# Flexible illumination for ultra-fine resolution with 0.33 NA EUV lithography

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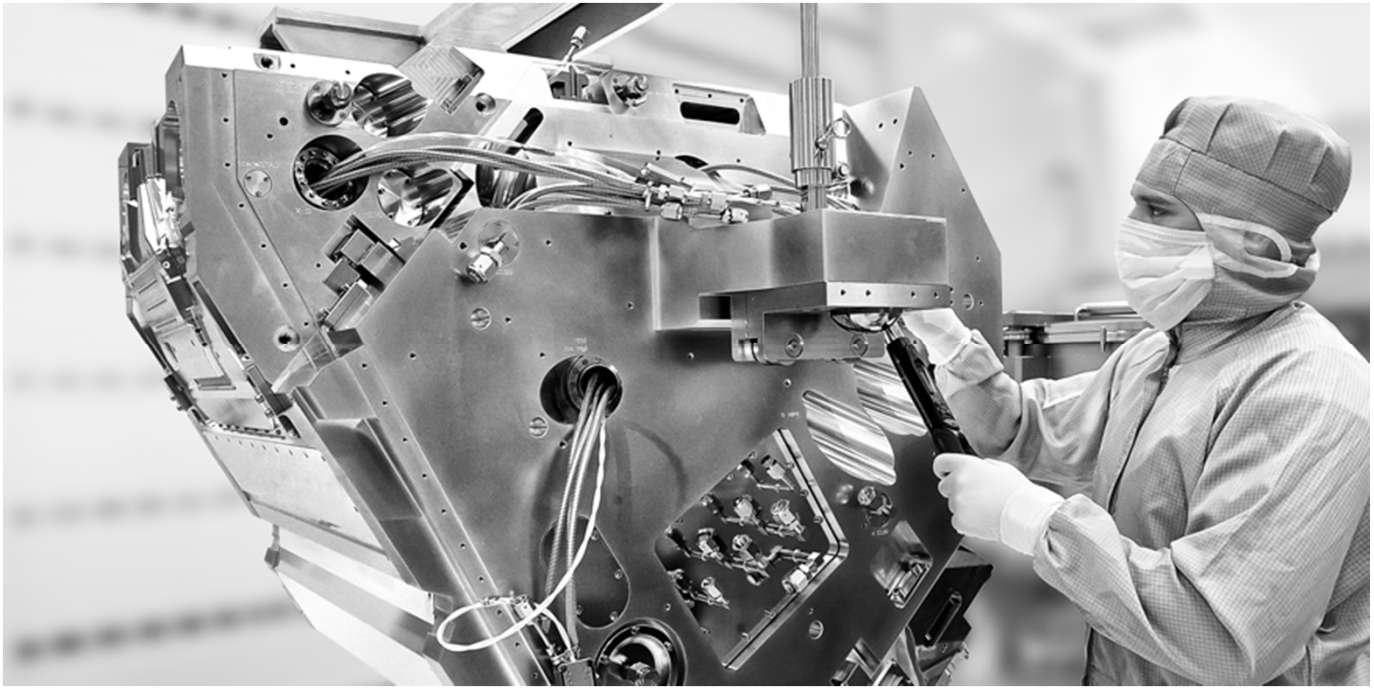
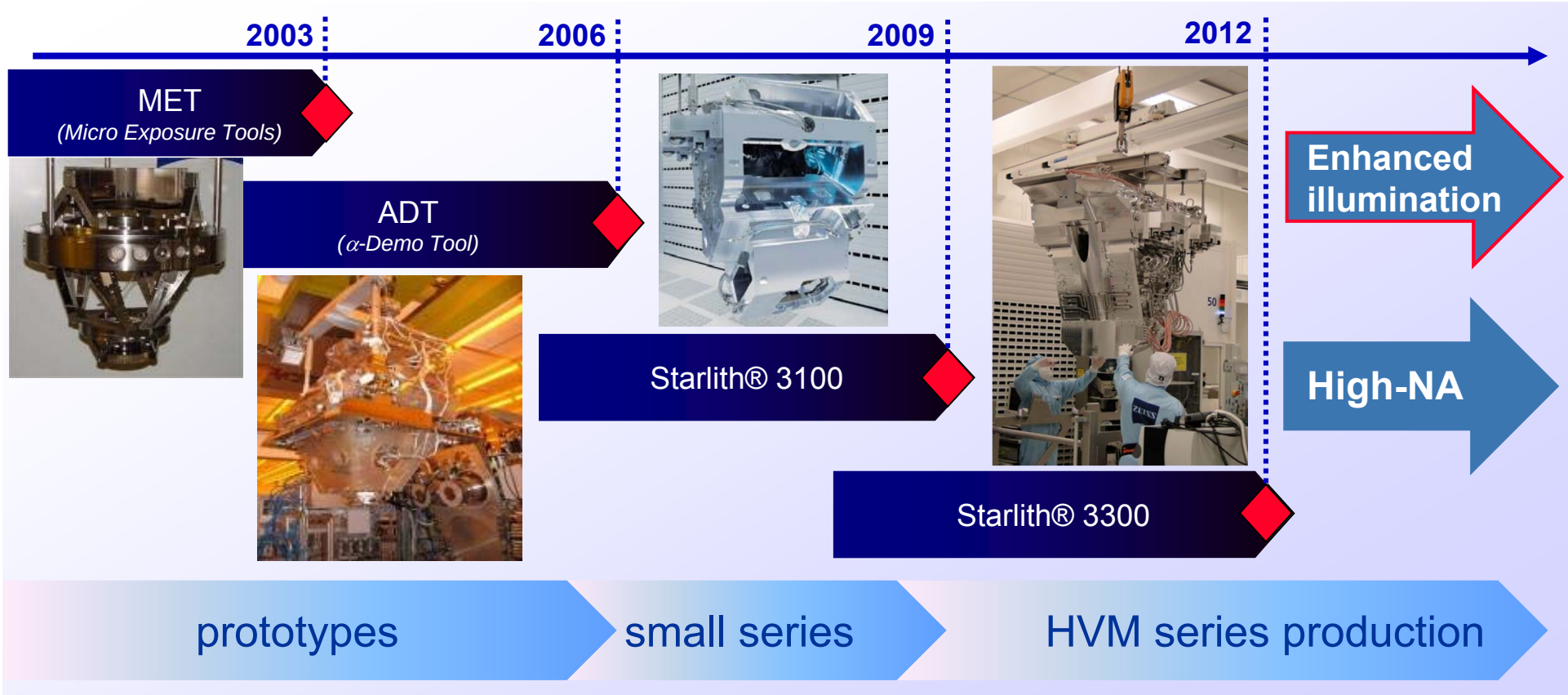


2016 International Symposium on Extreme Ultraviolet Lithography, Hiroshima, Japan, 2016-10-24

# EUV program at ZEISS

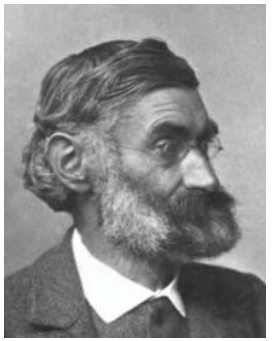


# Resolution enhancement by low-k1 illumination

$$\text{Resolution} = k_1 \cdot \frac{\lambda}{NA}$$

$\lambda$ = 13.5 nm

$NA$ = 0.33



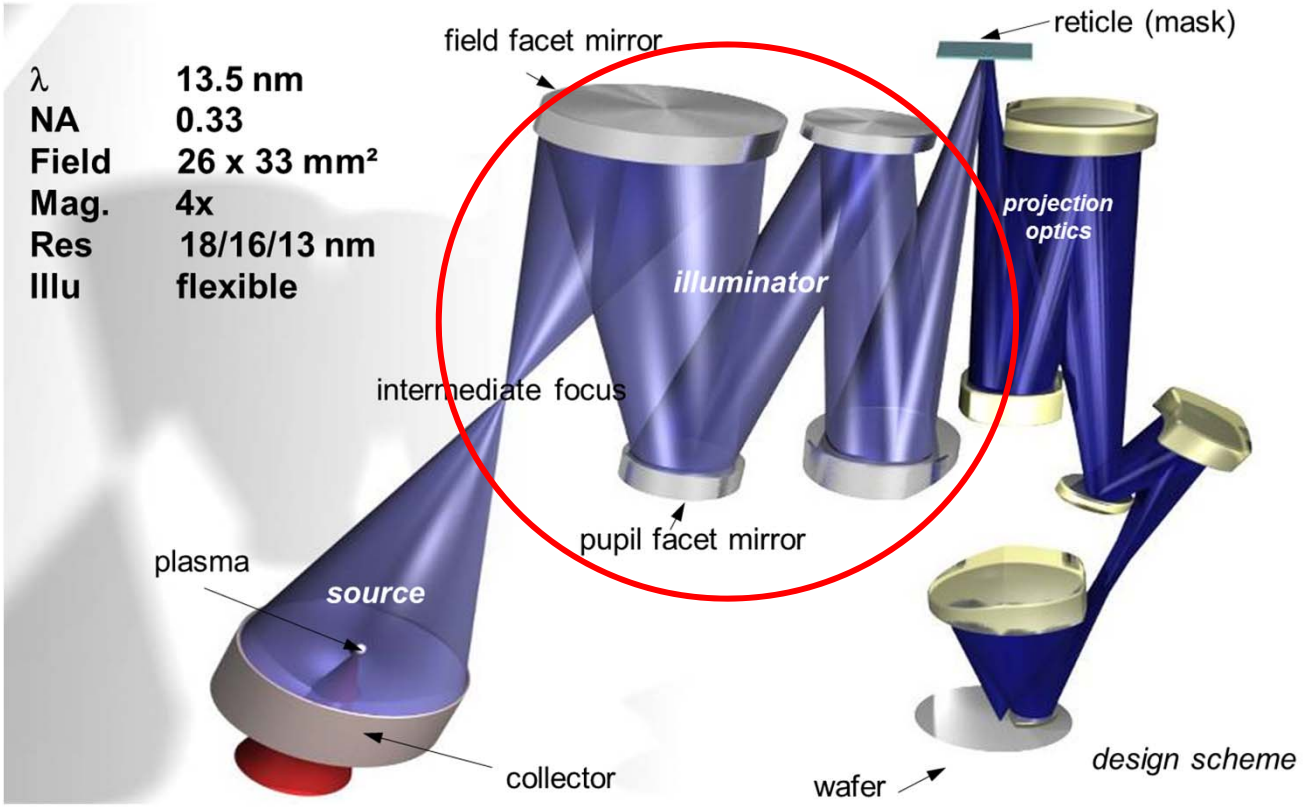
Ernst Abbe (1873)

Reduce the process factor $k_1$

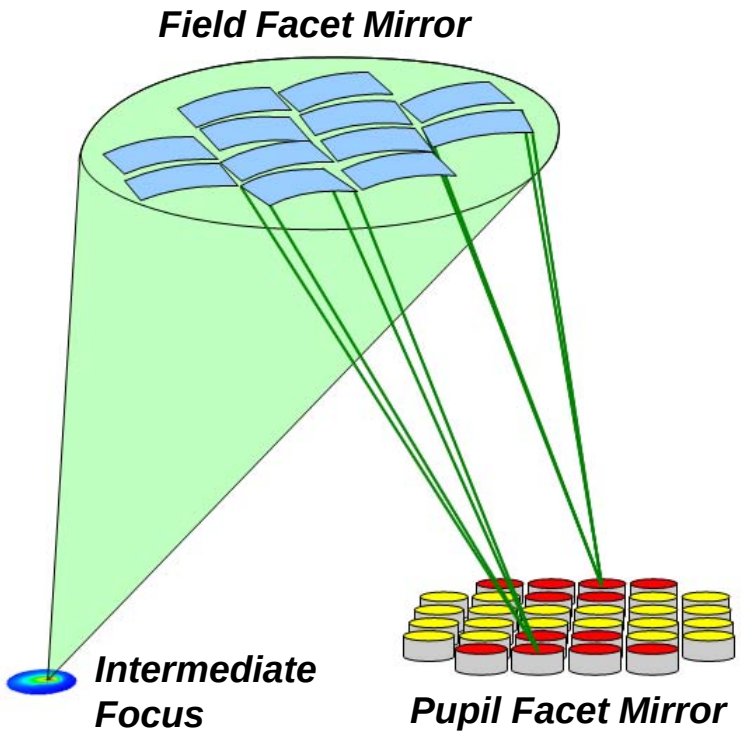
by applying enhanced **illumination** (similar as in DUV lithography)

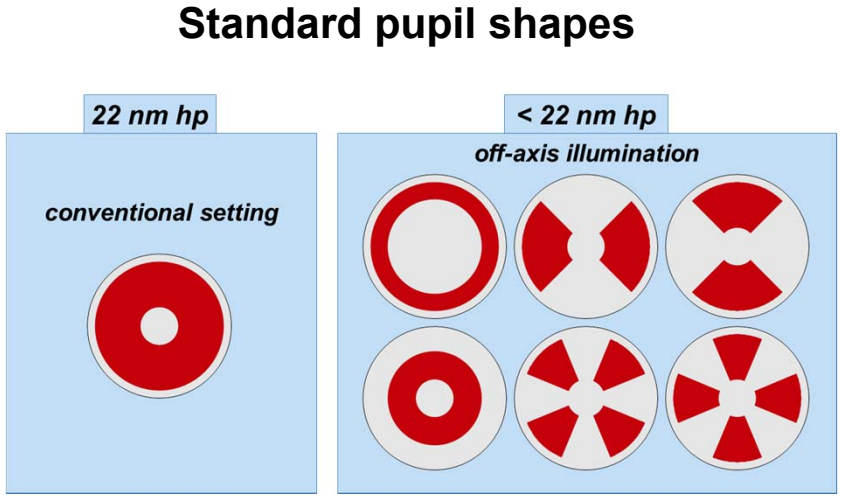
- high sigma settings
- smaller pupil fill ratio
- customized freeform pupils

# Starlith® 3300 optical train



# Starlith® 3300 illuminator: Actuated fly's eye unit enables lossless setting changes



# Pupil Fill Ratio (PFR) of EUV pupils

Pupil Fill Ratio (PFR) definition: the area of the pupil filled with energy

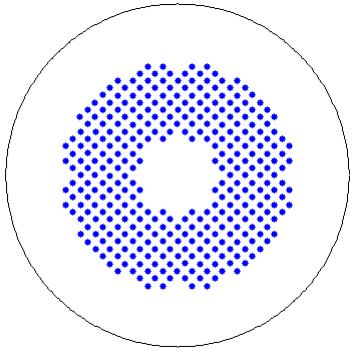
$$PFR = \frac{\sum_{n=1}^{N} I_n}{I_{\max} \cdot N}$$

$N$: number of grid pixels with $\sigma \leq 1$

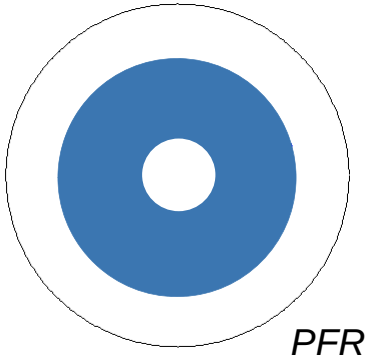
$I_n$: intensity of grid pixel $n$

$I_{max}$: max. intensity of any grid pixel

**not** applicable to discrete EUV pupils directly

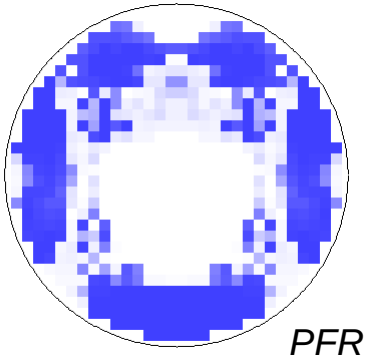


applicable to corresponding tophat envelope



*PFR = 40%*

also applicable to greyscale freeforms

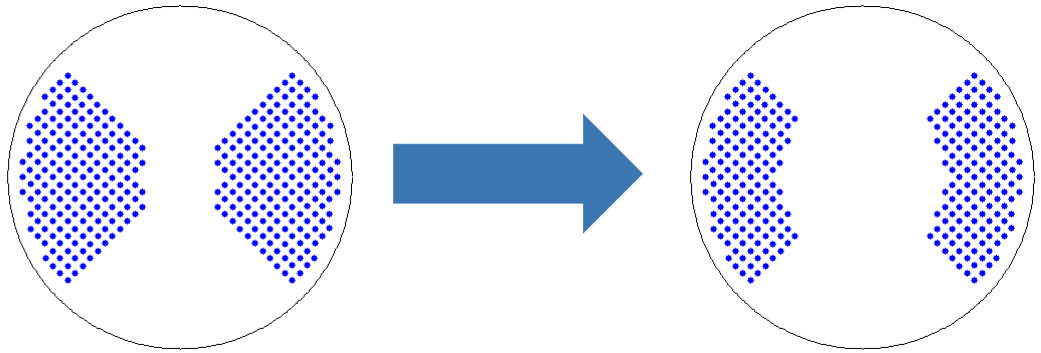


*PFR = 43%*

# Decrease the Pupil Fill Ratio (PFR) on the Starlith® 3300 illuminator

Pupil shapes with smaller PFR can be supported on the Starlith® 3300 illuminator, by switching off pupil channels, **reducing the illuminator efficiency**.

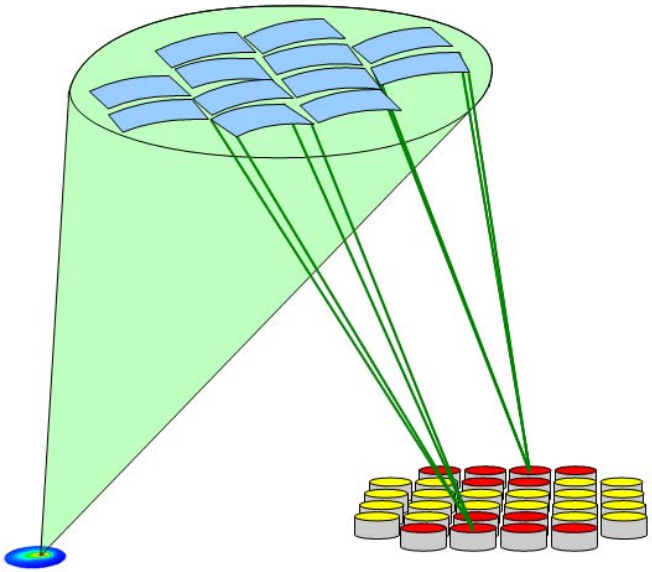
$$\text{illuminator efficiency} = \frac{\text{total energy which is used in the actual pupil}}{\text{total energy in the pupil if all channels were switched on}}$$



*illuminator efficiency = 100%* *illuminator efficiency = 78%*

# Higher pupil flexibility
# by increased number of pupil facets

**Pupil switching mechanism**



**Starlith® 3300:**

one field facet can address two pupil channels

**New generation:**

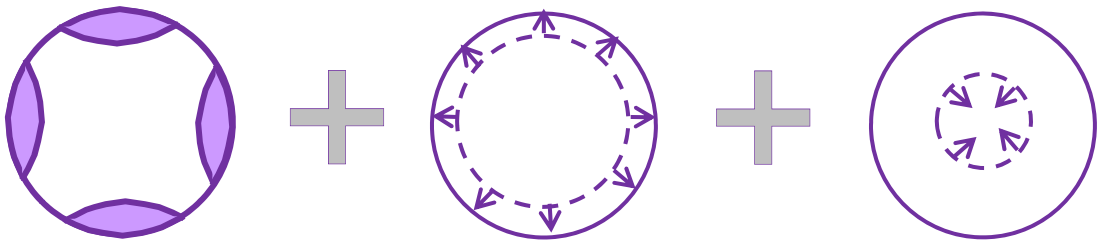
one field facet can address many pupil channels

→ **decrease pupil filling**

→ **enable ≥ 20% pupil fill ratio at full illuminator efficiency**

# New generation illumination for low-k1 imaging

**Decrease pupil filling** **Extend sigma range**

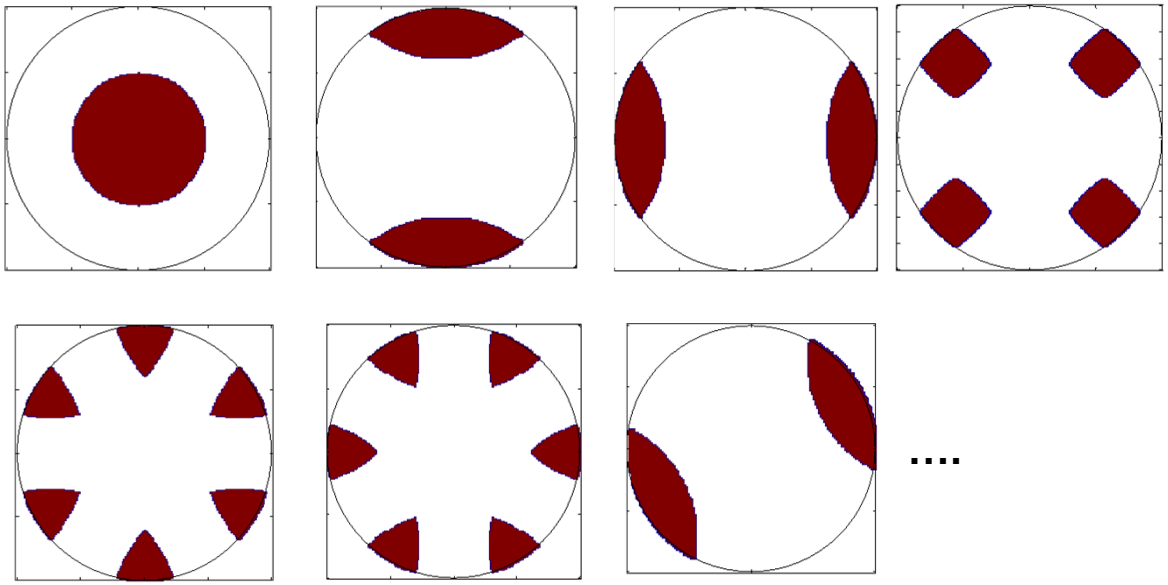


**Optimized pole shapes & maximum pupil flexibility**

- Highest possible resolution down to 13 nm with NA = 0.33 and $k_1$= 0.32
- New & more illumination settings for upcoming nodes at full throughput

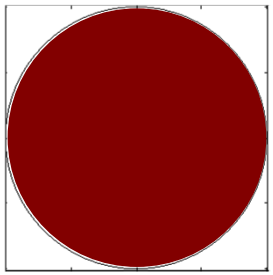
# New generation pupil shapes

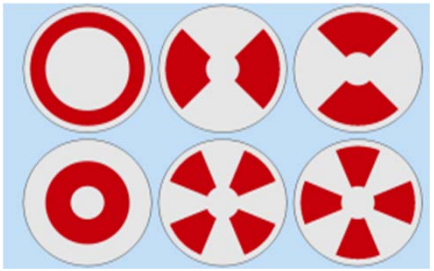
**Pupil shapes with 20% pupil fill ratio**



....

**... and with larger pupil fill ratio**

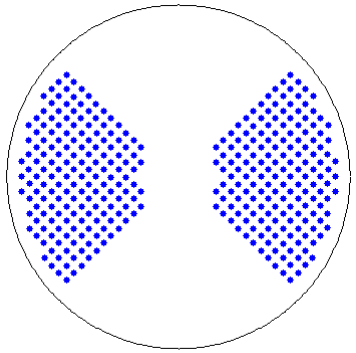




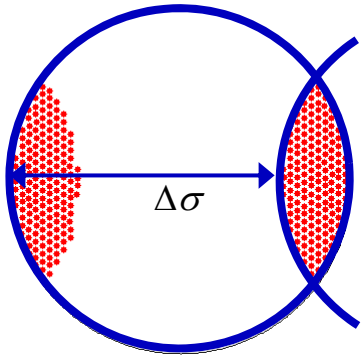
standard settings 3300

# Leafshape Dipoles for 13 nm half-pitch resolution at 100% illuminator efficiency

**Starlith® 3300**



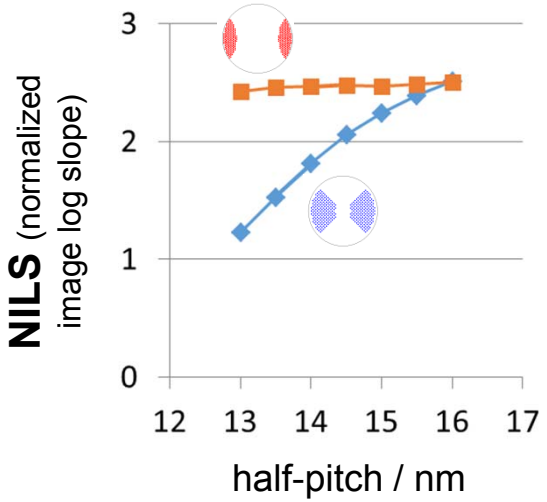
**New generation**




$$\Delta\sigma = \frac{\lambda}{NA \cdot p} = \frac{13.5\,\text{nm}}{0.33 \cdot 26\,\text{nm}} = 1.57$$

≈ 20% pupil fill ratio

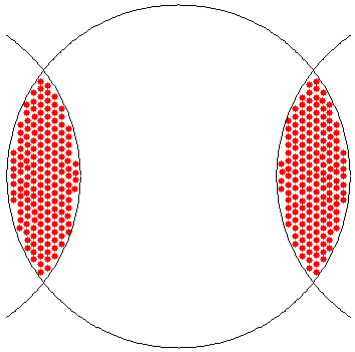
aerial image simulation
(zero defocus, topographic mask)




→ 13 nm resolution at full throughput

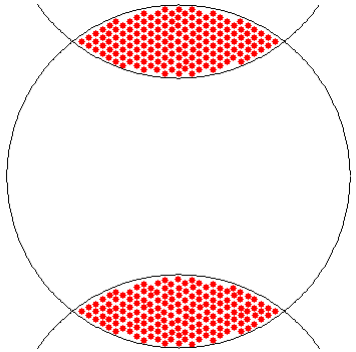
# Dipoles for 13 nm half-pitch resolution
# Quasar for 18 nm half-pitch H & V

**Dipole X**



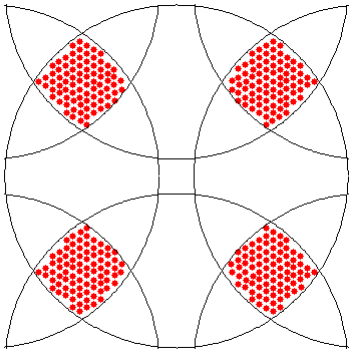
vertical Lines&Spaces
**13 nm** half-pitch

**Dipole Y**



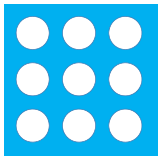
horizontal Lines&Spaces
**13 nm** half-pitch

**Quasar**



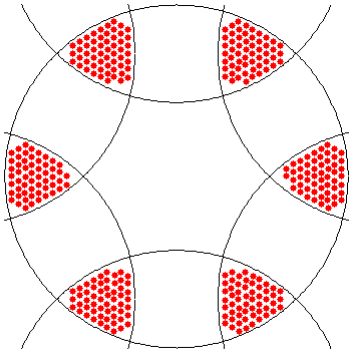
H&V Lines&Spaces
18 nm half-pitch

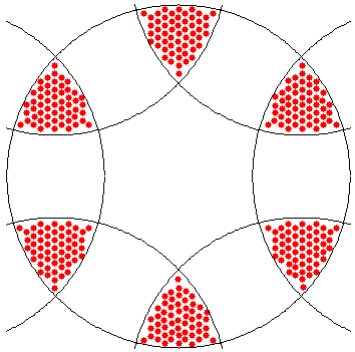
Contact Hole array
18 nm half-pitch



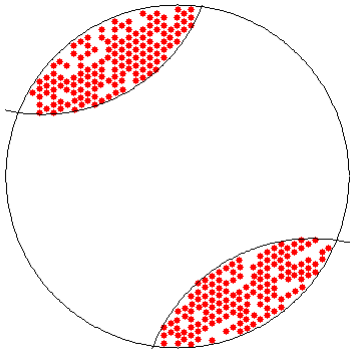
# Hexapoles and Rotated Dipoles for DRAM

## Hexapoles

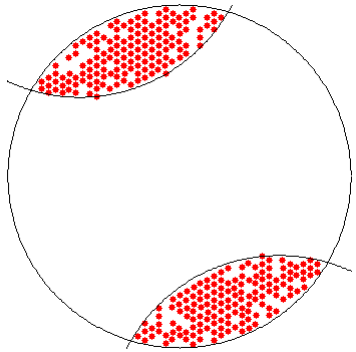




## Rotated Dipoles 30°

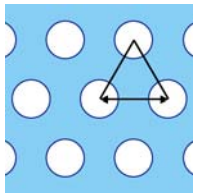


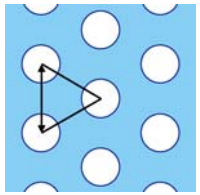
## Rotated Dipoles 22°



for DRAM storage node (hexagonal contact hole array)

16.5 nm half-pitch Single Exposure





15 nm hp Double Patterning

for DRAM active area

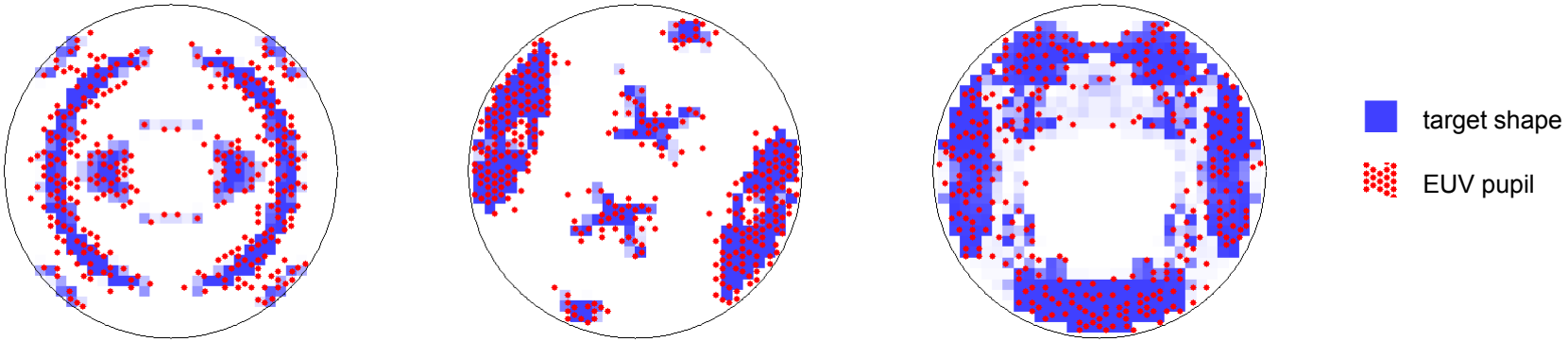
13 nm hp SE

# Freeform pupil shapes

**SMO pupil**
for logic cut mask

**rotated pupil shape**
for DRAM brickwalls

**y-asymmetric**
3D mask compensation



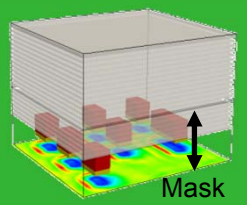

all examples without light loss (100% illuminator efficiency) on new generation illumination system

# Source mask optimization (SMO): Tachyon SMO NXE flow

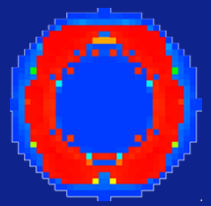
Tachyon FEM+ Model:
- Jones Pupil
- Aberrations
- 3D mask model
- Resist model

**New EUV stages (green boxes) for NXE:33x0 FlexPupil optimization**

Mask defocus optimization

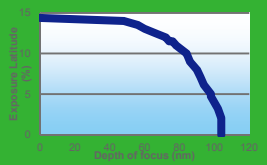



Freeform pupil & mask co-optimization



Discrete mirror state & mask co-optimization

Final pupil & OPC mask analysis



**CDU, Δshift, EPE**

NXE:33x0 pupil verification & connectivity

# Pupil properties taken into account in Tachyon SMO NXE flow


to achieve best match of optimized freeform pupil to final EUV pupil:

- min/max sigma range of illuminator generation
- minimum pupil fill ratio for lossless pupil (i.e. **100% illuminator efficiency**)

3300: min **PFR** ≈ 40%

new generation: min **PFR** ≥ 20%

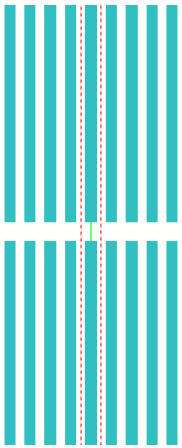
# ZEISS models integrated into Tachyon SMO NXE flow

Discrete mirror state & mask co-optimization

ZEISS pupil prediction model integrated into Tachyon SMO flow

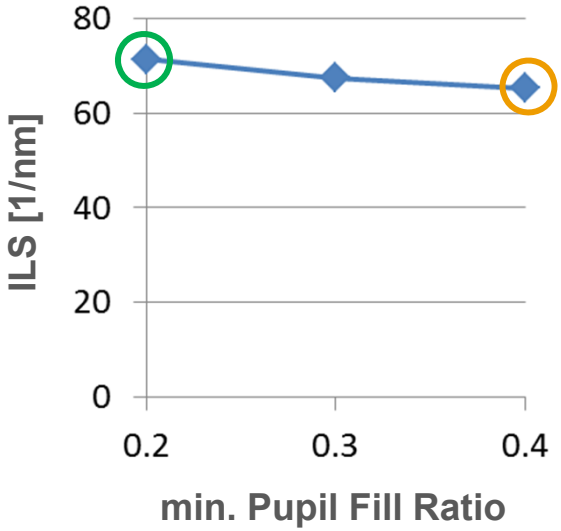
→ Tachyon SMO results can make use of illumination properties most effectively

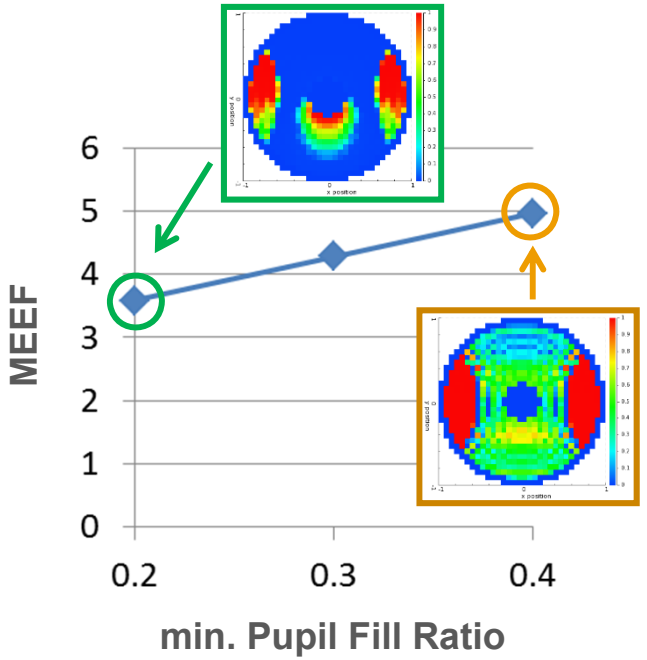
# Tip-to-tip pattern: 13 nm half-pitch, 24 nm gap



with 3D mask model

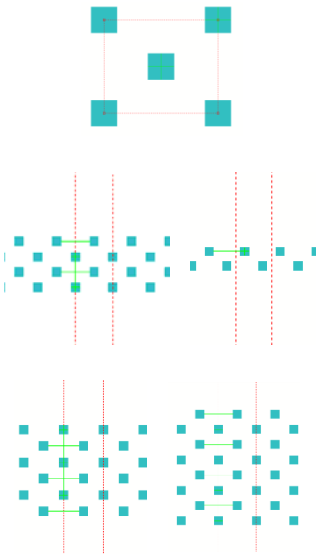
**SMO results: Freeform pupils**



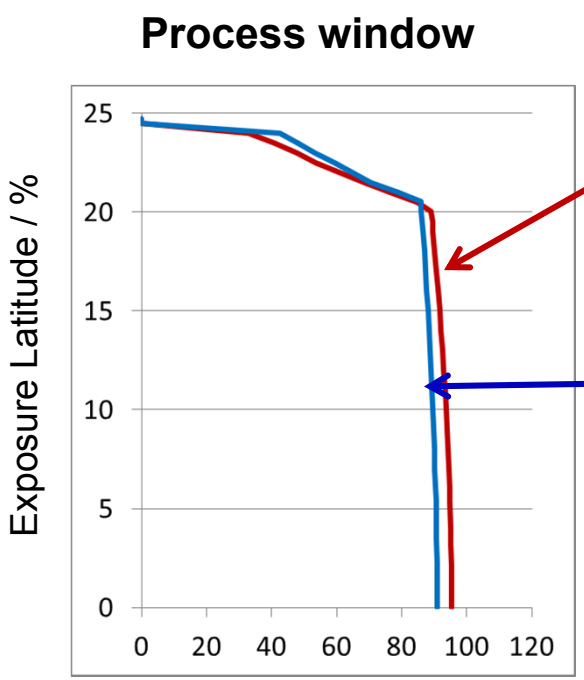



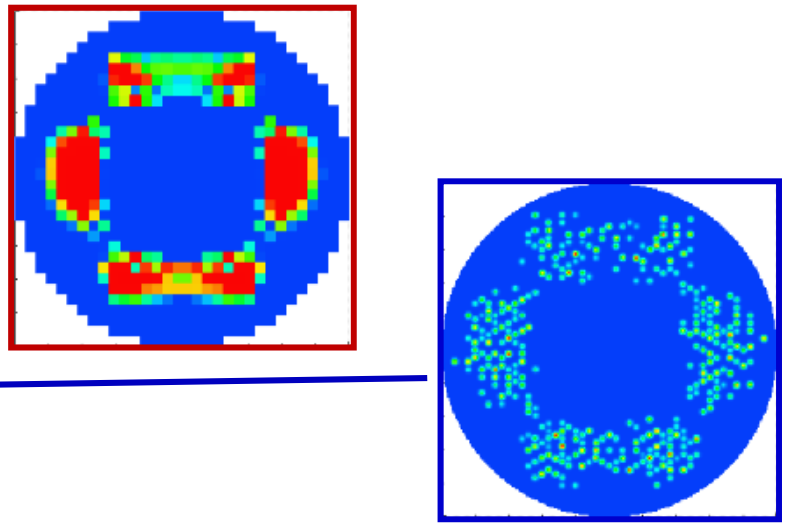

→ **benefit of reduced 20% pupil fill ratio for ILS and MEEF.**

# Via array: 20 nm squares, 42 nm min. pitch



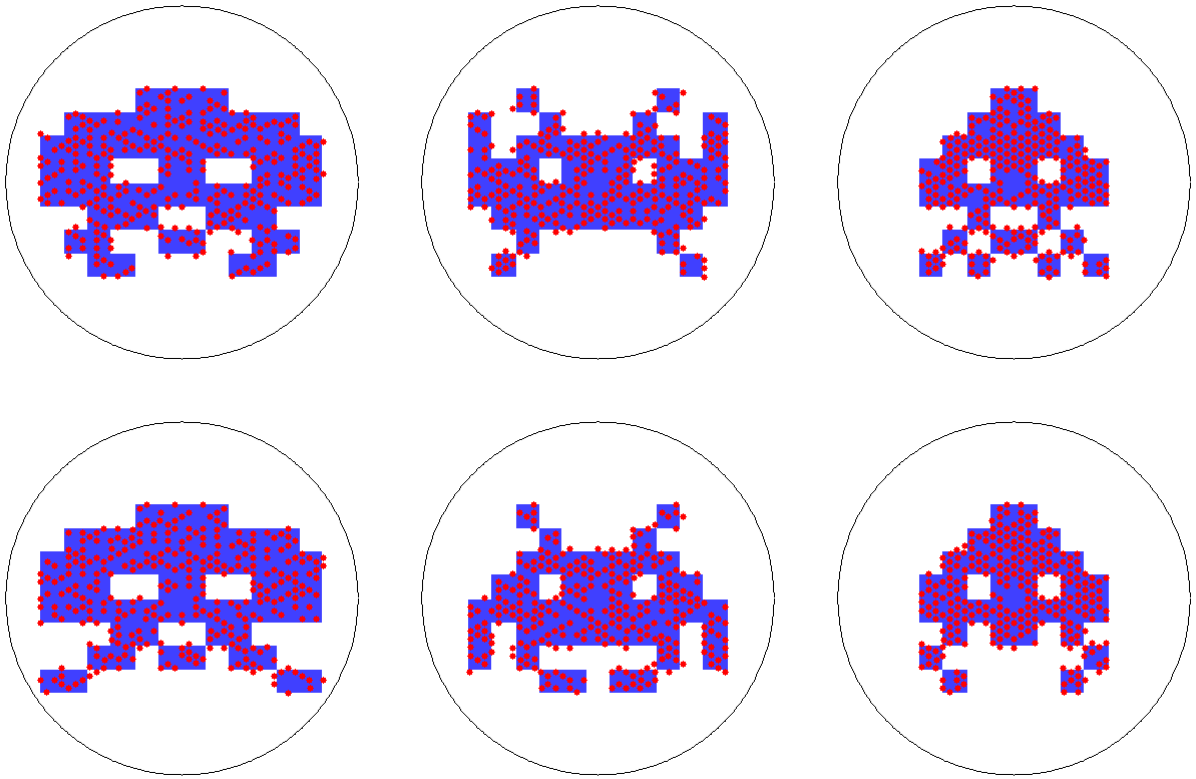
with 3D mask model



→ **Process window of freeform pupil is maintained by EUV pupil.**
(100% illuminator efficiency)

# Arbitrary freeform pupil shapes are possible



target shape

EUV pupil

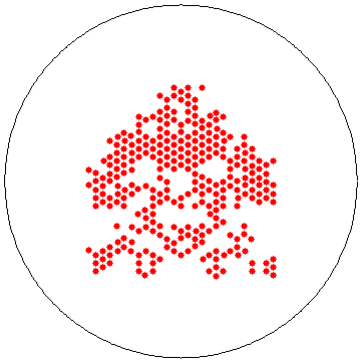
Shapes designed by
Tomohiro Nishikado (1978)

# Pupil tuning can adjust proximity bias

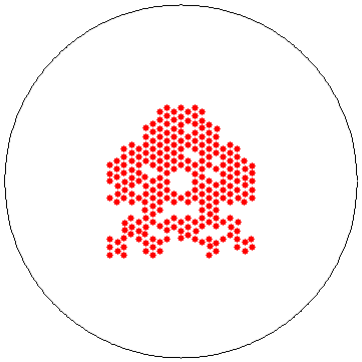
after mask tape-out, tweek the process to adjust the proximity curve, i.e. iso-dense bias?

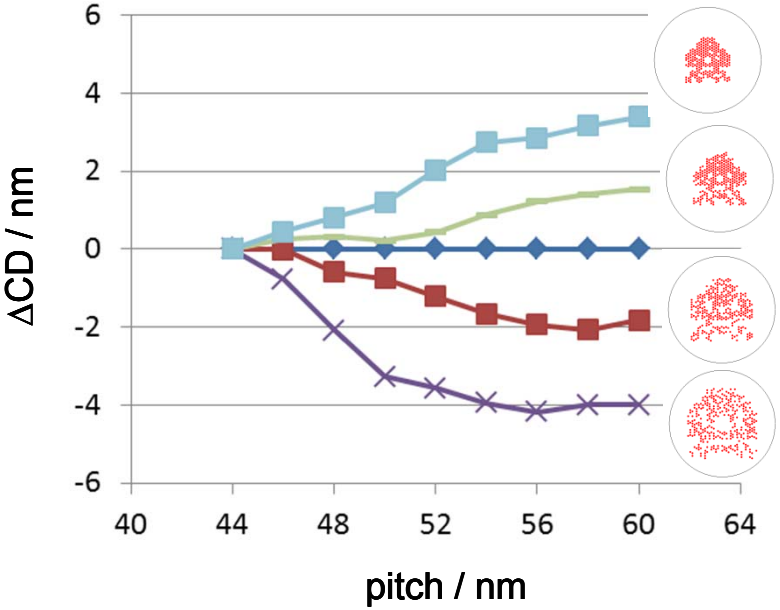
→ adjust the pupil by switching a few pupil spots

original pupil



after pupil tuning

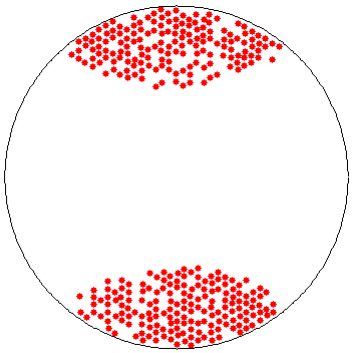


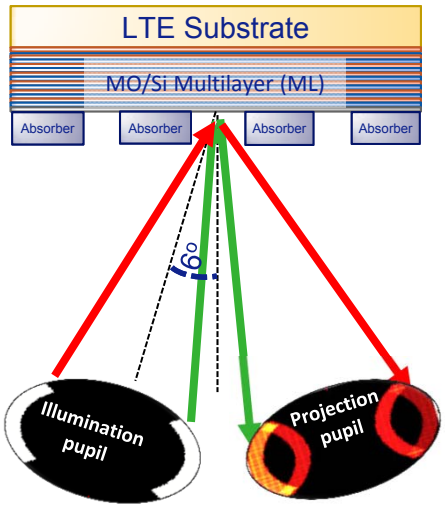


# Another challenge for pupil tuning: 3D mask induced pattern shift through focus

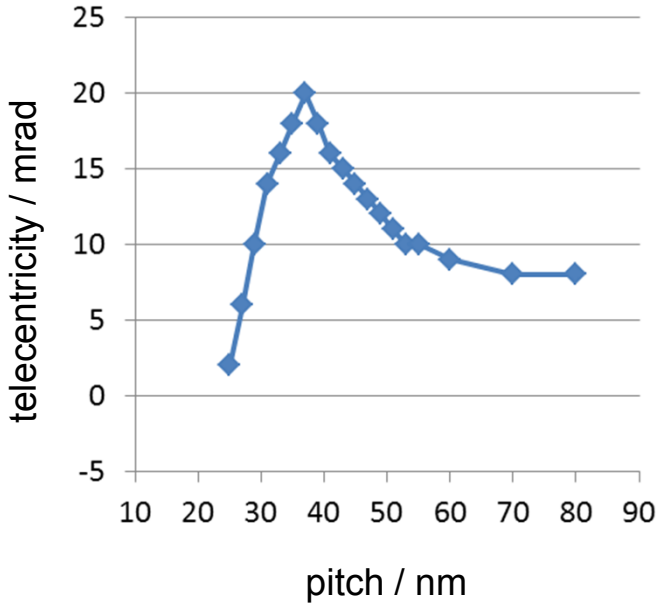
due to oblique incidence on mask,
3D mask effect can induce imaging telecentricity
(placement error divided by defocus)

Dipole Y





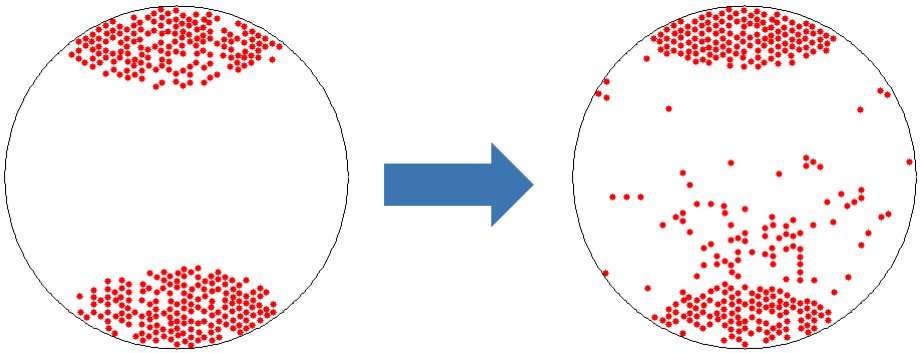

Pattern shift through focus



# Pupil tuning can compensate for 3D mask induced pattern shift through focus

→ adjust the pupil (induce a pupil imbalance) to compensate for the 3D mask induced telecentricity through pitch
(while maintaining the proximity behavior)

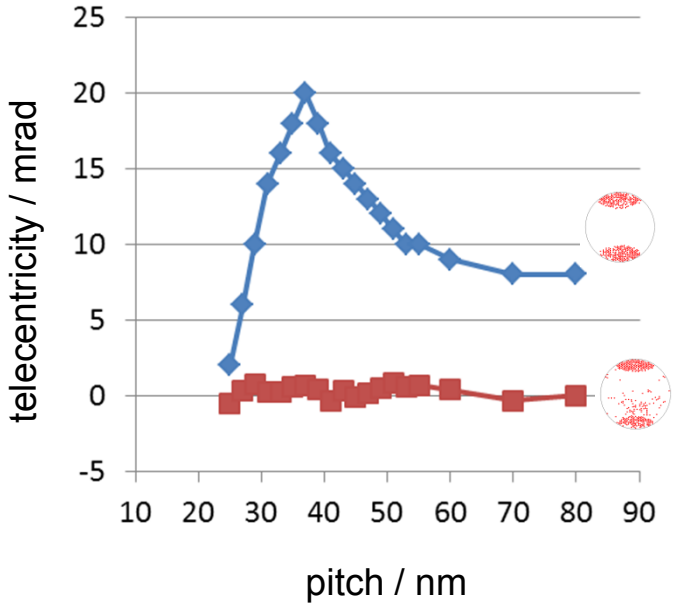
before tuning



after pupil tuning



Pattern shift through focus



# Summary: Flexible illumination at 0.33 NA

- New generation EUVL illumination will support 20% pupil fill ratio (PFR) at full illuminator efficiency, and cover the full sigma range.
- Will provide lossless pupil shapes for ultimate imaging resolution for 0.33 NA EUVL at 13 nm half-pitch, or bi-directional imaging at 18 nm half-pitch H&V.
- High pupil flexibility ensures support of Source Mask Optimization (SMO).
  - can generate arbitrary customized freeform pupils with ≥ 20% pupil fill ratio.
  - Predictive illuminator model is integrated in Tachyon SMO software.
- High pupil flexibility supports pupil matching and Pupil Tuning applications.

# The roadmap continues: High NA

**High NA EUVL will enable further shrink below 8 nm resolution.**

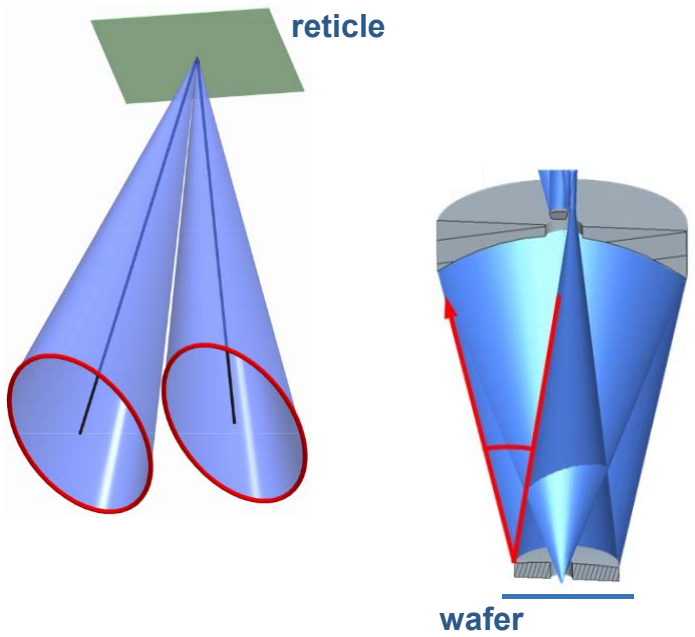
**High NA EUVL from illuminator perspective:**

- larger angles
- anamorphic system

  MAG 4x in x, MAG 8x in y

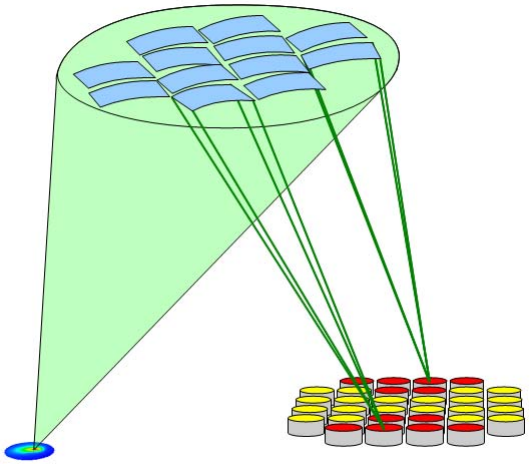
  Angular cone of illumination light at reticle will be elliptical.

- central obscuration in the projection pupil

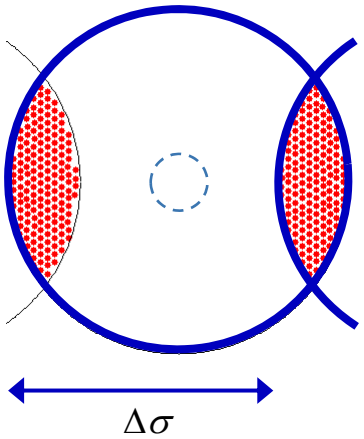


# Flexible illumination for High NA

same Flex Pupil concept can be used

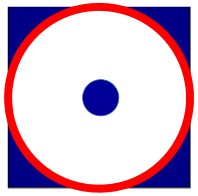


Dipole setting for ultimate resolution




20% pupil fill ratio for ≤ 8 nm resolution

POB obscuration



not limiting the illumination

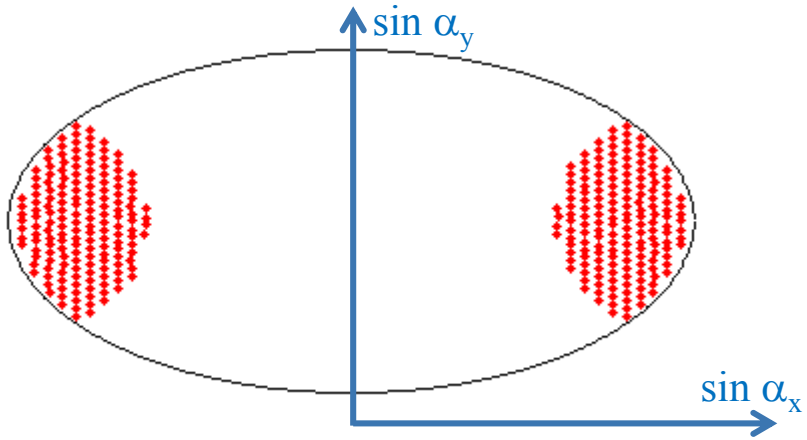
no need to put illumination light into the pupil center

# Flexible illumination for High NA

**Anamorphic system:**

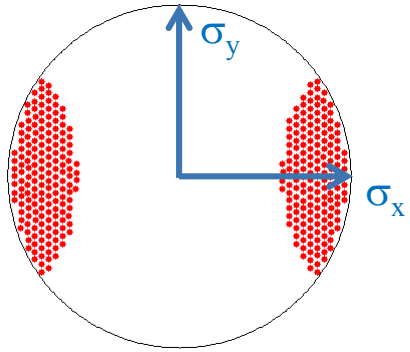
*physical angles*

- illumination pupil looks elliptical
- simulation SW takes the actual angles into account for 3D mask calculation




*normalized pupil coordinates ("sigma")*

- pupil looks circular, by definition of sigma coordinates
- business as usual for lithographer



# Conclusion

- **High pupil flexibility at 0.33 NA**
  - will provide lossless pupil shapes for 13 nm half-pitch resolution.
  - will provide arbitrary lossless pupils with ≥ 20% PFR, for SMO and Pupil Tuning.
  - Predictive illuminator model is integrated in Tachyon SMO software.
- **Extension to High NA EUVL**
  - Flex illuminator concept can be extended to High NA anamorphic litho optics.
  - will provide lossless pupil shapes for ≤ 8 nm half-pitch resolution and support SMO and Pupil Tuning applications.
  - Low-k1 EUVL for subsequent nodes will be enabled by flexible low-PFR illumination on high-NA EUVL systems.

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