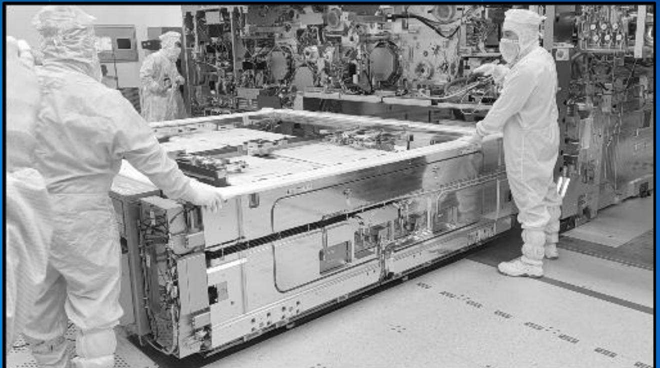

High NA EUV: Getting closer to introduction

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EUVL Workshop 2022 | online

Public

Outline

Status EUV

Introduction High NA EUV

Technical opportunities of High NA

- High NA contrast benefits enabling improved pattern fidelity
- On-Product overlay control strategy considerations for High NA

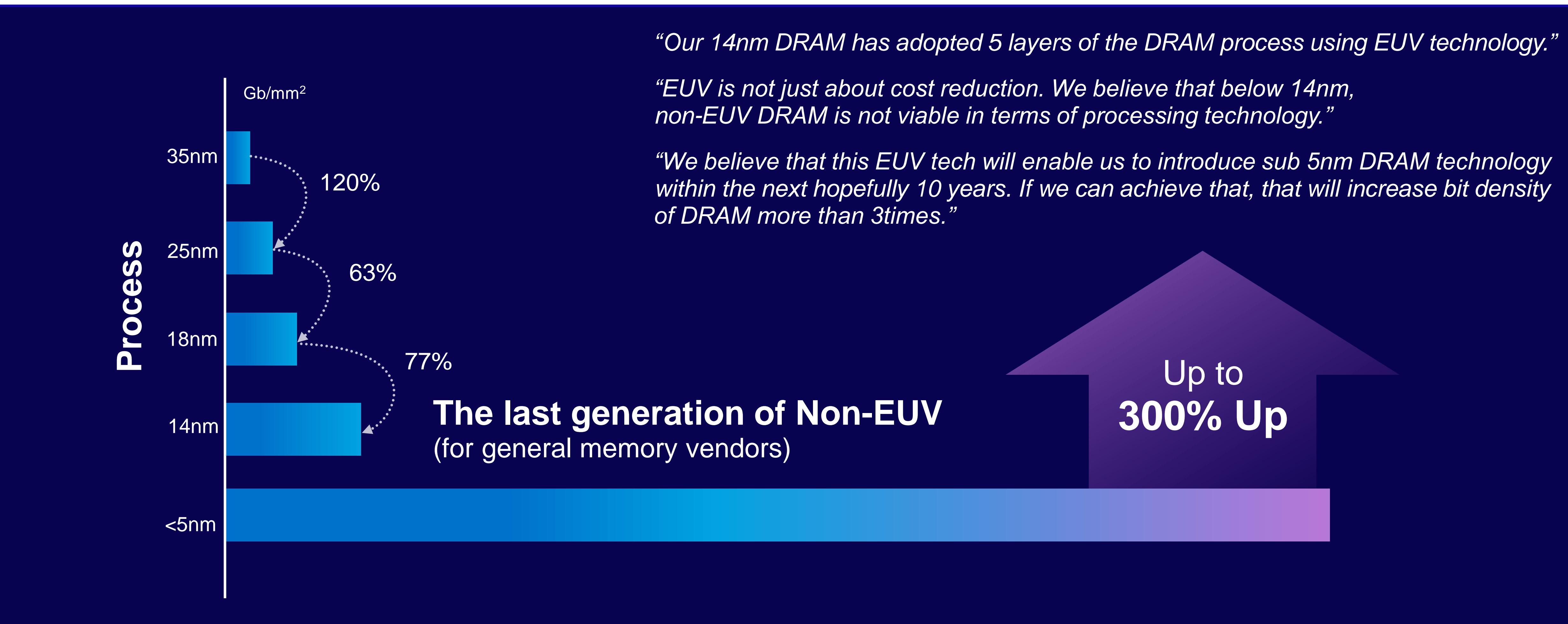
ECO-system

High NA architecture and integration status

Outlook and conclusions

“Key enabler for DRAM bit growth: EUV”

“Sustaining process scaling by high resolution patterning”



Source: Samsung, Jinman Han, EVP Memory Sales and Marketing, Samsung Investor forum, November 2021

Number of wafers exposed on EUV systems grows rapidly

Cumulative # wafers exposed on EUV

4 Mln

Number of systems shipped (cumulative) NXE:3400B/C and NXE:3600D

Number of systems shipped (cumulative)
NXE:3400B/C and NXE:3600D

Year	Quarter	Systems shipped (cumulative)
2019	Q1	31
2019	Q2	38
2019	Q3	45
2019	Q4	53
2020	Q1	55
2020	Q2	62
2020	Q3	76
2020	Q4	85
2021	Q1	92
2021	Q2	102
2021	Q3	115
2021	Q4	127
2022	Q1	136

NXE:3600D increases throughput by >18% over NXE:3400C

NXE:3800E

Quarter	Throughput [wafers per hour]	Series	System
'14 Q1		20mJ/cm²	NXE:3300B
'14 Q2		20mJ/cm²	NXE:3300B
'14 Q3		20mJ/cm²	NXE:3300B
'14 Q4		20mJ/cm²	NXE:3300B
'15 Q3		20mJ/cm²	NXE:3350B
'15 Q4		20mJ/cm²	NXE:3350B
'16 Q2		20mJ/cm²	NXE:3350B
'16 Q4		20mJ/cm²	NXE:3350B
'17 Q1		20mJ/cm²	NXE:3400B
'17 Q3		20mJ/cm²	NXE:3400B
'17 Q3		20mJ/cm²	NXE:3400B
'18 Q1		20mJ/cm²	NXE:3400B
'19 Q1		20mJ/cm²	NXE:3400B
'19 Q3		20mJ/cm²	NXE:3400B
'19 Q2		30mJ/cm² – 3400C	NXE:3400C at customers
'19 Q4		20mJ/cm²	NXE:3400C ASML factory
'20 Q1		20mJ/cm²	NXE:3400C
'20 Q1		30mJ/cm² – 3400C	NXE:3400C at customers
'21 Q1		30mJ/cm² – 3600D	NXE:3600D ASML factory
'21 Q3		(faded)	NXE:3600D at customers
'21 Q4		(faded)	NXE:3600D ASML factory
(faded)		(faded)	NXE:3800E, Next 220 wph roadmap

Throughput [wafers per hour]: 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180

Legend:
- 20mJ/cm²
- 30mJ/cm² – 3400C
- 30mJ/cm² – 3600D

>17x in ~5 years

Productivity at higher dose (30mJ/ cm²)

NXE:3300B

NXE:3350B

NXE:3400B

NXE:3400C

NXE:3600D

NXE:3400C ASML factory

NXE:3400C at customers

NXE:3400C at customers

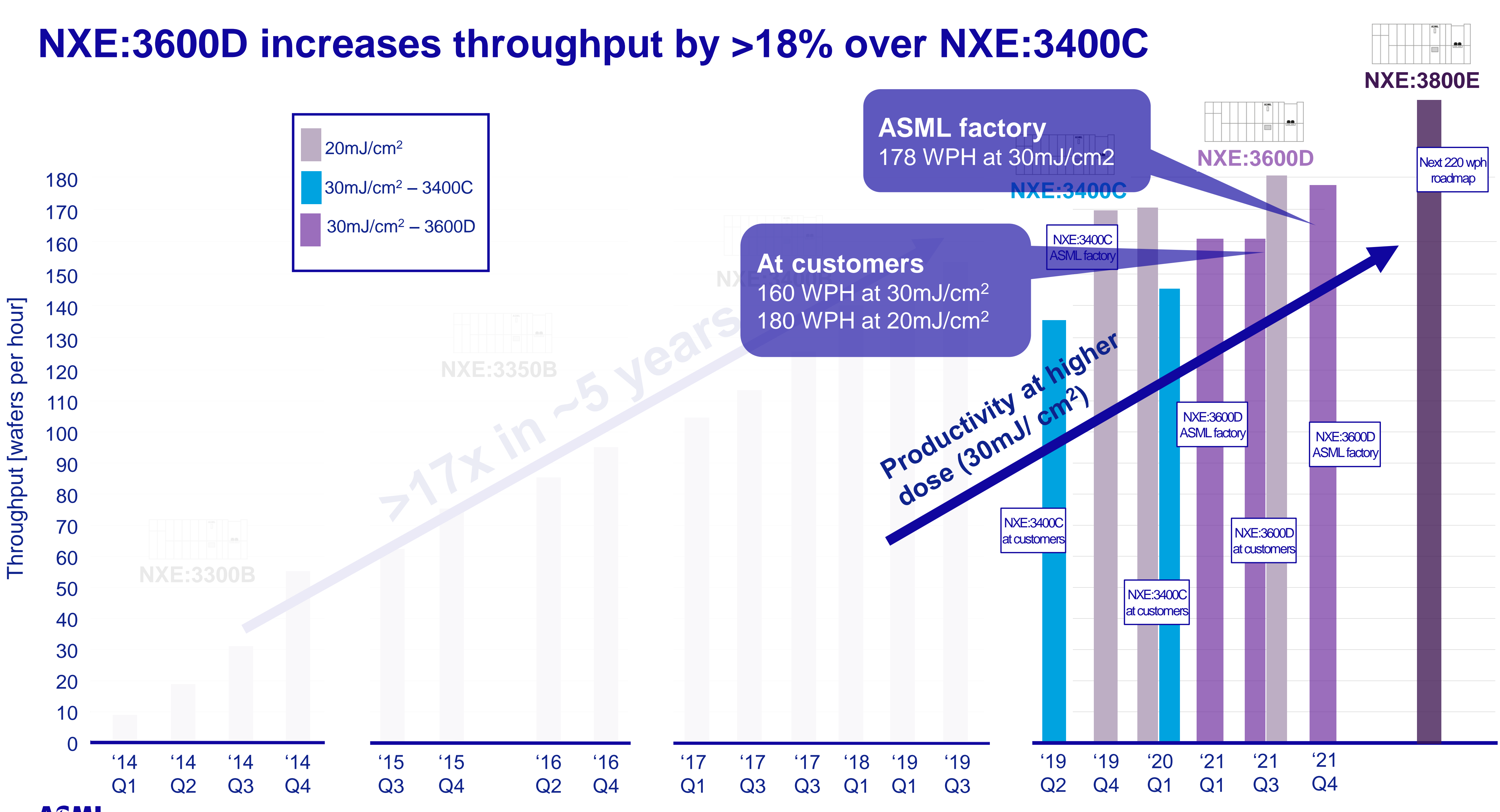
NXE:3600D ASML factory

NXE:3600D ASML factory

NXE:3600D at customers

Next 220 wph roadmap

'14 Q1, '14 Q2, '14 Q3, '14 Q4, '15 Q3, '15 Q4, '16 Q2, '16 Q4, '17 Q1, '17 Q3, '17 Q3, '18 Q1, '19 Q1, '19 Q3, '19 Q2, '19 Q4, '20 Q1, '21 Q1, '21 Q3, '21 Q4


NXE:3600D increases throughput by >18% over NXE:3400C
20mJ/cm2
30mJ/cm2 – 3400C
30mJ/cm2 – 3600D
Throughput [wafers per hour]
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
NXE:3300B
NXE:3350B
>17x in ~5 years
ASML factory
178 WPH at 30mJ/cm2
At customers
160 WPH at 30mJ/cm2
180 WPH at 20mJ/cm2
NXE:3400C
NXE:3600D
NXE:3800E
Next 220 wph roadmap
NXE:3400C ASML factory
NXE:3400C at customers
NXE:3400C at customers
NXE:3600D ASML factory
NXE:3600D at customers
NXE:3600D ASML factory
Productivity at higher dose (30mJ/ cm2)
'14 Q1
'14 Q2
'14 Q3
'14 Q4
'15 Q3
'15 Q4
'16 Q2
'16 Q4
'17 Q1
'17 Q3
'17 Q3
'18 Q1
'19 Q1
'19 Q3
'19 Q2
'19 Q4
'20 Q1
'21 Q1
'21 Q3
'21 Q4

NXE:3600D

Enabling 1.7nm On Product Overlay at increased productivity of 160 WPH (30 mJ/cm^2)

Improvements in Overlay, Imaging, Productivity achieved by, amongst others:

- Projection optics aberration reduction
- Fast aberration measurements and control
- Improved mask temperature control
- Improved wafer stage flatness
- Higher wafer level power
- Reduced wafer overhead

Projection optics aberration reduction in Coma and Three-foil clearly visible via multi-bar Pattern Placement Error test

Illumination Pupil for horizontal features

High sensitivity to Z8,11,20

dPPE [nm]

0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4

-12.7 -8.5 -4.2 0.0 4.2 8.5 12.7

Slit position [mm]

Pitch 300nm vs Pitch 34nm - Horizontal

Avg. NXE:3600D
Avg. NXE:3400C

Illumination Pupil for vertical features

High sensitivity to Z7,10,19

dPPE [nm]

1.0
0.8
0.6
-0.4
-0.2
-0.0
-0.2
-0.4
-0.6
-0.8

-12.7 -8.5 -4.2 0.0 4.2 8.5 12.7

Slit position [mm]

Pitch 300nm vs Pitch 34nm - Vertical

The delta Pattern Placement Error (dPPE) is the relative placement error between different features.

See SPIE EUVL 2021 Paper 11854-28 |
0.33 NA EUV systems for High Volume Manufacturing, Smeets et al.

NXE:3600D Matched Machine Overlay improvement confirmed in ASML factory acceptance testing

Matched Machine overlay [nm]

1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

NXE:3400C

spec.1.5nm

NXE:3600D

spec.1.1nm

X 0.8nm
Y 0.8nm
Best result to date

Each bar represents one system at ASML Factory Acceptance Testing

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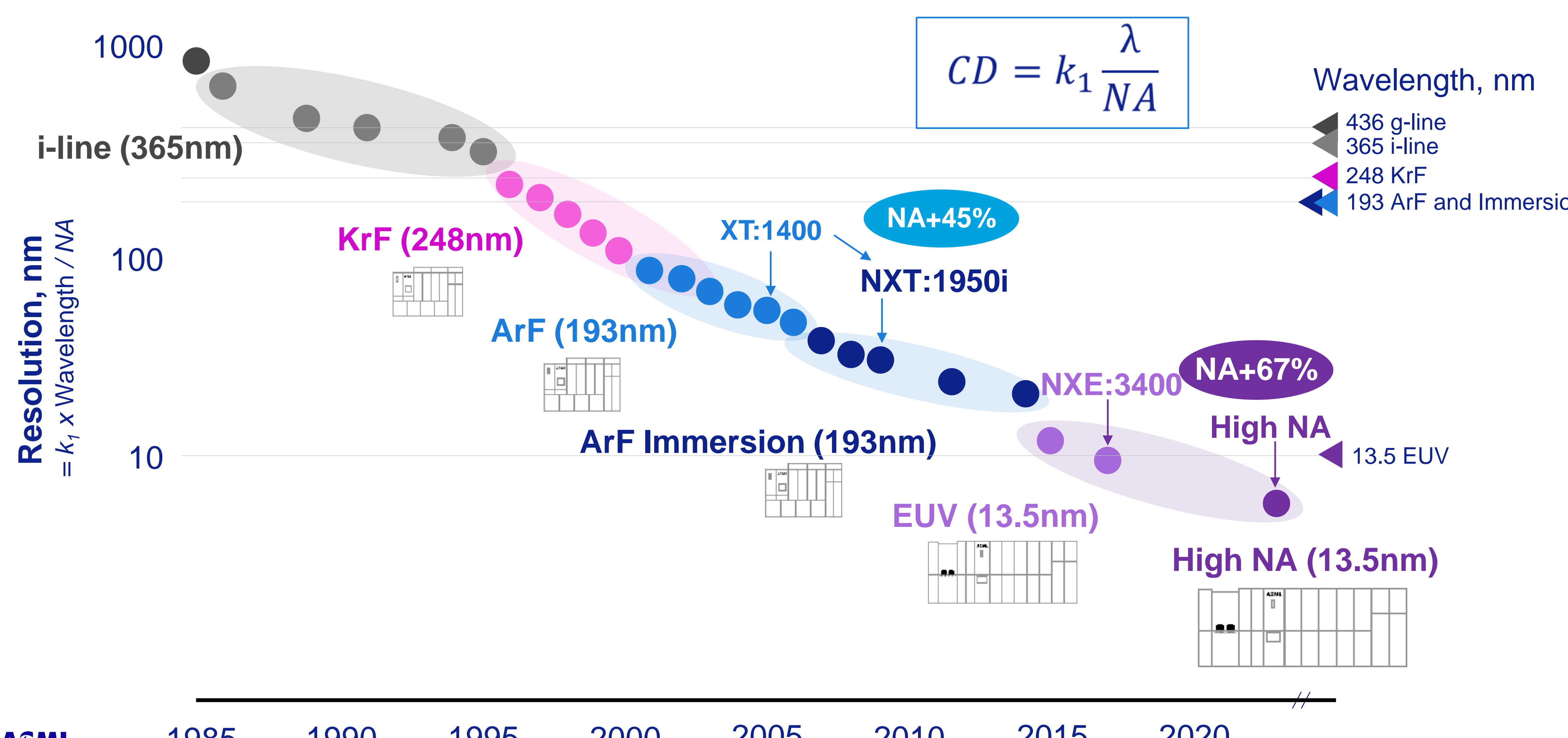
Over 35 years 2 orders of magnitude resolution reduction

by working on Wavelength, NA and k_1



The basics for High NA EUV are found in the elements

At 13.5nm refractive indices are close to 1, absorption ≠ 0

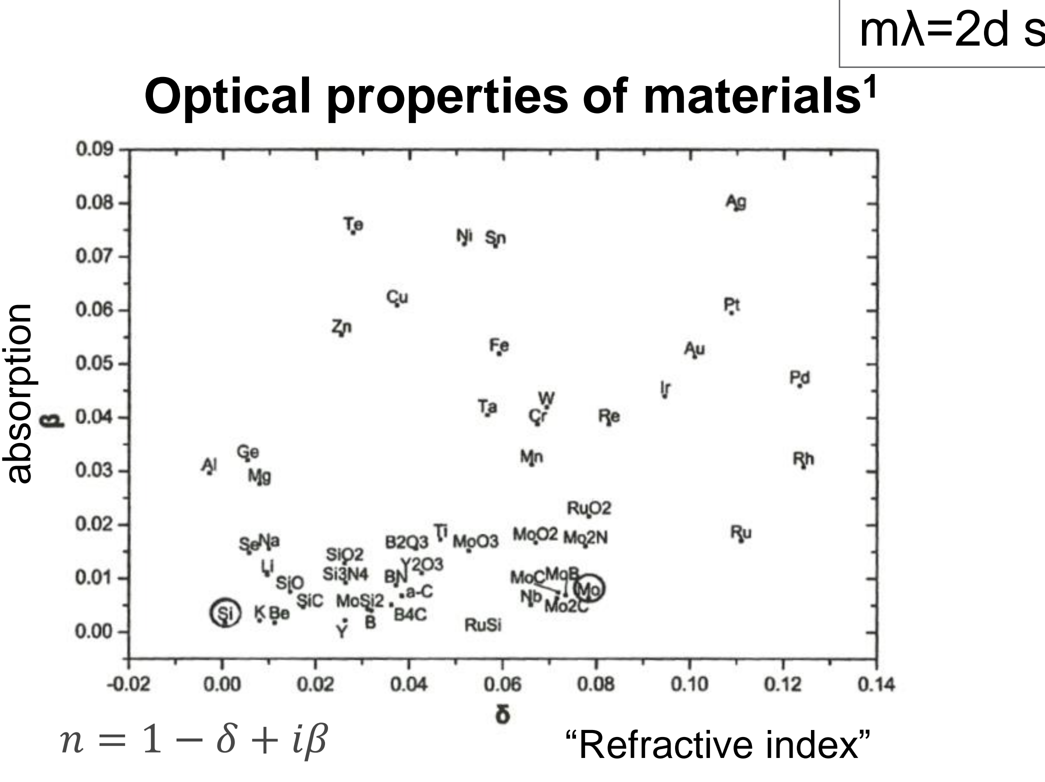
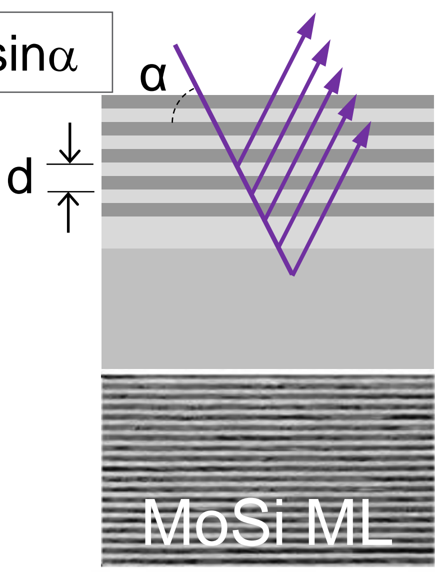
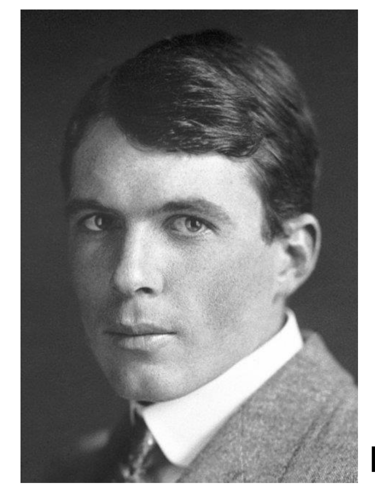


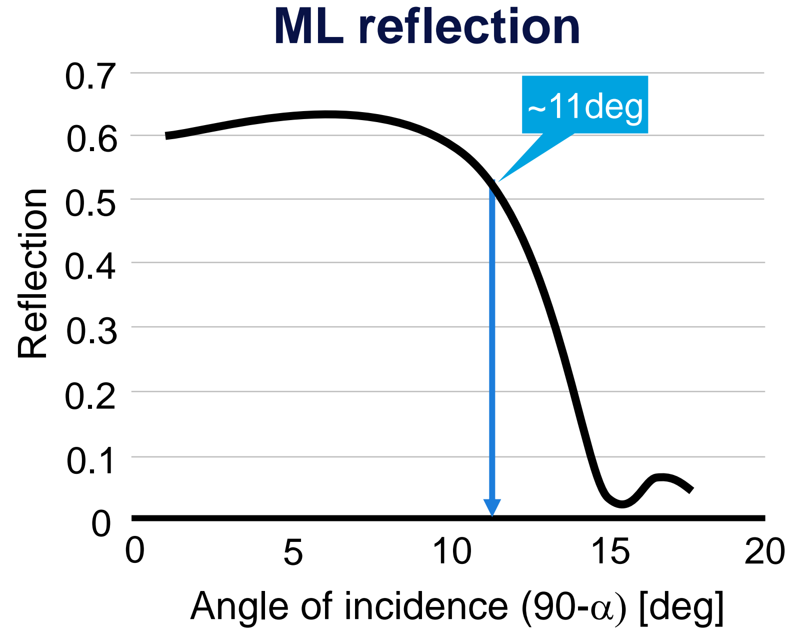
Figure 2.3: Real (δ) and imaginary (β) parts of the refractive index of several elements at the wavelength of 13.5 nm [18].

[1] Chart is from Eric Louis, Physics and technology development of multilayer EUV reflective optics, PhD thesis, University of Twente, The Netherlands, 2012





Lawrence Bragg[2]



Absorption:

- Mirrors
- Vacuum
- Source powers

Refractive index:

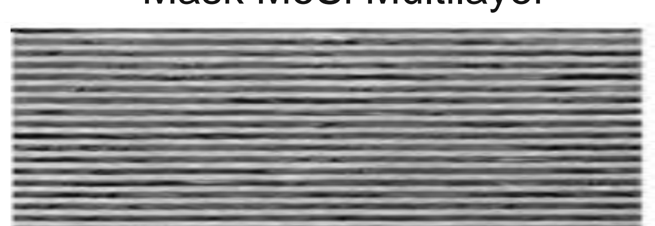
- Bragg reflectors (Multi-layers, ML)
- Angular dependency

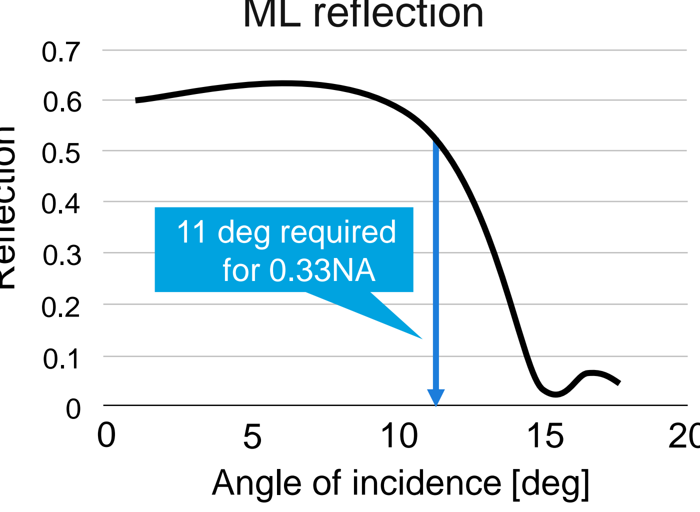
[2] Note: It was Lawrence Bragg who first described diffraction to lattices in crystals. Lawrence is the son of William Bragg. Both received the Nobel Prize for Physics in 1915. See: https://www.nobelprize.org/prizes/physics/1915/summary/. Thanks to Joerg Zimmermann for pointing this out

EUV High NA requires an anamorphic lens…

…and has the same resolution in x and y

Mask MoSi Multilayer



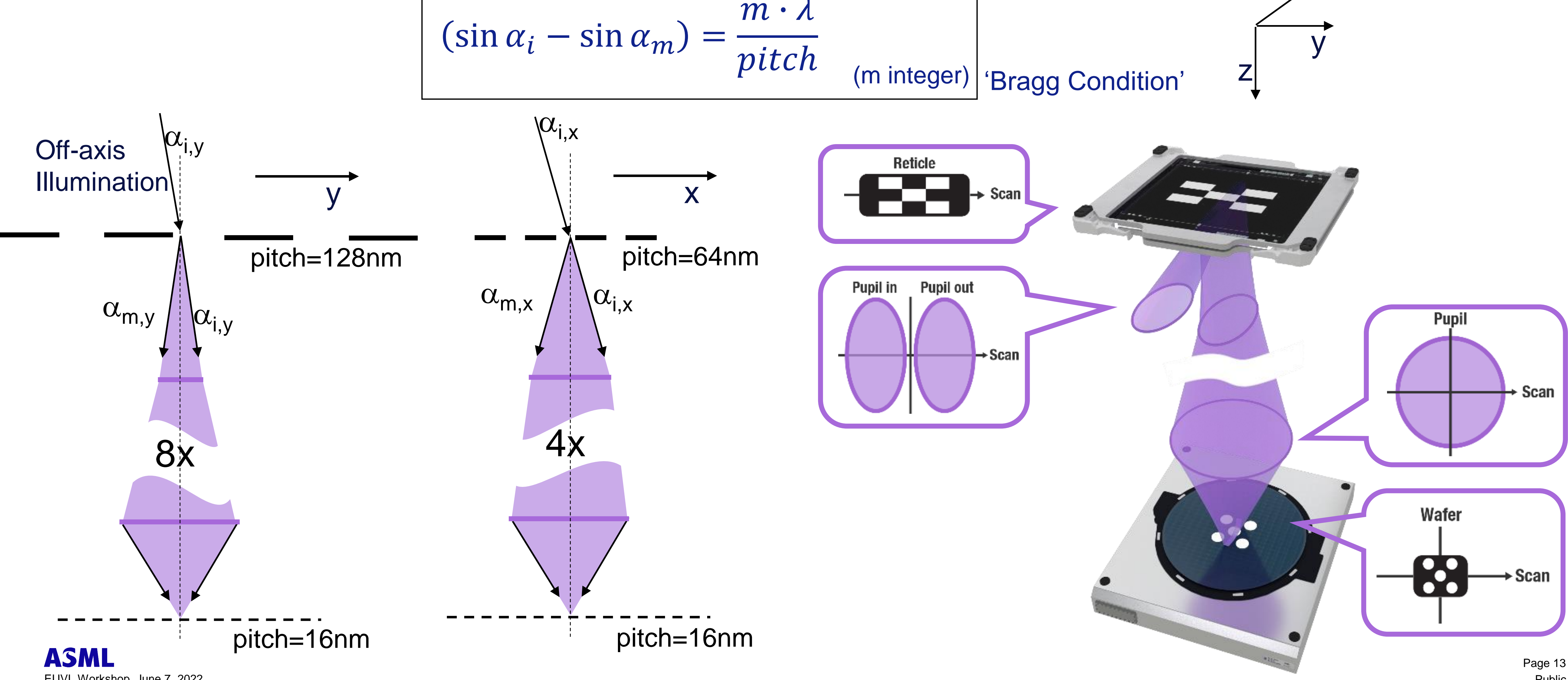


~18deg
~9deg
~11deg
~8deg
4x/8x
0.55NA
16.5 mm
0.55NA prints a Half Field
104 mm
132 mm
Mask
4x
26 mm
33 mm
Wafer
0.33NA
0.33NA prints a Full Field

Note: for simplicity M3D effects are ignored, only multi-layer effect taken into account

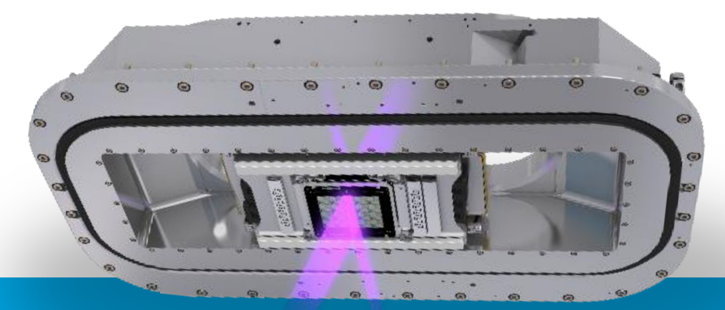
Anamorphic projection lens has same resolution in x & y

Elliptical illumination pupil is transformed in a round exit pupil

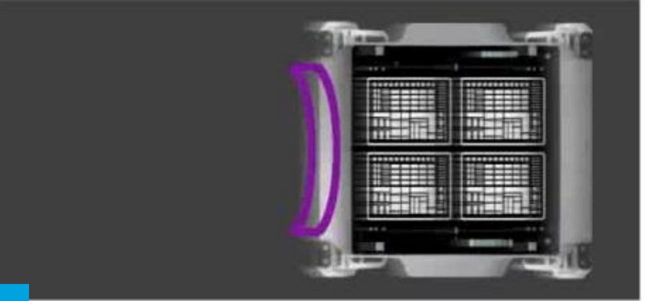


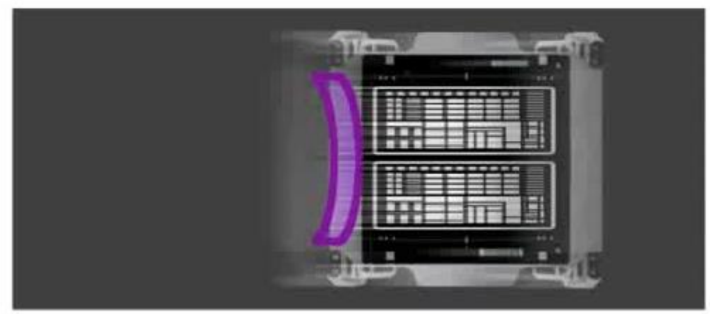
High NA and fast stages enables 220 Wph

188 half fields per wafer

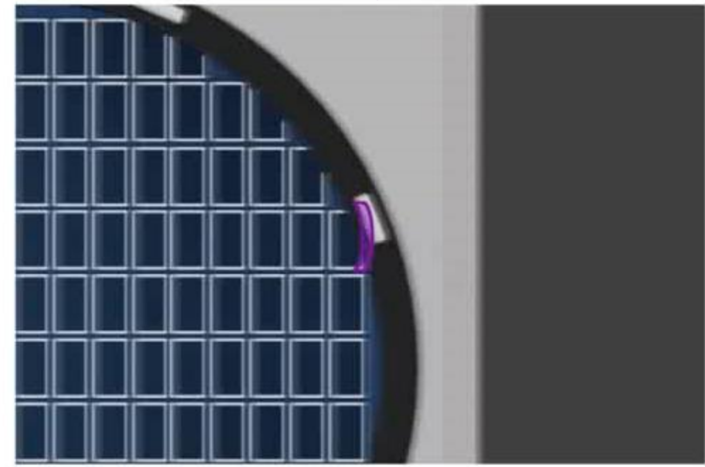


Acceleration of mask stage ~4x

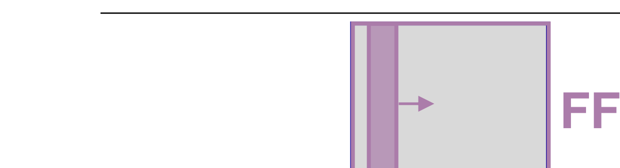




Projection: 0.55 NA

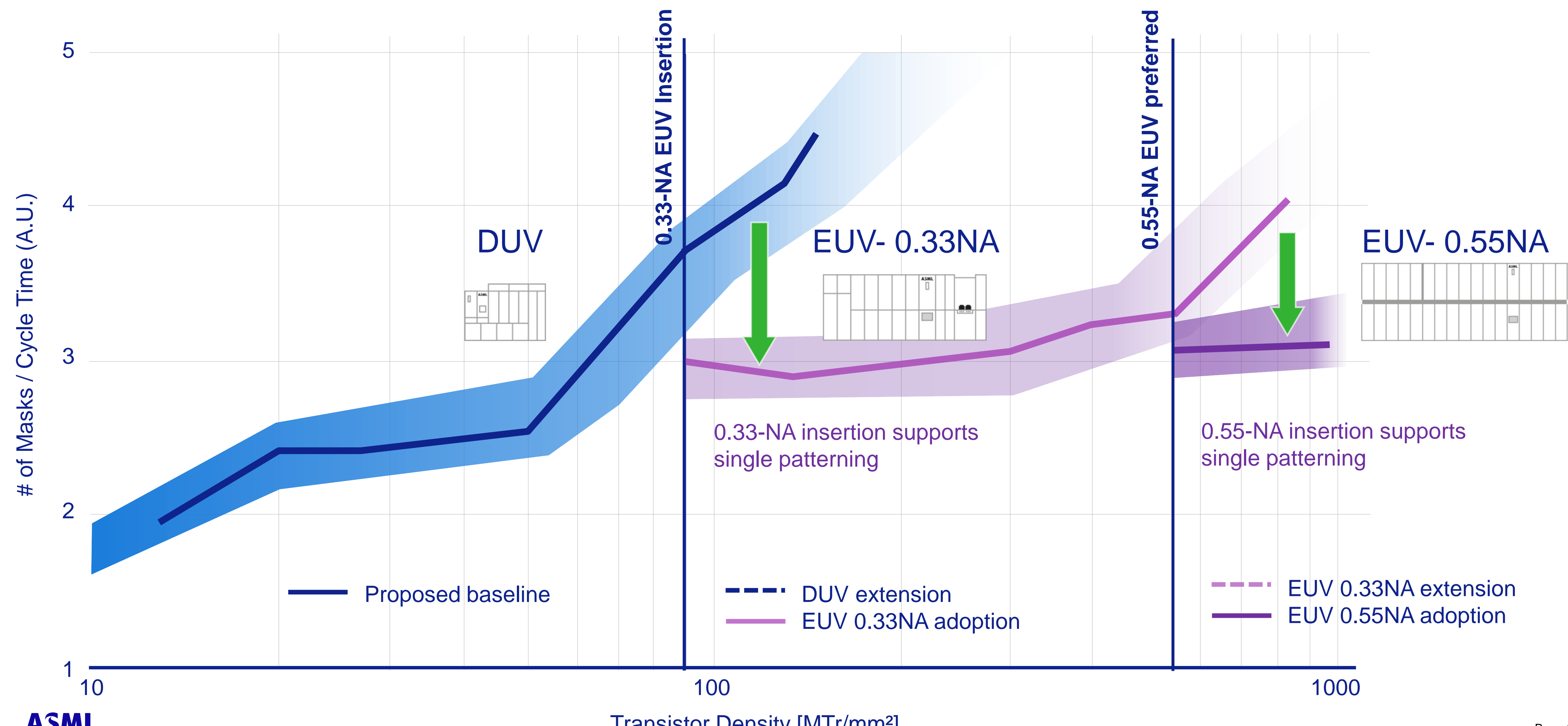


Acceleration of wafer stage ~2x



High NA keeps number of masks & cycle time acceptable

Repetition of adoption of EUV technology



EUV 0.55 NA added to EUV portfolio to support high-volume manufacturing in 2025 - 2026

Wavelength	NA, Half pitch	2020	2021	2022	2023	2024	≥2025

DUV (ArFi) — 1.35 NA, 38 nm

- **NXT:2000i** 2.0 nm | 275wph
- **NXT:2050i** 1.5 nm | 295wph
- **NXT:2100i** 1.3 nm | 295wph
- **NEXT**

EUV

0.33 NA, 13 nm

- **NXE:3400C** 1.5 nm | 135 wph[2] / 145wph[3]
- **NXE:3600D** 1.1 nm | 160wph
- **NXE:3800E** <1.1 nm | >195wph / 220wph[3]
- **NXE:4000F** <0.8 nm | >220wph

Customer timing 0.55 NA

- **Early Access ASML**
- **Customer** R&D
- **Customer** HVM

0.55 NA, 8 nm

- **EXE:5000** at ASML fab
- **EXE:5000** <1.1 nm | 150wph[1]
- **EXE:5200B** <0.8 nm | 220wph

wafers/hours (wph) are based on 30mJ/cm²
1) 185wph@20mJ/cm2
2) 170wph@20mJ/cm²
3) Throughput upgrade

Product: Matched Machine Overlay (nm)|Throughput(wph)

Product status Released | Development | Definition

- **EUV 0.55 NA higher resolution enables 1.7x smaller features and 2.9x increased density**
- **EUV 0.55 NA higher imaging contrast enables 40% improvement in local CDU and improves productivity on critical layers**

Christophe Smeets et al: 0.33NA EUV systems for high-volume manufacturing [12051-4]
Greet Storms et al: High NA EUV enabling cost efficient scaling for N+1 technology nodes [12051-6]

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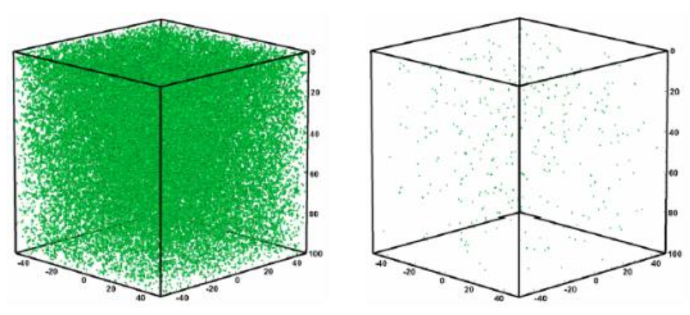
Key to continue Moore's law: Resist, Dose, Contrast

Things to remember:
- Resist
- Dose / Power / Transmission
- Contrast → High NA / illuminator / mask

EUV comes with less photons/J

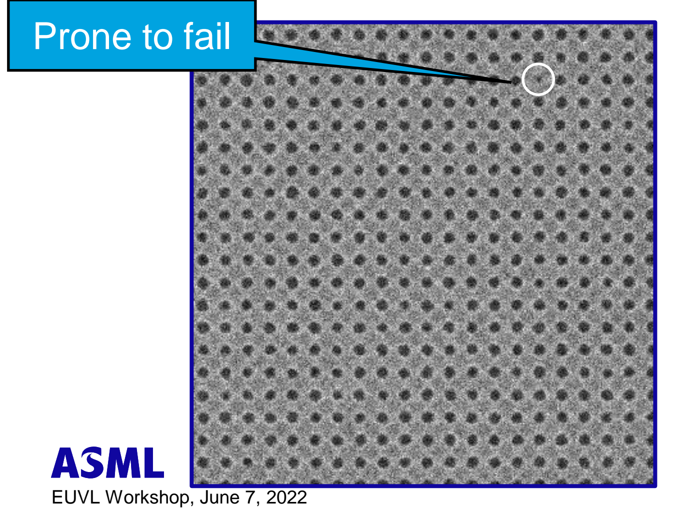


10nm CH, 20mJ/cm2 → 1000 photons

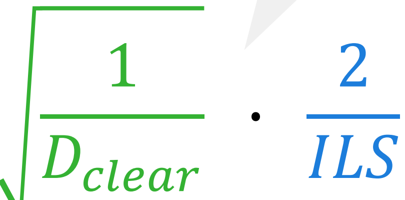
30% absorption → 300 photons

30% determines the edge → 100 photons

→ 1 photon ~ 1% dose!



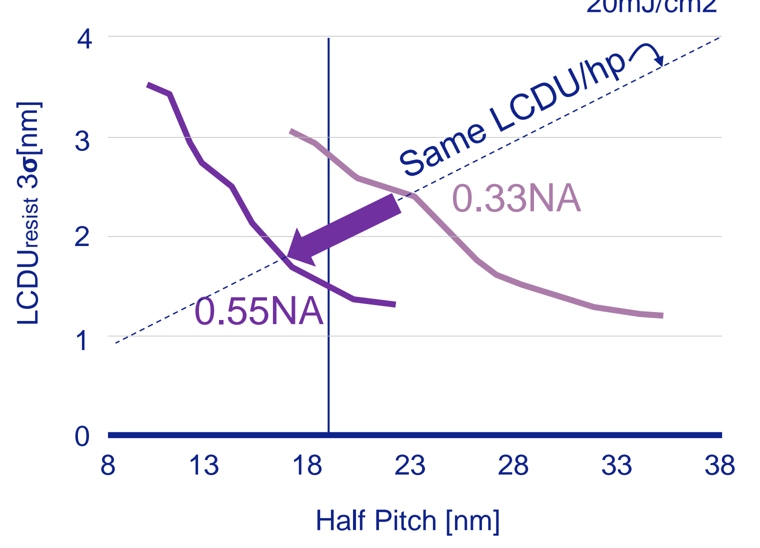
Resist (blur/chemistry) **Dose** **Contrast**



$$LCDU = 3 \cdot \sqrt{\frac{h\nu}{f \cdot \alpha \cdot Area}} \cdot \sqrt{\frac{1}{D_{clear}}} \cdot \frac{2}{ILS}$$

Whereby:
- σ = resist blur
- D_{clear} = dose to size
- ILS = image log slope
- p = pitch

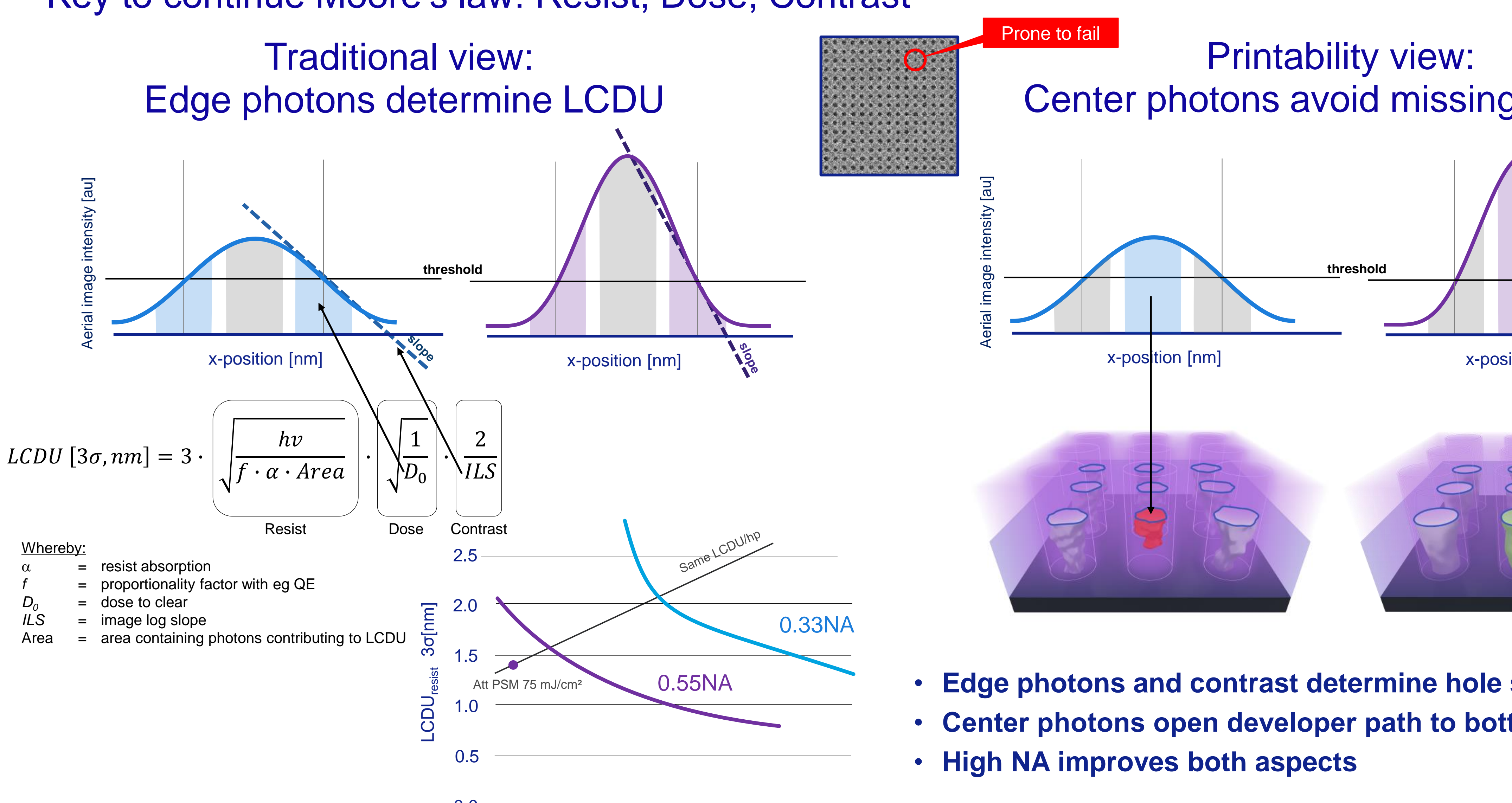
High NA lower resolution at same dose



- Minimize Local variation by
  - Improved resist: absorption ↑, blur ↓ , chemical shot noise ↓
  - Maximize contrast: high NA, advanced mask

High NA contrast reduces Local CDU and defects

Key to continue Moore's law: Resist, Dose, Contrast



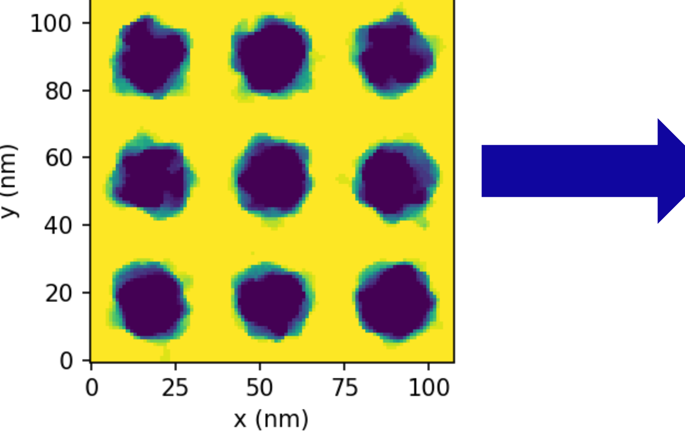
- **Edge photons and contrast determine hole size variability**
- **Center photons open developer path to bottom "pipe cleaners"**
- **High NA improves both aspects**

SPIE. ADVANCED LITHOGRAPHY | **Reference**: Jan van Schoot et al.: High-NA EUV Lithography Exposure System Key Advantages and Program Progress, SPIE-AL 2021, 11609

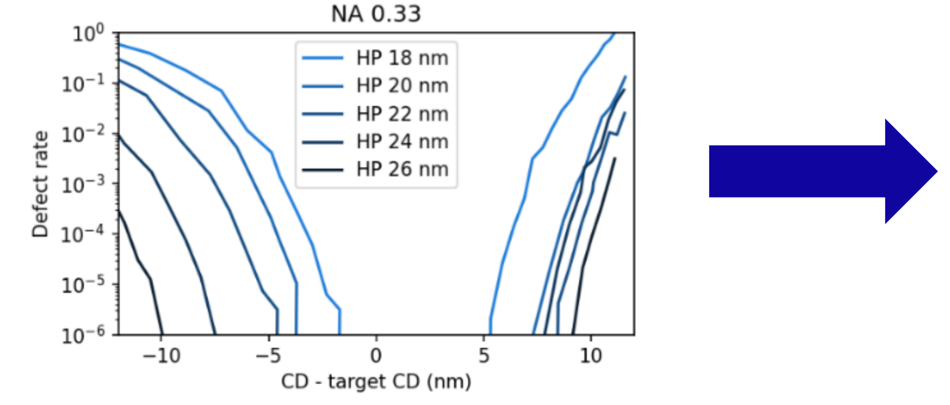
0.55NA gives large defect reduction or resolution gain at lower dose

3D stochastic resist model predictions assuming identical resist for 0.33 and 0.55NA

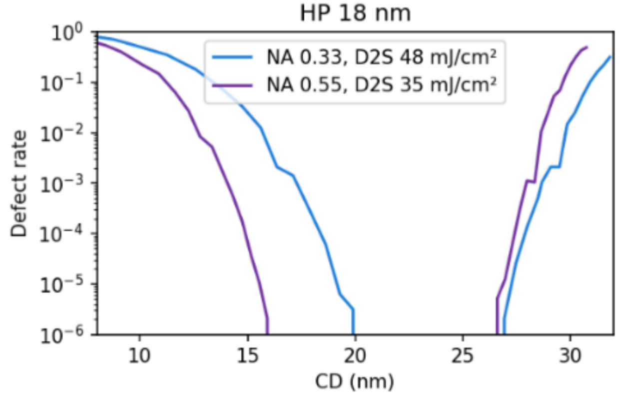
Stochastic simulations of regular contact holes



Process window reduces as pitch shrinks

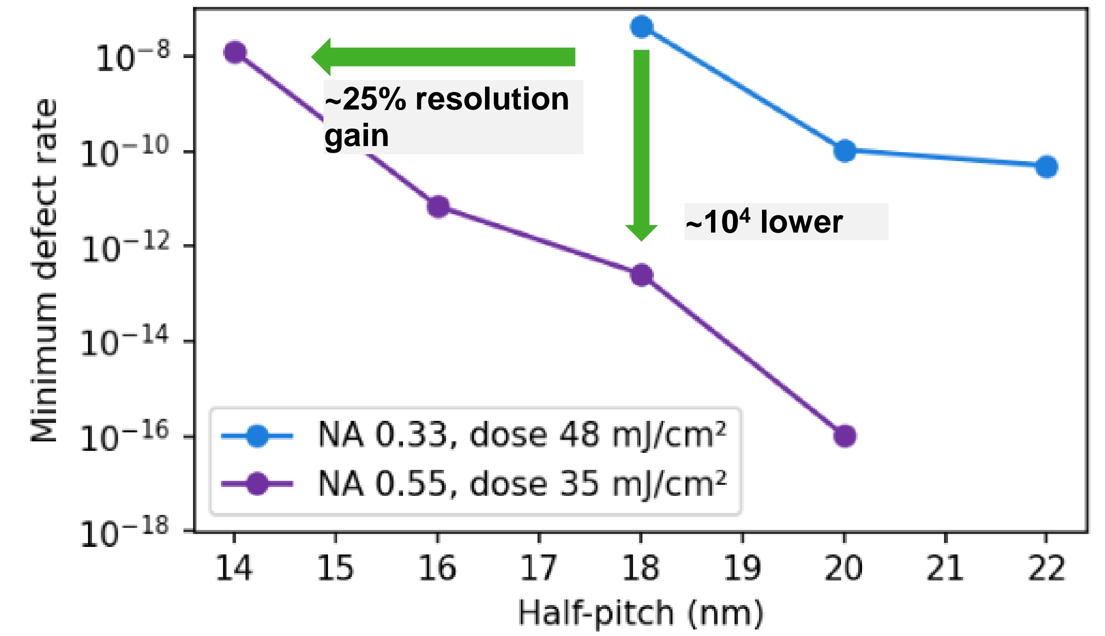


High NA increases process window at ~30% lower dose for same reist



Resist assumptions:

- Resist thickness: 20 nm
- Absorptivity: 15 μm^{-1}
- Tonality: PTD
- QE = 0.4
- Blur (1σ): 2 nm

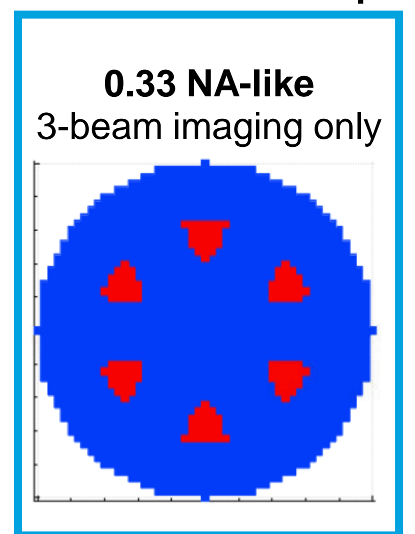


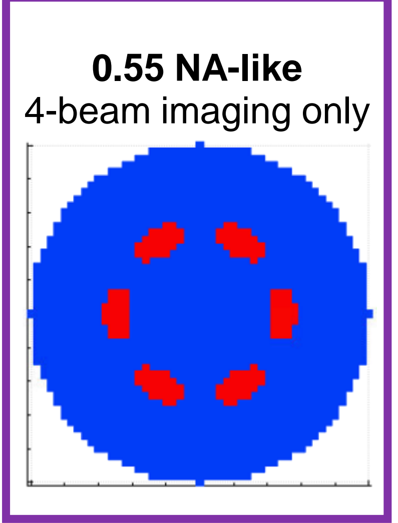
High NA @ ~30% lower dose:

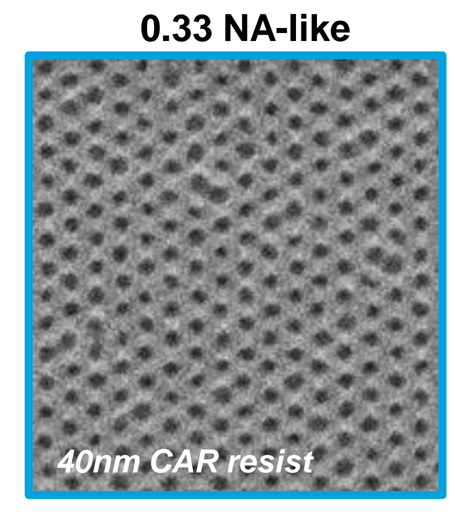
- ~10^4 lower defect rate at 18nm HP
- ~25% reduced pitch (14nm HP) at equal defect rates

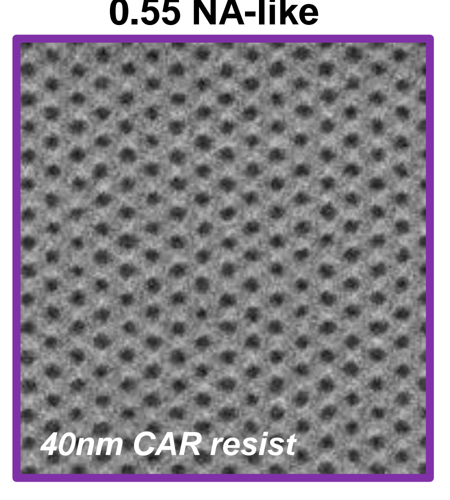
Thanks to Luc van Kessel for support

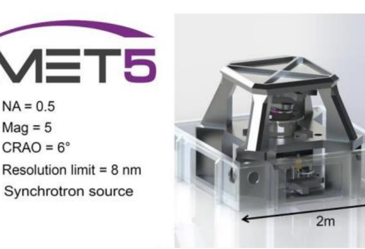
Experimental verification on 0.5NA MET5 shows clear benefit of high contrast on LCDU performance for 16nm half pitch hexagonal CHs





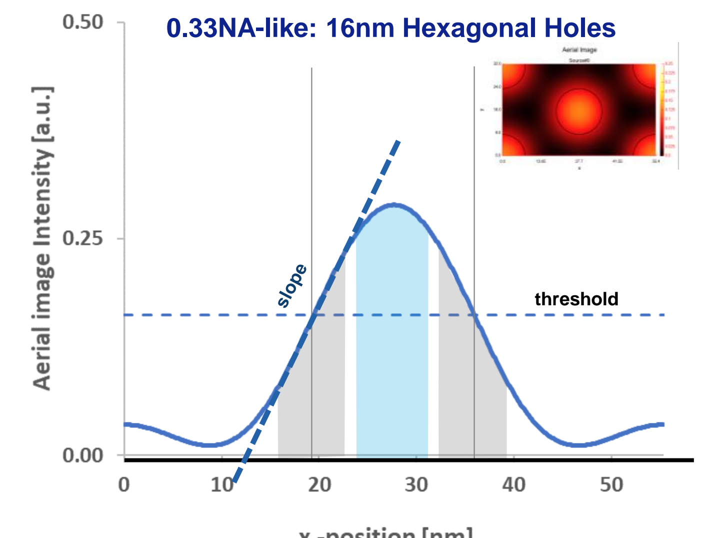


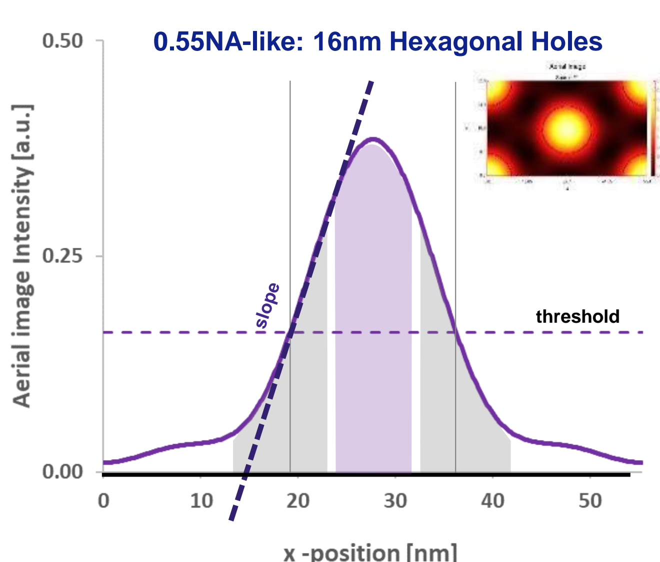




CXRO
THE CENTER FOR X-RAY OPTICS

In-resist data	3-beam imaging		4-beam imaging
Dose (mJ/cm^2)	63.0	-9% →	57.5
CD (nm)	15.8		15.6
LCDU (nm)	4.36	-28% →	3.15
Defects in FoV	7		0



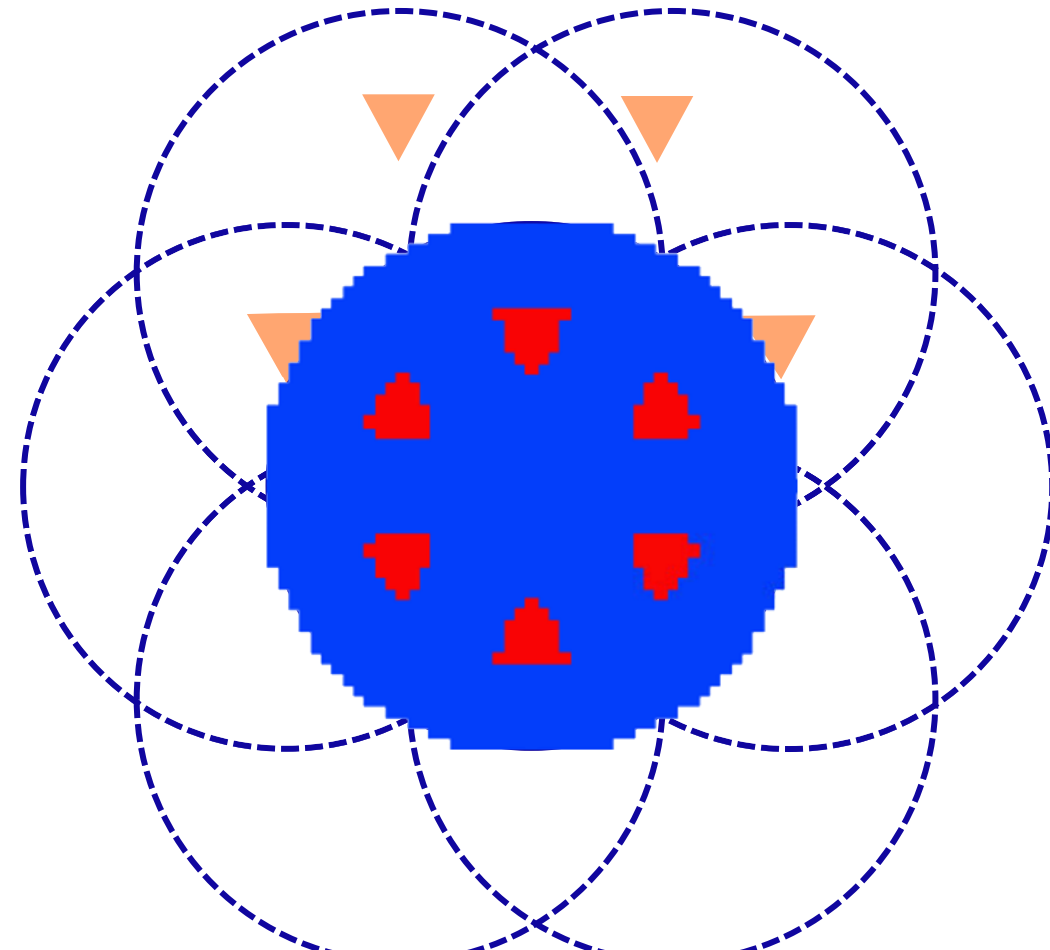


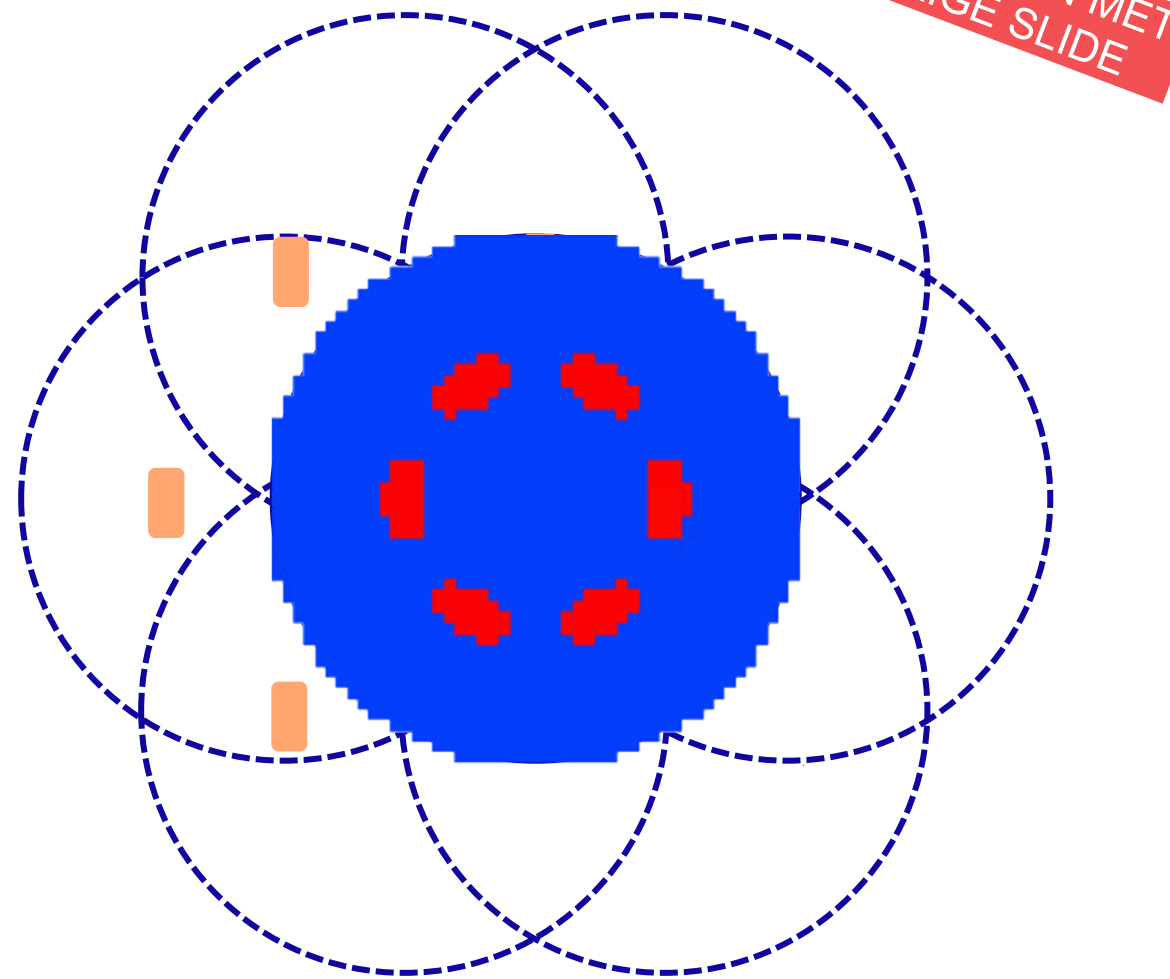
Thanks to Herman Nicolai, Jara Garcia Santaclara and Gerardo Bottiglieri for support

3-beam vs 4-beam imaging for hexagonal CHs

Hexagonal array gives 6 diffraction orders (1st order) per 0th order pole (source point)

ANIMATION MET VORIGE SLIDE





Each 0th order pole interferes with 2 diffraction orders

→ 3-beam imaging **(2 out of 6 diffraction orders captured by NA)**

Each 0th order pole interferes with 3 diffraction orders

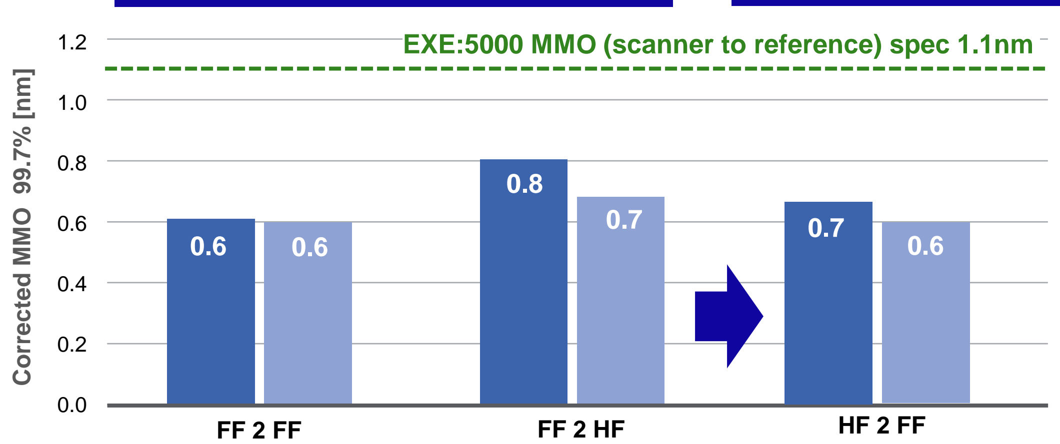
→ 4-beam imaging **(3 out of 6 diffraction orders captured by NA)**

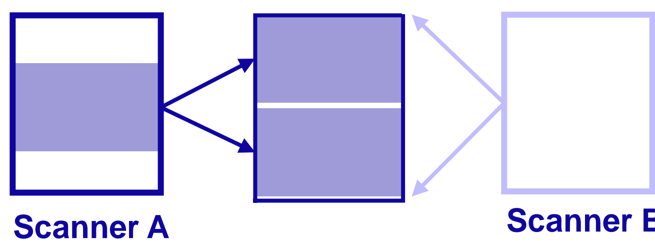
No impact from EXE field on system overlay matching strategy and performance

Matched machine overlay

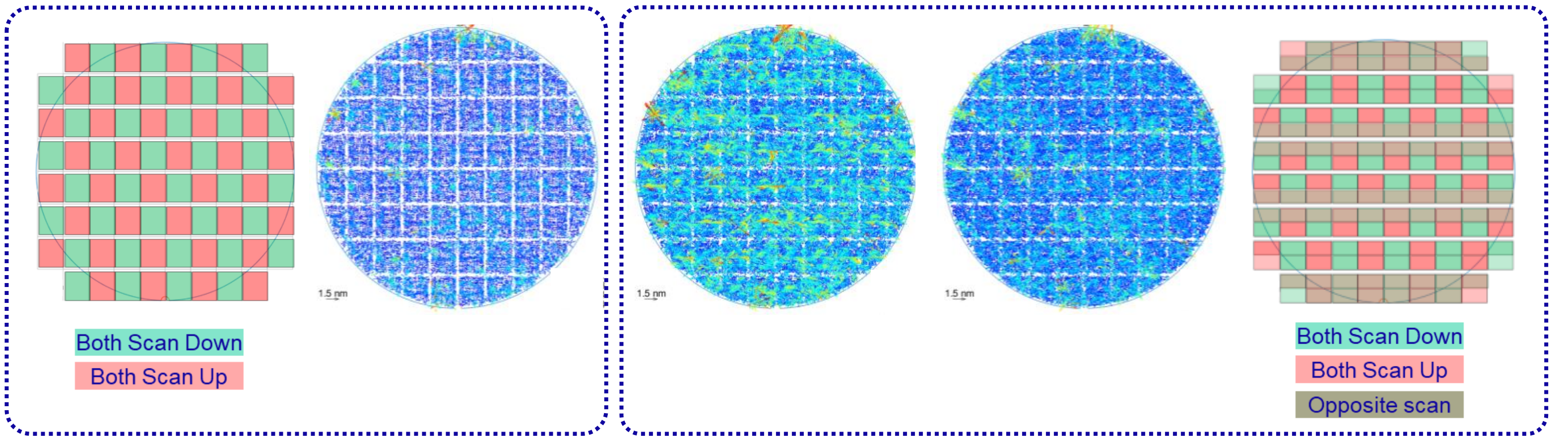
- No effects from step and scan direction differences visible in the results
- Scanner impact from half field to full field overlay matching can be mitigated in the EXE systems setup and control
- Half field exposures have more overlay correction potential; this may require attention when defining a through stack on-product overlay control scenario

Corrections per exposure
18par **Half field** calculated





Mimic Full Field / Half Field exposures on 0.33NA



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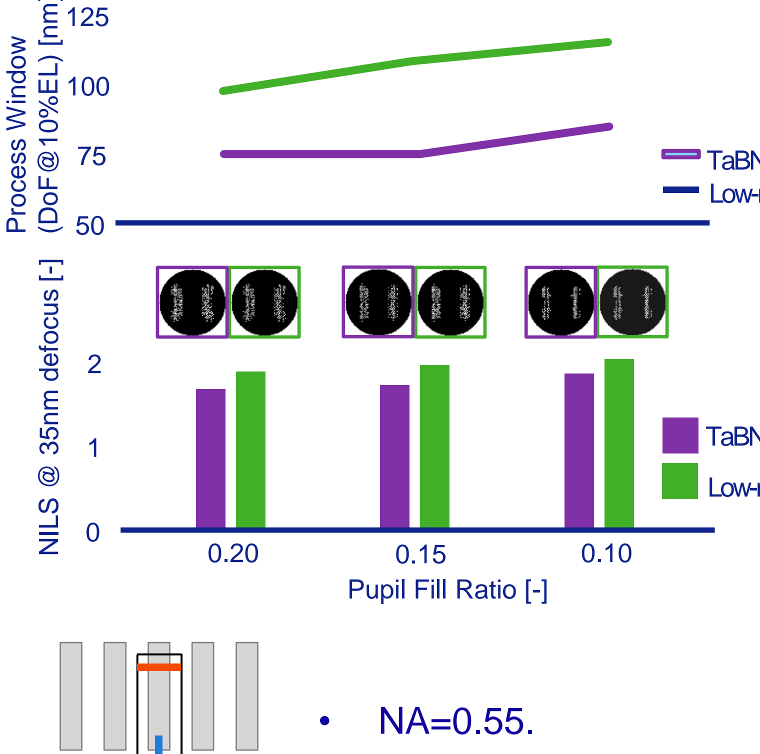
Low-n Mask improves Process Window and reduces dose

Simulations on High NA, experiments on NXE:3400C

Improved contrast and DoF

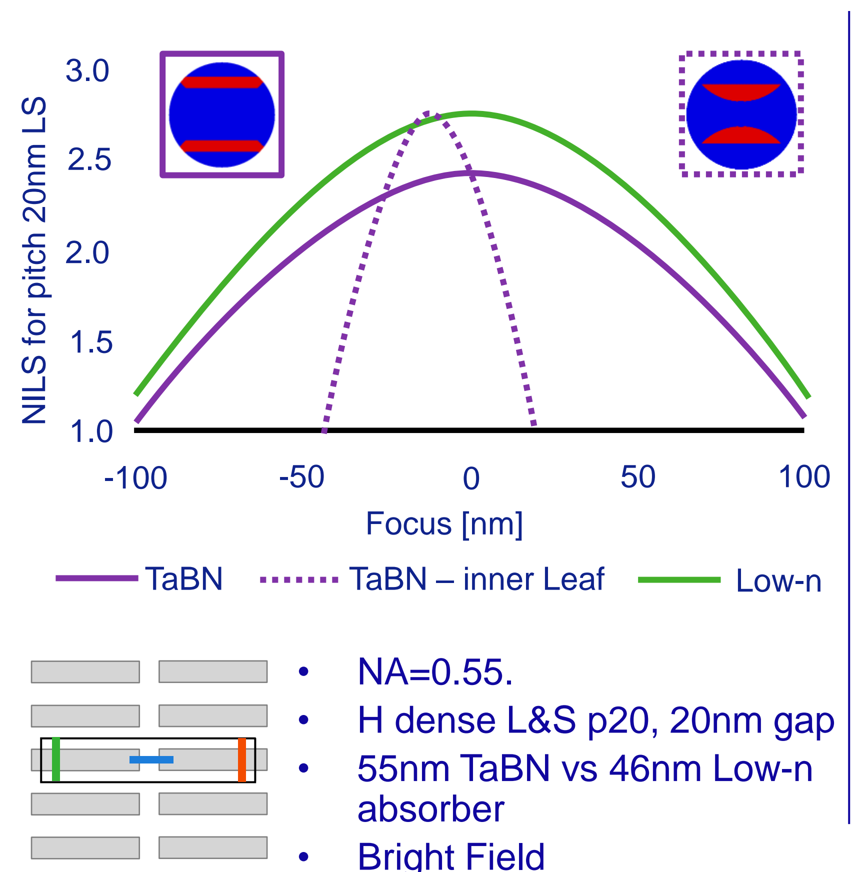
Combined with low pupil fil ratio



- NA=0.55.
- Vertical dense L&S
- pitch 22nm, 21nm gap

Improved contrast and DoF

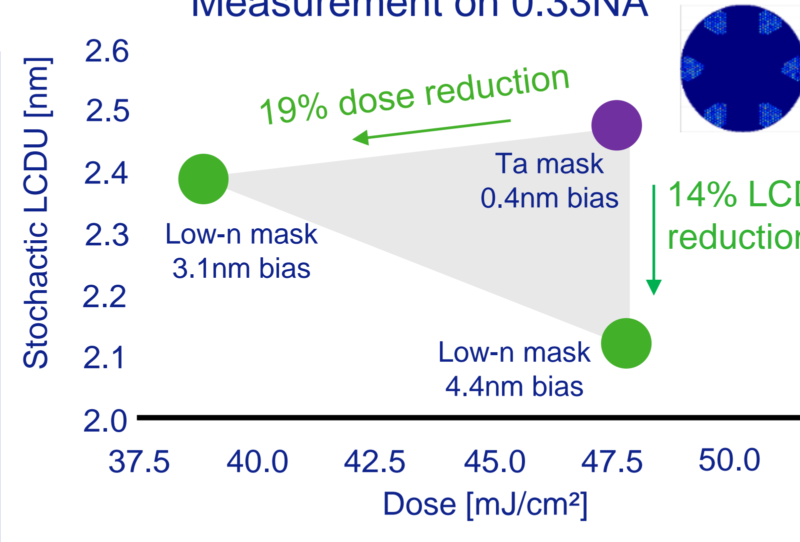
Enables gap CD 20→16nm at NILS=3.2

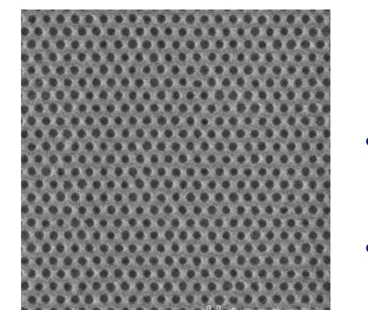


- NA=0.55.
- H dense L&S p20, 20nm gap
- 55nm TaBN vs 46nm Low-n absorber
- Bright Field

Reduced dose and LCDU

Measurement on 0.33NA





- Pitch 38nm Hex contacts
- measurements at ASML on NXE:3400C

SPIE. ADVANCED LITHOGRAPHY | Jos Benschop et al.: EUV lithography: Past, present and future, SPIE-AL 2021

SPIE. PHOTOMASK TECHNOLOGY + EUV LITHOGRAPHY | Eelco van Setten et al: High-NA EUV imaging, From system introduction towards low-k1 extension, PMJ/EUVL 2021

SPIE. PHOTOMASK TECHNOLOGY + EUV LITHOGRAPHY | M. van Lare et al. Optimizzation flow for EUV low-k1 logics with the low-n mask, EUVL 2021

Pitch 28nm – Tip to Tip printability

Low-N Bright Field mask has the best performance for target T2T 20nm

PITCH 28NM --T2T PRINTABILITY

LOW-N BF MASK HAS THE BEST PERFORMANCE FOR TARGET T2T 20NM

Benefit of low-N experimentally demonstrated on tip-to-tip features:

+20% Exposure Latitude.

Length
T2T CD
Width

Model
T2T Model CD[nm]
Mask T2T CD[nm]
Binary BF
SIMULATION

T2T with
Mask T2T CD [nm]
Low-n DF
Binary DF
Low-n BF
Binary BF
WAFER DATA

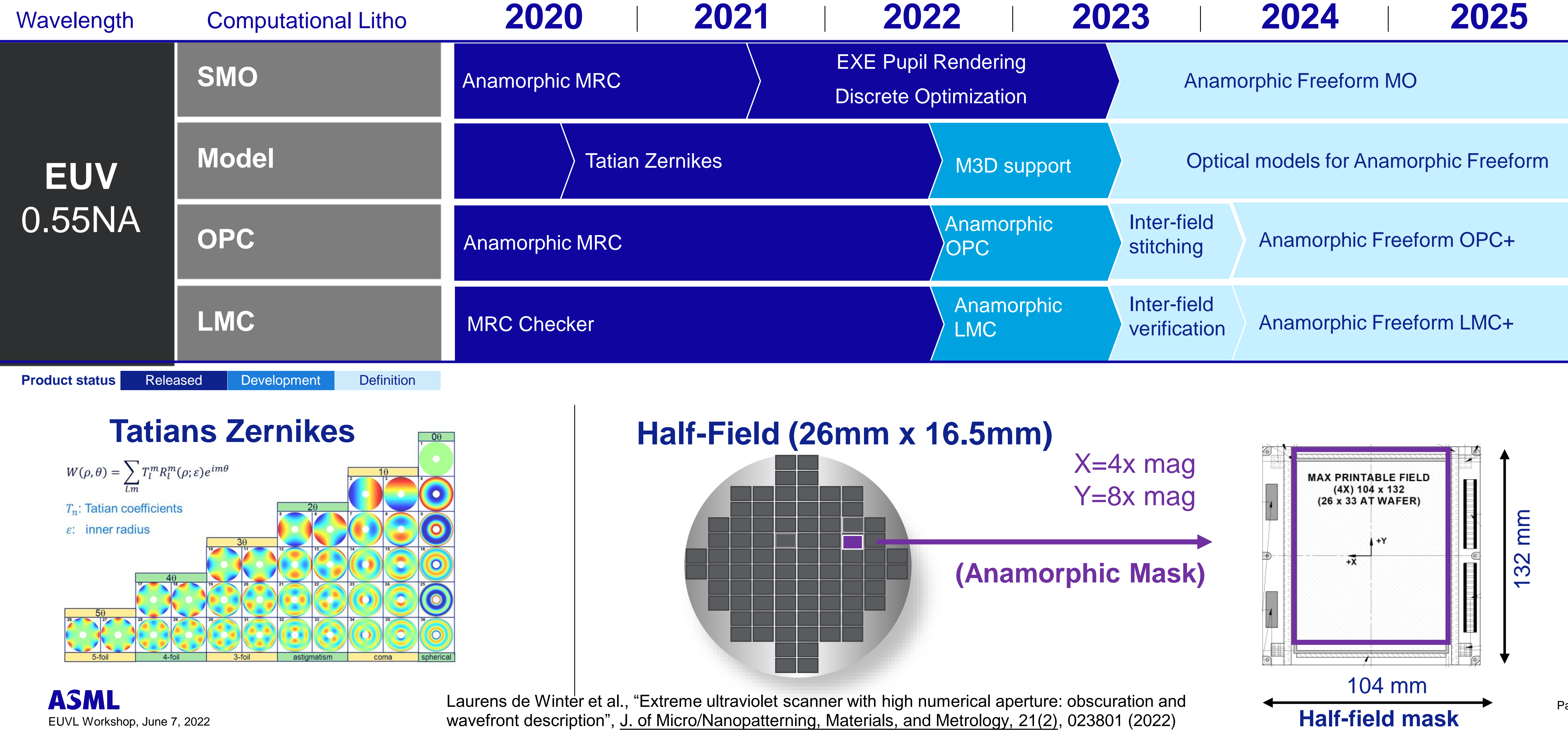
Target T2T CD 20nm
EL[%]
DOF[nm]
Binary BF
Low-n BF

Low-n BF T2T 20nm

- DF mask needs aggressive MRC to print target T2T CD 20nm
- BF mask can print target T2T 20nm without hitting current MRC
  - Low-n mask uses slightly larger mask T2T to print small target T2T
  - Low-n provides larger process window for target T2T 20nm

Tachyon Computational Litho roadmap for High NA

Anamorphic functionality available Q2’22, well in time for 1st exposures



Laurens de Winter et al., “Extreme ultraviolet scanner with high numerical aperture: obscuration and wavefront description”, J. of Micro/Nanopatterning, Materials, and Metrology, 21(2), 023801 (2022)

Continuous resist improvement for multiple use cases shown by 0.33NA

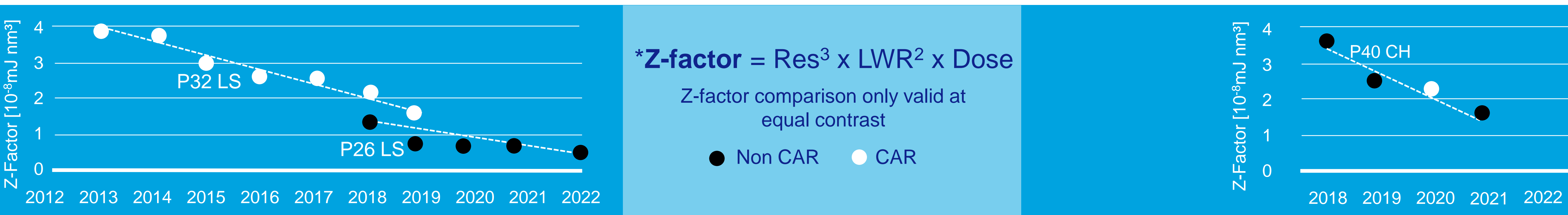
	2019	2020	2021	2022
Resist type	Non-CAR	Non-CAR	Non-CAR	Non-CAR
Resolution: (P26 LS)				
Dose [mJ/cm²]	45	47	50	40
LWR_{unb} [nm]	3.0	2.9	2.8	2.8
Z-factor [10^{-8}mJ nm³]	**0.89**	**0.87**	**0.86**	**0.69**

	2019	2020	2021
Resist type	Non-CAR	CAR	Non-CAR
Resolution: (P40 Hexagonal Pillars/CH)			
Dose [mJ/cm²]	65	61	53
LCDU [nm]	2.2	2.1	2.0
Z-factor [10^{-8}mJ nm³]	**2.5**	**2.3**	**1.7**

P40 Hexagonal CH evaluation ongoing for 2022

Lines and Spaces

Contact Holes



CAR: Chemical Amplified Resist

Jara G. Santaclara et al.: Resist and reticle activities towards High-NA EUV ecosystem readiness, SPIE-ALP 2022

8nm LS demonstrated with Metal Oxide Resist

Resist testing for ultimate resolution

PAUL SCHERRER INSTITUT PSI

Resolution [hp]	13nm	12nm	11nm	10nm	9nm	8nm
Metal Oxide Resist (MOR)	62 mJ/cm²	58 mJ/cm²	75 mJ/cm²	59 mJ/cm²		
Chemically Amplified Resist (CAR)	58 mJ/cm²	55 mJ/cm²	42 mJ/cm²			

CXRO THE CENTER FOR X-RAY OPTICS

Resolution [hp]	13nm	12nm	11nm	10nm	9nm	8nm
MOR Pillars & Lines and Spaces						
CAR Lines and Spaces						

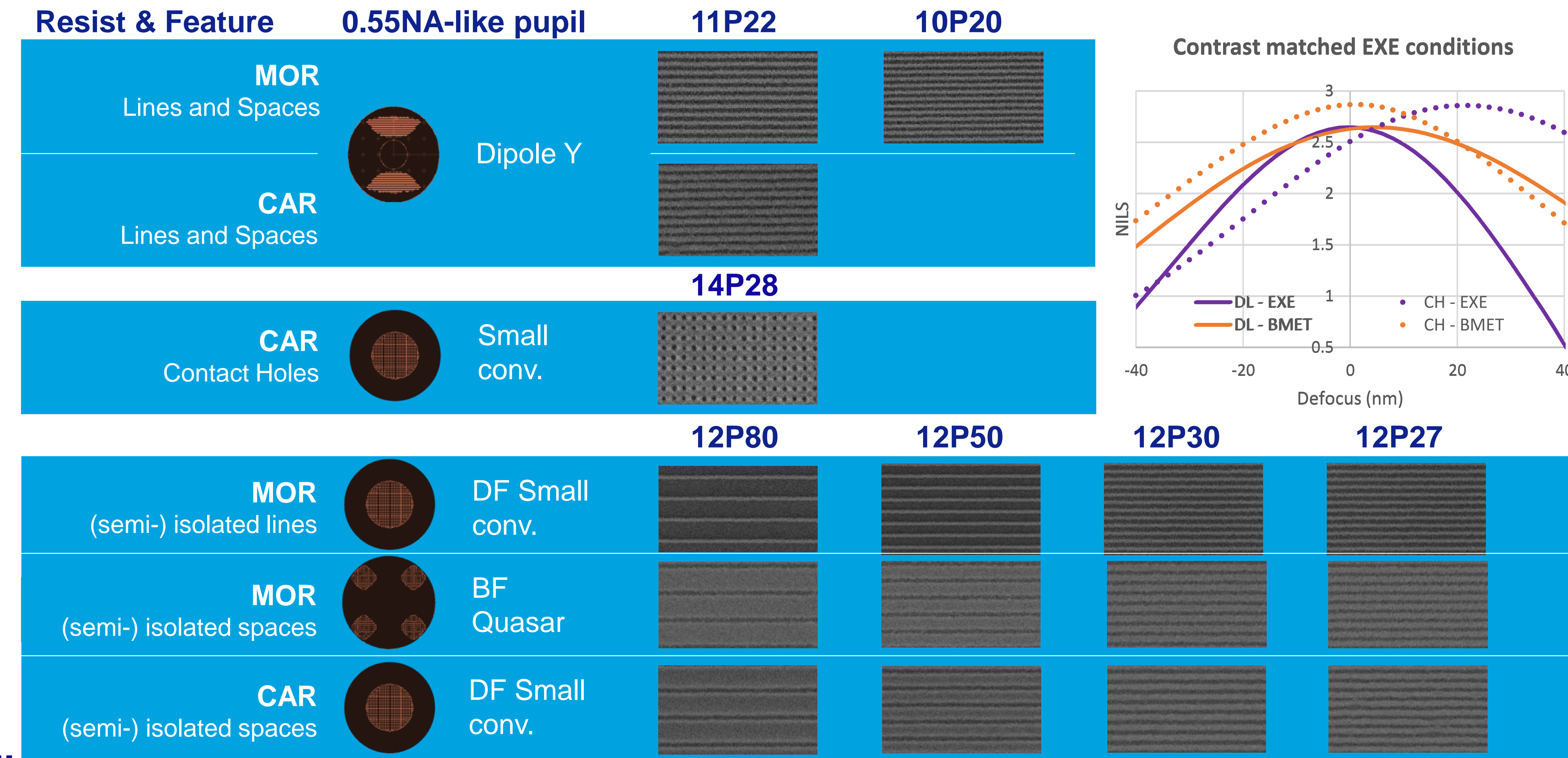
SPIE. ADVANCED LITHOGRAPHY+ PATTERNING

T. Allenet et al., EUV resist screening update: progress towards high-NA lithography [12055-5]

Jara G. Santaclara et al.: Resist and reticle activities towards High-NA EUV ecosystem readiness, SPIE-ALP 2022

High resolution achieved for CAR & MOR at High NA illumination conditions

Resist testing at High NA matched contrast



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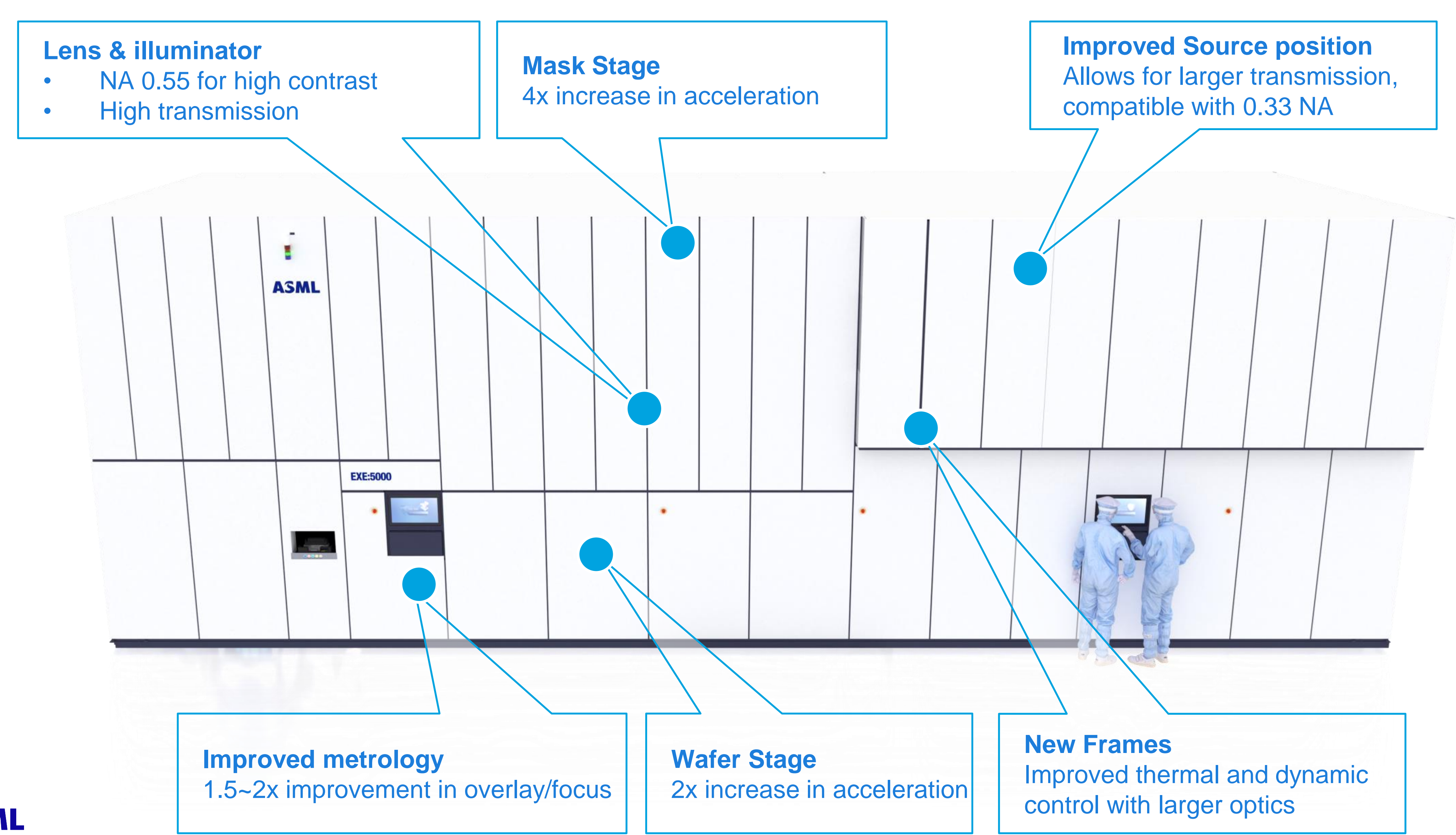
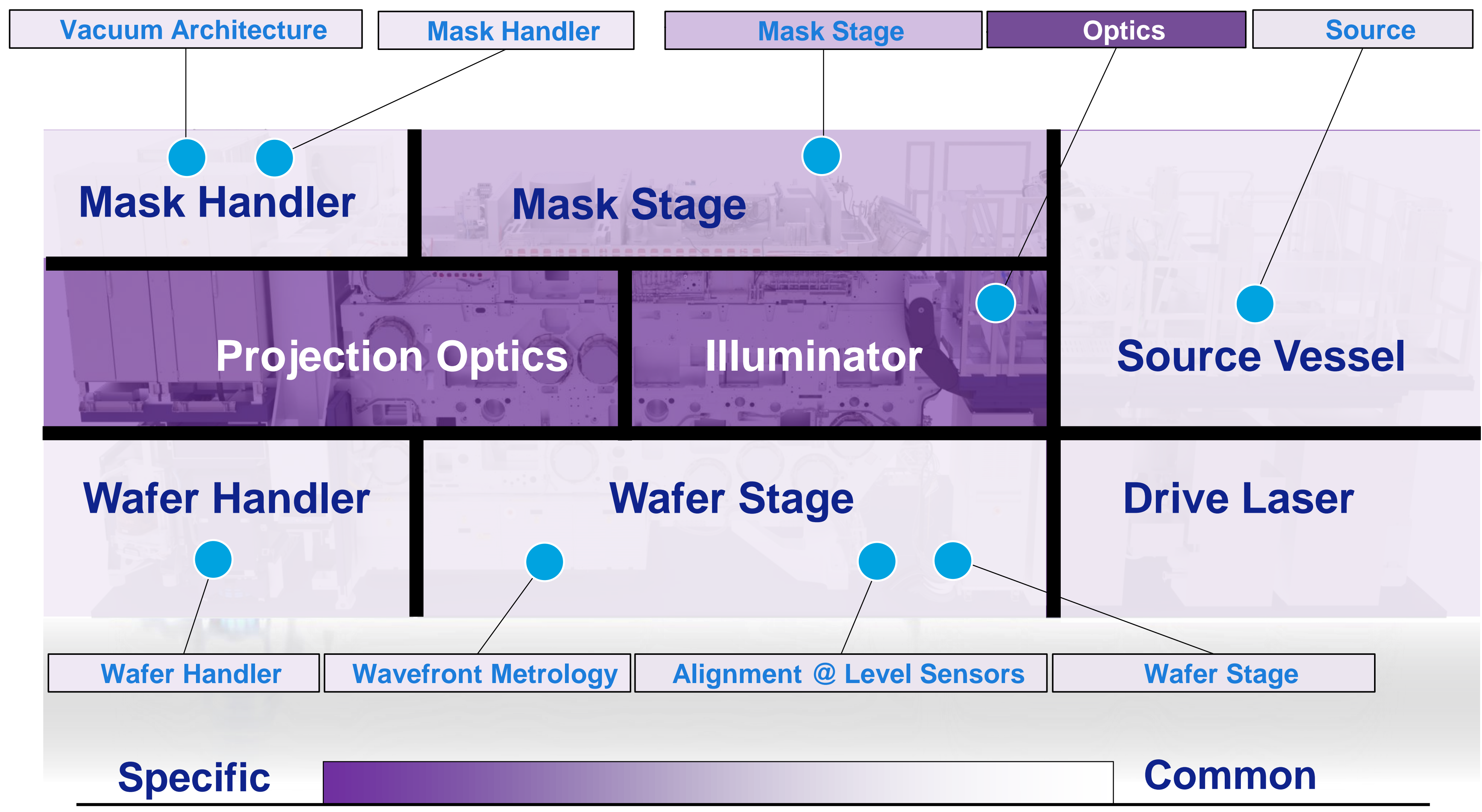
High NA system architecture finalized and system assembly started



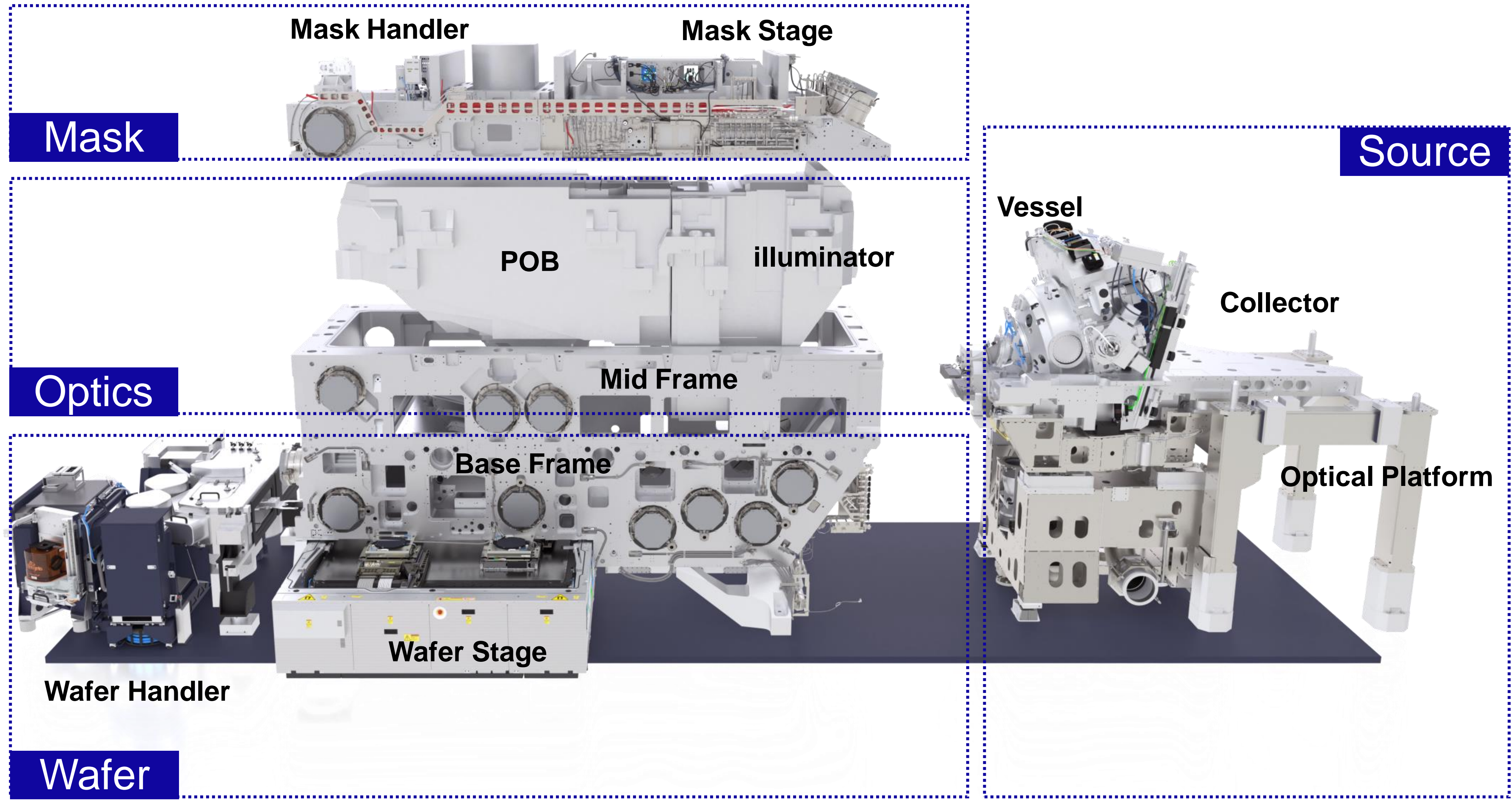
High NA system architecture finalized

Maximized commonality between 0.33NA and 0.55NA platforms



High NA system consists of 4 independent testable subsystems

Improved testability and cycle time



Scalability of EUV source power beyond 500W proven to be feasible

Product:
- NXE:3100
- NXE:3300B
- NXE:3400
- NXE:3600D

Research:
- Low duty cycle
- Open loop
- Dose controlled

Dose controlled EUV power [Watts]

0, 100, 200, 300, 400, 500, 600

2010, 2012, 2014, 2016, 2018, 2020, 2022

> 530 W of open-loop power generated at 60 kHz for nearly 7 hours

power to scanner [W]

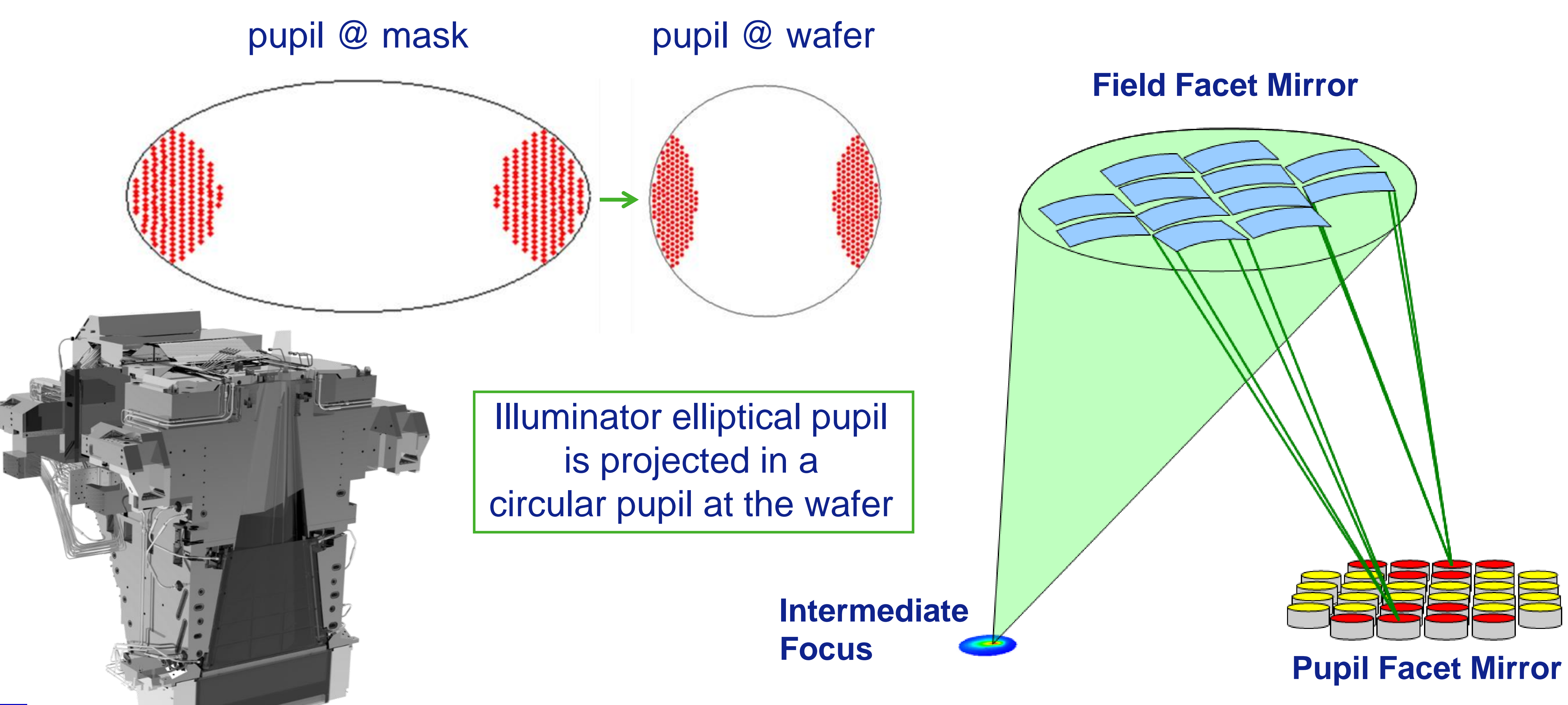
0, 100, 200, 300, 400, 500, 600

time [hours]

0, 1, 2, 3, 4, 5, 6

High NA flexible illuminator design available

Principle NXE:3300/3400 illuminator can be reused



See Joerg Zimmermann et al. “Flexible illumination for ultra-fine resolution with 0.33 NA EUV lithography”, EUVL Symposium 2016

Illuminator offers large flexibility

Standard Sources and free form pupils available in Tachyon

High NA standard pupil shapes

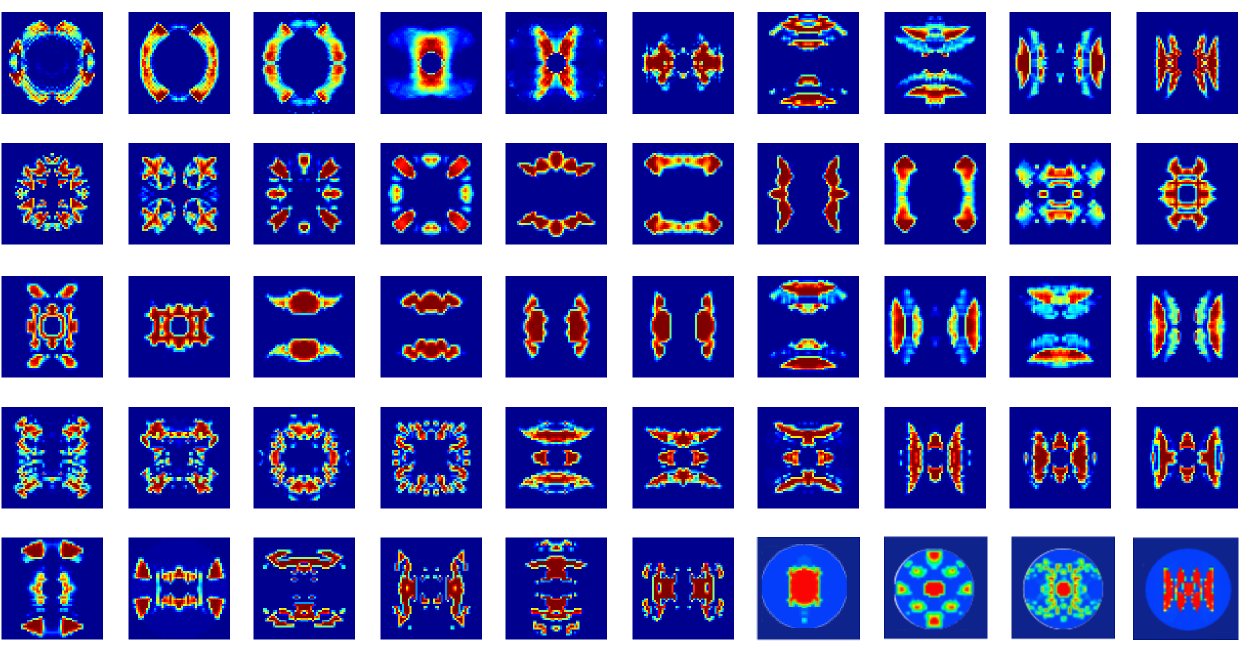
quasi conventional | small annular | medium annular | small conventional

dipole X | dipole Y | medium dipole X | medium dipole Y

quasar | hexapole X | hexapole Y | leaf hexapole X

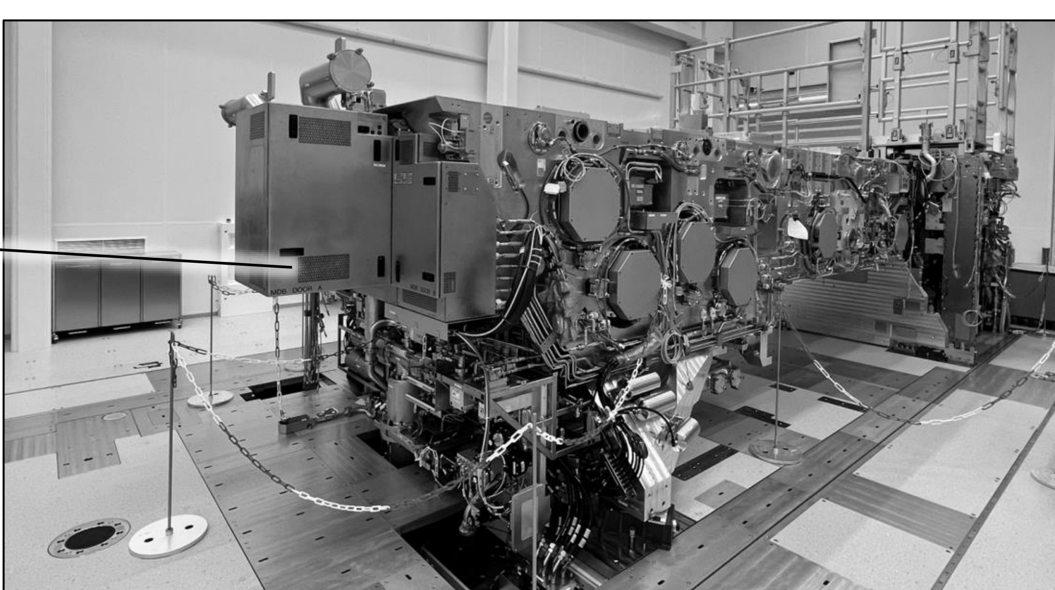
leaf hexapole Y | small dipole X | small dipole Y | slim dipole X | slim dipole Y

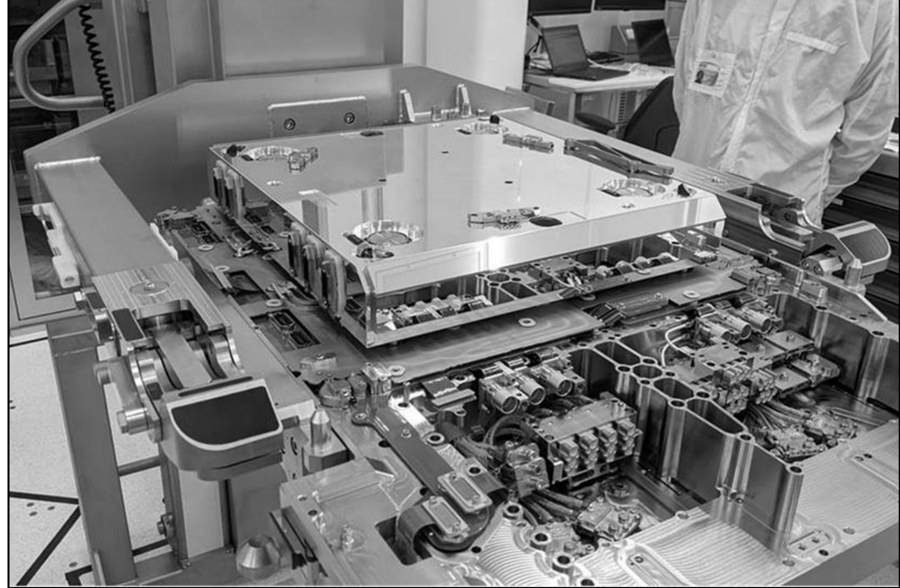
High NA examples from Tachyon SMO

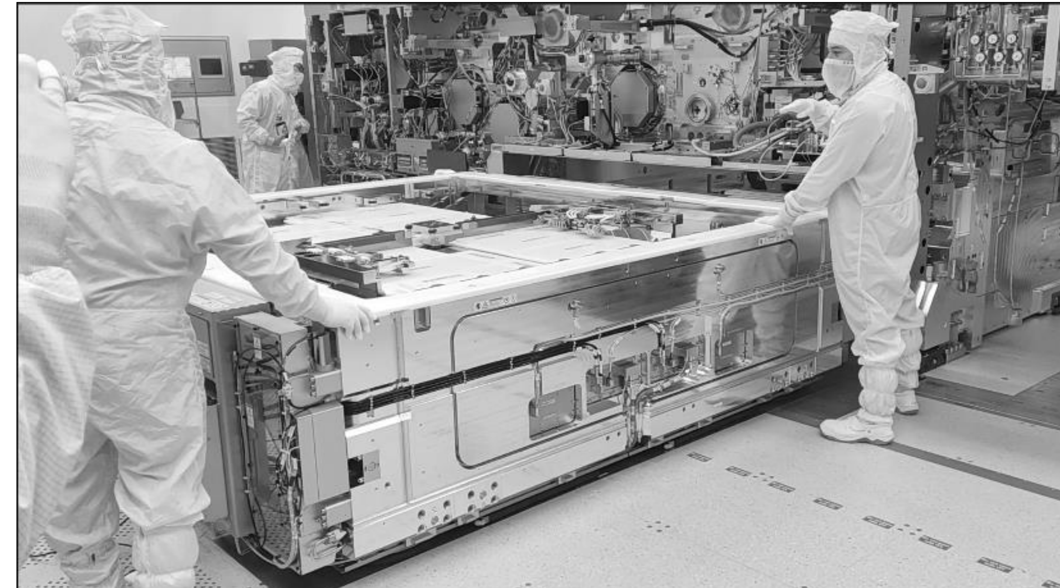


Wafer Sub-system

Wafer Handler
Assembly of Atmospheric and Vacuum handlers completed, functional testing (e.g. electrical, robots) ongoing at supplier







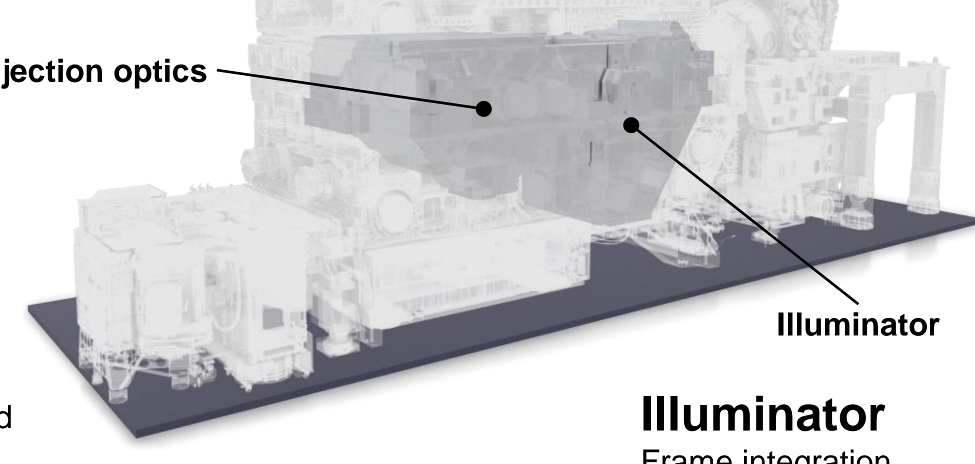
Wafer Stage
Positioning Module finished, functional test on qualification tool ongoing at ASML.
Base Module finished and functional test in qualification test rig ongoing at supplier

Optics Sub-system: Assembly and qualification in progress

Mirrors at final shape, mirror metrology system reached final accuracy level

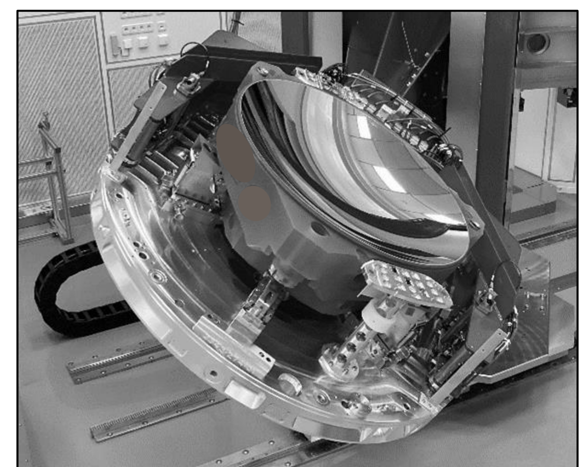
Projection optics

Frame integration



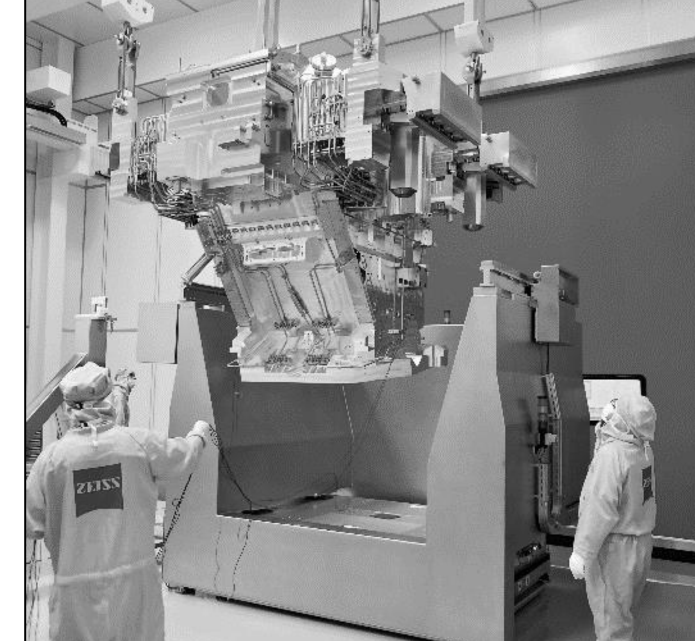
Coated mirror

Qualified with reflectometer and interferometer



Illuminator

Frame integration



Paul Graeupner et al.: EUV optics, status, outlook and future, SPIE-AL 2022

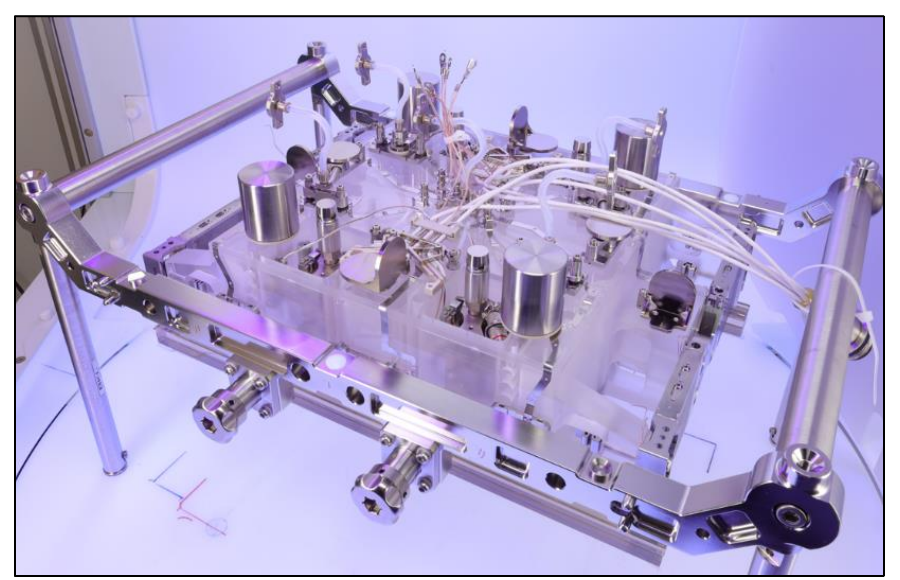
Christian Karlewski et al: EUV Optics in high volume manufacturing, PMJ 2022

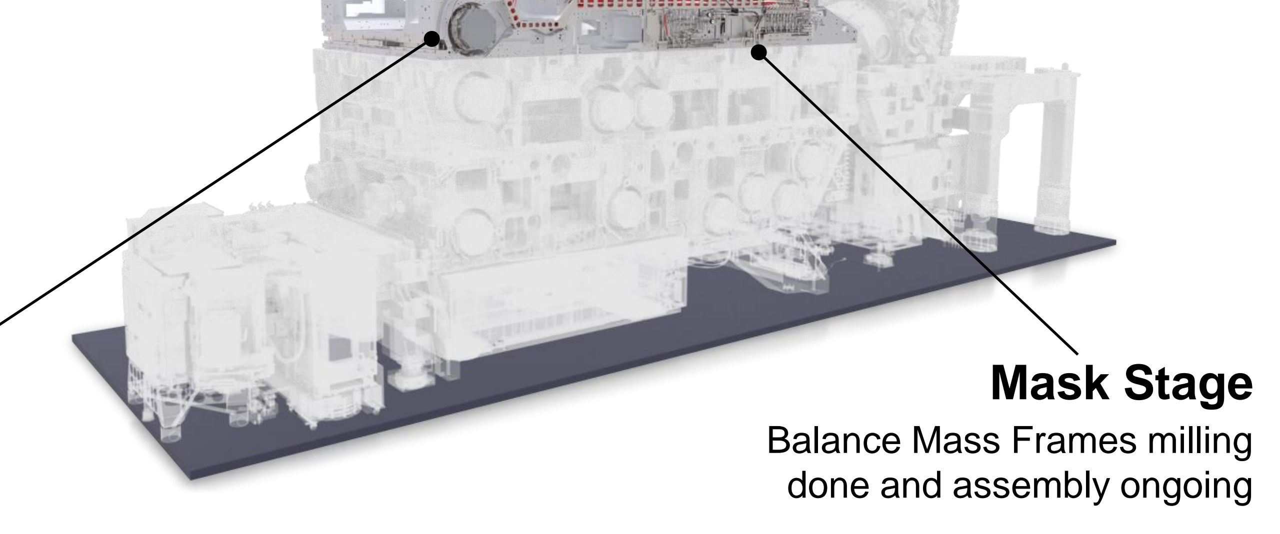
More info: Simon Bihr et al.: this workshop

Mask Sub-system

Top Frame – integration has started

Mask Handler Load Lock and Out-of-Vacuum Robot installed

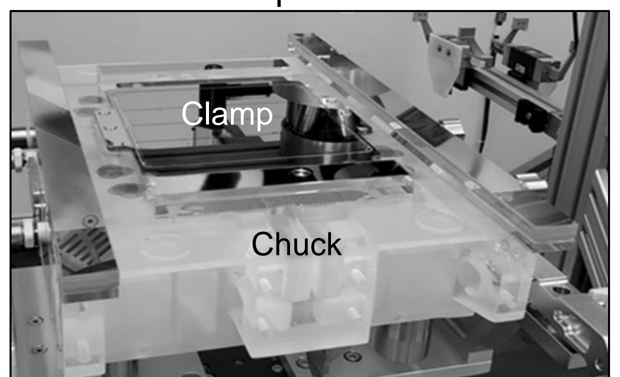




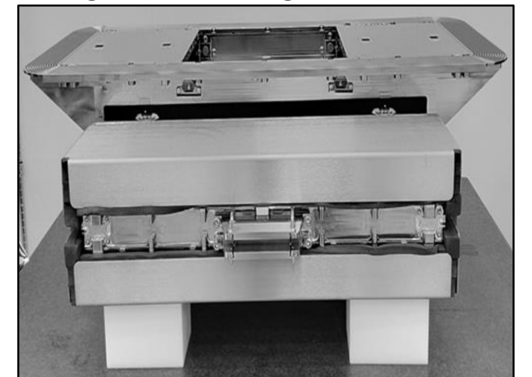
Mask Stage

Balance Mass Frames milling done and assembly ongoing

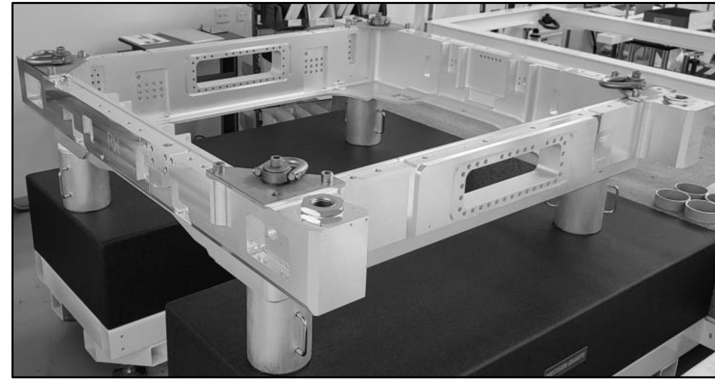
Chuck and clamp bonded



Long-stroke MagLev delivered



Balance Mass Static frame



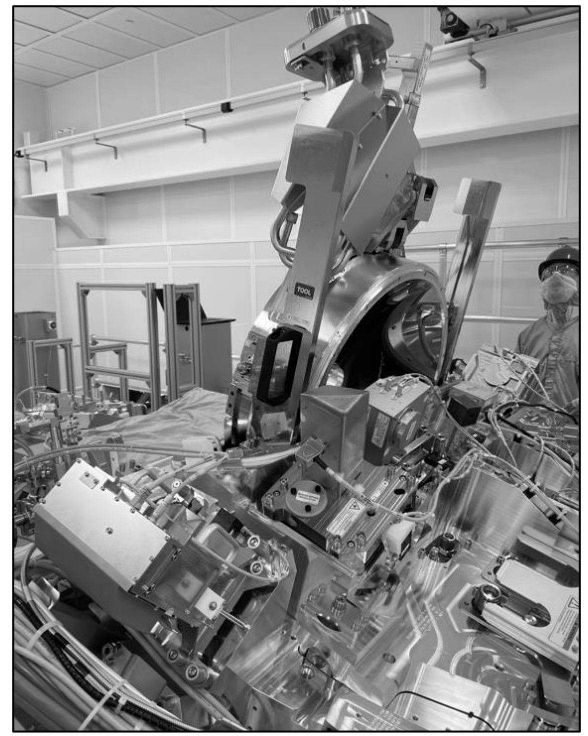
Source Sub-system
installed in Veldhoven & San Diego

Vessel

Collector

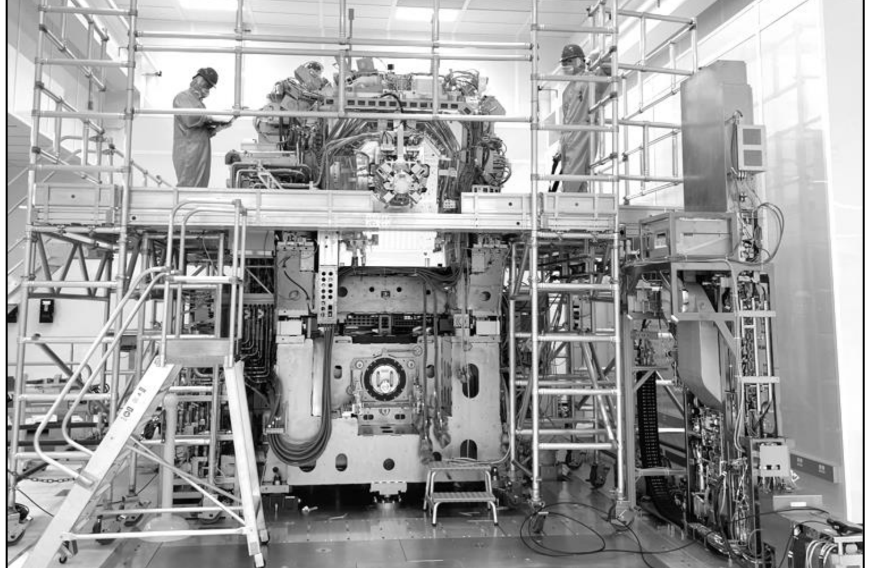
Optical Platform

Collector installed in San Diego factory



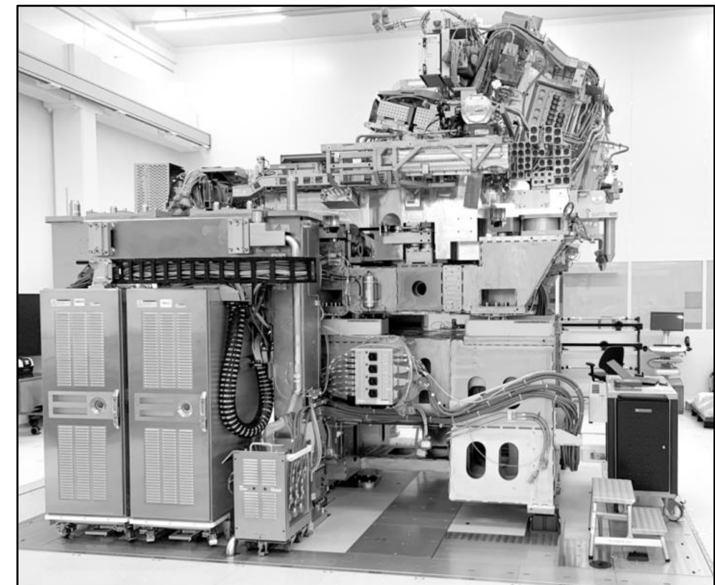
Engineering Source in San Diego
Used for qualification testing

All connections completed, vessel is under vacuum/H2
First EUV light achieved on new source



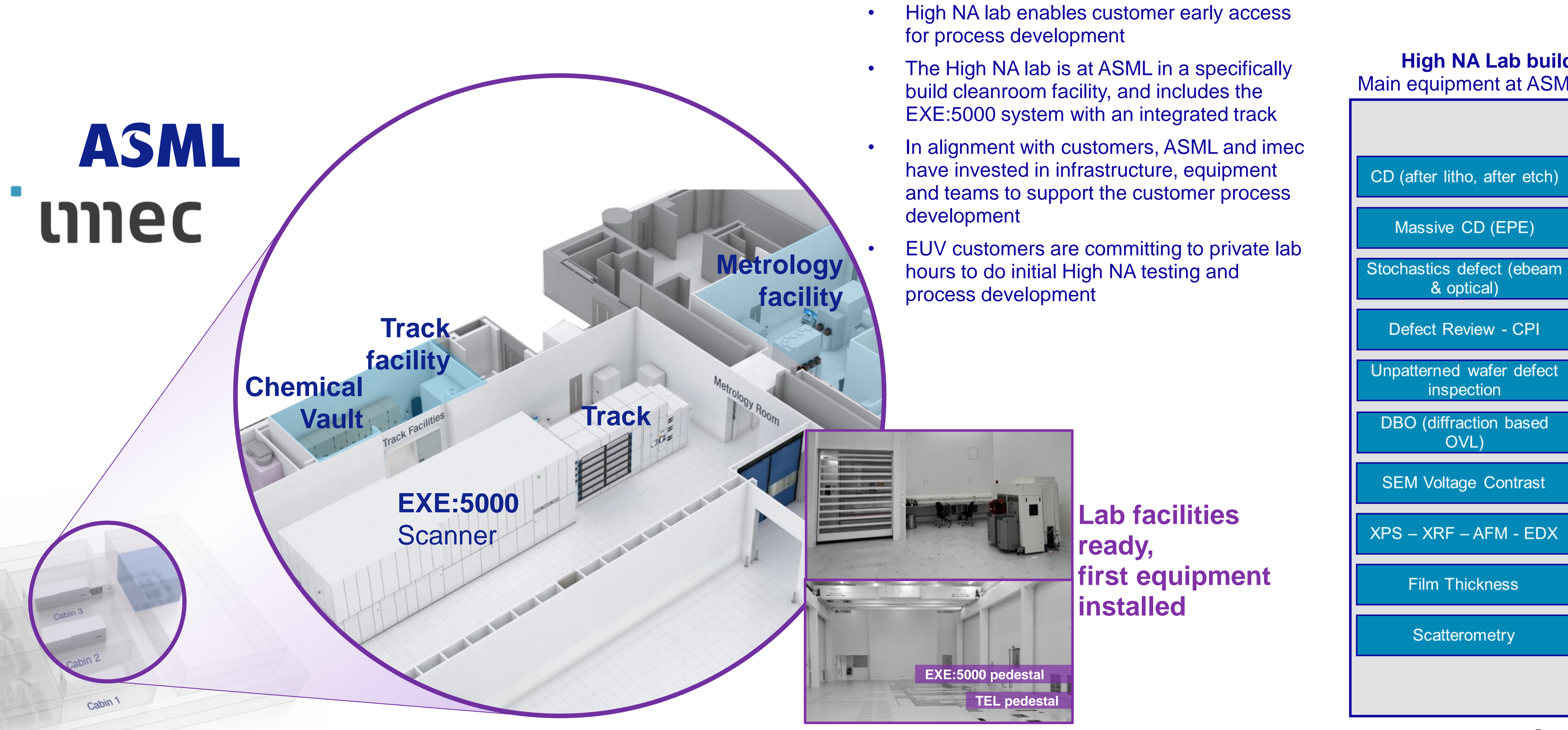
1st Source in VHV
Used for Proto-1 system

Mean time to repair testing is ongoing



High-NA Lab: enables early process development for customers starting 2023

- High NA lab enables customer early access for process development
- The High NA lab is at ASML in a specifically build cleanroom facility, and includes the EXE:5000 system with an integrated track
- In alignment with customers, ASML and imec have invested in infrastructure, equipment and teams to support the customer process development
- EUV customers are committing to private lab hours to do initial High NA testing and process development



High NA Lab build:
Main equipment at ASML

- CD (after litho, after etch)
- Massive CD (EPE)
- Stochastics defect (ebeam & optical)
- Defect Review - CPI
- Unpatterned wafer defect inspection
- DBO (diffraction based OVL)
- SEM Voltage Contrast
- XPS – XRF – AFM - EDX
- Film Thickness
- Scatterometry

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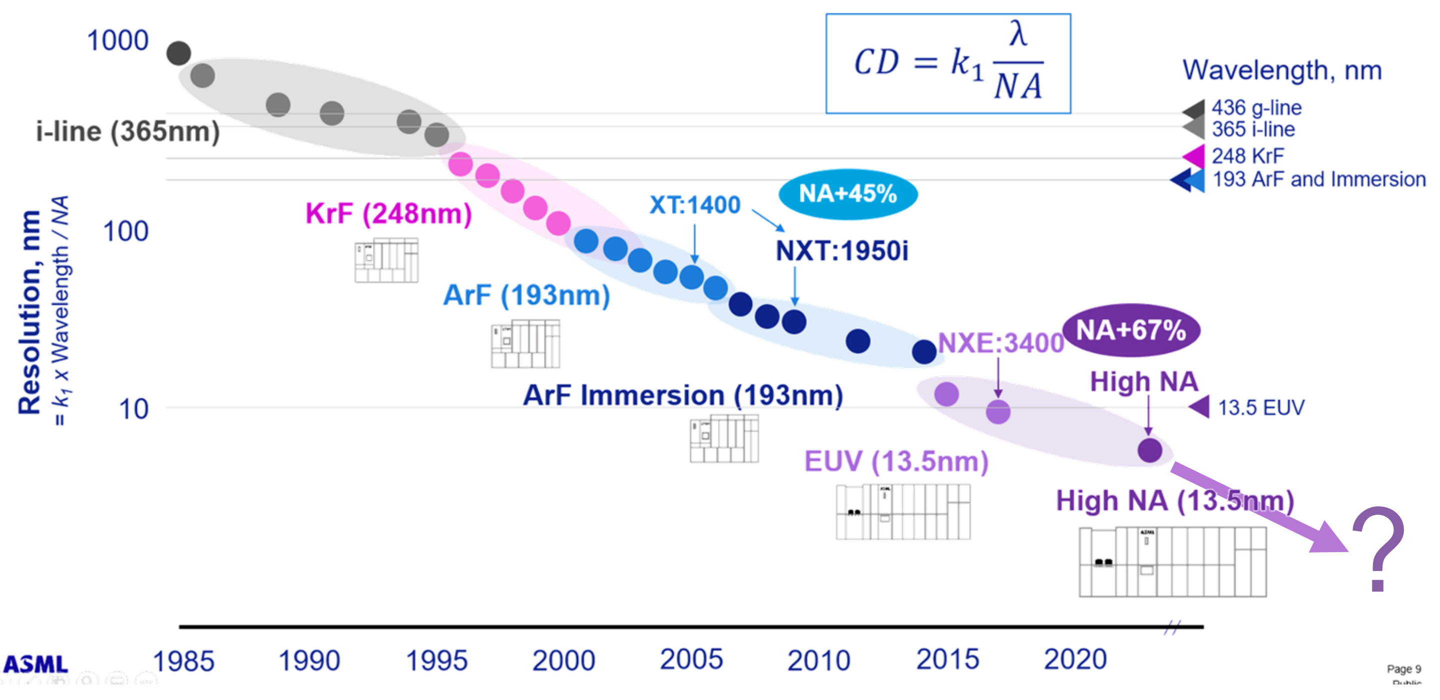
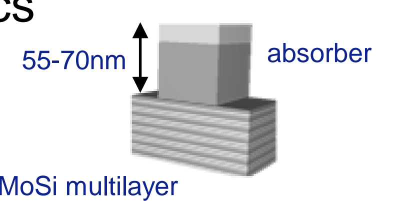
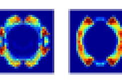
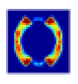
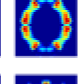
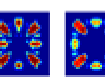
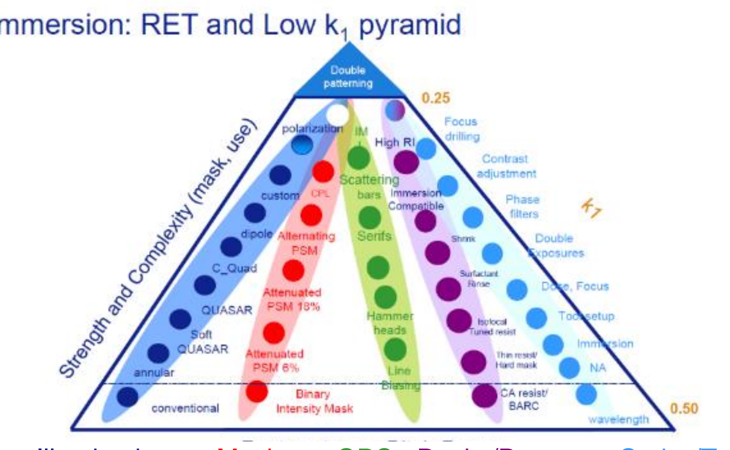
What are the next steps?

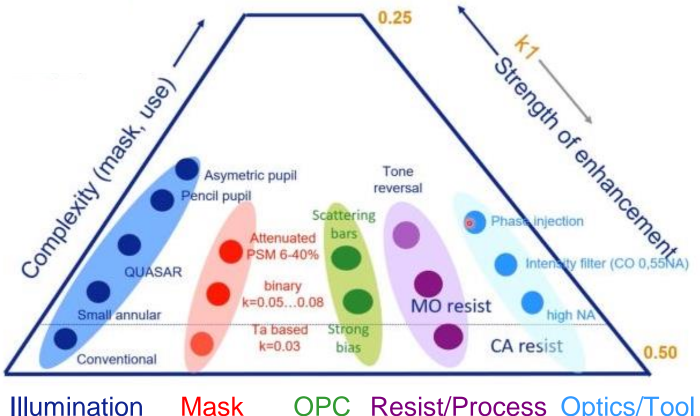


- Next to productivity and overlay, we keep pushing the envelope to improve on imaging essentially as we did in KrF and ArF
- New challenges are M3D, stochastics







Pyramids by Jo Finders, ASML

Summary

High NA is logical roadmap extension by improving contrast

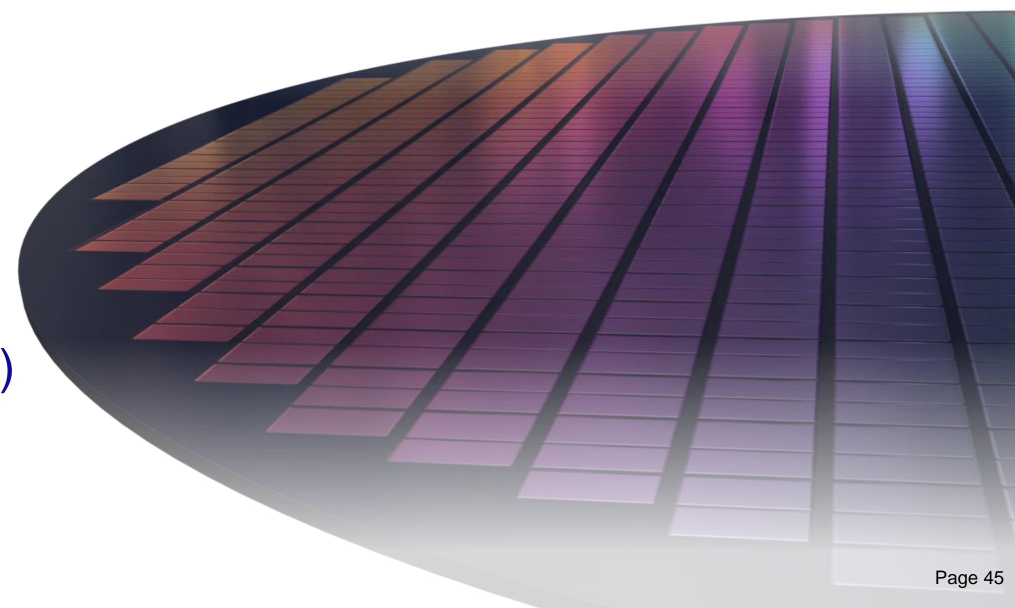
- Contrast is improved by a new anamorphic lens; imaging well controlled
- LCDU and defect print rate reduced by improved contrast, dose and resist
- No impact on overlay matching by introduction of half field
- Throughput maintained by stage accelerations, transmission and source power
- Economical printing for both intermediate pitches (low dose) and tight pitches (avoid DE)

High NA EUV Scanner realization is in full progress

- Modules are designed in in production phase
- Integration of independent testable sub-systems ongoing
- Zeiss is producing mirrors at full speed. Frames for High NA EUV optics are in the integration process

High NA ecosystem developments ongoing

- Advanced absorbers (eg. low-n) are desired (also for 0.33NA)
- Masks and resists are steadily improving
- Tachyon supports High NA



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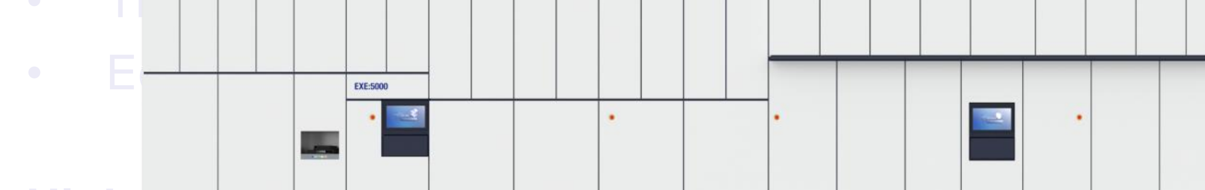

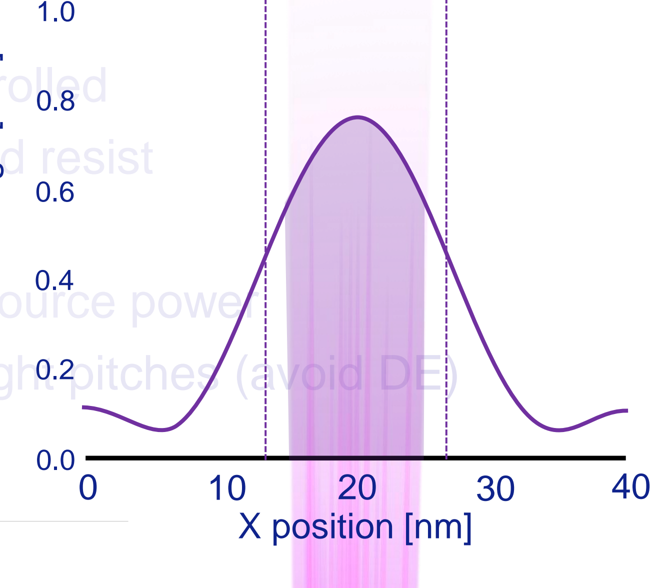

- Modules are designed in in production phase
- Zeiss is producing mirrors at full speed. Frames for High NA EUV optics a

High contrast puts the photons where you need them

High NA ecosystem developments ongoing

- Advanced absorbers (eg. low-n) are desired (also for 0.33NA)
- Masks and resists are steadily improving
- Tachyon supports High NA

Special thanks goes to:

- Greet Storms
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- Christophe Smeets
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- Luc van Kessel
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- Zuhal Tasdemir, PSI
- Patrick Naulleau, CXRO
- Chris Anderson, CXRO
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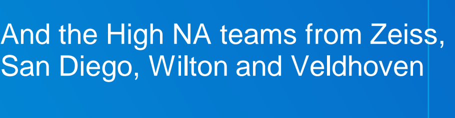
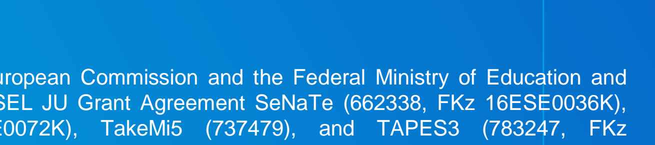
- Rudy Peeters
- Diederik de Bruin
- Kaustufe Bhattacharyya
- Kars Troost
- Teun van Gogh
- Boudewijn Sluik



And the High NA teams from Zeiss, San Diego, Wilton and Veldhoven

Jan van Schoot
Director of System Engineering
jan.van.schoot@asml.com

Veldhoven, The Netherlands



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