2 million microlens channels
- 0.55-NA, 6.3X Schwarzschild projection optics (2 mirrors)
- Ø 600-mm secondary mirror
- Ø 5-mm image field









- Ø 15 µm, 16.5-µm center spacing (hex array)
- ~12 phase zones per lens element
- elliptical zones (aberration compensation)
- <0.05 wave P-V phase error over 3% λ band

Comparison with e-beam (mask writing)

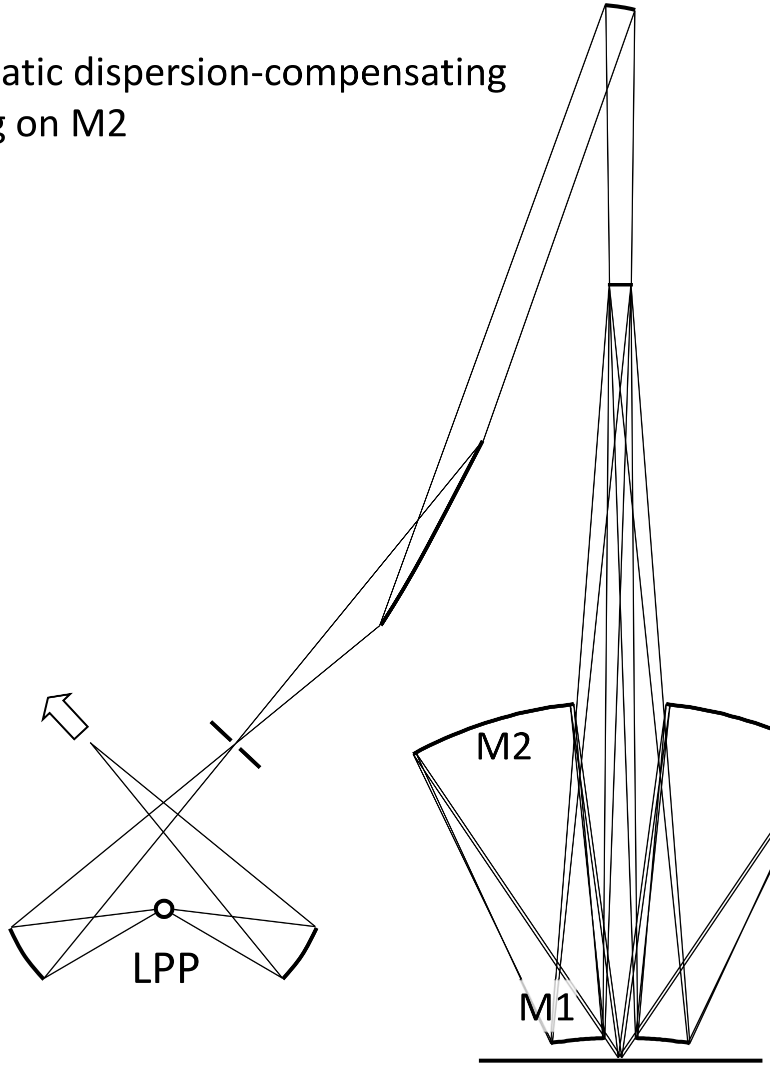
	IMS multibeam*	Maskless EUVL**
Resolution	11 nm HP	8 to 10 nm HP
Writing grid step	5 nm	4 nm
Throughput	10 h/mask	2.5 to 5 h/mask
Exposure dose	100 μC/cm^2 (~10 mJ/cm^2)	800 mJ/cm^2: flood 58 mJ/cm^2: isolated point, at peak (12.9-nm FWHM) 202 mJ/cm^2: isolated line, at peak (12.9-nm FWHM)

* E. Platzgummer, C. Klein, and H. Loeschner, "Electron multibeam technology for mask and wafer writing at 0.1 nm address grid," J. Micro/Nanolithogr. MEMS MOEMS 12(3), 031108 (2013).

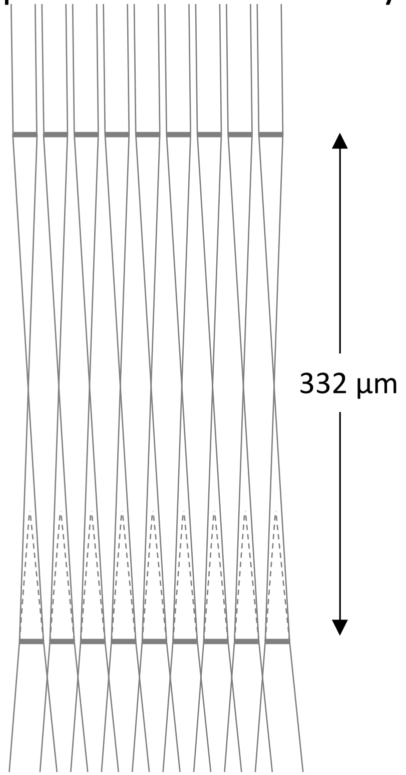
** Kenneth C. Johnson, "Maskless EUV lithography, an alternative to e-beam," J. Micro/Nanolith. MEMS MOEMS 18(4), 043501 (2019).

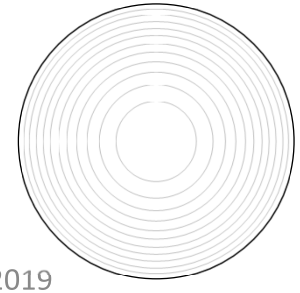
Diffractive Projection Optics

Chromatic dispersion-compensating grating on M2



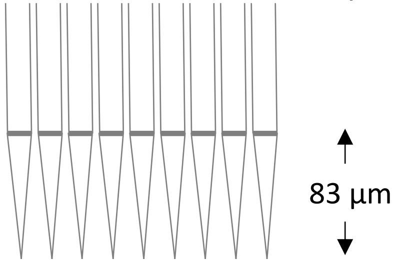
Conventional projection optics, chromatically corrected Schupmann microlens array



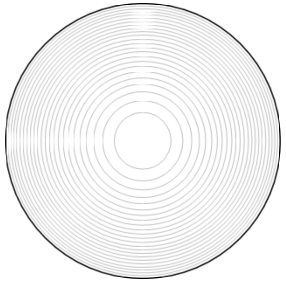


0.045-NA, 12 phase zones,
Minimum zone width ~300 nm
(for Ø 15-µm lens)

Diffractive projection optics, singlet microlens array (Chromatic correction in M2)



0.09-NA, 24 phase zones,
minimum zone width ~150 nm
(for Ø 15-µm lens)

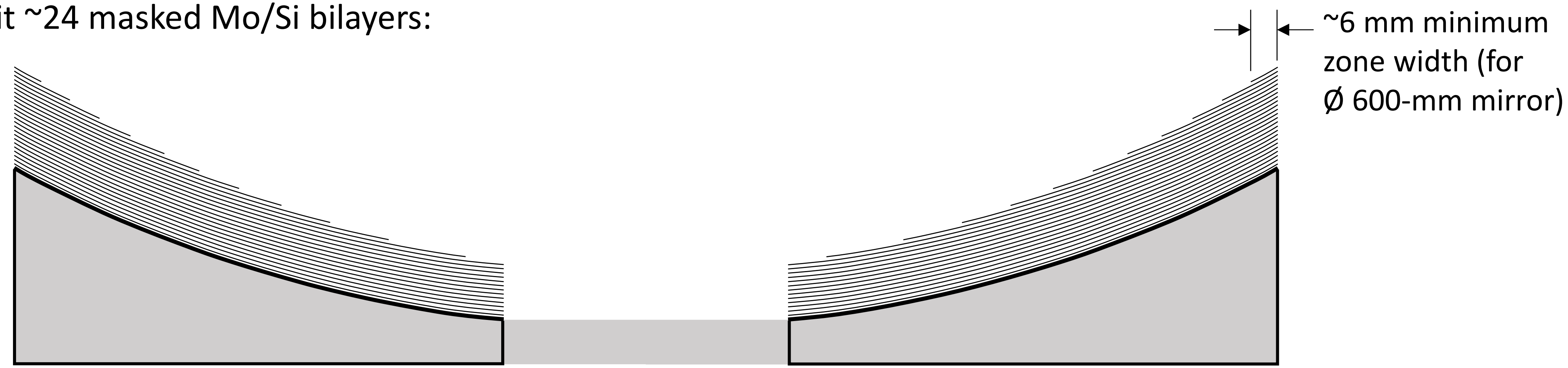


M2 grating construction

Chromatic aberration from 24-zone microlenses can be corrected with 24-zone diffractive mirror.

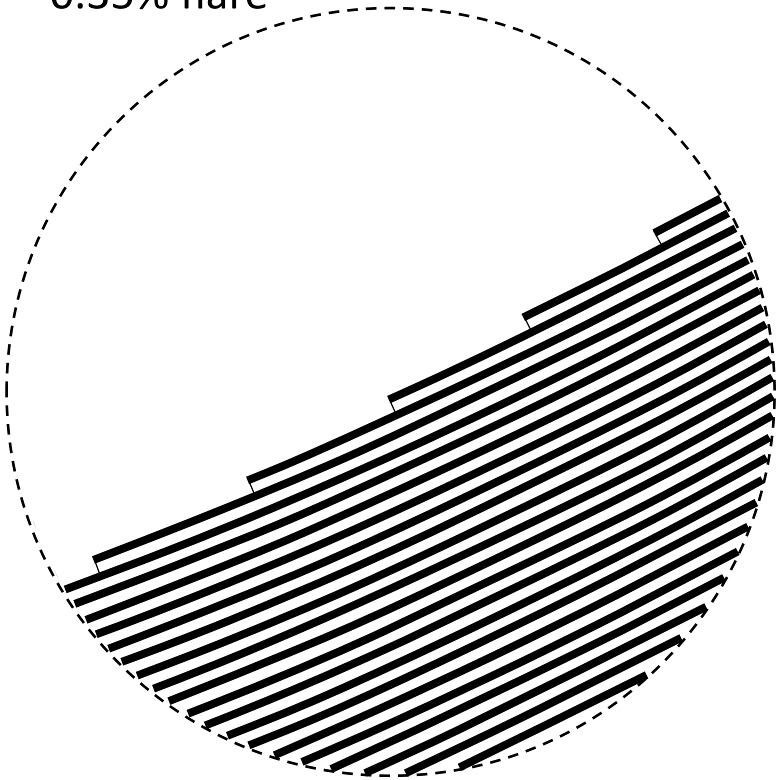
Deposit ~40-50 Mo/Si bilayers for λ=13.5nm (or ~200 B/La for 6.7nm):

Deposit ~24 masked Mo/Si bilayers:

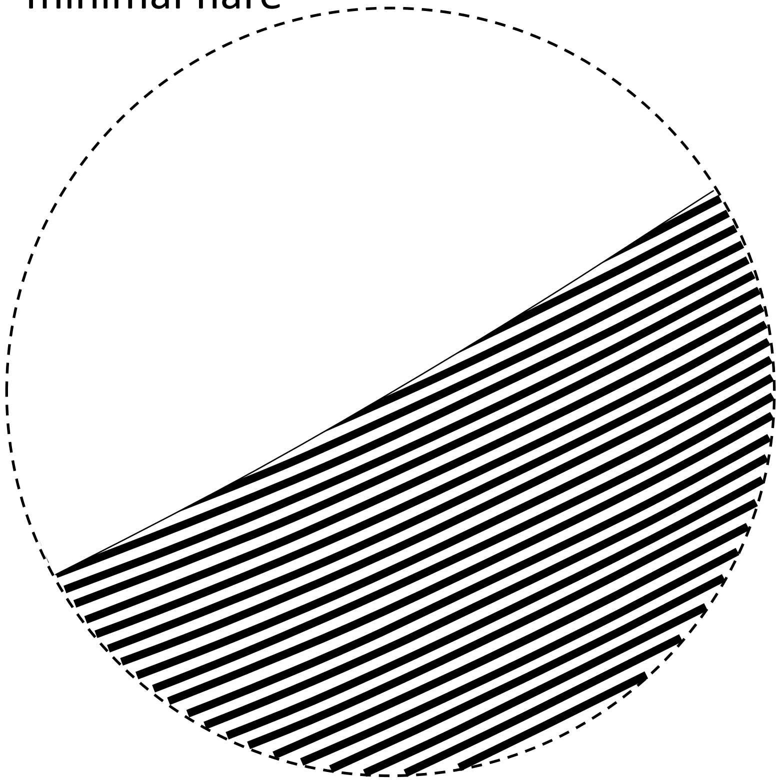


Stepped vs smooth M2 grating surface

Stepped (discontinuous-edge deposition):
~0.35% flare

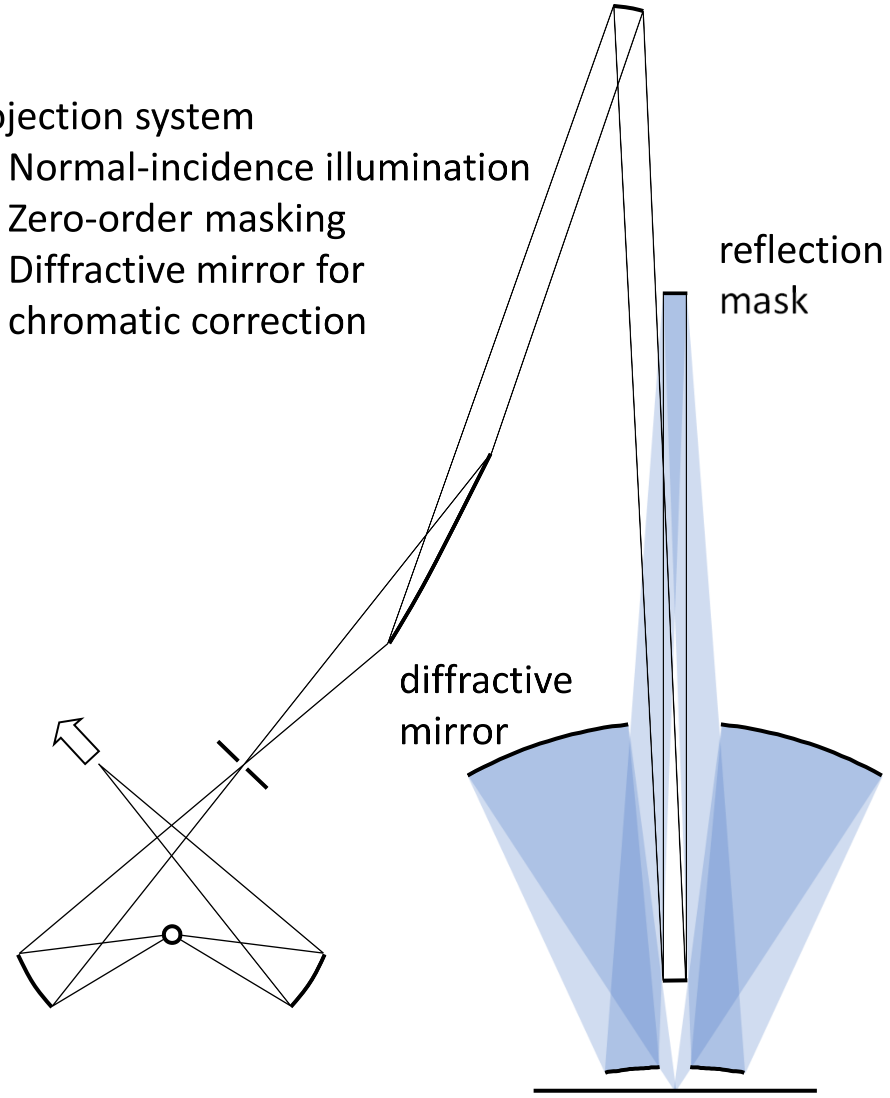


Smooth (gradient-edge deposition):
minimal flare

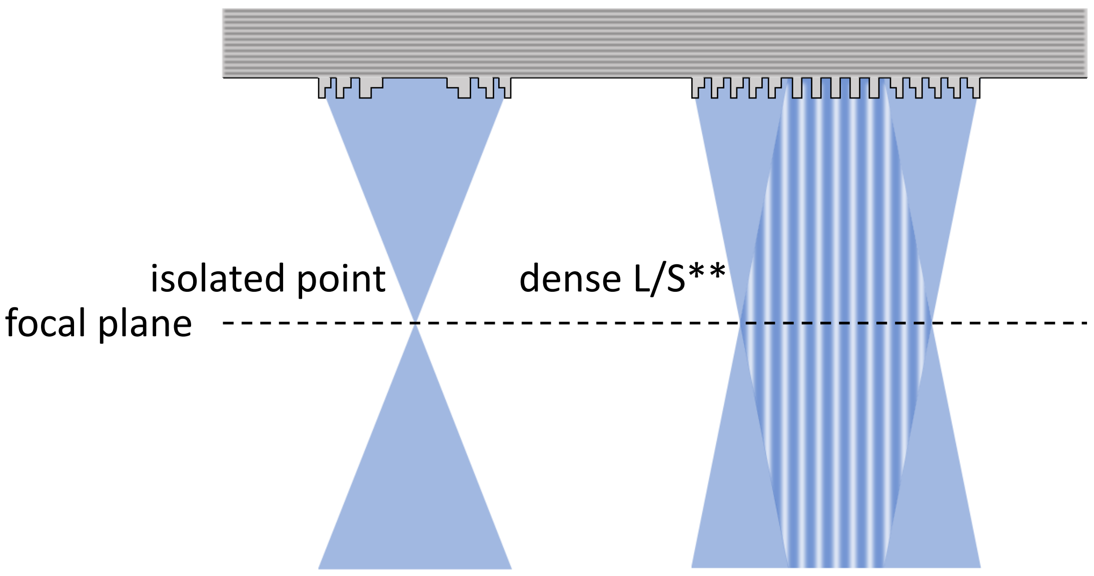


Holographic mask-projection EUV lithography

Projection system
- Normal-incidence illumination
- Zero-order masking
- Diffractive mirror for chromatic correction



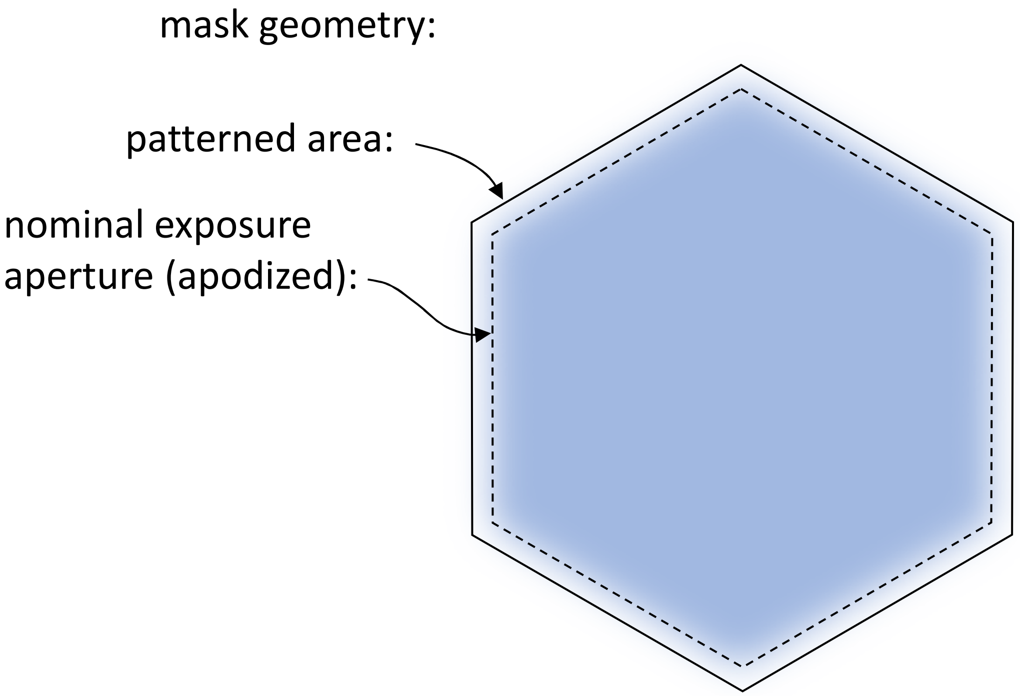
"holographic" (diffractive) mask*



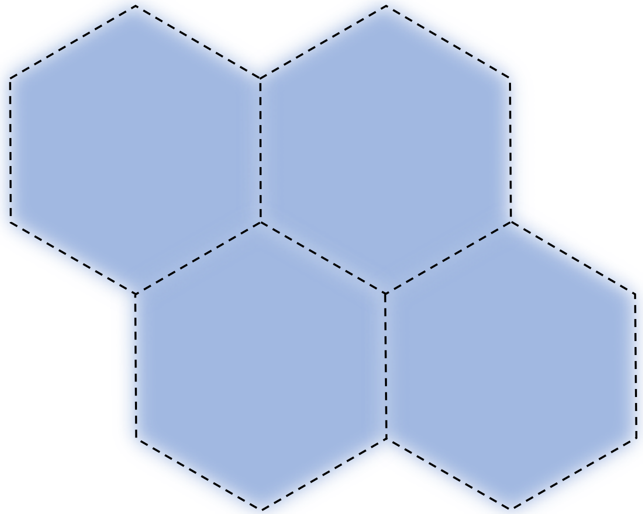
Advantages:
- High dose (esp. on isolated features)
- Aberration correction
- Relatively insensitive to mask defects
- Can correct/neutralize 3D effects (?)

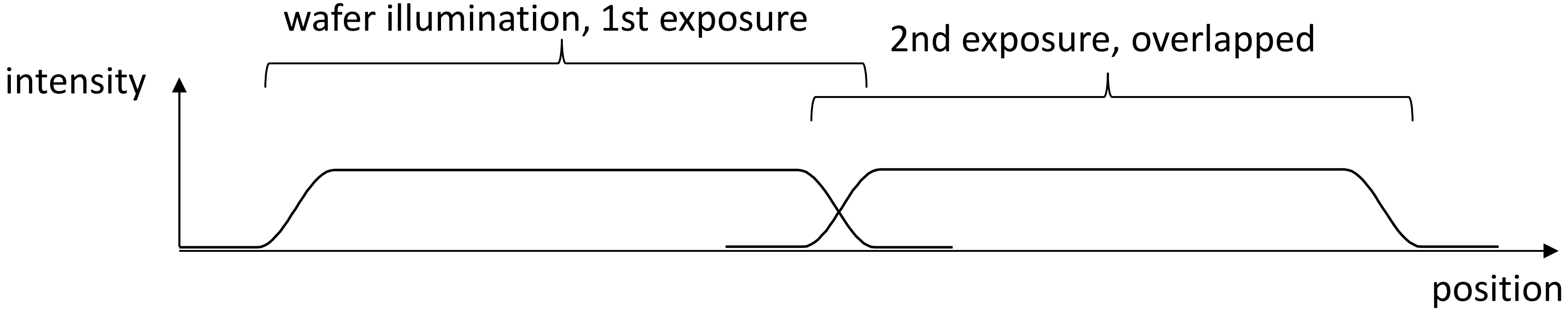
* US Patent 7,499,149 (ASML);
Sub-Wavelength Holographic Lithography;
Holographic masks for computational proximity lithography with EUV radiation
** Ultrahigh efficiency EUV contact-hole printing with chromeless phase shift mask

Step-and-repeat with apodized field stitching

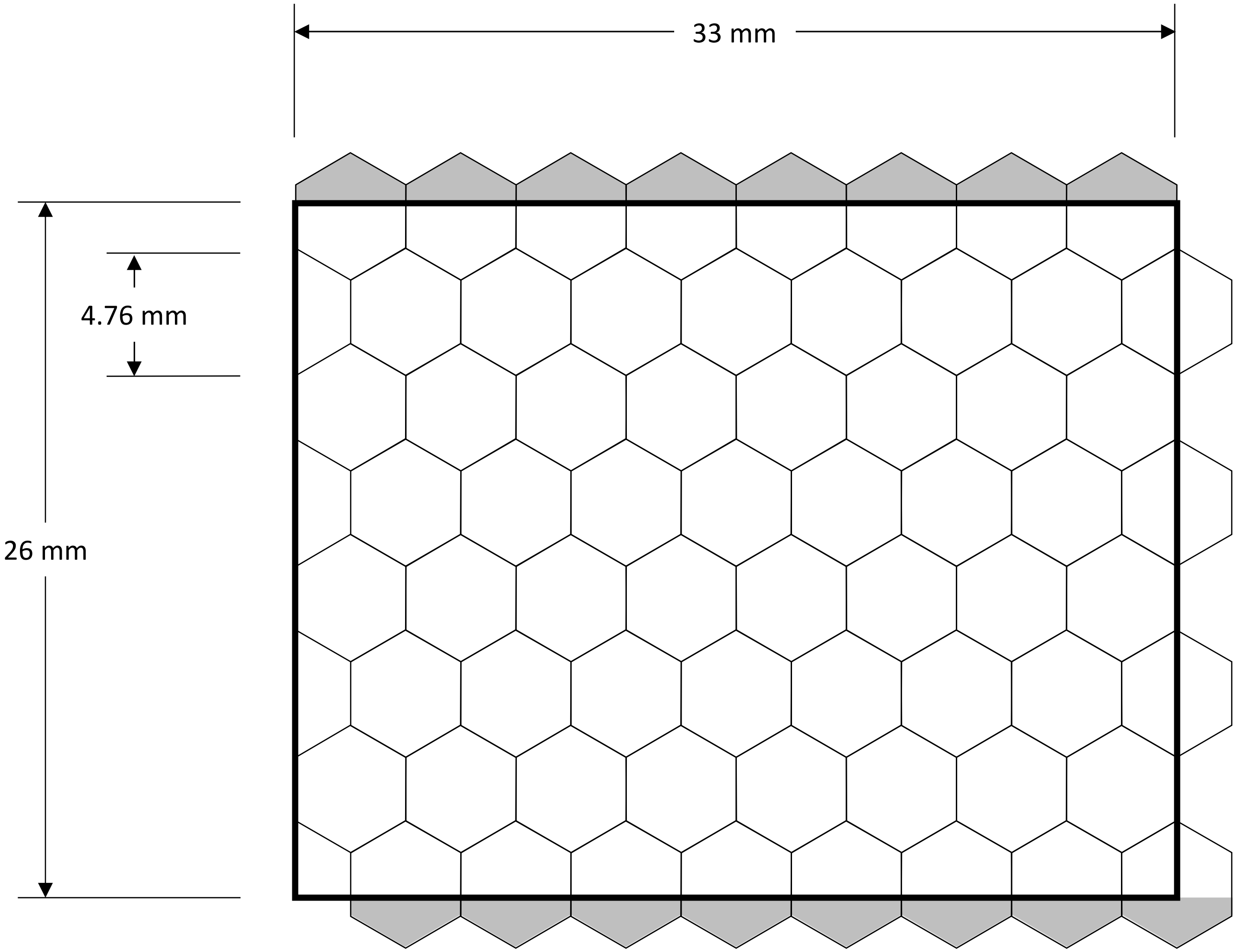


overlapped field stitching
(Apodization avoids edge diffraction effects.)





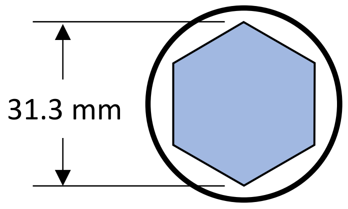
64 mask fields per die



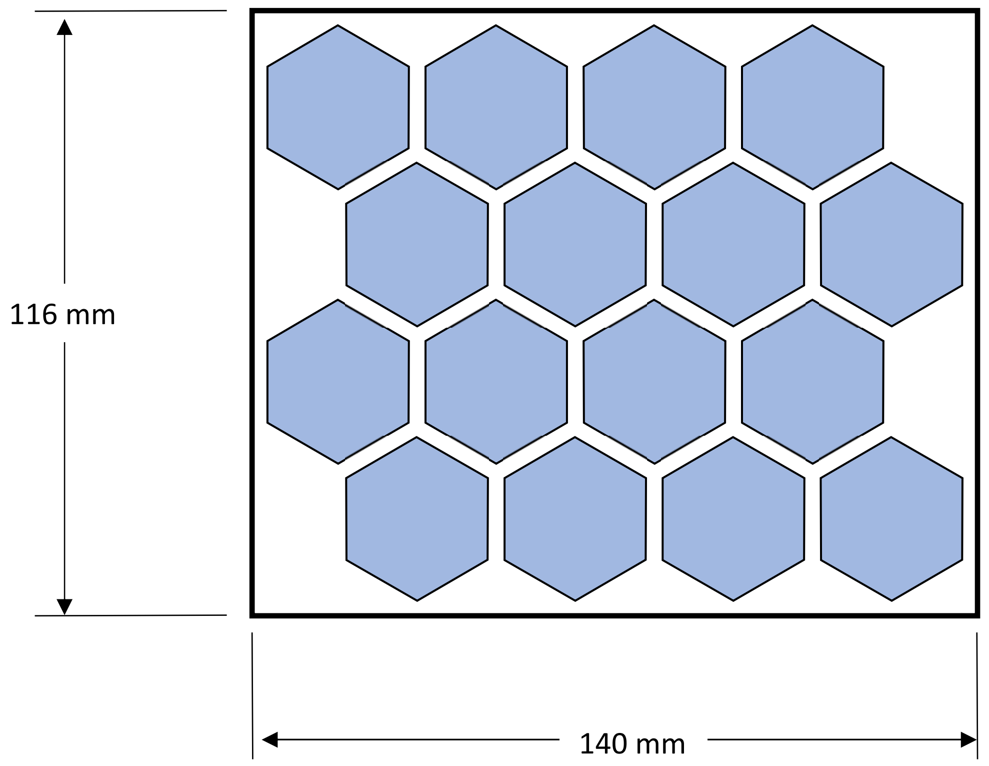
8×8 field pattern is periodically tiled over full wafer.

Mask layout options

1 exposure field per mask:



16 fields per mask:



Opportunities for Diffraction Optics in Nanofabrication

- Actinic EUV mask inspection/metrology: Potential order-of-magnitude improvement in phase sensitivity
- Maskless EUV lithography
  - Mask writing: High dose, high throughput
  - Wafer writing: Preproduction development for EUV HVM
- Mask-projection lithography (holographic) @ 6.7 nm
  - Normal incidence → minimal 3D effects
  - High dose
  - Aberration correction → simpler, more efficient projection optics
  - Minimal defect sensitivity
  - Neutralize mask 3D effects (?)
- Potential spin-off applications (DUV/VIS, laboratory microscopy, photonic crystals and metamaterials, …)