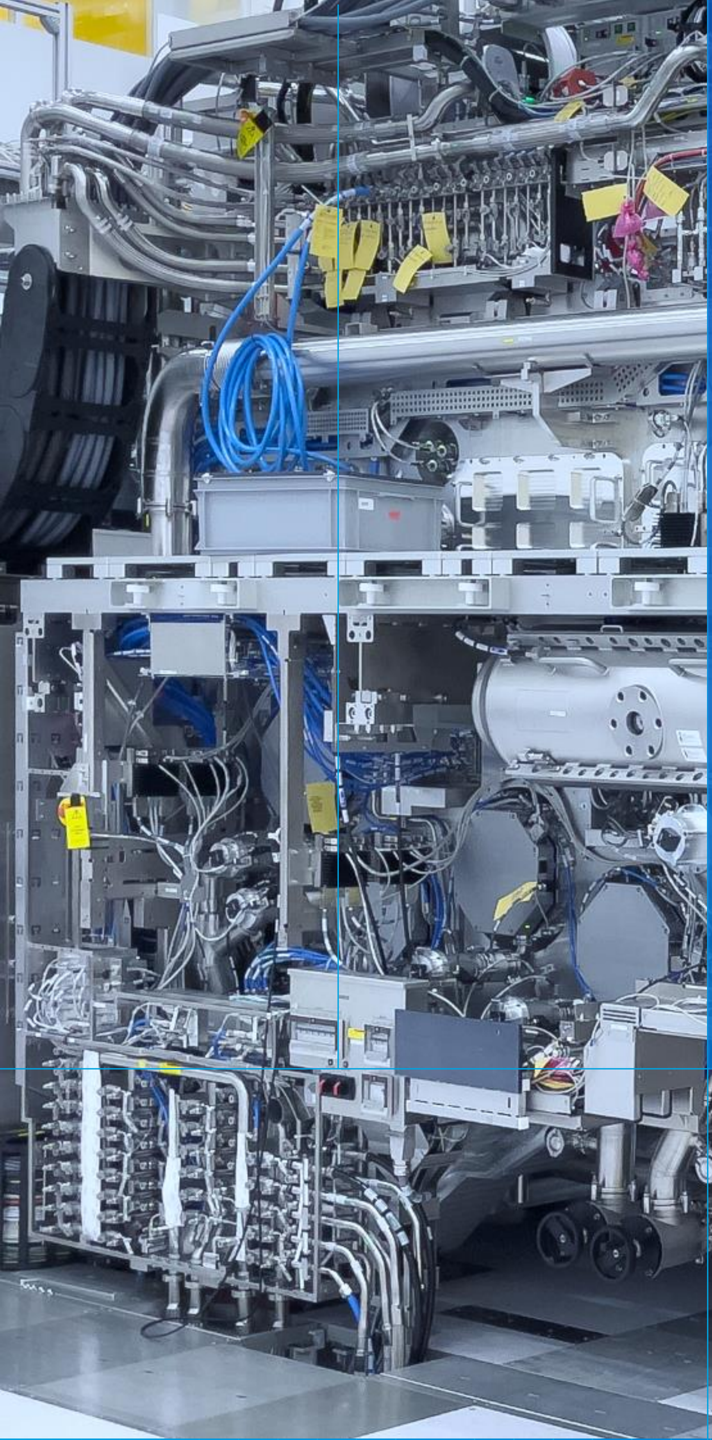
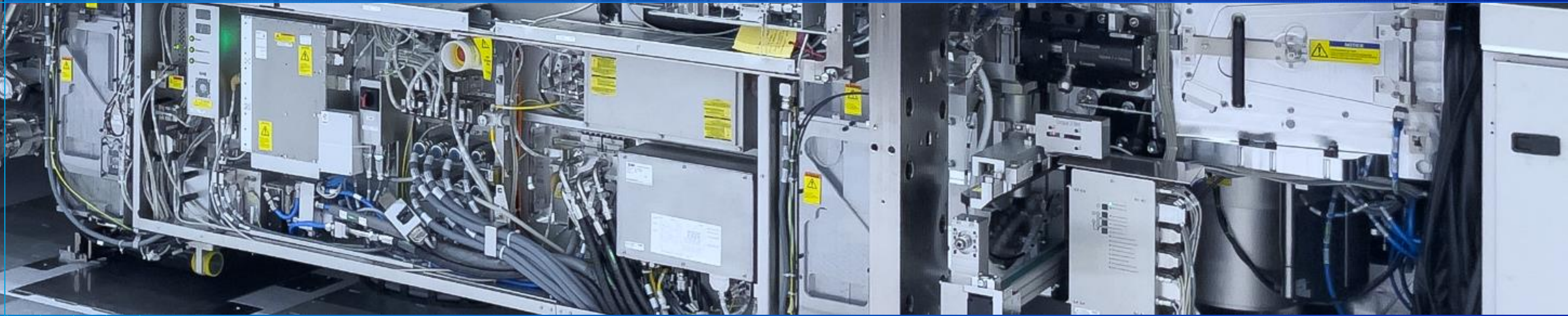
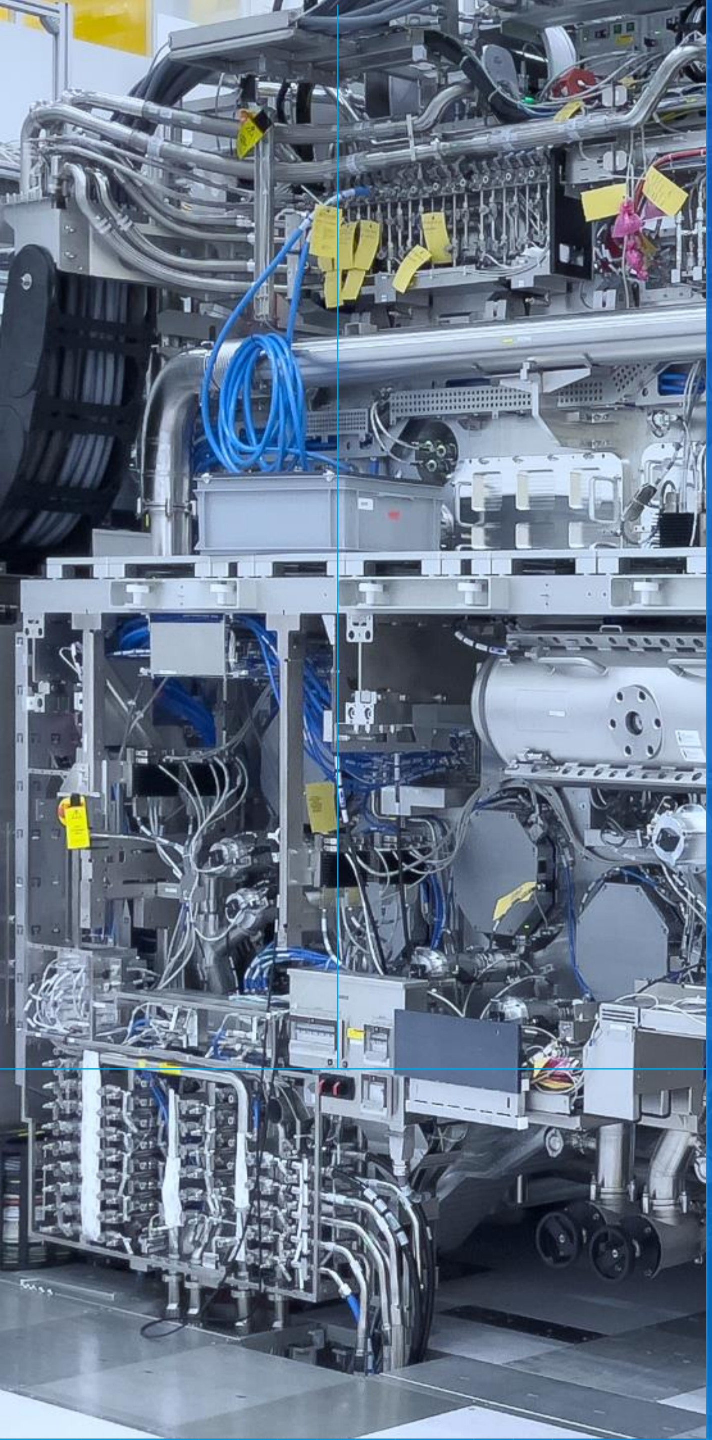


The High NA EUV exposure tool:
Nearing completion and next steps

Jan van Schoot, Sjoerd Lok, Rob van Ballegoij, Eelco van Setten, Jo Finders, Diederik de Bruin, Rudy Peeters, Peter Vanoppen
ASML Veldhoven, The Netherlands

Paul Graeupner, Peter Kuerz, Thomas Stammler
Carl Zeiss SMT GmbH, Oberkochen, Germany

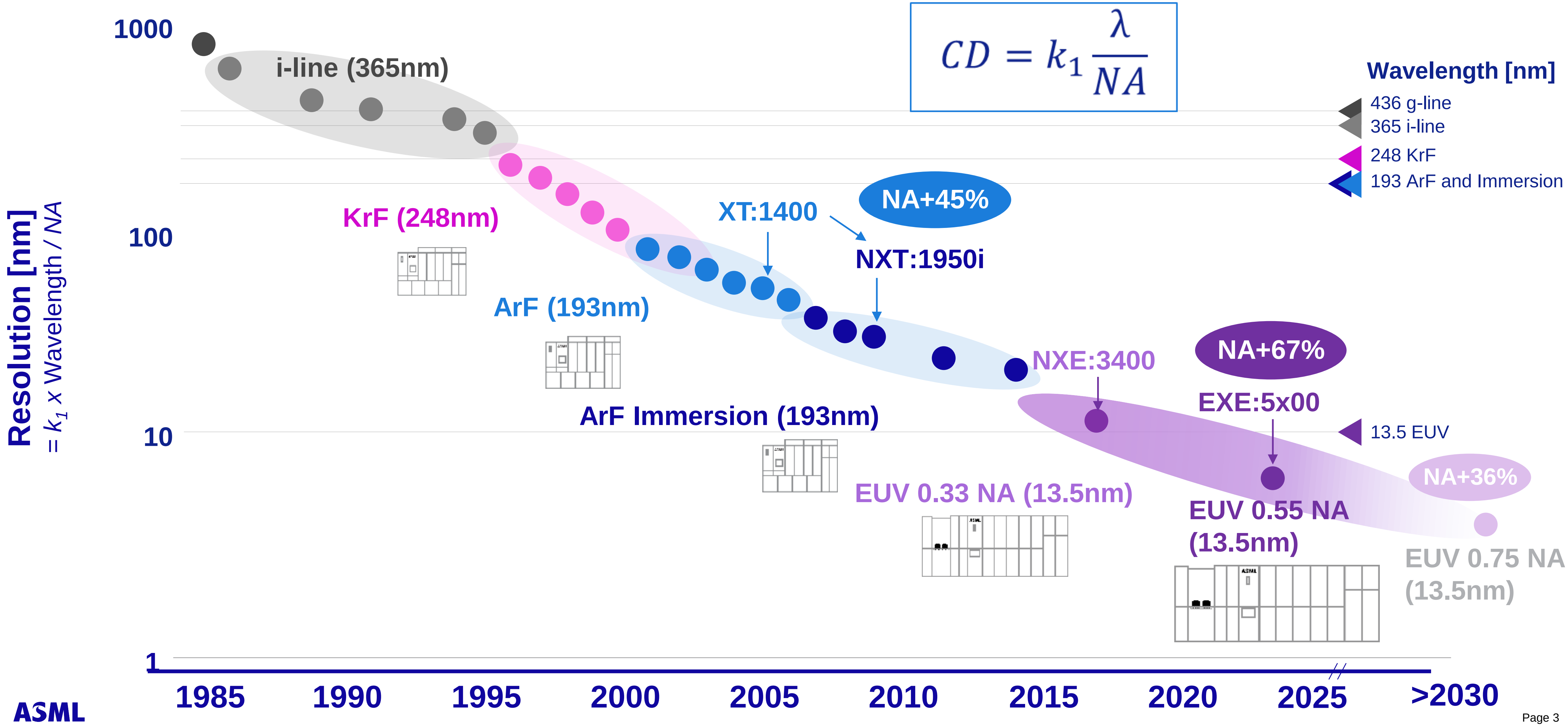




1. EUV product roadmap
2. High NA refresher
3. High NA Integration update
4. High NA Eco system
5. What’s next?
6. Summary

2 orders of magnitude resolution reduction over 35 years continues…

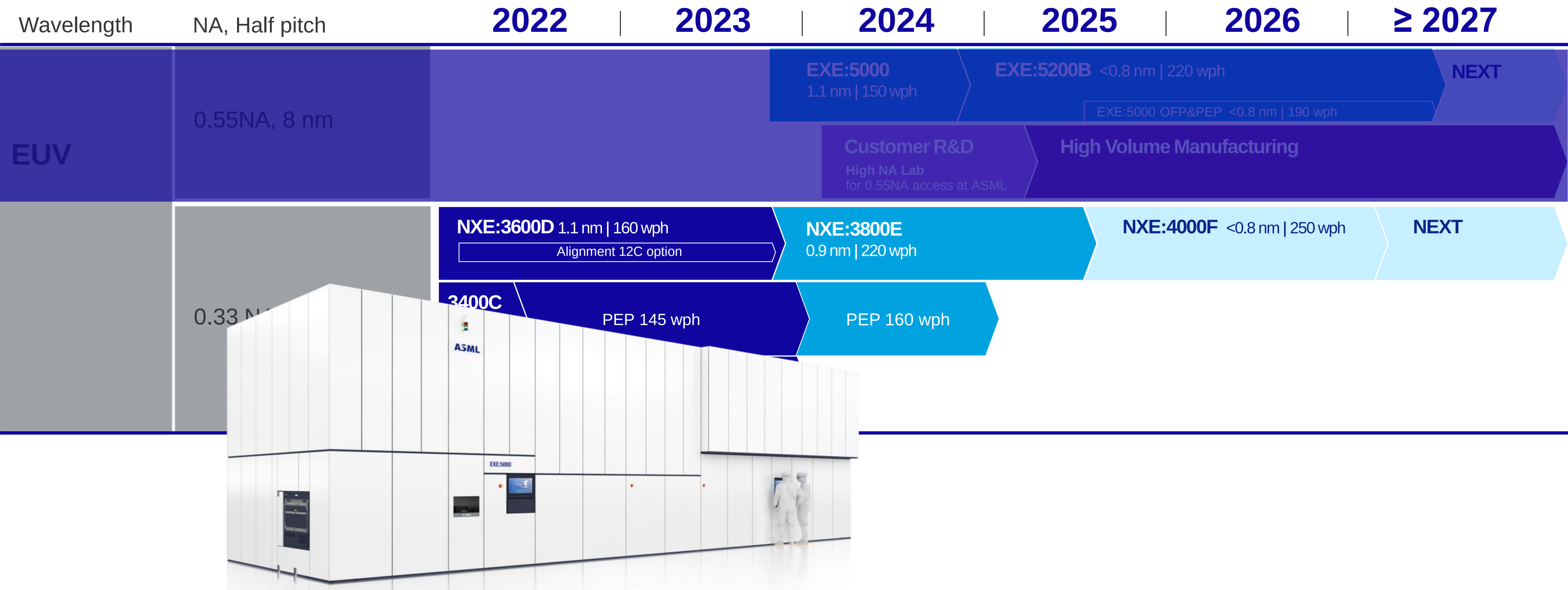
by working on wavelength, Numerical Aperture and illumination (k_1)



ASML

Public

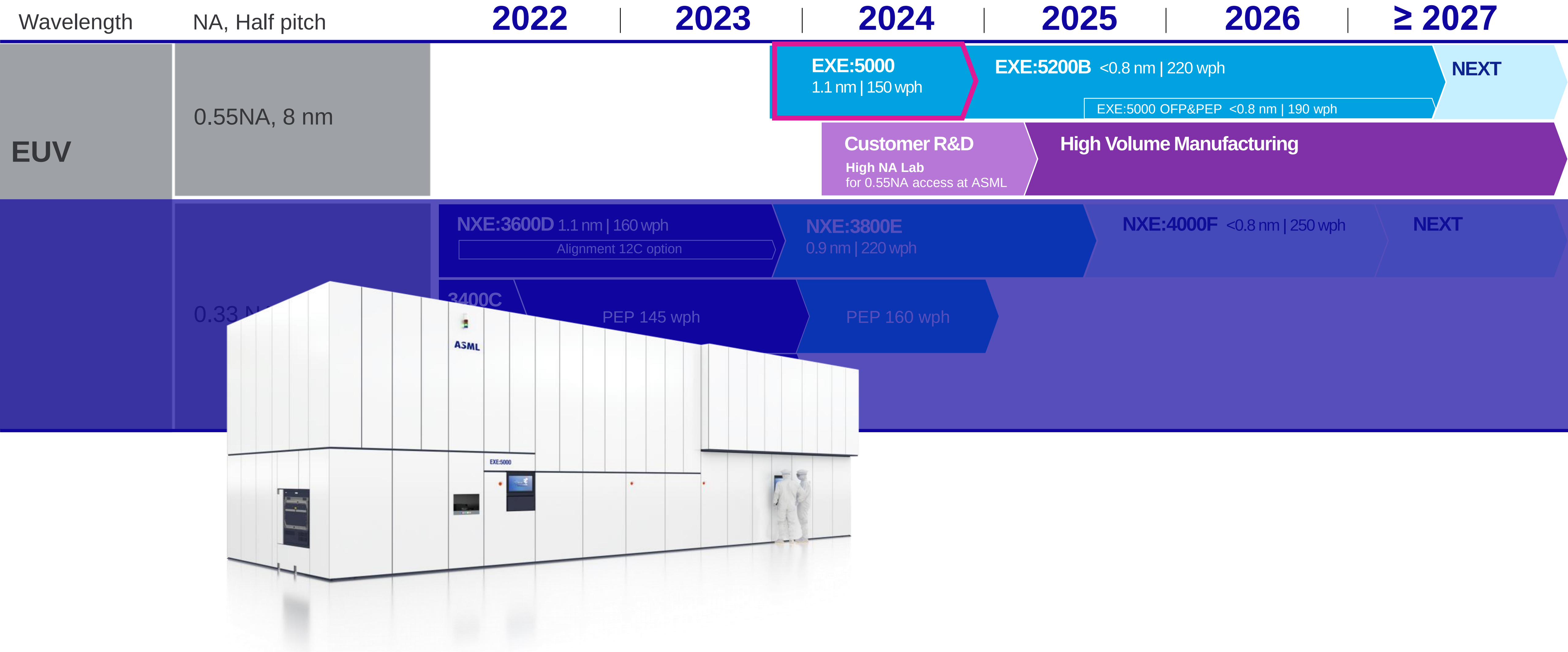
EUV product roadmap



Raymond Maas et al., Industrialization of EUVL and Future Roadmap (P62)

Product	Matched Machine Overlay (nm) | Throughput(wph)
Product status	Released | Development | Definition

EUV product roadmap



Product	Matched Machine Overlay (nm) | Throughput(wph)		
Product status	Released	Development	Definition

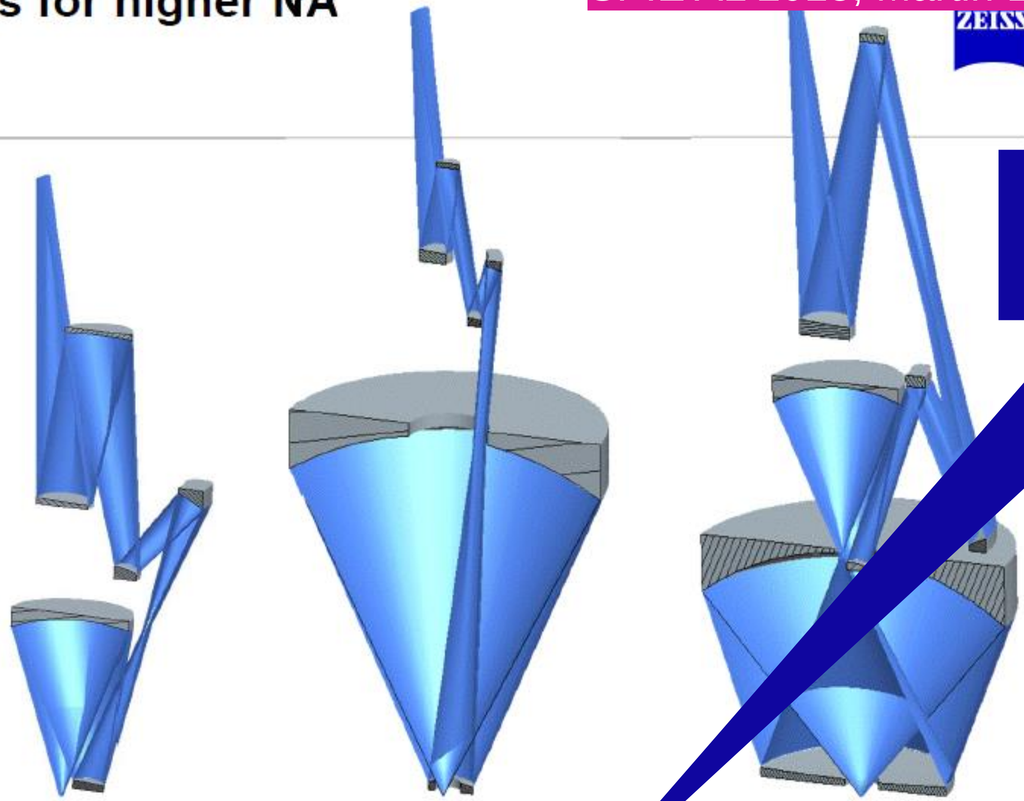
Some history, how it all started

Projection optics for higher NA

SPIE AL 2013, Martin Lowish

Challenges of projection optics for higher NA:

- manufacturing of large mirror
- Larger tracklength



schematic designs – for illustration only.

NA	0.33	0.45	0.60
# of mirrors	6	6	8
Relative transmission	100 %	~100 %	<40 %

0.45NA, full field: too close to 0.33NA

Or a low transmission, M3D not an issue yet…

Carl Zeiss SMT GmbH SPIE Advanced Lithography 28 February 2013 26

Some history, how it all started

SPIE AL 2013, Martin Lowish

Projection optics for higher NA

ZEISS

Chall
proje
for hi

• manu
mirror

• Large

schem

NA	
# of mi	
Relativ	

Carl Zeis

2013 Sematech Workshop, Kaiser/van Schoot

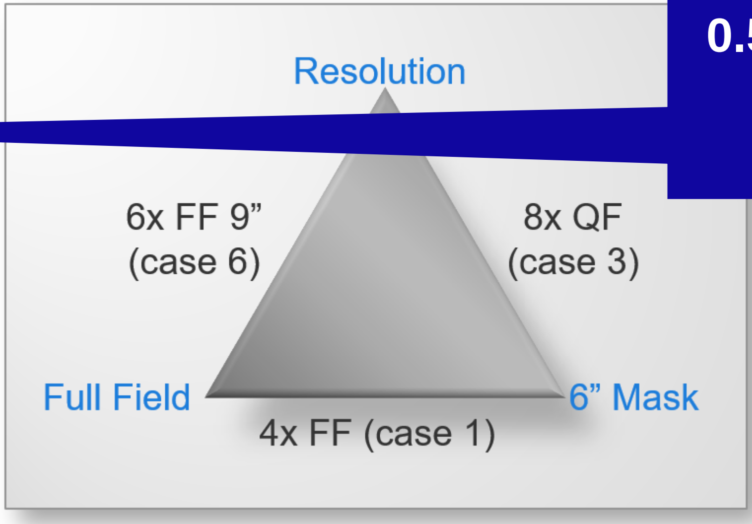
ZEISS ASML

Summary: there is no free lunch!

Slide 12

The aim of High NA is resolution

- Small fields, 0.5NA, 8nm
  - Largest NA, 6M, 6"
  - Throughput impact
    - Partly mitigate by faster stages
  - Stitching
- Full fields, 0.45NA, 9nm
  - Largest throughput
  - But: 9" reticles
    - Or 300mm Ø wafer like reticles, helps infrastructure

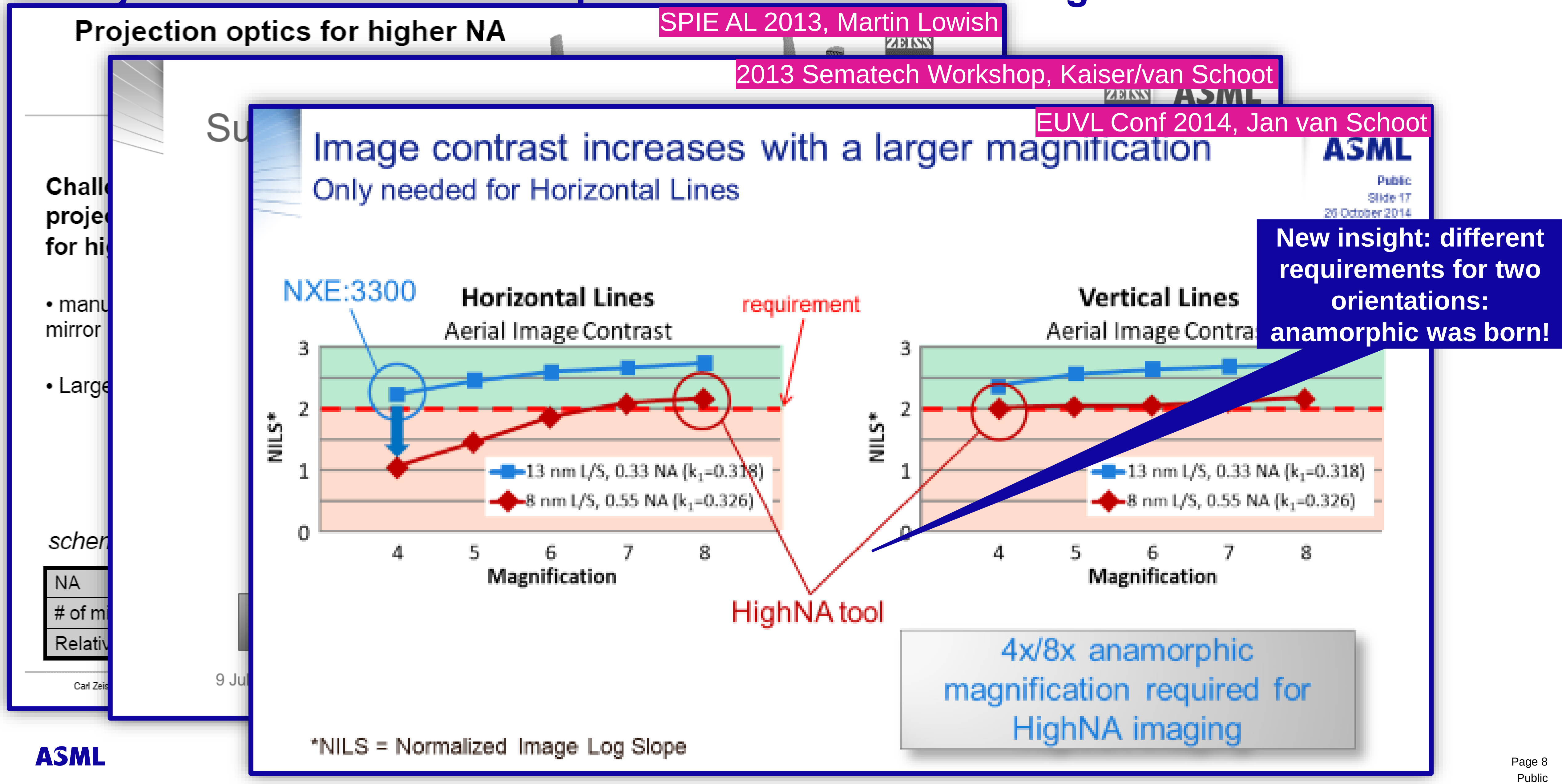


0.5NA, Quarter Field: More insight, low throughput

Largest NA with 6M at 6"– extendibility is ASML's / Zeiss' preference

9 July 2013, Sematech Workshop on High NA, Winfried Kaiser, Jan van Schoot

~10 years from idea 'Anamorphic Half Field' to first image EXE:5000

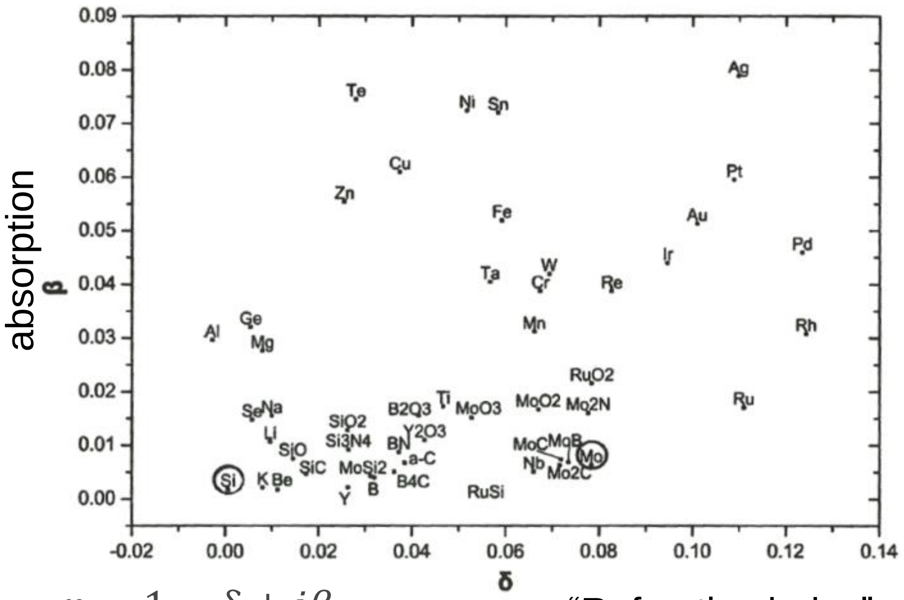


The basics for High NA EUV are found in the elements

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

$m\lambda = 2d \sin\alpha$

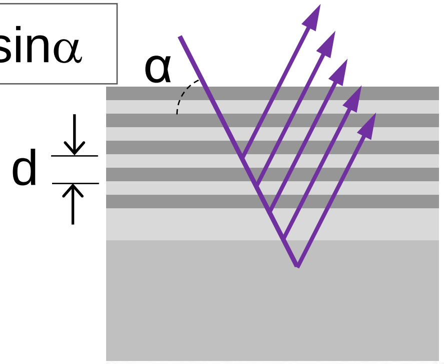
Optical properties of materials[1]

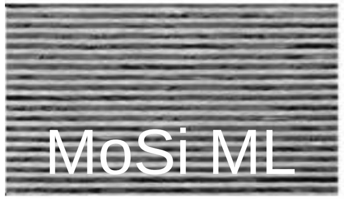


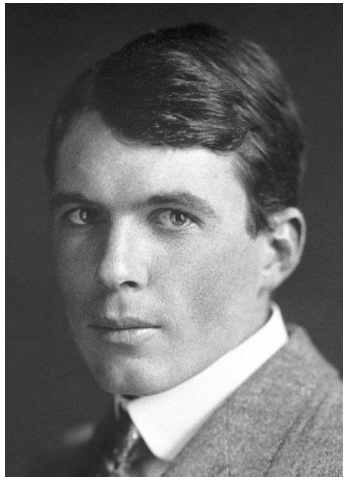
$n = 1 - \delta + i\beta$ "Refractive index"

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

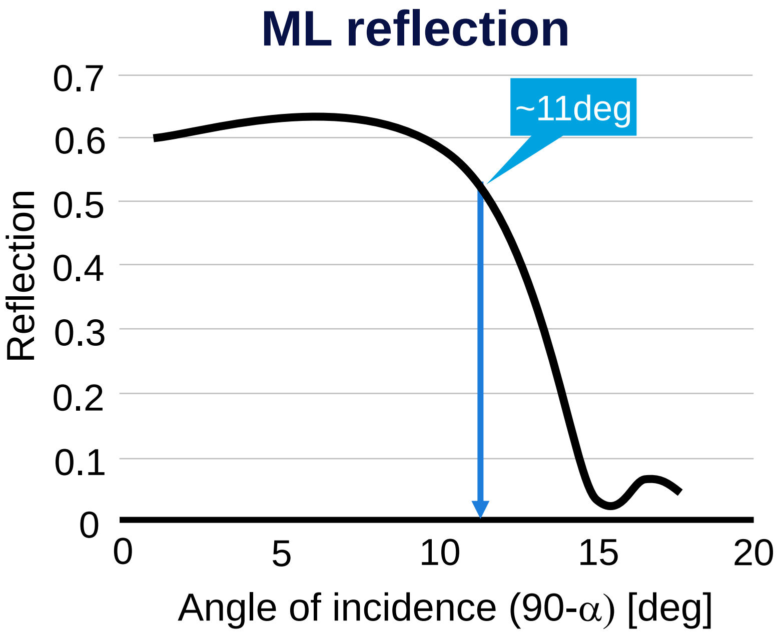
[1] Chart is from Eric Louis, Physics and technology development of multilayer EUV reflective optics, PhD thesis, University of Twente, The Netherlands, 2012







Lawrence Bragg[2]



Absorption:

- Mirrors
- Vacuum
- Source powers

Refractive index:

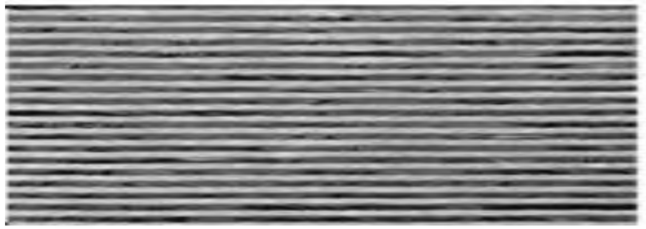
- Bragg reflectors (Multi-layers, ML)
- Angular dependency

[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

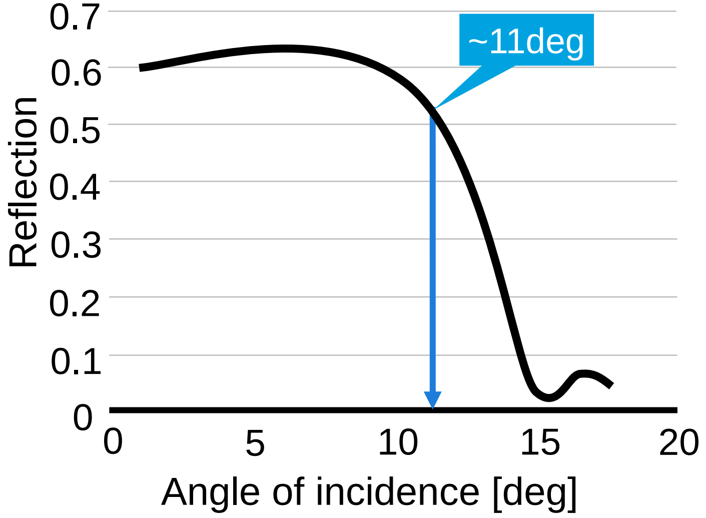
Anamorphic Optics overcome Angular limitations of Multi Layer Mirrors

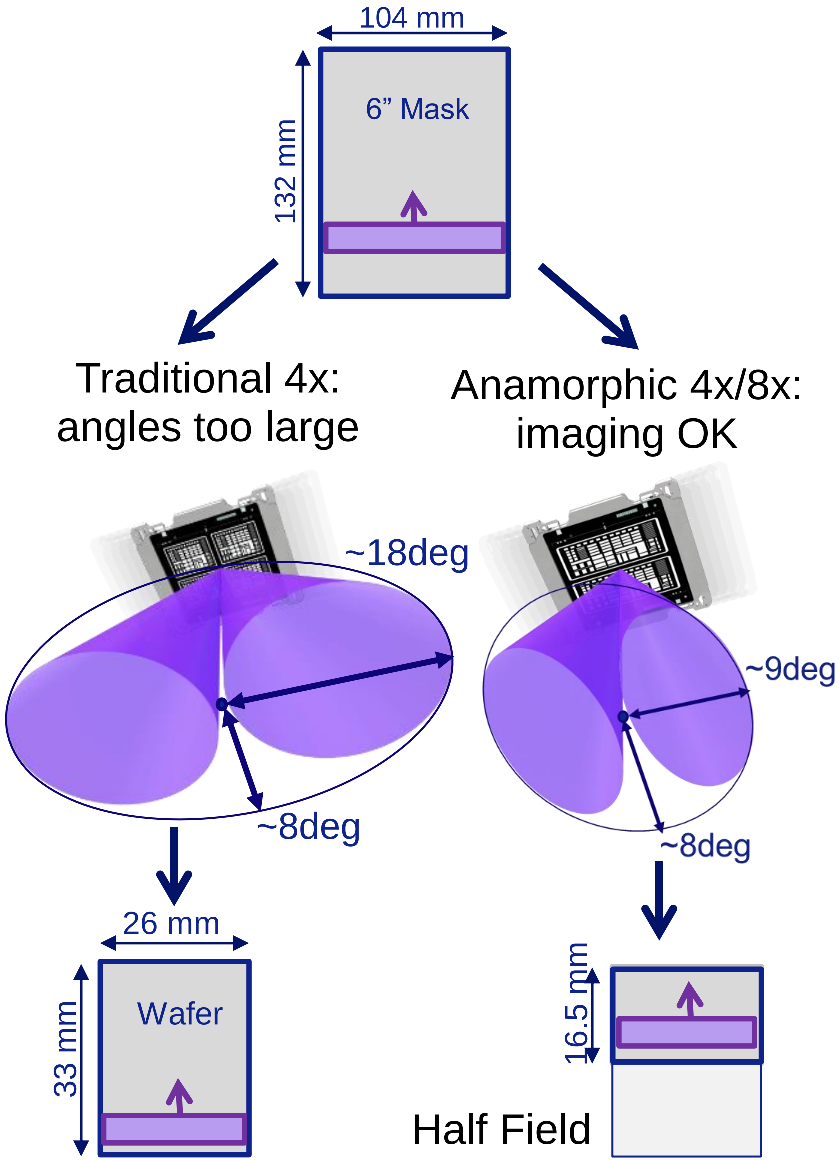
While allowing for good productivity with faster stages

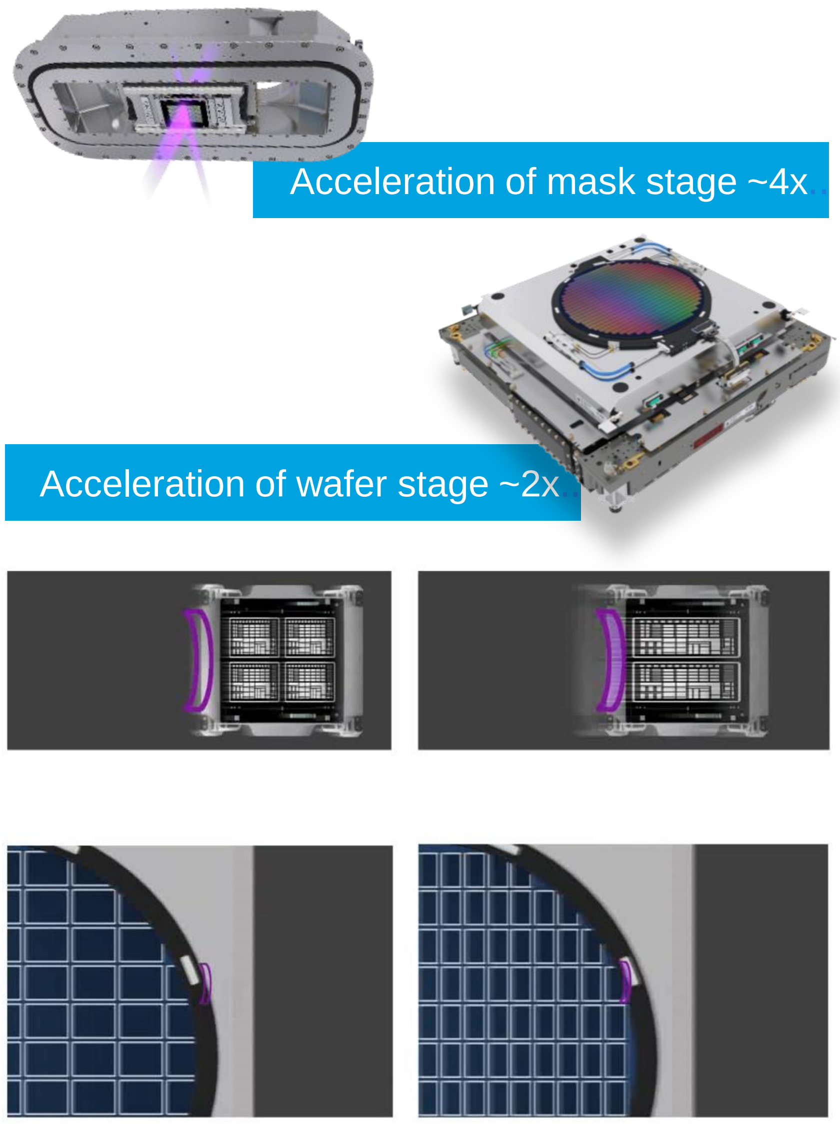
Mask MoSi Multilayer



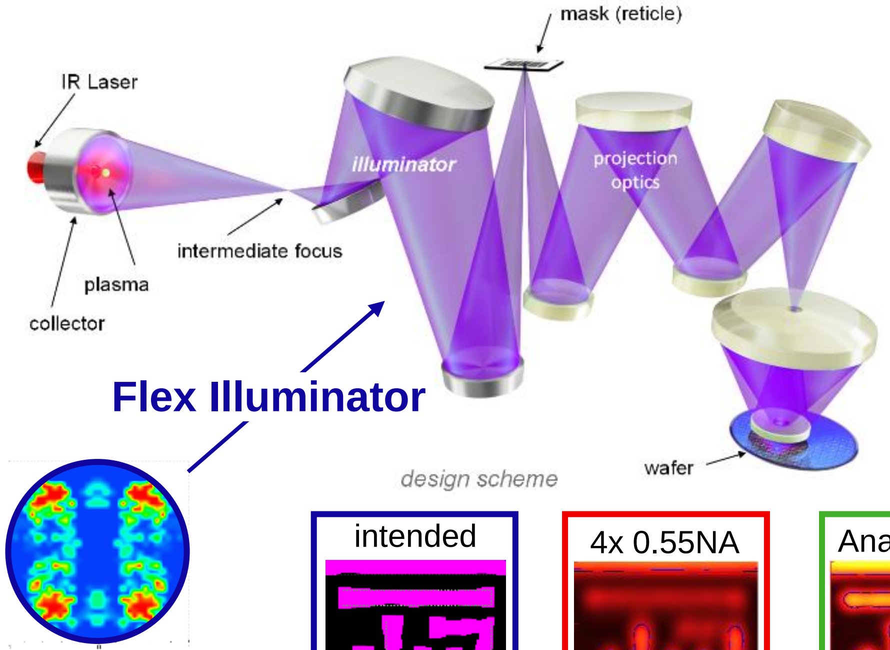
ML reflection



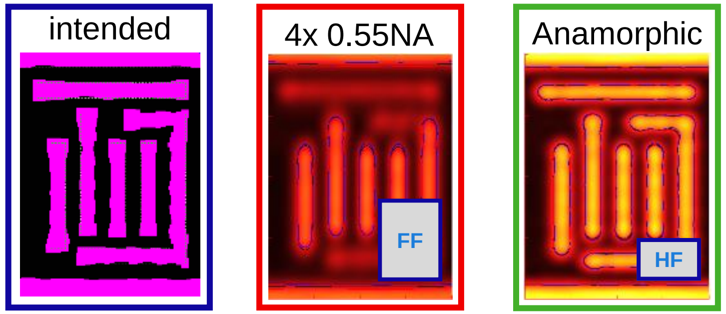


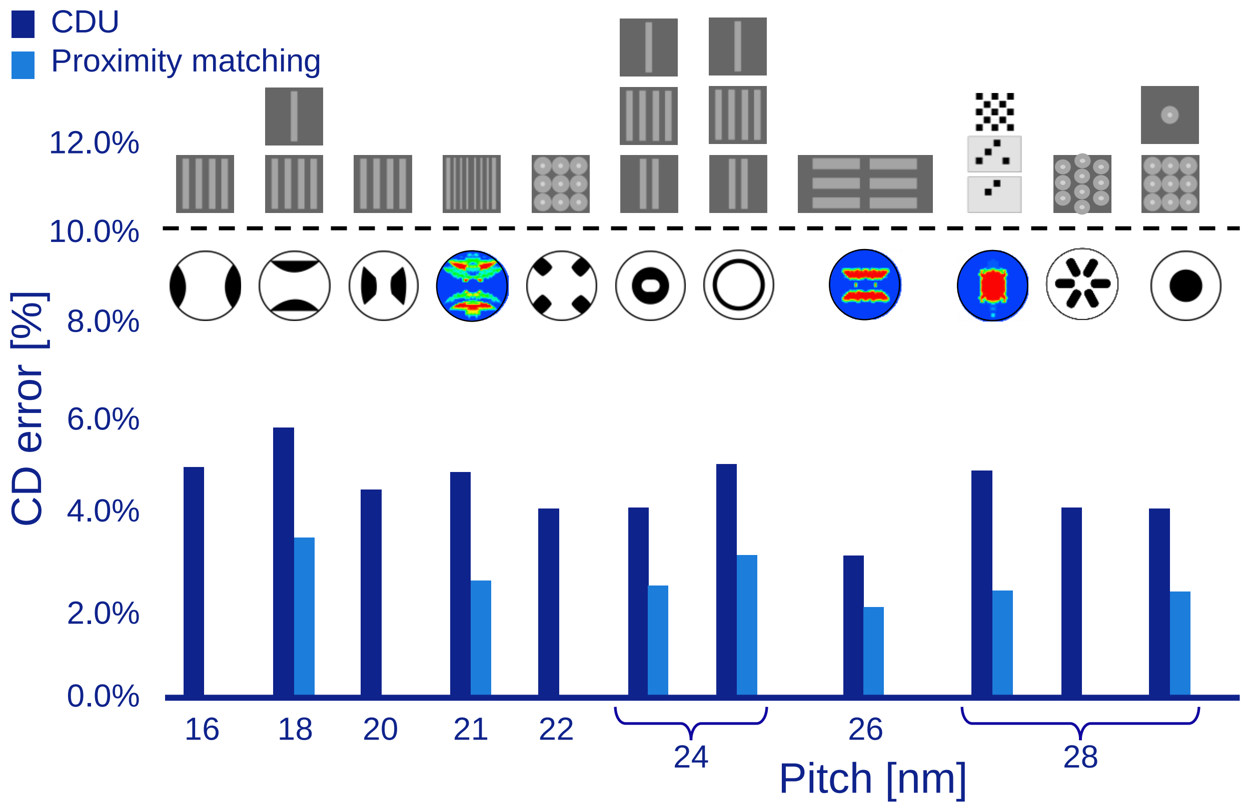


An anamorphic imaging system delivers good images to the wafer



Logic N5 Metal-1, 11nm lines, SMO is done at 8x

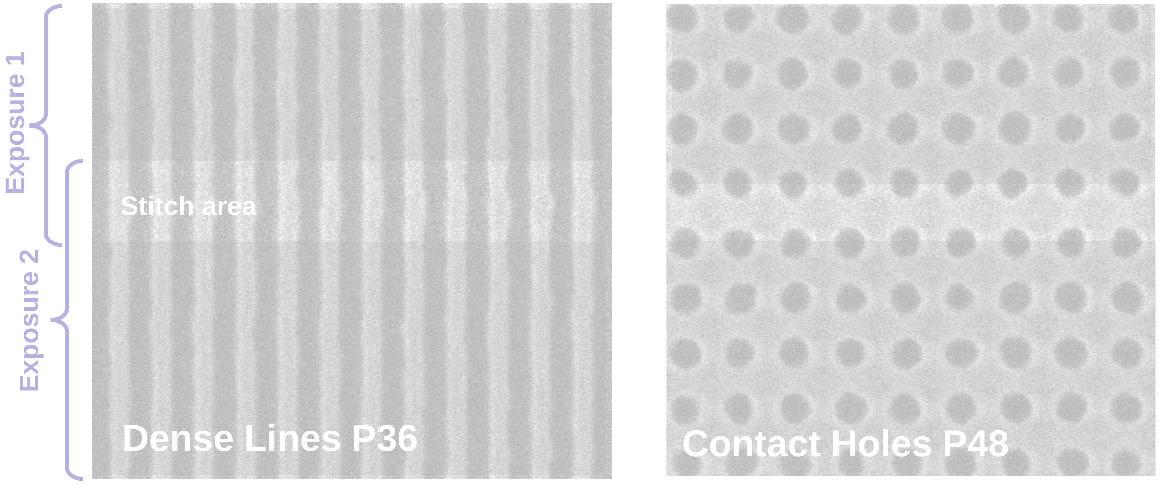


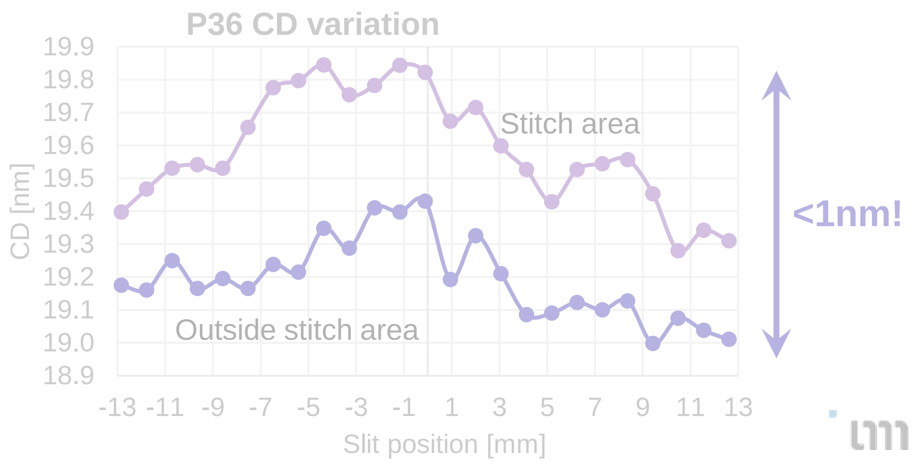


Half Field needs special measures for stitching and matching

Both stitching and matching have been demonstrated successfully on NXE

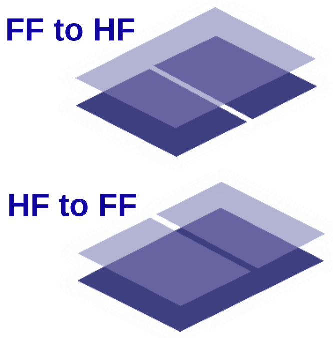
For chips > Half Field, stitching is needed

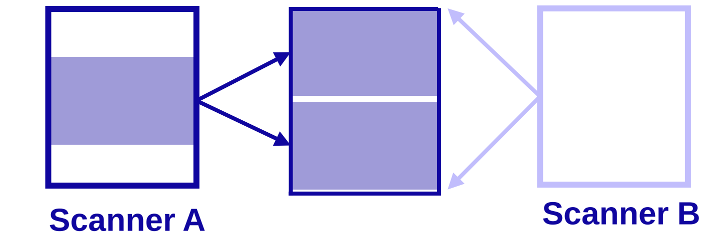


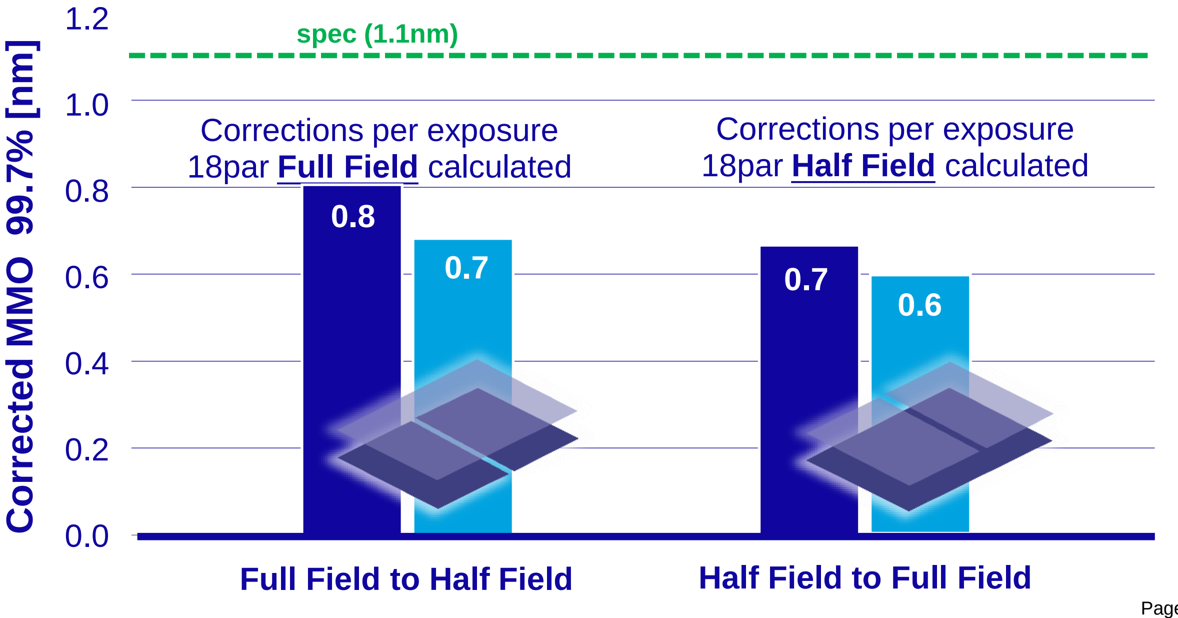


imec

Half Field to Full Field Matching







Customers are publicly announcing adoption of High NA EUV

All current 0.33NA EUV customers are committed to High NA

SK hynix / SAMSUNG — OCT '22

Samsung Electronics·-SK hynix ordered 'High NA' EUV exposure equipment for 2-nano process

Source: Electronic Times

SAMSUNG — JUN '22

"Samsung Seals a Deal with ASML to Procure Next-generation EUV Lithography Equipment"

tsmc — JUN '22

"TSMC will bring in **High-NA EUV** scanners in 2024 to develop the associated infrastructure and patterning solution needed for customers to fuel innovation," said **Y.J. Mii, senior vice president of research & development,** during TSMC's technology symposium in Silicon Valley.

Micron — MAY '22

High-NA EUV needed for planar DRAM roadmap

intel — JAN '22

"Intel's focus is to stay at the forefront of semiconductor lithography technology and we've been building our EUV expertise and capacity over the last year. Working closely with ASML, we will harness **High-NA EUV's** high-resolution patterning as one of the ways we continue Moore's Law and maintain our strong history of progression down to the smallest of geometries," **said Dr. Ann Kelleher, executive vice president and general manager of Technology Development at Intel**

Press Release

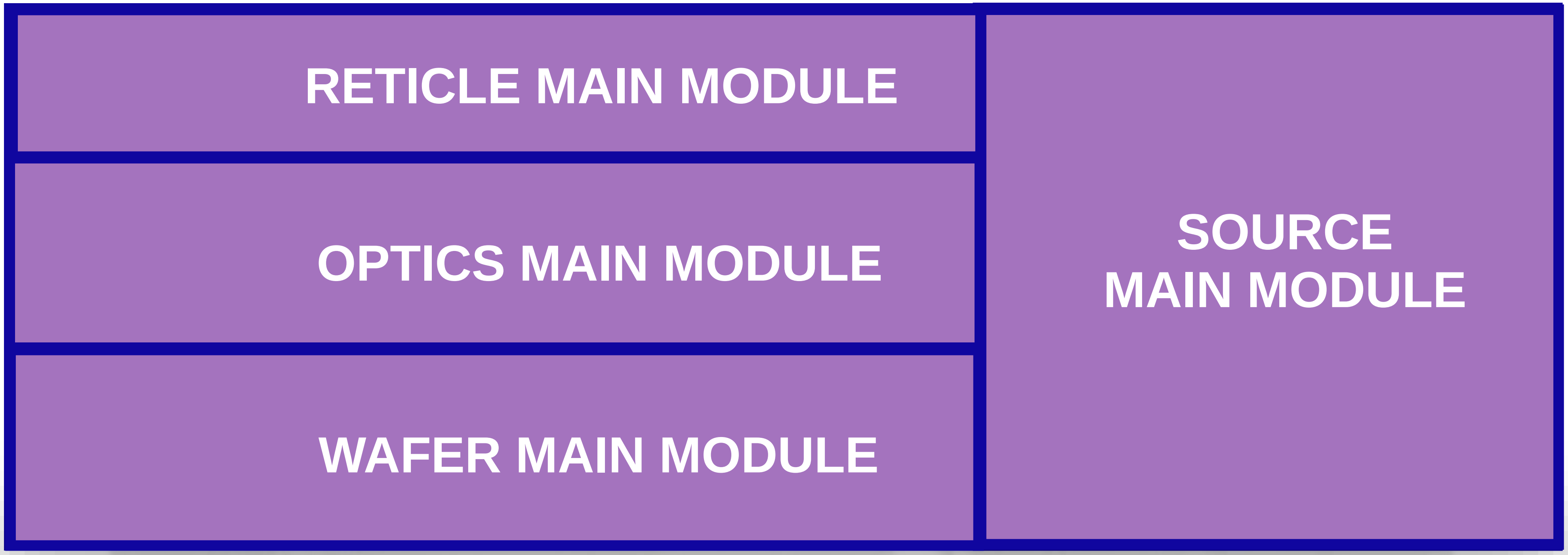
Presented

ASML

High NA commonality is maximized with EUV 0.33 NA

To reduce introduction risk and improve High NA maturity

4 independently testable main modules



ASML

High NA designed with focus on serviceability

- Accessibilty
- Service times
- Recovery to manufacturing

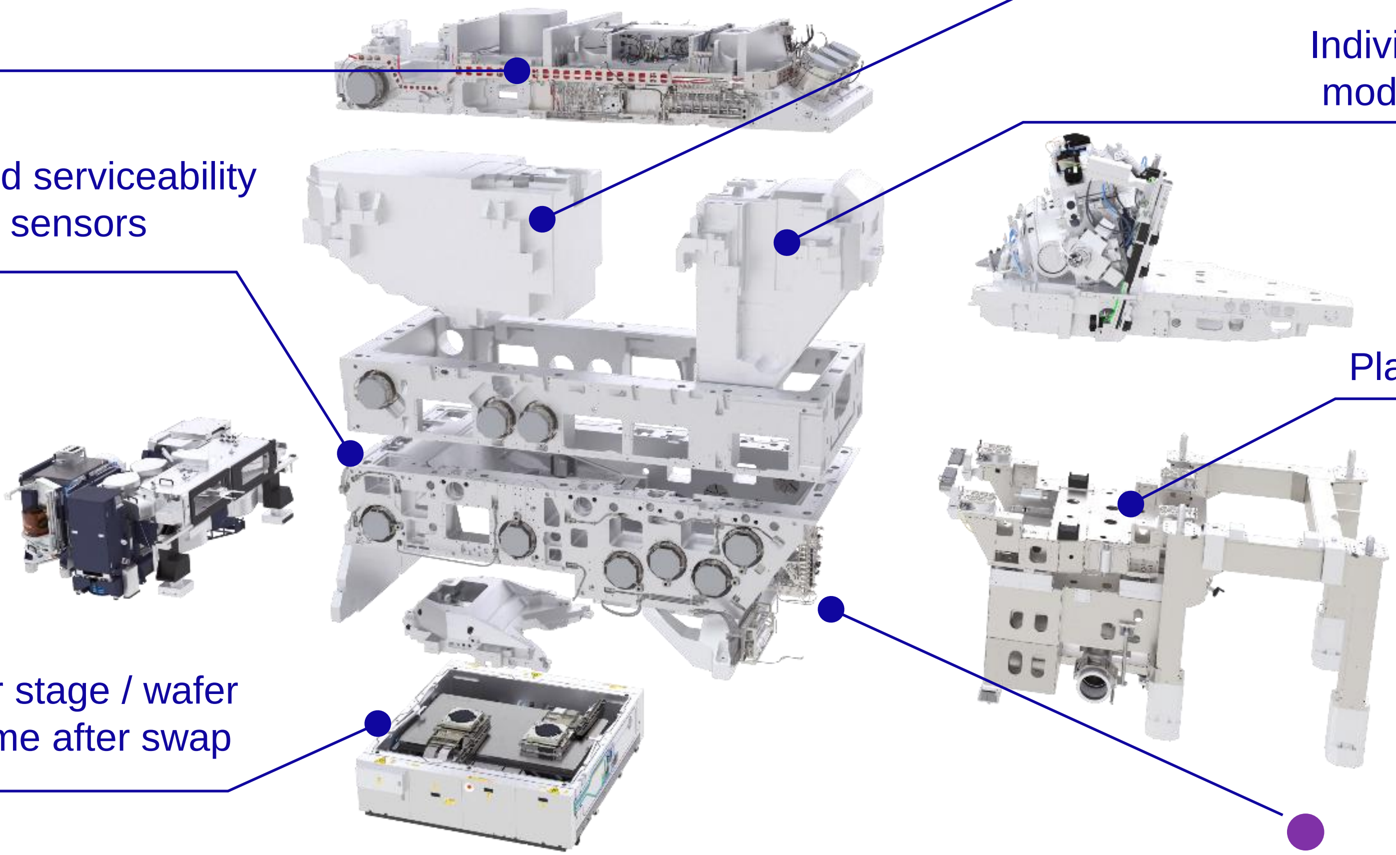
Modular architecture allows for faster thermal and metrology recovery after service

Reticle stage is removed without need for removal of other parts

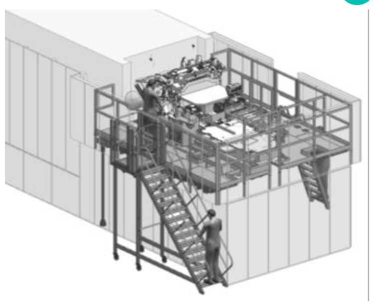
Individual POB mirror modules can be swapped

Individual illuminator mirror modules can be swapped

New frame for fast access and serviceability of alignment of measurement sensors



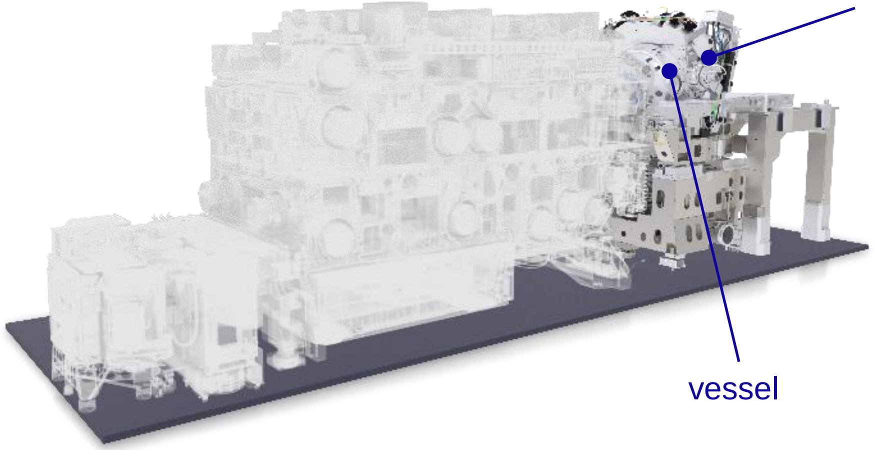
Platform for easy access to source



Improved interface for wafer stage / wafer clamp to reduce recovery time after swap

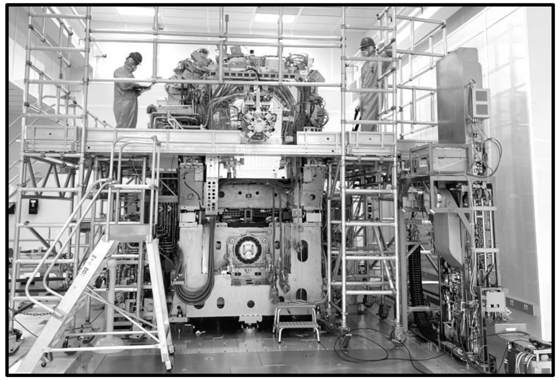
Water circuits compartmentalized for raster service

Three High NA source Main Modules qualified at ASML



0.55NA source is common with 0.33NA, but with a different orientation

One High NA source
Main module
First light achieved



2022

Three EXE:5000 sources fully qualified at ASML

EXE:5000 power spec met

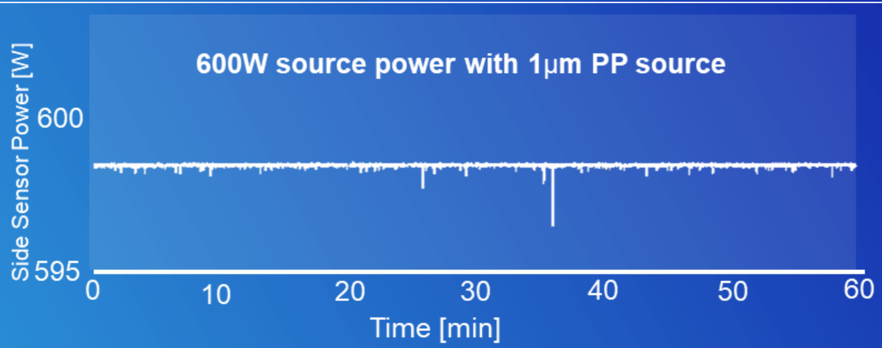
EXE:5000

source built into the system

Tin management verified over >100Gpls

EXE:5200

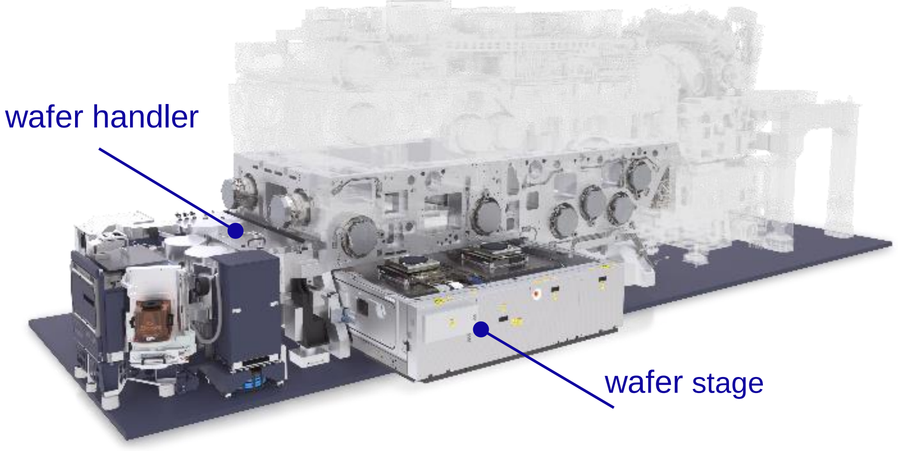
EXE:5200 source power level with proto type source



2023

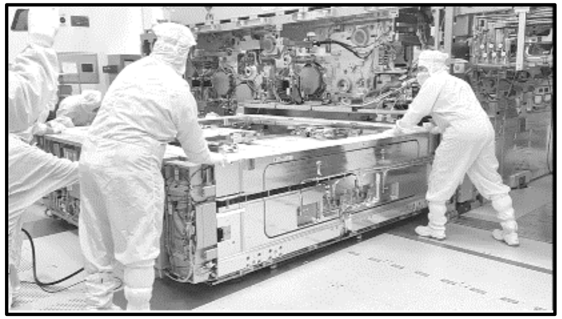
ASML

Four Wafer Main Modules built, and wafer stage motion under servo control



0.55NA wafer stage and wafer handler are common with 0.33NA

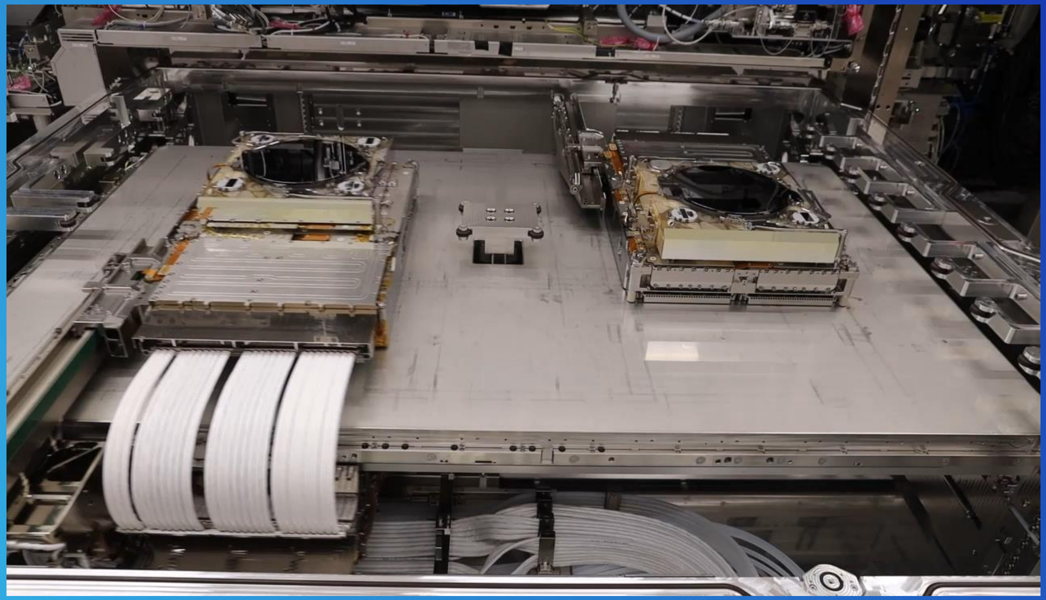
Built of first wafer main module ongoing Wafer stage installed

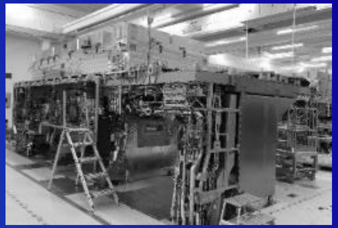


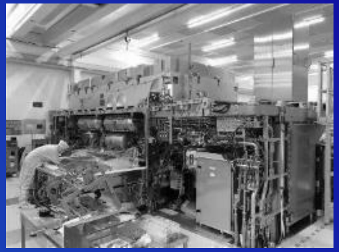
2022

Wafer stage motion under servo control

Four wafer main modules built and used for qualification and maturation of High NA

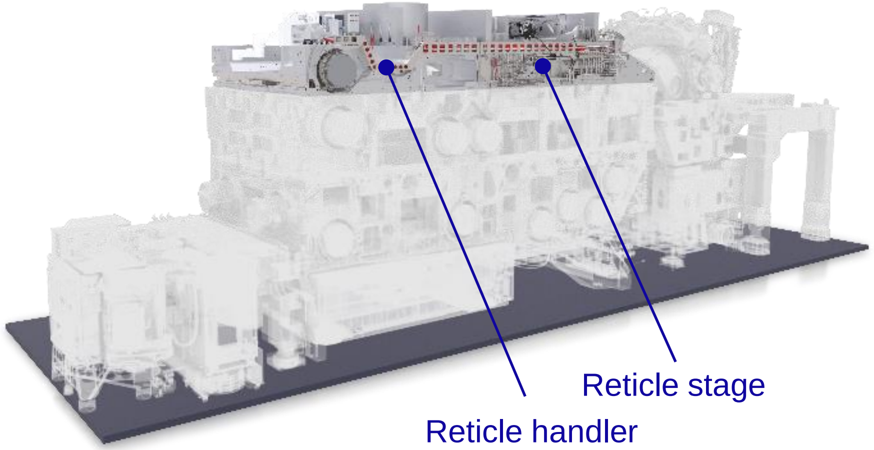


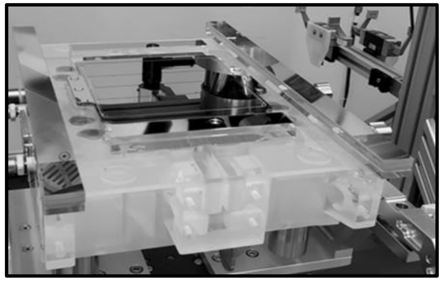


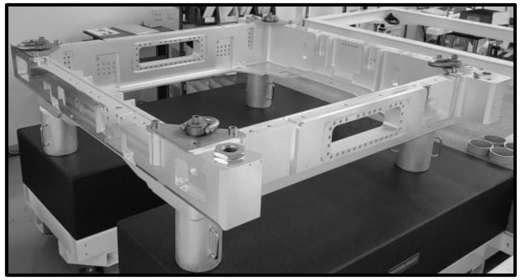


2023

Reticle Main Module built, and reticle handler cycling completed





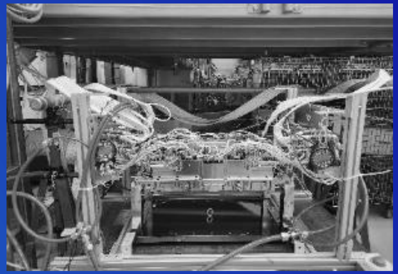


Reticle main module parts at ASML Wilton

2022

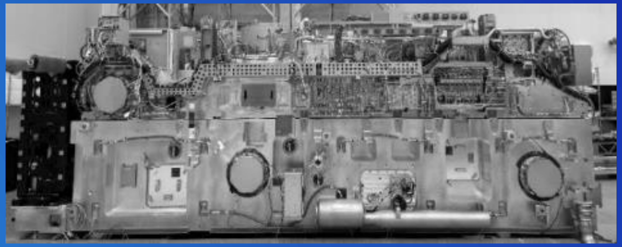
Reticle main module built
Reticle handler cycling completed

Reticle Handler build stand



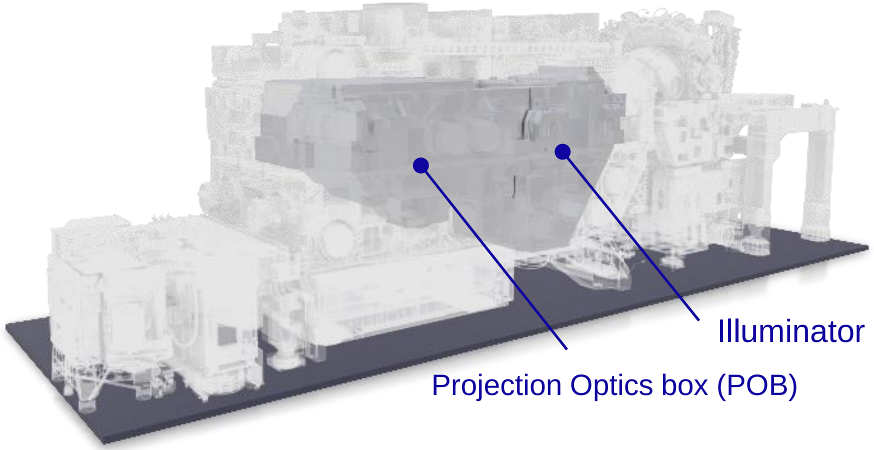
Reticle Stage qualification stand

Reticle Main Module

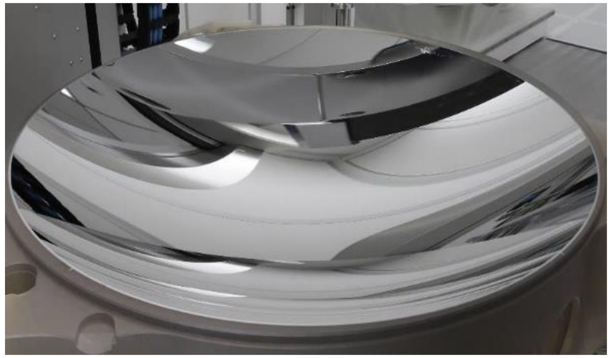


2023

High NA mirrors meet specification and forerunner POB installed in system



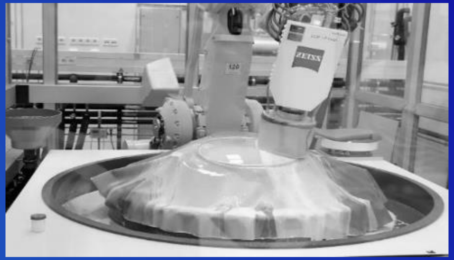
First coated mirror



2022

All High NA mirrors are meeting design specs for wavefront, transmission and flare

Forerunner POB installed in the system
to de-risk new mechanics, actuator & electronics



Mirror production ramp ongoing

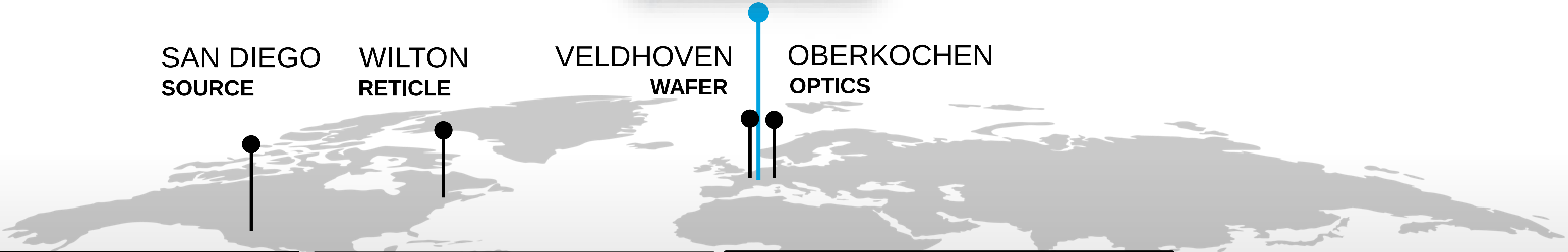
Mirrors within spec for multiple customer tools

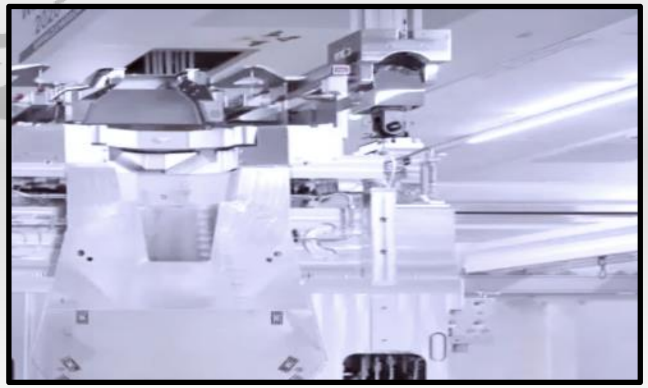
2023

Good integration progress of the four main High NA modules

to support High NA ramp in 2024

System integration in Veldhoven





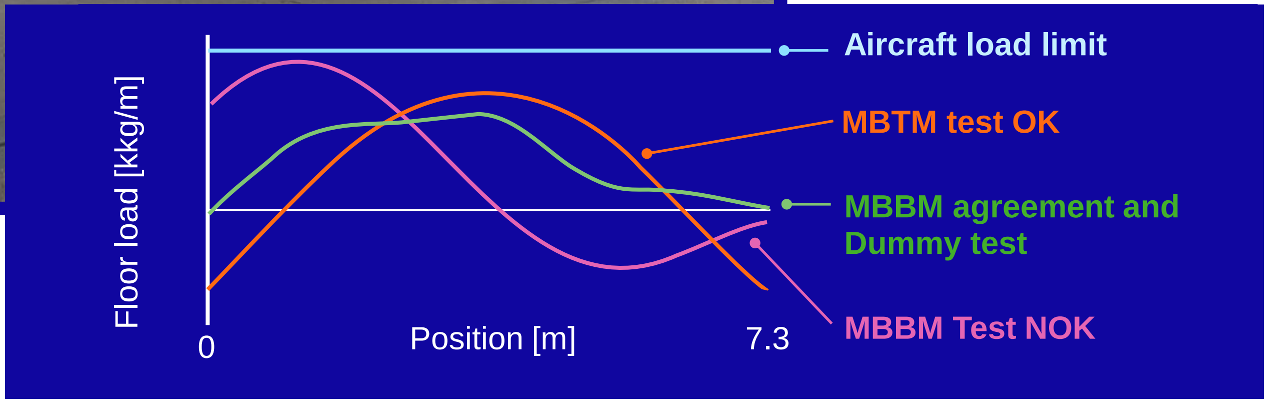
SOURCE:
Target power of >360W achieved and more than 100 giga pulses ran on the source

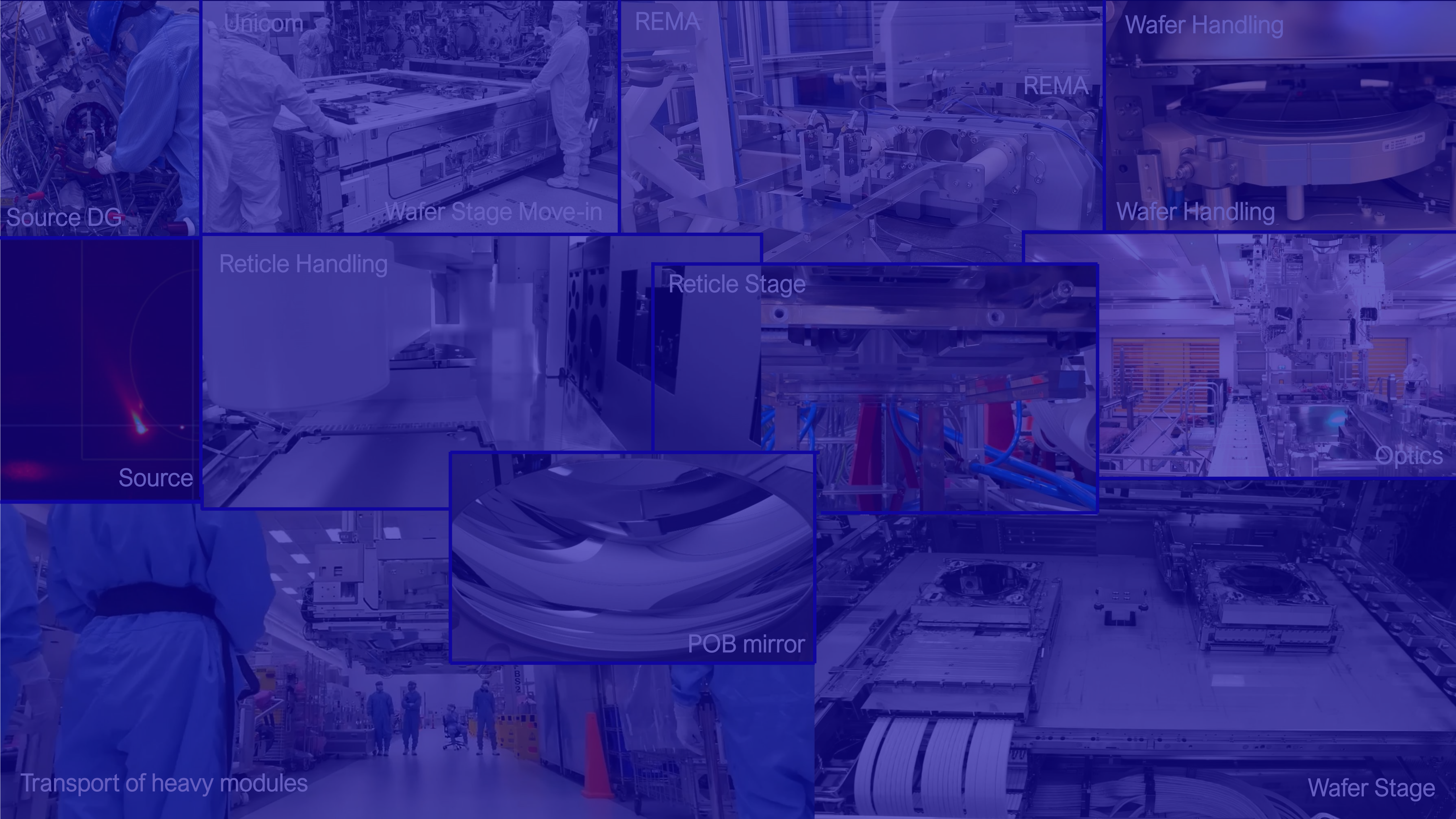
RETICLE:
Reticle main module built, integration in progress, reticle cycling qualified

WAFER:
Four main modules built, integration in progress, wafer stage motion under servo control

OPTICS
All mirror types are meeting specification. POB and illuminator build in progress

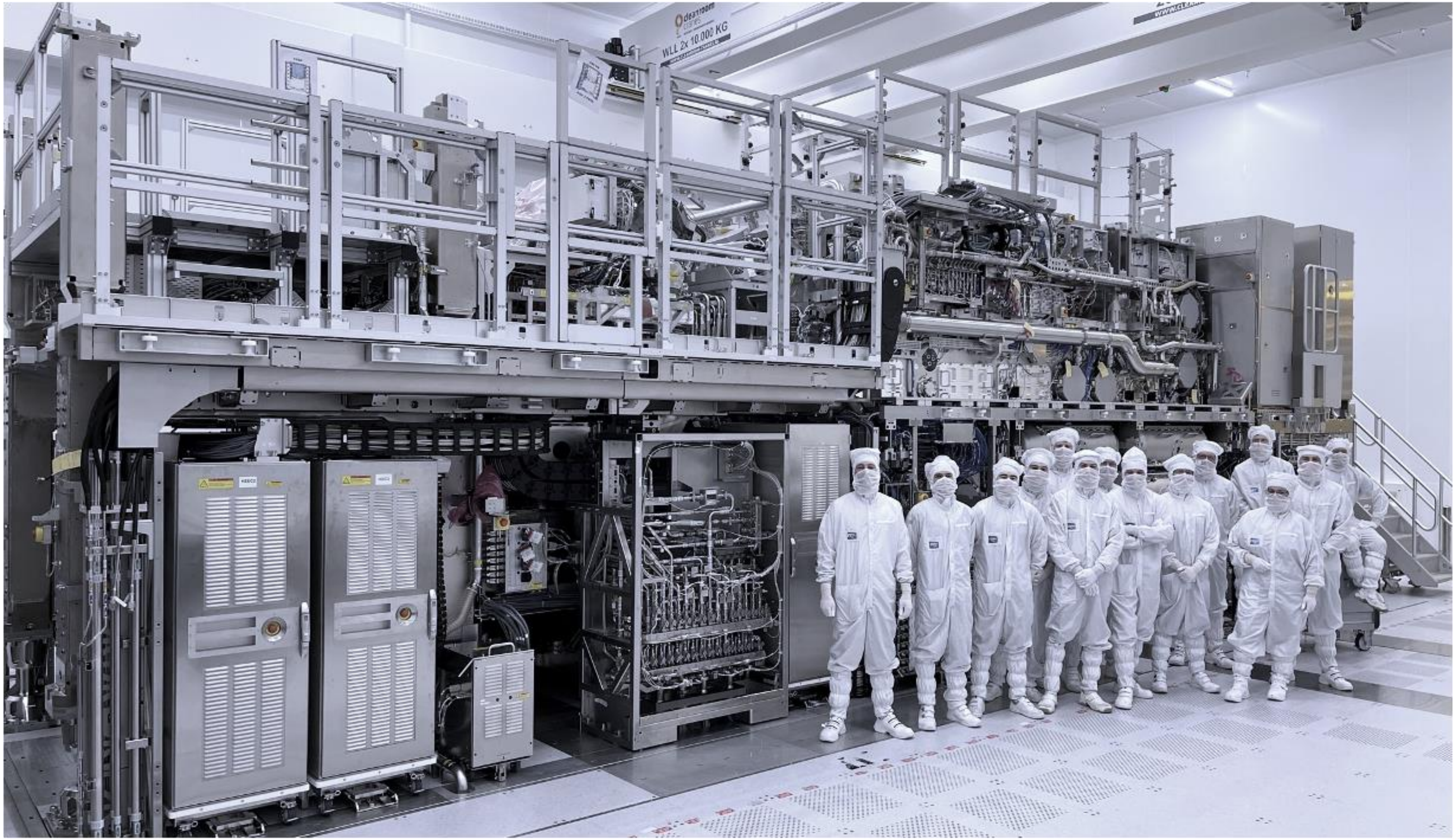
Unloading Top Module at Luxembourg airport



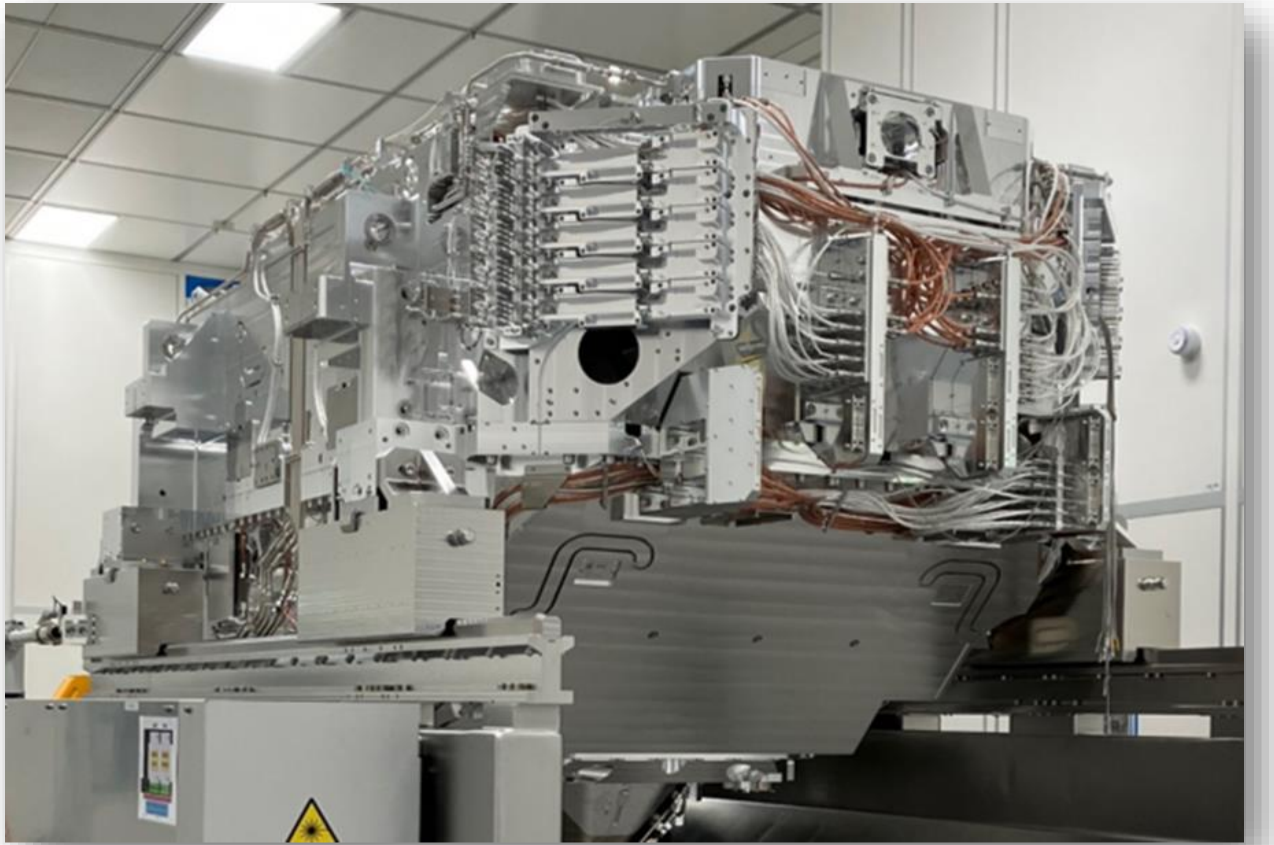

Unicom
REMA
Wafer Handling
REMA
Source DG
Wafer Stage Move-in
Wafer Handling
Reticle Handling
Reticle Stage
Source
Optics
POB mirror
Transport of heavy modules
Wafer Stage

First EXE:5000 system completely build

Wafer, Reticle, Source and Optics Main Modules installed, and first EXE:5000 built

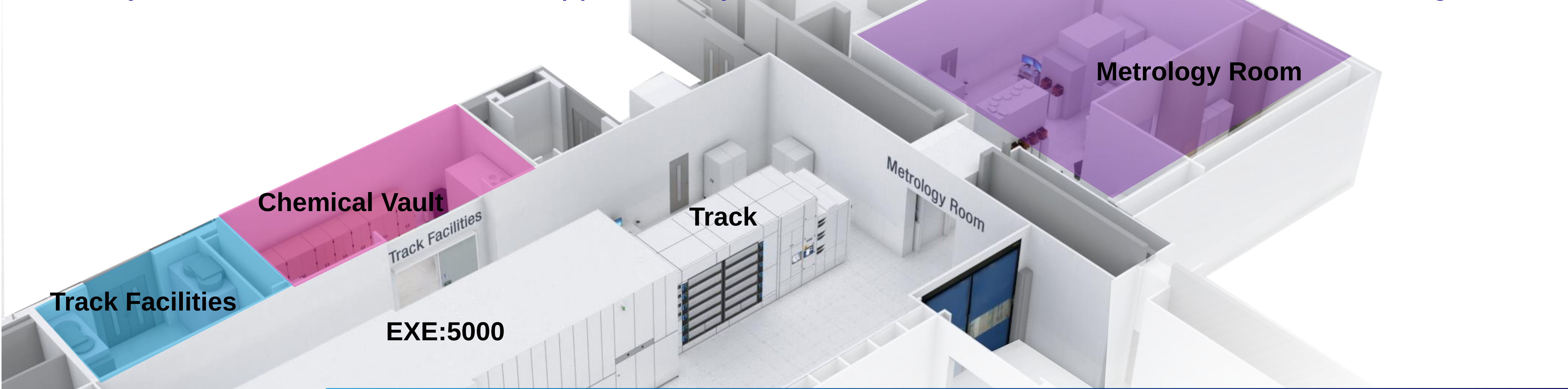


1st Sharp Illuminator and iPOB being shipped to Veldhoven!

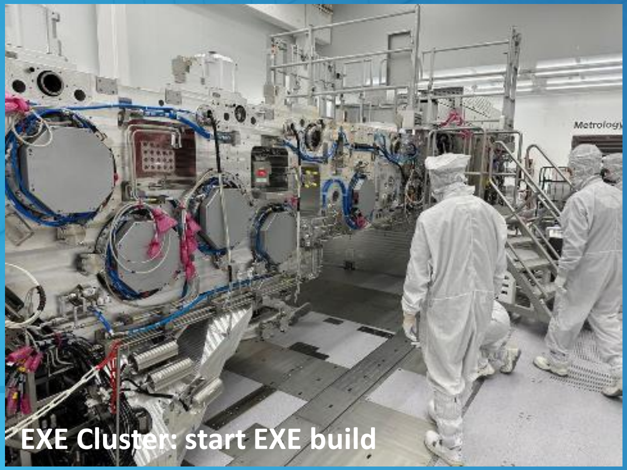


High NA Lab offers customer access for early process development

Ready to receive customers and suppliers early 2024; EXE:5000 install started towards first image



Progress High NA Lab



EXE Cluster: start EXE build

Metrology: HMI installed

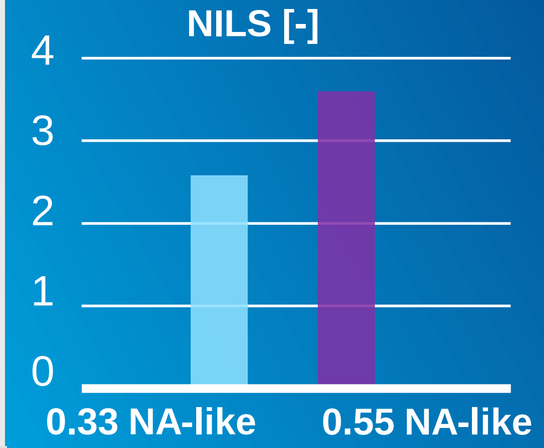
Facilities: BX100 installed

Experimental verification on 0.5NA MET5 shows 28% LCDU reduction

with High NA-like settings compared to 0.33NA-like settings

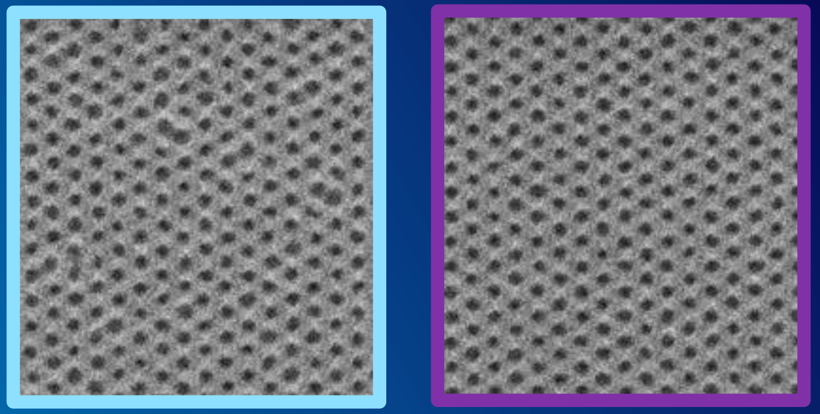
In-resist data	0.33NA		0.55NA
Dose (mJ/cm^2)	63.0	-9%	57.5
CD (nm)	15.8		15.6
LCDU (nm)	4.36	-28%	3.15
Defect (SEM FOV)	7		0

High NA contrast on LCDU performance for 16 nm half pitch hexagonal CHs



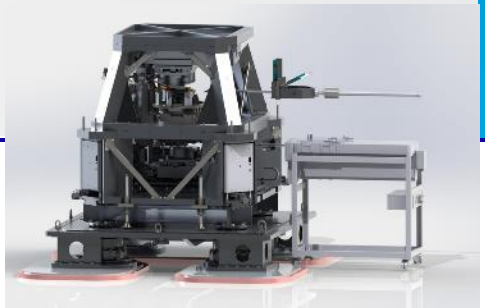
0.33NA-like

High NA-like



CAR resist

CAR resist



MET5
Advanced Light Source
Lawrence Berkeley National Laboratory

ASML

Potential reticle roadmap towards 0.55NA and beyond

All aspects of mask stack (absorber, cap and ML) being considered

Timing	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Half Pitch L/S / CH		13/ 18		11 / 16		10 / 14		9 / 12.5		8 / 11.5

POR

- POR

Low-n at optimized thicknesses for M3D phase optimization

- 46nm Low-n absorber, MoSi ML
- 56nm - V L/S
- 49nm CHs
- ~40nm Low-n, mid-k

Optimized Cap technology for minimum variability through M3D intensity

- POR – Ru (3.5nm)
- Improved cap, Reduced intermixing, improved OLT, compatibility low-n absorber etch

Optimum multilayer for minimum variability and optimized M3D intensity effects

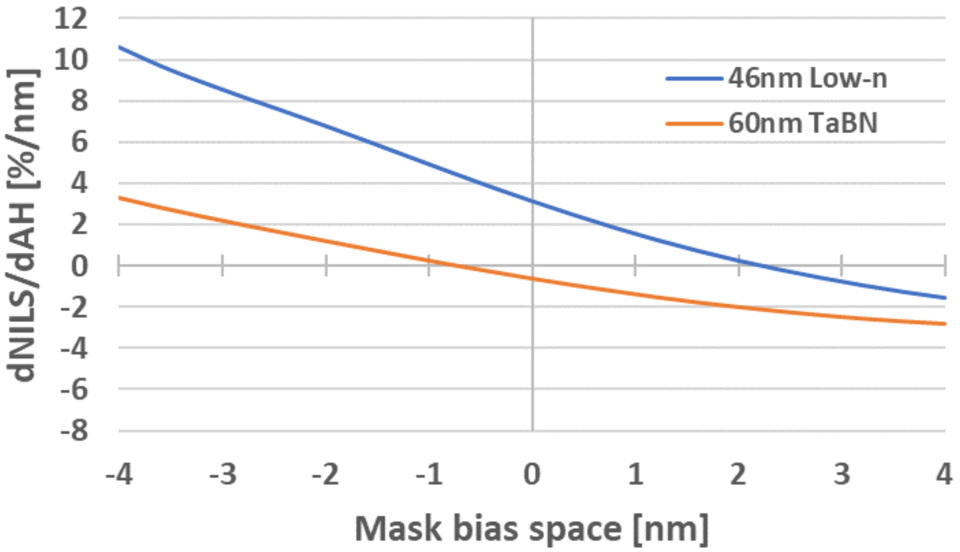
- Alternative ML, reduced Zeff and M3D (nTC), improved full band EUVR

Claire van Lare et al., Masks for optimized imaging with High-NA EUVL (P11)

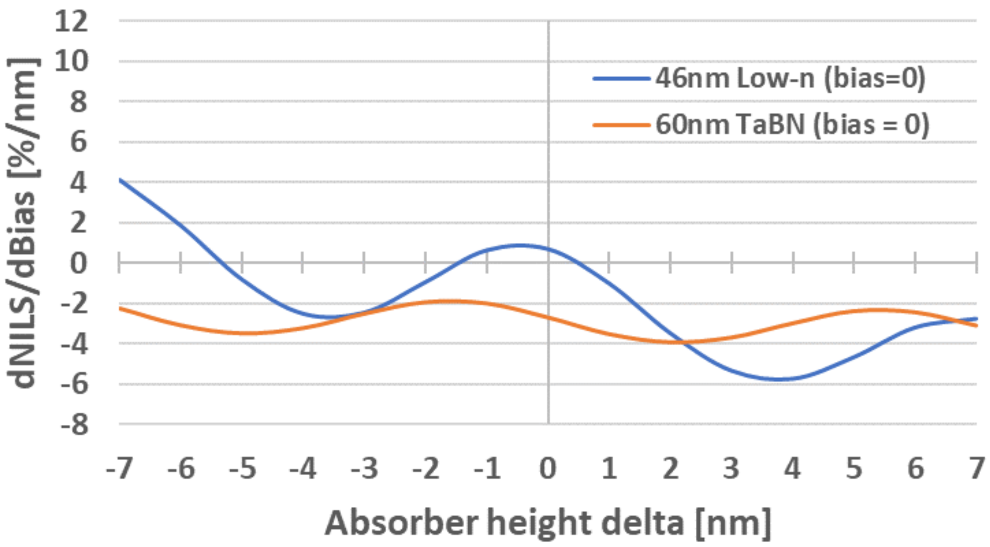
Low-n mask shows ~ 2x-3x higher sensitivity to mask making errors

0.33NA P28V L/S

NILS sensitivity for absorber height



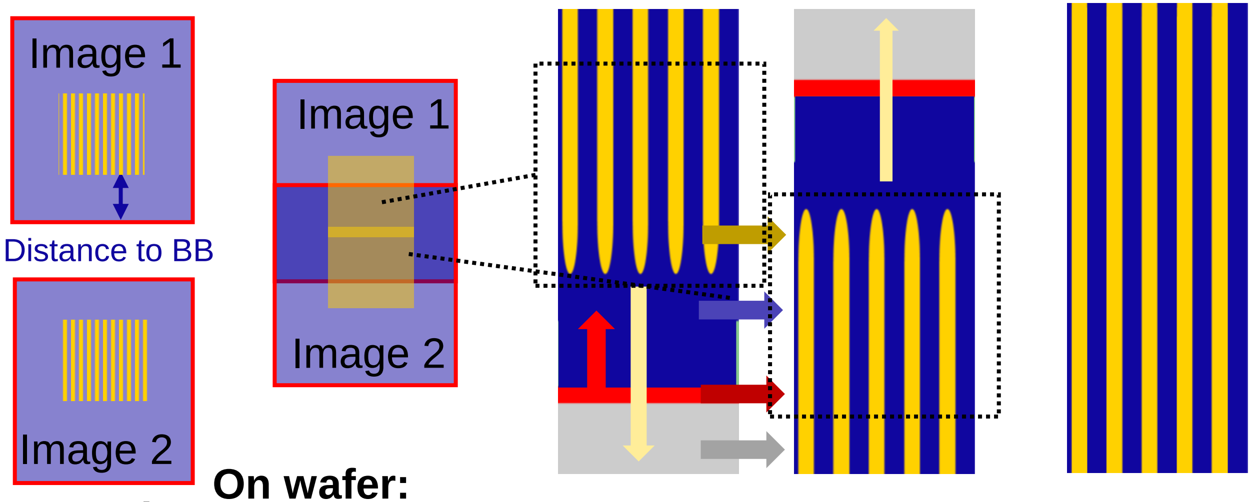
NILS sensitivity for mask bias



- Low-n mask requires tighter control of absorber height and CD writing errors to prevent contrast loss

We need to consider additional field-to-field interactions to create connection between High NA fields in the same layer

Stitching (with electrical connection)



On mask

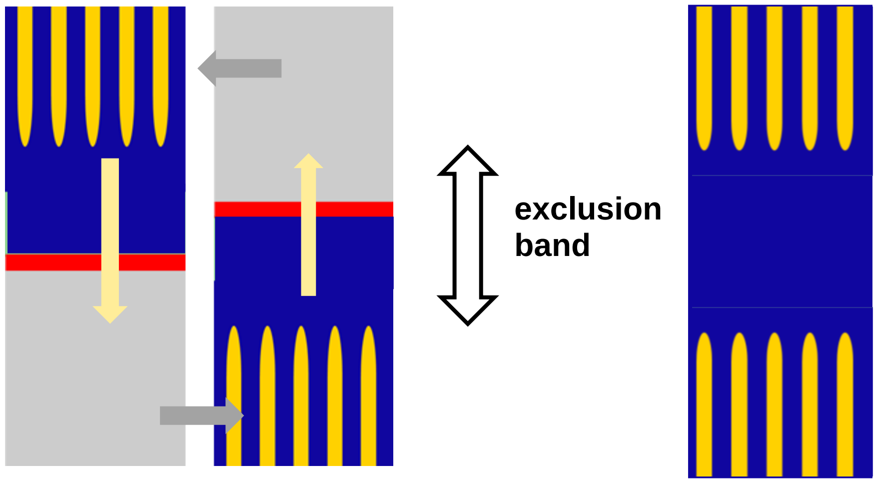
On wafer:
Image overlap

Main interactions in stitching areas:

- Aerial image interaction
- Absorber (Abs) reflection
- Abs to BB transition
- BB accuracy / vicinity
- BB reflection
- Field to field flare

No connection or 0.33 NA

(or structures further away from stitching)



Main interactions in stitching areas:

- Black border reflection
- Field to field flare

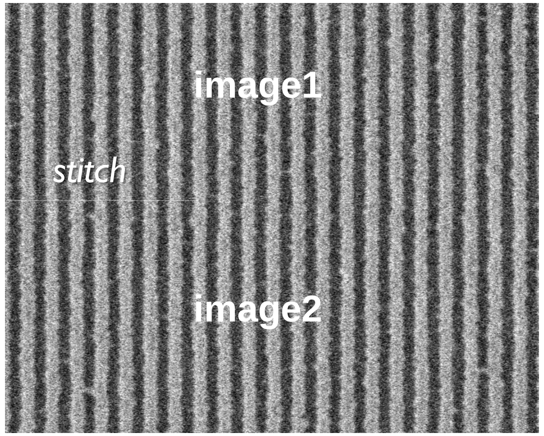
These interactions will not be discussed here. See earlier publications:

V. Wiaux et al. Stitching enablement for anamorphic imaging: a ~1µm exclusion band and its implications. EUVL, 2020

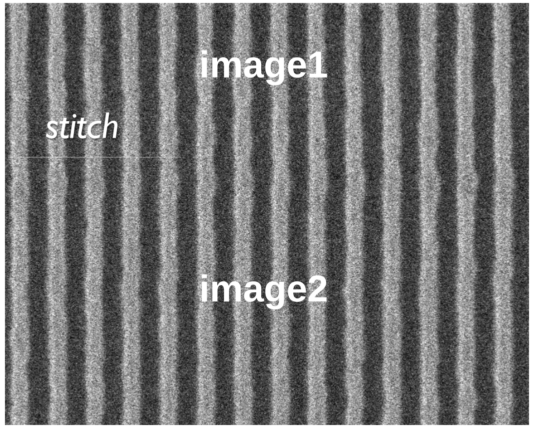
N. Davydova et al. Impact of an etched EUV mask black border on imaging and overlay. BACUS, 2012

At resolution stitching is demonstrated on NXE:3400 at imec

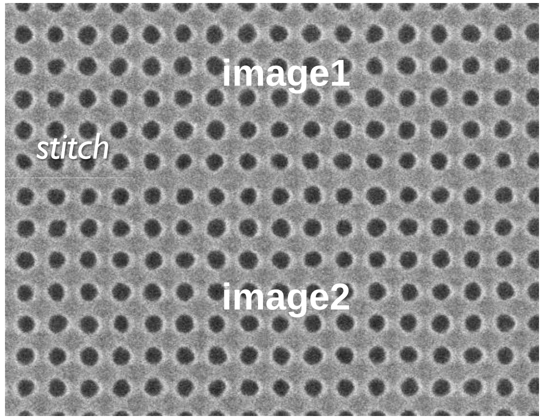
Increased CDU and local CD variation at stitching → further evaluation ongoing



Lines / Spaces P24

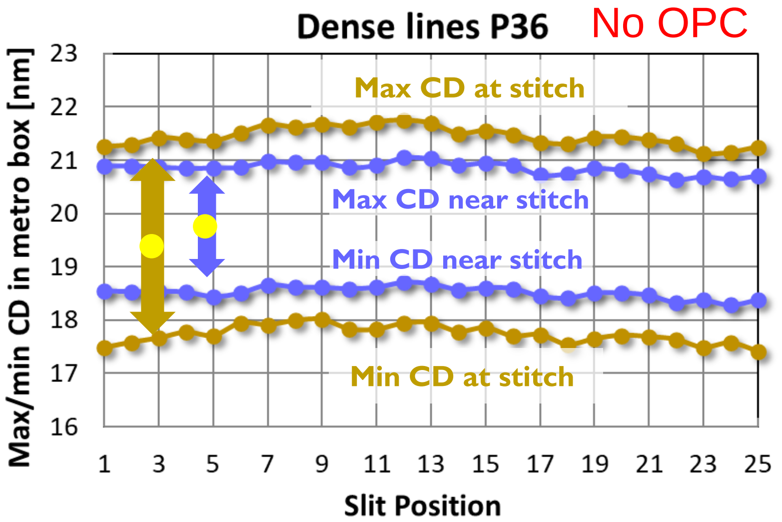


Lines / Spaces P36

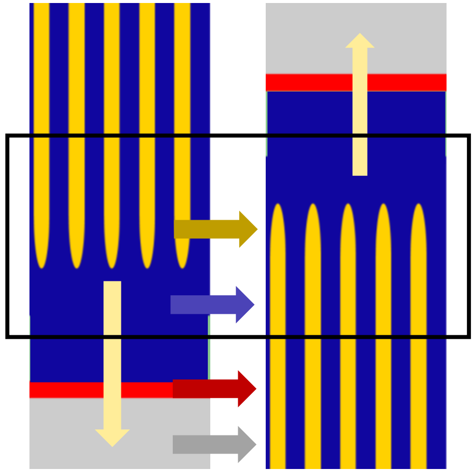


Contact Holes P48

Local CD variation band through slit at / near stitching



Mask / OPC / scanner vendors collaboration is required to enable in-die stitching



Main interactions in stitching areas:

- Aerial image cross-talk
- Absorber reflection
- Abs to BB transition
- Black border reflection
- Field to field flare

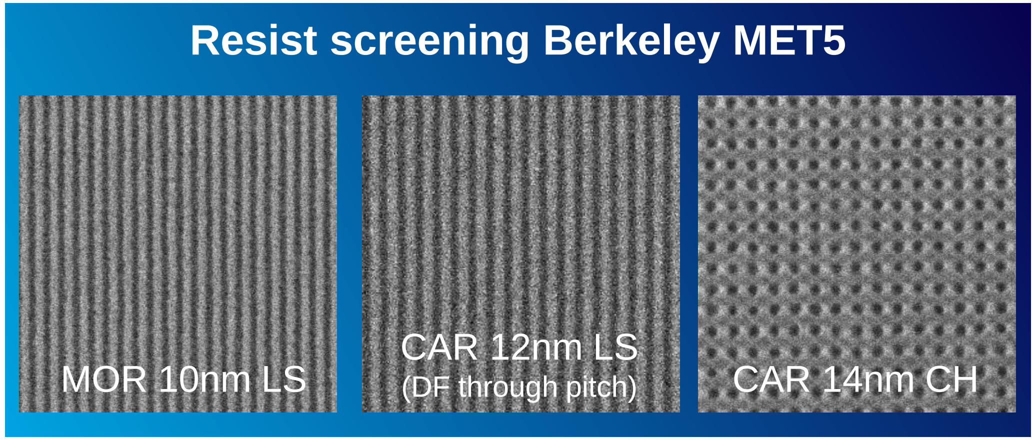
Key items to enable in-die stitching
OPC: Aerial image cross-talk modeling and OPC strategy
OPC / RET: Absorber reflectivity control for low-n mask
Mask: Black Border (BB) edge placement control and BB / absorber transition
Mask: improved resolution and line end control

EXE:5000 process selection towards scanner qualification

Baseline resists identified - Screening continues to further improve performance

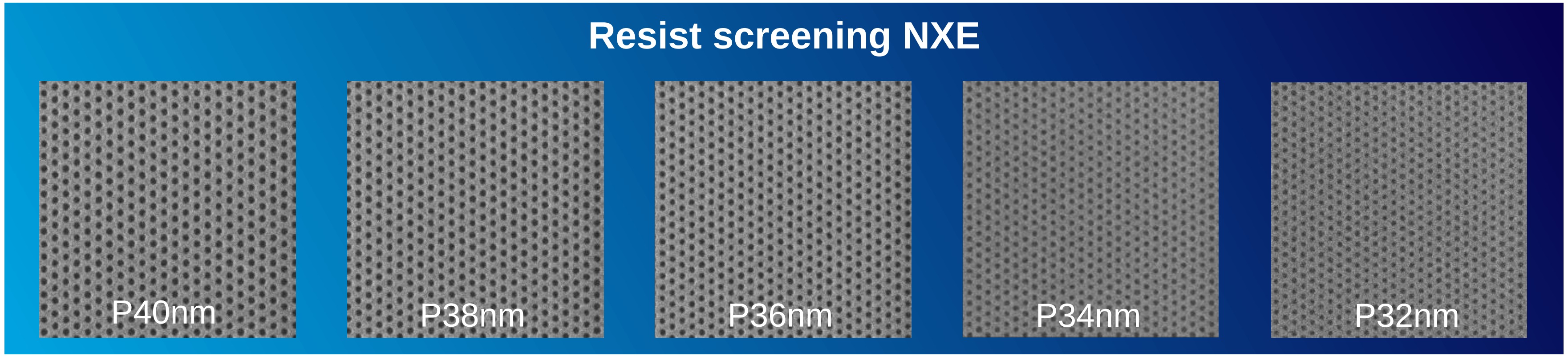
Resist selection for scanner qualification done on BMET5:

- Resolution beyond NXE capabilities
- 0.5 NA projection lithography tool
- Matched illumination settings



Baseline resists are optimized on NXE with dedicated pupils and full track capability:

- 10nm DL by assessing 12nm DL
- 14nm CH by assessing 16nm CH



EUV product roadmap

Wavelength | NA, Half pitch | 2022 | 2023 | 2024 | 2025 | 2026 | ≥ 2027

EUV

0.55NA, 8 nm

- **EXE:5000** 1.1 nm | 150 wph
- **EXE:5200B** <0.8 nm | 220 wph
  - EXE:5000 OFP&PEP <0.8 nm | 190 wph
- **NEXT**
- **Customer R&D** – High NA Lab for 0.55NA access at ASML
- **High Volume Manufacturing**

0.33 N

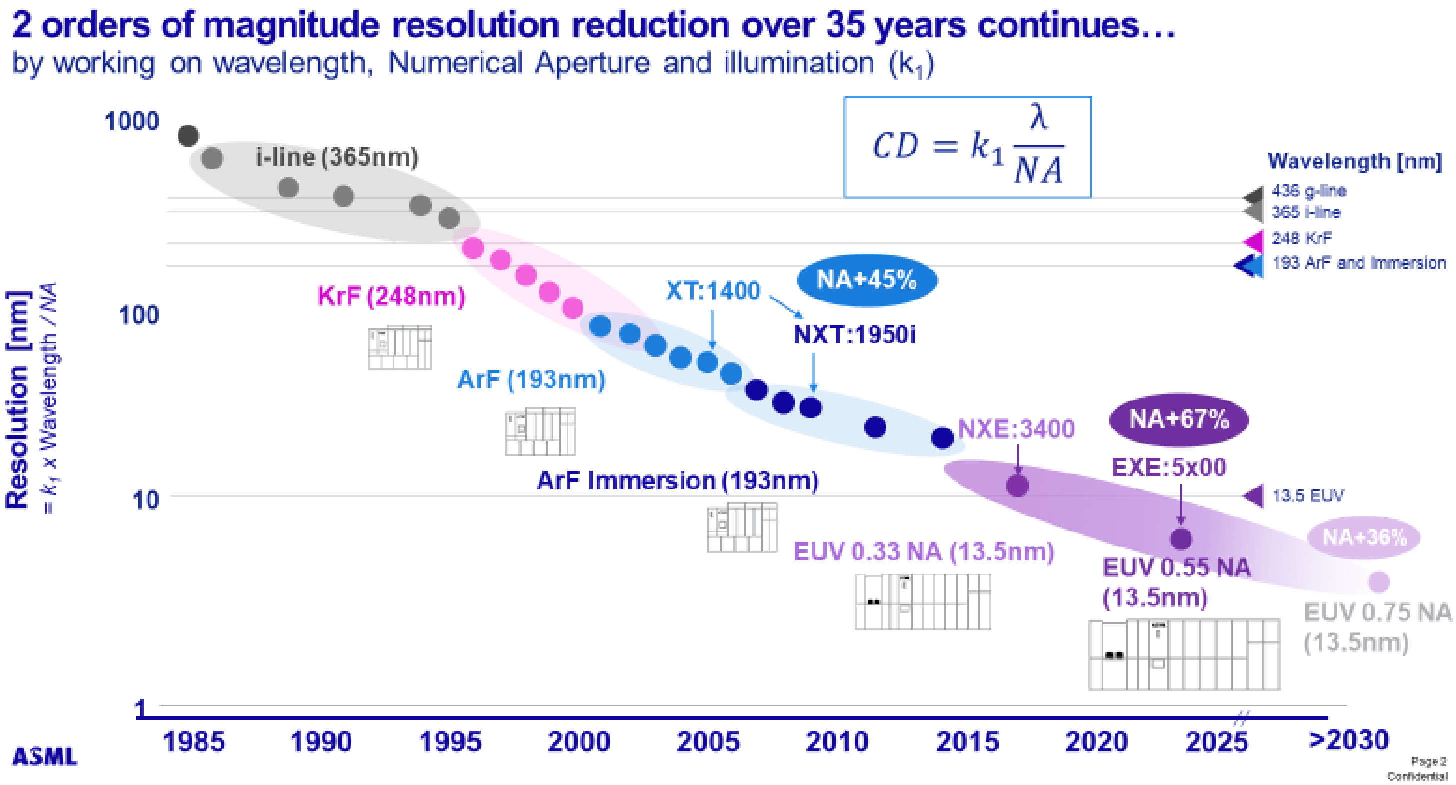
- **NXE:3600D** 1.1 nm | 160 wph
  - Alignment 12C option
- **NXE:3800E** 0.9 nm | 220 wph
- **NXE:4000F** <0.8 nm | 250 wph
- **NEXT**
- **3400C** – PEP 145 wph – PEP 160 wph

Product	Matched Machine Overlay (nm) | Throughput(wph)		
Product status	Released	Development	Definition

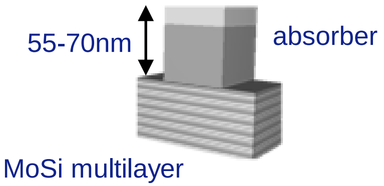
ASML

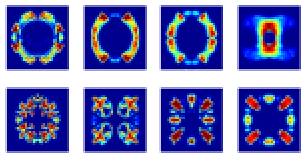
Public

What are the next steps?

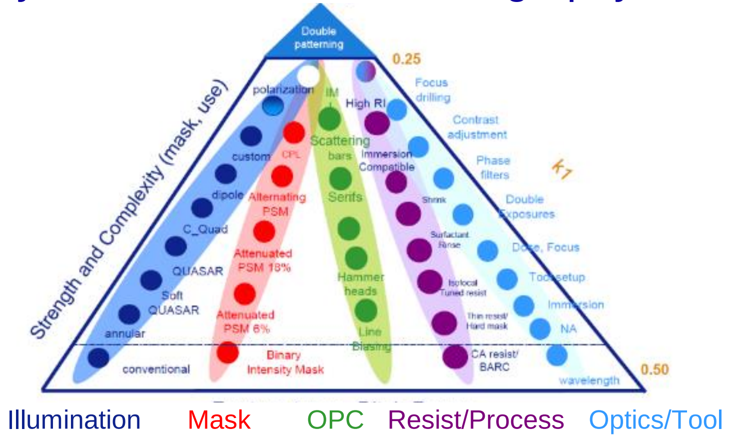


- Next to productivity and overlay, we keep pushing the envelope to improve on imaging essentially as we did in KrF and ArF
- New challenges are M3D, stochastics

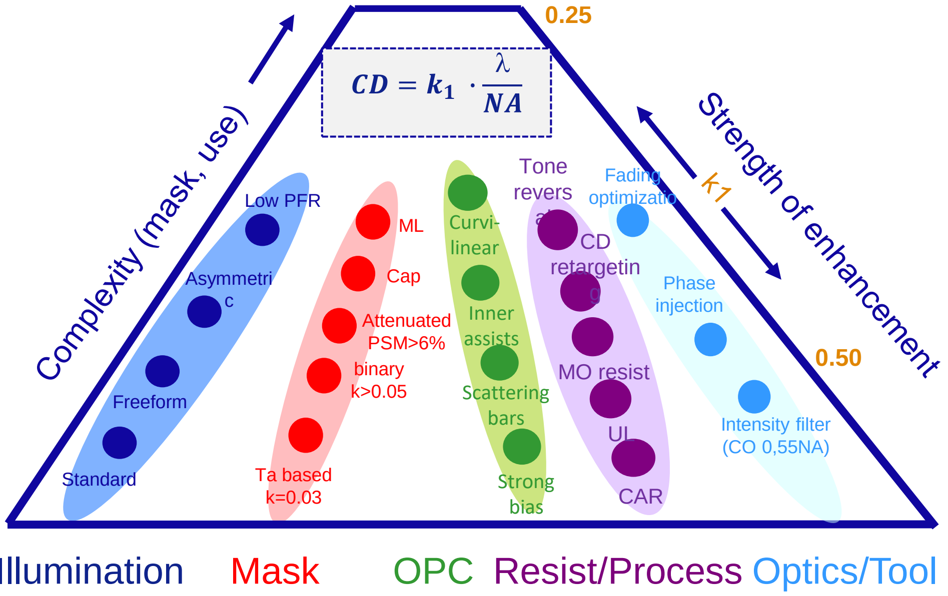




Low k_1 pyramid for immersion lithography



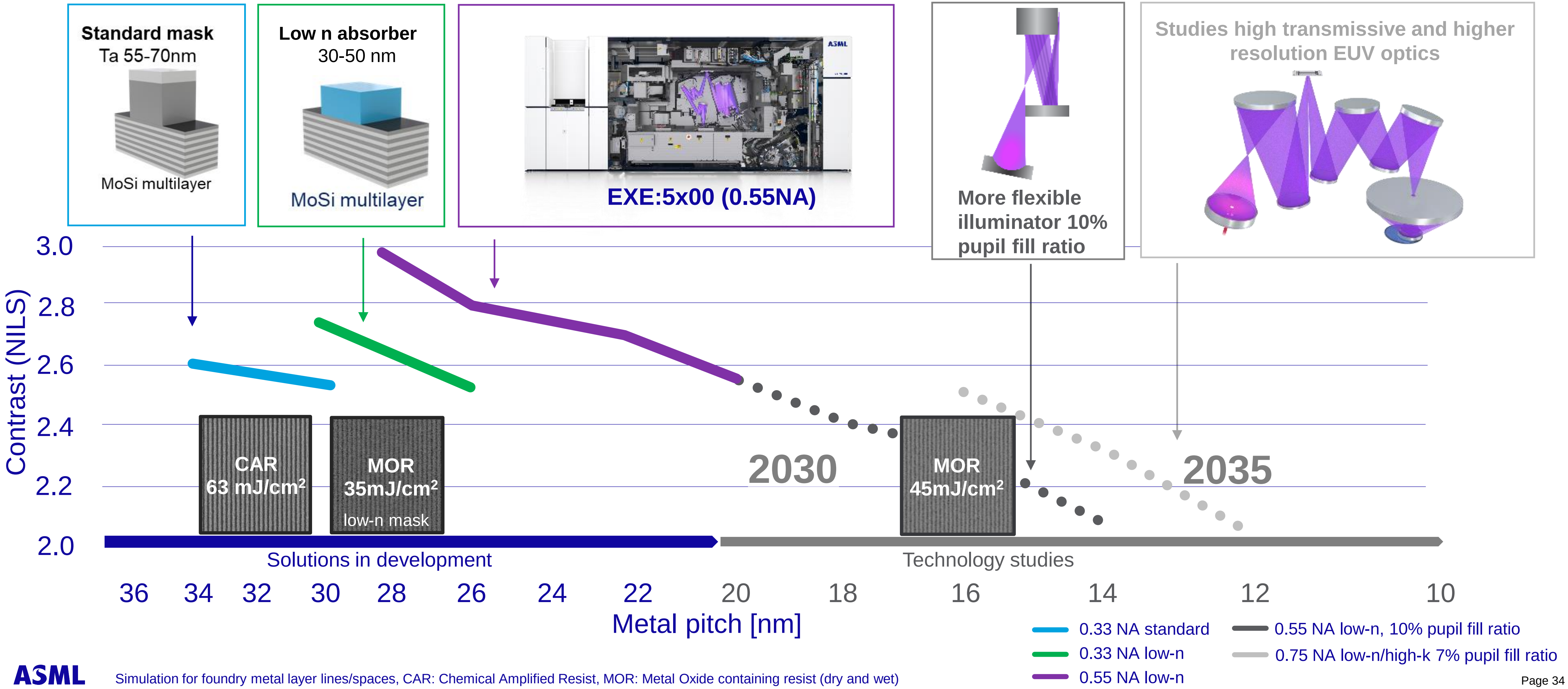
Low k_1 pyramid for EUV lithography



Pyramids by Jo Finders/Eelco van Setten, ASML

The EUV scanner roadmap maintains image contrast for future nodes

Low n mask absorber, improved resist, higher NA optics and more flex illuminator with low pupil fill



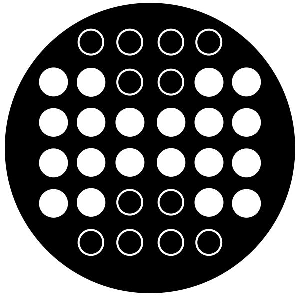
Simulation for foundry metal layer lines/spaces, CAR: Chemical Amplified Resist, MOR: Metal Oxide containing resist (dry and wet)

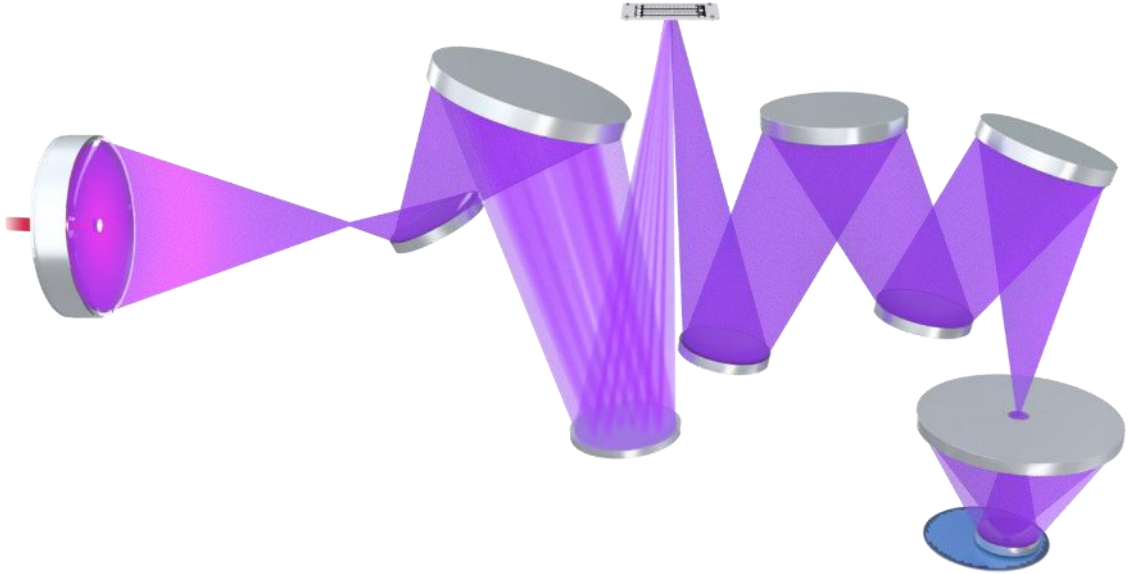
High-Transmission / high-flexibility Illumination for EUV extention[1]

Enabling low-k1 imaging at high productivity

Current 0.55 NA

Pupil Fill Ratio >20%

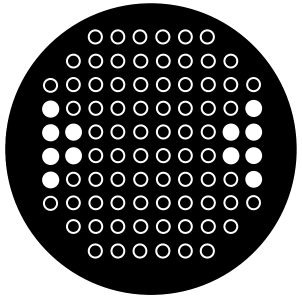


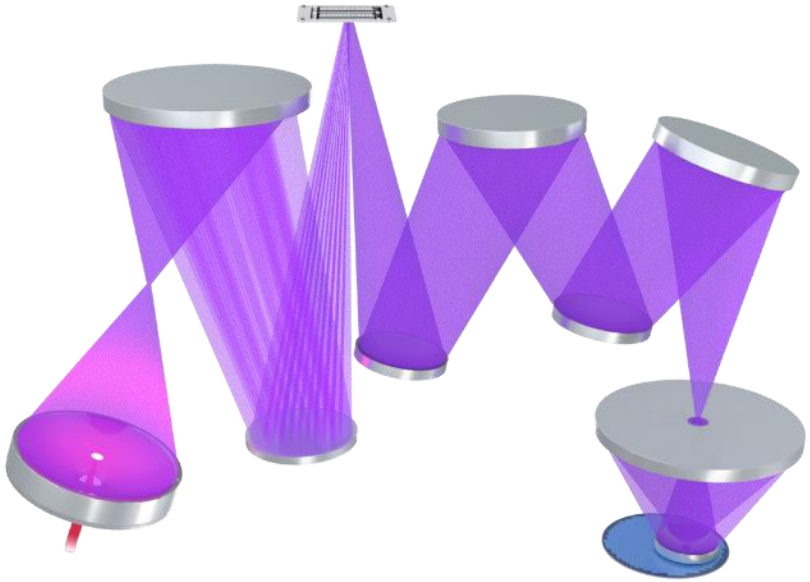


New concept

0.55 NA evolution

Pupil Fill Ratio >10%, increase transmission by removing 1 mirror



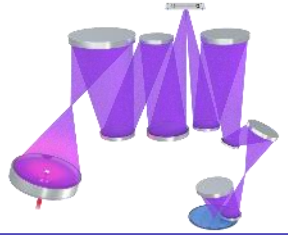
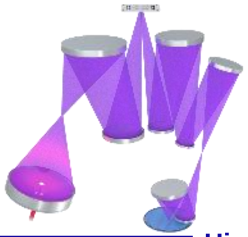
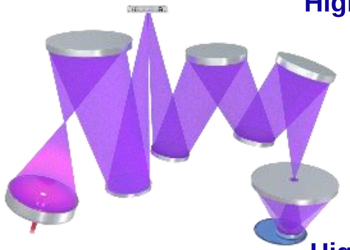
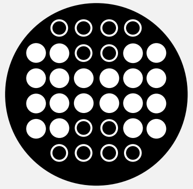
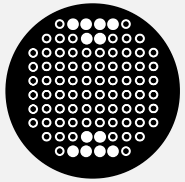


[1] In cooperation with Car Zeiss SMT

Public

EUV common platform strategy and extend portfolio with EUV >0.75 NA[1]

Moving all EUV products to a cost-effective common platform further rationalizing manufacturing

Metrology/production		in ambient/as is	in vacuum/as is	In vacuum/Production rationalization
No pupil obscuration	0.33			 High transmission 0.33 NA
Pupil obscuration to limit angular angles	0.55			 High transmission 0.55 NA
	> 0.75			 Hyper NA
Illuminator		Pupil Fill Ratio >20%		High flexibility, High transmission Illumination Pupil Fill Ratio ~10% 

[1] In cooperation with Car Zeiss SMT

Summary

High NA is an evolutionary step for EUV technology with new optics

- Enabling a significant step on the lithography roadmap by improving contrast and resolution
- All 0.33 NA customers are committed to High NA, and publicly announced High NA adoption

High NA EUV Scanner realization is in full progress

- Good progress on all main modules integration towards full system built, to support High NA ramp in 2024
- High NA platform commonality is maximized with EUV 0.33NA to reduce introduction risk and improve platform maturity

ECO system

- Further ECO-system improvements required. Good overlay performance full field to half field
- Progress on mask and resist supports lithography extension and continues to provide both improved contrast and productivity. Low-n close to HVM adoption
- At resolution stitching demonstrated. Further development needed, low-n under study

High NA Lab

- High NA lab enables customer early access for process development
- On track to start High NA Lab with EXE:5000 access early 2024

What's next

- Investigating continuation of the EUV roadmap

Special thanks goes to:

- Jara Garcia Santaclara
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- Rudy Peeters
- Diederik de Bruin
- Christophe Smeets

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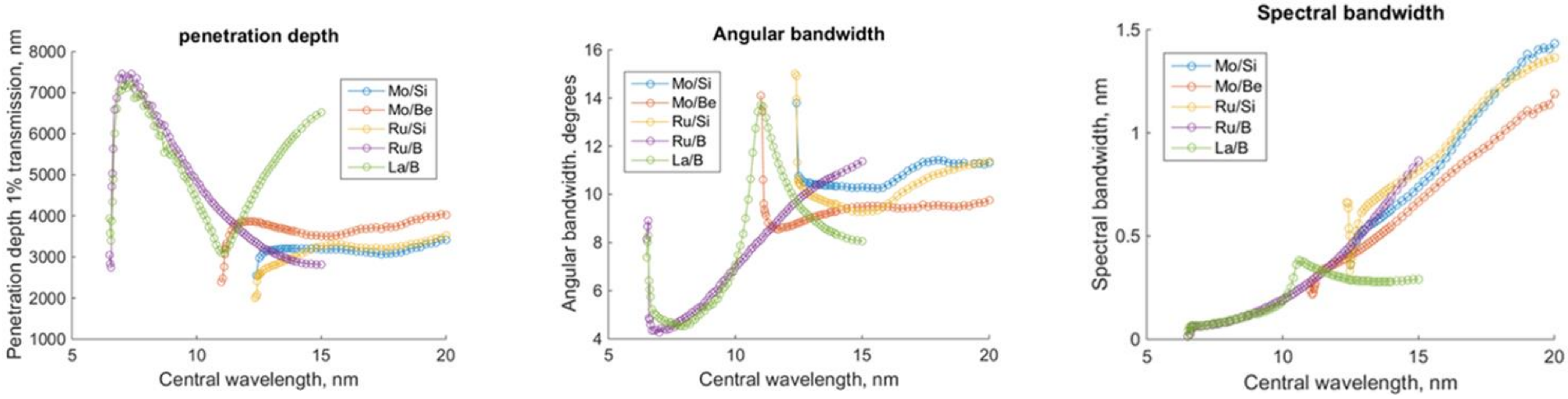
Why is 13.x nm a good choice

- Down to 13nm smaller wavelength enables resolution at acceptable Depth of Focus (DoF)

$$\boldsymbol{R} = k_1 \frac{\boldsymbol{\lambda}}{NA} \qquad \boldsymbol{DOF} = k_2 \frac{\lambda}{NA^2} = \frac{k_2}{k_1^{\,2}} \frac{R^2}{\boldsymbol{\lambda}}$$

- However, below 13nm the larger penetration depth of light leads to decreased spectral bandwidth (limits source power) as well as angular bandwidth (an issue for optics design leading to larger optics and mask leading to increased demag => smaller field size).



Source: A. A. Zameshin∗, A. E. Yakshin, A. Chandrasekaran, and F. Bijkerk
“Angular and Spectral Bandwidth of Extreme UV Multilayers Near Spacer Material Absorption Edges”
Journal of Nanoscience and Nanotechnology Vol. 19, 602–608, 2019