EUVL: Challenges to Manufacturing Insertion

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International Workshop on EUV Lithography
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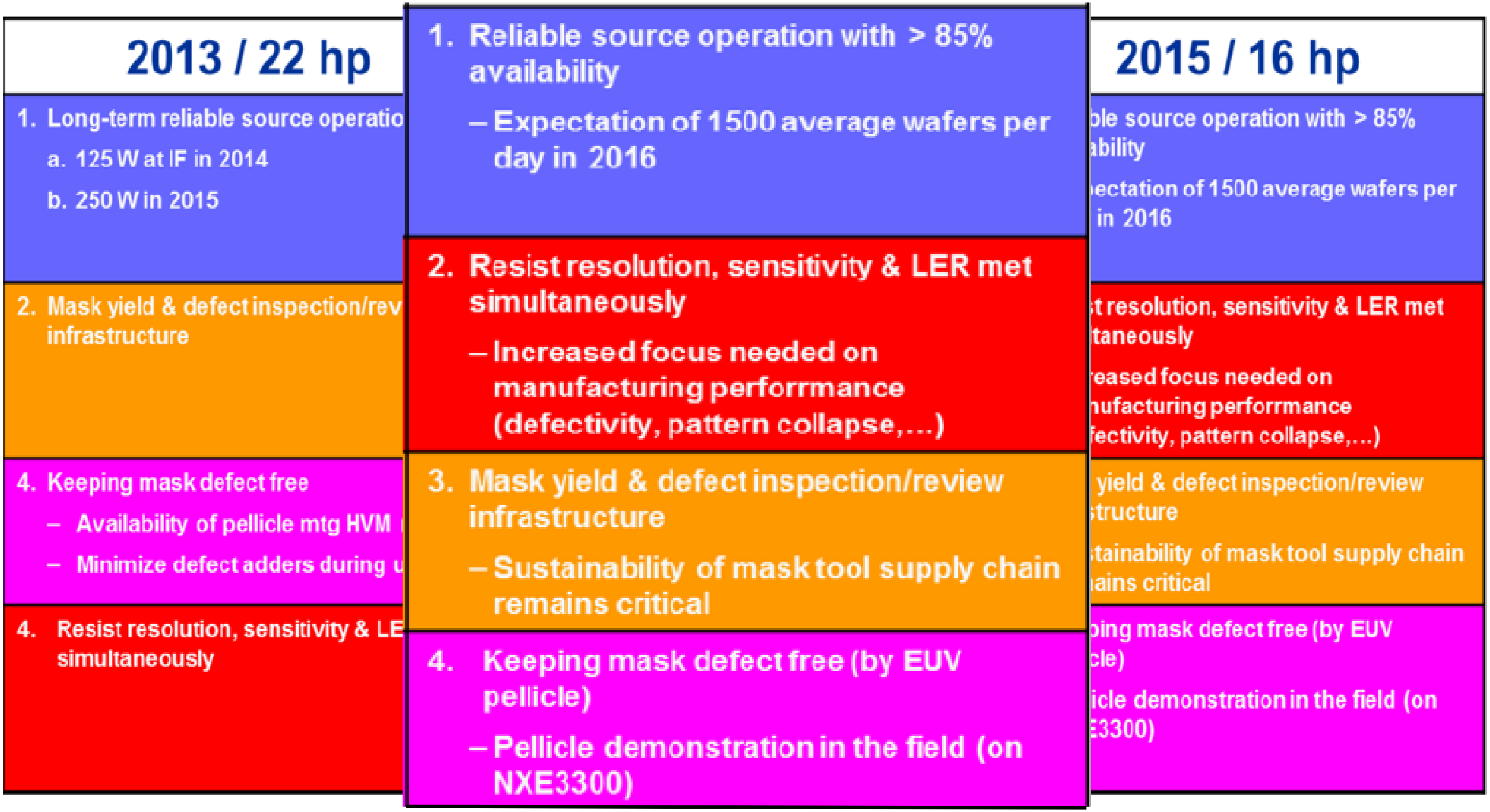
EUV Critical Issues List

- EUV Critical Issues, as identified & ranked at International Symposia on EUV Lithography, were:



2013 / 22 hp

1. Long-term reliable source operatio
   a. 125 W at IF in 2014
   b. 250 W in 2015
2. Mask yield & defect inspection/rev infrastructure
4. Keeping mask defect free
   – Availability of pellicle mtg HVM (
   – Minimize defect adders during u
4. Resist resolution, sensitivity & LE simultaneously

1. Reliable source operation with > 85% availability
   – Expectation of 1500 average wafers per day in 2016
2. Resist resolution, sensitivity & LER met simultaneously
   – Increased focus needed on manufacturing performmance (defectivity, pattern collapse,...)
3. Mask yield & defect inspection/review infrastructure
   – Sustainability of mask tool supply chain remains critical
4. Keeping mask defect free (by EUV pellicle)
   – Pellicle demonstration in the field (on NXE3300)

2015 / 16 hp

ble source operation with > 85% ability
ectation of 1500 average wafers per in 2016
t resolution, sensitivity & LER met taneously
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yield & defect inspection/review structure
tainability of mask tool supply chain ains critical
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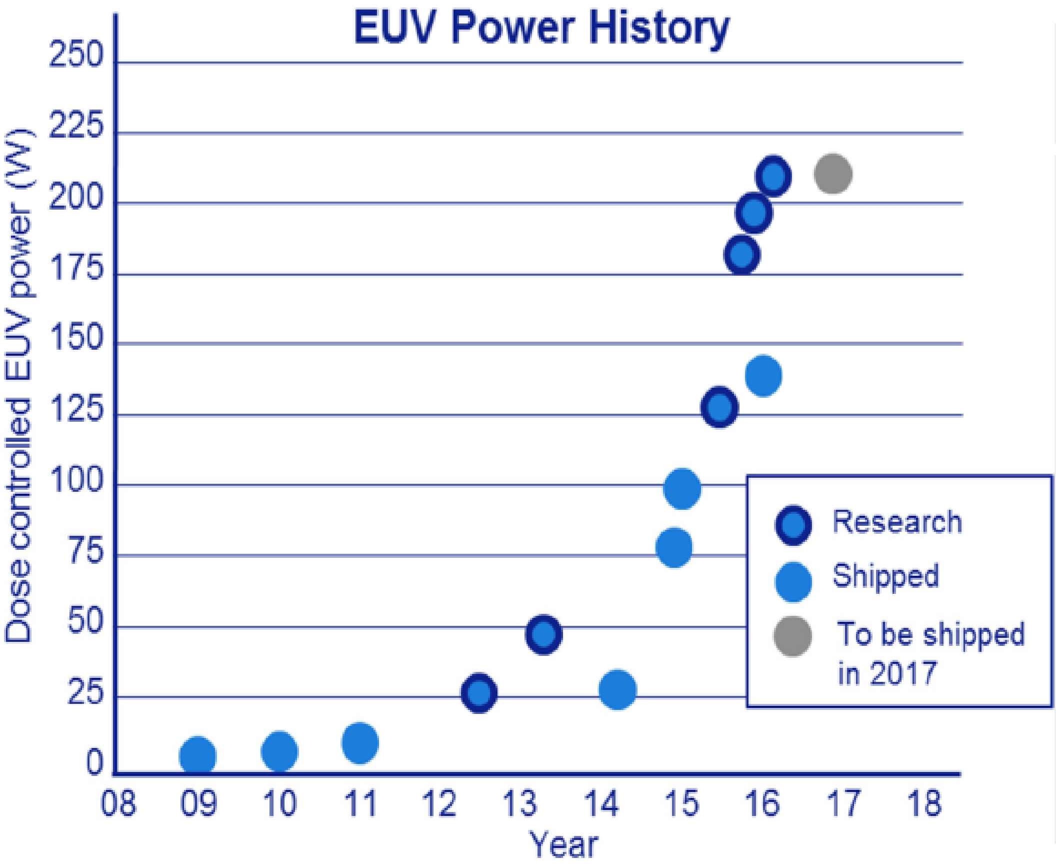
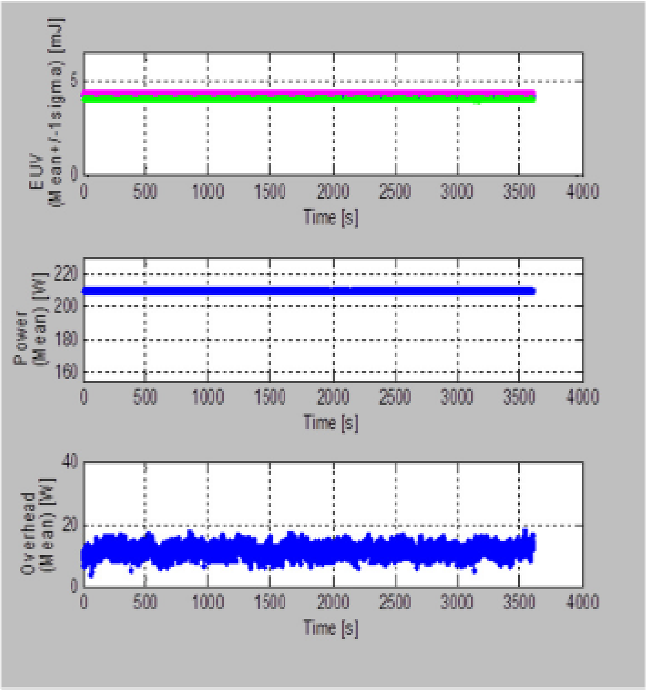
icle demonstration in the field (on E3300)

EUV Source Power Progress

- 7 nm node HVM Source Power Requirement: 205 W at IF (~1000 wafers per day/scanner @ Product Dose)



210W with dose in specifications obtained on development sources

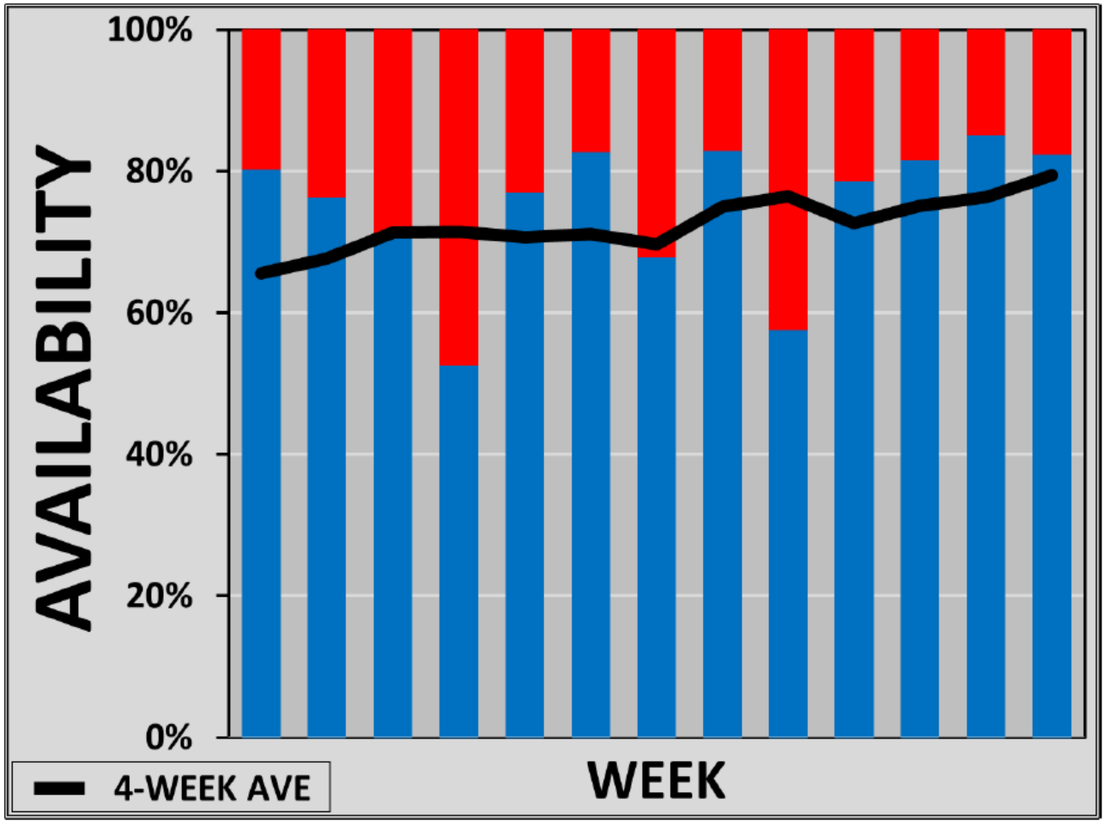


Ref: A. Schafgans, et al., “Scaling LPP EUV sources to meet high volume manufacturing requirements,” SPIE Advanced Lithography, 10143-51, San Jose, CA, 1 Mar 2017.

NXE Source/Scanner Availability

- 7 nm node Source/Scanner HVM Availability Requirement: >94%

NXE:3350 combined system availability

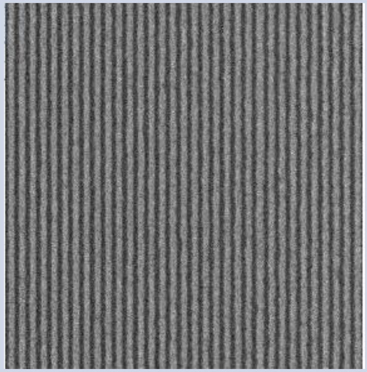
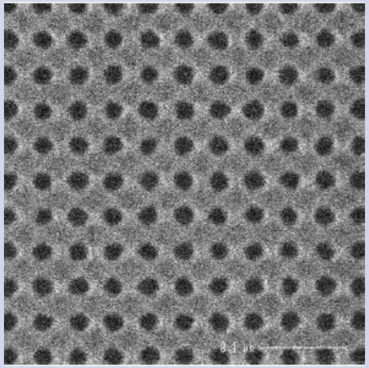


- Introduction of NXE:3350 reduced XLD
- NXE:3350 combined availability exceeding 75% by end of 2016
- System availability expectations continue to increase

Ref: B. Turkot, “EUV lithography readiness for high volume manufacturing,” SPIE Advanced Lithography, 10143-1 San Jose, CA, 27 Feb. 2107.

Resist Resolution & LWR/LCDU

- 7 nm node HVM Resist Resolution & LWR/LCDU Requirements:
  - 18 nm HP Lines & Spaces & 2.0 3σ LWR (post etch)
  - 20 nm HP Dense Contact Holes & 3.0 3σ LCDU

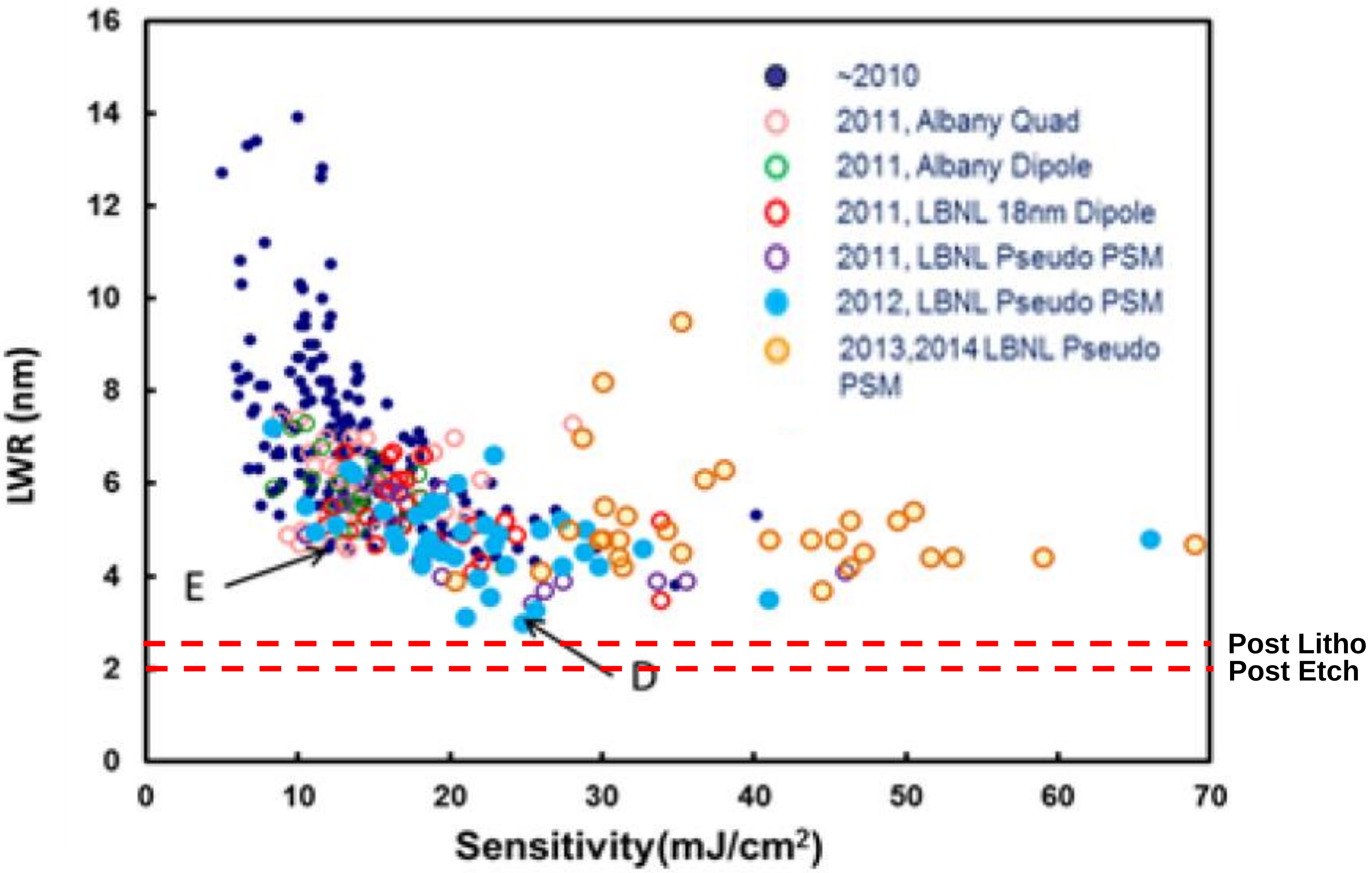
	13nm HP Dense L/S	20 nm HP Contacts
NXE:3400 Scanner Leaf-shape Dipole Y & Quasar illumination 20% Pupil Fill Ratio		
Dose	34 mJ/cm^2	NA
LWR/LCDU	3.8 nm (3σ)	3.0 nm (3σ)

Ref: O. Yildirim, et al., "Improvements in resist performance towards EUV HVM," SPIE Advanced Lithography, 10143-22, San Jose, CA, 1 Mar. 2017.

Ref: M. vd Kerkhof, "Enabling sub-10 nm node lithography: presenting the NXE:3400B scanner," SPIE Advanced Lithography, 10143-9, San Jose, CA, 28 Feb. 2017.

Resist LWR/Sensitivity Tradeoff

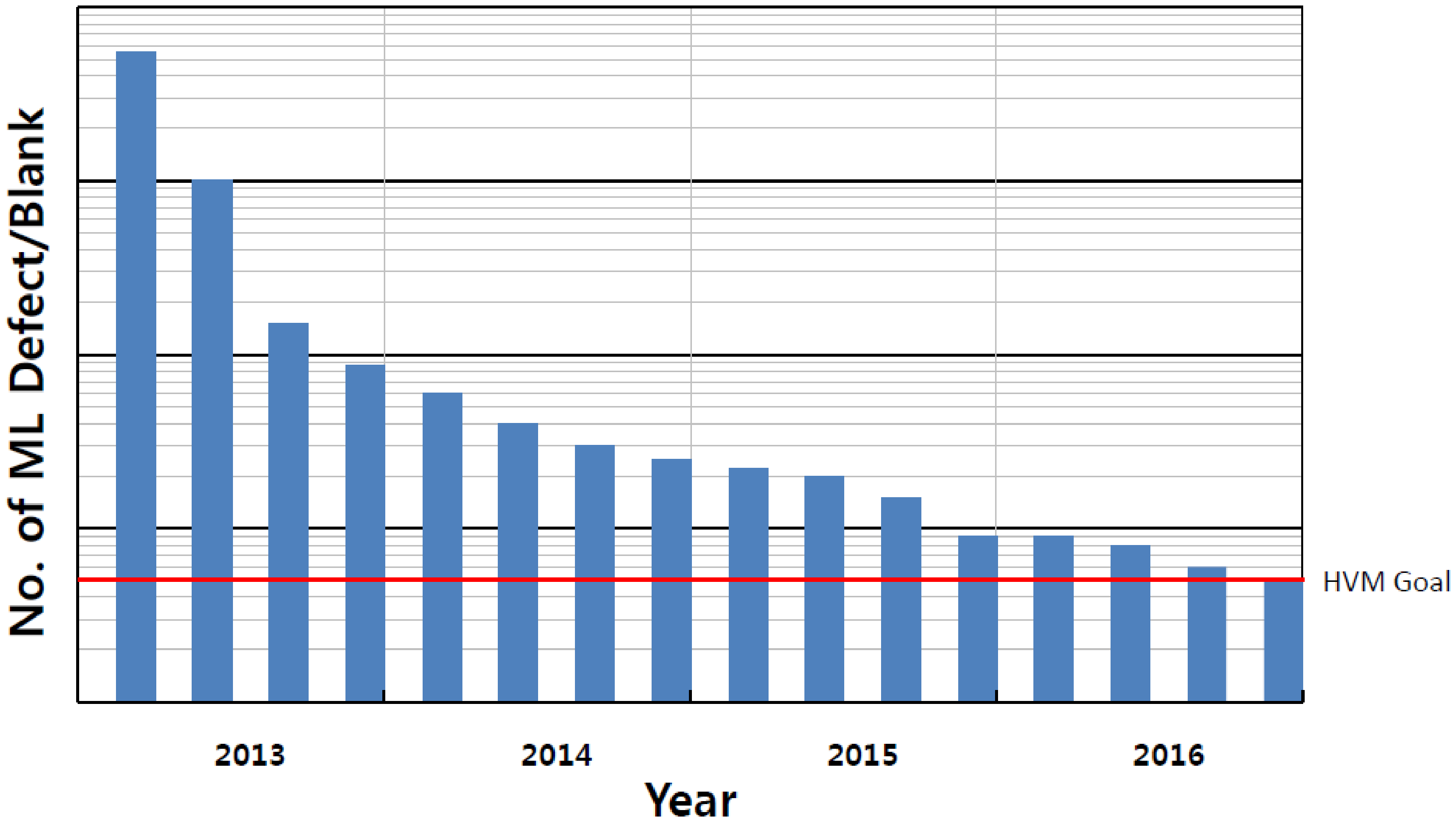
- 7 nm node HVM Resist LWR Requirement: ~2.0 nm Post Etch



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

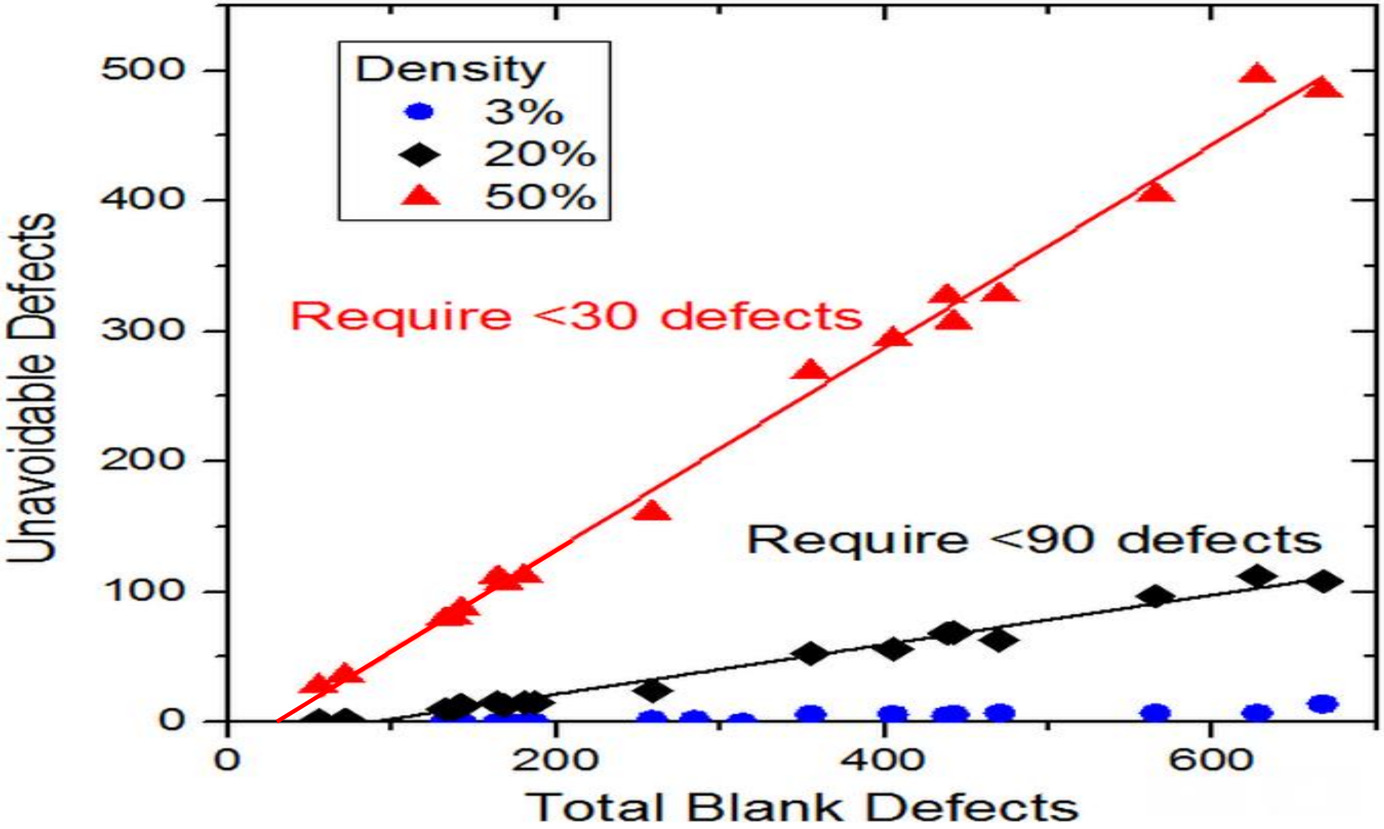
- 7 nm node HVM Mask Blank Defectivity Requirements:
  - Large defects (> 60 nm SiO_2): zero
  - Total defects (> 23 nm SEVD): low single digits



Ref: S.-S. Kim, “Progress in EUV lithography toward manufacturing,” SPIE Advanced Lithography,” 10143-2, San Jose, CA, 27 Feb. 2017.

Mask Blank Defect Mitigation

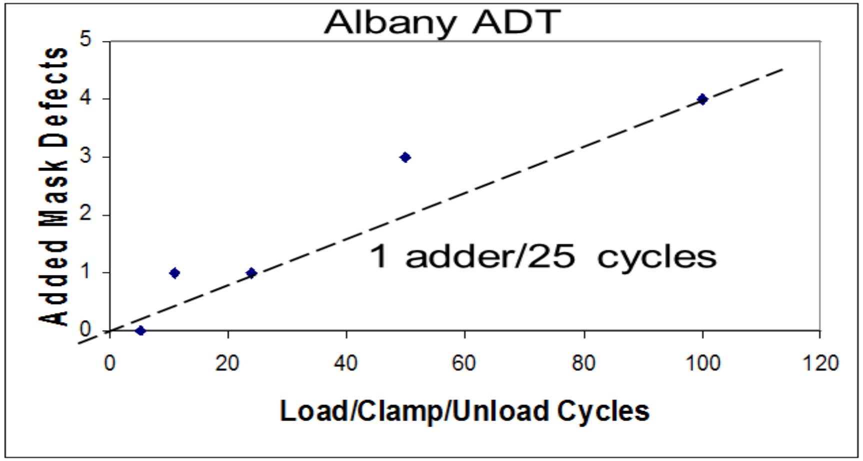
- 7 nm node HVM Mask Blank Defectivity Requirements:
  - Large defects (> 60 nm SiO_2): zero
  - Total defects (> 23 nm SEVD): number depends on mask pattern density



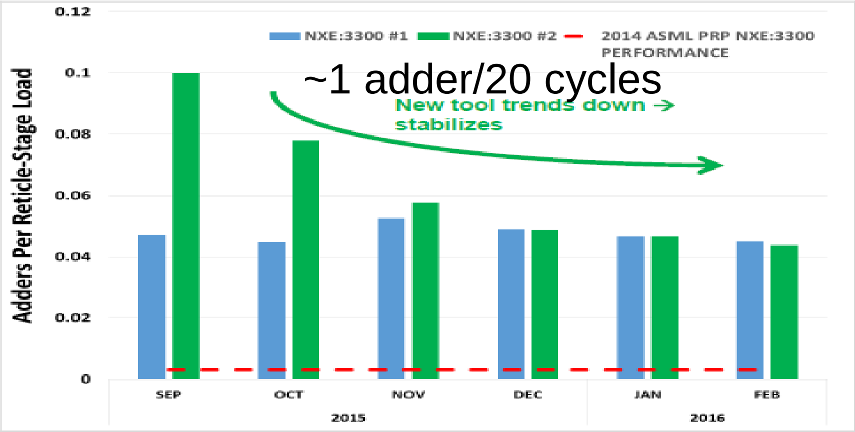
Ref: J. Qi, et al., "Defect avoidance for EUV photomask readiness at the 7 nm node," Photomask Japan 2016.

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.

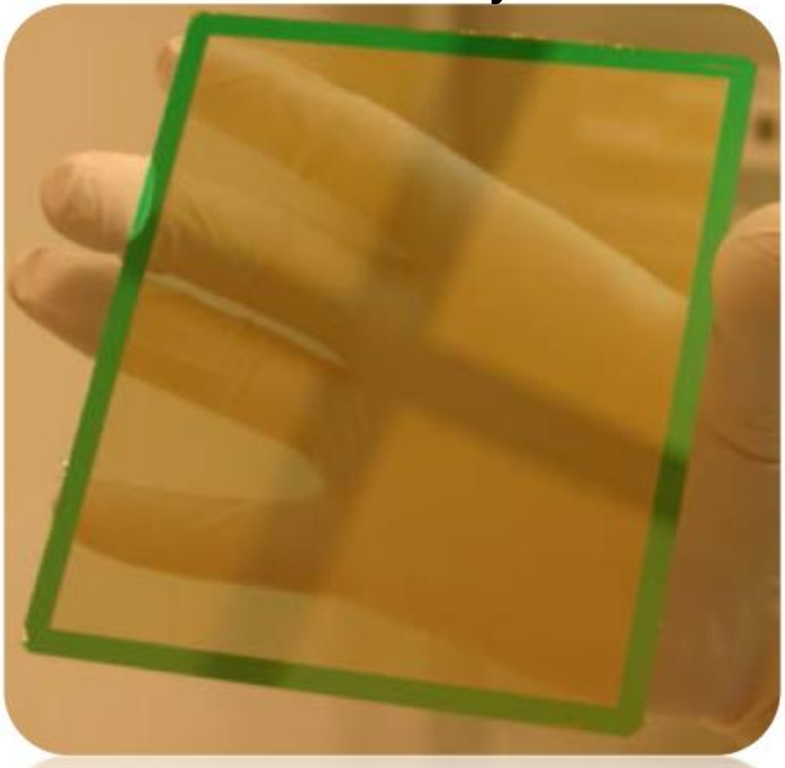


~1 adder/20 cycles

Ref: B. Turkot, "EUV progress towards HVM readiness," SPIE Advanced Lithography, San Jose, California, 22 Feb 2016

- Scanner particle adder rate is still too high for HVM without pellicle.
- 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

Current Status of EUV Critical Issues

- Exposure tools (light source, optics, focus & alignment systems)

Improvement still needed in power & reliability

- Resists

Adequate for 7 nm, but better LCDU required for future nodes

- Masks

Actinic inspection tools need to be brought to maturity and deployed

- Process control

EUV-specific issues have been identified and solutions are being implemented

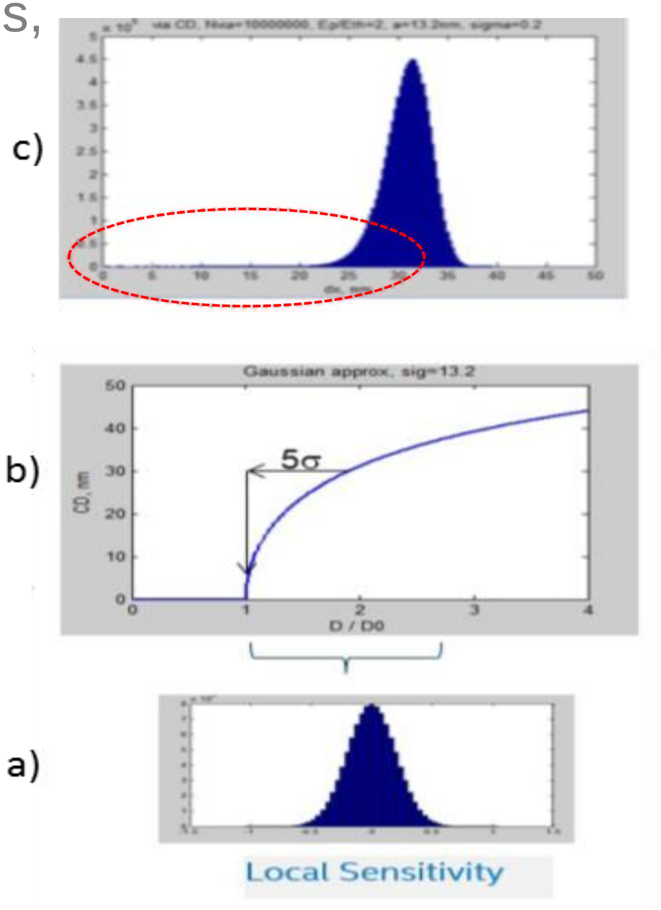
List of Remaining EUV Issues

- For the first time ever the EUV critical issues identified and ranked yearly at the International Symposia on EUV Lithography are not gating the insertion of EUV into manufacturing!

- The bulk of EUV R&D should now be focused on the three remaining EUV issues that need additional work:
  - Mitigating Stochastic Effects (near term)
  - Compensating for EUV Mask 3D Effects (near term – using SMO, slightly longer term – using advanced EUV mask stacks)
  - Imaging with High-NA EUV Projection Optics (longer term)

Impact of Stochastic Effects

- Higher LER & LCDU, increased local top loss, & reduced resolution
  - Micro bridges & line breaks (L/S patterning)
  - Missing or “kissing” contacts (C/H patterning)



Results from the numerical modelling of 10 million 30 nm CD vias, showing how vias with a normal distribution of CDs (a) will be mapped to a CD distribution with an asymmetric tail at low doses (c) using a transfer function based on a simple threshold model for the resist (b).

Ref: R. Bristol & M. Krysak, Proc. SPIE **10143** (2017) 101430Z

- Higher minimum k_1 value for EUV printing than for 193 nm printing
- Limit to benefit of higher image contrast available with high NA optics

Ref: T. Brunner, et al., Proc. SPIE **10143** (2017) 101431E

Mitigation of Stochastic Effects (1)

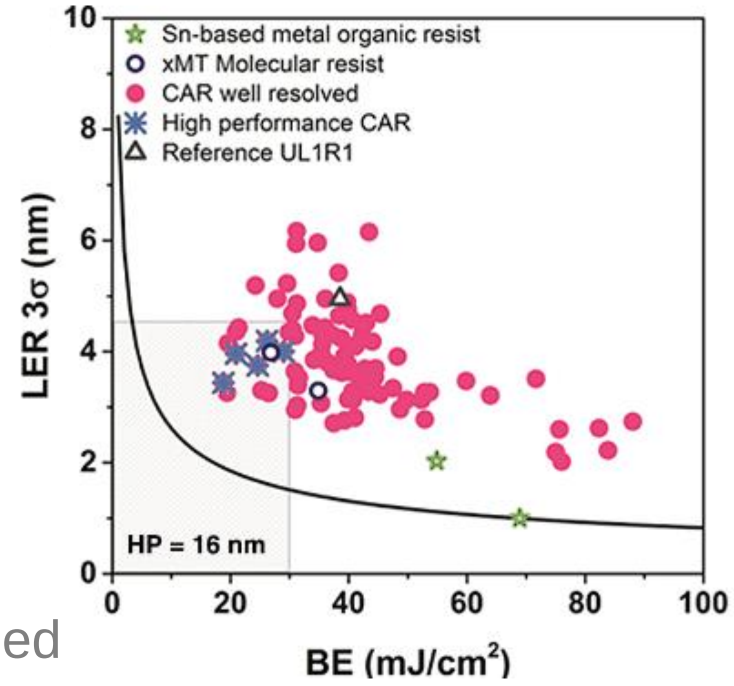
- Higher EUV dose & increased EUV absorption can reduce the photon shot noise contribution

Note: Availability of EUV sources with significantly higher power are too far out in time & higher EUV doses can lead to cross linking

LER versus best energy (BE) values from more than 95 exposures using 2 different CARs at 16 nm HP

Ref: E. Butrago, et al., J. Micro/Nanolith MEMS MOEMS **15** (2016) 033502

16-nm half-pitch lines/spaces



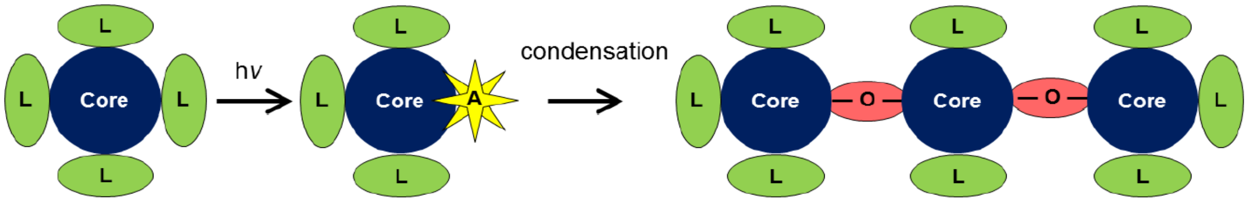
- New EUV resist materials are needed
  - Smaller reactive volume
  - More uniform distribution of components
  - Fewer (only one?) component(s)
  - Higher dissolution contrast

Mitigation of Stochastic Effects (2)

- New EUV resist materials would ideally have smaller reactive volumes & a more uniform distribution of components

Organo-metalic Resists

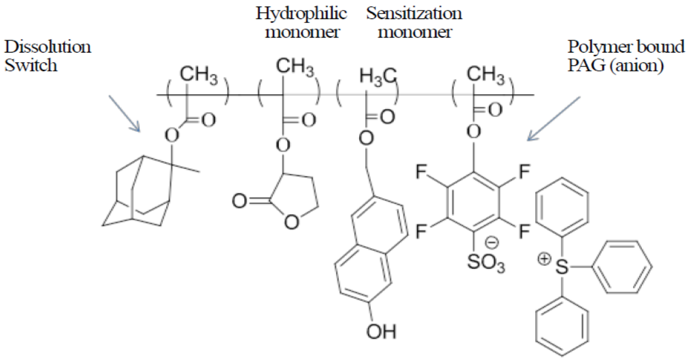
Ref: W. Hinsberg & S. Meyer, Proc. SPIE **10146** (2017) 1014604



Note: HfO_2 or ZrO_2 nanoparticle core + organic shell (ligands) is only 2-3 nm in size but may still limit the maximum resolution

Polymer-bound PAG Resists

Ref: J. Thackeray, et al., J. Photopolym. Sci. Technol. **24** (2011) 179-188

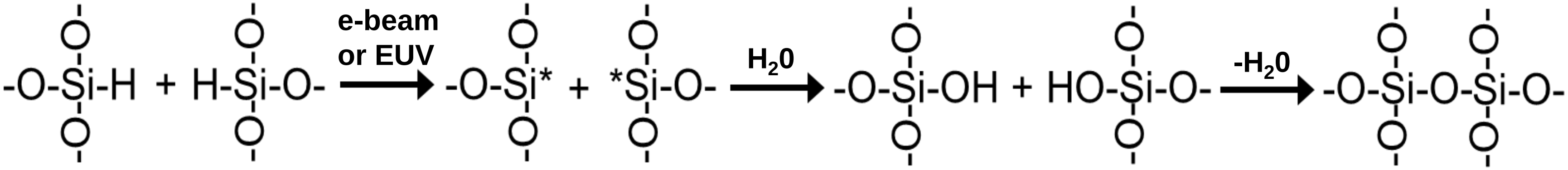


Note: Attaching PAG to polymer backbone is one way to ensure more uniform distribution of components & reduce chemical shot noise

Mitigation of Stochastic Effects (3)

- New EUV resist materials should also have fewer (preferable only one) component & higher dissolution contrast

Hydrogen Silsesquioxane Resist Ref: H.Namatsu, et al., Microelectron. Eng. **42** (1998) 69-76

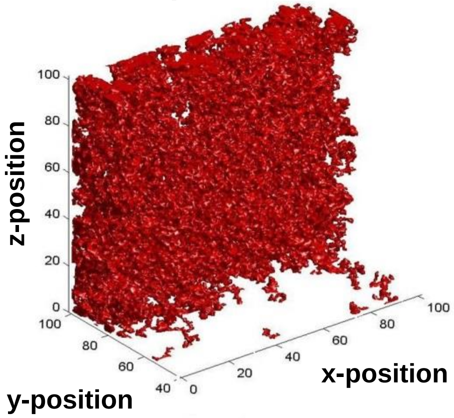


$-O-Si-H + H-Si-O- \xrightarrow{\text{e-beam or EUV}} -O-Si^* + {}^*Si-O- \xrightarrow{H_20} -O-Si-OH + HO-Si-O- \xrightarrow{-H_20} -O-Si-O-Si-O-$

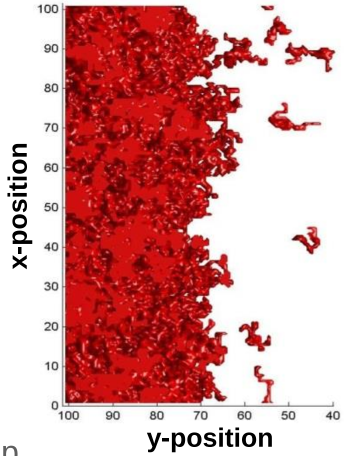
Note: SiH bond scission by e-beam or EUV radiation, reaction with moisture, SiO_2 formation via cross-linking but requires very high doses

Higher Dissolution Contrast Resists Ref: Simulation of CAR resist courtesy Gerard Schmid

Developed Sidewall

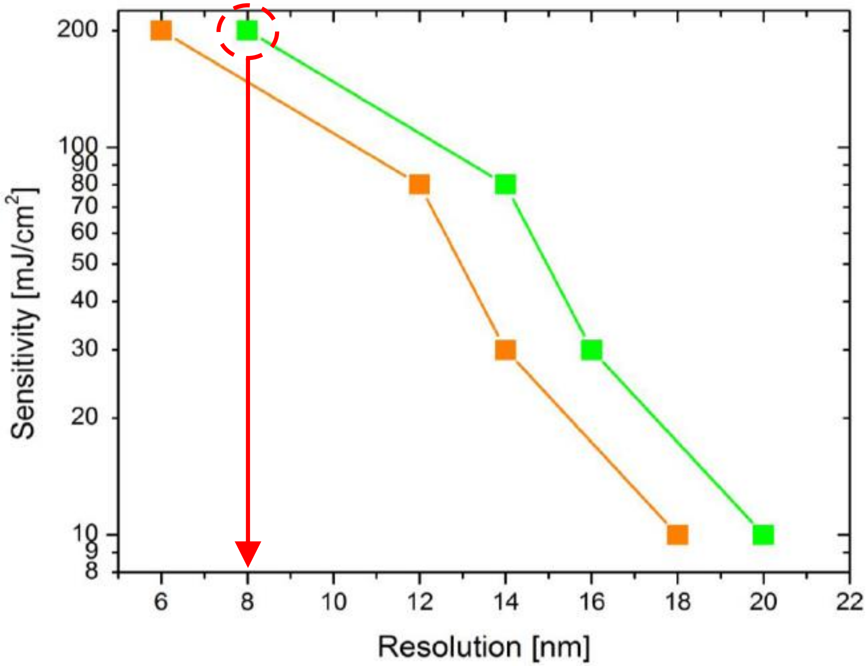


Developed Sidewall

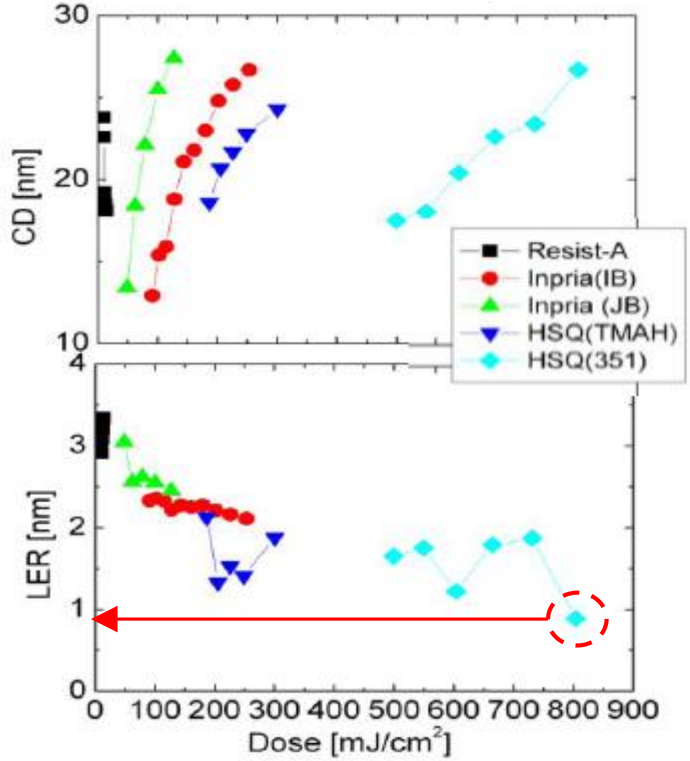


Current Limits of Inorganic Resist Materials

- EUV-IL Patterning of Inpria & HSQ resists



Data Courtesy of Yasin Ekinci, PSI

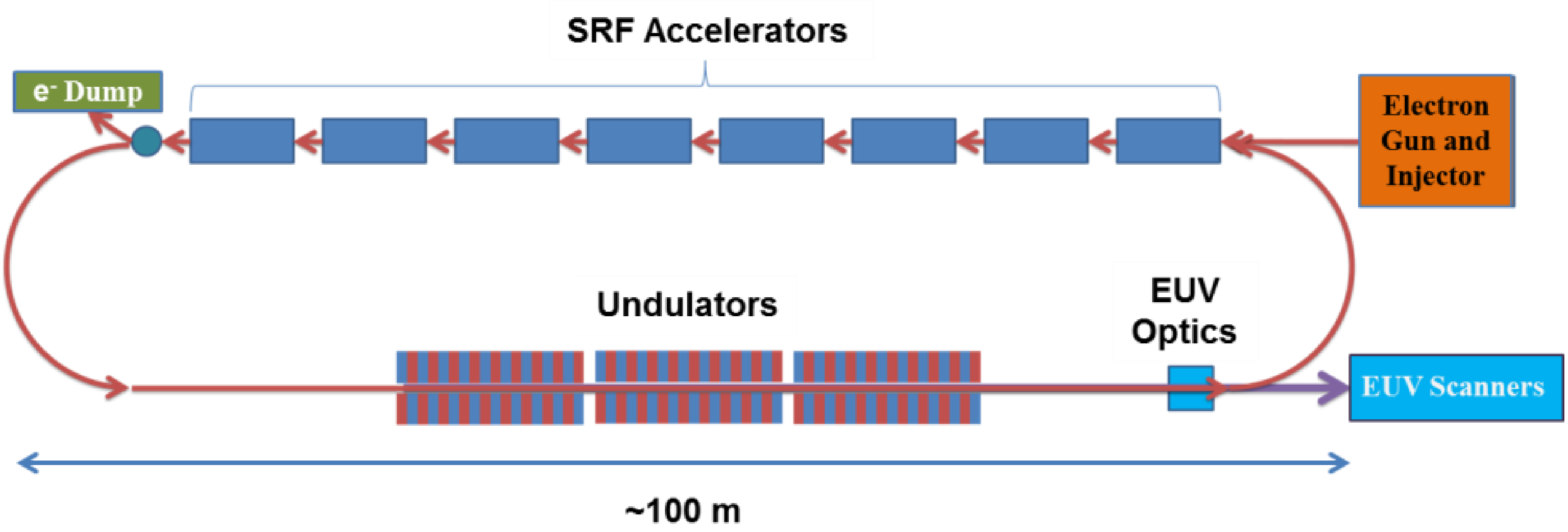


Note: HSQ has demonstrated 8 nm L/S resolution and sub-1 nm LER

- Suggestions for future work
  - Photoresist materials that function via main chain scission
  - EUV resist materials with the ultra-regularity of a crystalline film

More Powerful & Efficient EUV Sources

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

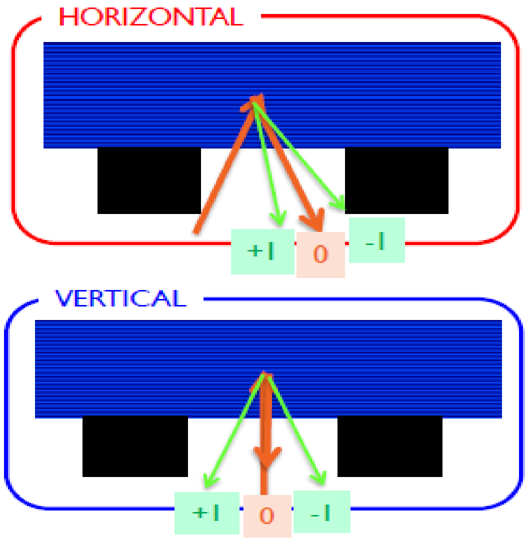


Item	Target	Motivation/Implication
Power	>20 kW	Ten 1kW scanners (50% transport loss)
Availability	>99%	Some redundant system hardware required
CoO	~$250M CapEx, ~$20M OpEx	2x better than CoO for 10 LPP sources
General Configuration	Energy Recovery LINAC @ ~2K SASE Output	Maximize efficiency & minimize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

Ref: E. Hosler et al., Proc. SPIE **9422** (2015) 94220D.

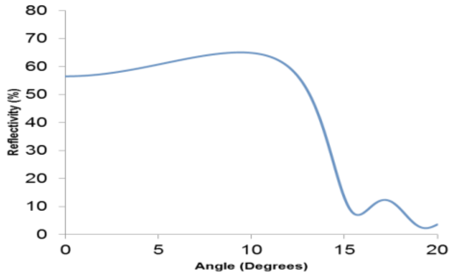
EUV Mask 3D Effects

Mask Shadow Effect

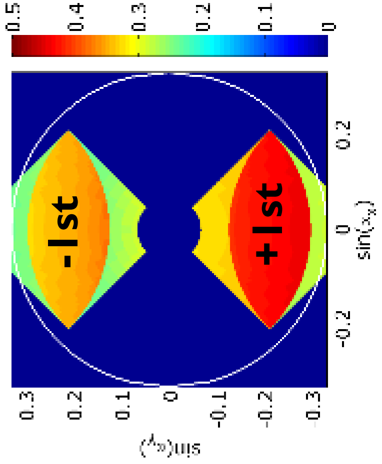


Horizontal-Vertical Print Difference

Reflectivity Apodization

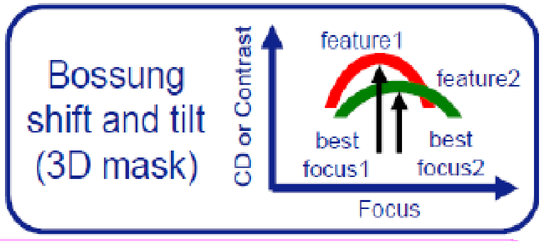


Pupil Filling @ 0.33 NA
16 nm HP Horizontal L/S

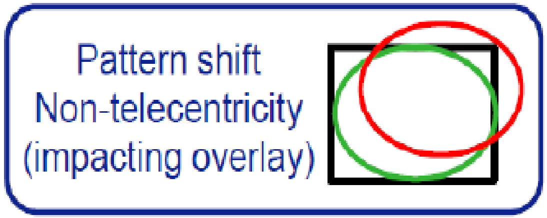


Diffraction Imbalance

Telecentricity Errors



Bossung shift and tilt (3D mask)

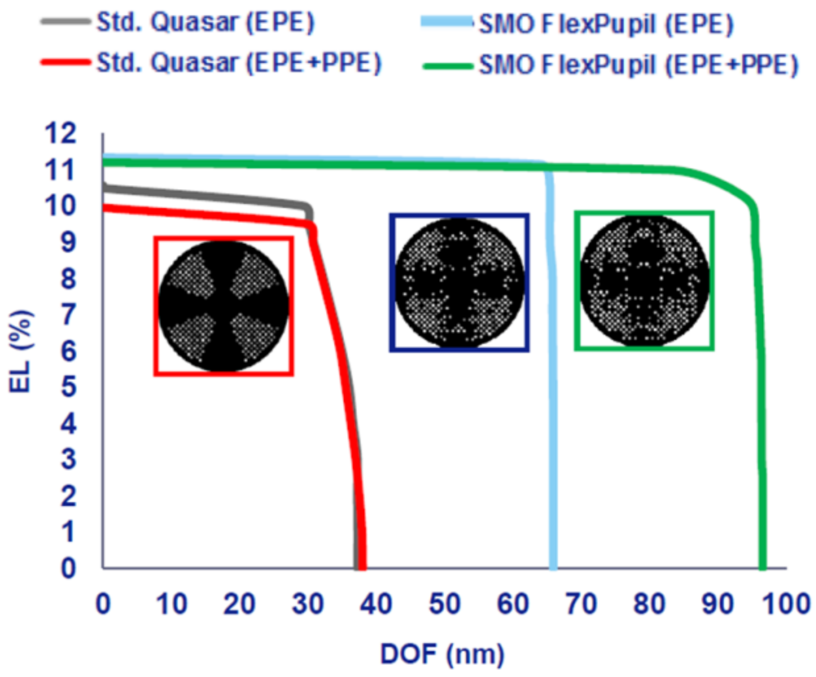


Pattern shift
Non-telecentricity (impacting overlay)

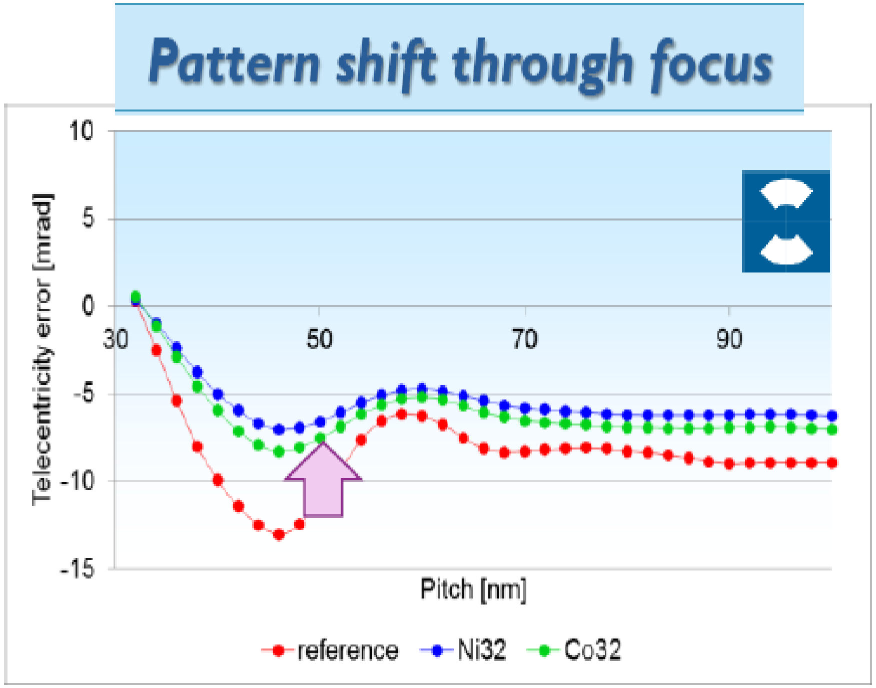
Through-Focus Pattern Shift

Compensating for EUV Mask 3D Effects

- The impact of mask 3D effects on the printing of a 7 nm logic metal level using a 0.33 NA NXE scanner can be reduced using pattern-placement-aware SMO software (left) and by utilizing Ni or Co-based absorbers instead of current Ta-based absorbers (right).



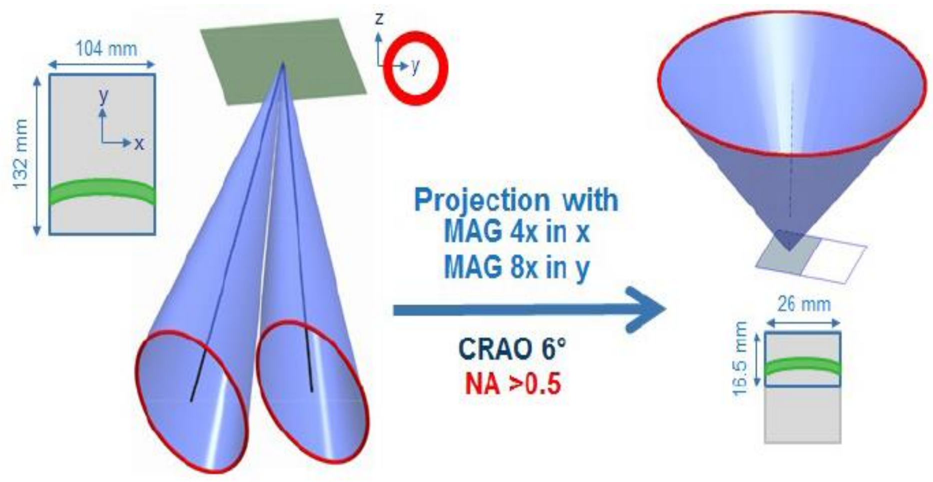
Ref: S. Hsu, et al., "EUV resolution enhancement techniques (RETs) for k_1 0.4 and below," Proc. SPIE 9422, 94221I (2015).

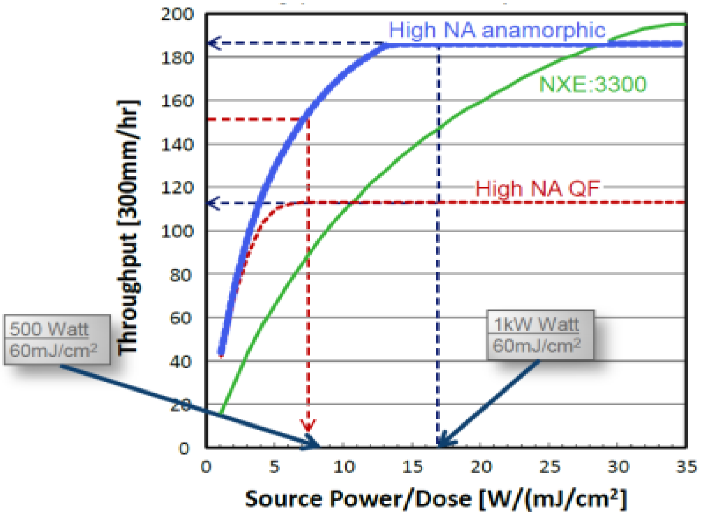


Ref: V. Philipsen, et al., "Reducing EUV mask 3D effects by alternative metal absorbers," 10143-32, SPIE Advanced Lithography, 1 Mar 2017.

Higher NA EUV Projection Optics

- 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 the printing of 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.

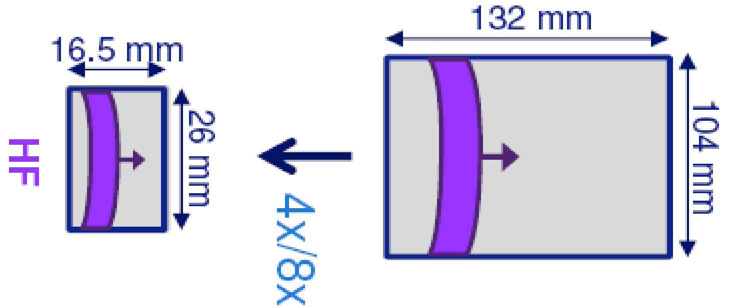
Ref: B. Kneer, et al., “EUV lithographic anamorphic system optics for sub-9-nm resolution,” Proc. SPIE 9422, 94221G (2015).

Imaging with Higher-NA EUV Projection Optics

- Learning to print with a much smaller DOF (~1/3 that of a 0.33 NA system).

$$\frac{\lambda}{NA^2} = \frac{13.5}{0.55^2} = 44\ \mathrm{nm}$$

- A 0.55 NA anamorphic system will print a smaller (half-size) image field—stitching will be required to print a full 33 mm x 26 mm field.



- A larger wafer fab clean room will be needed to accommodate high-NA scanners.
- A new set of mask infrastructure tools will be required; a higher resolution blank inspection tool, a higher resolution pattern mask inspection tool, and a higher NA EUV AIMS tool.

Ref: S.-S. Kim, “Progress in EUV lithography toward manufacturing,” SPIE Advanced Lithography,” 10143-2, San Jose, CA, 27 Feb. 2017.

Summary

- Advantages of EUV lithography are superior pattern fidelity, wider process windows, and potential for extendibility to future nodes.
- Disadvantages of EUV lithography are higher costs & complexity (than ArFi lithography) and infrastructure immaturity.
- Source/scanner availability is not yet at the level needed for SE EUV CoO comparable to triple patterning 193i CoO at the 7 nm node.
- Resist resolution, LER, and sensitivity are adequate for 7-nm, but better LCDU will be required for future nodes.
- Mask blank defectivity and yield are continuously being improved:
  - Actinic tool will be needed for blank inspection, pattern mask inspection and defect repair verification at HVM.
- Three remaining topics that still need additional work are:
  - Mitigating stochastic effects:
    - with higher EUV doses to reduce photon shot noise (less desirable option)
    - developing new EUV resist materials with smaller reactive volume, more uniform distribution of components, fewer components & higher dissolution contrast
  - Compensating for EUV mask 3D effects.
  - Imaging with higher NA projection optics.

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- IMEC: Vicky Philipsen
- Intel: Robert Bristol, Marie Krysak & Britt Turkot
- Kempur Microelectronics: Mark Neisser
- SUNY Poly: Robert Brainard
- Paul Scherrer Institute: Elizabeth Buitrago & Yasin Ekinci
- Samsung: Seong-sue Kim