New Source and Imaging Capabilities of the SHARP EUV Mask Microscope

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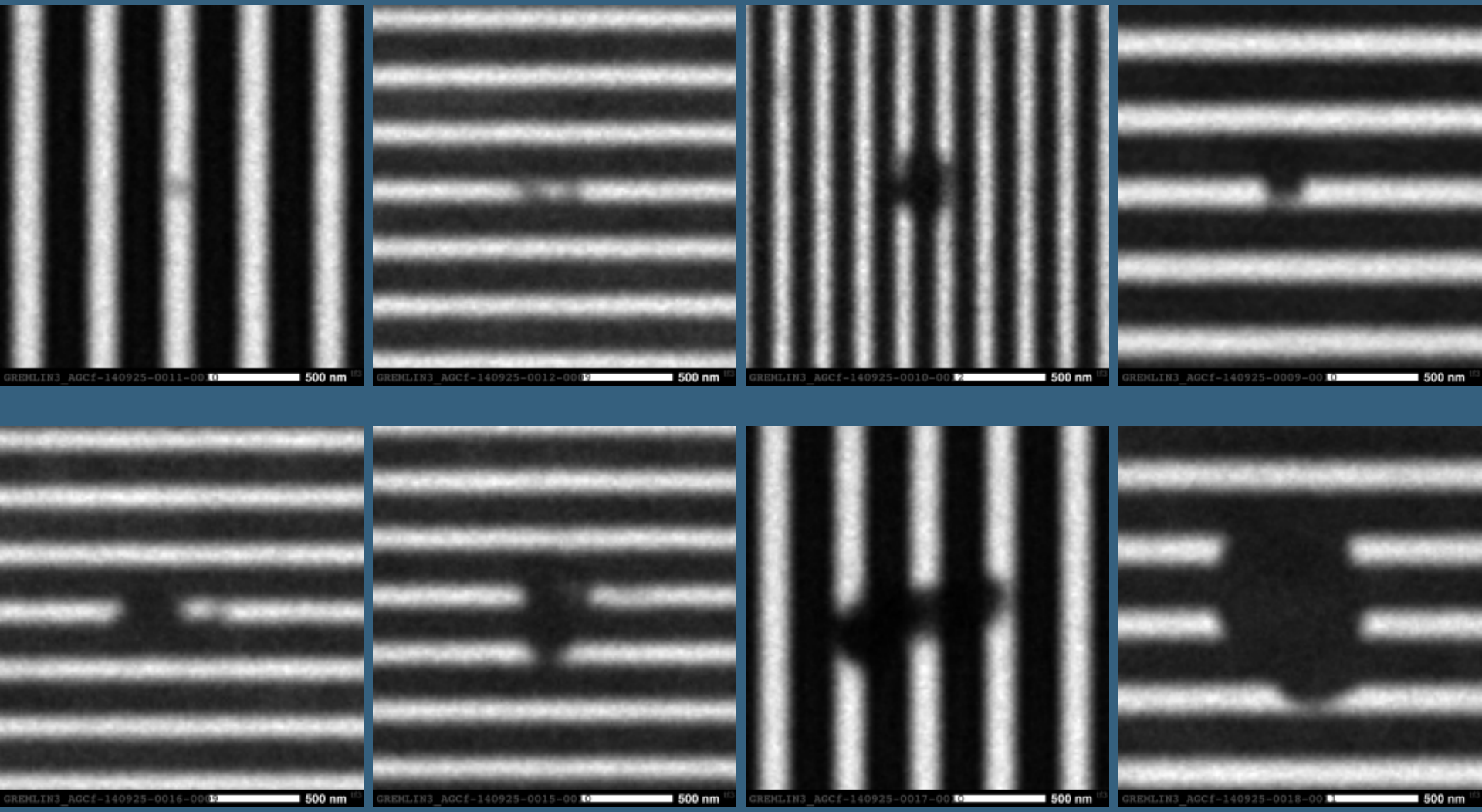
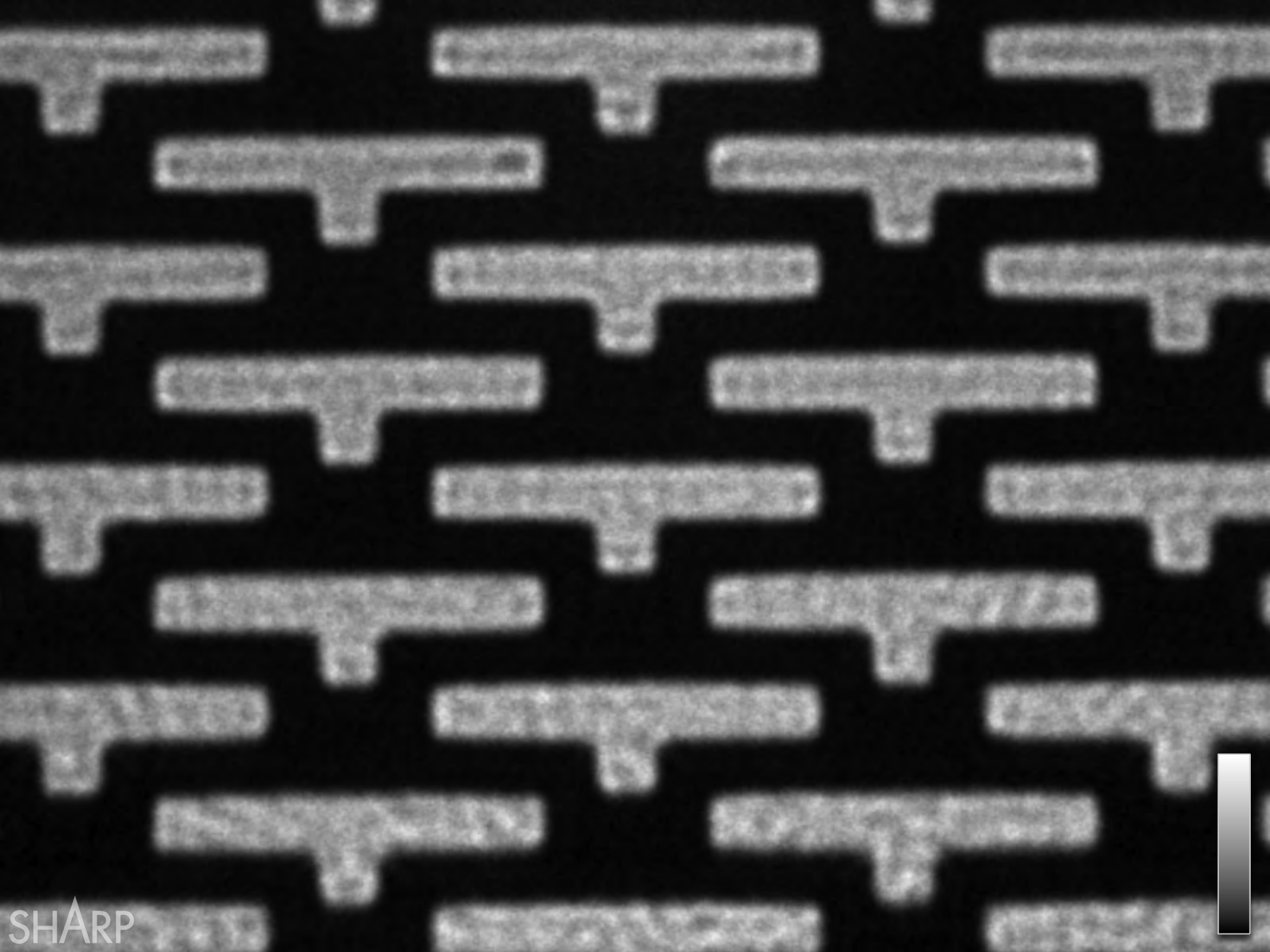
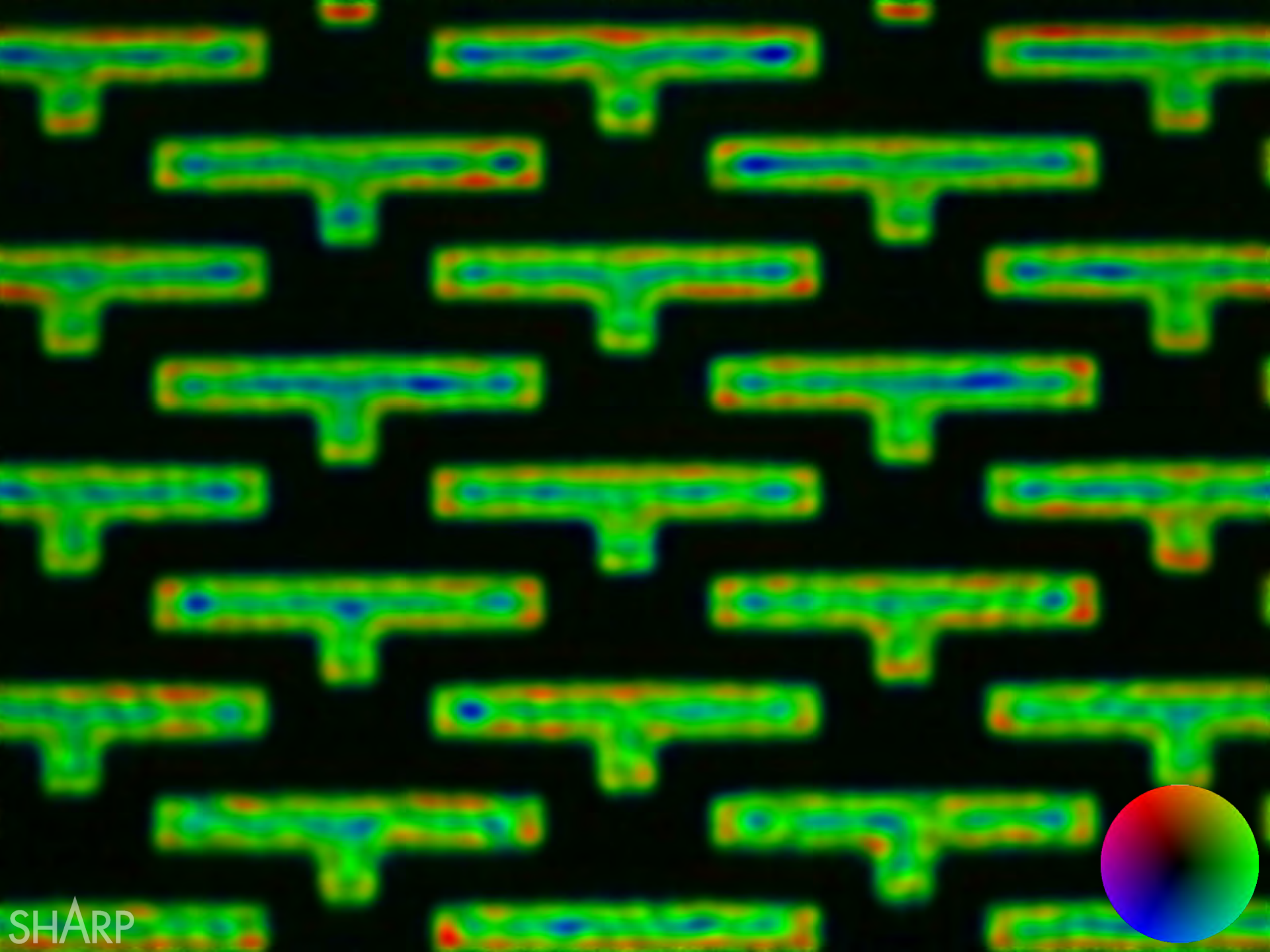
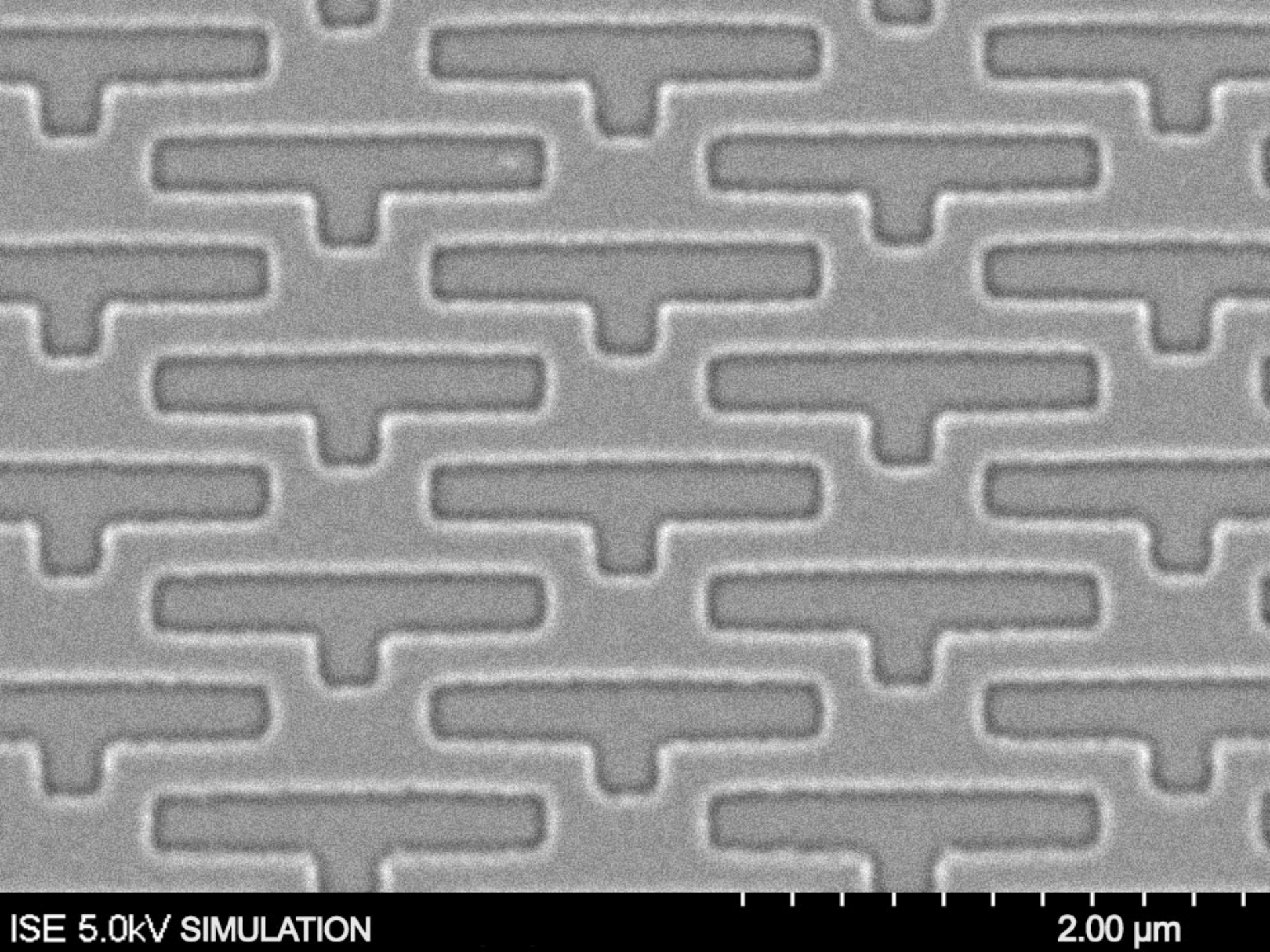
Markus Benk, Antoine Wojdyla, Alex Donoghue, David Johnson,
James Macdougall, Weilun Chao,
Ryan Miyakawa, Yow-Gwo Wang, and Patrick Naulleau



Courtesy Mangat, Wood: **GlobalFoundries**


SHARP


SHARP


ISE 5.0kV SIMULATION
2.00 µm

$$I \xrightarrow{?} \phi$$

SHARP
$I(\sigma)$
$\phi(x)$
Goldberg
Benk
Wojdyla

SHARP

SEMATECH HIGH-NA ACTINIC RETICLE REVIEW PROJECT

Source: Synchrotron

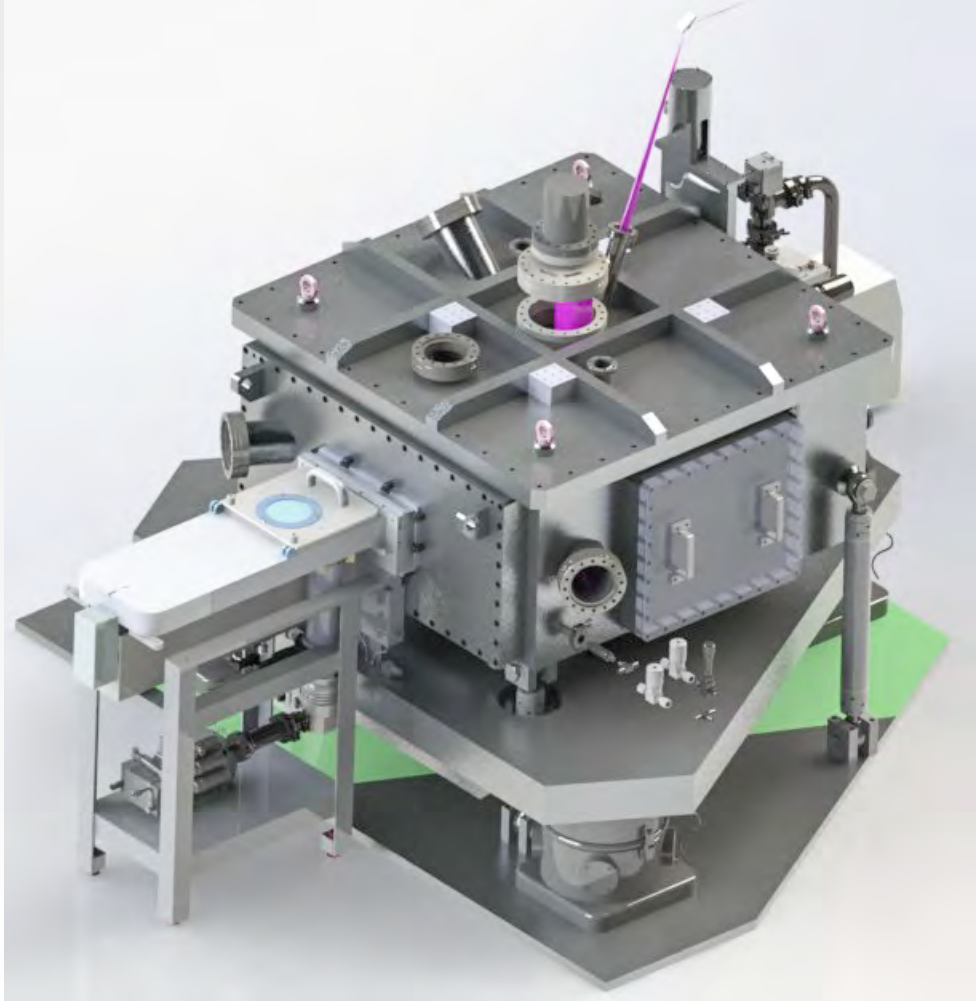
Optics: Mirrors & Zoneplate-lenses

4×NA: 0.25–0.625

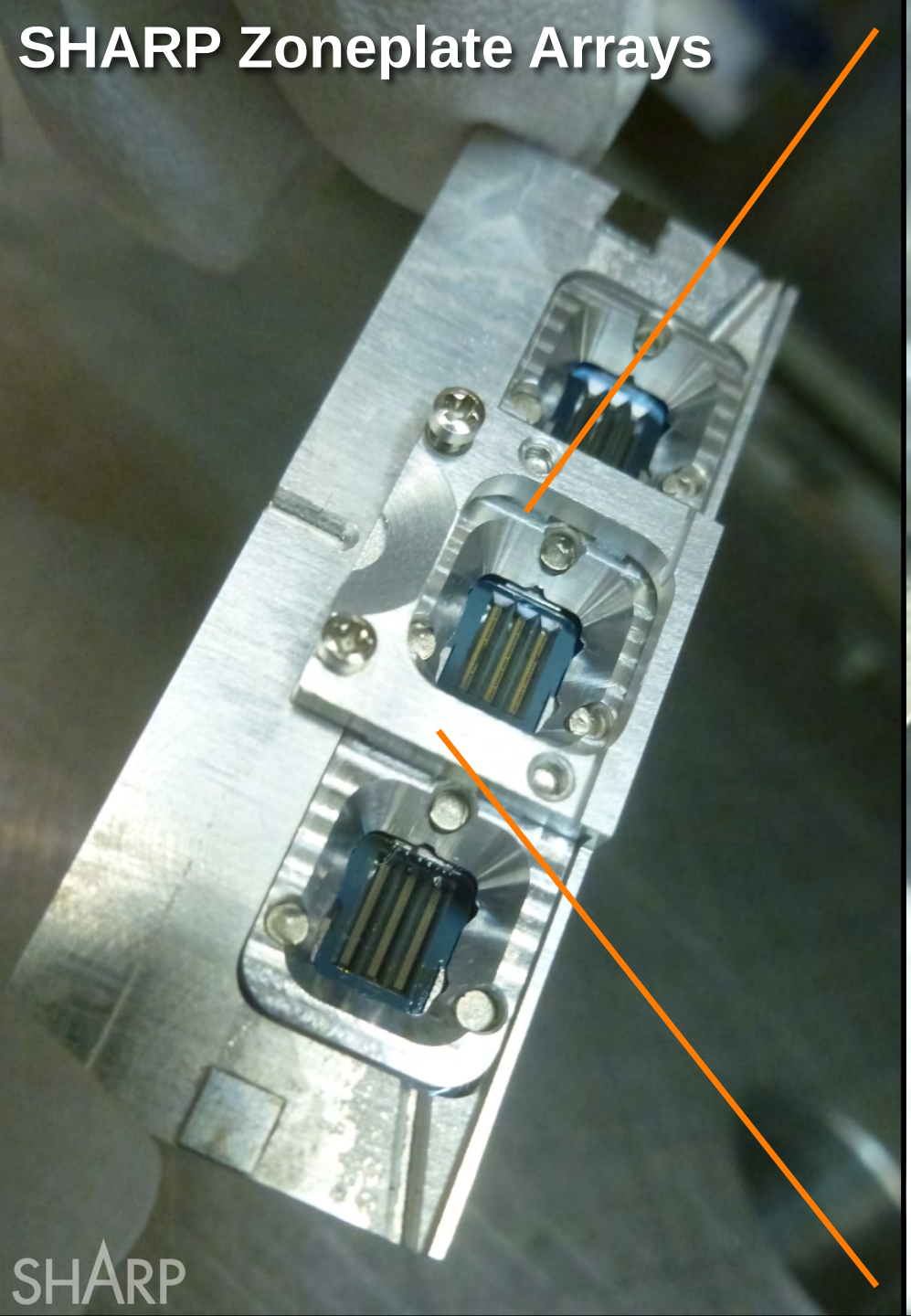
σ: Programmable

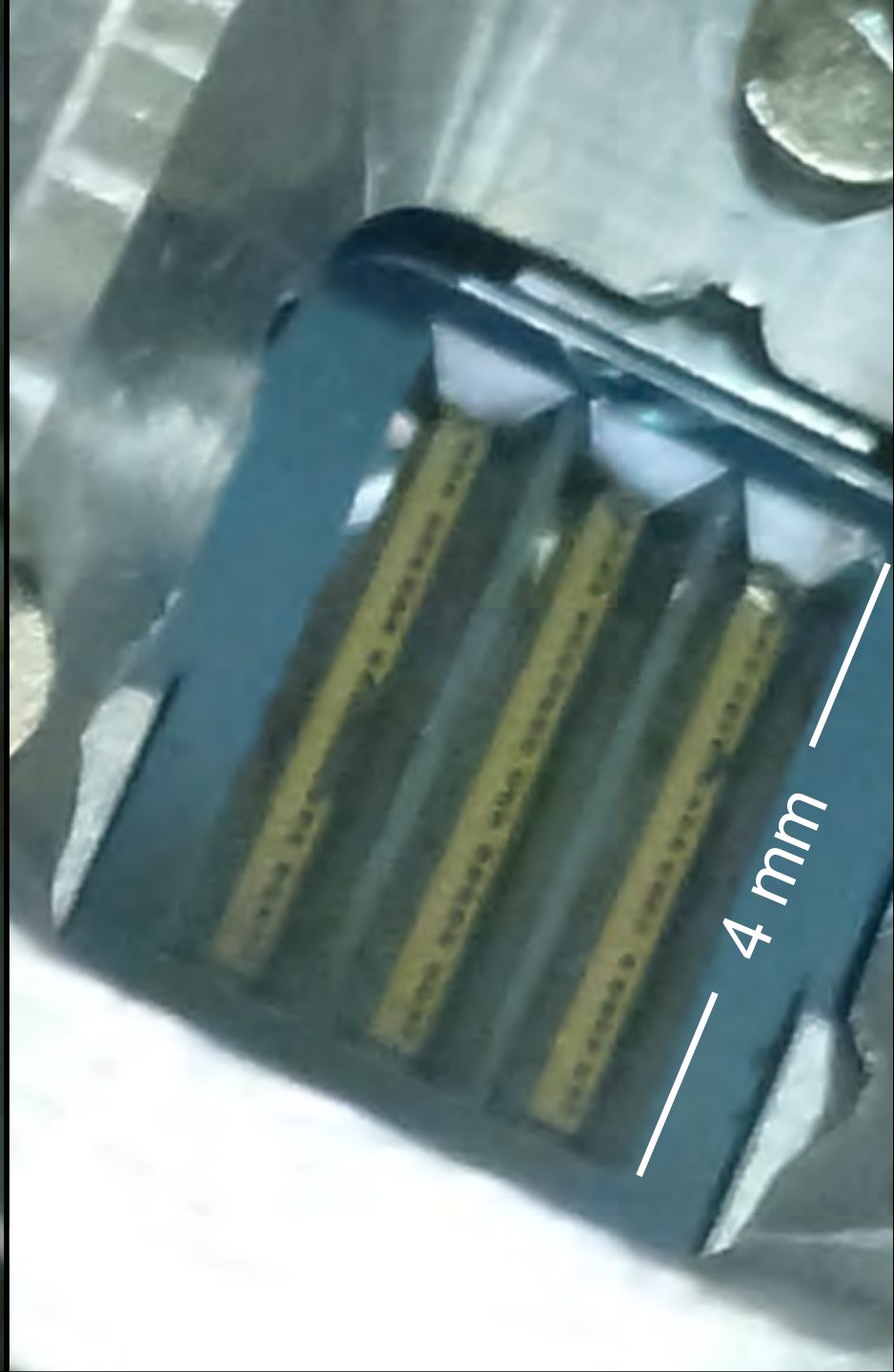
Nav: Full-mask *xy*

Speed: ~8 series/hr



SHARP Zoneplate Arrays





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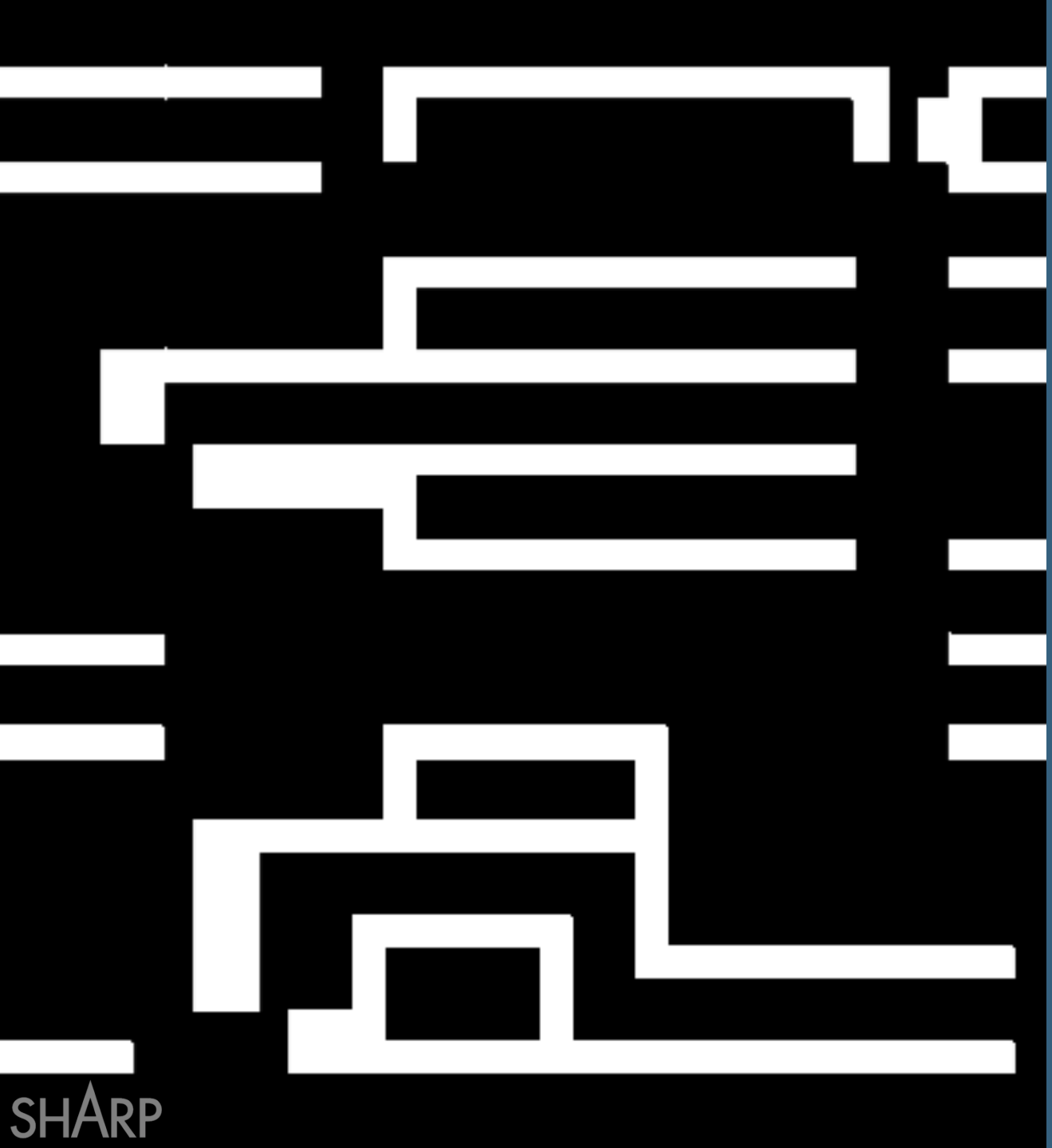
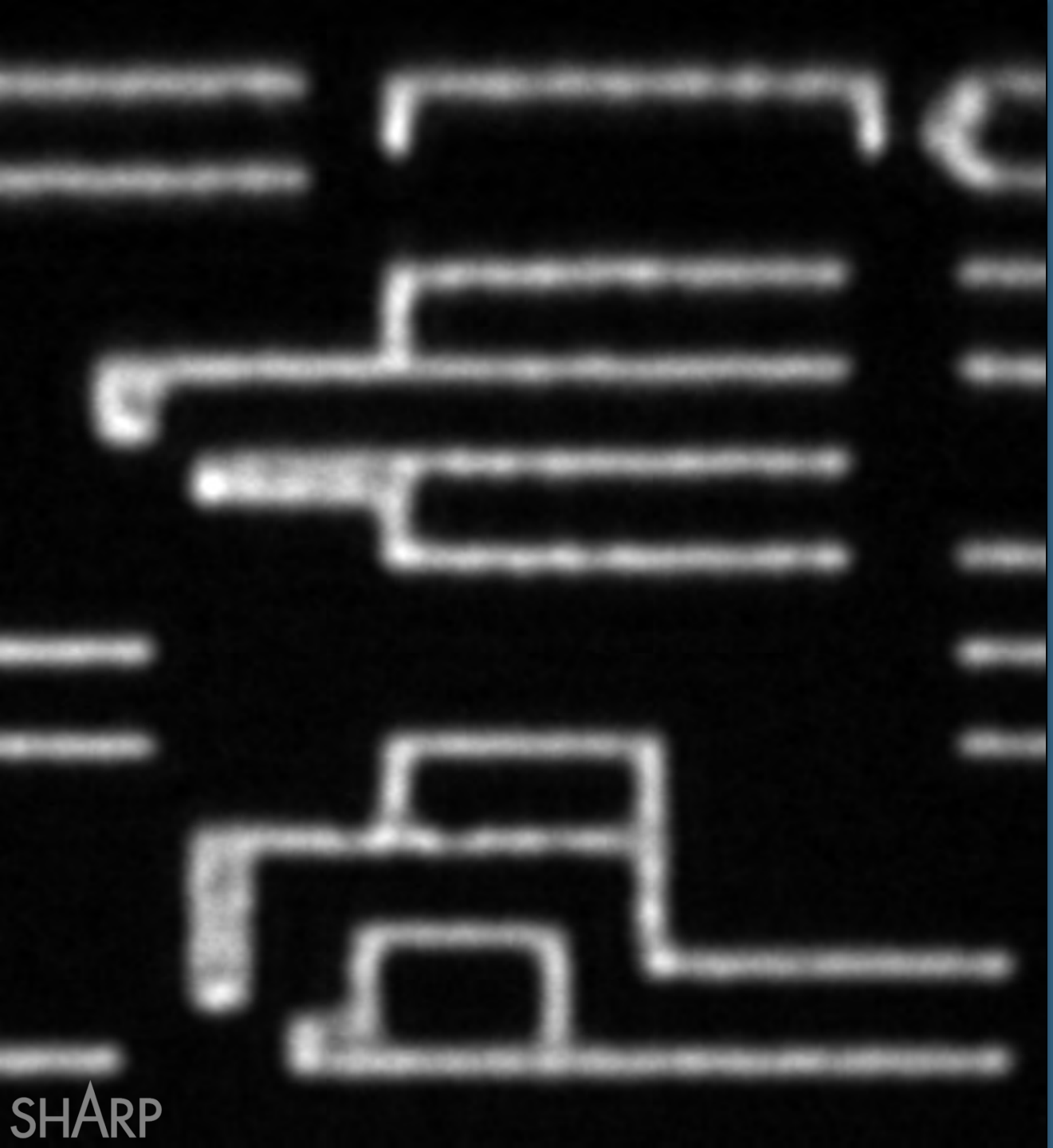
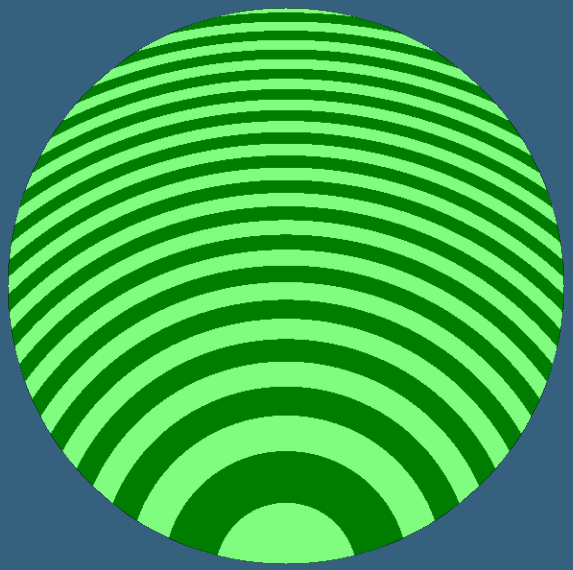


logic pattern

0.5 µm

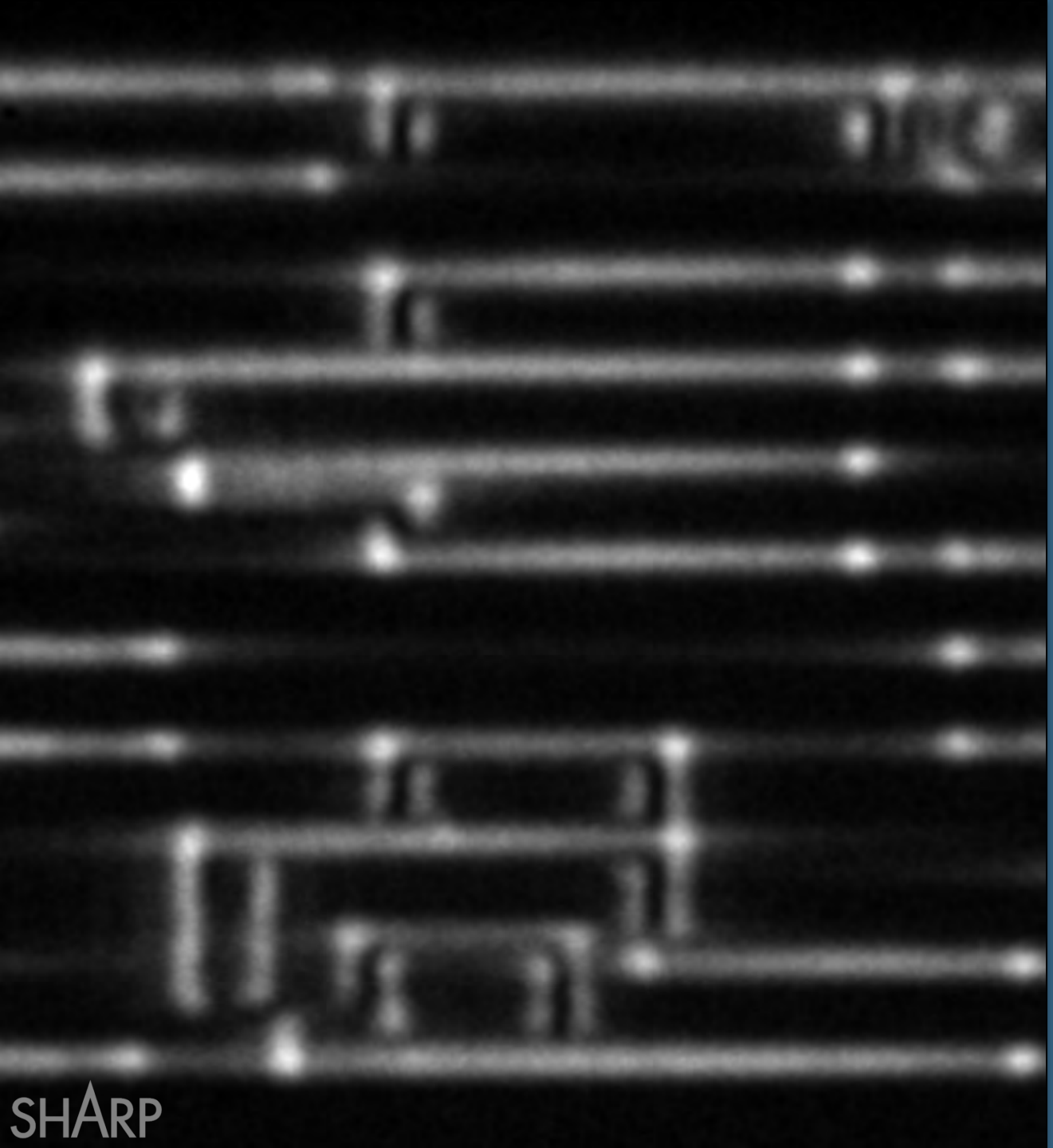




conventional lens

0.5 µm

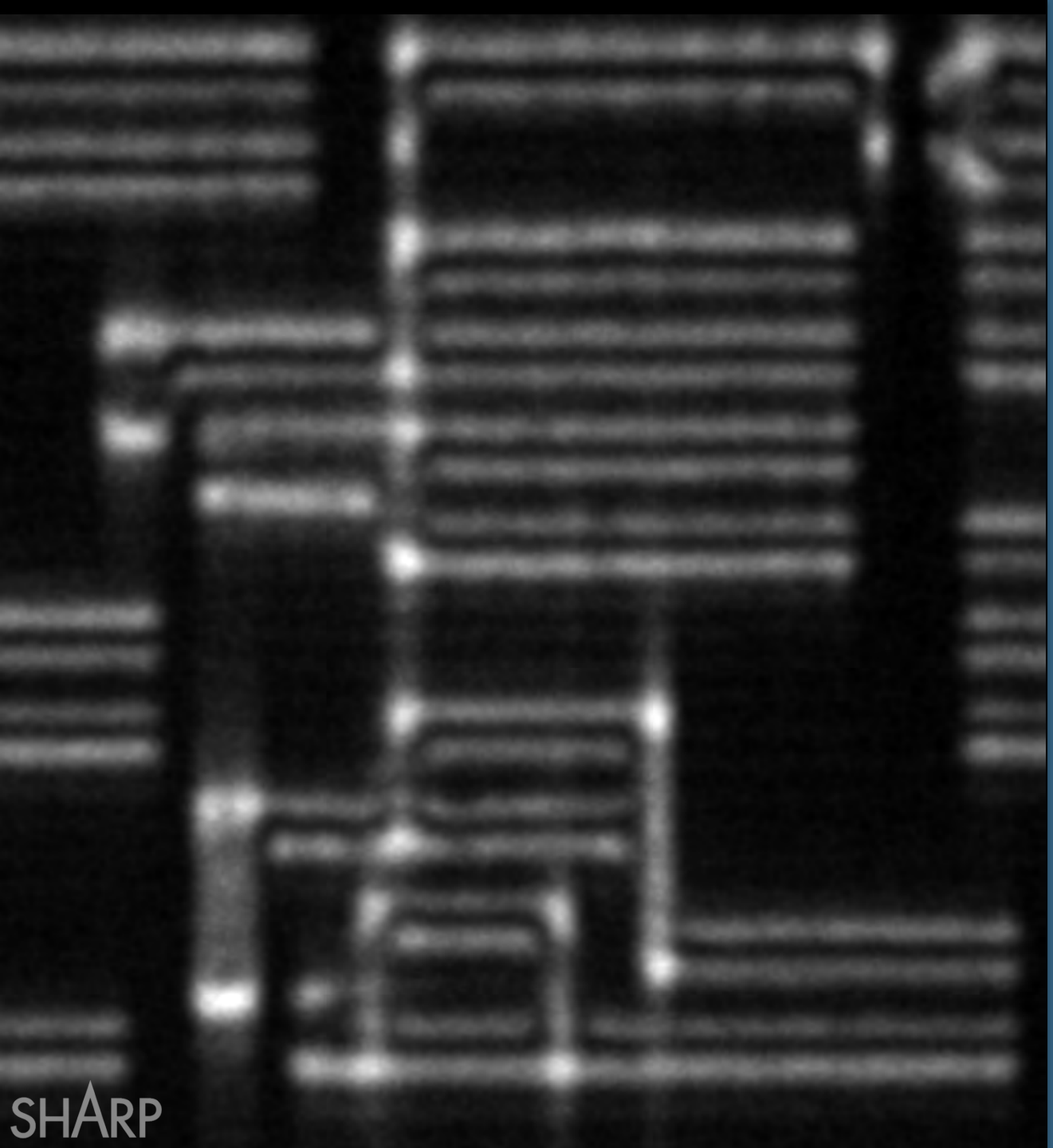
SHARP



Differential X lens

$\partial I / \partial x$

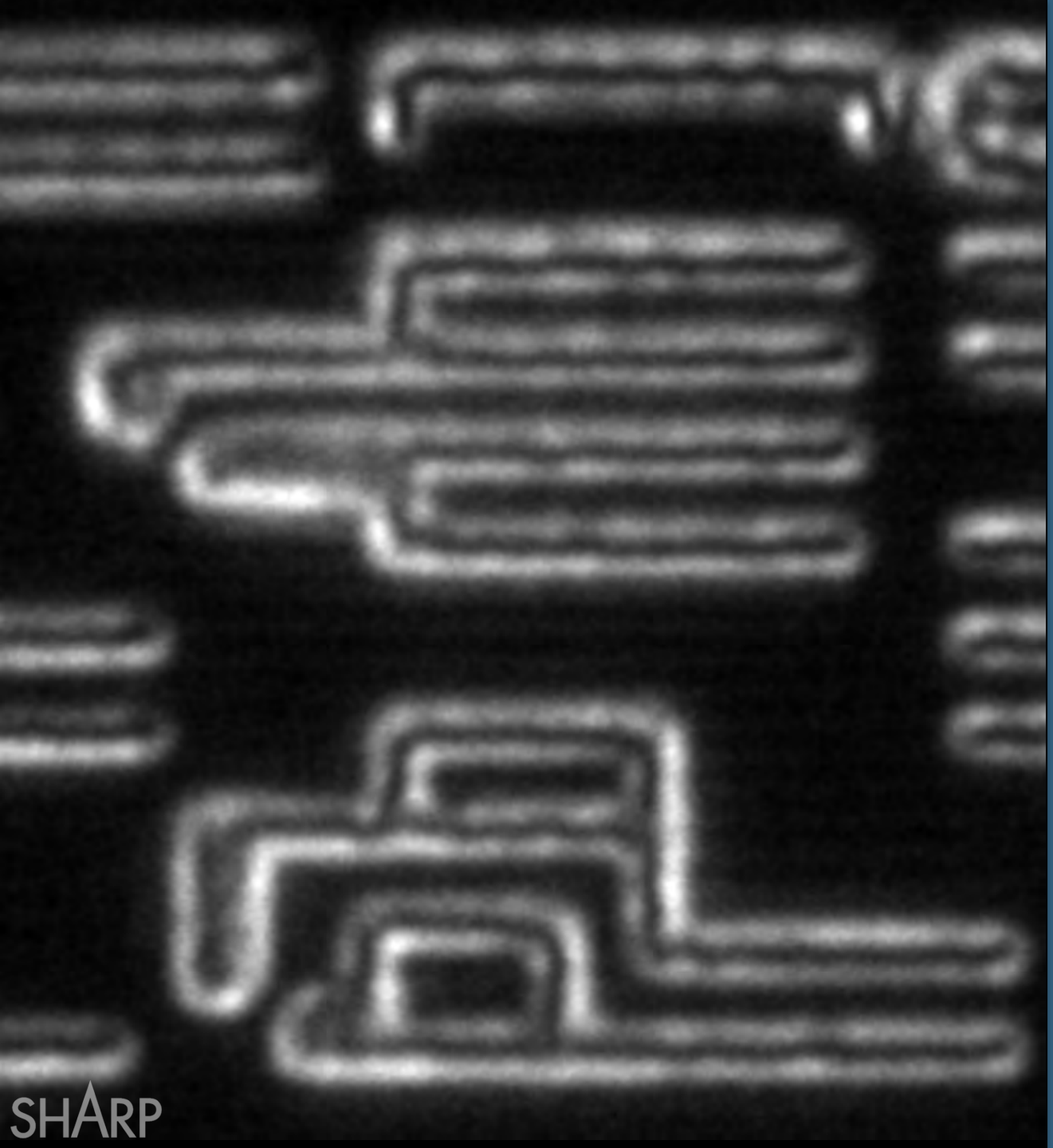
0.5 µm



Differential Y lens

$\partial I / \partial y$

0.5 µm



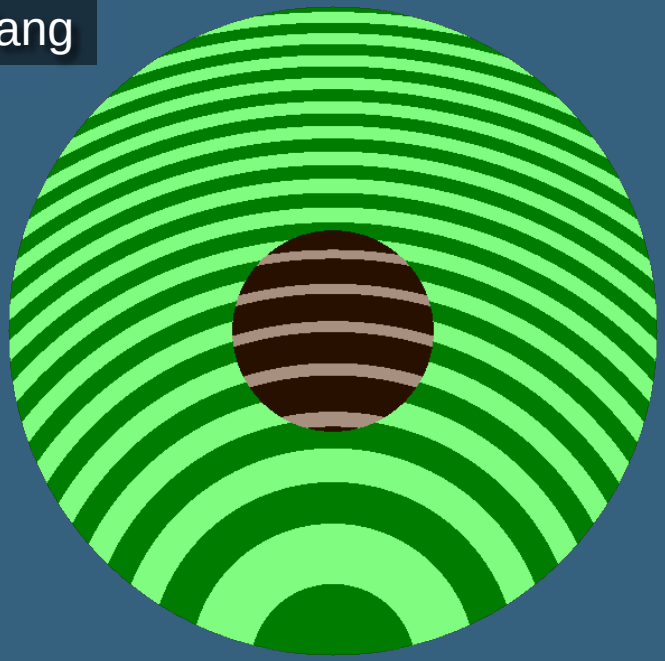
Spiral phase

0.5 µm

Zernike phase contrast (ZPC)

Markus Benk

Yow-Gwo Wang



See: SPIE Advanced Lithography 2015

See: *Talk today, 10:15 am*

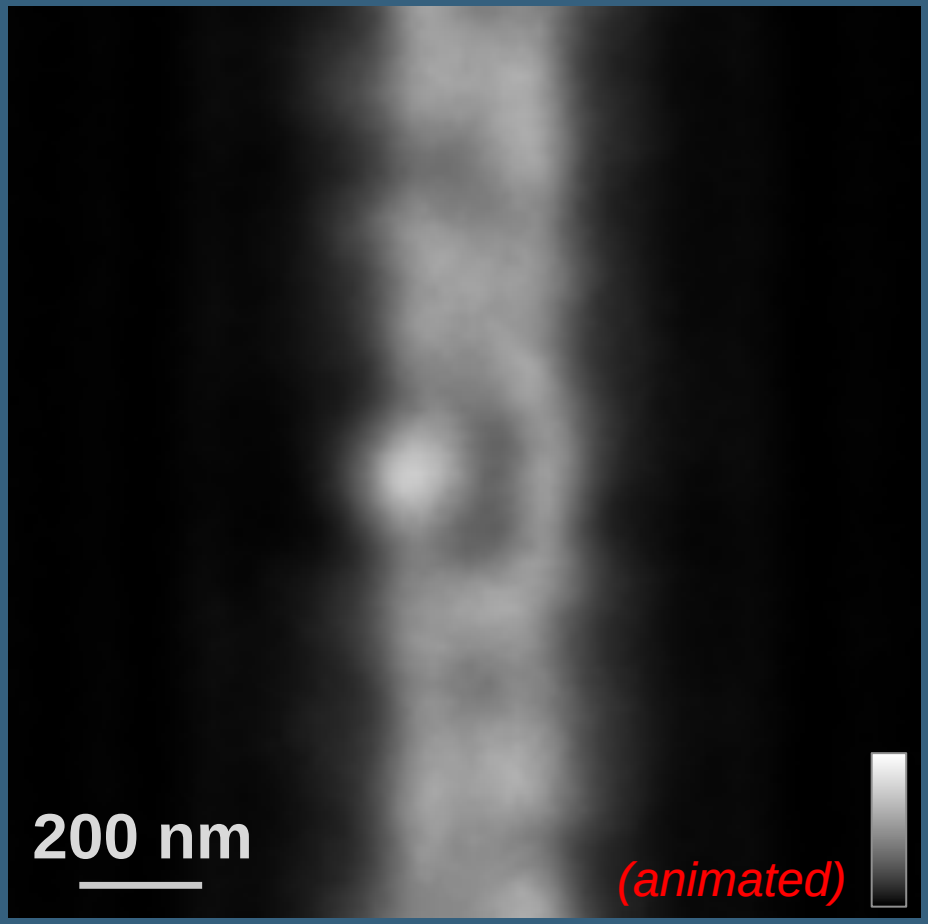
Through-Focus Phase Reconstruction*

Modified Gerchberg-Saxton Method

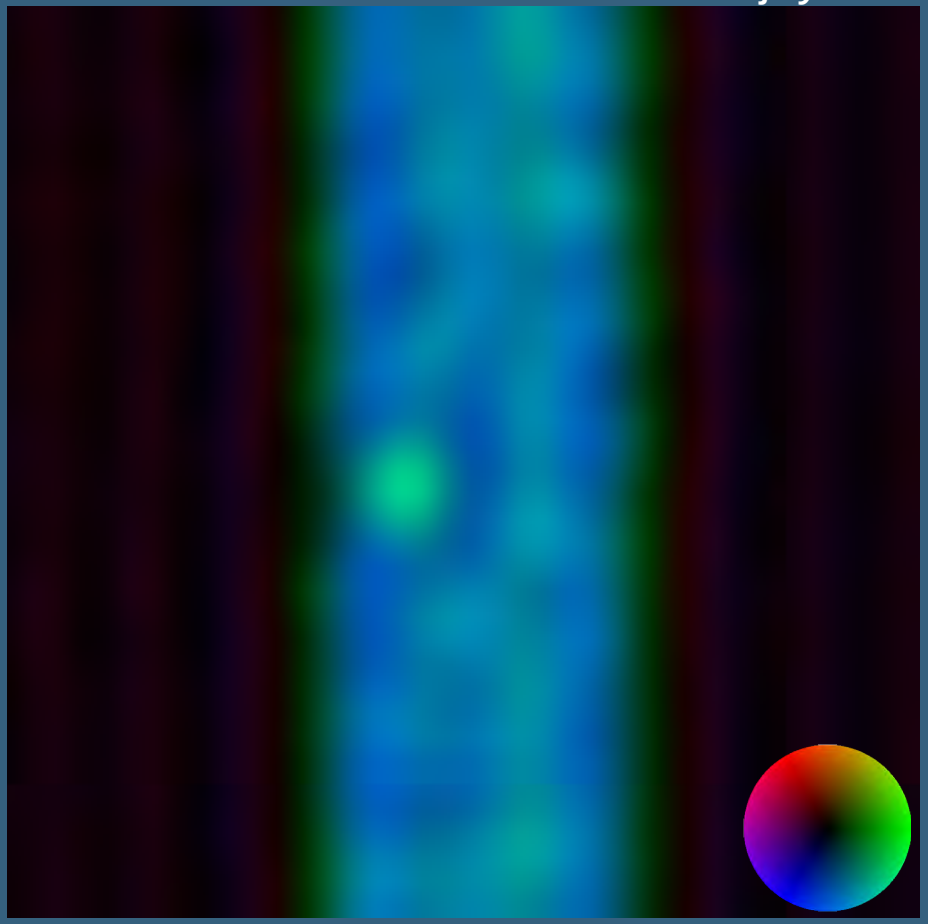
*Mochi, *et al.* SPIE **79691X** (2011).

Mochi

Wojdyla

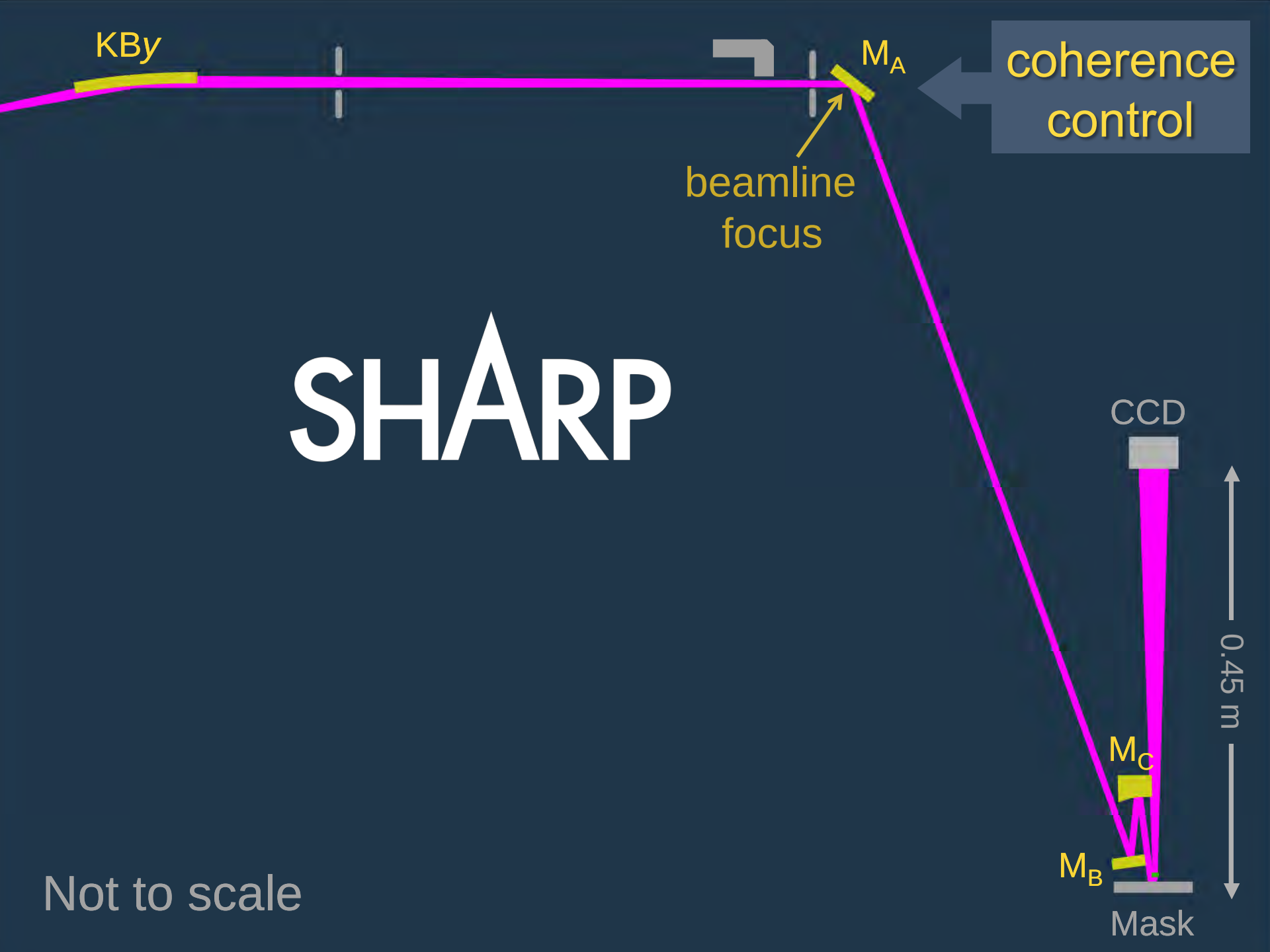


through-focus, Δz = 400 nm



complex amplitude, 35° phase bump

SHARP


KBy
M_A
coherence control
beamline focus
SHARP
CCD
0.45 m
M_C
M_B
Mask
Not to scale

Poster

Fourier Ptychography Microscopy with the SHARP EUV Microscope for increased imaging resolution based on illumination diversity

Antoine Wojdyla*, M P Benk, D G Johnson, A Donoghue, K A Goldberg
Lawrence Berkeley National Laboratory

The SHARP EUV mask microscope has demonstrated **significantly increased spatial resolution** and **quantitative phase measurement** using an emerging microscopy technique called *Fourier Ptychography Microscopy* (FPM). FPM relies on SHARP's programmable illuminator and inherently high spatial coherence to image the mask sample from **many different angles of illumination**.

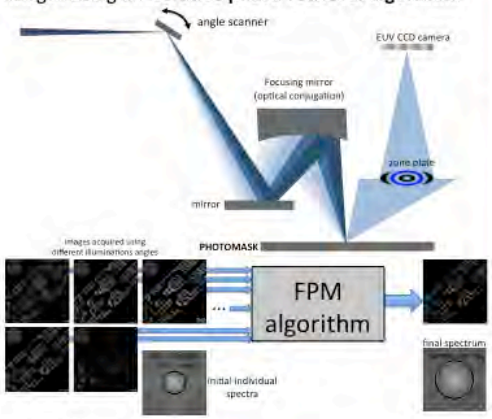
Images are reconstructed ptychographically, in the Fourier-domain, synthesizing an expanded numerical aperture with a real-space image that contains the complex field reflected from the mask. **We have recently demonstrated 50 nm resolution with a 0.33 4xNA lens.**

Introduction

SHARP is a synchrotron-based EUV zoneplate microscope that delivers at-wavelength aerial images of EUV photomasks. SHARP emulates current and future EUV printing tools and is used to research nearly every area of mask development. It features a Fourier Synthesis Illuminator capable of replicating any illumination condition.

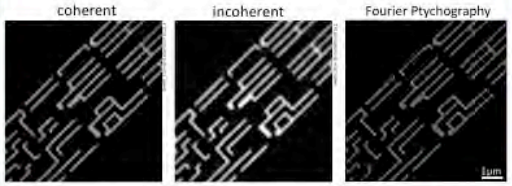
Principle

Fourier Ptychography consists in taking **multiple coherent images** of an object using **different illumination conditions**, and then recombining these images using an **iterative phase-retrieval algorithm**.

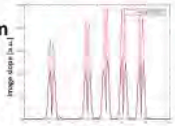


Increase in resolution

FPM synthesizes a higher-NA than the lens used to record the images.



This enables us to to reach **sub-40 nm resolution** (mask-side) with a 0.33 4xNA lens, compared to the conventional 82 nm diffraction limit.

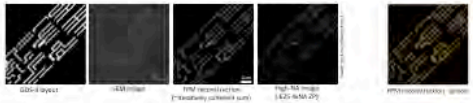


increase of line slope with FPM

Furthermore, the **field of view** and the **depth of focus** are increased compared to imaging with a higher NA lens; **lens aberrations can determined and corrected** during the reconstruction process [2].

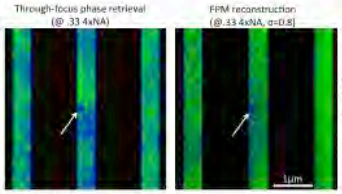
Validating data

FPM reconstruction is consistent with data acquired using other characterization techniques [3], with the advantage of being at-wavelength.

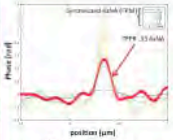


Phase defects characterization

The combination of all **the data yields quantitative phase information about the sample, point by point.**



amplitude (brightness) and phase (color) of a phase defect



influence of resolution on phase information

Compared with other phase retrieval techniques [4], the sharpness of phase information is increased. The **reconstruction of the actual angular spectrum** allows us to **perform numerical analysis** of the object (refocusing, restriction to various lens NAs, and the effect of various illuminations.)

Conclusion

FPM extends SHARP'S capabilities for EUV mask imaging, and allows us to achieve both increased resolution and quantitative phase measurement without requiring modifications to the existing hardware.

Acknowledgements

Thanks to Anne Rudack (SEMATECH) and Pawitter Mangat (Global Foundries) for their support, and to Roarke Horstmeyer (CalTech) for the fruitful conversations. This work was funded by SEMATECH through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

References

[1] G Zheng *et al.* Nature Photonics **7**, 9 (2013) doi: 10.1038/nphoton.2013.187
[2] X. Ou *et al.*, Optics Express **22**, 5 (2014) doi: 10.1364/OE.22.004960
[3] S A George *et al.* JVSTB 28:C6E23 (2010) doi: 10.1116/1.3502436
[4] I Mochi *et al.* JVSTB 28, 6:C6E11 (2011) doi: 10.1117/12.881652

*contact : awojdyla@lbl.gov http://sharp.lbl.gov

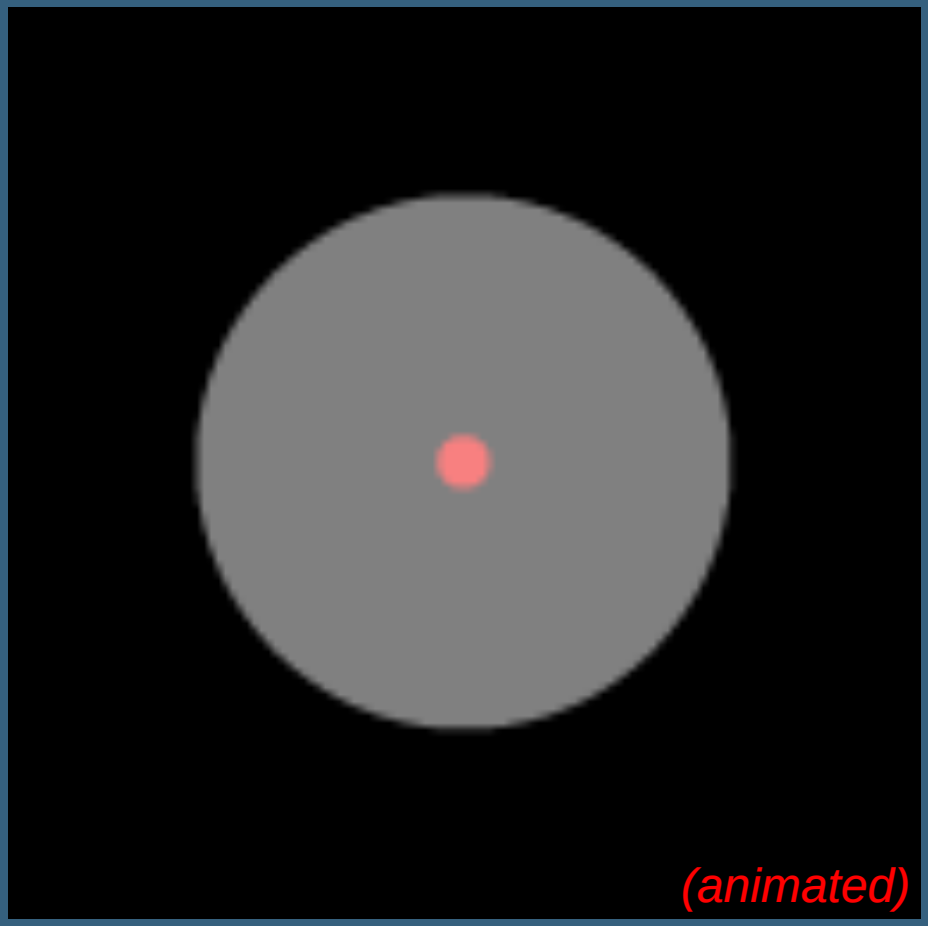
Antoine Wojdyla

Fourier Pytchography Microscopy*

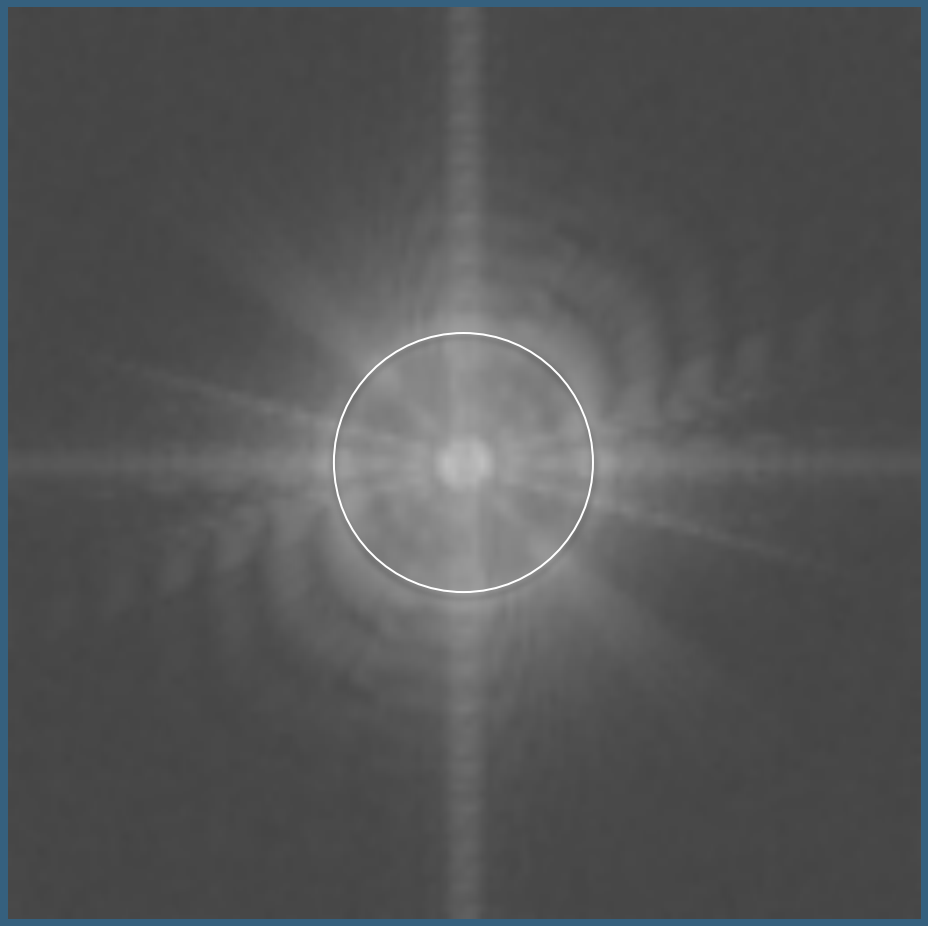
Mathematically synthesize high-NA from many coherent views

*G. Zheng, *et al.* Nature Photonics **7**, 9 (2013).

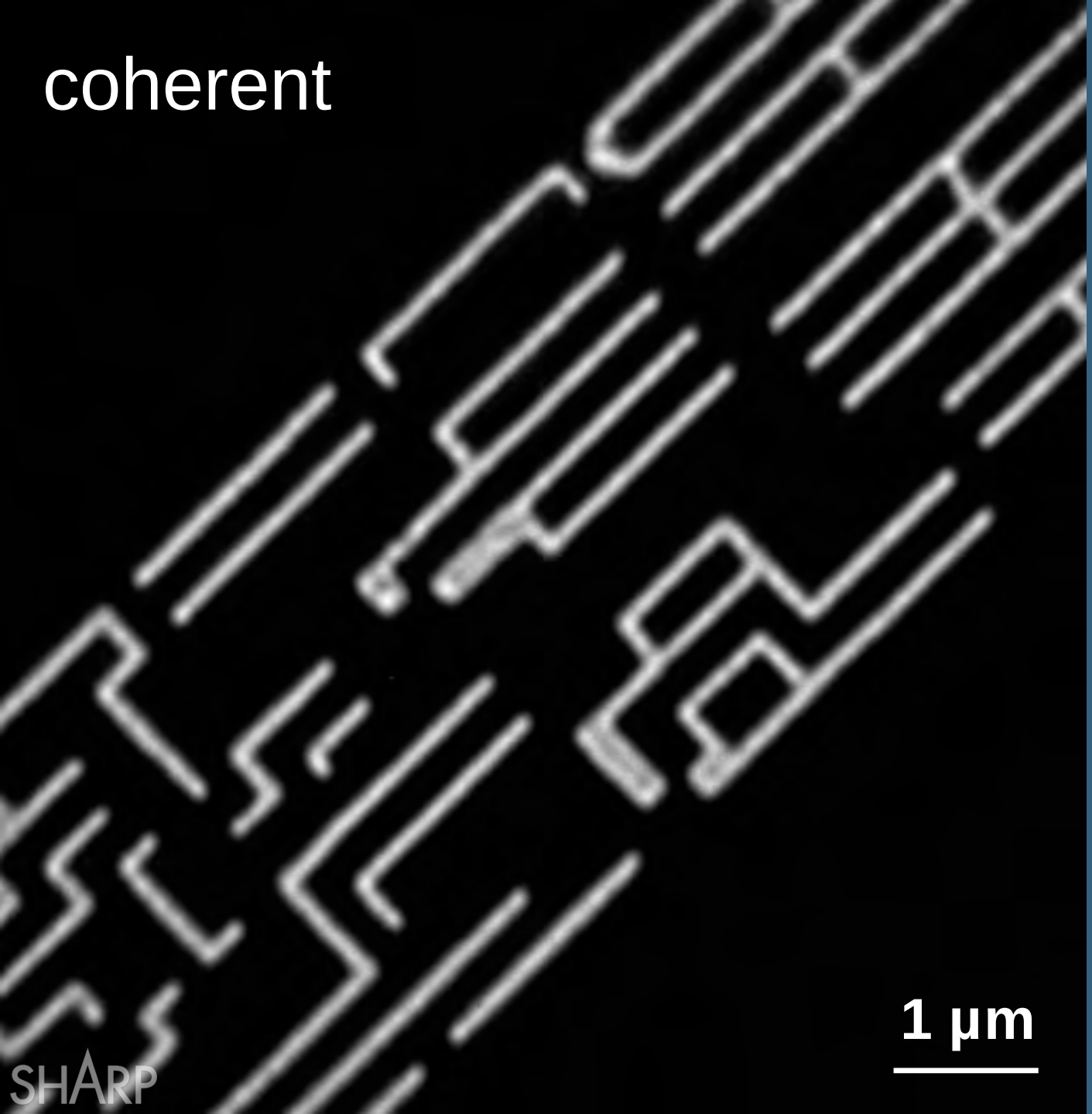
Wojdyla

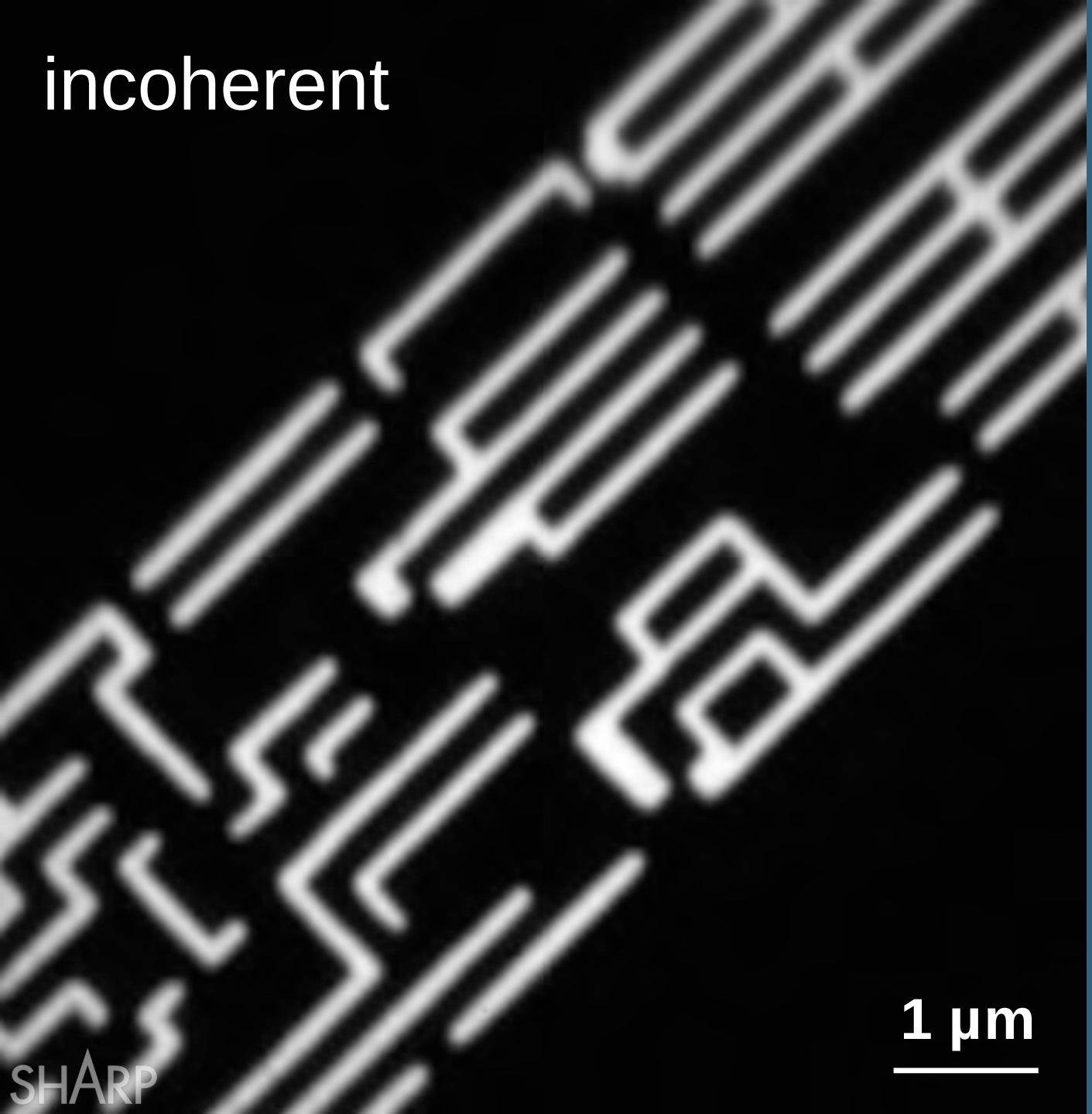


Illumination angles



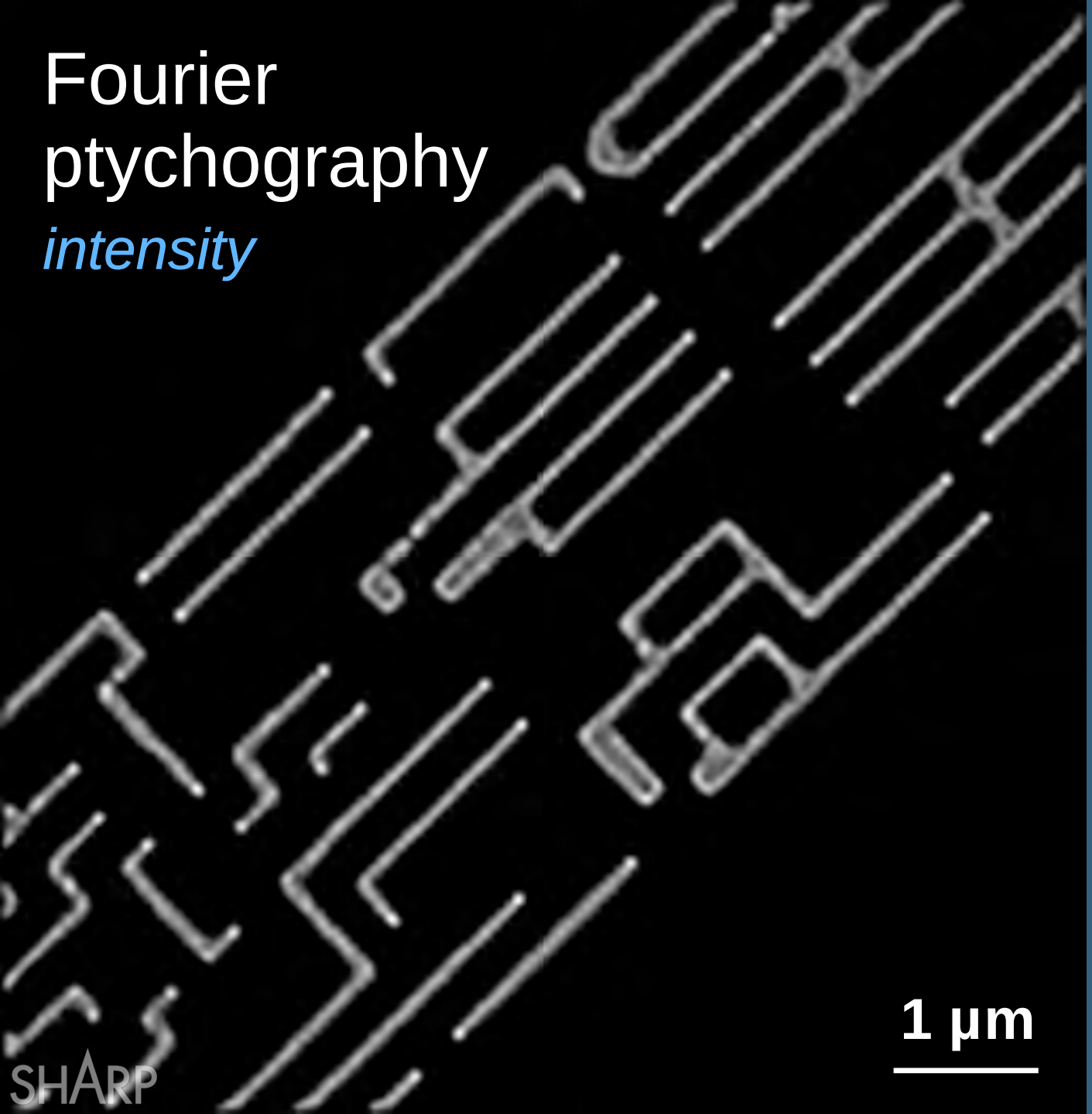
Fourier-domain reconstruction


coherent
1 µm
SHARP

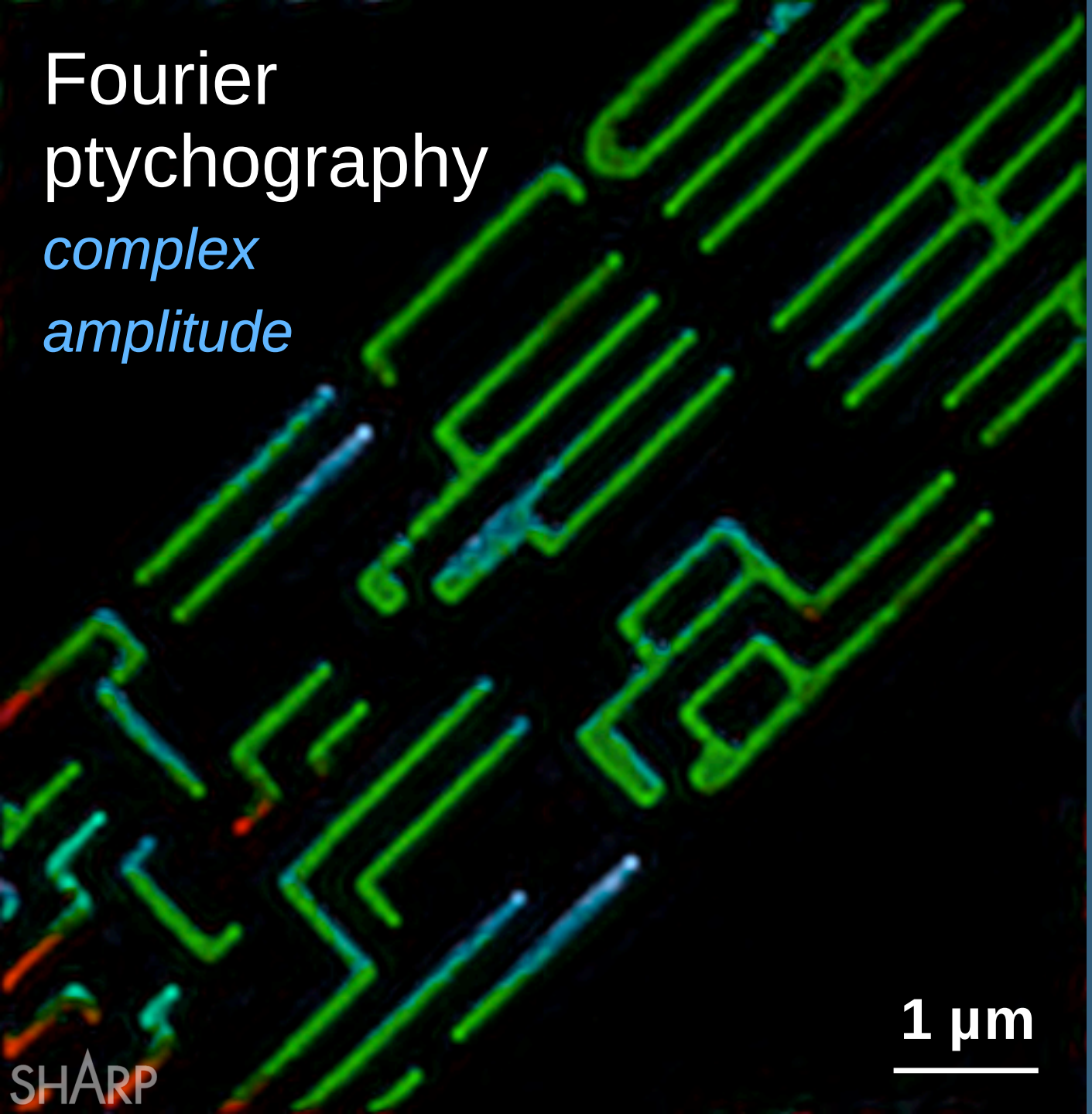

incoherent
1 µm
SHARP

Fourier ptychography

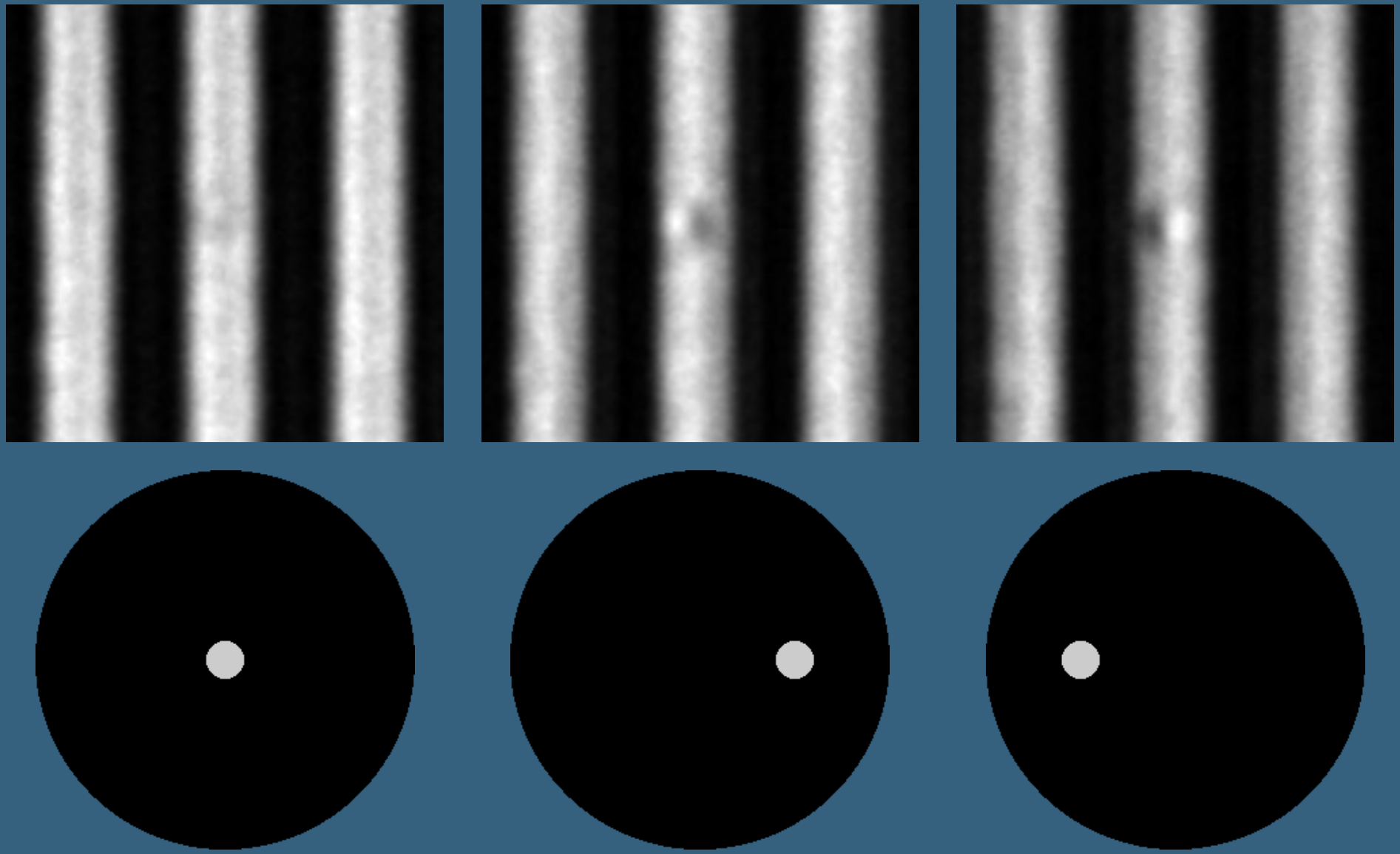
intensity



SHARP


Fourier
ptychography
complex
amplitude
1 µm
SHARP

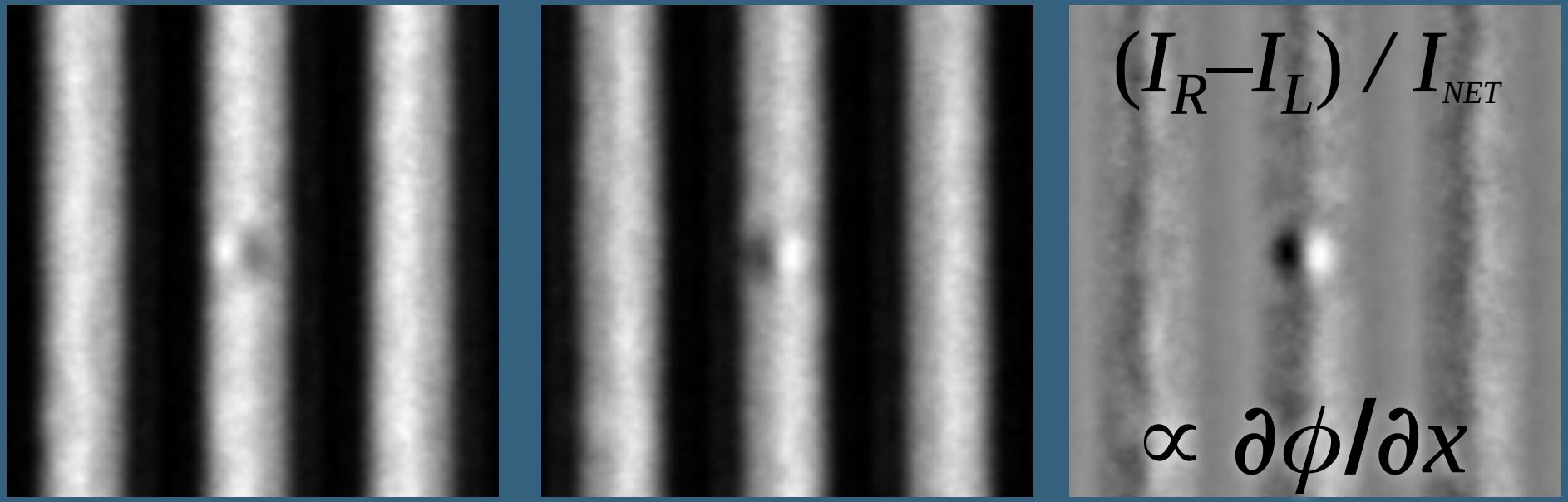
Differential Phase-Contrast Microscopy*

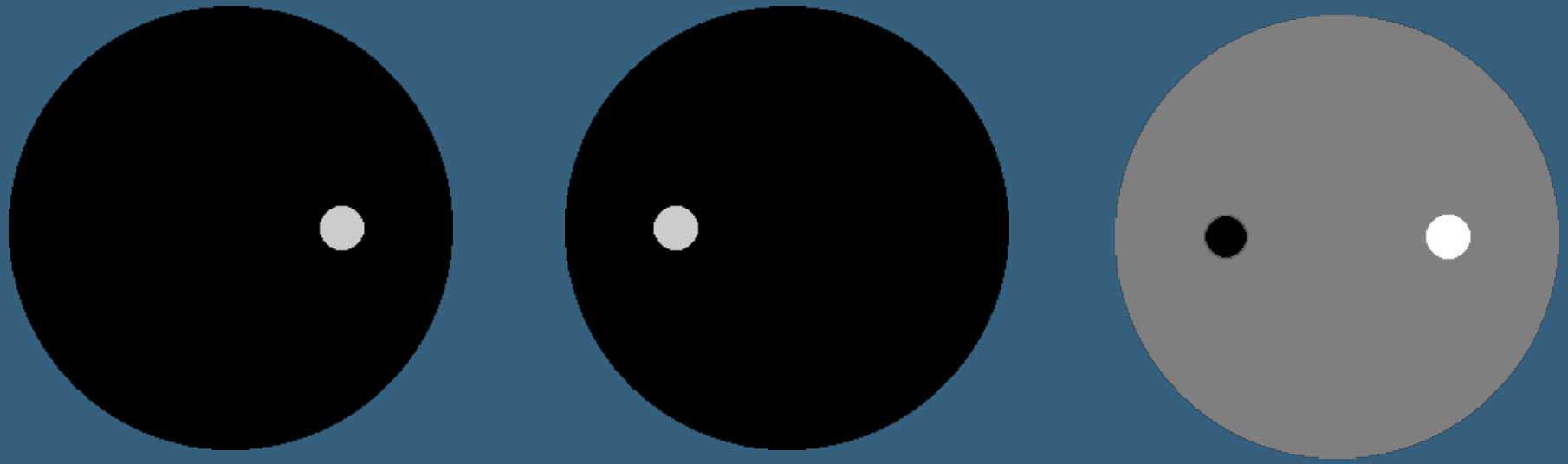


*Mehta, *Optics Letters* **34** (13), 2009 • Tian, *Optics Letters* **39** (5), 2014

• Xibin Zhou, Dominic Ashworth, Kevin Cummings, *EUVL Symposium* 2014

Differential Phase-Contrast Microscopy*

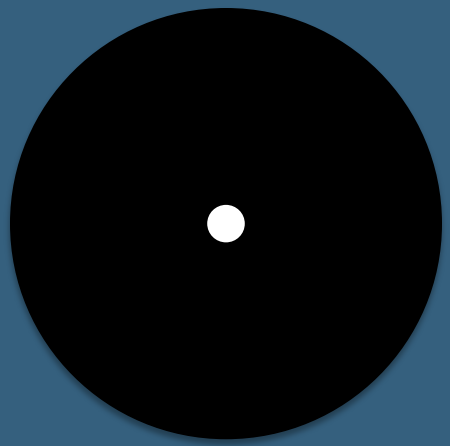




*Mehta, *Optics Letters* **34** (13), 2009 • Tian, *Optics Letters* **39** (5), 2014
• Xibin Zhou, Dominic Ashworth, Kevin Cummings, *EUVL Symposium* 2014

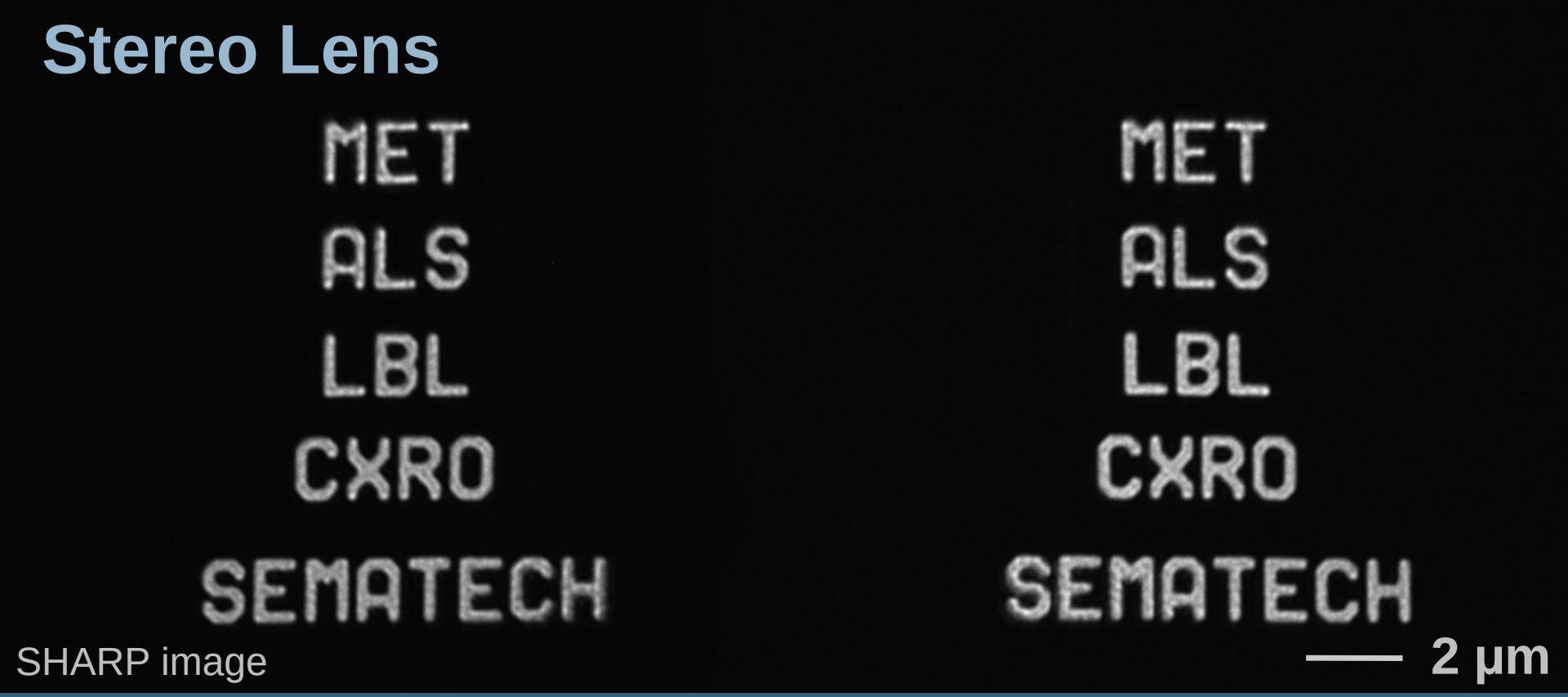
Conventional Lens

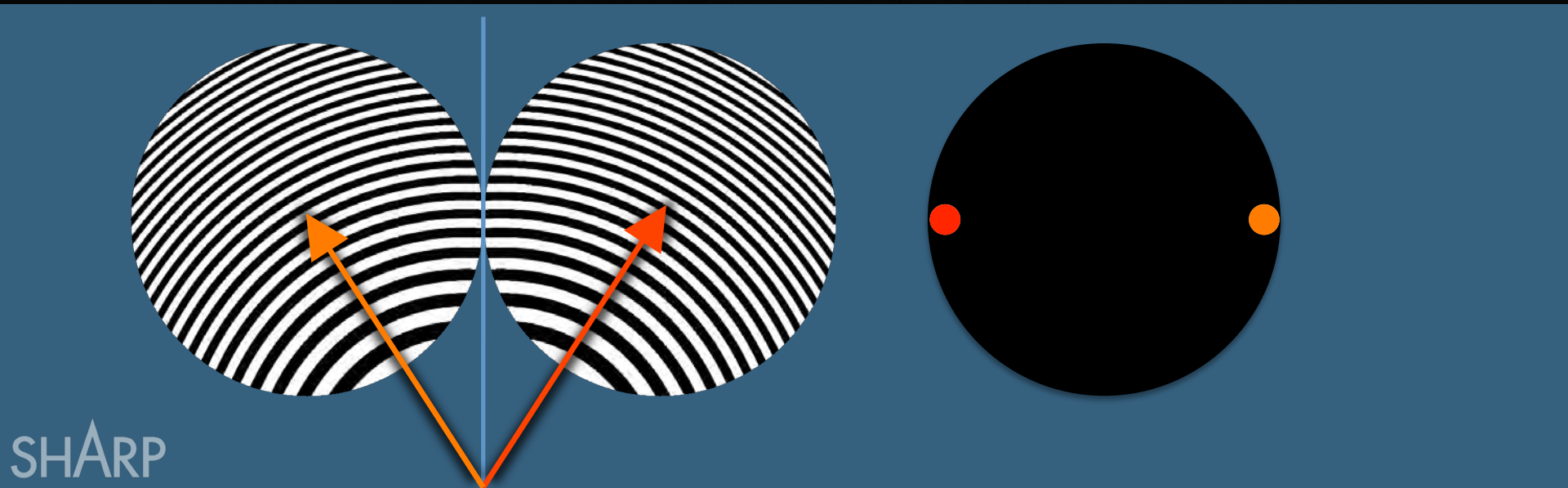
SHARP image

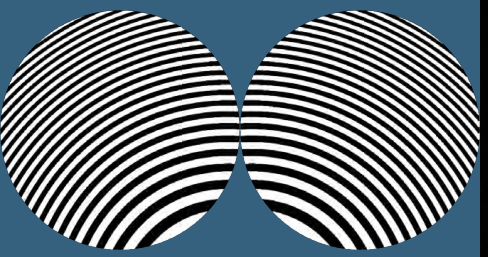


SHARP

Stereo Lens


MET
ALS
LBL
CXRO
SEMATECH
MET
ALS
LBL
CXRO
SEMATECH
SHARP image
2 µm


SHARP

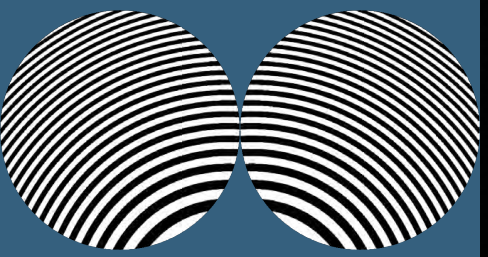


Stereo Lens

- **LEFT**
- ***CENTER***
- ***RIGHT***

Working toward 3D imaging

SHARP

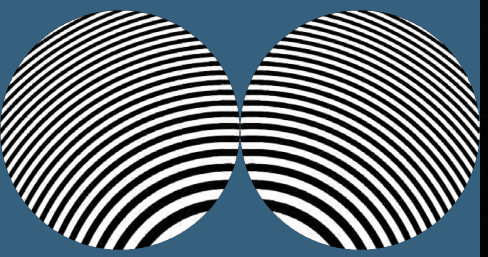


Stereo Lens

- **LEFT**
- ***CENTER***
- ***RIGHT***

Working toward 3D imaging

SHARP



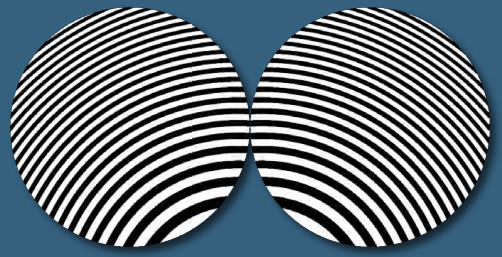
Stereo Lens

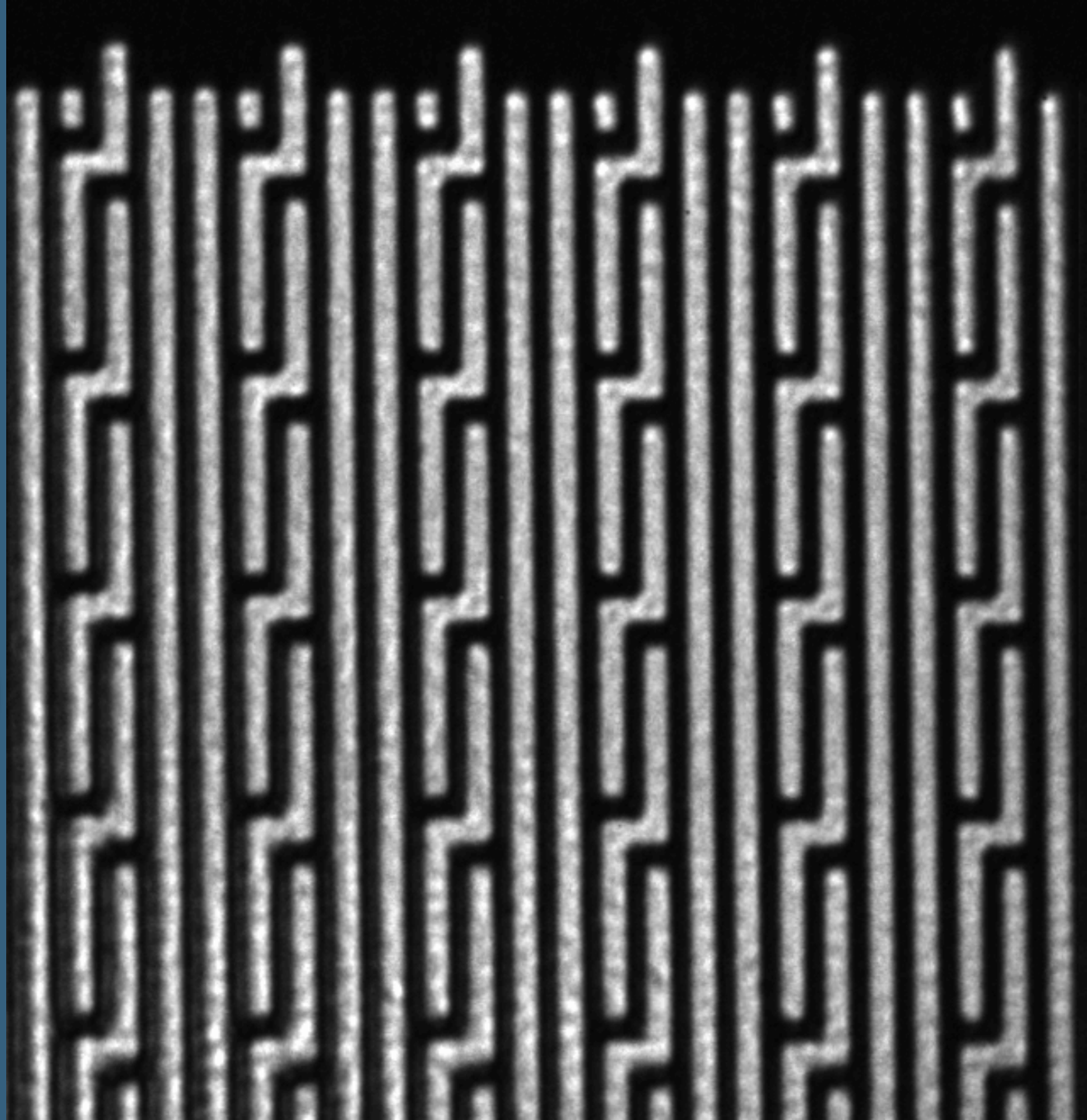
- **LEFT**
- ***CENTER***
- ***RIGHT***

Working toward 3D imaging

SHARP

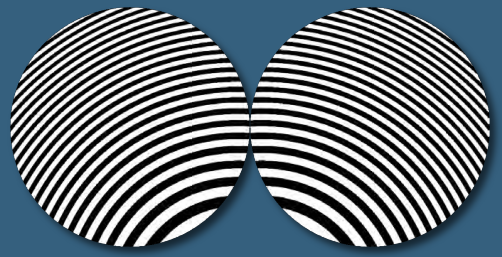
- LEFT
- *RIGHT*

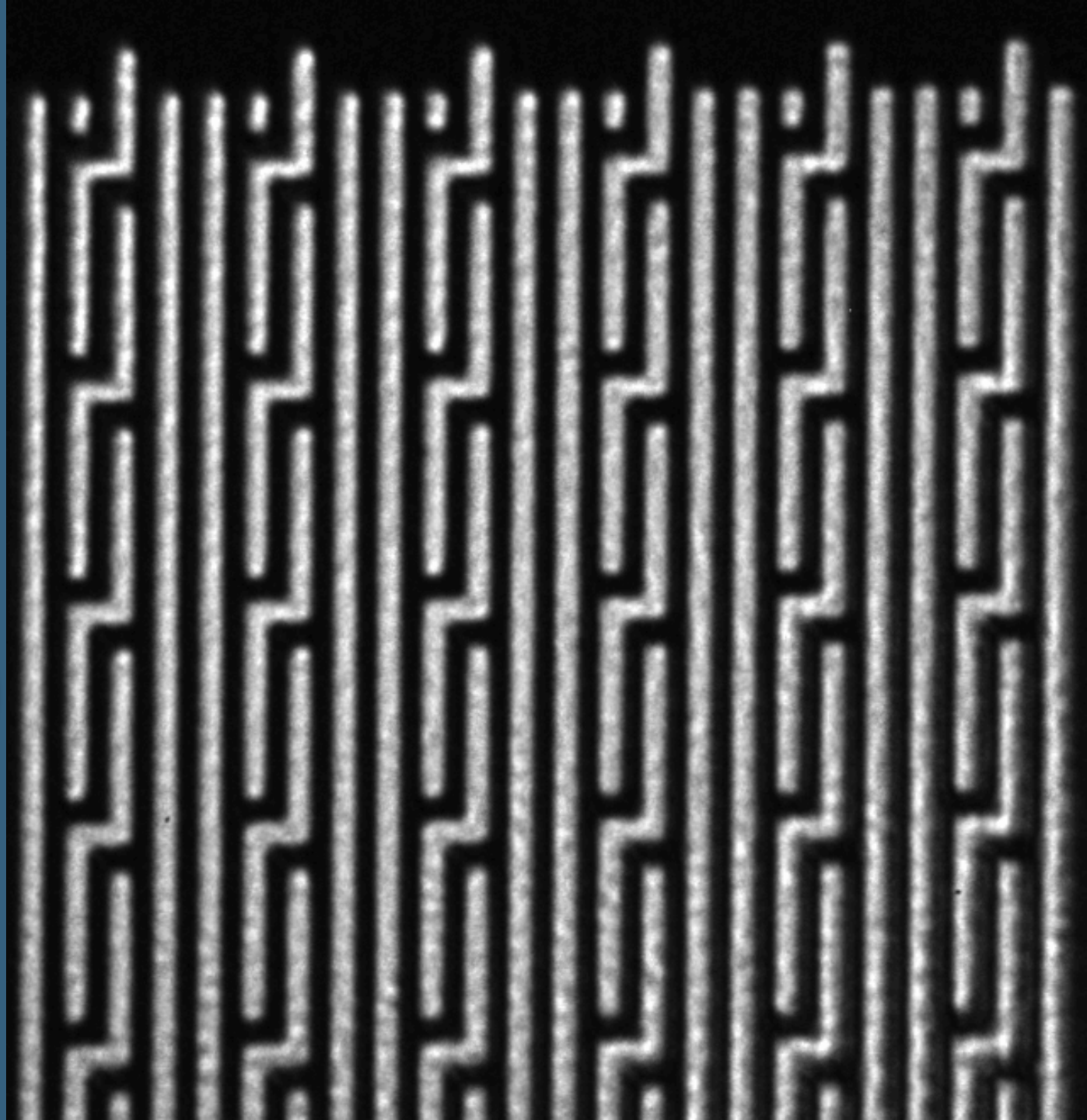




SHARP

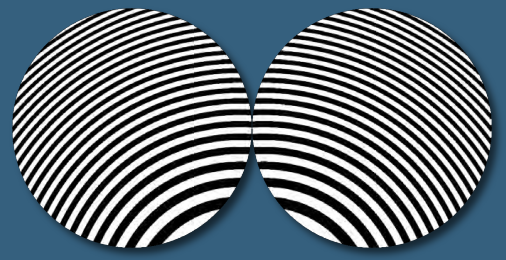
- LEFT
- *RIGHT*





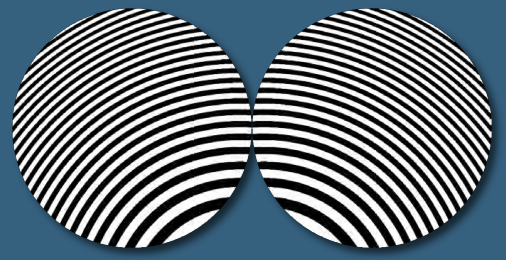
SHARP

- LEFT
- *RIGHT*



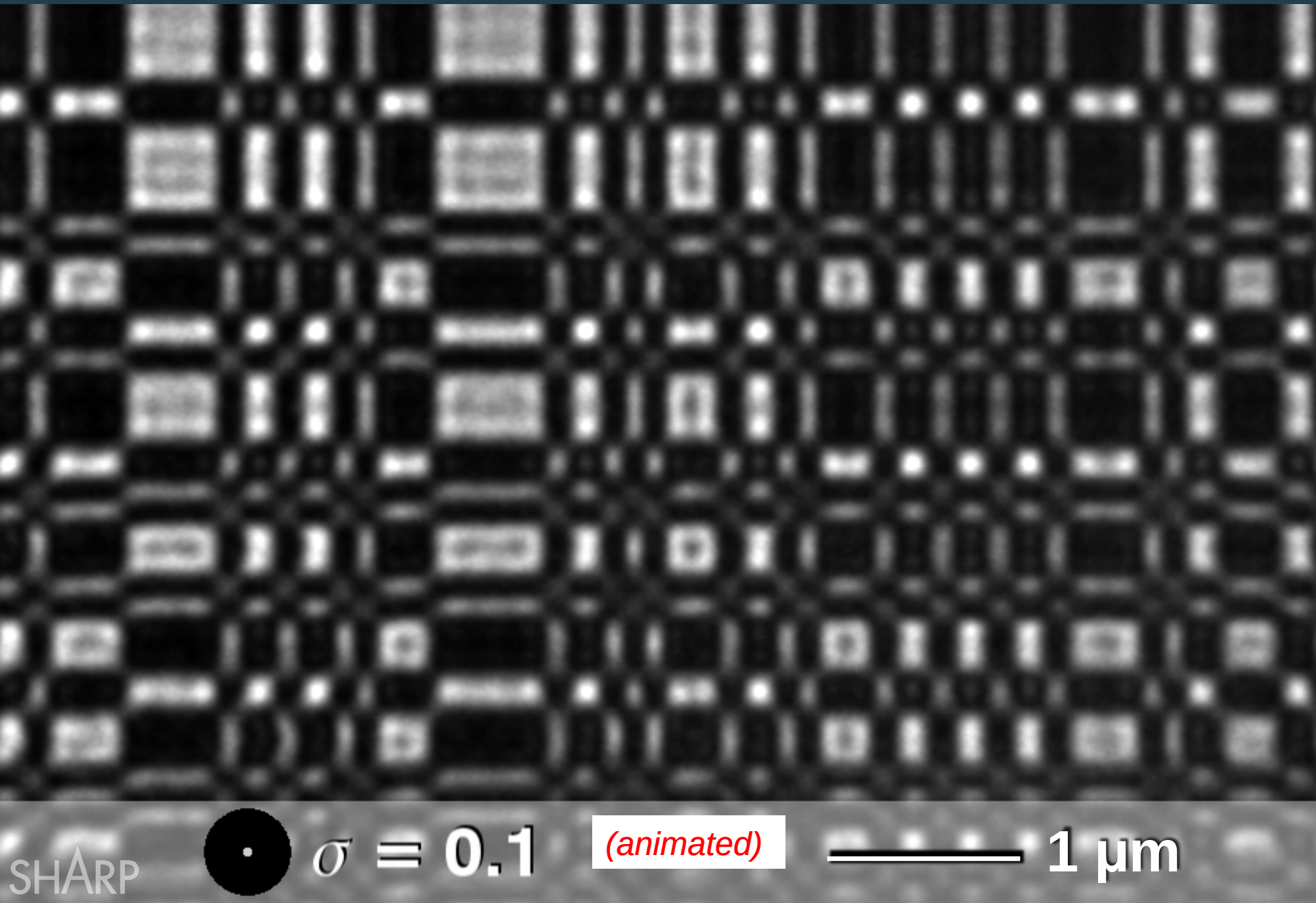
SHARP

- LEFT
- *RIGHT*

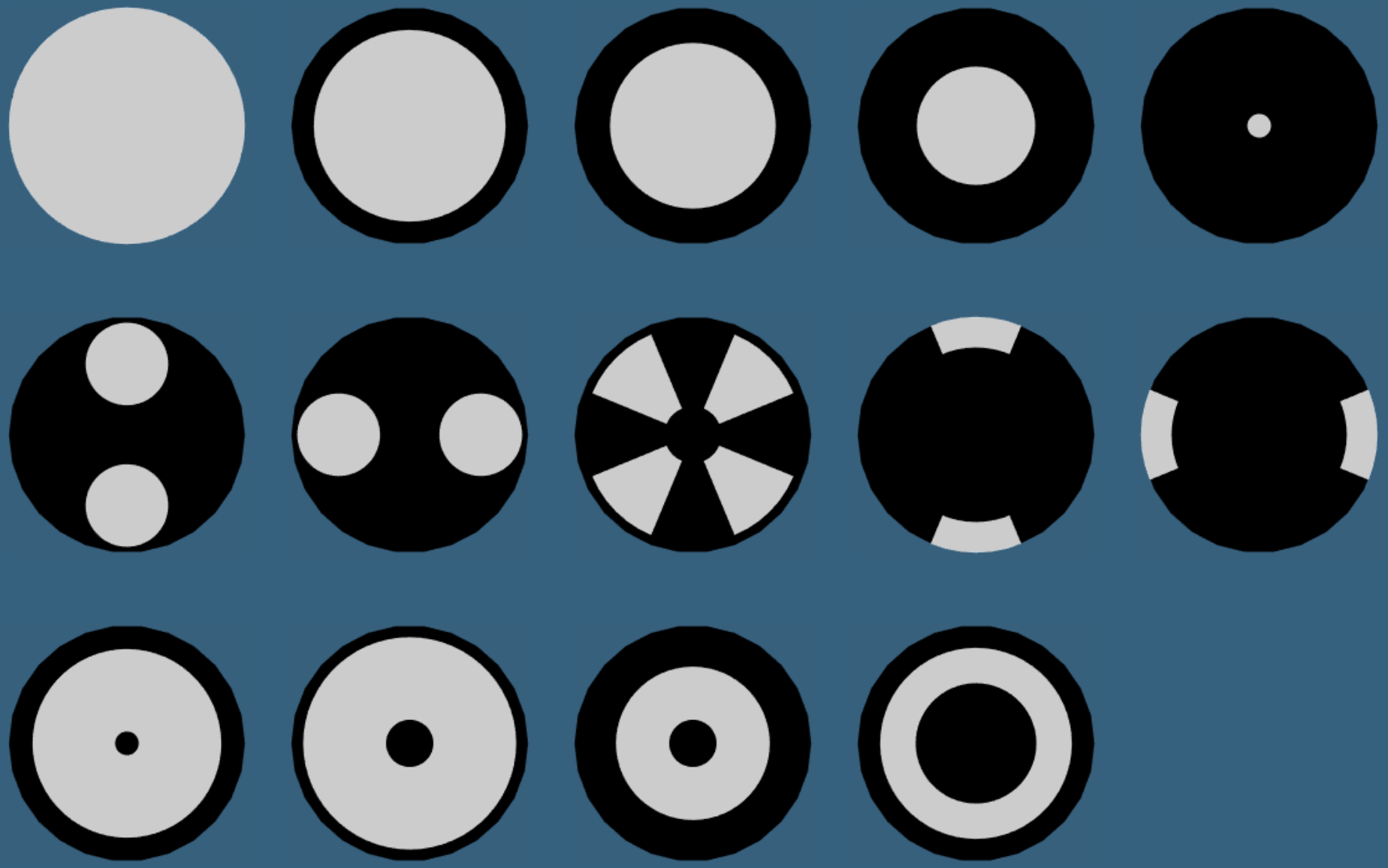


SHARP

Coherence affects roughness (speckle)

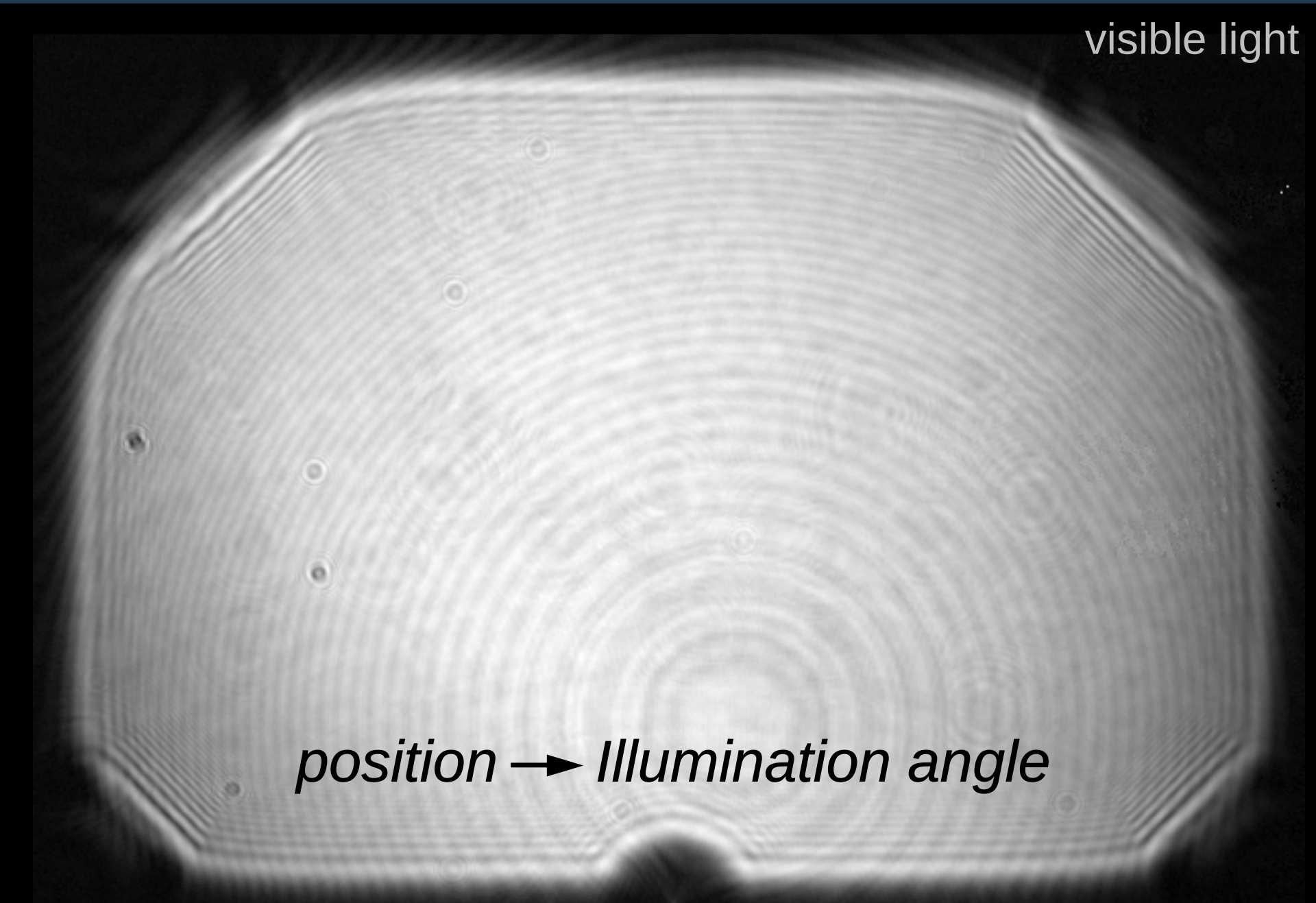


Users' illumination pupil-fill requests

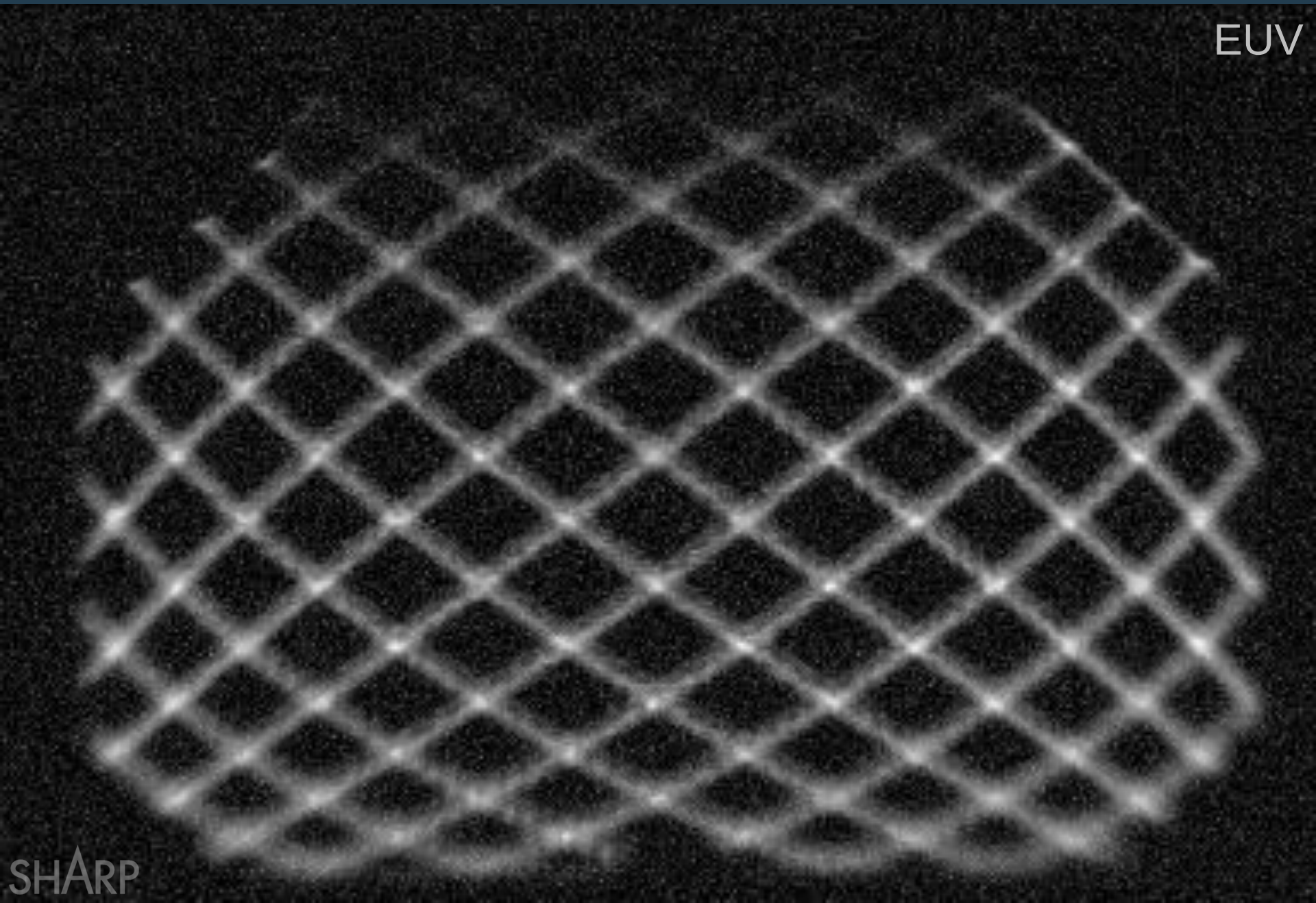


SHARP

SHARP condenser

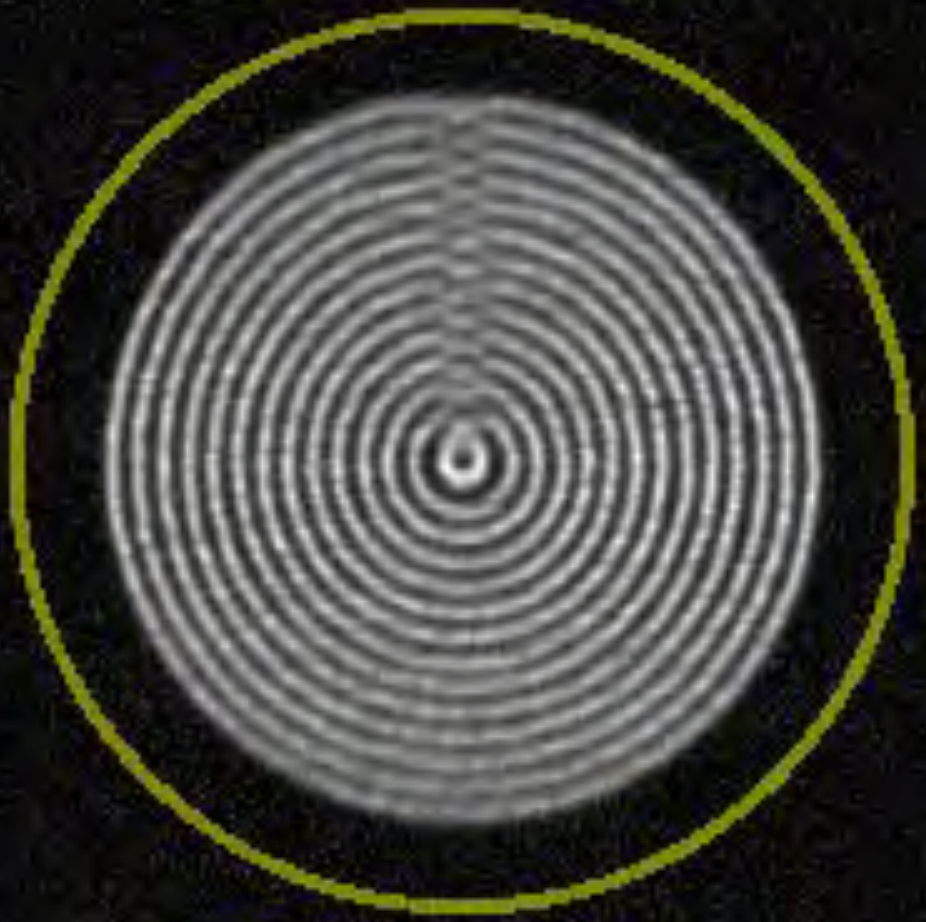


Coherence Control: Pupil Fill Patterns



Coherence Control: Pupil Fill Patterns

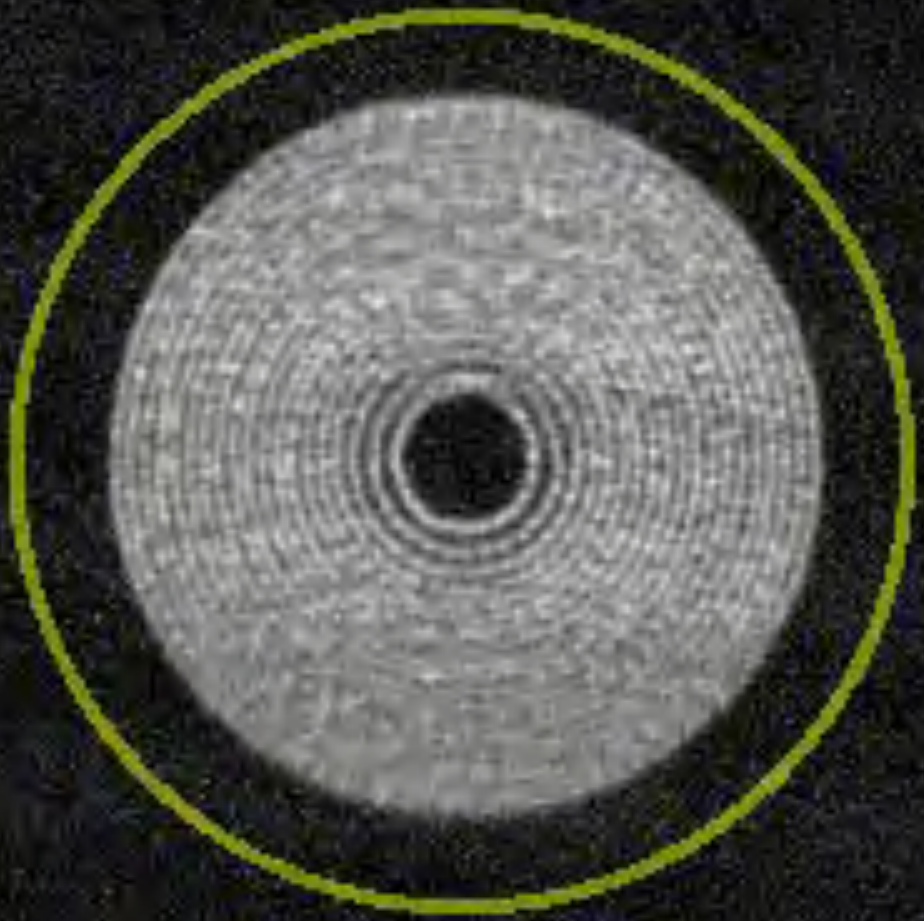
0.5 4xNA 0.8 σ 8° CRA



SHARP

Coherence Control: Pupil Fill Patterns

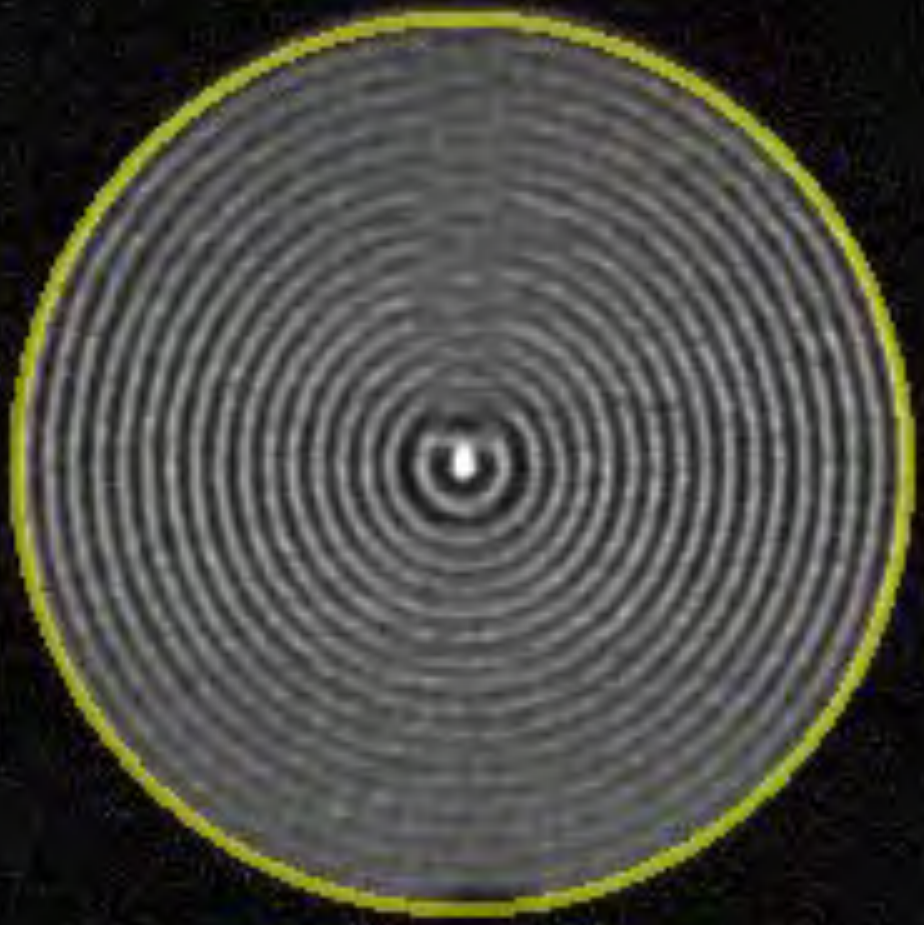
0.5 4xNA **0.2–0.8 σ** **8° CRA**



SHARP

Coherence Control: Pupil Fill Patterns

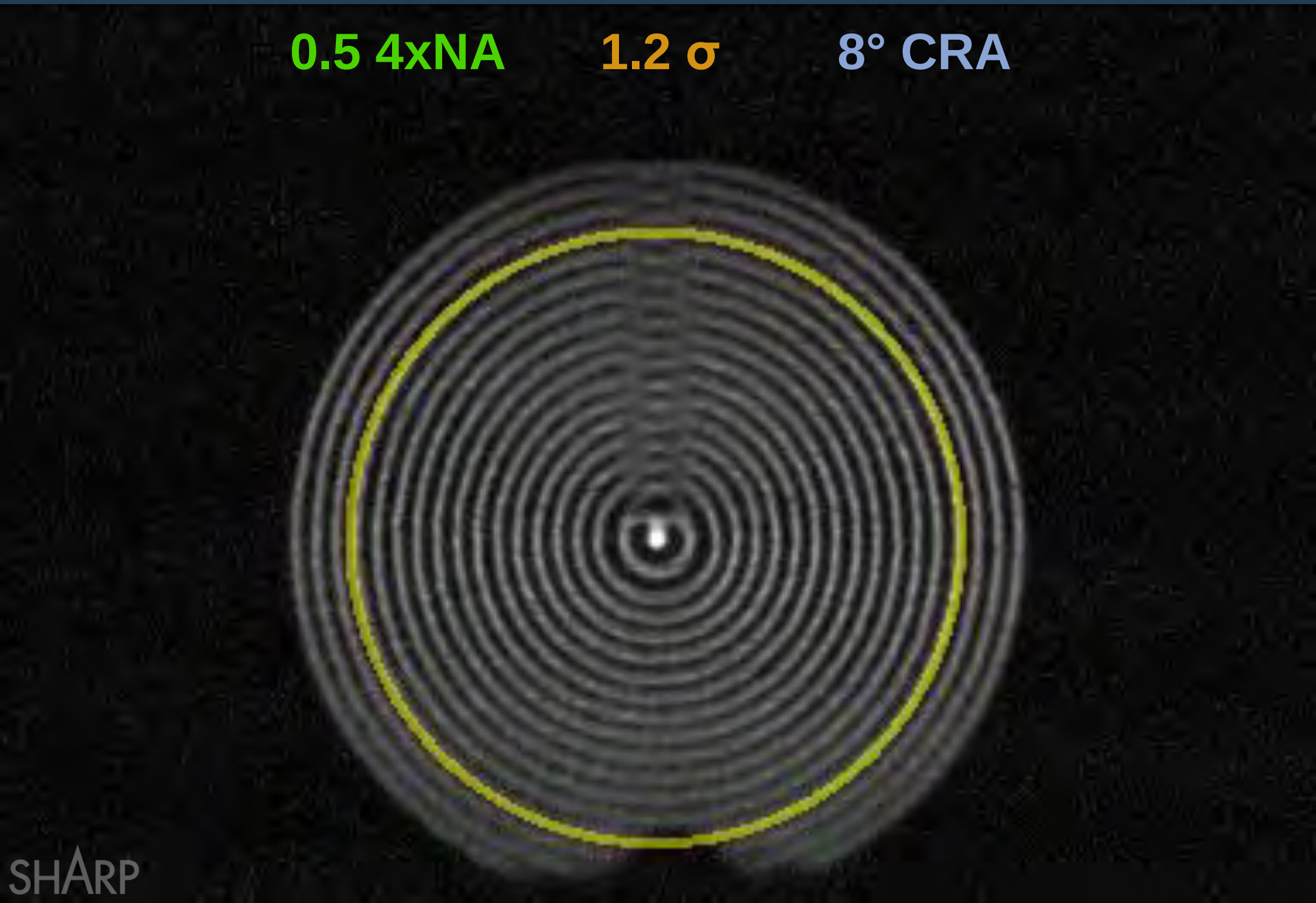
0.5 4xNA **1.0 σ** **8° CRA**



SHARP

Coherence Control: Pupil Fill Patterns

0.5 4xNA 1.2 σ 8° CRA



SHARP

Coherence Control: Pupil Fill Patterns

0.625 4xNA 1.0 σ 10° CRA

SHARP

Coherence Control: Pupil Fill Patterns

0.25 4xNA **1.0 σ** **6° CRA**

SHARP

Coherence Control: Pupil Fill Patterns

0.25 4xNA 0.2 σ 6° CRA

SHARP

Coherence Control: Pupil Fill Patterns

0.25 4xNA 0.05 σ 6° CRA

SHARP

Coherence Control: Pupil Fill Patterns

0. 5 4xNA 0.4–0.8 σ 8° CRA

SHARP

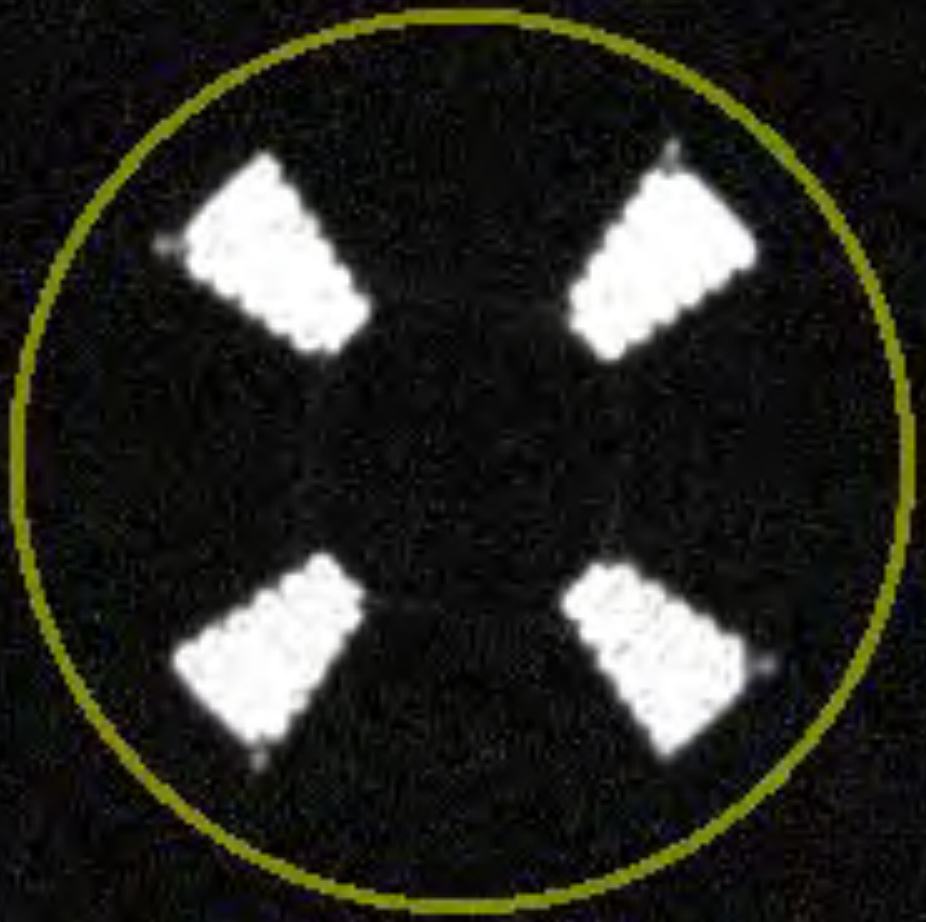
Coherence Control: Pupil Fill Patterns

0.5 4xNA **0.4–0.8 σ** **8° CRA**

SHARP

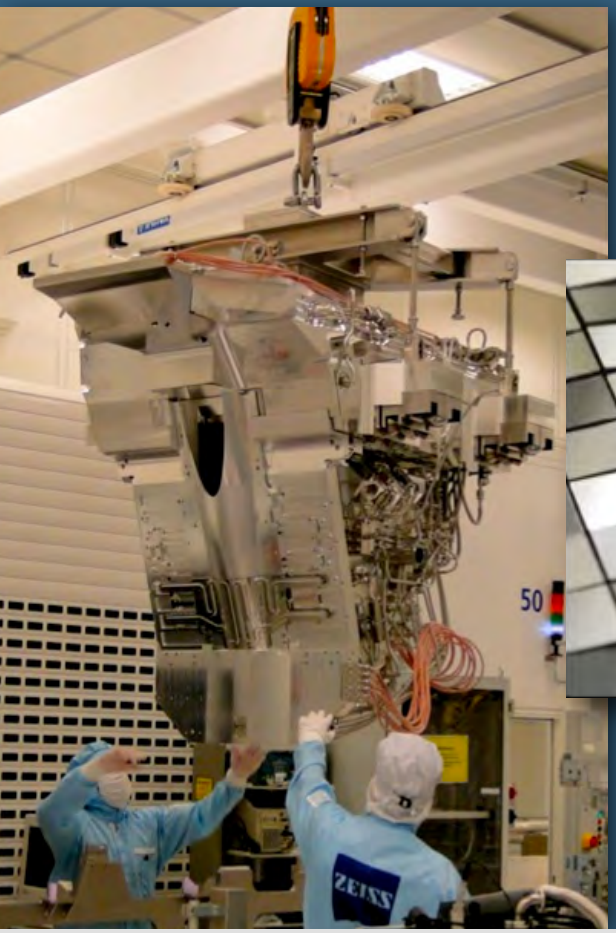
Coherence Control: Pupil Fill Patterns

0.5 4xNA **0.4–0.8 σ** **8° CRA**

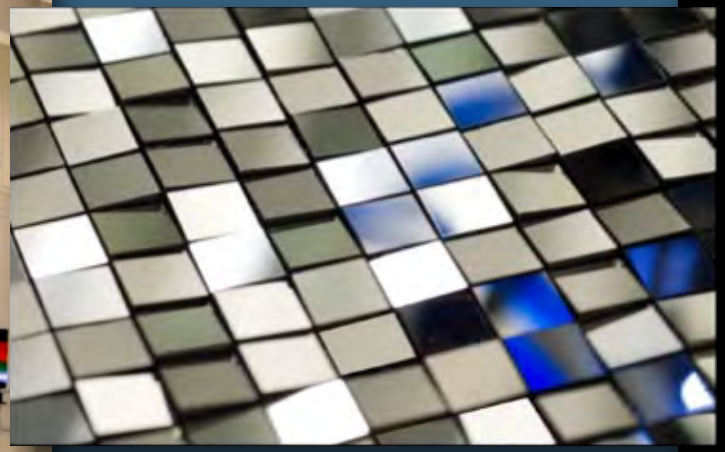


SHARP

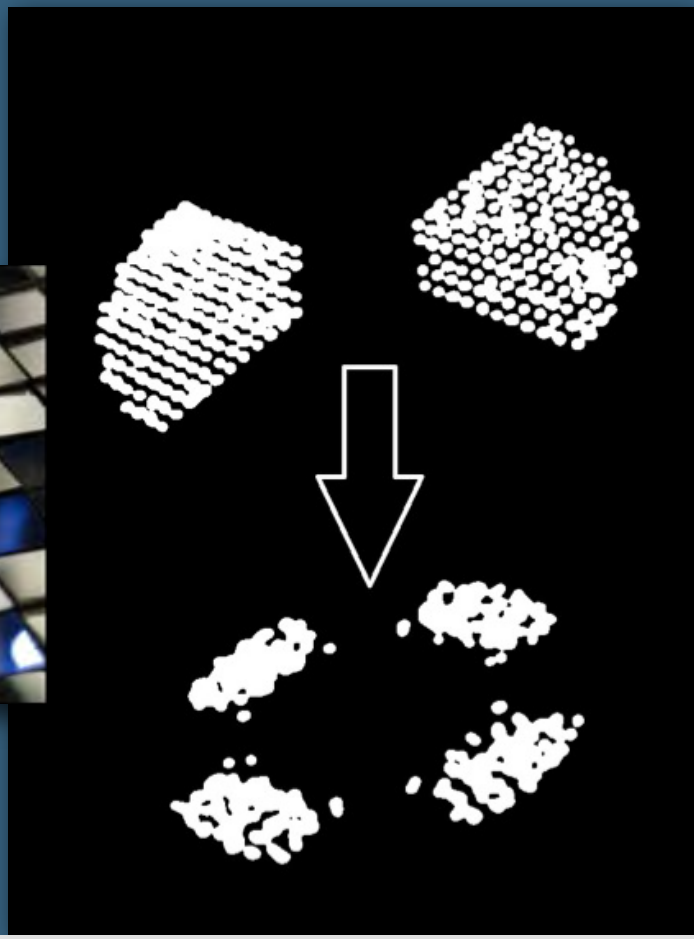
“From performance validation to volume introduction of ASML’s NXE platform”
H. Meiling, *et al.*, *SPIE* **8322,** 83221G (2012).



NXE:3300B illuminator

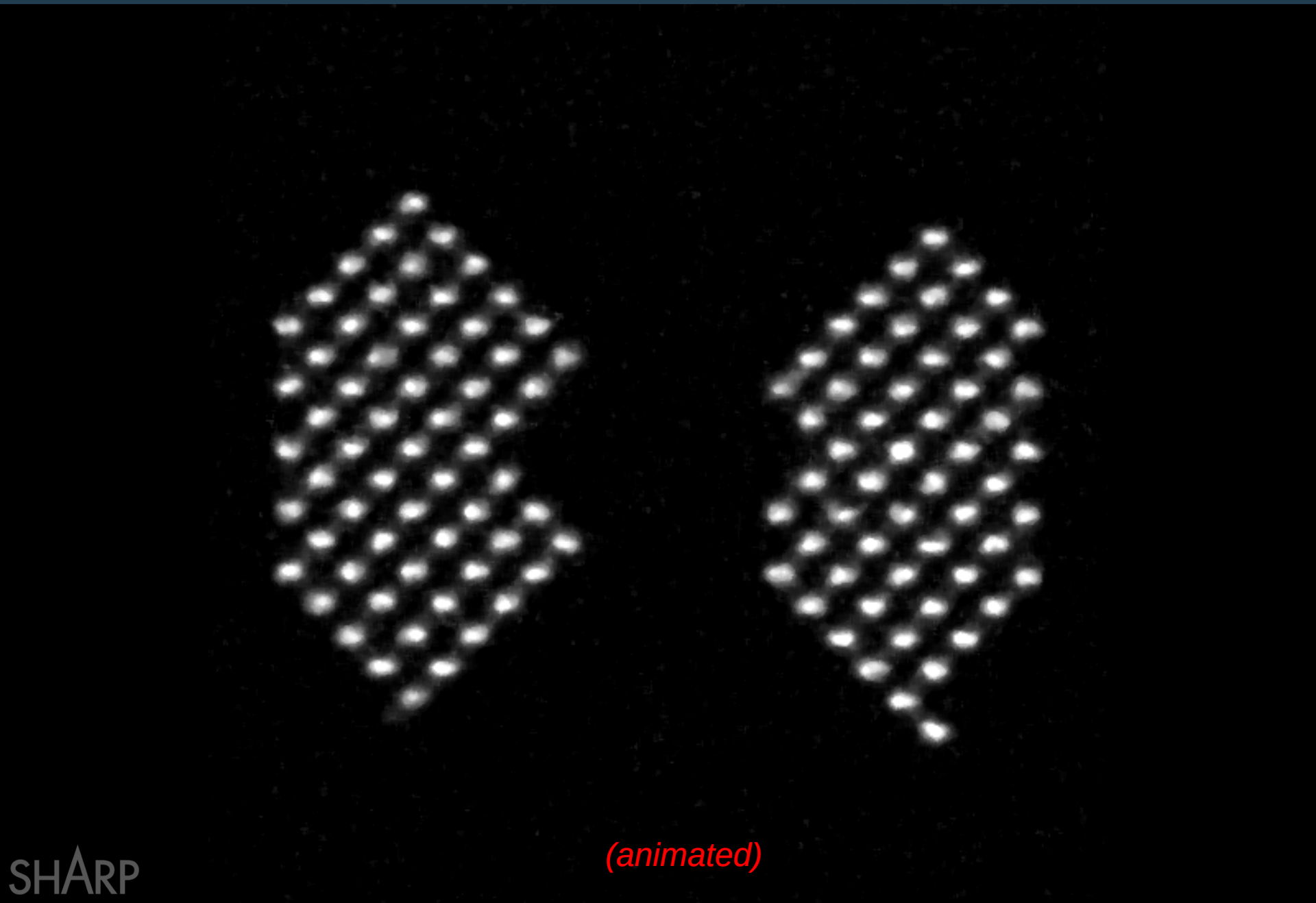


faceted pupil mirror



“EUV Lithography Industrialization Progress”
Rudy Peeters, **[ASML] (2014-10-27)**

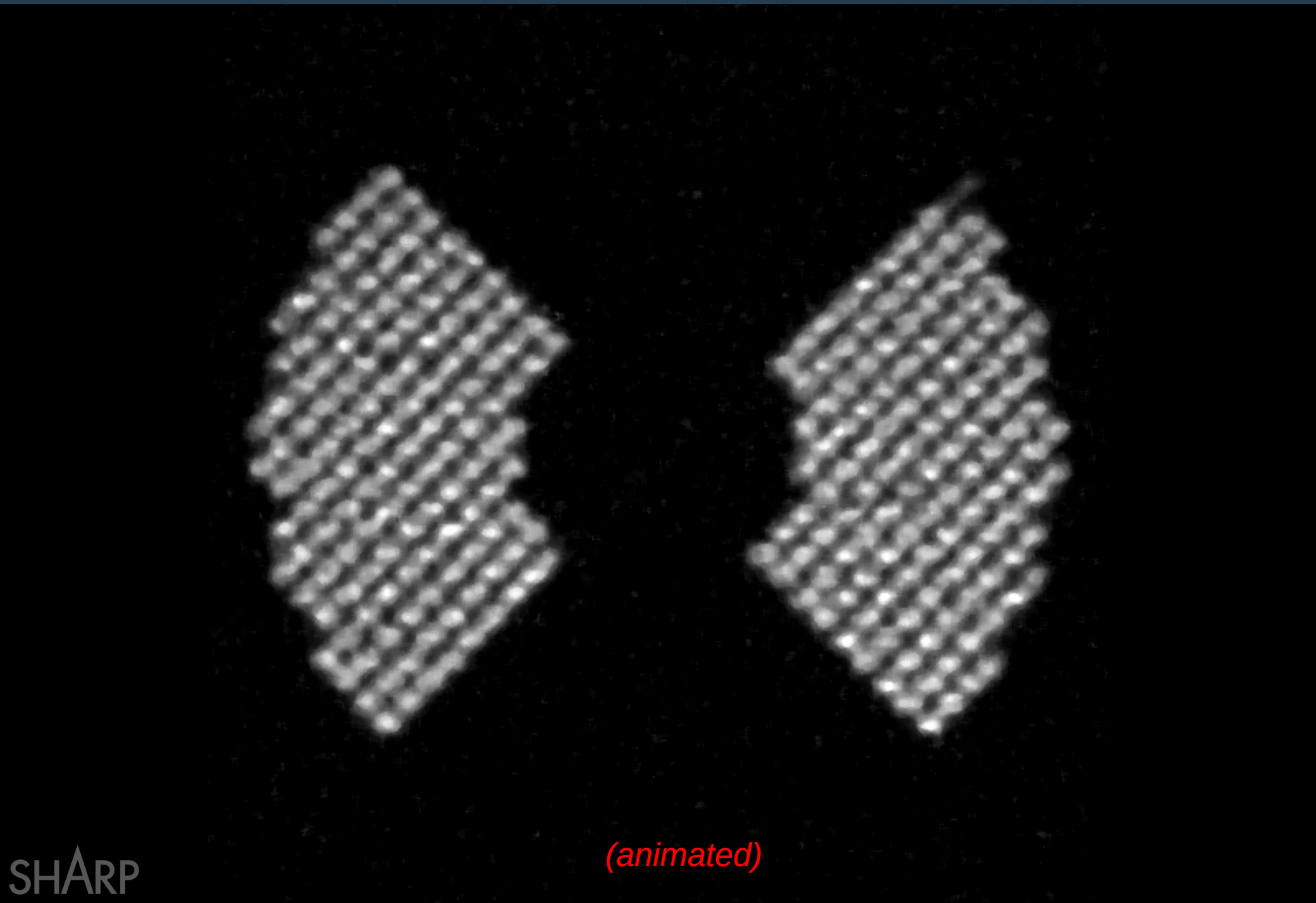
Coherence Control: Pupil Fill Patterns



(animated)

SHARP

Coherence Control: Pupil Fill Patterns



SHARP

“Freeform illumination sources: An experimental study of source-mask optimization for 22 nm SRAM cells.”

J. Bekaert, *et al.*, SPIE **7640,** 764008 (2010). [**ASML, Zeiss**]

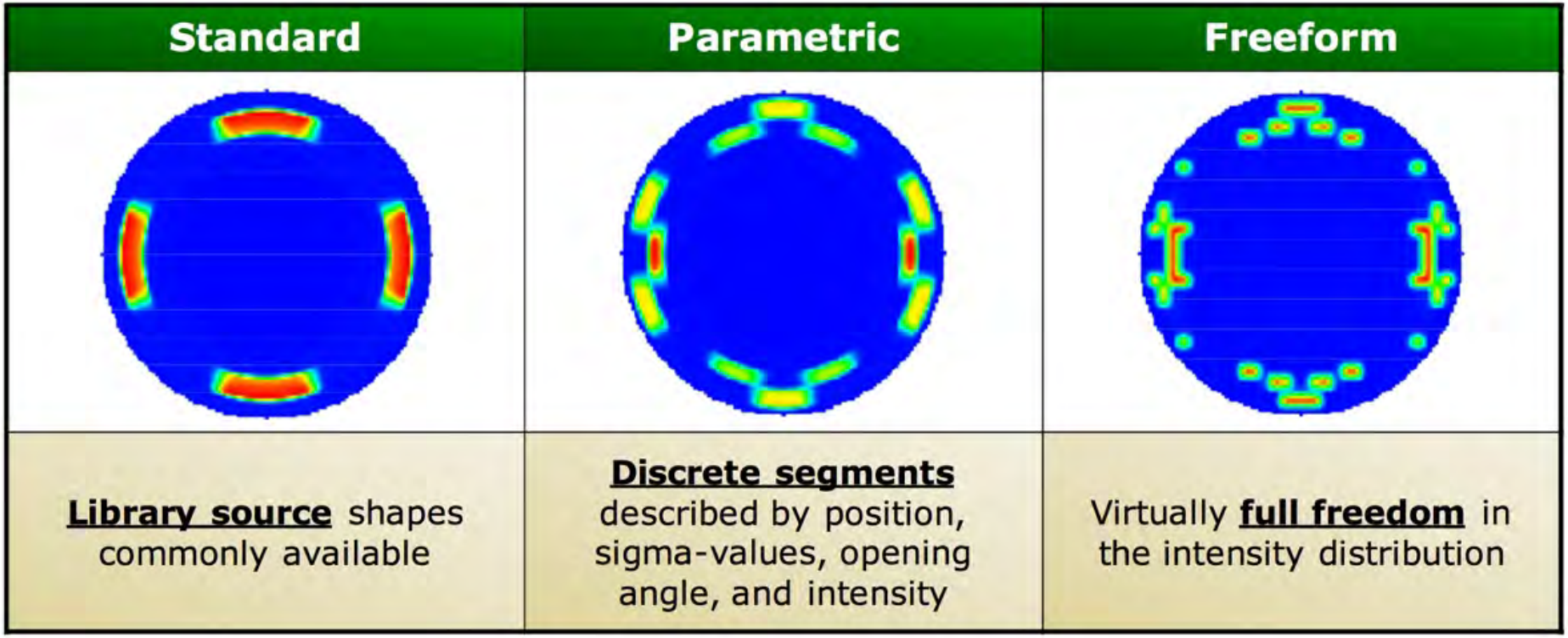
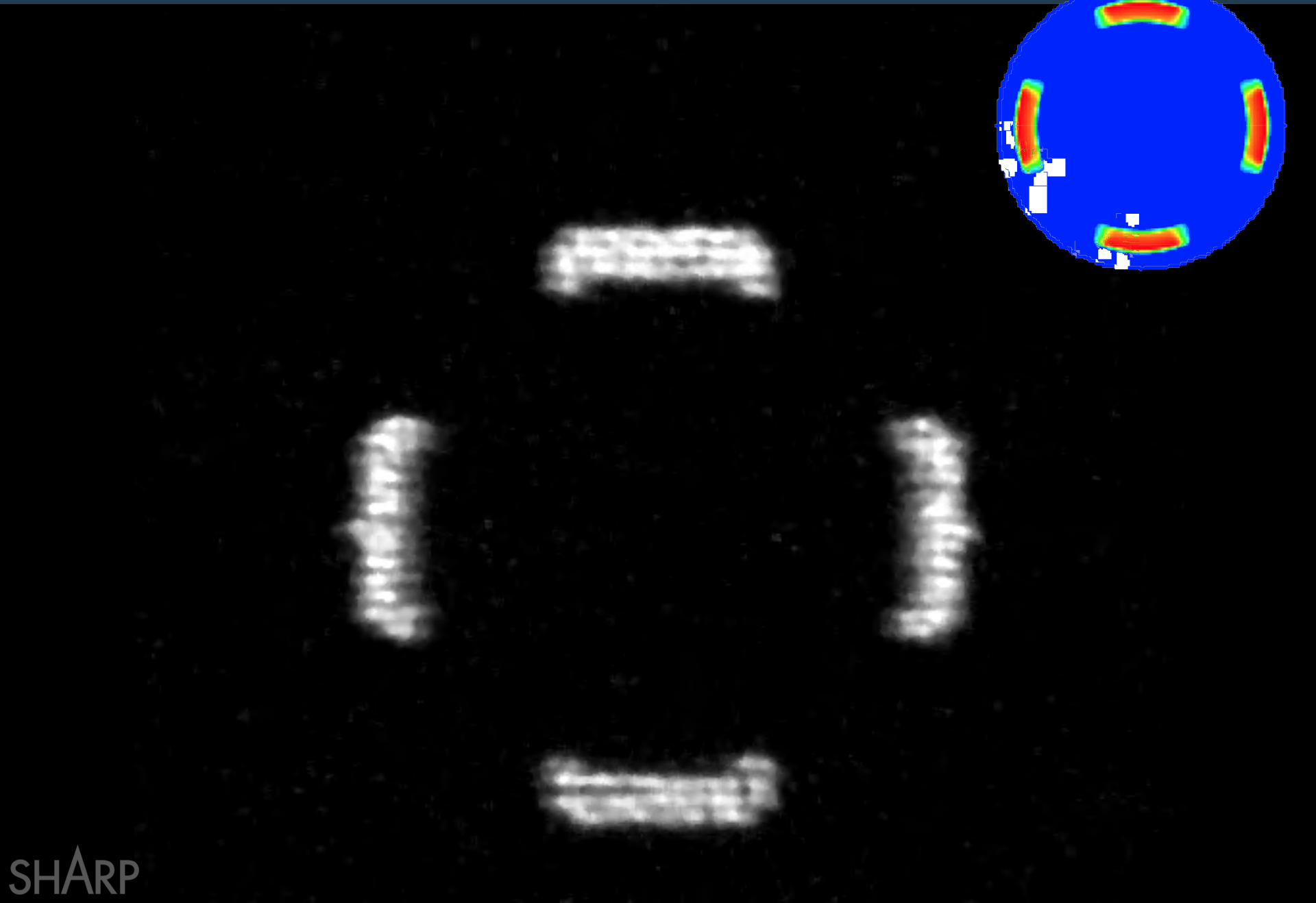
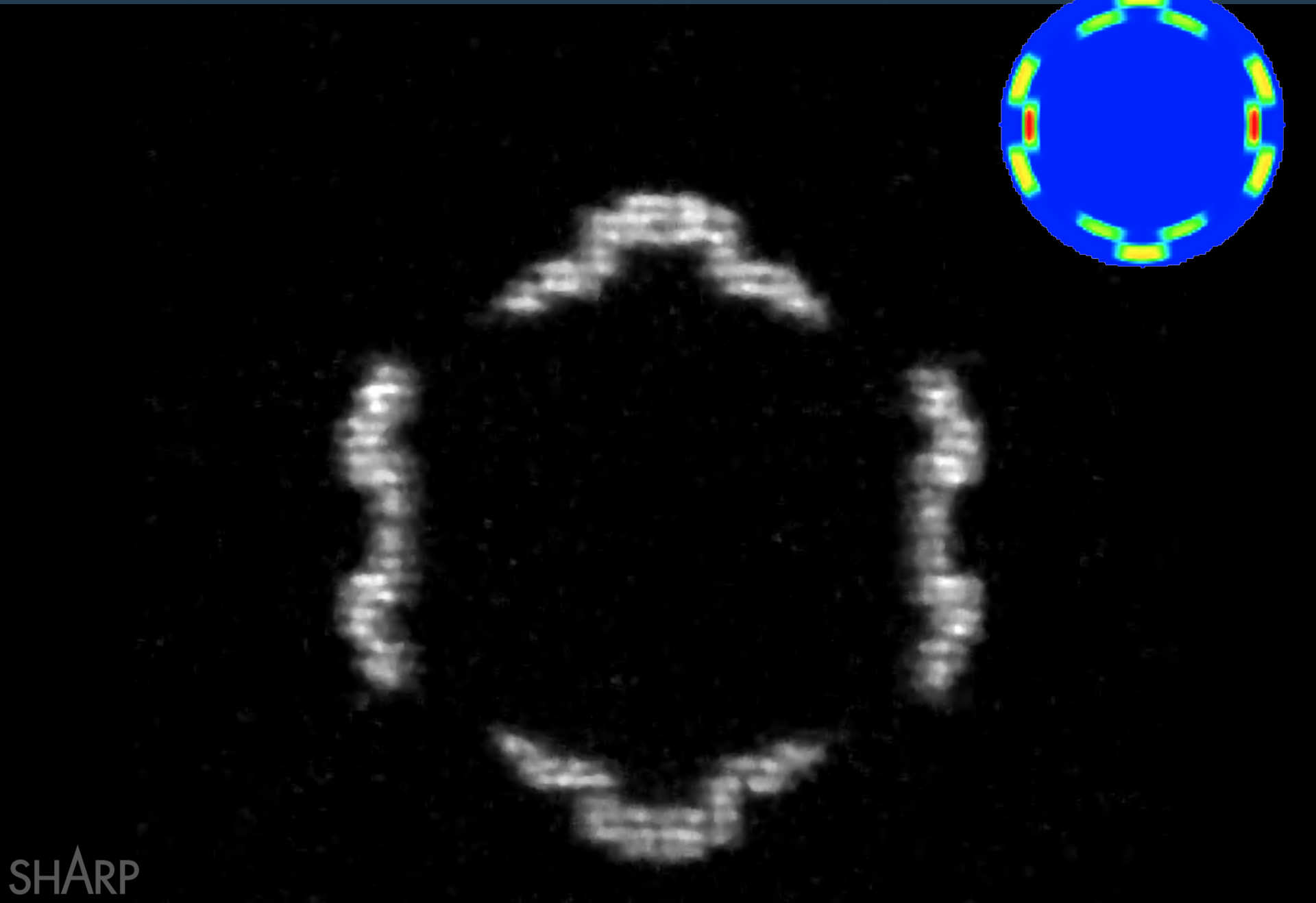


Figure 2. Description and example of a standard, parametric, and freeform source type. These are the illumination choices for optimization in ASML BRION Tachyon SMO.

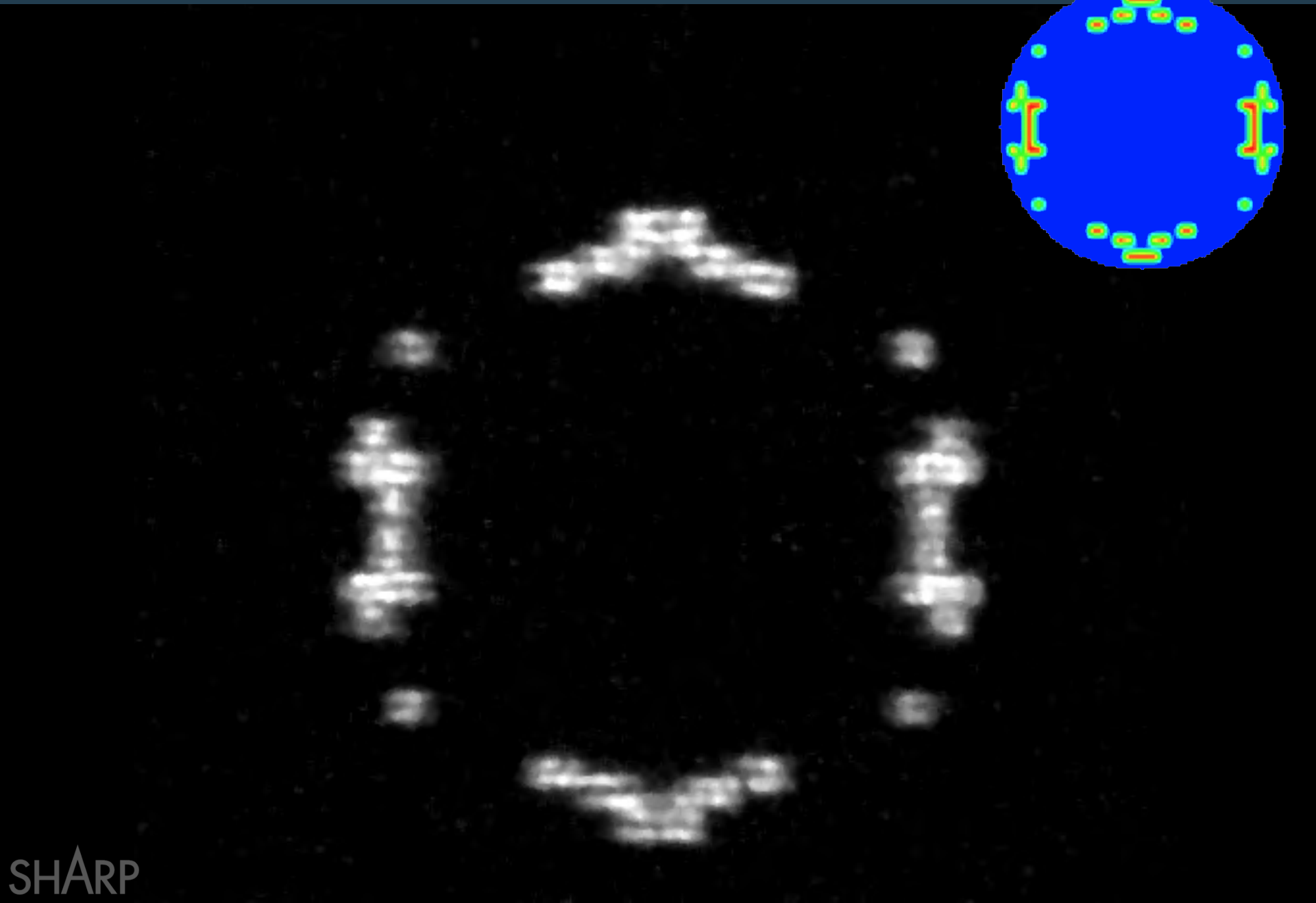
Freeform source patterns



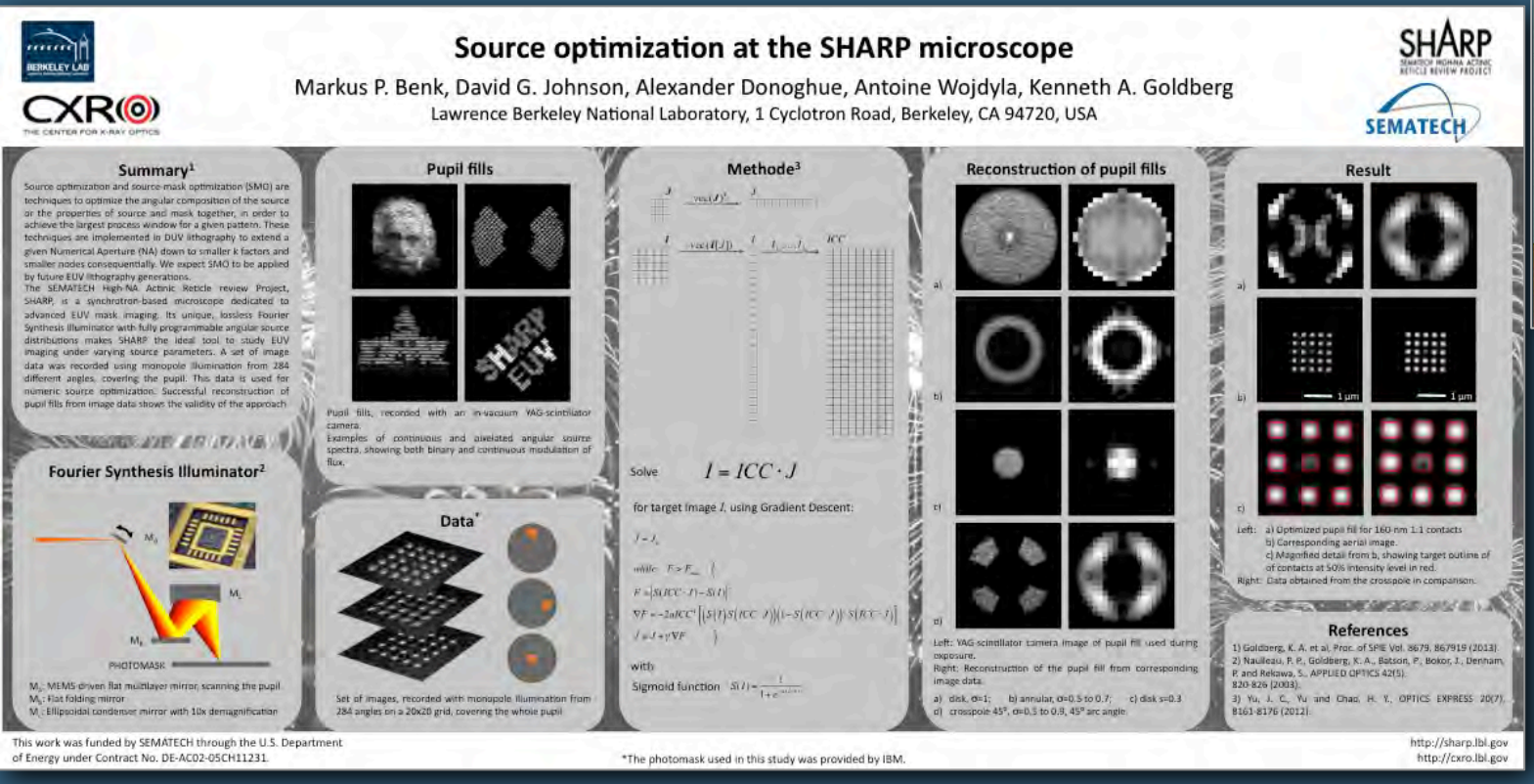
Freeform source patterns



Freeform source patterns



Poster



Source optimization at the SHARP microscope

Markus P. Benk, David G. Johnson, Alexander Donoghue, Antoine Wojdyla, Kenneth A. Goldberg
Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

Summary[1]

Source optimization and source-mask optimization (SMO) are techniques to optimize the angular composition of the source or the properties of source and mask together, in order to achieve the largest process window for a given pattern. These techniques are implemented in DUV lithography to extend a given Numerical Aperture (NA) down to smaller k factors and smaller nodes consequentially. We expect SMO to be applied by future EUV lithography generations.
The SEMATECH High-NA Actinic Reticle review Project, SHARP, is a synchrotron-based microscope dedicated to advanced EUV mask imaging. Its unique, lossless Fourier Synthesis illuminator with fully programmable angular source distributions makes SHARP the ideal tool to study EUV imaging under varying source parameters. A set of image data was recorded using monopole illumination from 284 different angles, covering the pupil. This data is used for numeric source optimization. Successful reconstruction of pupil fills from image data shows the validity of the approach.

Fourier Synthesis Illuminator[2]

M_D: MEMS-driven flat multilayer mirror, scanning the pupil
M_R: Flat folding mirror
M_C: Ellipsoidal condenser mirror with 10x demagnification

Pupil fills

Pupil fills, recorded with an in-vacuum YAG-scintillator camera.
Examples of continuous and pixelated angular source spectra, showing both binary and continuous modulation of flux.

Data*

Set of images, recorded with monopole illumination from 284 angles on a 20x20 grid, covering the whole pupil

Methode[3]

Solve $I = ICC \cdot J$

for target image I, using Gradient Descent:

$J = J_0$

while $F > F_{min}$ {

$F = \|S(ICC \cdot J) - S(I)\|$

$\nabla F = -2\alpha ICC^T \left[\left(S(I)\right) S(ICC \cdot J) \right] \left(1 - S(ICC \cdot J)\right) S(ICC \cdot J) \left(1 - S(ICC \cdot J)\right) \right]$

$J = J + \gamma \nabla F$ }

with

Sigmoid function $S(I) = \frac{1}{1+e^{-\alpha(I-\beta)}}$

Reconstruction of pupil fills

Left: YAG-scintillator camera image of pupil fill used during exposure.
Right: Reconstruction of the pupil fill from corresponding image data.

a) disk, σ=1; b) annular, σ=0.5 to 0.7; c) disk s=0.3
d) crosspole 45°, σ=0.5 to 0.9, 45° arc angle.

Result

Left: a) Optimized pupil fill for 160 nm 1:1 contacts
b) Corresponding aerial image.
c) Magnified detail from b, showing target outline of of contacts at 50% intensity level in red.
Right: Data obtained from the crosspole in comparison.

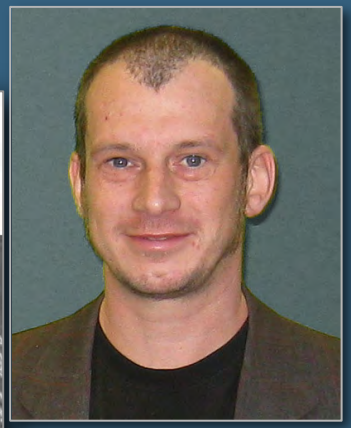
References

1) Goldberg, K. A. et al. Proc. of SPIE Vol. 8679, 867919 (2013).
2) Naulleau, P. P., Goldberg, K. A., Batson, P., Bokor, J., Denham, P. and Rekawa, S., APPLIED OPTICS 42(5), 820-826 (2003).
3) Yu, J. C., Yu and Chao, H. Y., OPTICS EXPRESS 20(7), 8161-8176 (2012).

This work was funded by SEMATECH through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

*The photomask used in this study was provided by IBM.

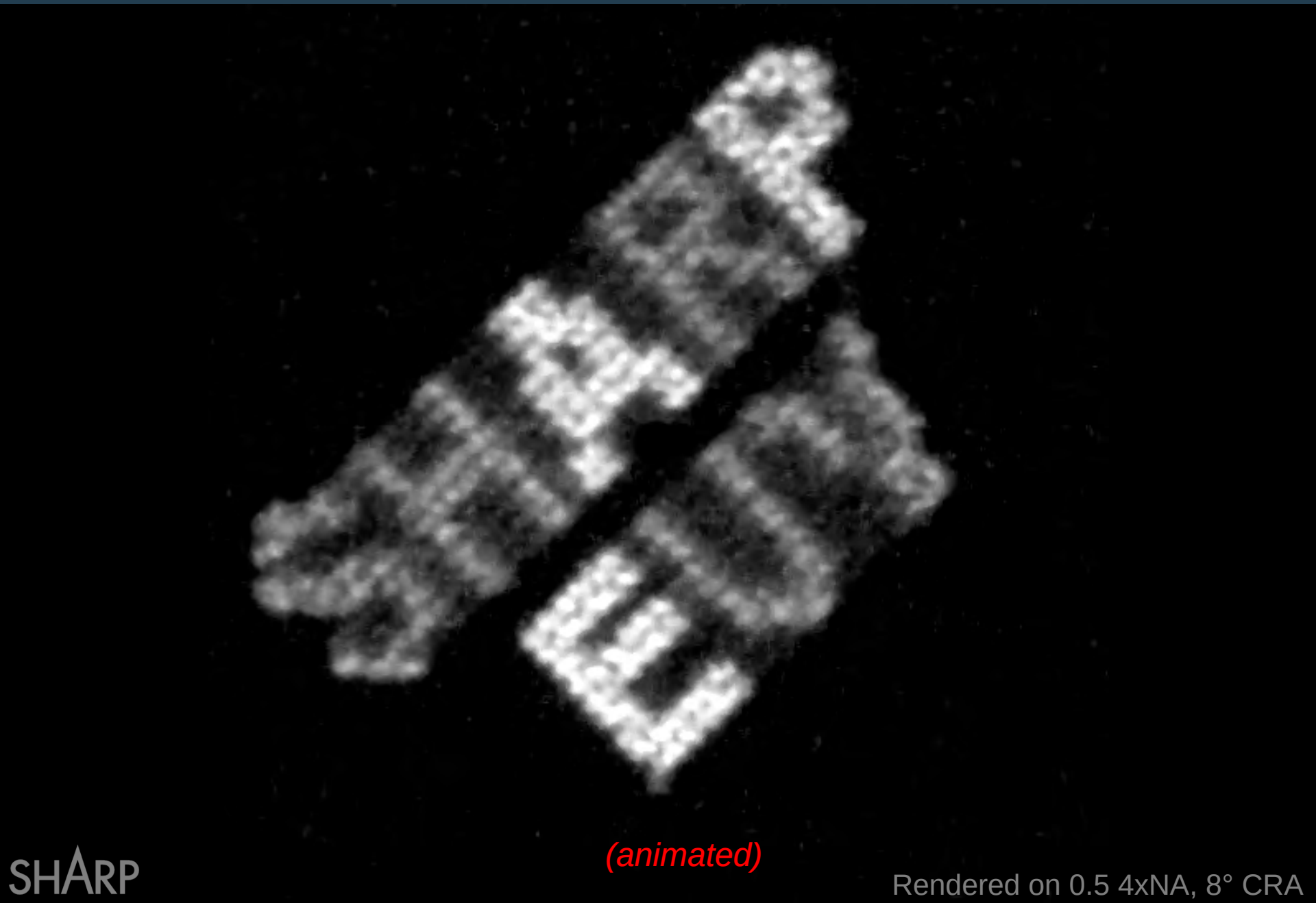
http://sharp.lbl.gov
http://cxro.lbl.gov



Markus Benk

SHARP

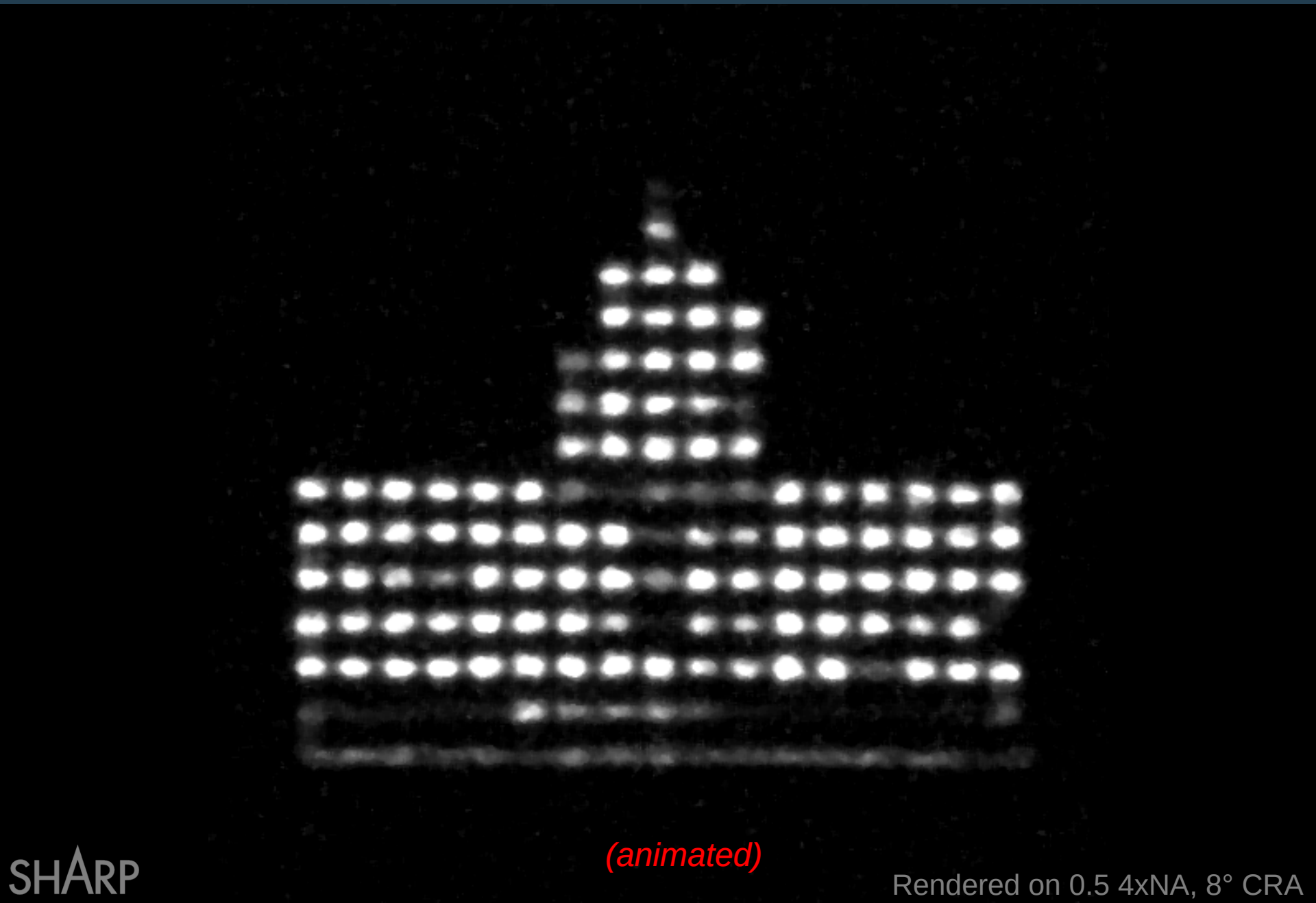
Freeform source patterns: *GRAYSCALE*



(animated)

Rendered on 0.5 4xNA, 8° CRA

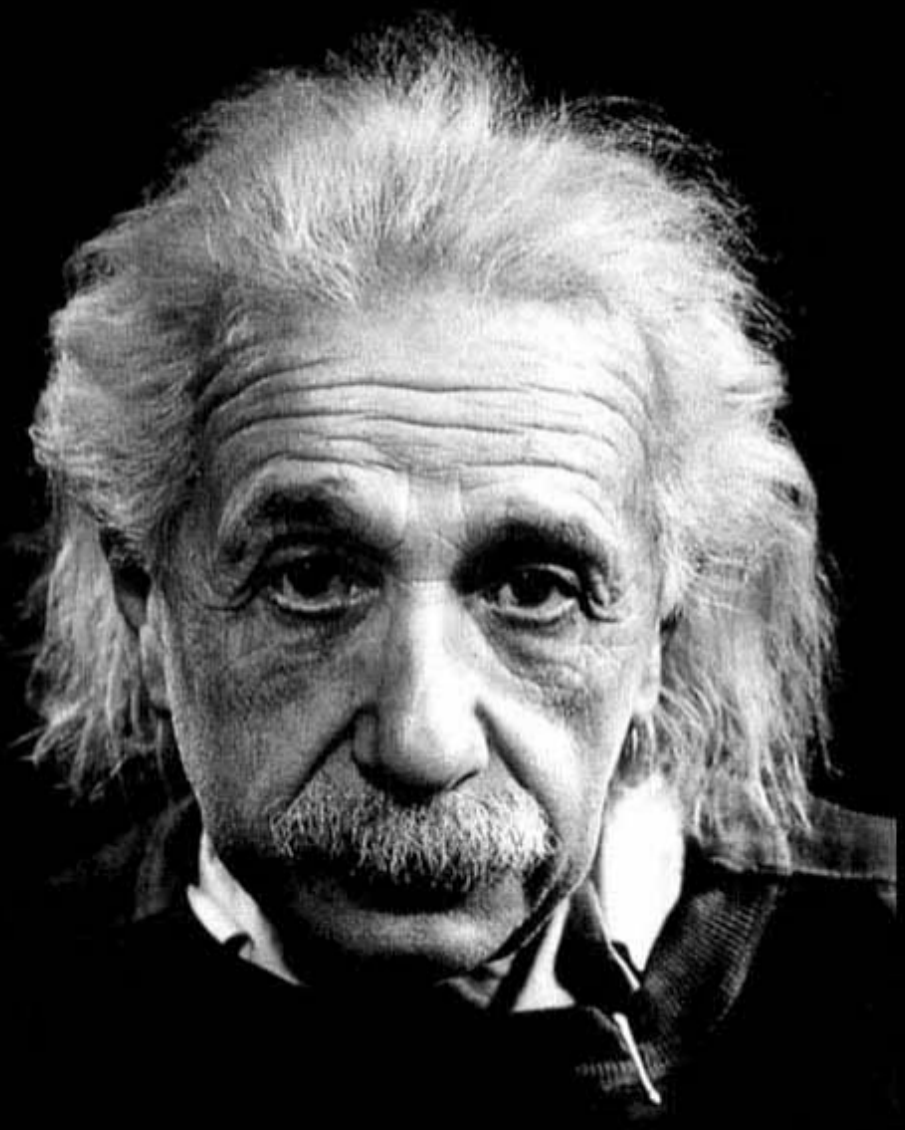
Freeform source patterns: *GRAYSCALE*



(animated)

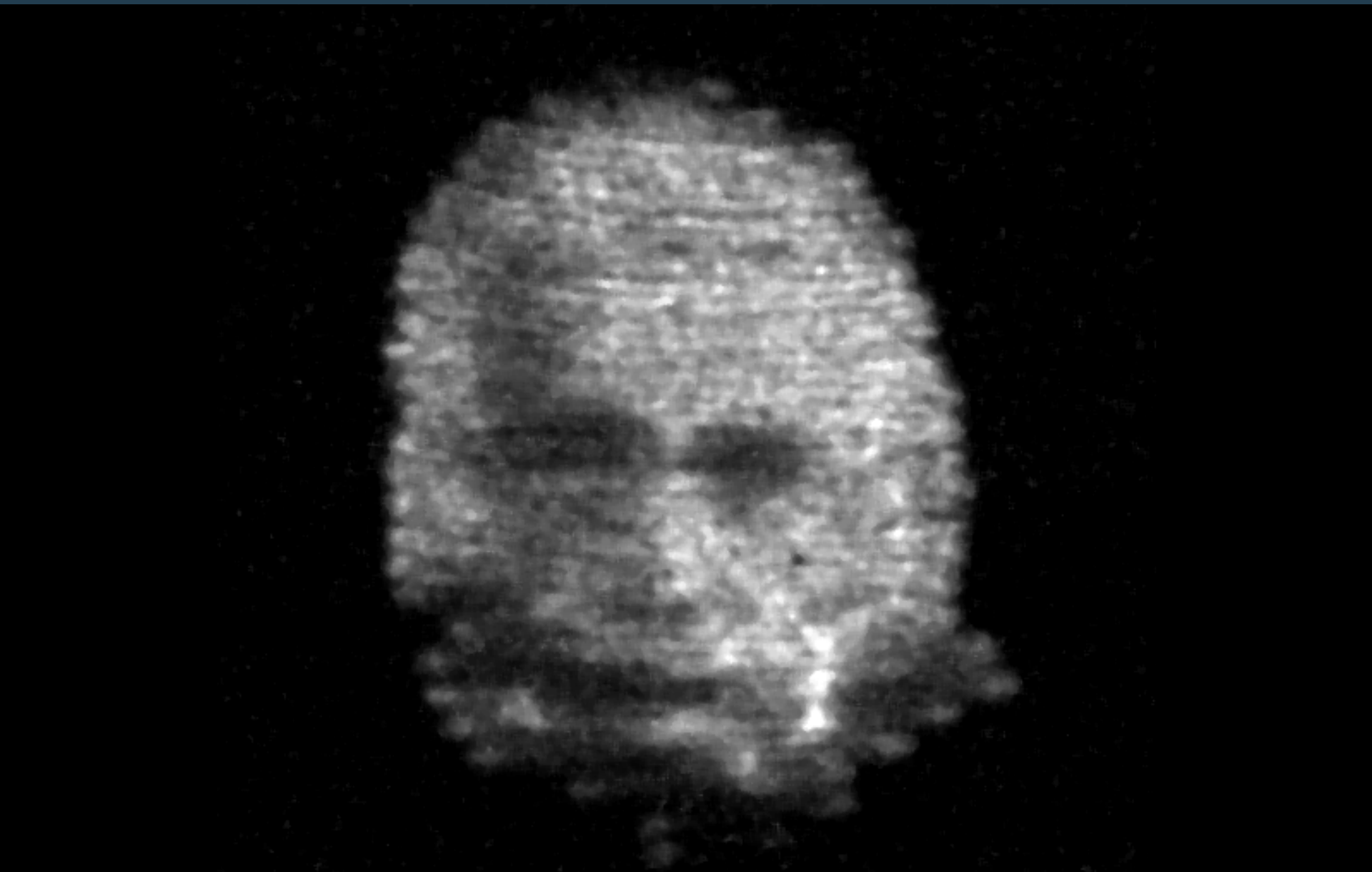
Rendered on 0.5 4xNA, 8° CRA

Freeform source patterns: *GRAYSCALE*



SHARP

Freeform source patterns: *GRAYSCALE*

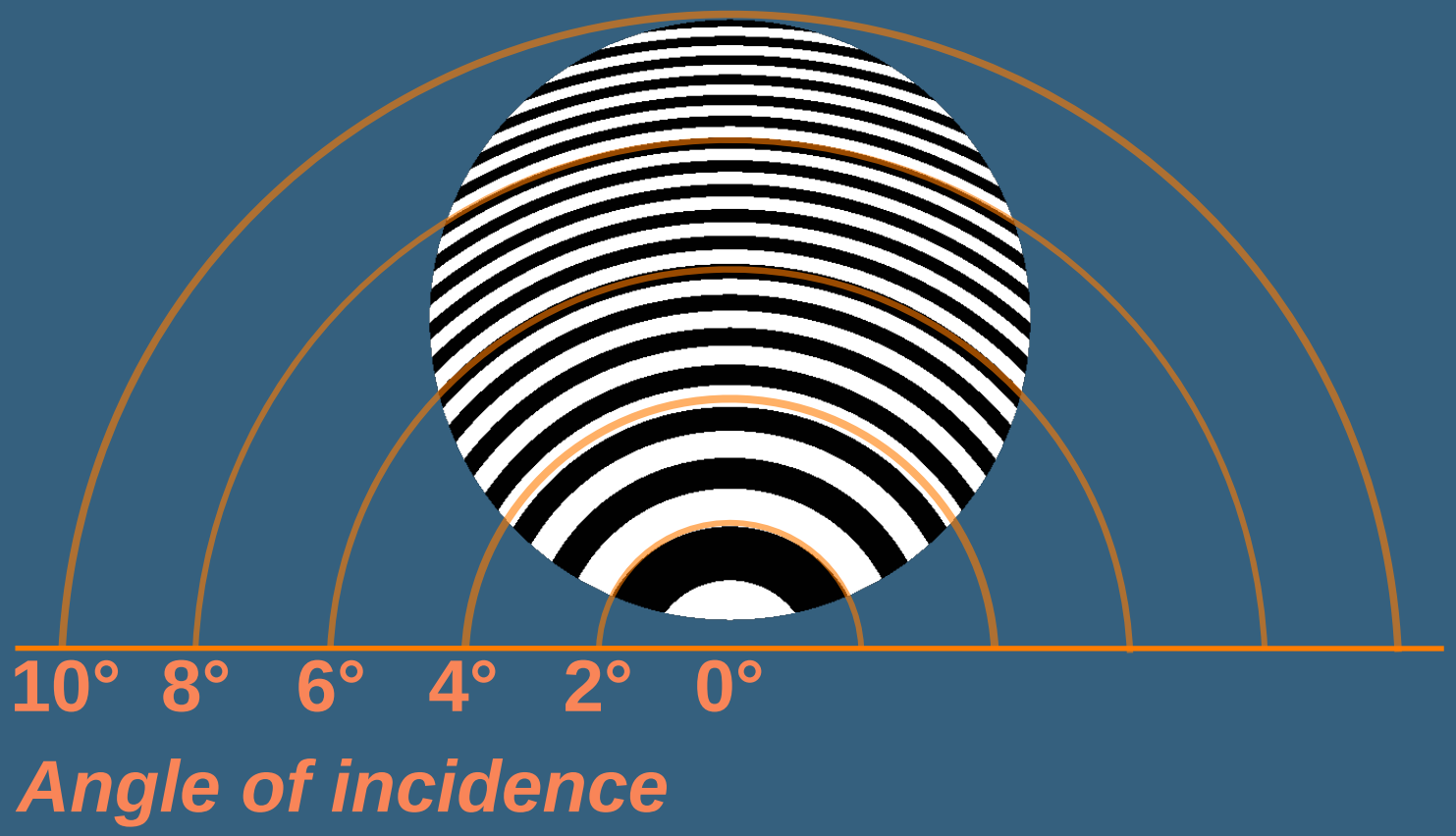


(animated)

SHARP

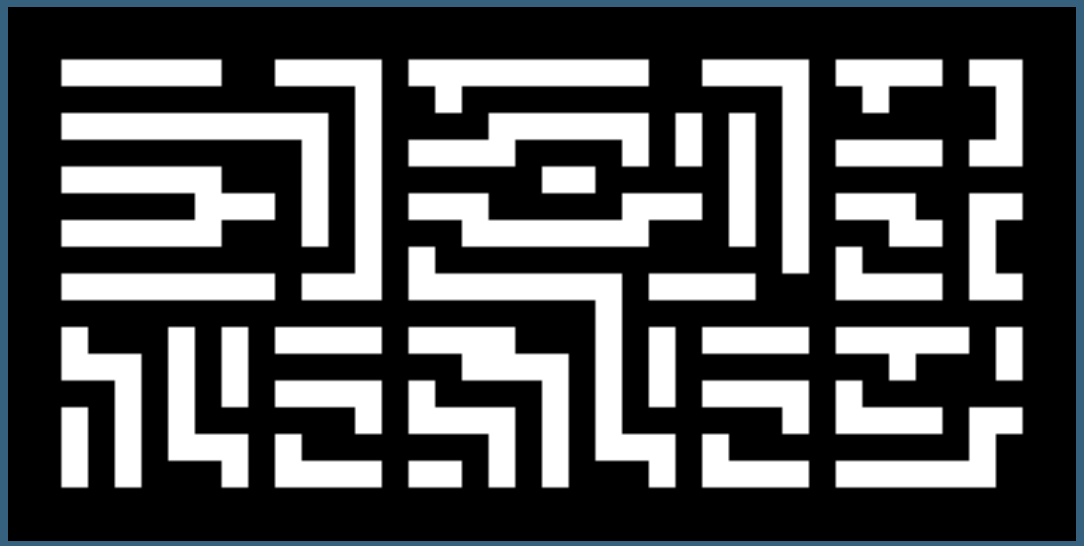
Rendered on 0.5 4xNA, 8° CRA

Off-axis angles complicate EUV lens & ML design



SHARP

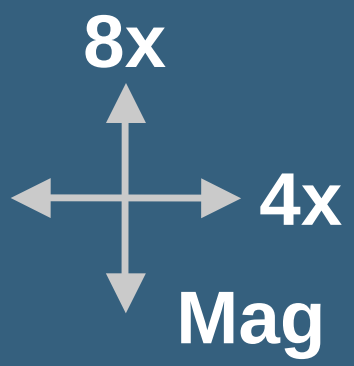
Anamorphic EUV optics and SHARP

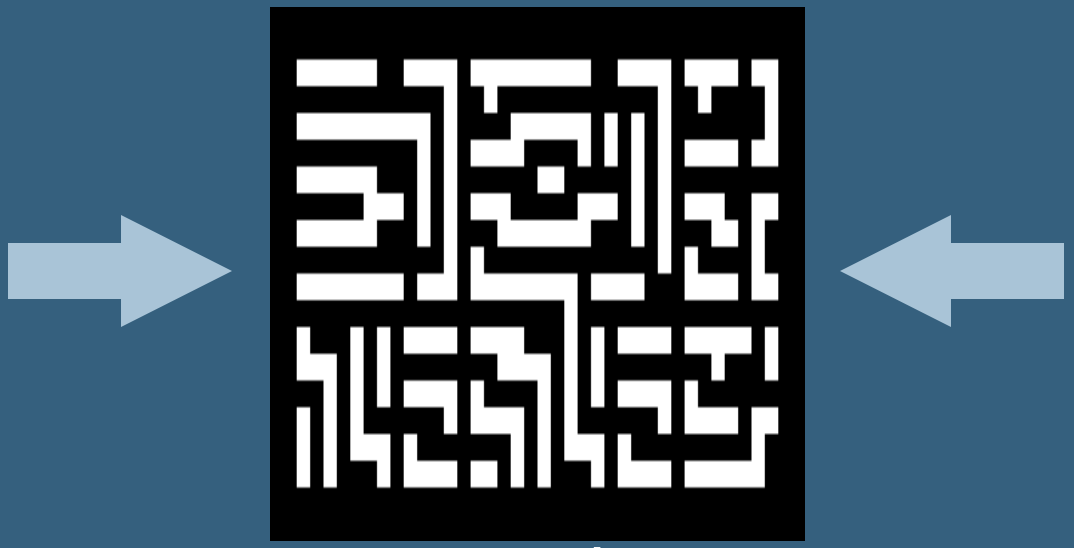


mask

SHARP

Anamorphic EUV optics and SHARP

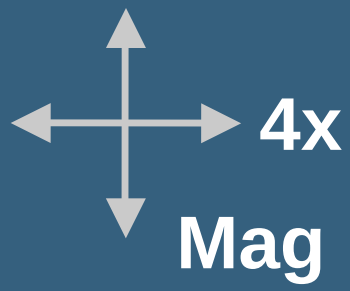


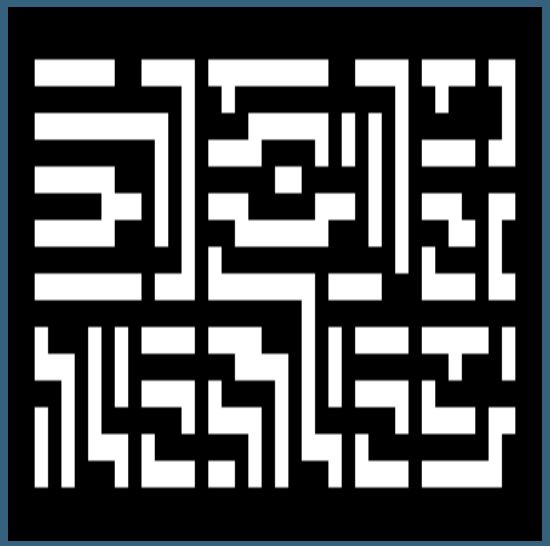


mask

SHARP

Emulating *anamorphic* lenses in SHARP



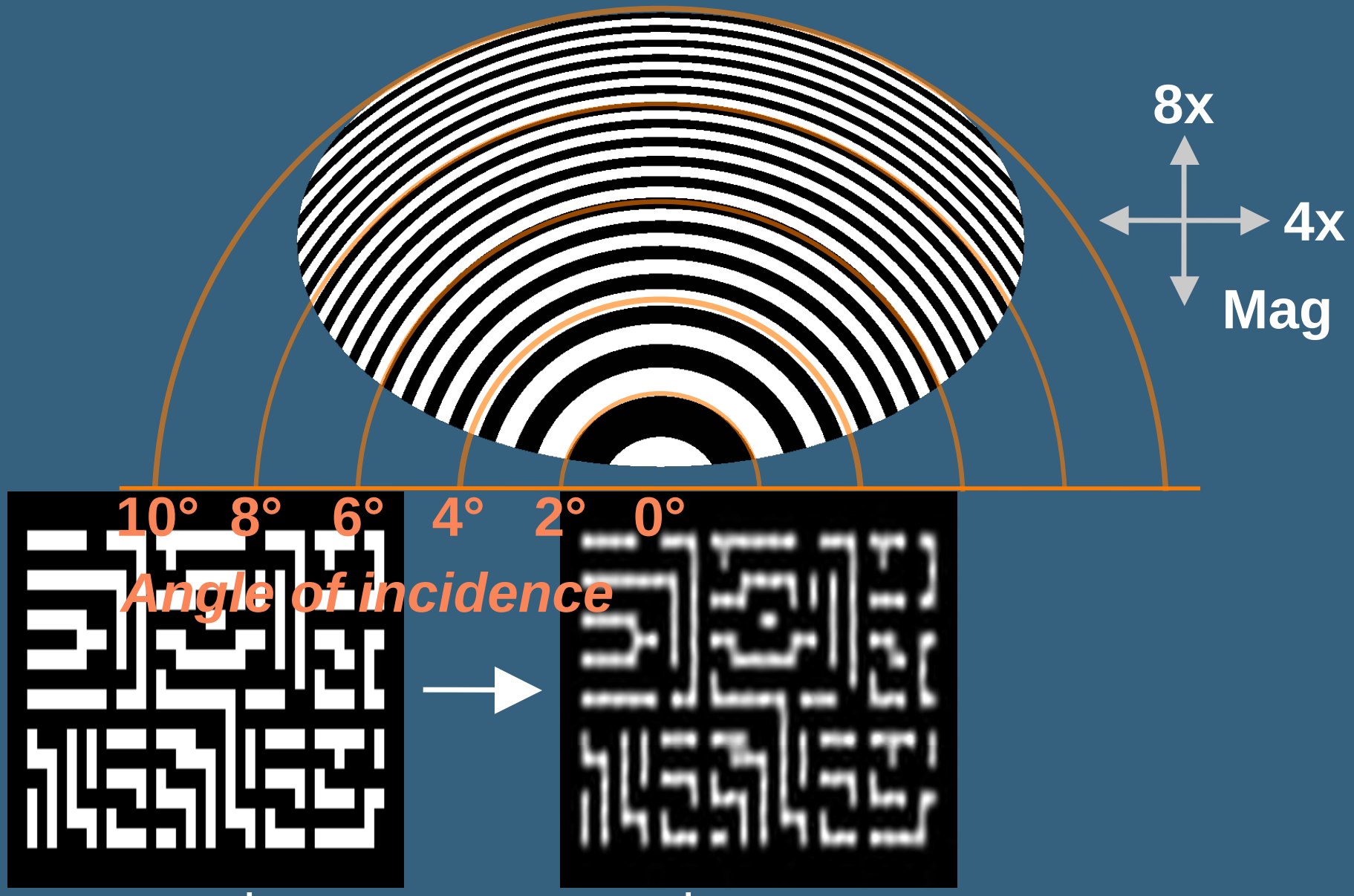


mask

image

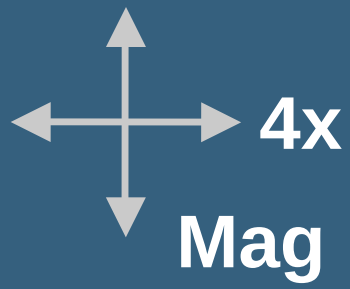
SHARP

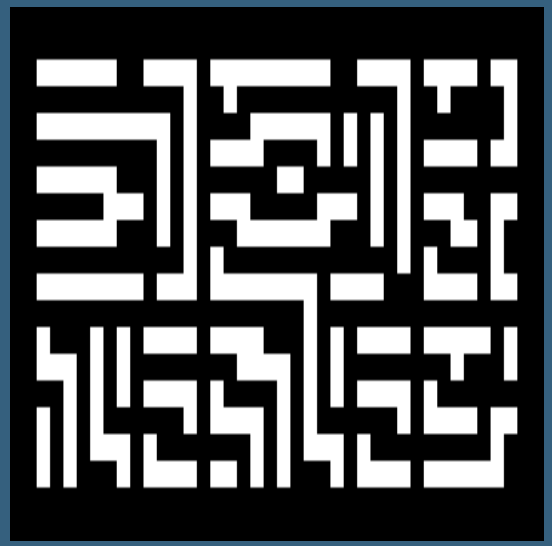
Emulating *anamorphic* lenses in SHARP



SHARP

Emulating *anamorphic* lenses in SHARP

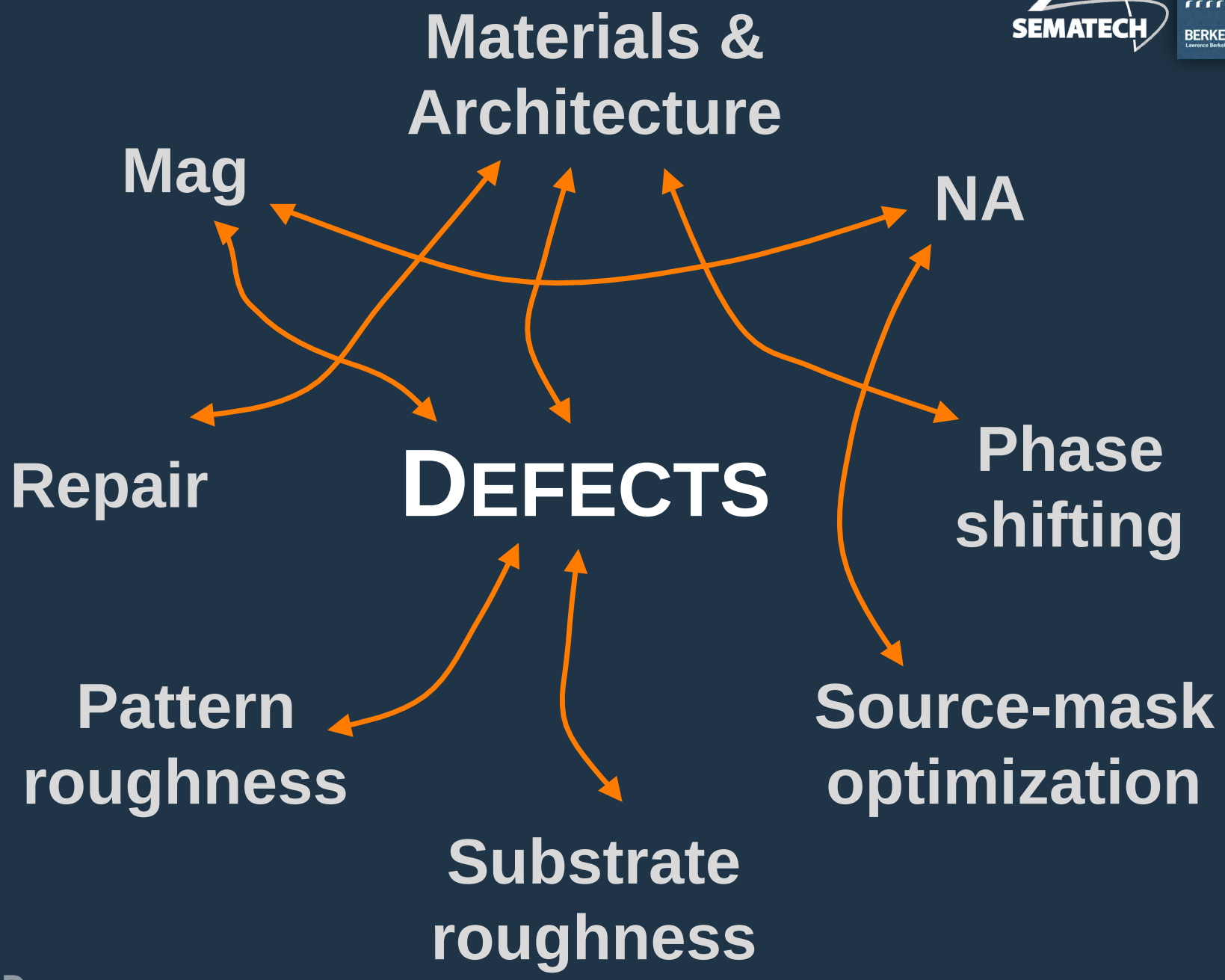




mask

image stretch

SHARP


Materials & Architecture
Mag
NA
Repair
DEFECTS
Phase shifting
Pattern roughness
Source-mask optimization
Substrate roughness

SHARP

Measuring Phase

- Differential Lenses
- Zernike Phase Contrast
- Through-focus Phase Reconstruction
- Fourier Ptychography Microscopy
- Differential Phase Contrast

Stereo lenses, a path to 3D

Source customization for SMO

- Binary *and Grayscale* Sources

Anamorphic lens emulation (future)

SHARP

Come work with us!

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Frank Goodwin
Stefan Wurm
Kevin Cummings

GlobalFoundries:

Pawitter Mangat, Obert Wood

RIT:

Zachary Levinson, Bruce Smith

Intel:

John Magana

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