The Need for Speed: Computations for EUV Lithography

EUV lithography implemented at different node than originally conceived

Summary

EUVL is the only viable solution for 45 nm

- Integration of all EUVL modules demonstrated feasibility of the EUVL technology
- Mask costs are affordable – defect mitigation and repair methods demonstrated
- Suppliers are engaged to commercialize the technology
- Remaining technical challenges have been identified and are actively being addressed
- Commercialization emphasis is required

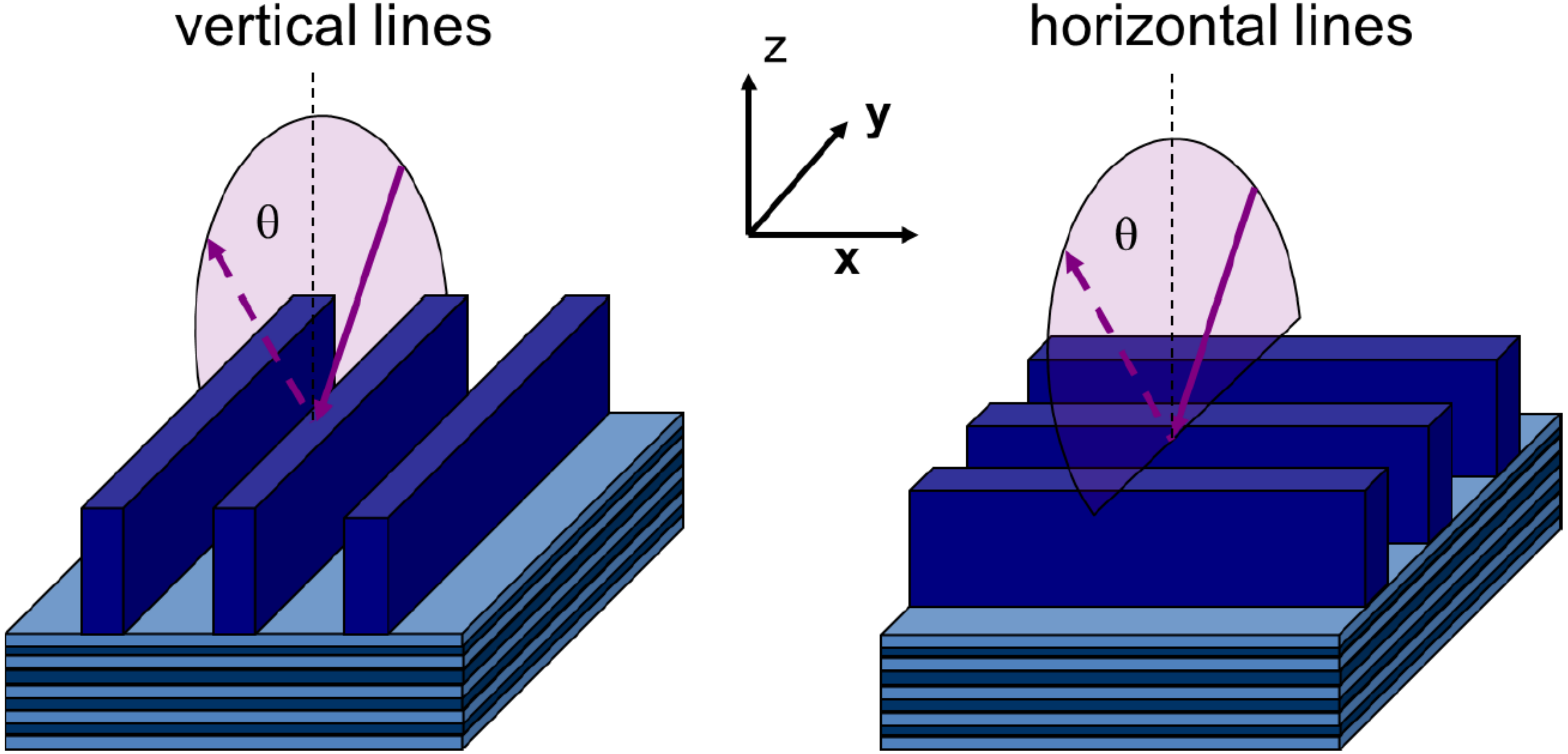
Gwyn:PMJ:4/17/03:27

EUVL EUV LLC

Gwyn and Silverman, “EUV Lithography Transition from Research to Commercialization,” Photomask Japan, 2003

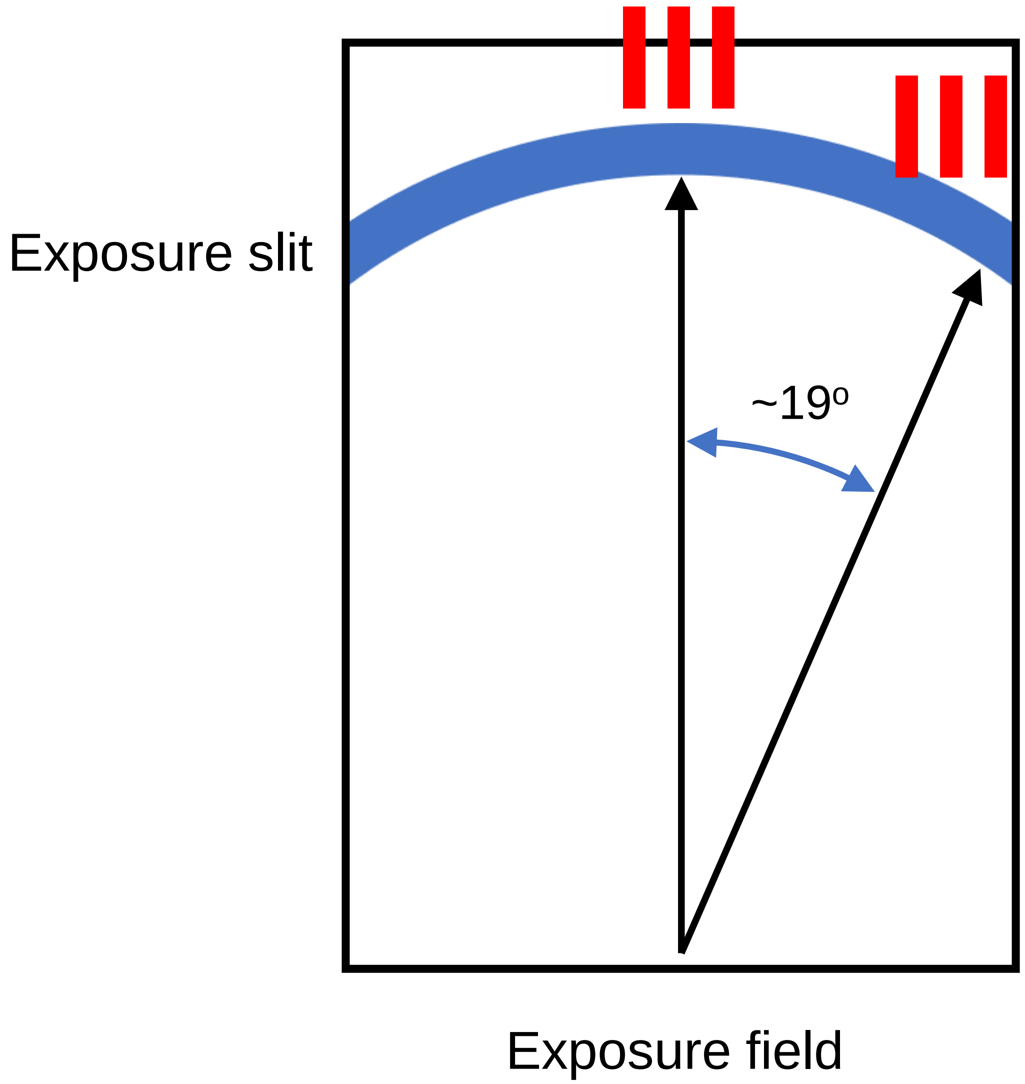
Minimum pitch = 160 nm

Horizontal-vertical bias due to oblique illumination



Erdmann,et al.
"Characterization and mitigation of 3D mask effects in extreme ultraviolet lithography." *Advanced Optical Technologies* 6, no. 3-4 (2017)

Biases in-between



- Ring-field optics have long been used in scanning lithography
  - Reduced aberrations

Mask 3D effects were recognized early: Pitch dependence for focus

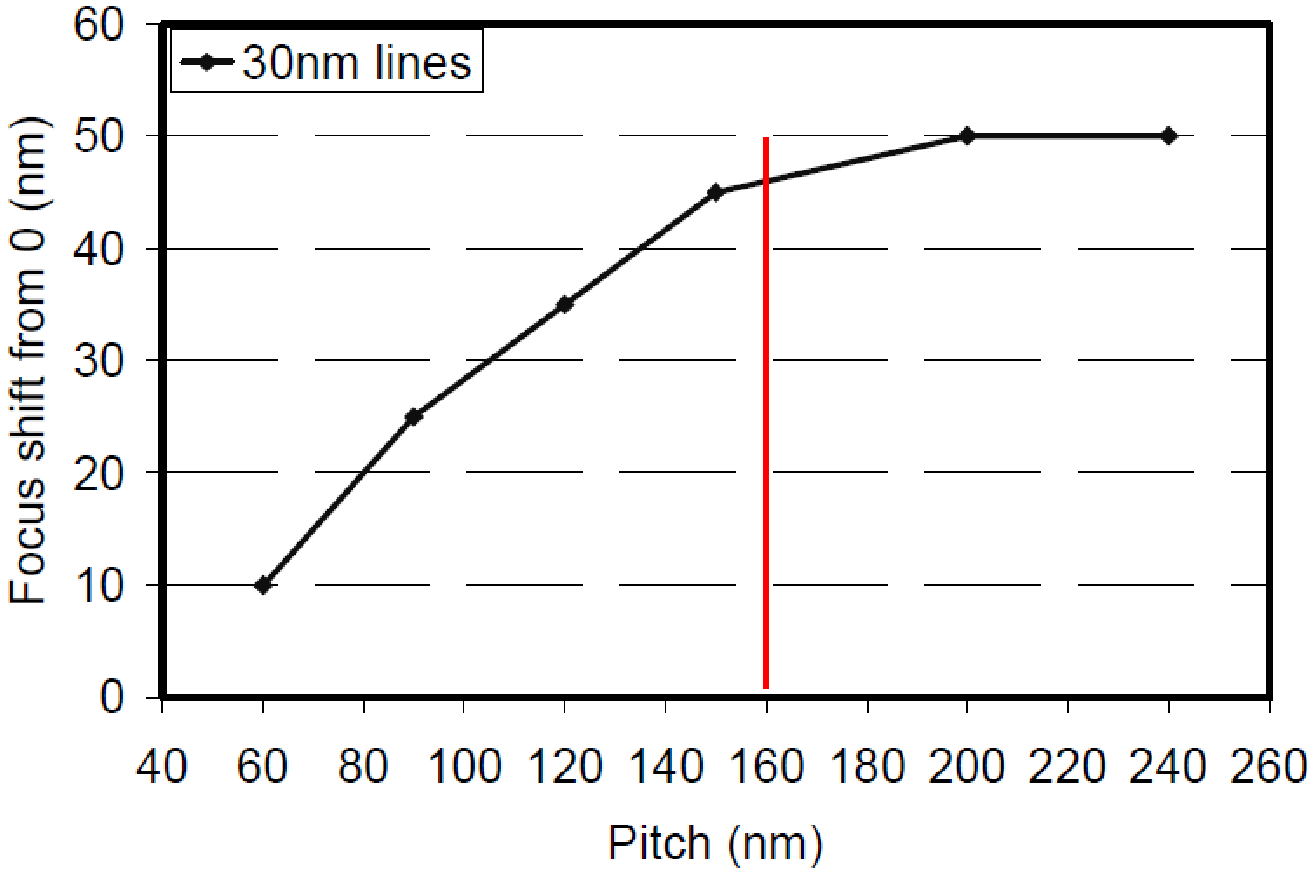


Fig. 2. Focus shift as a function of pitch for 30nm lines.
The light incident angle is 5-degree.

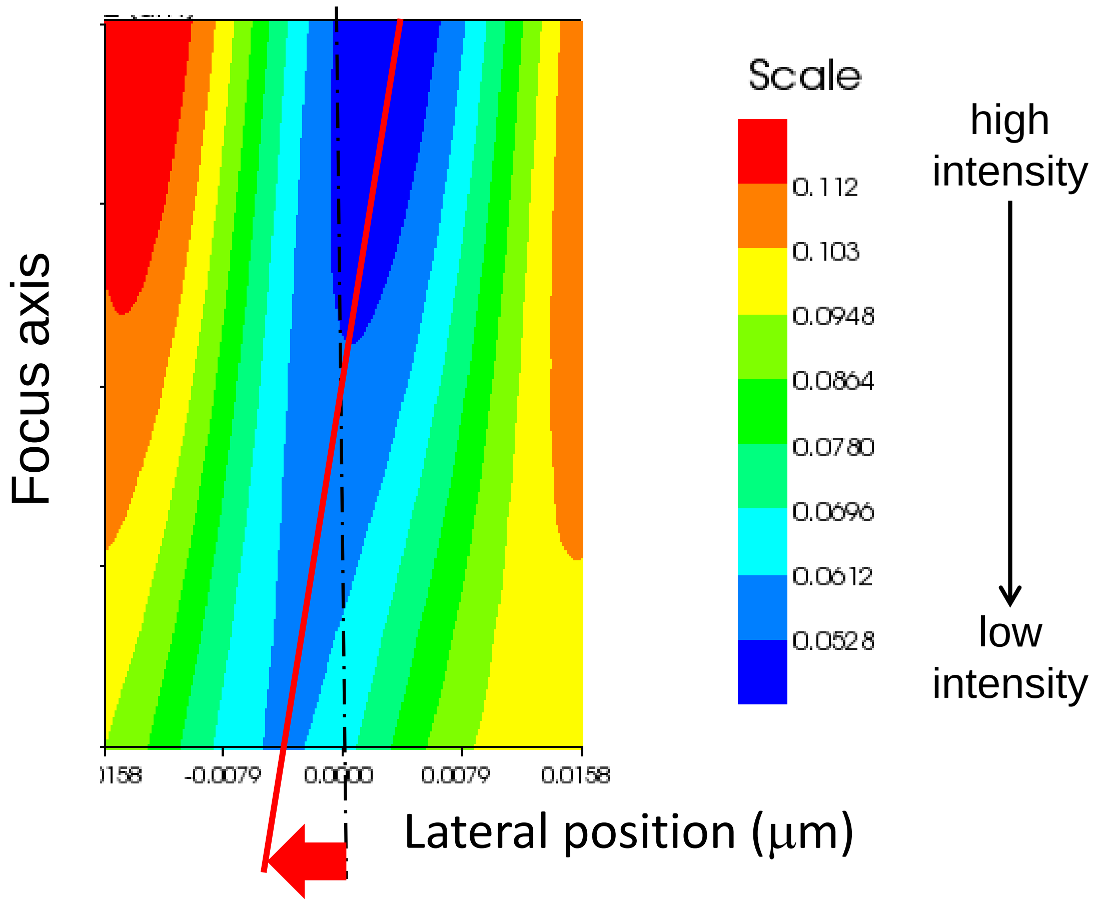
Pei-Yang Yan,

"Understanding Bossung Curve Asymmetry and Focus Shift Effect in EUV Lithography,"

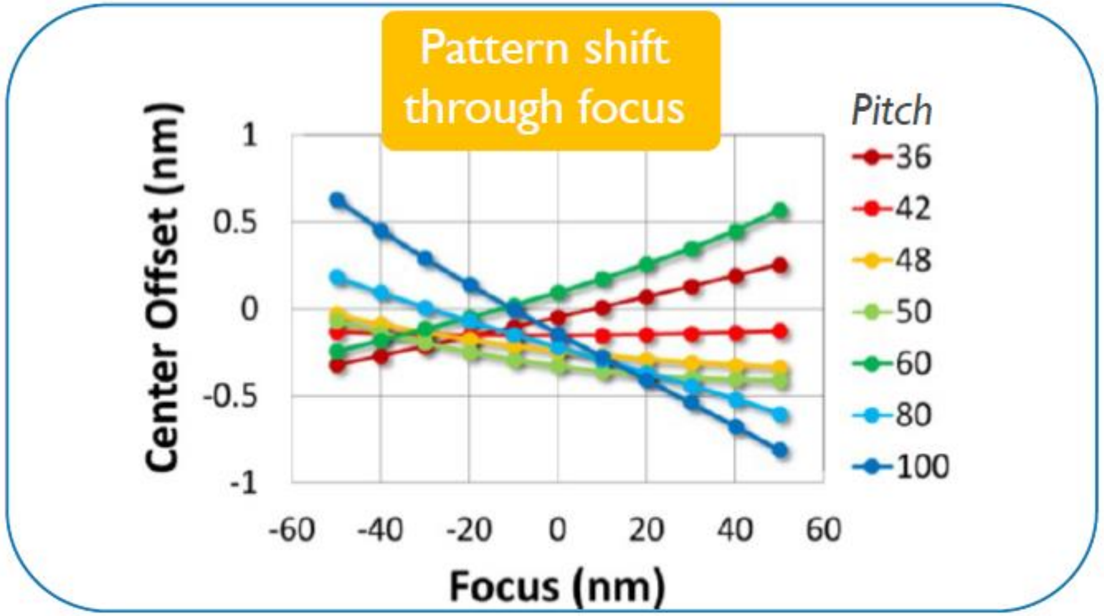
BACUS Symposium on Photomask Technology,

2001

Pattern placement errors through focus



S. Raghunathan, et al., “Characterization of Telecentricity Errors in High-Numerical-Aperture Extreme Ultraviolet Mask Images,” 3-beams (2014)

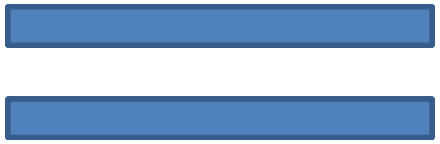


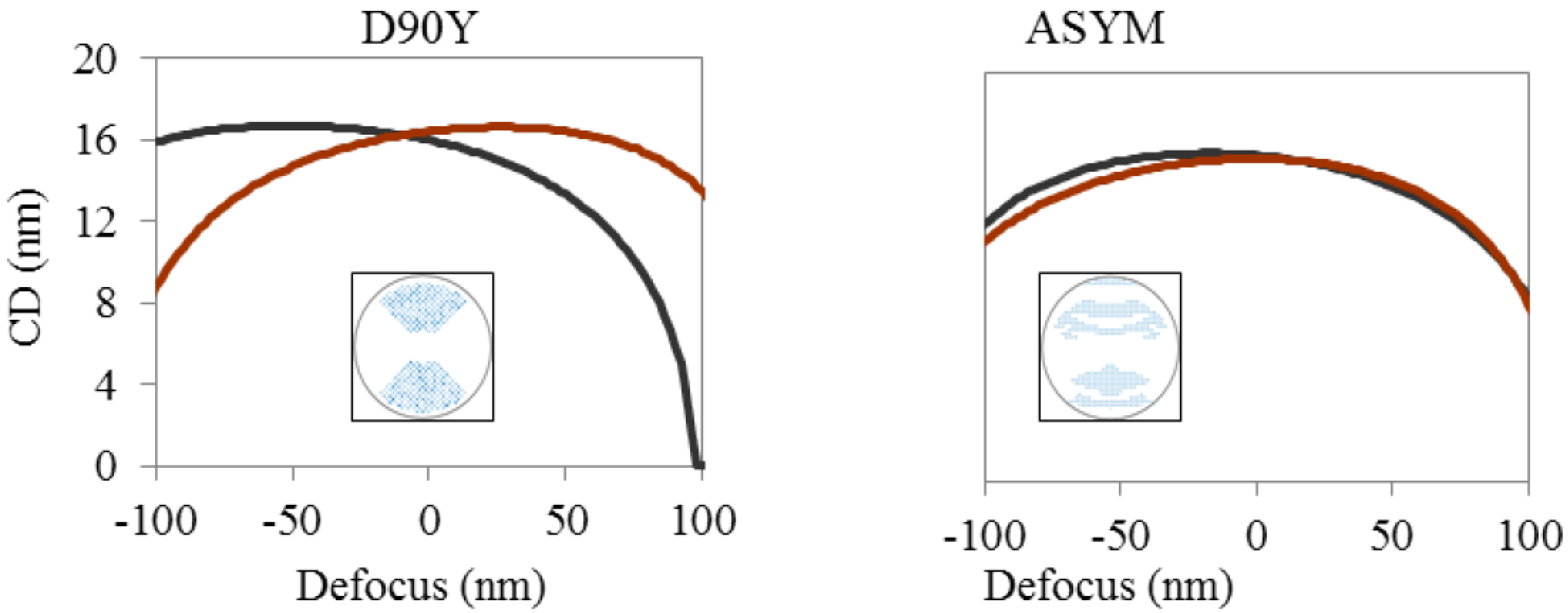
L. Van Look, et al., “Mask 3D Effect Mitigation by Source Optimization and Assist Feature Placement” (2016)

This is new: Overlay needs to be considered when employing process window-aware OPC!

Mask 3D effects drive need for complex illumination

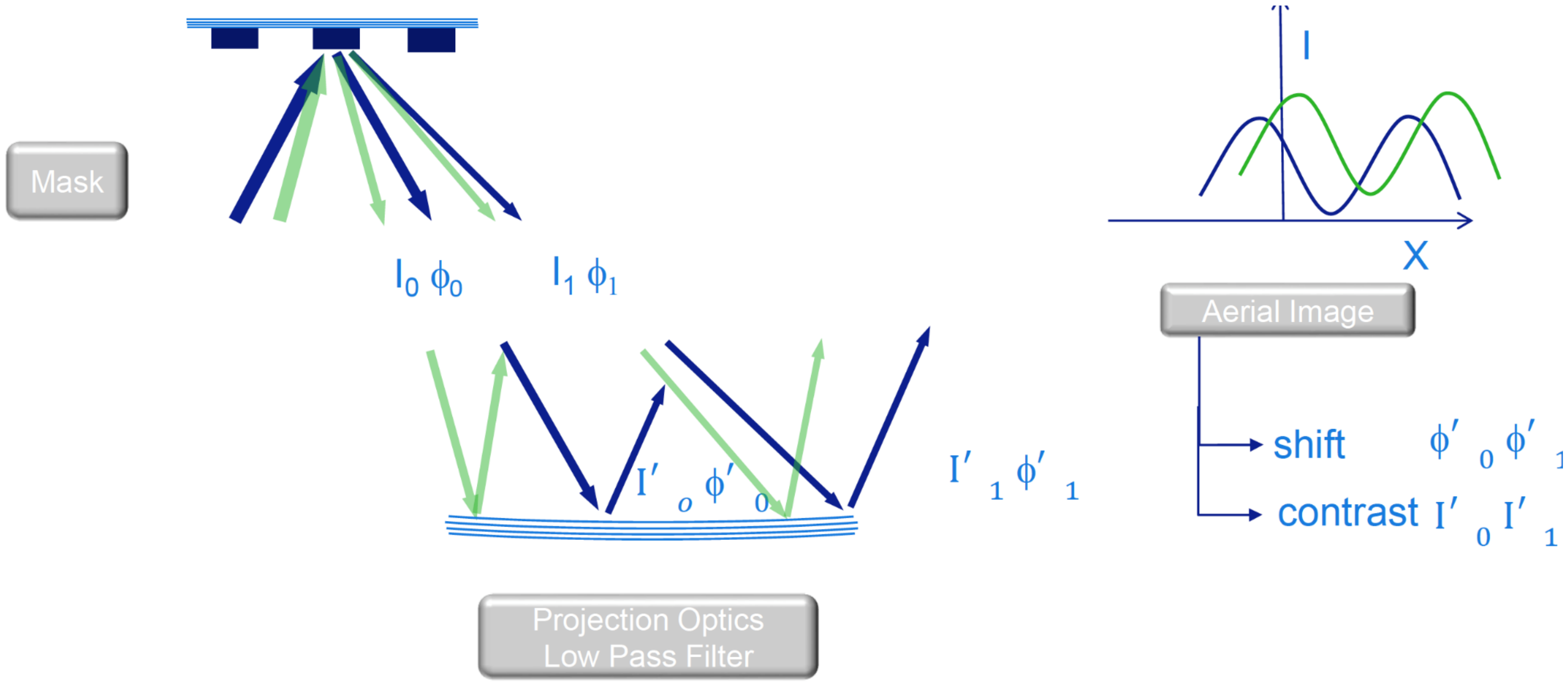
CD versus focus for 2-bar structures, 32 nm pitch:





T. Last, et al. “Illumination pupil optimization in 0.33-NA extreme ultraviolet lithography by intensity balancing for semi-isolated dark field two-bar M1 building blocks,” JM3 (2016)

Image blurring due to mask 3D effects

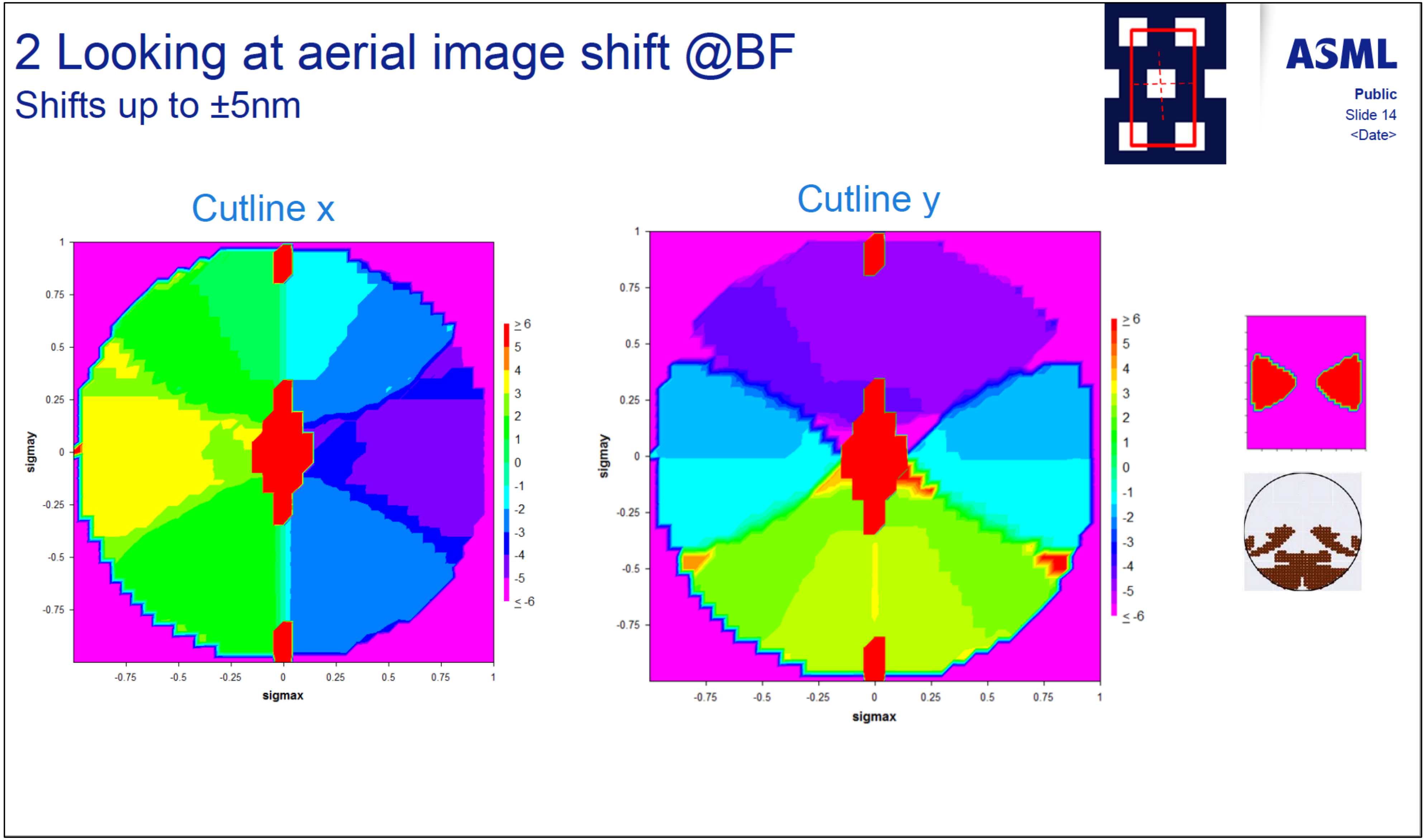


Images from different source points are displaced laterally

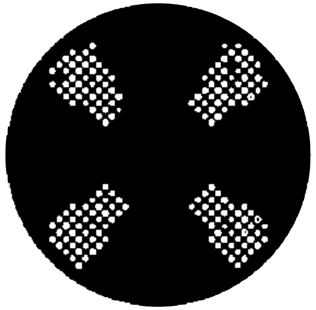
→ extended sources result in blurred images

Jo Finders, 2017 EUVL Symposium

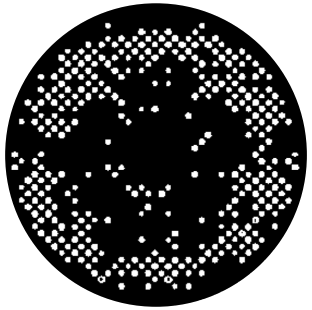
21 nm hp image blurring example



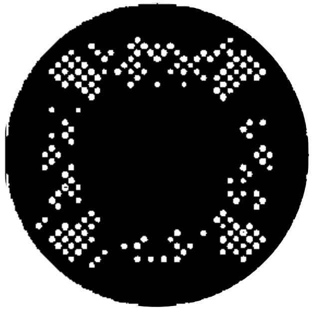
Need to maintain normalized image log-slope (NILS) to address LER



Quadrupole illumination

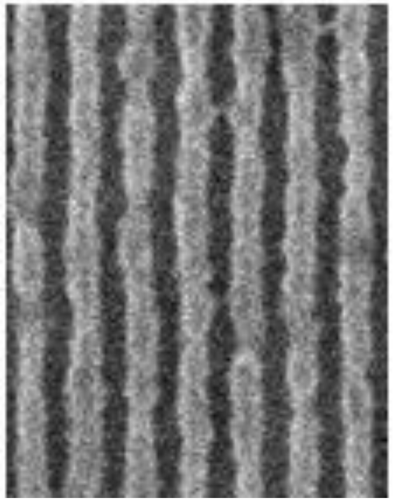


SMO standard solution



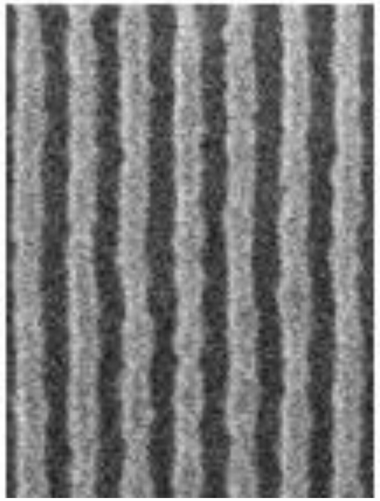
SMO NILS optimized

32-nm pitch lines/spaces



NILS = 1.61
LER = 3.6 nm

NILS = 1.57
LER = 3.7 nm



NILS = 2.05
LER = 2.6 nm

"Application of EUV resolution enhancement techniques (RET) to optimize and extend single exposure bi-directional patterning for 7nm and beyond logic designs"

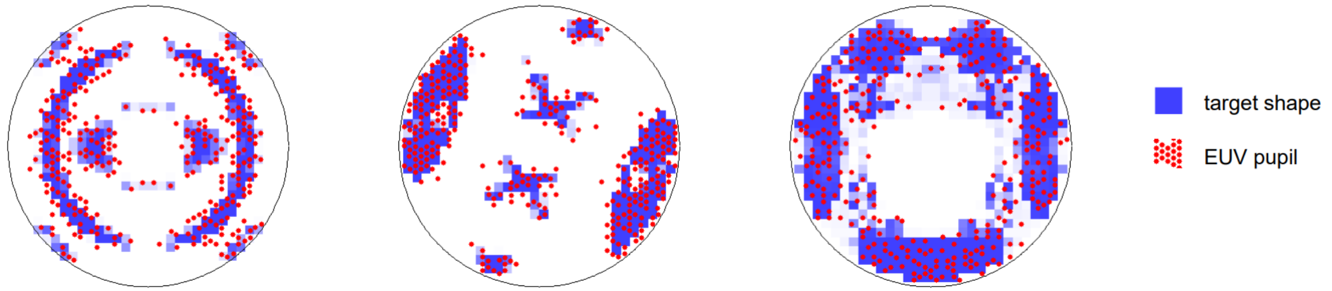
Ryoung-Han Kim et. al.,

SPIE Advanced Lithography Symposium (2016)

Freeform illumination is now available for EUV lithography

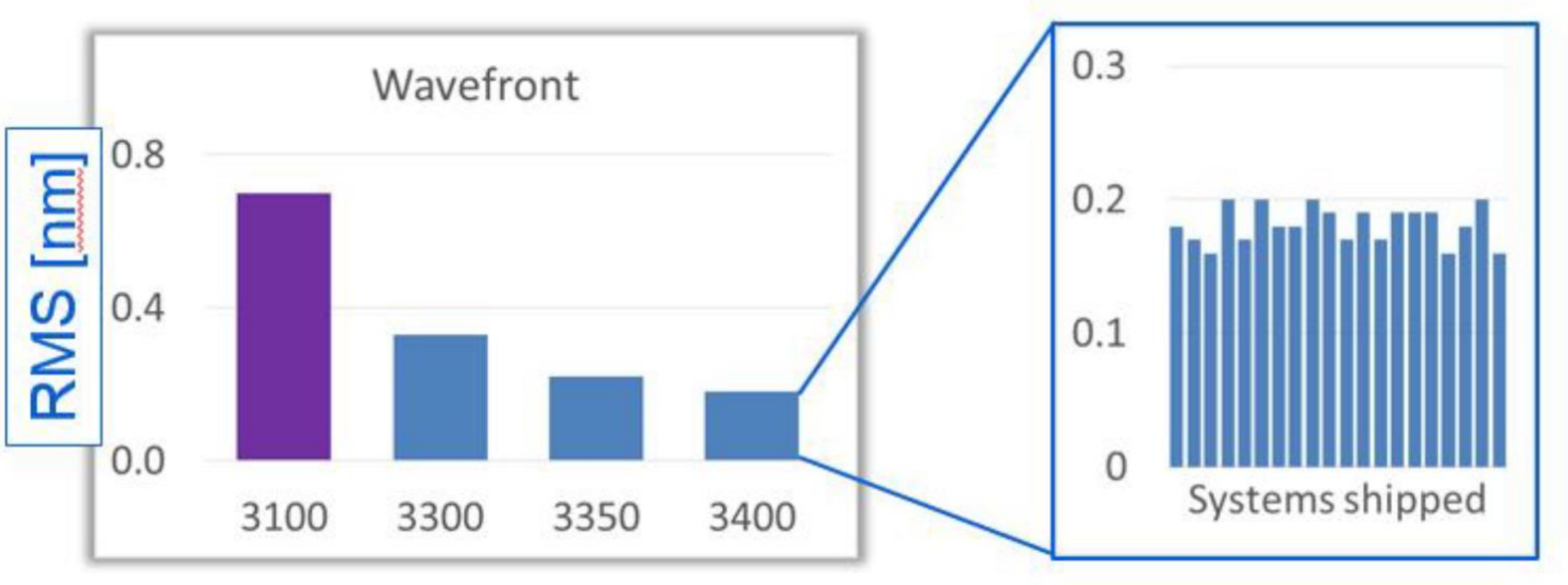
Freeform pupil shapes

SMO pupil	**rotated pupil shape**	**y-asymmetric**
for logic cut mask	for DRAM brickwalls	3D mask compensation



all examples without light loss (100% illuminator efficiency) on Starlith® 3400 illumination system

Aberrations are significant for EUV lithography



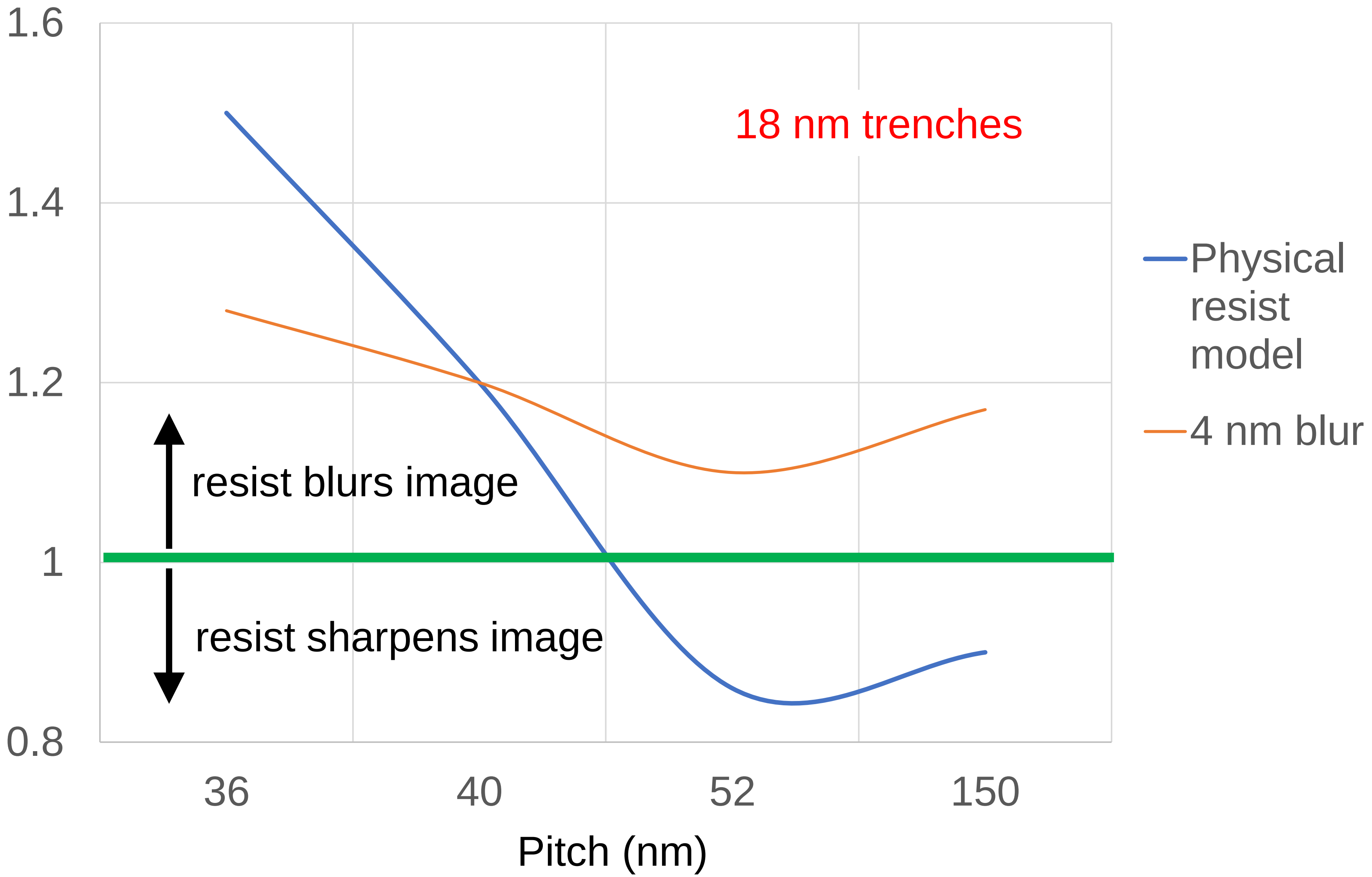
0.2 nm = 15 mλ

Winfried Kaiser, Semicon Korea, 2018

Complex resist physics

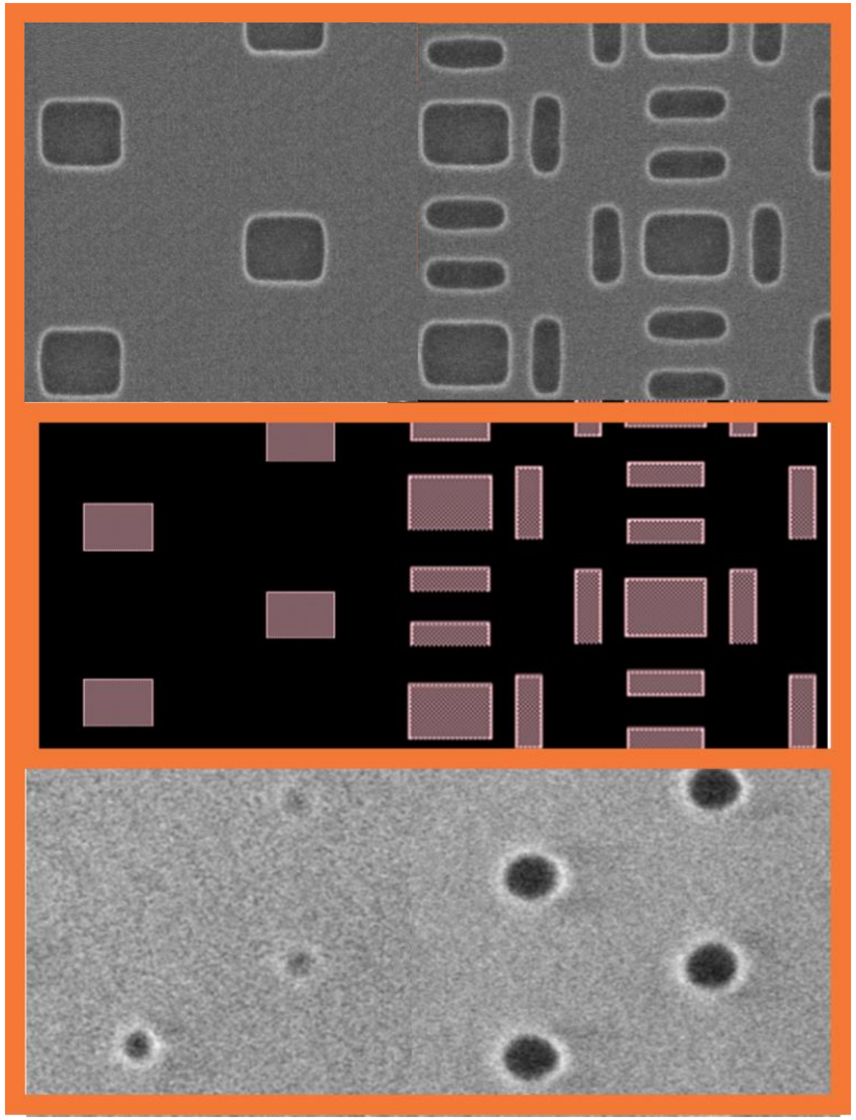
$$\frac{\text{Image log-slope}}{\text{Resist-edge log-slope}}$$

- OPC models need to contend with pitch-dependent resist-blur



Adapted from S. Hansen, JM3

Sub-resolution assist features (SRAFs) for EUV lithography



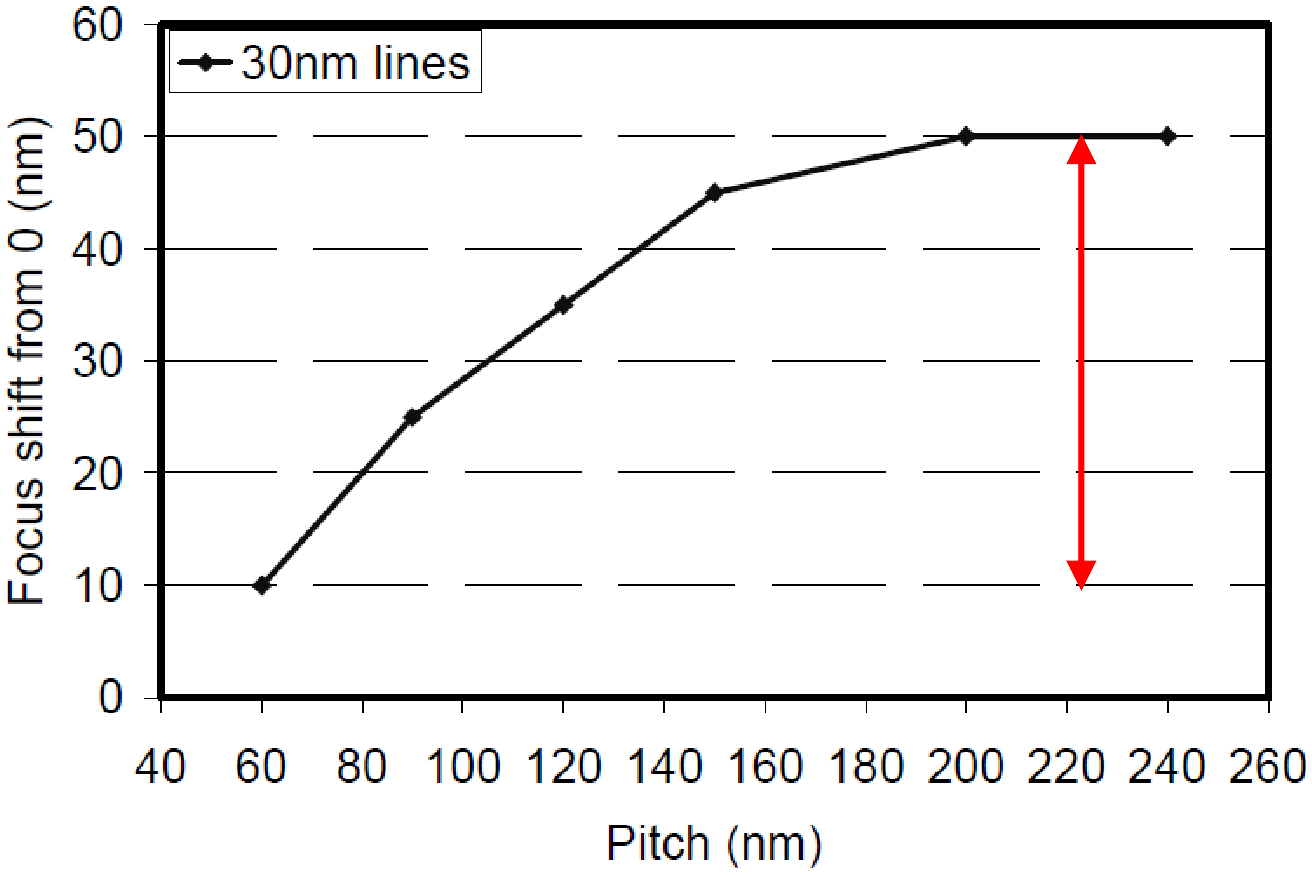
Mask SEM image

Design layout

Developed resist on-wafer SEM image

Deniz Civay, et al.,
"Subresolution assist features in extreme ultraviolet lithography,"
JM3 (2015)

Application of SRAFs significantly reduces range of focus shifts



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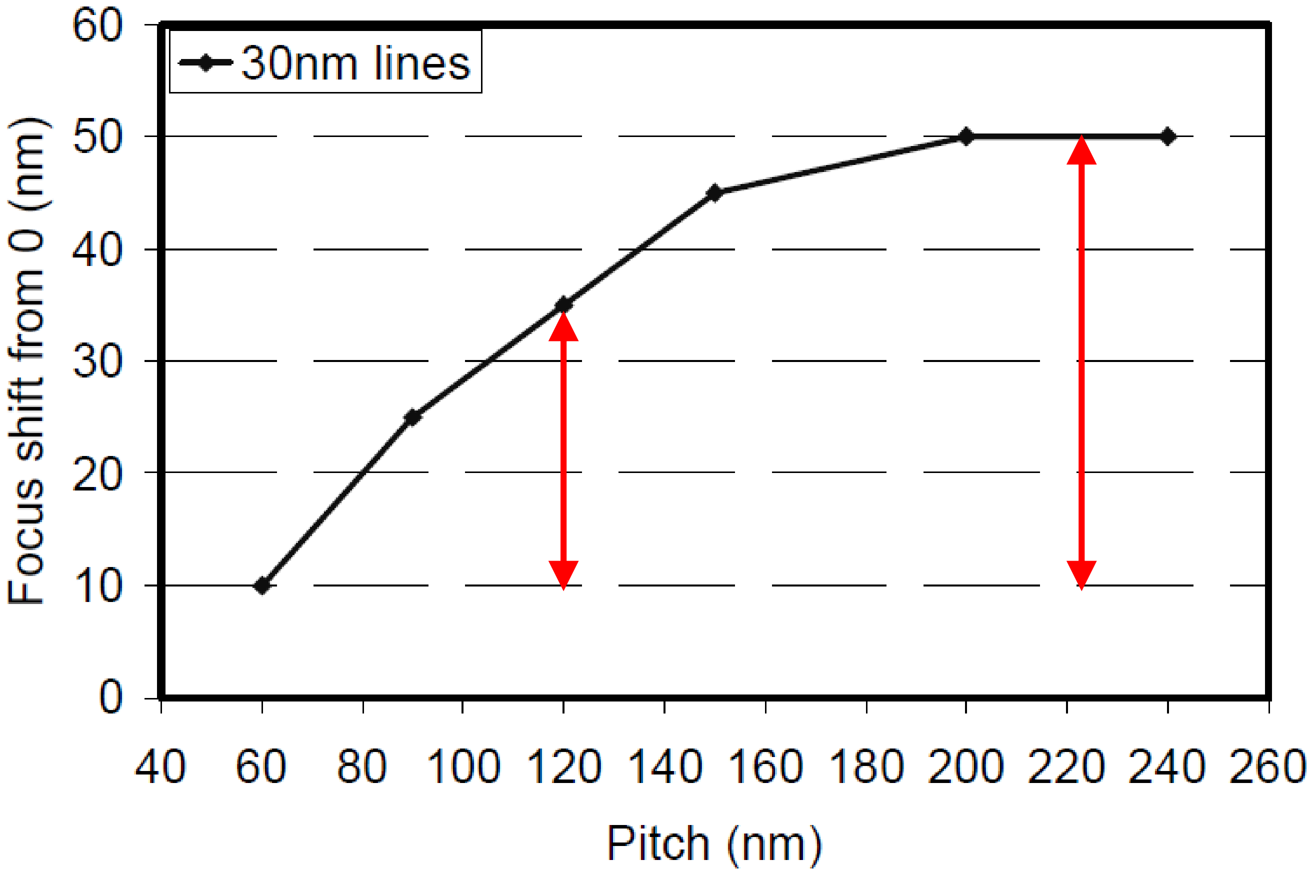


Fig. 2. Focus shift as a function of pitch for 30nm lines. The light incident angle is 5-degree.

~40% reduction in best focus variation

Pei-Yang Yan,

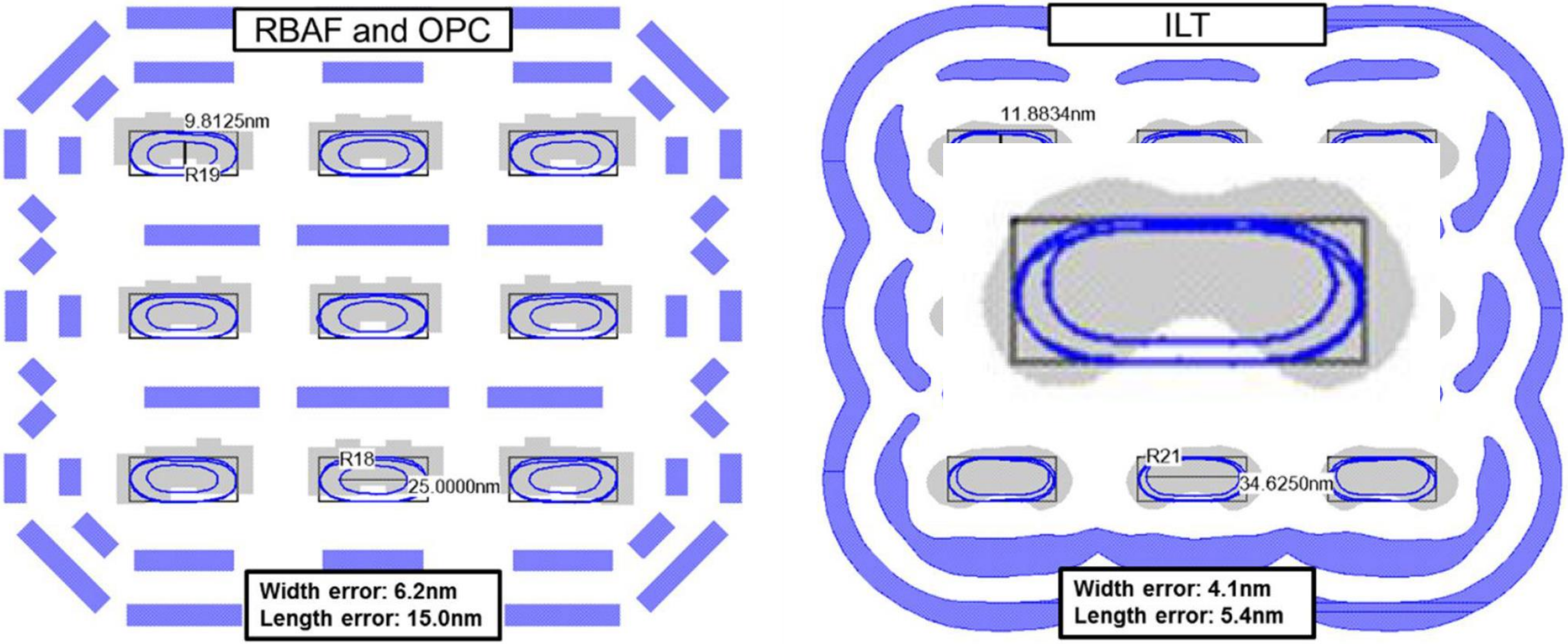
"Understanding Bossung Curve Asymmetry and Focus Shift Effect in EUV Lithography,"

BACUS Symposium on Photomask Technology,

2001

The future is curvilinear

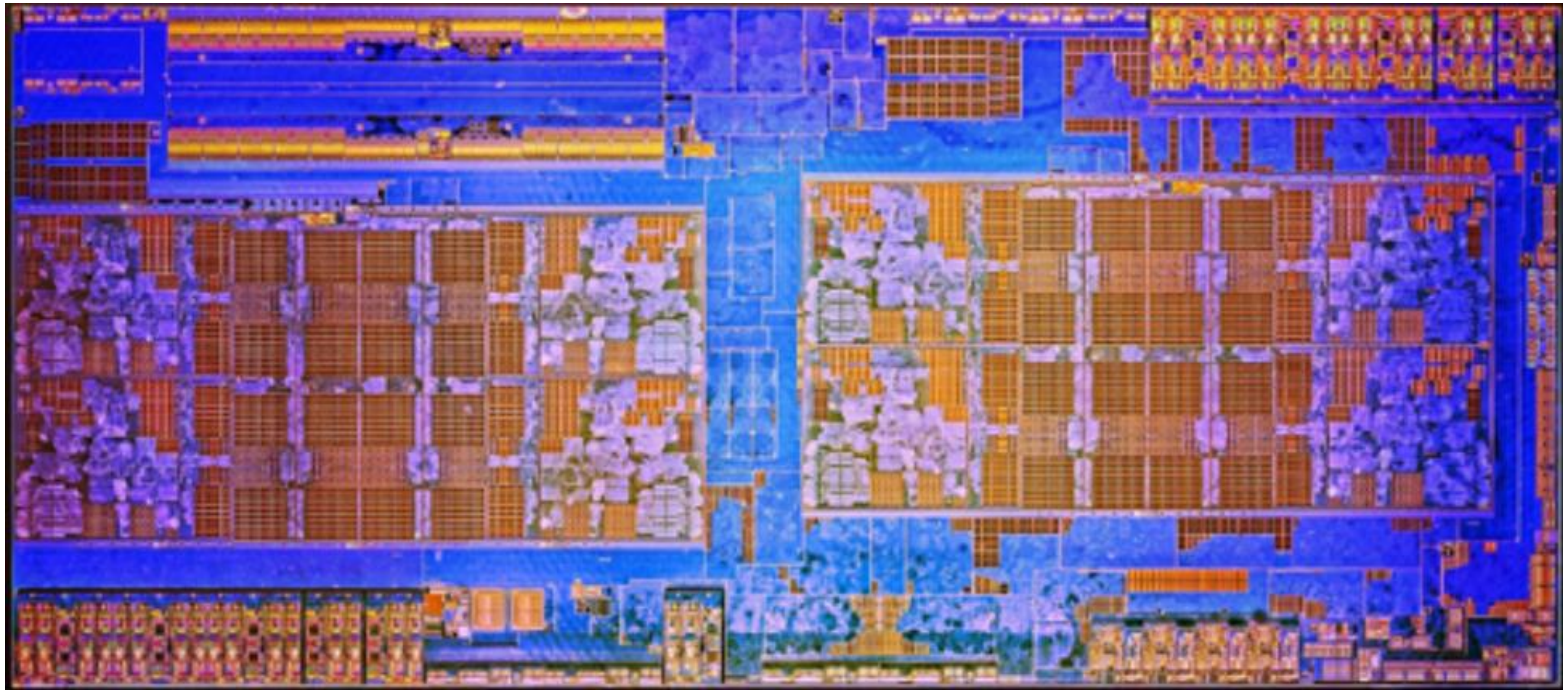
70 nm X-pitch,
60 nm Y-pitch



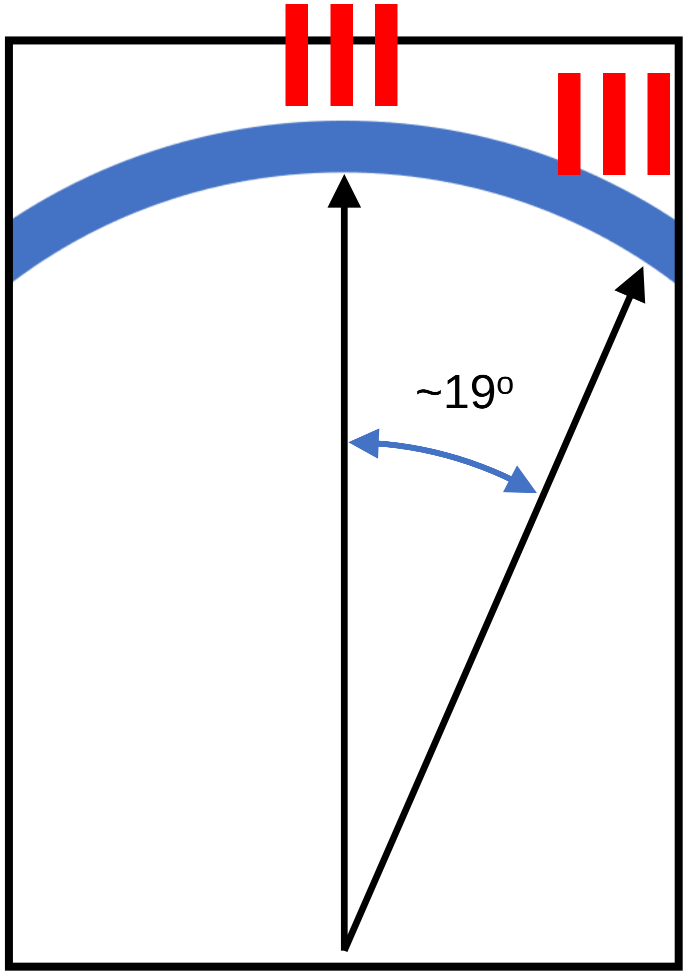
K. Hooker, A. Kazarian, X. Zhou, J. Tuttle, G. Xiao, Y. Zhang, and K. Lucas "New methodologies for lower-K1 EUV OPC and RET optimization." Proc. SPIE Vol. 10143 (2017)

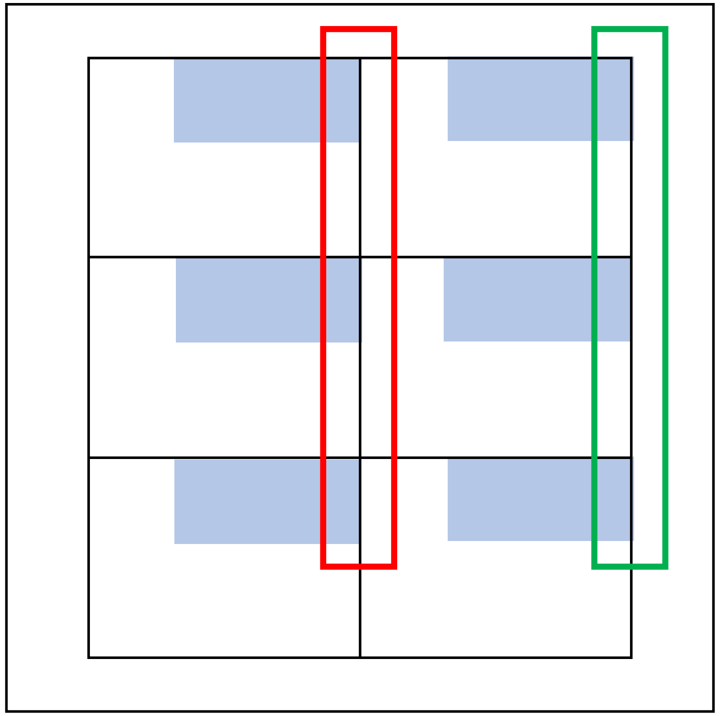
Many geometries in today's chips creates big computational problem

- AMD's Ryzen 7 microprocessor has 4.8B transistors



Ring-field EUV optics kills hierarchy – another computation complexity





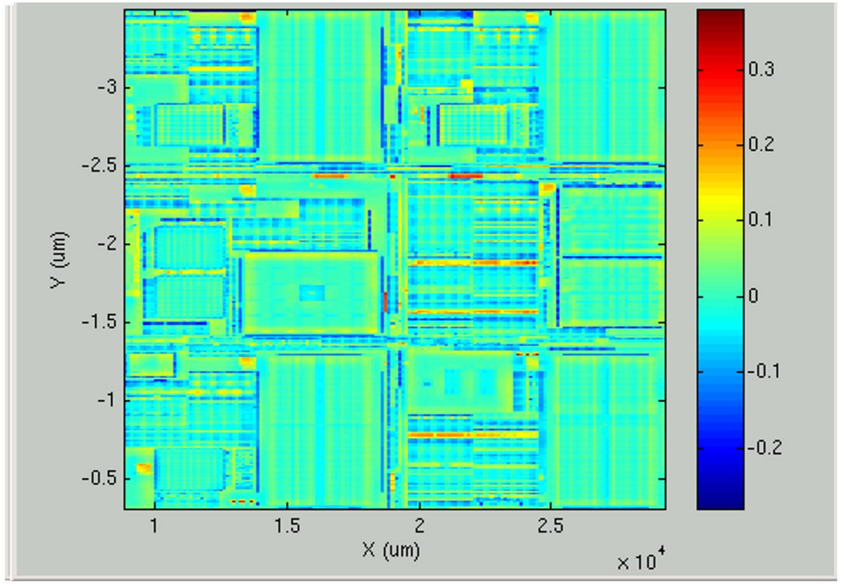
Flare also breaks hierarchy

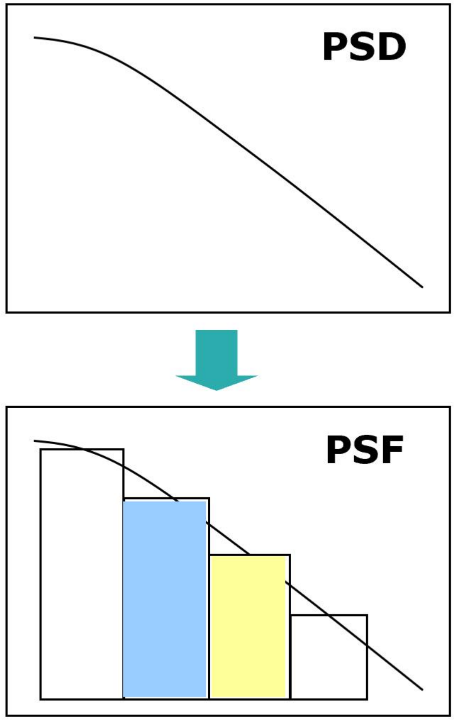
OPC Development: flare compensation

AMD Smarter Choice

- Based on optics PSD and mask pattern density calculations

Long-range density effects





Current situation

- The physics of EUV lithography necessitates computations more complex than those encountered in optical lithography
  - Significant mask 3D effects
    - Multiple manifestations
      - Plane of best focus dependent on pitch and position within arrays
      - Image blur
      - Pattern placement shifts
    - Variations across the slit
  - Flare and aberrations
  - Complex resist behavior

- Support needed for curvilinear features

- Large chip sizes at the leading edge creates need for fast computational capabilities

Lithography simulations are amenable to parallel computations

Mask

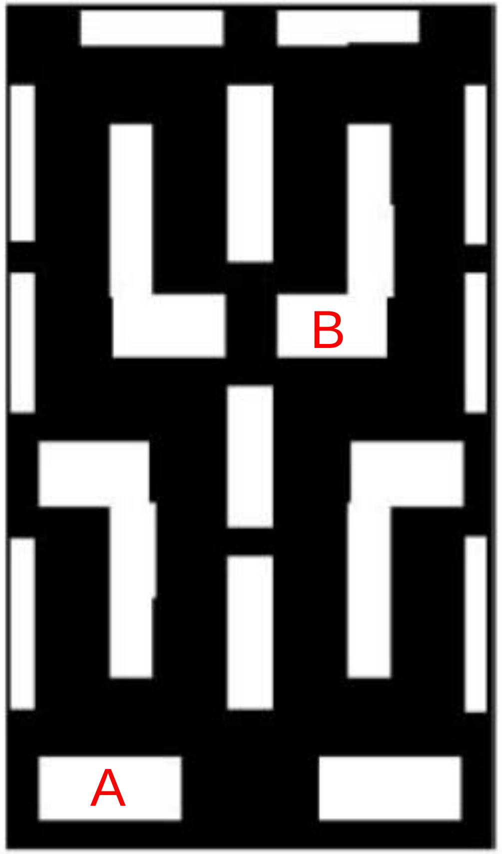
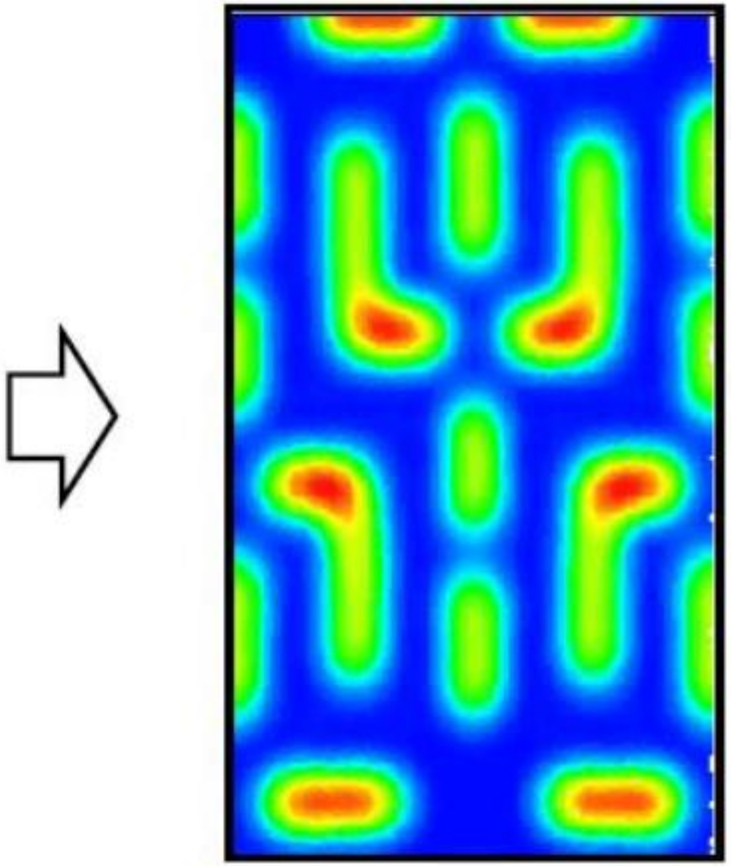


Image intensity



P. De Bisschop,
JM3, 2018

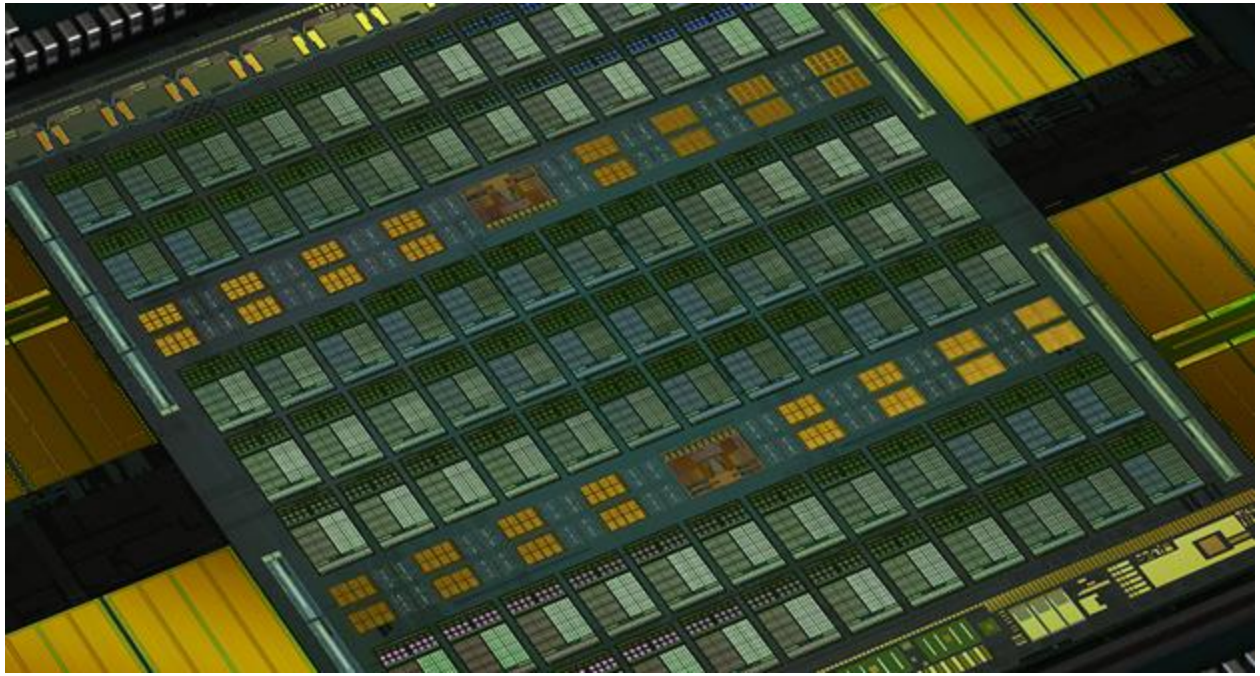
Lithography simulations are amenable to parallel computations

- Use of multiple servers with multiple-core processors are used routinely for optical lithography
- Example
  - 64 core microprocessors
  - 100 servers
  - 6400 cores
- OPC computations can still take 24 hours or more for optical lithography
- Inverse lithography calculations can take so long that they are often applied only to select patterns
- Greater computational capability will be needed for EUV lithography

Lithographic calculations extensively involve FFTs

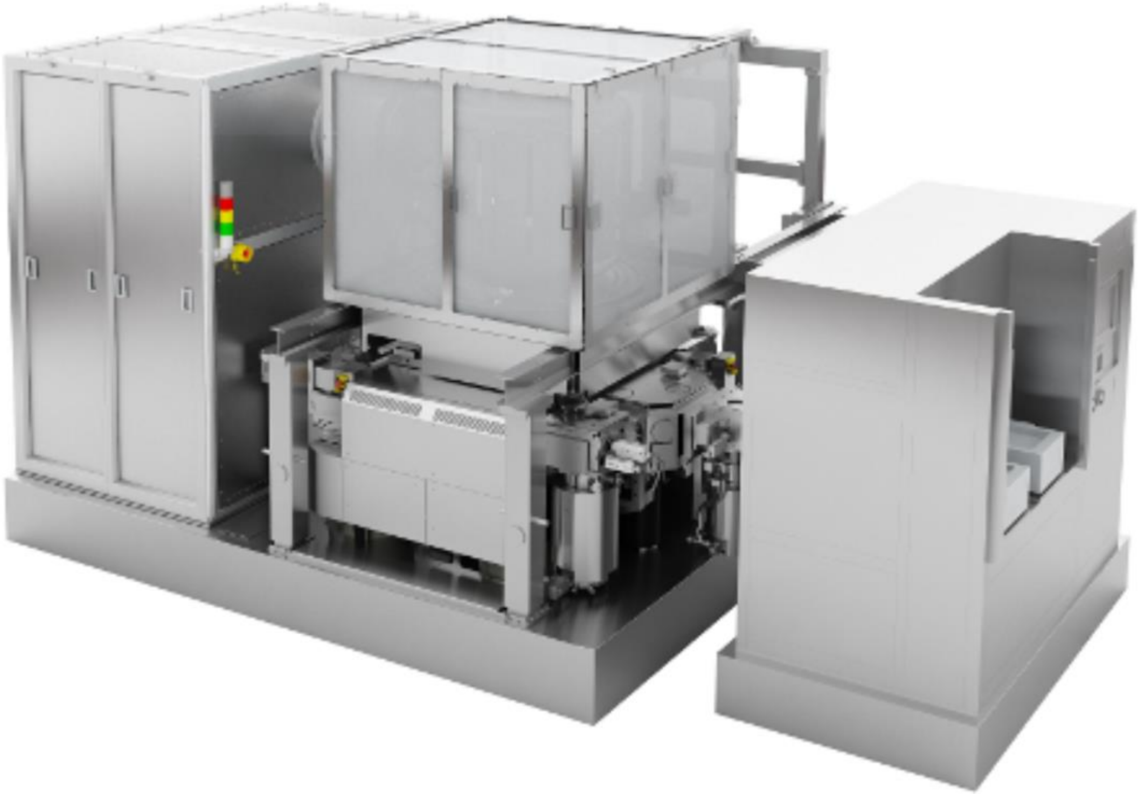
Parallel computations: New paradigm with GPUs

Nvidia Volta GPU:
5120 cores

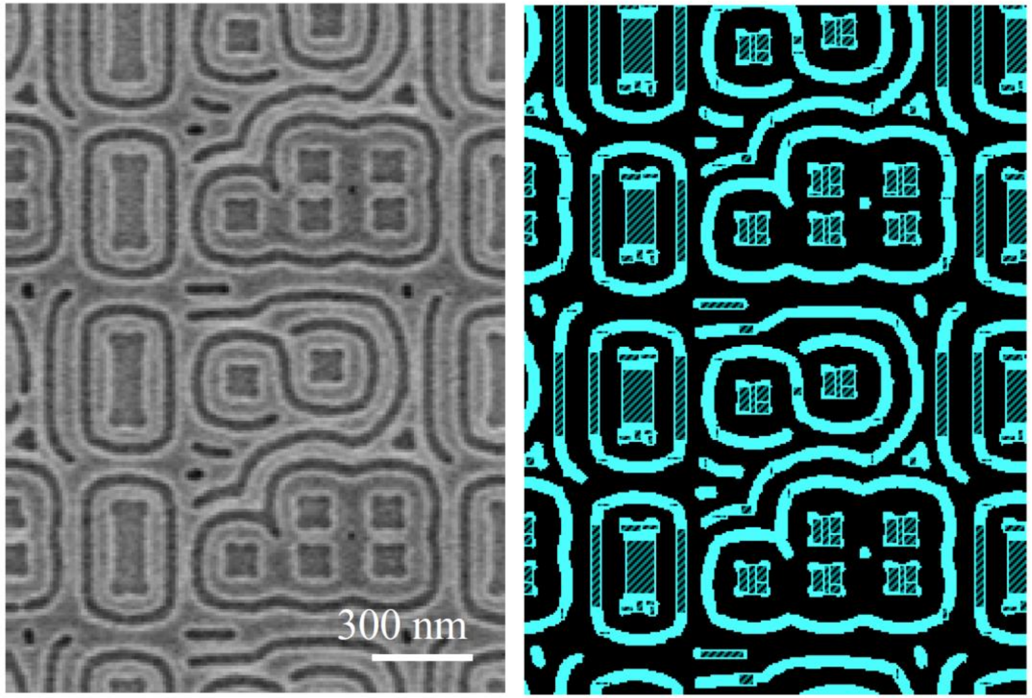


Curvilinear shapes: practical with multi-beam mask writing

Return to raster scanning



IMS MBMW-101



Patterns created with Nuflare MBM-1000

Summary

- Future OPC/RET for EUV lithography will necessarily be very complex
  - Mask 3D effects
    - Increases need for SRAFs
  - Resist physics

- Large chips manufactured with leading-edge lithography necessitate powerful computational and mask-making capabilities

- Fortunately, the infrastructure is becoming available to support solutions
  - GPU’s can provide a path to a much higher degree of parallel computing
  - EUV exposure tools now have freeform pupil shaping capabilities
  - Multiple-beam mask writers enable curvilinear patterns