EUV Lithography: Past, Present & Future

GLOBALFOUNDRIES

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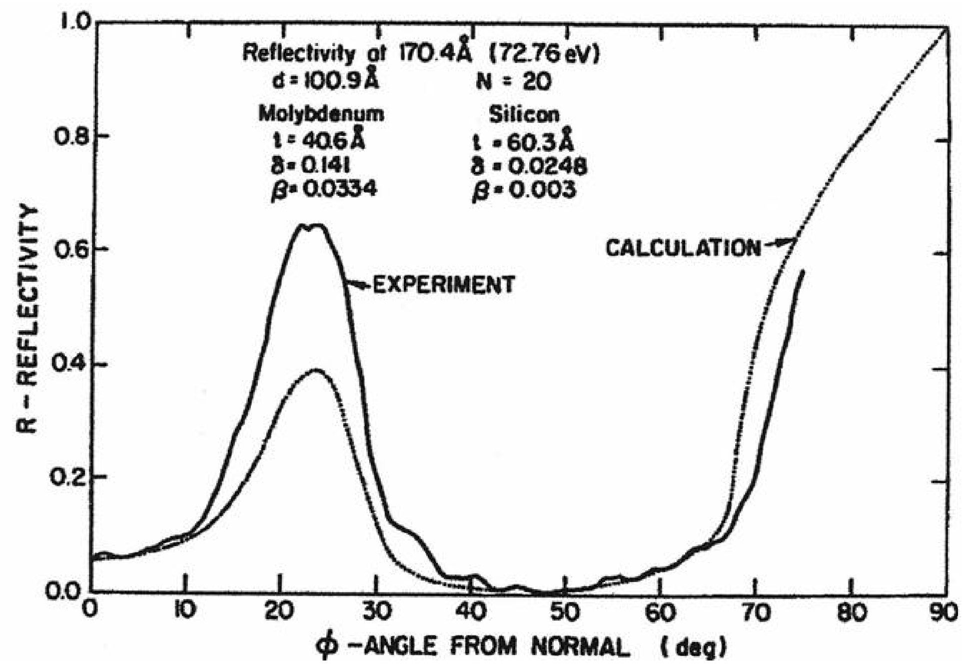
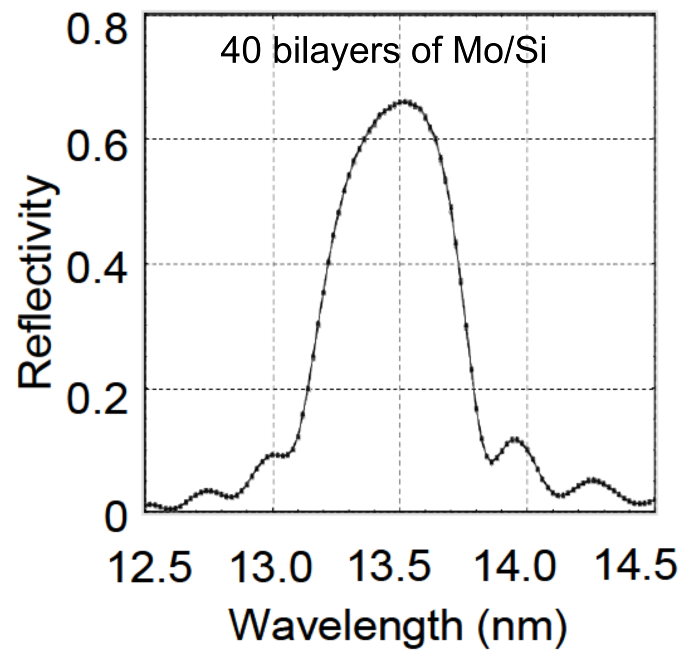
The Past: Early Critical Issues

- What was known in the mid-1980's and what was not?
  - + High normal incidence EUV reflectivity was demonstrated in 1985



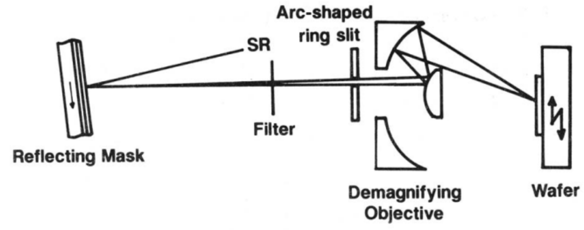


Ref: T.W. Barbee, et al., "Molybdenum-silicon multilayer mirrors for the extreme ultraviolet, Appl. Opt. 24, 883 (1985).

  - – Few suitable reflective imaging systems were available
  - – Fabrication & testing of precision aspheres was an art not a science
  - – EUV light sources were highly immature

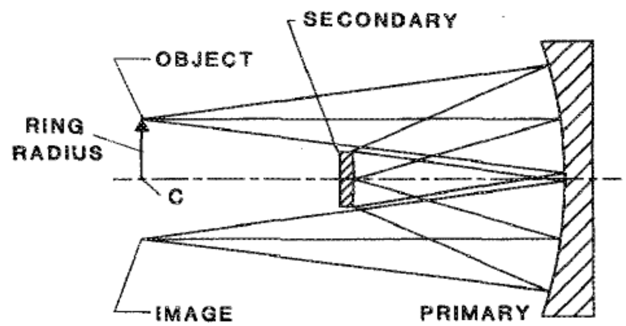
Reflective Imaging Systems: Designs

- Three well-known reflective imaging systems in the 1980's:
  - 20:1 Schwarzschild microscope objective:
    - 2 spherical mirrors
    - supported reduction imaging
    - small image field



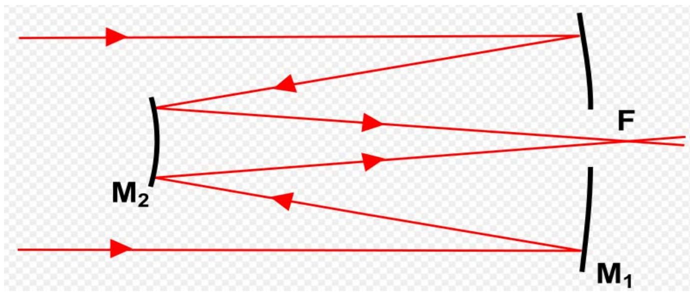
Ref: H. Kinoshita, et al., "Soft x-ray reduction lithography using multilayer mirrors," J Vac. Sci. Technol. B 7, 1648 (1989)

  - 1:1 Offner relay:
    - 2 spherical mirrors
    - 1:1 imaging only
    - large image field possible with scanning



Ref: O.R. Wood, et al., "Short wavelength annular-field optical system for imaging tenth-micron features," J Vac. Sci. Technol. B 7, 1613 (1989)

  - Cassegrain (Ritchey-Chrétien) telescope:
    - 2 hyperbolic mirrors
    - mirrors difficult to test without null
    - wide image field
    - Some imaging aberrations remain

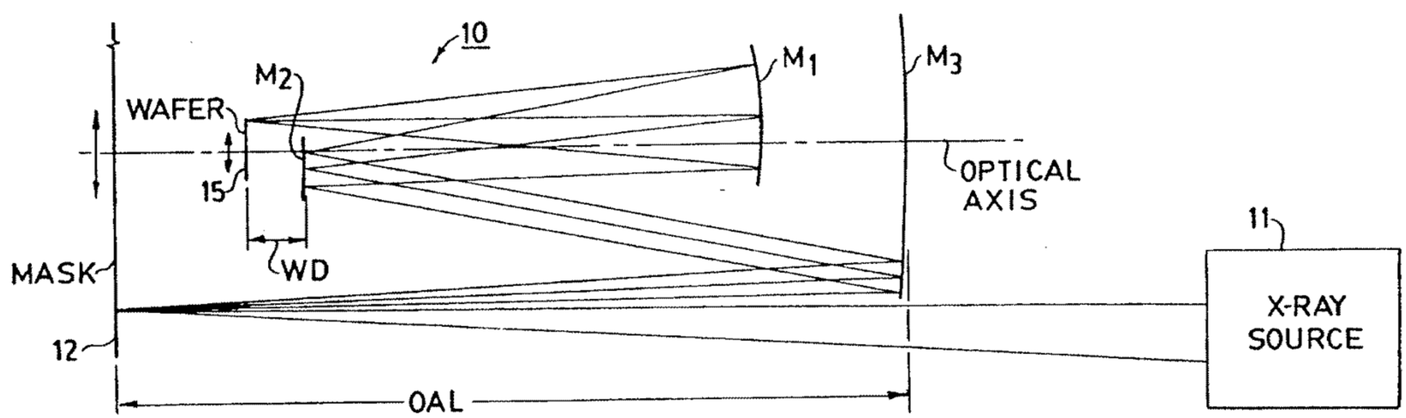


Ref: https://en.wikipedia.org/wiki/Ritchey-Chrétien_telescope

Reflective Imaging Systems: Lessons Learned

- Some lessons learned from the early EUV imaging work:
  - Optics must be telecentric on the image side (to prevent mag. change with defocus)
  - Scanning ring-field designs are the simplest systems that can print a large image field
  - <u>The use of aspheres cannot be avoided</u>

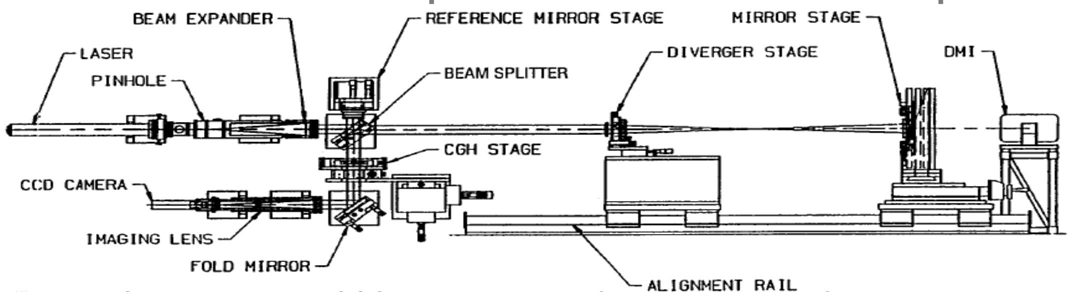
- Example of early three-mirror imaging system design:
  - 1 x 25 mm ring-field, 0.1 NA, 0.1 μm resolution
  - M2 is a 92 mm dia on-axis convex asphere with 1.5 μm max asp departure



Ref: J.H. Bruning, et al., “X-ray projectiion lithography camera,” US Patent 5,220,590, June 15, 1993

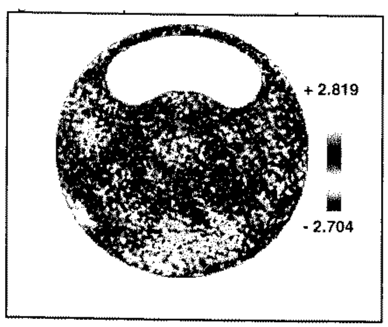
Fabrication & Testing of Aspheres

- Tinsley fabricated COSTAR optics for the Hubble Space Telescope

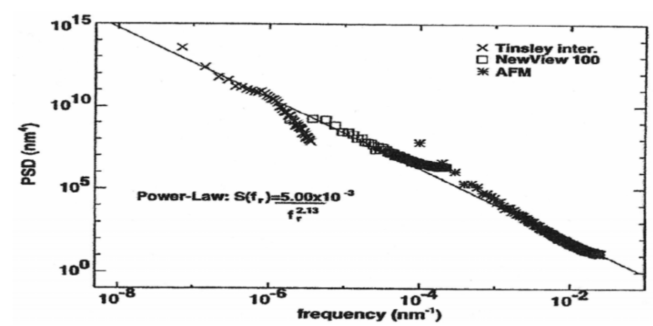


Ref: L. Feinberg, M. Wilson, '"Hubble Space Telescope COSTAR asphere verification with a modified computer-generated hologram interferometer, Appl. Opt.32, 1788 (1993).

- NIST ATP Program: fabrication and testing of M2 asphere
  - Four leading optics manufacturers fabricated copies of the M2 asphere using conventional artisan polishing, ion milling, and computer-controlled polishing
  - Metrology methods included phase-measuring interferometry with a a refractive null, PMI with a computer-generated hologram null and a custom non-null Fizeau interferometer



Interferogram of the best M2 mirror (0.6 nm RMS error)

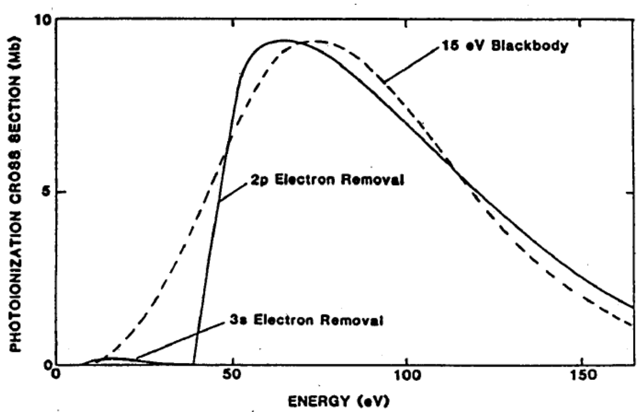


PSD for the convex aspheric M2 substrate

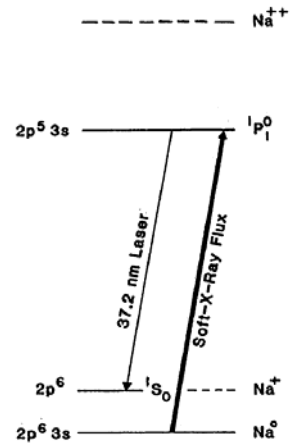
Ref: D.A. Tichenor, et al., "Progress in the development of EUV imaging systems," OSA TOPS on Extreme Ultraviolet Lithography, 1996
Ref: D.R. Gaines, et al., "Surface characterization of optics for EUV Lithography," OSA TOPS on Extreme Ultraviolet Lithography, 1996

EUV Applications of Laser Plasma Sources

- Short wavelength laser development

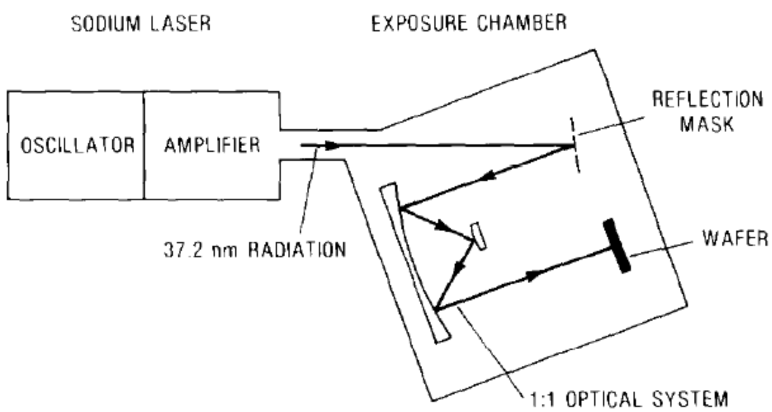


Energy level diagram for Sodium



Ref: Silfvast & Wood, "Photoionization lasers pumped by broadband soft-x-ray flux from laser-produced plasmas," J. Opt. Soc. Am B 4, 609 (1987)

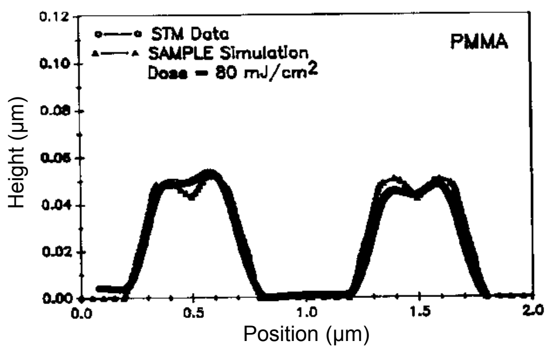
- Proposal for tenth micron lithography with a 37.2 nm sodium laser



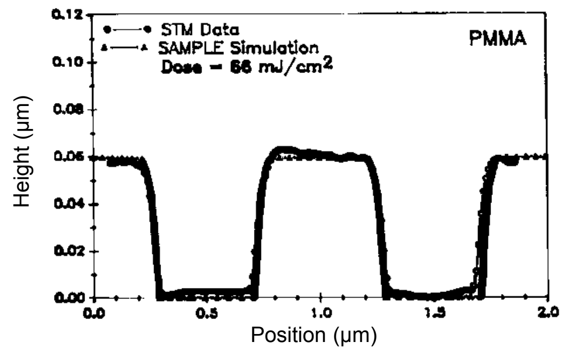
Ref: Silfvast & Wood, "Tenth micron lithography with a 10 Hz 37.2 nm sodium laser," Microelectronic Engineering 8, 3 (1988).

EUV Applications of Synchrotron Sources

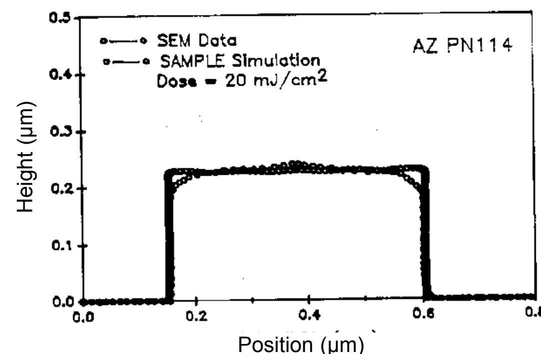
- Early EUV imaging demonstrations



Iridium-coated SC optics at 37.5 nm



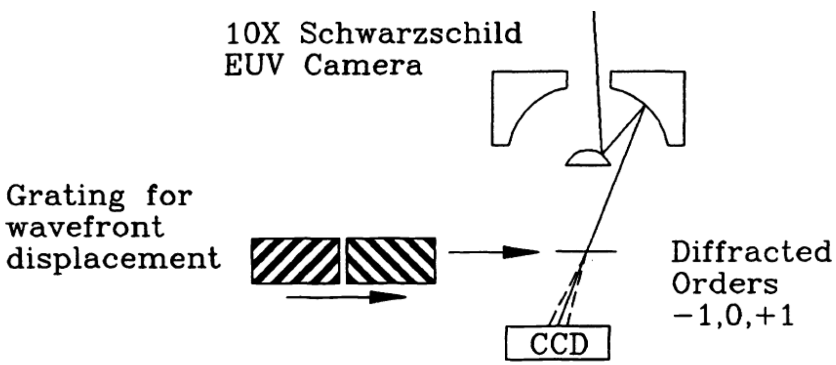
Mo/Si-coated SC optics at 13.9 nm



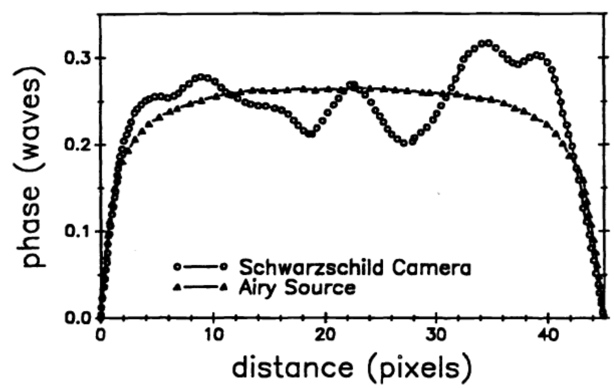
Ru/B4C-coated SC optics at 6.8 nm

Ref: O.R. Wood, et al., "Wavelength dependence of the resist sidewall angle in EUV lithography," J. Vac. Soc. Technol. B 12, 3841 (1994).

- Interferometric testing of reflective imaging system



Experimental arrangement for lateral-shearing interferometry



Comparison of measured wfe with profile from circular aperture

Ref: A.A. MacDowell, et al., "Interferometric testing of EUV lithography cameras," Proc. SPIE 3152, 202 (1997).

The Present: Current Critical Issues

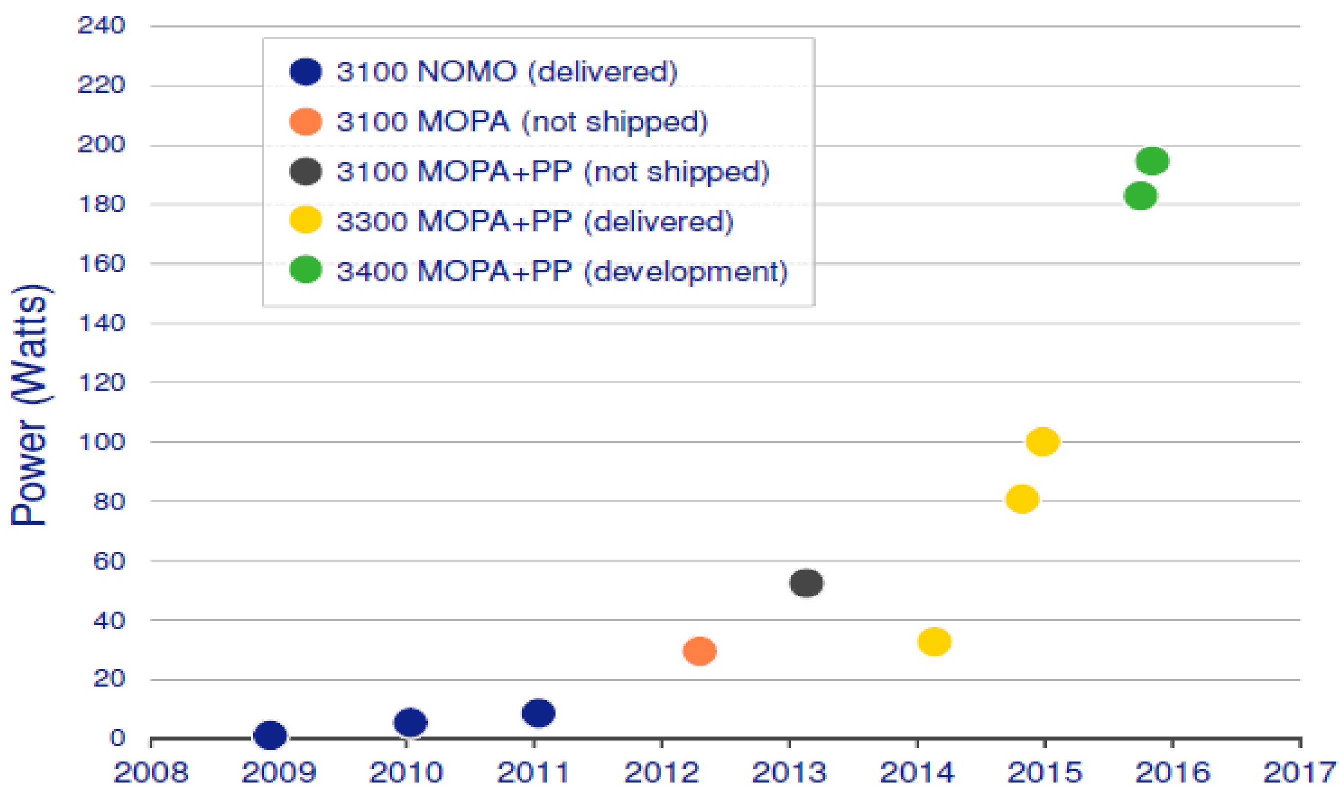
- EUV Critical Issues as identified & ranked by International Symposium on EUV Lithography Steering Committees

2013 / 22 hp	2014 / 16 hp	2015 / 16 hp
1. Long-term reliable source operation with a. 125 W at IF in 2014 b. 250 W in 2015	1. Reliable source operation with > 75% availability – 125 W at IF in 1H / 2015 (at customer)) – 250 W at IF in 1H / 2016 (HVM entry at customer)	1. Reliable source operation with > 85% availability – Expectation of 1500 average wafers per day in 2016
2. Mask yield & defect inspection/review infrastructure	2. Resist resolution, sensitivity & LER met simultaneously – Progress insufficient to meet 2015 introduction target	2. Resist resolution, sensitivity & LER met simultaneously – Increased focus needed on manufacturing performrmance (defectivity, pattern collapse,…)
4. Keeping mask defect free – Availability of pellicle mtg HVM req't – Minimize defect adders during use	3. Mask yield & defect inspection/review infrastructure – Enable high yield defect free mask blank supply chain	3. Mask yield & defect inspection/review infrastructure – Sustainability of mask tool supply chain remains critical
4. Resist resolution, sensitivity & LER met simultaneously	3. Keeping mask defect free – Availability of pellicle mtg HVM req't : need integrated industry strategy for solution – Minimize defect adders during use	4. Keeping mask defect free (by EUV pellicle) – Pellicle demonstration in the field (on NXE3300)

EUV Source Power Progress

- 7 nm node HVM Source Power Requirement: 250 W at IF
  (~1000 wafers per day @ Product Dose)

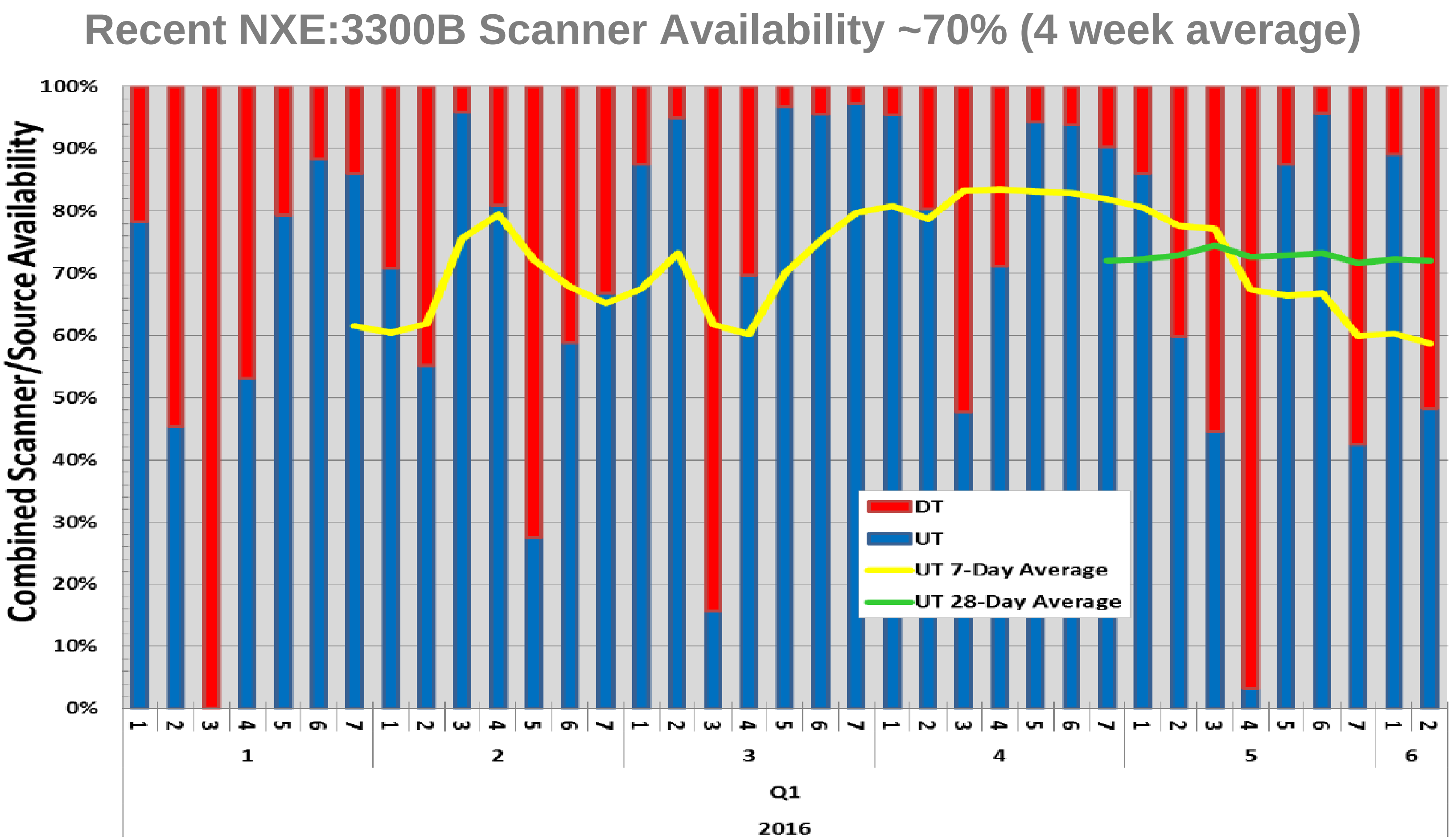
Progress in LPP EUV source power at IF since 2009



Ref: A. Pirati, “EUV lithography performance for manufacturing: status and outlook,” SPIE Advanced Lithography, 9776-10, San Jose, CA, 23 Feb. 2106.

NXE Source/Scanner Availability

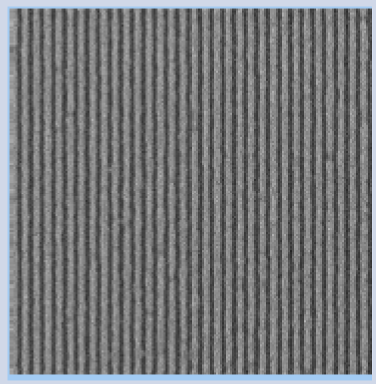
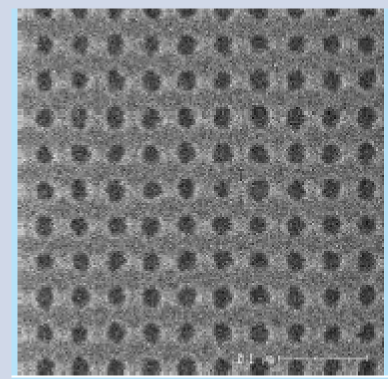
- 7 nm node HVM Scanner Availability Requirement: >95%



Ref: B. Turkot, "EUV progress towards HVM readiness," SPIE Advanced Lithography, 9776-1, San Jose, CA, 22 Feb. 2106.

Resist Resolution, Sensitivity & LWR

- 7 nm node HVM Resist Resolution Requirements:
  - 18 nm HP Lines & Spaces
  - 20 nm HP Dense Contact Holes

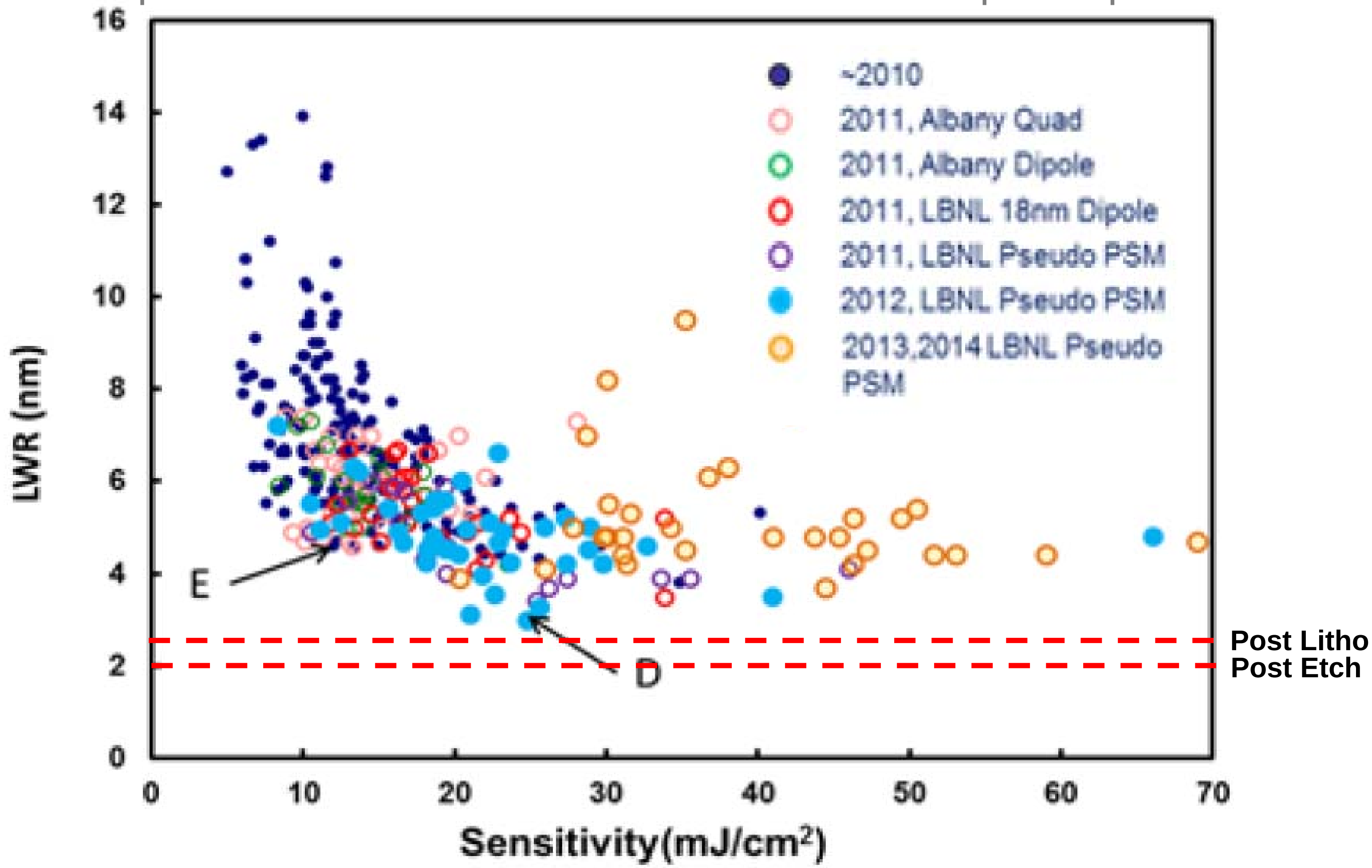
	13 nm Dense L/S	**20 nm Contact Holes**
SEM image @ BE/BF		
Dose	~40 mJ/cm^2	29.5 mJ/cm^2
LWR/LCDU	4.5 nm	3.9 nm

Ref: A. Pirati, “EUV lithography performance for manufacturing: status and outlook,” SPIE Advanced Lithography, 9776-10, San Jose, CA, 23 Feb. 2106.

Resist LWR/Sensitivity Tradeoff

- 7 nm node HVM Resist LWR Requirement: ~2.0 nm Post Etch

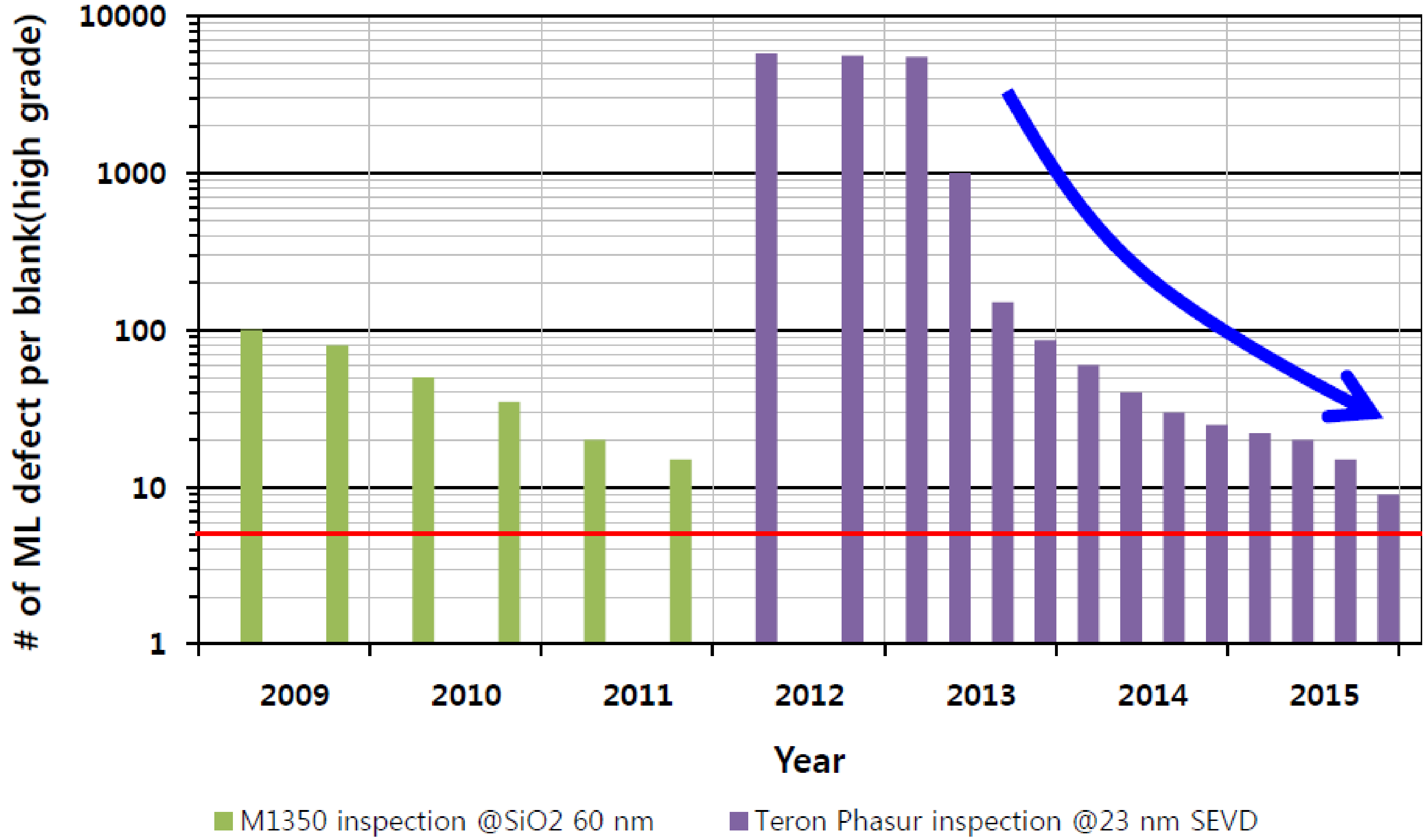
Experimental tradeoff between LWR and resist photospeed



Ref: M Neisser,et al., "Novel resist approaches to enable EUV lithography in high volume manufacturing extensions to future nodes," Proc. SPIE 9422, 9422OL (2015)

Mask Blank Defectivity Trend

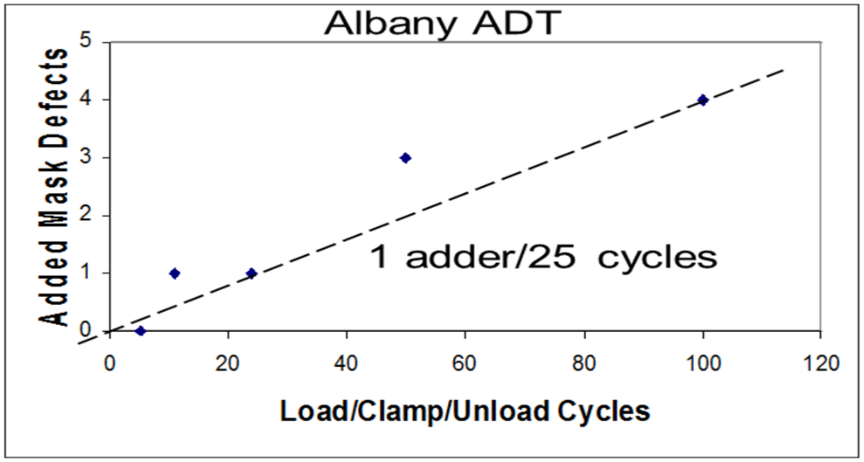
- 7 nm node HVM Mask Blank Defectivity Requirements:
  - Large defects (> 60 nm SiO_2): zero
  - Total defects (> 23 nm SEVD): single digits



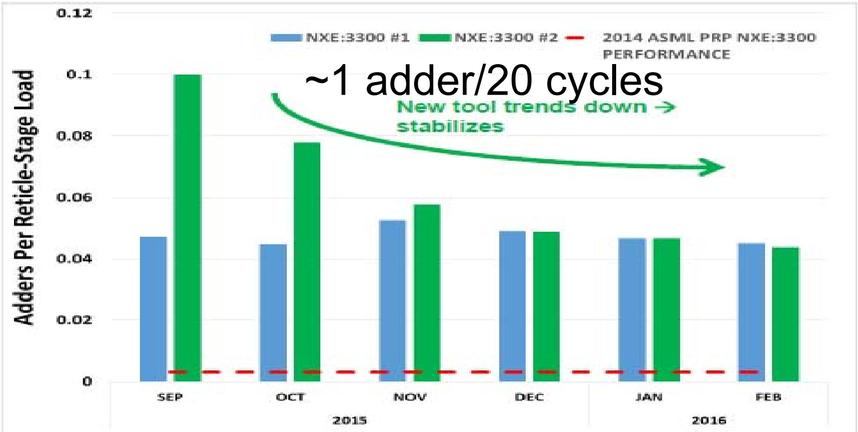
Ref: S.-S. Kim, “EUV lithography progress and Perspective,” SPIE Advanced Lithography,” 9776-2, San Jose, CA, 22 Feb. 2016.

Mask Pellicle Status

- Frontside Particle Adder Data



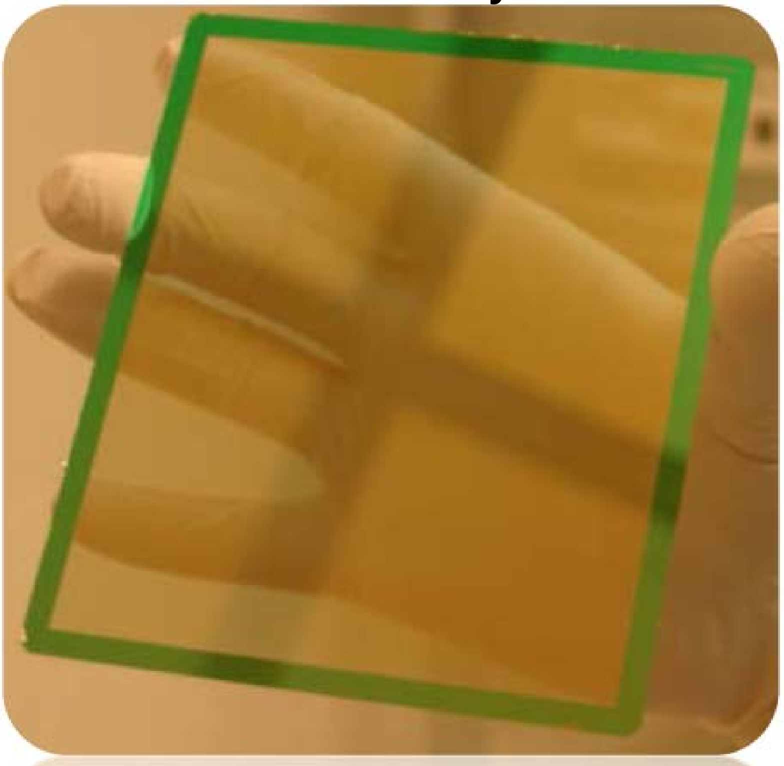
Ref: O.R. Wood, et al., “Impact of frequent particle removal on EUV mask lifetime,” International EUVL Symposium, Kobe, Japan, 19 Oct. 2010.



Ref: B. Turkot, “EUV progress towards HVM readiness,” SPIE Advanced Lithography, San Jose, CA 22 Feb 2016

- Scanner defectivity is decreasing but not to zero
- Pellicle will be required!

Photo of Full-Field Poly-Si Pellicle



T = 85% (single pass)

Ref: C. Zoldesi, “EUV pellicles is ready for next step: industrialization,” SPIE Advanced Lithography, San Jose, CA, 26 Feb 2015

The Future: EUV Extendibility

- According to the Rayleigh equation for resolution, $CD = k_1 \lambda/NA$, EUV lithography can be extended by using a higher numerical aperture (NA) imaging system, further decreasing the EUV exposure wavelength (λ) or by employing one or more resolution enhancements techniques (RETs) that would allow operation at a smaller value of k_1.

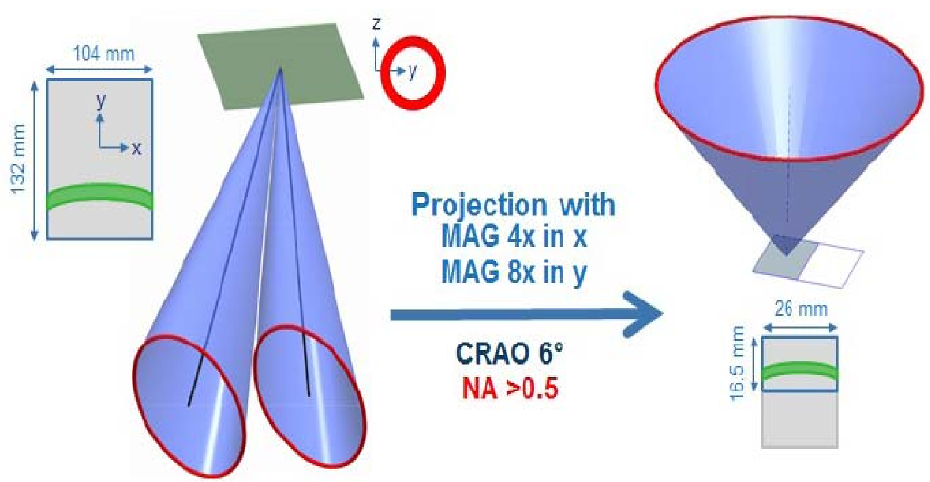
Resolution limits at 13.5 nm wavelength versus numerical aperture

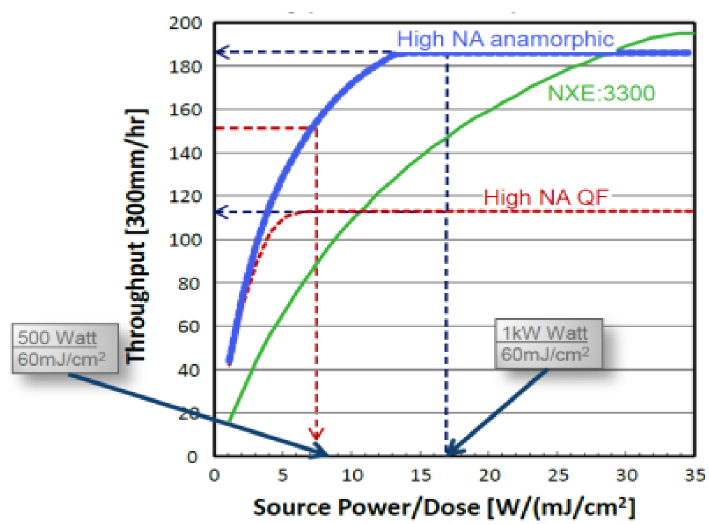
NA	0.33	0.40	0.45	0.50	0.55	0.60
Resolution @ k_1=0.3 single exposure / nm	12.3	10.1	9.0	8.1	7.4	6.8

- Because extensive development work will be required for all of these lithography extensions options, insertion of EUV lithography in production with a full suite of RETs is unlikely before 2017-18, EUV lithography with imaging system NAs higher than 0.33 is unlikely before 2020-22, and EUV lithography at wavelengths shorter than 13.5 nm is unlikely before 2024-26.

Extension to Higher Numerical Aperture (NA)

- Anamorphic projection optics, with 4x magnification ratio in the x-direction and 8x magnification ratio in the y-direction, will reduce the angular spread at the mask mainly in the y-direction, and will support a 26 mm x 16.5 mm image field at the wafer, retain a CRAO = 6°, and still allow a 6” mask to be used.



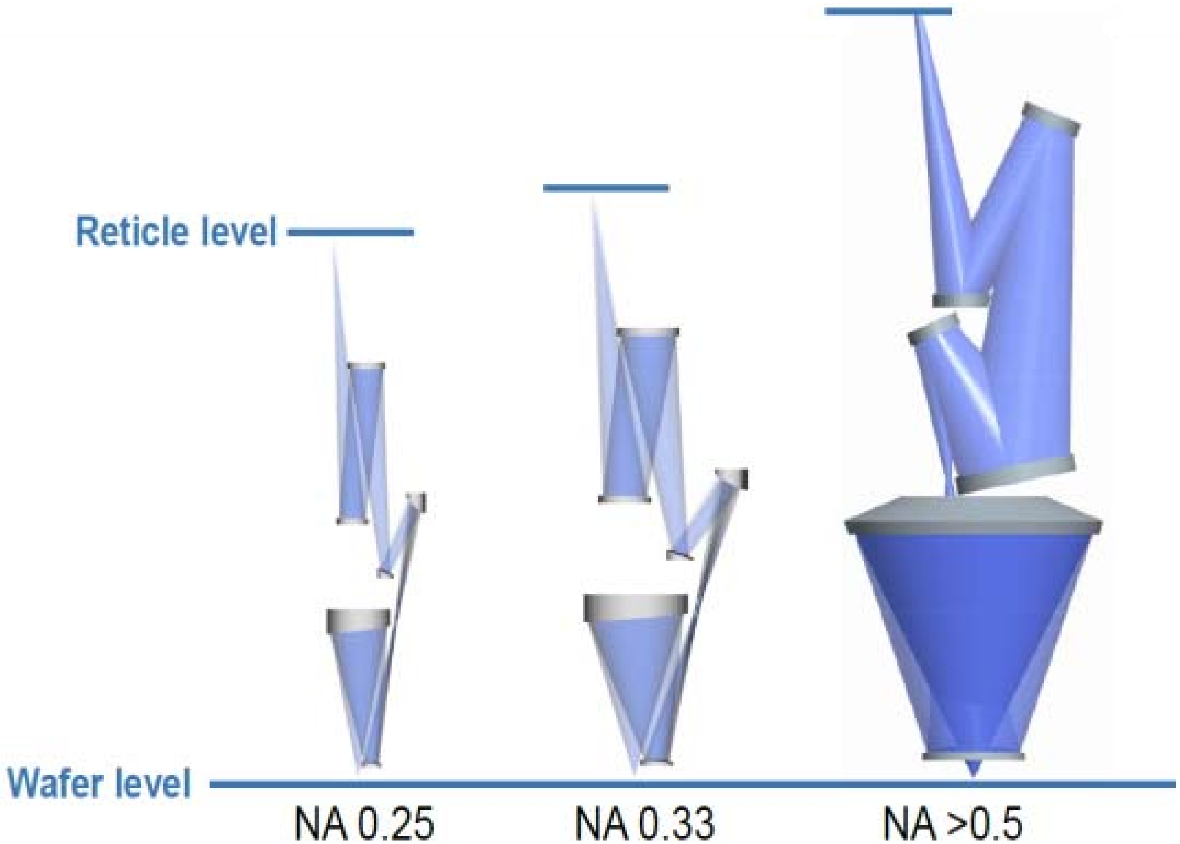


- Throughput versus source power/dose for anamorphic 4x/8x projection optics at NA > 0.5, quarter-field projection optics at NA > 0.5, and 0.33 NA projection optics in an NXE:3300 scanner.

Ref: B. Kneer, et al., “EUV lithographic anamorphic system optics for sub-9-nm resolution,” Proc. SPIE 9422, 94221G (2015).

Evolution of EUV Projection Optics

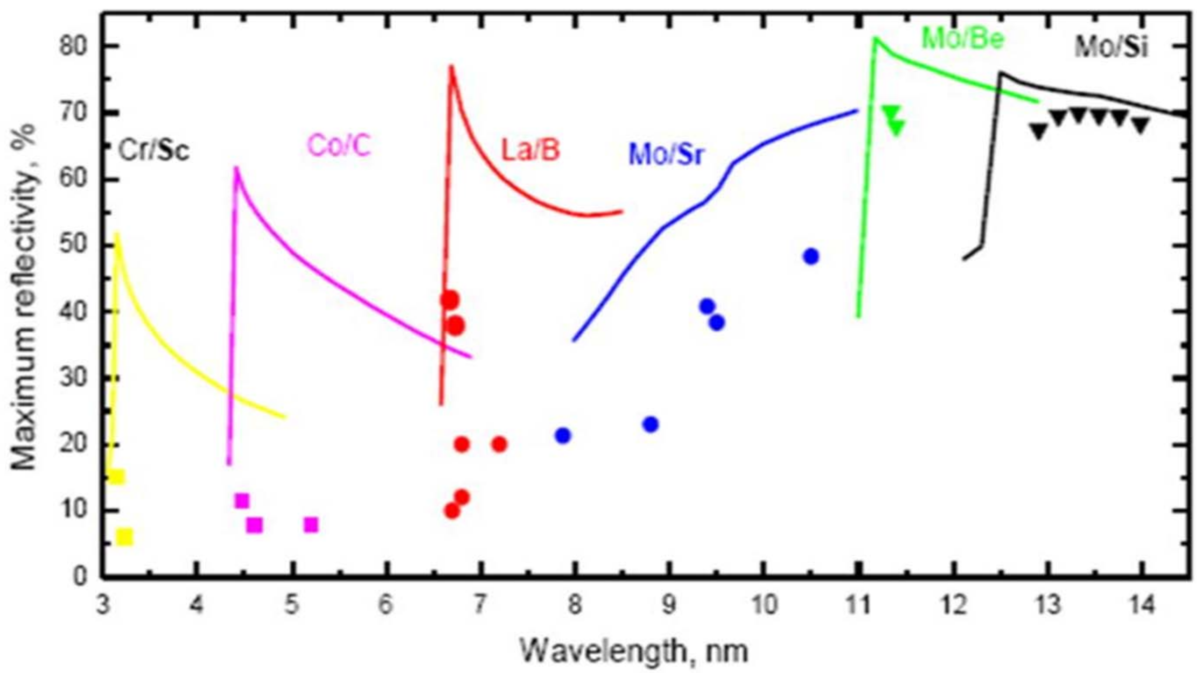
- Extension to higher NA projection optics will require larger mirrors with improved surface accuracy and more extreme aspheric departures and may require a small central obscuration.



Ref: B. Kneer, et al., "EUV lithographic anamorphic system optics for sub-9-nm resolution," Proc. SPIE 9422, 94221G (2015).

Extension to Shorter Wavelength (λ)

- Viable candidates for a new EUV exposure wavelength are available at only a few discrete EUV wavelengths near K-, L- and M-shell absorption edges which occur at 12.5 nm (Si), 11.4 nm (Be), 6.7 nm (B), 4.4 nm (C) and 3.1 nm (Sc).
- Maximum reflectivity of the most efficient multilayer coatings in the 3 to 14-nm wavelength range:



Ref: S. Yulin, et al., "EUV multilayer coatings: potentials and limits," 2012 EUV Litho Workshop, Maui, HI, June 7, 2012.

System Throughput at Shorter Wavelength

- Calculated throughput of 11 mirror ML-coated reflective imaging systems in the 3 to 14 nm wavelength region:

λ, Wavelength (nm)	13.5	9.5	6.8	4.4	3.1
Material Pair	Mo/Si	Ru/Y	La/B4C	Co/C	Cr/Sc
R, Reflectivity	0.74	0.59	0.74	0.525	0.59
Δλ , Bandwidth (nm)	0.6307	0.1976	0.0623	0.0240	0.0123
Δλ/λ (1 mirror) (%)	4.6721	2.0801	0.9397	0.5444	0.3941
R^{11} (11 mirrors)	0.0364	0.0030	0.0364	0.0008	0.0030
Δλ/λ (11 mirrors) (%)	2.311	0.9032	0.3403	0.2045	0.0129
FOM (11 mirrors)	1.000	0.032	0.147	0.002	<0.001

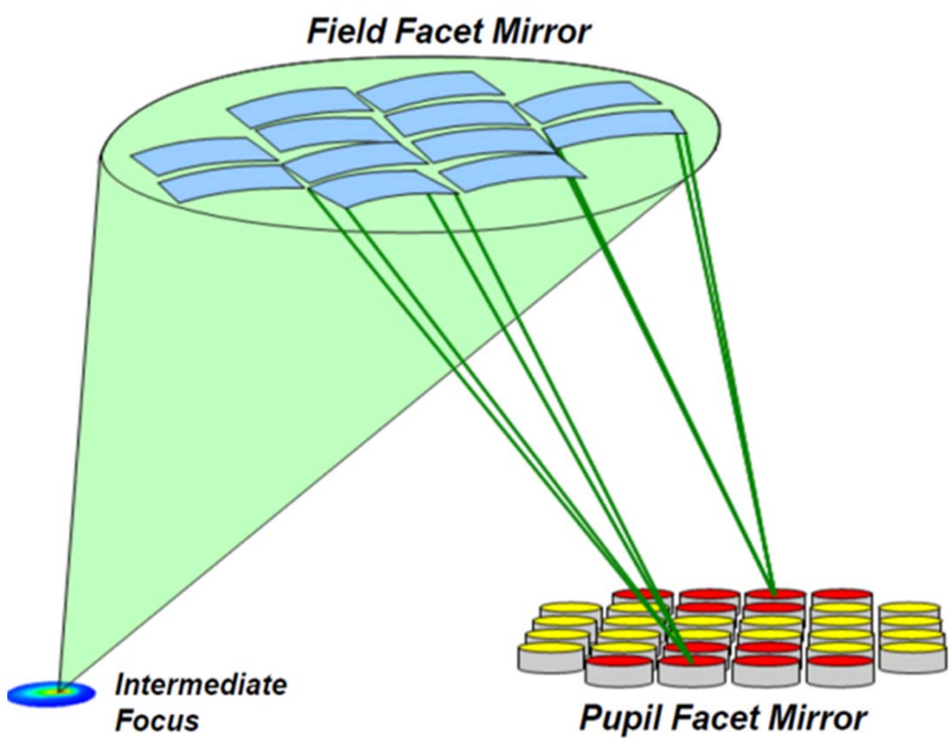
- From throughput considerations alone, the most viable new operational wavelength for EUV lithography would be ~6.8 nm
- An 11 mirror La/B ML-coated system at 6.8 nm wavelength will have a throughput ~7x lower than an 11 mirror Mo/Si ML-coated system at 13.5 nm.

Ref: Y. Platonov, et al., "Multilayers for present and future generations of EUVL," 2011 International Workshop on EUV and Soft-x-Ray Sources, Dublin, Ireland, 7-10 Nov 2011.

Extension via Resolution Enhancement

- Newly developed pattern placement aware SMO and Flex Pupil illuminator can extend single exposure EUV lithography at NA = 0.33 to k_1 = 0.4 and below.

Sketch of flexible loss-less illuminator

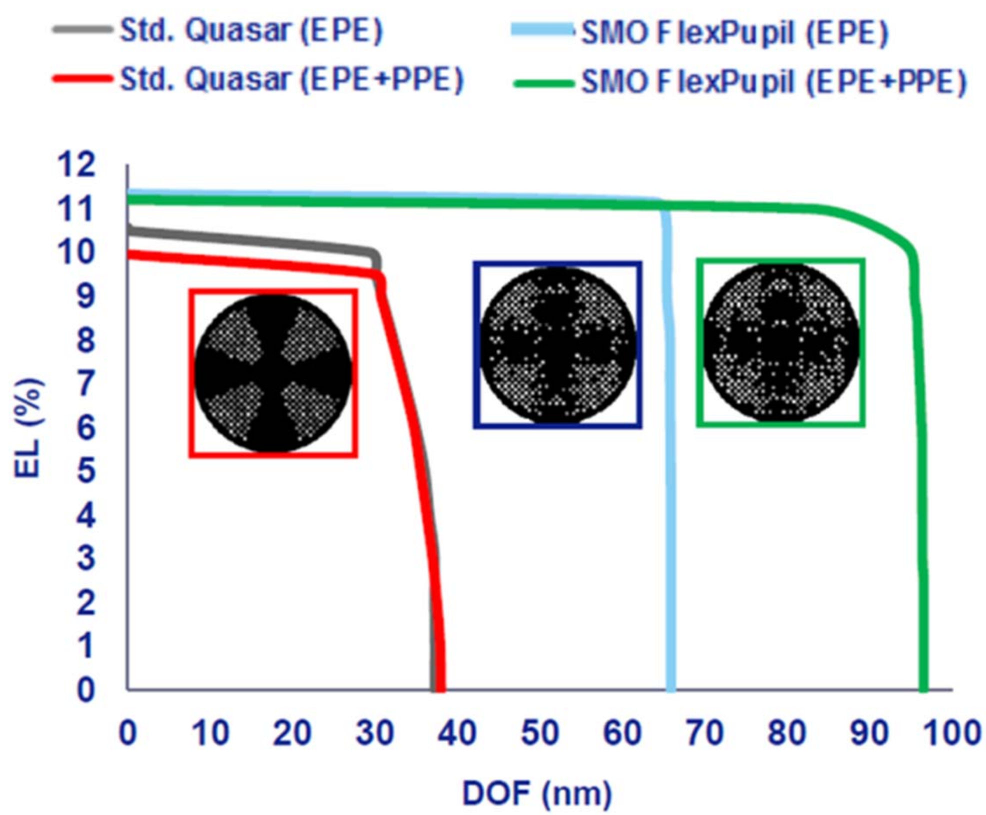


Example pupil fills

Ref: S. Migura, et al., "Anamorphic high-NA EUV lithography optics," Proc. SPIE 9661, 96610T (2015).

Printing at Smaller k_1 Values

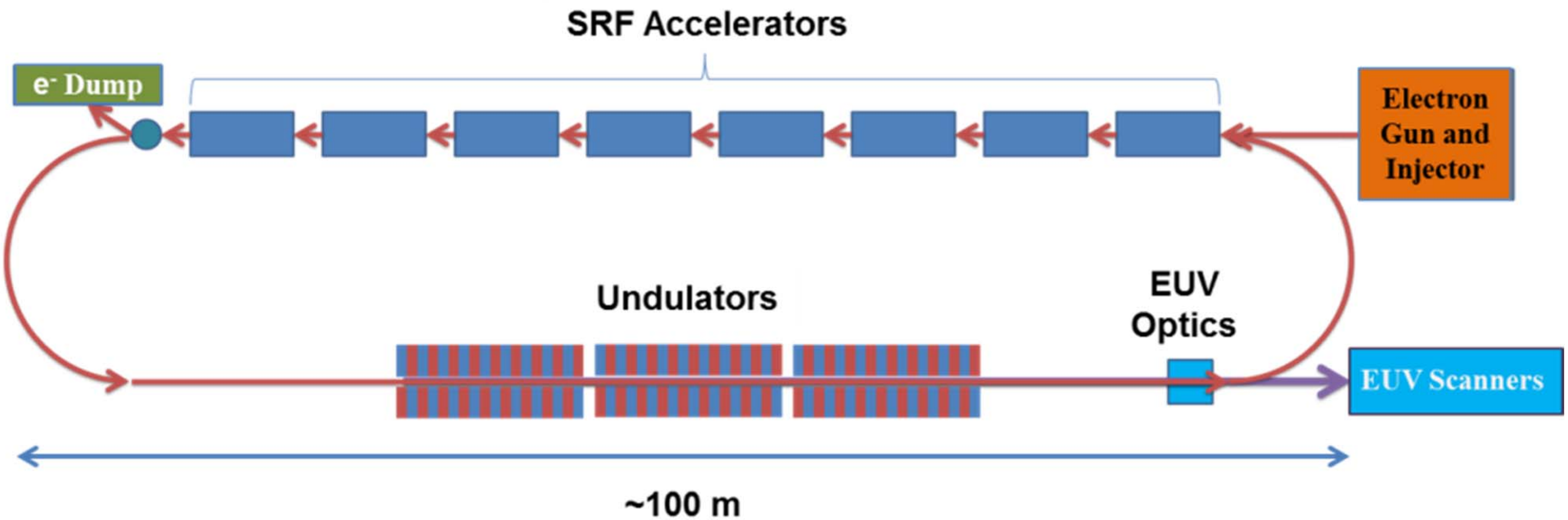
- Exposure-latitude versus depth-of-focus for the printing of a 7 nm logic metal level using a 0.33 NA NXE scanner with a standard Quasar pupil and with 2 different free-form pupils modeled using pattern-placement-aware source-mask-optimization (SMO) software



Ref: S. Hsu, et al., "EUV resolution enhancement techniques (RETs) for k_1 0.4 and below," Proc. SPIE 9422, 94221I (2015).

More Powerful & Efficient EUV Source

- Key components of a free-electron laser (FEL) EUV source



Item	Target	Motivation/Implication
Power	>20 kW	Ten 1kW scanners (50% transport loss)
Availability	>99%	Some redundant system hardware required
CoO	~$250M CapEx, ~$20M OpEx	2x better than CoO for 10 LPP sources
General Configuration	Energy Recovery LINAC @ ~2K SASE Output	Maximize efficiency & minimize cost
Timing	TBD	To intercept high-NA EUV scanner insertion

Ref: E. Hosler et al., "Considerations for a free-electron-laser based extreme-ultraviolet lithography program," Proc. SPIE 9422, 94220D (2015).

Summary

- Advantages of EUV lithography are wide process windows, high throughput (once source power and availability specs are met), and extendibility.
- Disadvantages of EUV lithography are higher costs & complexity (than ArFi lithography) and infrastructure immaturity.
- Source availability and source power at IF are not yet at the levels needed for SE EUV CoO comparable to multiple patterning 193i CoO when used at the 7LP node.
- Resist resolution and sensitivity are close to spec; resist LER is not. LER reduction via post processing will be required.
- Mask blank defectivity and yield are continuing to improve:
  - Defect repair, defect avoidance, and defect compensation techniques are still needed for finite mask yield.
  - Actinic tool are needed for blank inspection, pattern mask inspection and defect repair verification.
- After more than 30 years of development, topics that still need additional work include: EUV source and scanner availability, pellicle transmission, and resist LWR reduction.

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- Intel: Britt Turkot
- Kempur Microelectronics: Mark Neisser
- LBNL: Alastair MacDowell
- Rigaku: Yuriy Platonov
- Samsung: Seong-sue Kim
- Tropel: John Bruning
- Univ. of Central Florida: William Silfvast
- Univ. of Hyogo: Hiroo Kinoshita