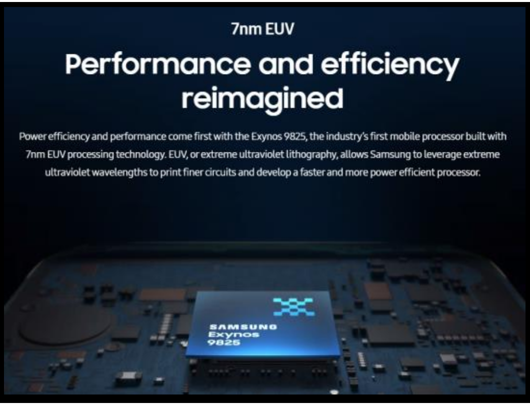
High-NA EUV Progress and Outlook

Jan van Schoot
ASML Veldhoven, The Netherlands

8 June 2021, EUVL Workshop, on-line

EUV is here: Customer flagship products are powered by EUV



7nm EUV

Performance and efficiency reimagined

Power efficiency and performance come first with the Exynos 9825, the industry's first mobile processor built with 7nm EUV processing technology. EUV, or extreme ultraviolet lithography, allows Samsung to leverage extreme ultraviolet wavelengths to print finer circuits and develop a faster and more power efficient processor.

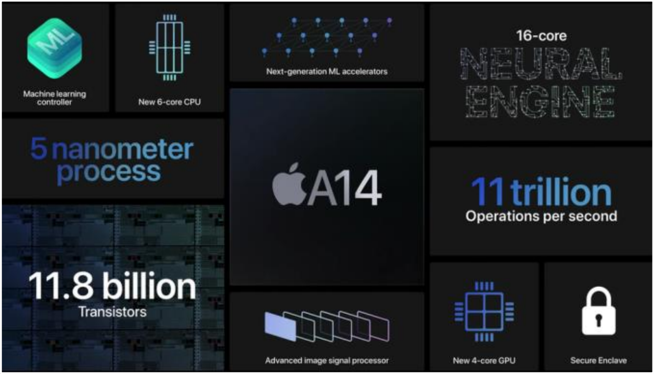
SAMSUNG

HUAWEI Kirin 990 Series[1]

Rethink Evolution

World's 1st Flagship 5G SoC powered with 7nm+ EUV[2]

HUAWEI



Source: https://www.samsung.com/semiconductor/minisite/exynos/products/mobileprocessor/exynos-9825/, https://consumer.huawei.com/en/campaign/kirin-990-series/

Outline

EUV is here: Status 0.33NA

What's next? Towards High-NA

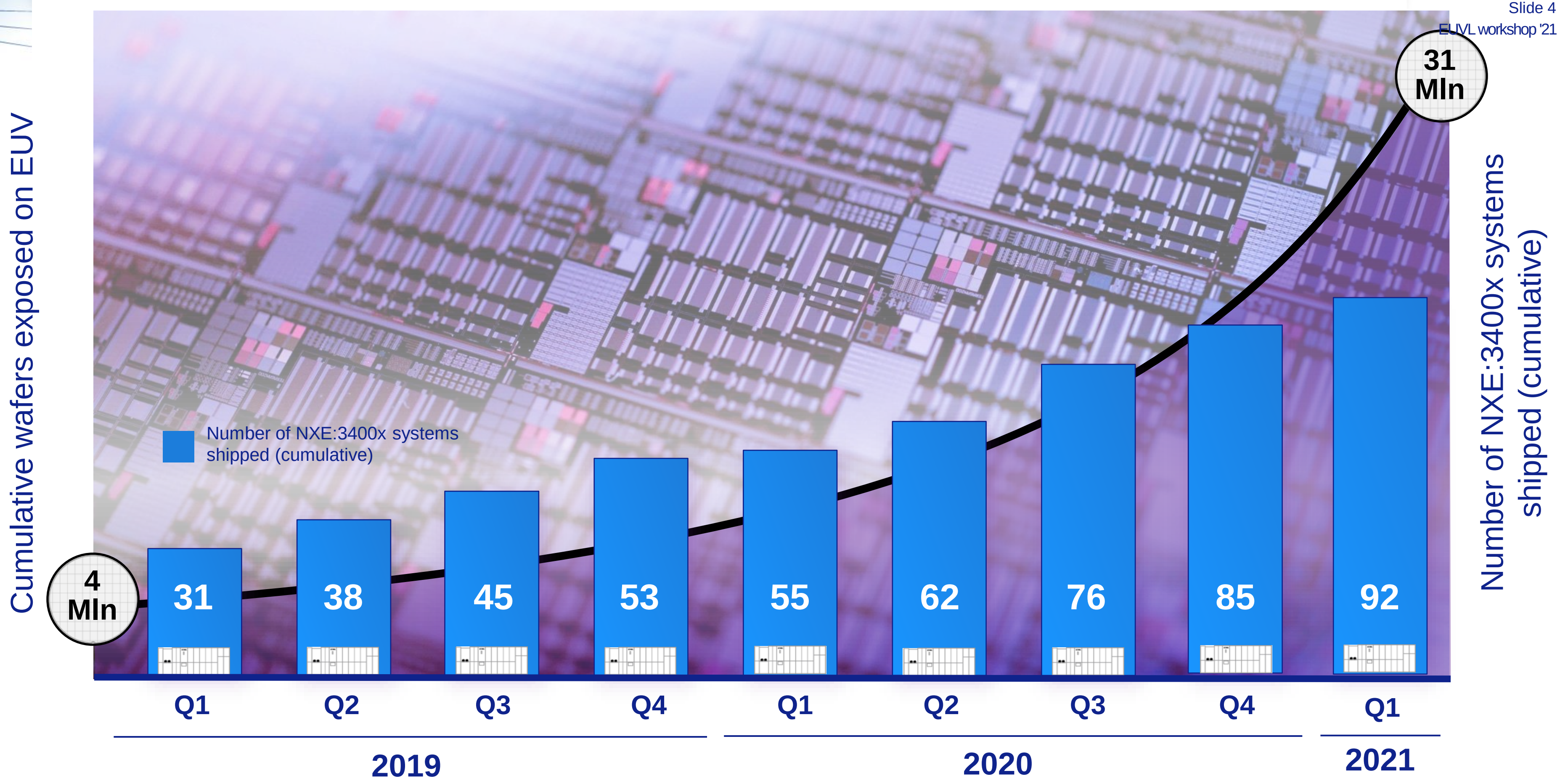
- Contrast
- Dose
- Resist

High-NA progress

- Architecture
- Industrialization

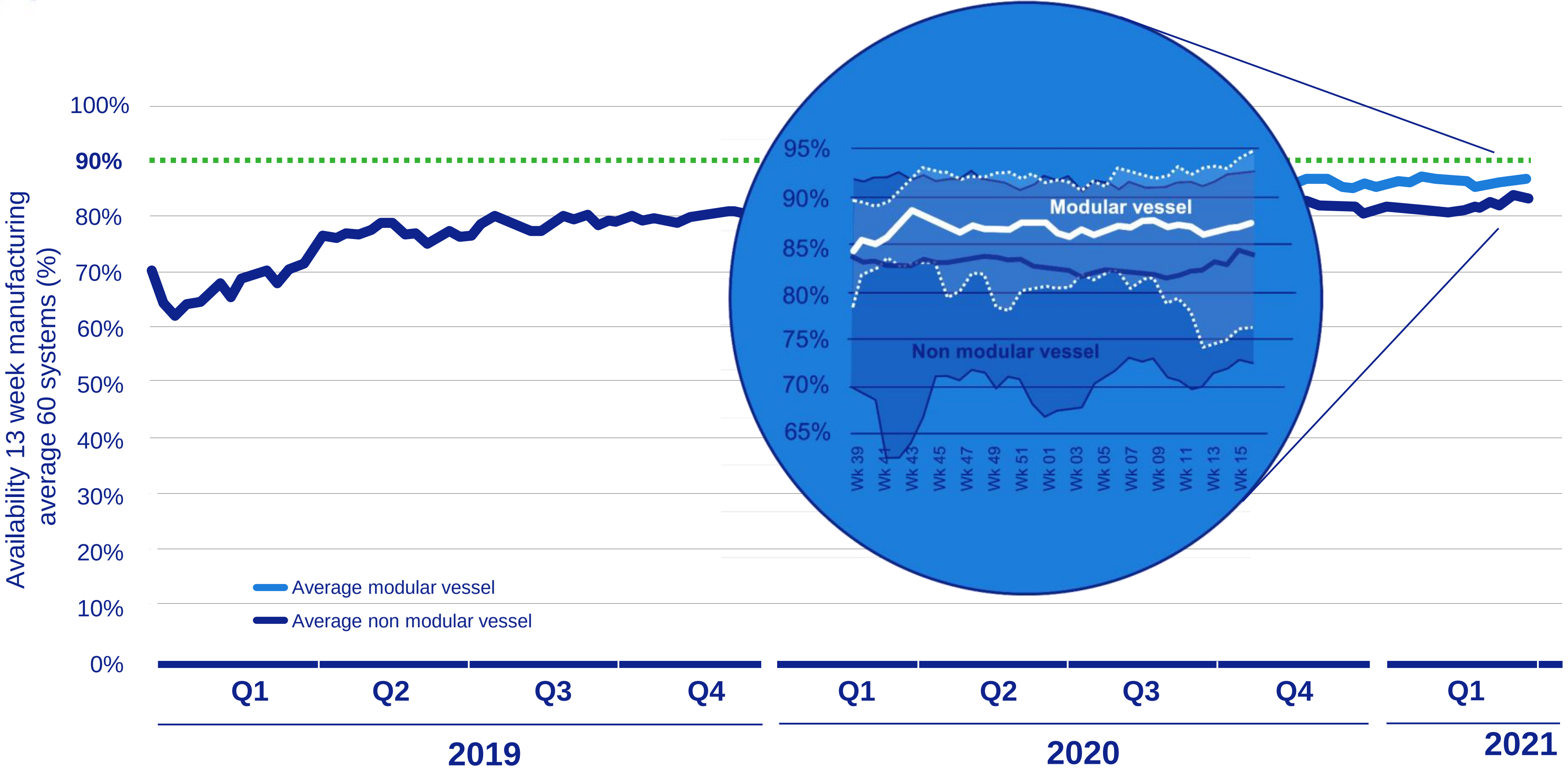
Summary

Wafers exposed on EUV systems grows rapidly



Modular vessel contributes to system availability

Improvement and variation reduction. MV up to 4% higher than GWE systems



NXE:3600D

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

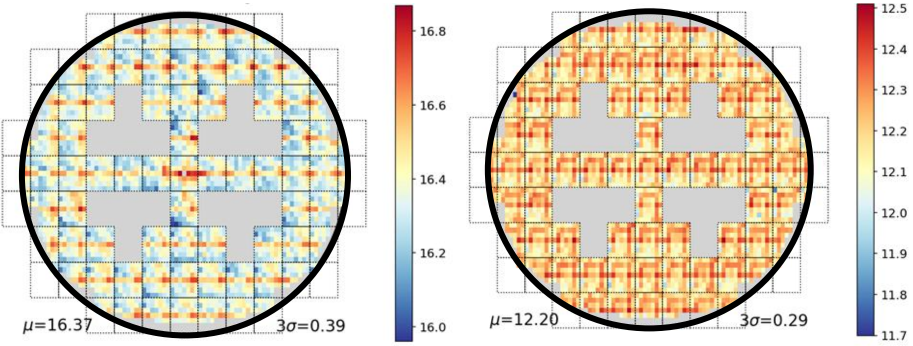
Improvements in Overlay, Imaging, Productivity achieved by, amongst others:

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

NXE:3600D imaging and overlay performance in spec

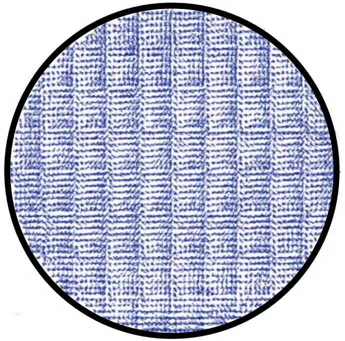
Imaging

Metric	Result	Spec
Full wafer CDU 16nm ISO	0.39 nm	0.7 nm
Full wafer CDU 13nm DL	0.29 nm	0.7 nm

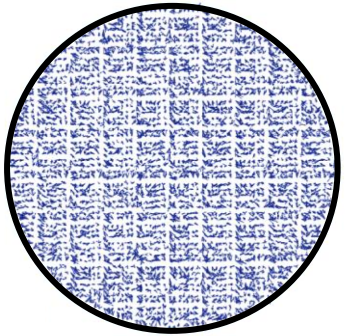


Overlay

Metric	Result	Spec
Dedicated Chuck Overlay	0.9 nm	0.9 nm
Matched Machine Overlay	1.1 nm	1.1 nm
EUV-DUV Machine Overlay* **(NXT:2050 to NXE:3600D, *33par CPE)**	0.82 nm	0.93 nm



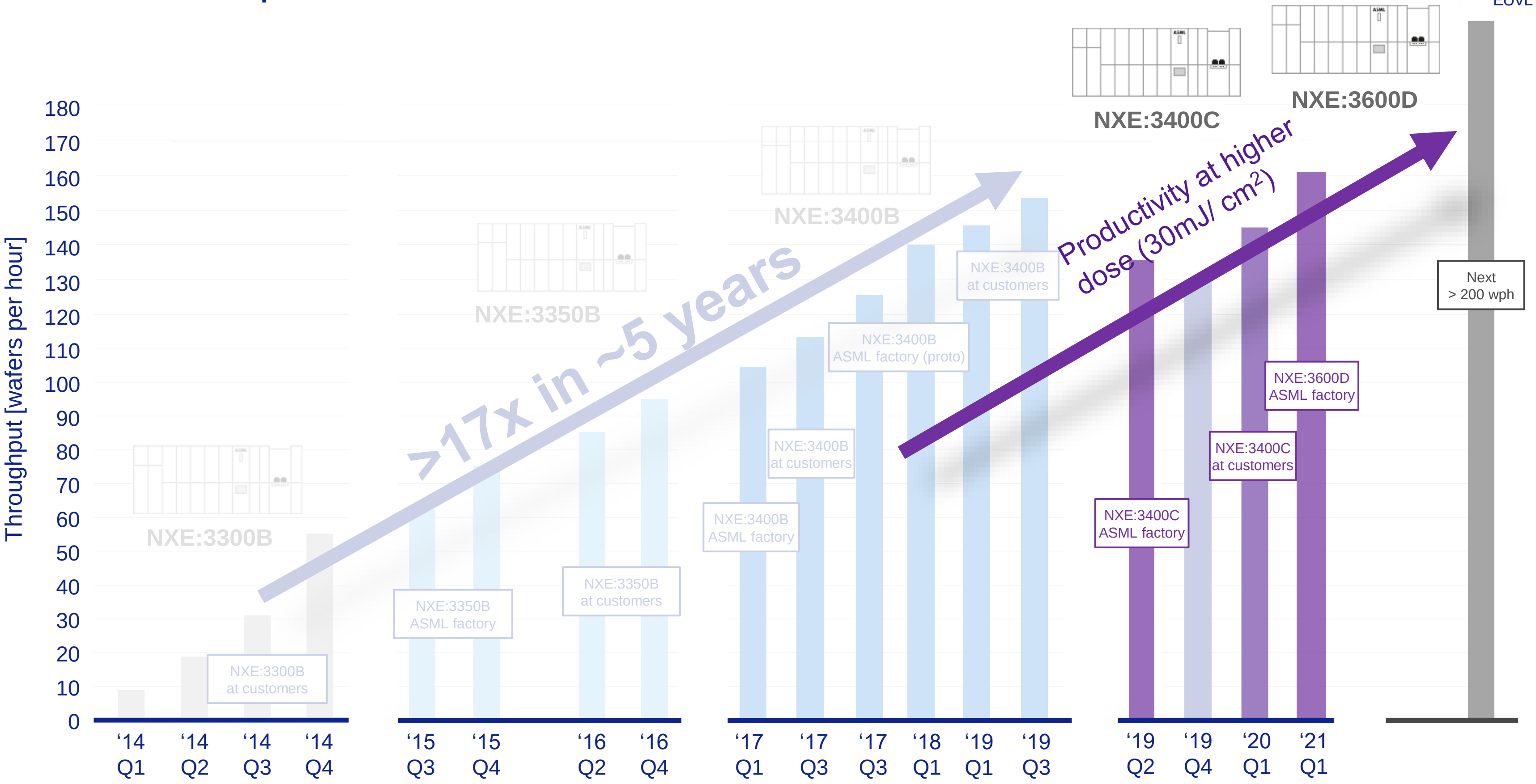
X: 0.8 nm
Y: 0.9 nm



X: 1.1 nm
Y: 1.0 nm

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

30mJ/cm^2 exposure dose



ATP test: 26x33mm^2, 96 fields, 20mJ/cm^2 / 30mJ/cm^2

Outline

EUV is here: Status 0.33NA

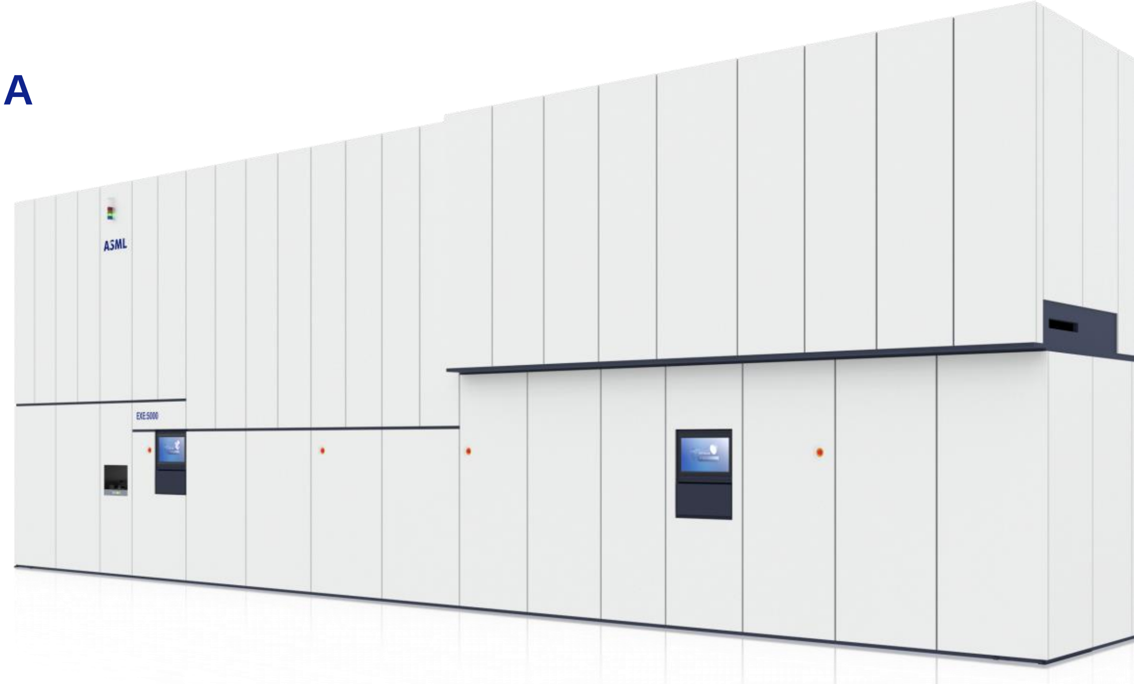
What's next? Towards High-NA

- Contrast
- Dose
- Resist

High-NA progress

- Architecture
- Industrialization

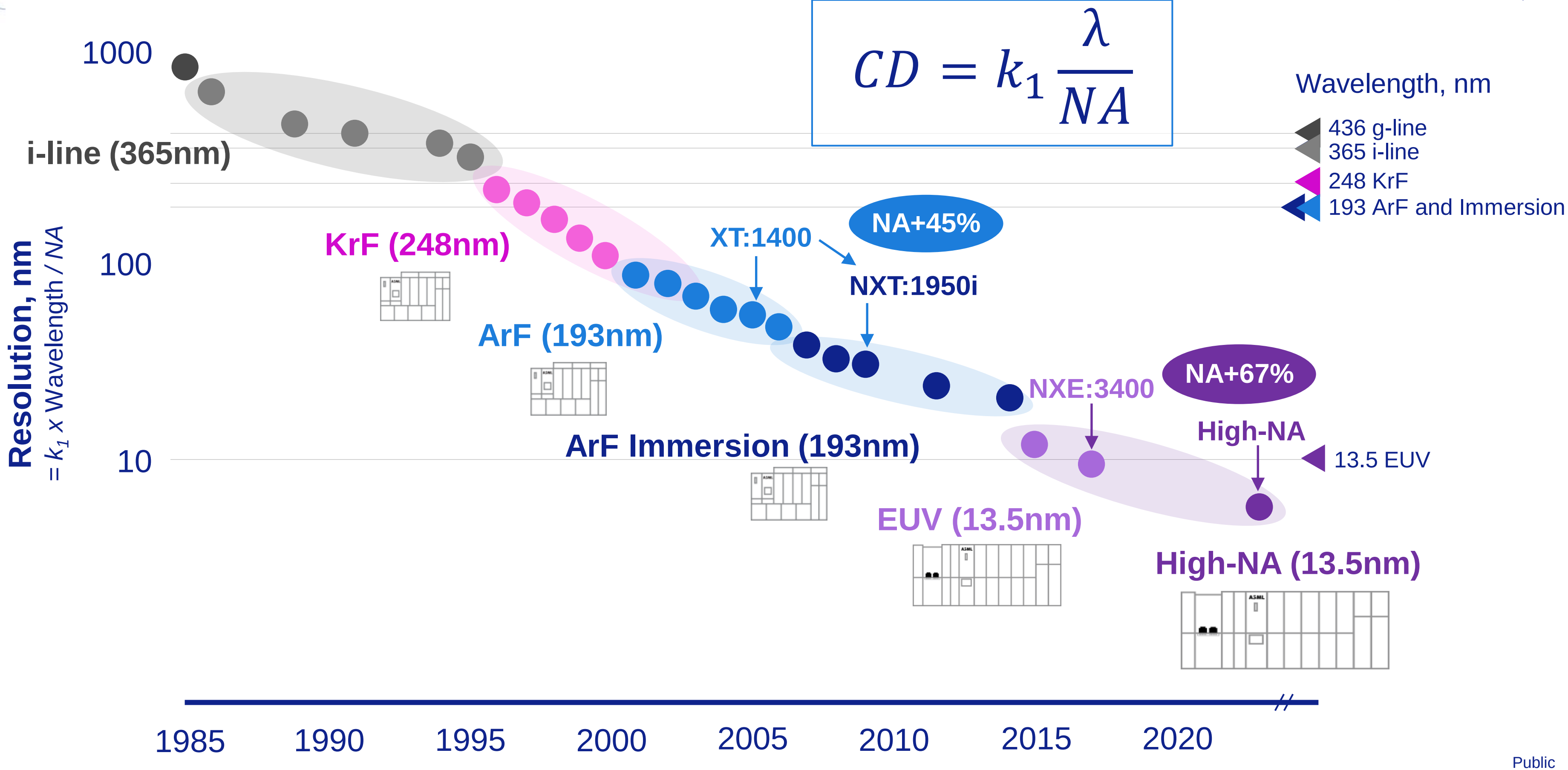
Summary



Over 35 years 2 orders of magnitude resolution reduction

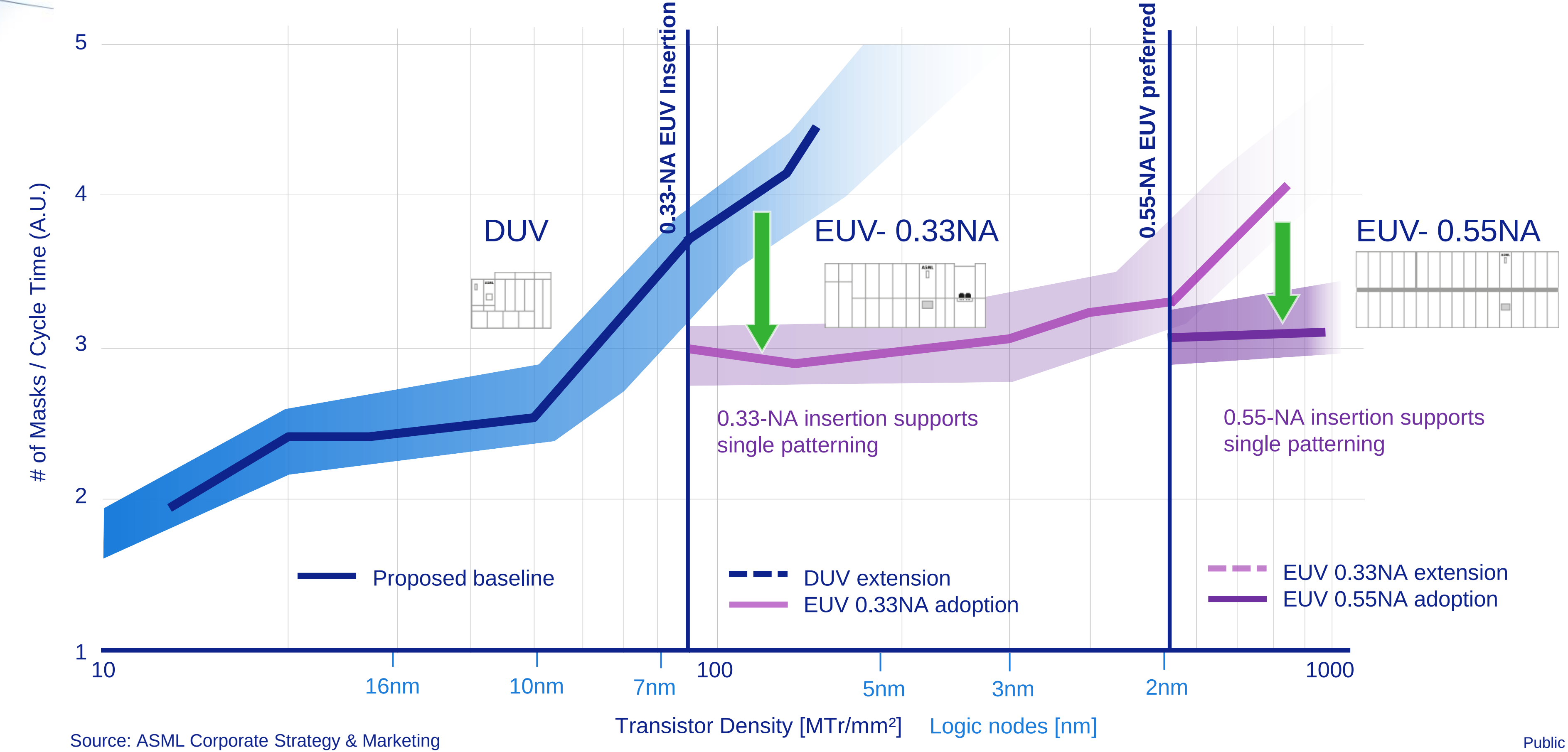
by working on Wavelength, NA and k1

$$CD = k_1 \frac{\lambda}{NA}$$



High-NA keeps number of masks and cycle time acceptable

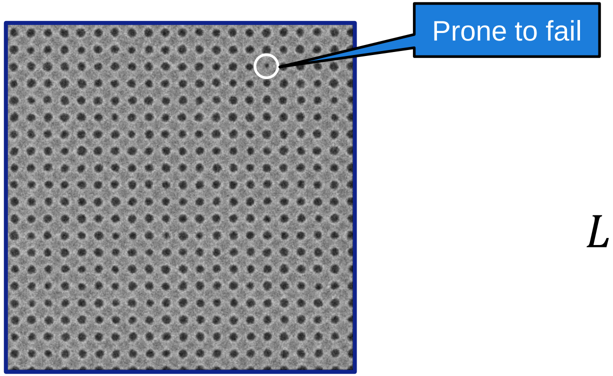
Repetition of currently ongoing adoption of EUV



Source: ASML Corporate Strategy & Marketing

High-NA EUV enables the continuation of Moore’s law

Key ingredients are Resist, Dose and Contrast



Prone to fail

Resist
(blur/chemistry)

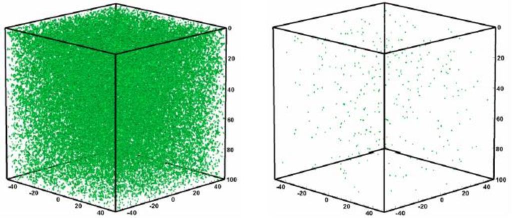
Dose

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

EUV comes with less photons/J



10nm CH, 20mJ/cm2 → 1000 photons

30% absorption → 300 photons

30% determines the edge → 100 photons

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

Outline

EUV is here: Status 0.33NA

What's next? Towards High-NA

- **Contrast**
- Dose
- Resist

High-NA progress

- Architecture
- Industrialization

Summary

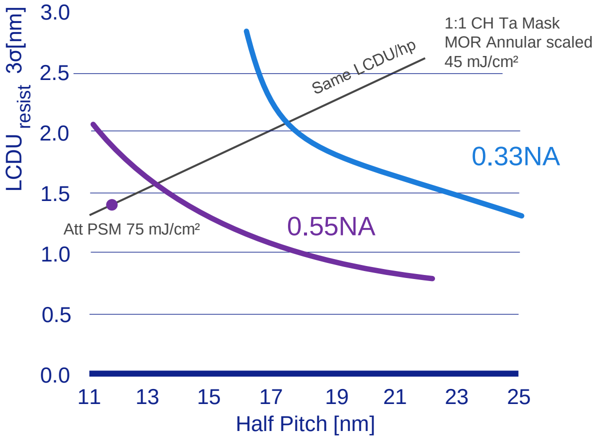
High-NA contrast reduces Local CDU and defects

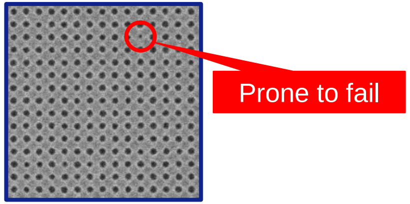
Key to continue Moore’s law: Resist, Dose, Contrast

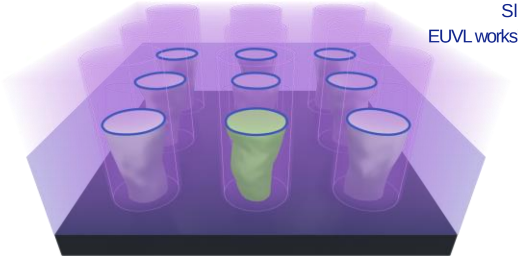
$$LCDU\,[3\sigma,nm] = 3\cdot \overset{\text{Resist}}{\boxed{\sqrt{\frac{h\nu}{f\cdot\alpha\cdot Area}}}}\cdot\overset{\text{Dose}}{\boxed{\sqrt{\frac{1}{D_0}}}}\cdot\overset{\text{Contrast}}{\boxed{\frac{2}{ILS}}}$$

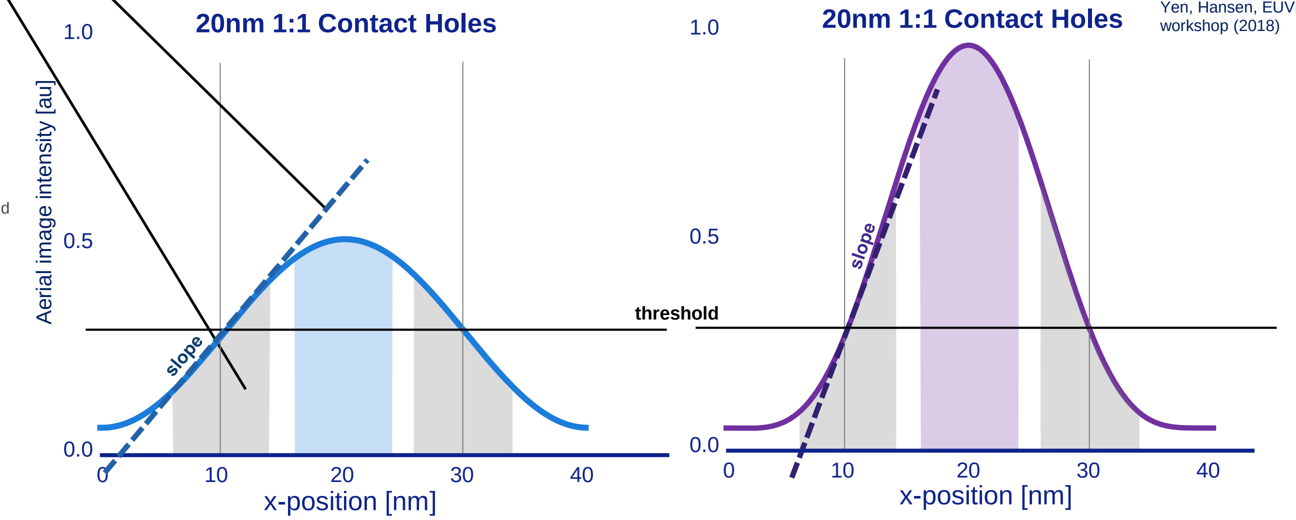
Whereby:
α = resist absorption
f = proportionality factor with eg QE
D_0 = dose to clear
ILS = image log slope
Area = area containing photons contributing to LCDU

High-NA: smaller CH’s at same dose









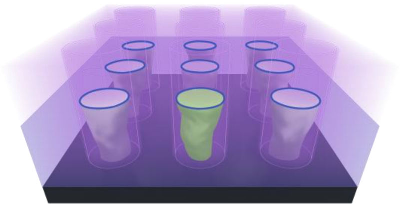
Yen, Hansen, EUVL workshop (2018)

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

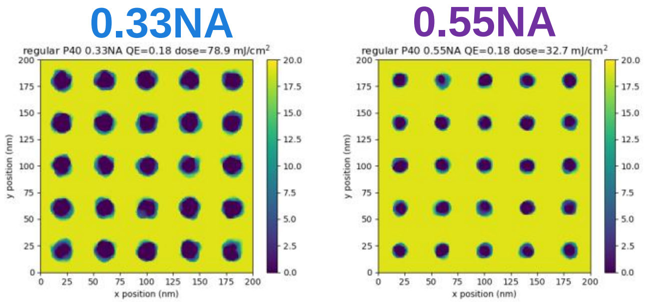
Reference: Jan van Schoot et al.: High-NA EUV Lithography Exposure System Advantages and Program Progress, EUVL 2020, 11517-12

High-NA contrast reduces Local CDU and defects

Allows for 2.5-4x lower dose printing same features

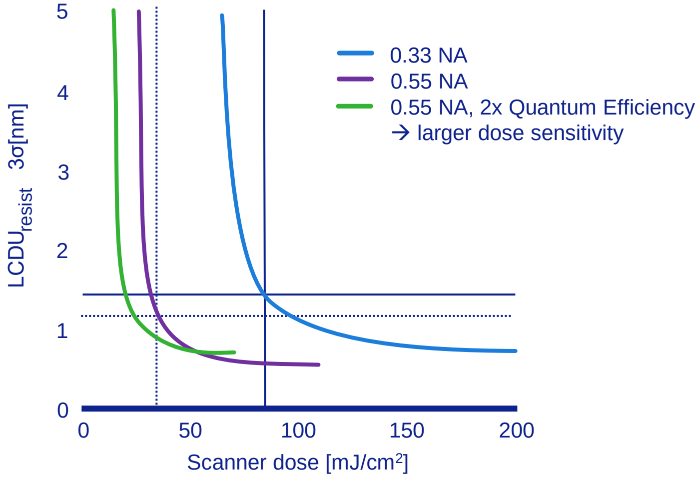


Regular P40 3D resist geometry simulated for 0.33NA & 0.55NA

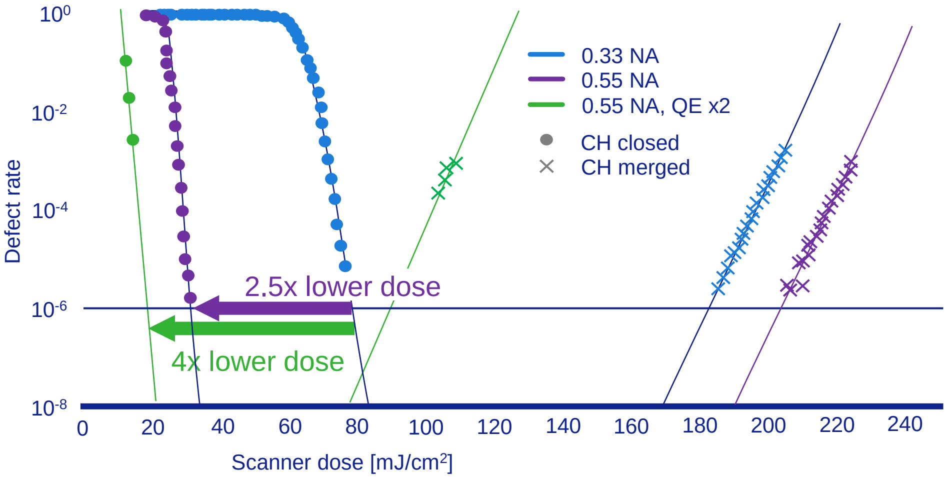


Note smaller size at equal defect rate → room for improvement

Significant reduction in LCDU due to higher image log slope



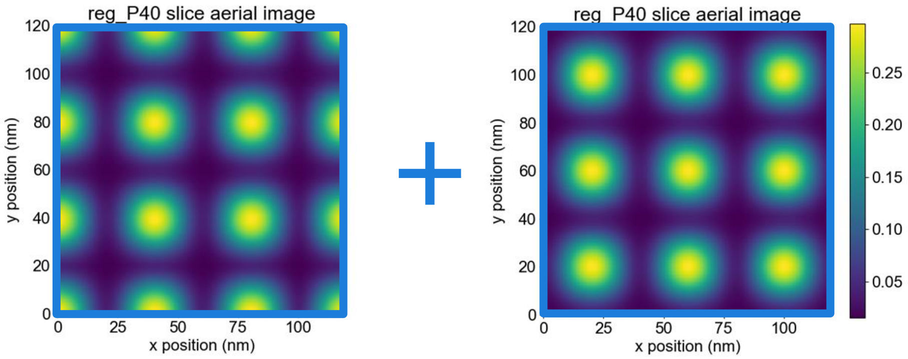
Larger defect free exposure window and lower dose for High-NA at print failure rate <1e-6:



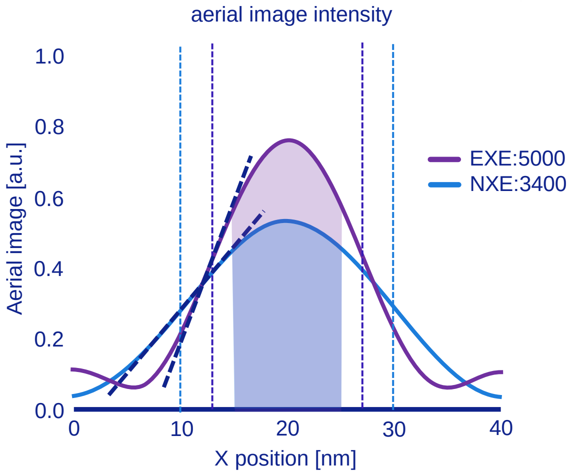
14nm CH’s: 0.55NA/SE prints at lower dose than 0.33NA/DE

At same defect rate, 0.55NA needs lower dose and avoids double exposure

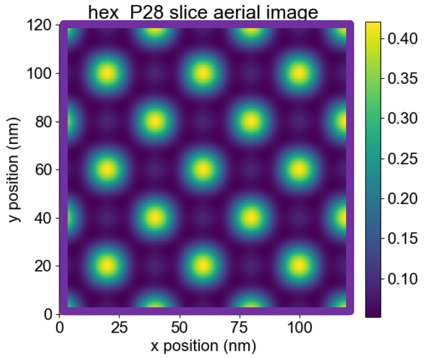
0.33 NA Double Expose



Aerial



0.55 NA Single Expose



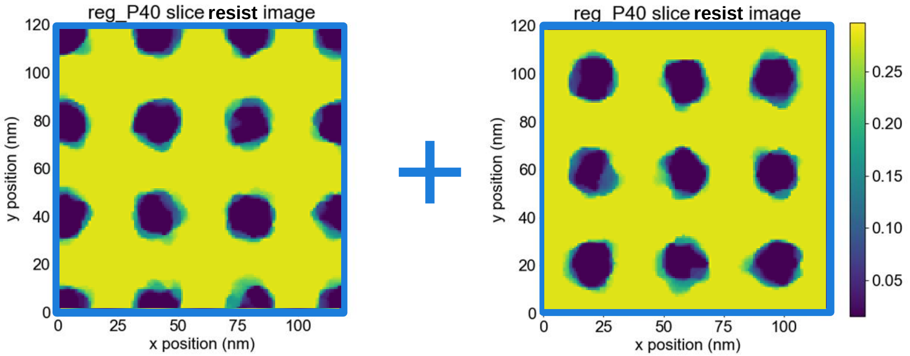
Larger slope and more local photons

Prediction: LCDU and defectivity better despite SE at smaller resolution

14nm CH's: 0.55NA/SE prints at lower dose than 0.33NA/DE

At same defect rate, 0.55NA needs lower dose and avoids double exposure

0.33 NA
Double Expose

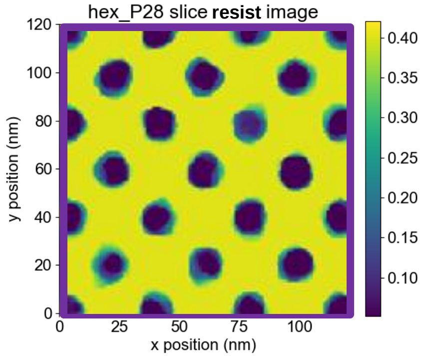


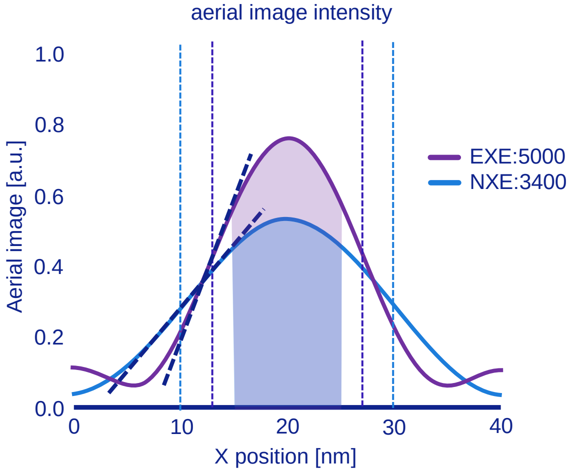
Resist

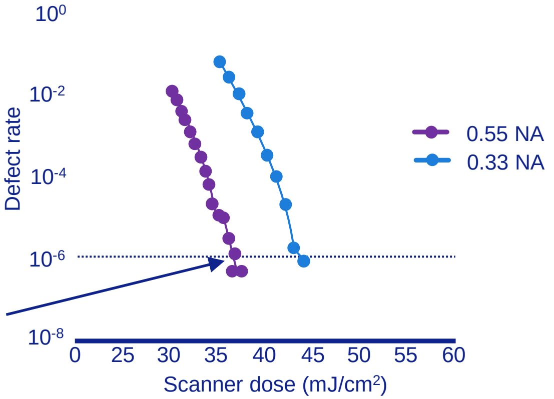
19.8nm @ 44 mJ/cm² LCDU: 1.8nm

14.7nm @ 37 mJ/cm² LCDU: 1.5nm

0.55 NA
Single Expose



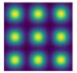
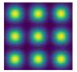


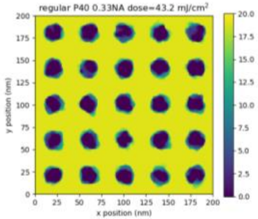


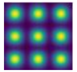
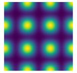
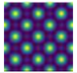
Same defect rate at lower dose and Single exposure

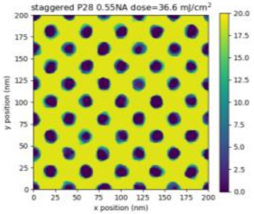
High-NA effective throughput ~2x as compared to 0.33NA

Printing a given feature at higher contrast with new stages

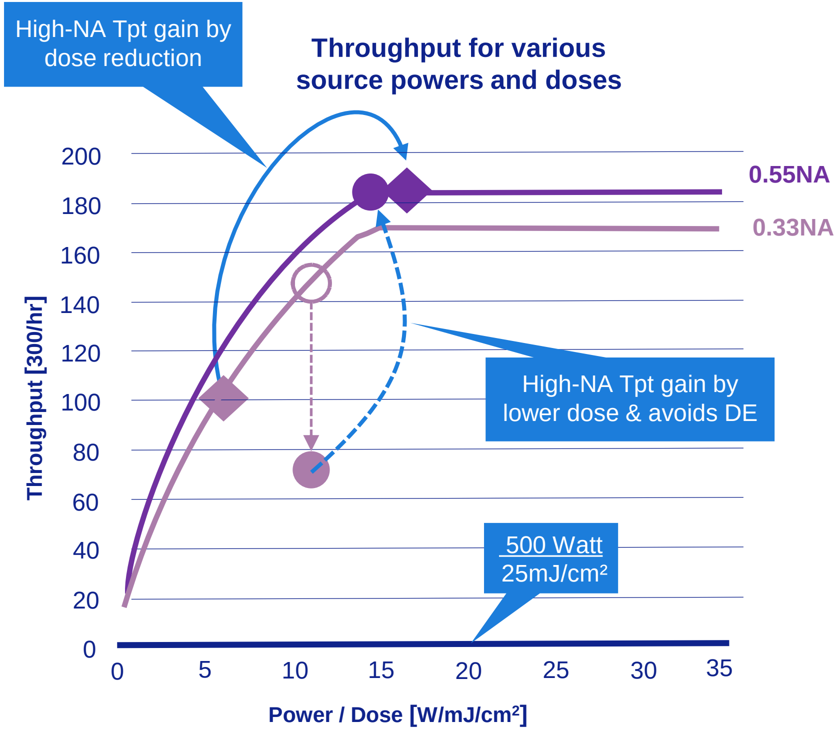
			**P40nm Dense CH**
# Exposures	0.33 NA **SE** ◆	0.55NA **SE** ◆	
Dose [mJ/cm^2]	79	33	
Tpt$_{eff}$ [WpH]	**100** →	**185**	



	 + 		**P28nm Staggered CH**
# Exposure	0.33 NA **DE** ●	0.55NA **SE** ●	
Dose [mJ/cm^2]	44	37	
Tpt$_{eff}$ [WpH]	**73** (145/2) →	**185** Additional processing needed	



Notes: All doses are chosen to achieve <10-6 defect rate
Source power = 500W assumed
Isotropic Resist model used, only PSN



Throughput for various source powers and doses

High-NA Tpt gain by dose reduction

High-NA Tpt gain by lower dose & avoids DE

500 Watt
25mJ/cm²

SE: Single Exposure
DE: Double Exposure, Litho-Etch-Litho-Etch
CH: Contact Hole
LCDU: Local Critical Dimension Uniformity

Advanced mask absorbers further improve imaging

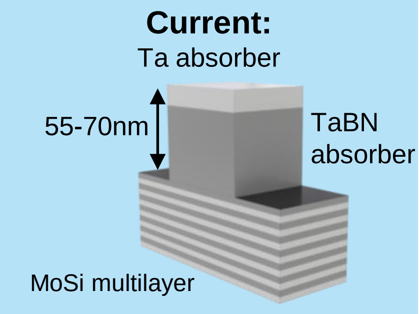
Contrast maintained using High-NA and advanced mask absorbers

Application timing	**2020**	**2022**	**2024**	**2026**	**2028**	**2030**
Lines and spaces [half pitch nm]	**18**	**15**	**14**	**12**	**10**	**8**
0.33NA NILS	2.6	2.6	2.4			
0.55NA NILS			2.9 / 3.0	2.7	2.6	
Staggered contact holes [half pitch nm]	**22**	**21**	**20**	**18**	**17**	**16**
0.33NA NILS	4.0	3.9	3.4	3.3		
0.55NA NILS				4.4	3.7	3.4

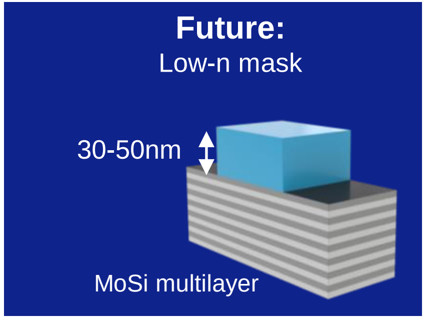
“low-n” a.k.a. “attPSM”

- Can be tuned to give diffracted orders ~same amplitude and phase **=> improves contrast**
- Optimum contrast at more open mask bias **=> improves throughput**
- Requires **dedicated** Source Mask Optimization (**SMO**) and Optical Proximity Correction (**OPC**)

Current:
Ta absorber



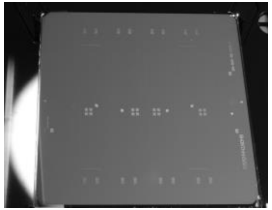
Future:
Low-n mask

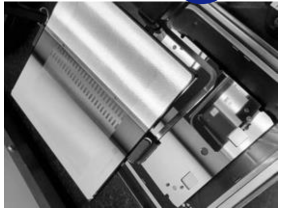


Low-n absorber superior for contrast and dose reduction

High-k reduces M3D fading as well, at expense of higher dose to size

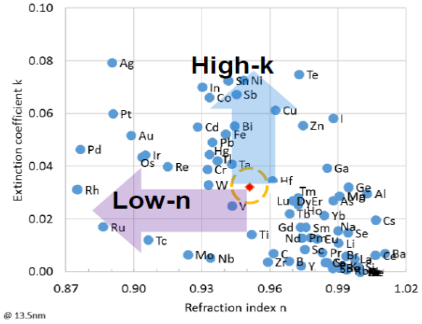
	High-k	Low-n	Next gen ML[1]
Contrast	+	++	+
Dose to size reduction	-	++ ①	+-
Best focus through feature reduction	+	+*	+
Non-telecentricity	+	+-	++ ③
General applicable for multiple features and nodes	+	+ ②	+


SPIE 2019


SPIE 2021

*In 2-beam imaging regime

[1] Wrt to current Ta mask



① Low-n mask is superior in contrast gain and dose reduction

② One low-n embodiment can cover multiple nodes and features

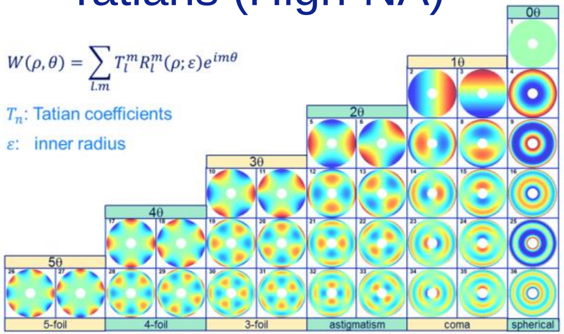
③ ML tuning mitigates M3D non-telecentricity

Tachyon Comp Litho High-NA Roadmap

Functional ~1yr before first exposures @ joint AMSL/Imec high-NA lab

Wavelength	Computational Litho	2020 | 2021 | 2022 | 2023 | 2024 | 2025			
EUV 0.55NA	**SMO**	Anamorphic MRC	EXE Pupil Rendering Discrete Optimization	Anamorphic Freeform MO	
	Model	Optics integration	Tatian Zernikes	M3D for non H/V patterns	Optical models for Anamorphic Freeform
	OPC	Anamorphic MRC	Anamorphic OPC	Anamorphic Freeform OPC+	Intra-field stitching
	LMC	MRC Checker	Anamorphic Verification	Anamorphic Freeform LMC+	Intra-field verification

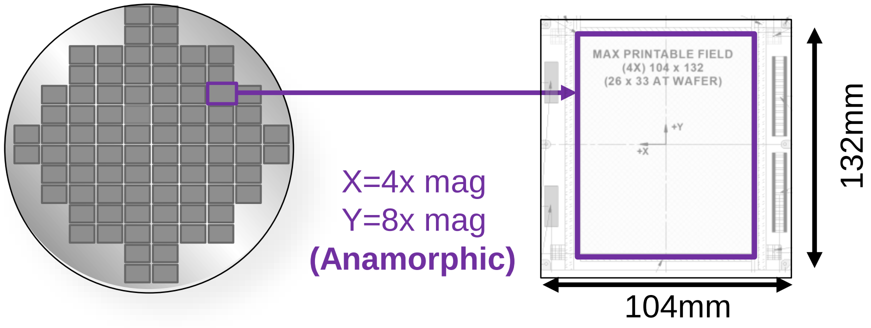
Tatians (High-NA)



$$W(\rho,\theta)=\sum_{l,m} T_l^m R_l^m(\rho;\varepsilon)e^{im\theta}$$

T_n: Tatian coefficients

ε: inner radius



X=4x mag
Y=8x mag
(Anamorphic)

Half-Field (26mm x 16.5mm)

Half-field reticle

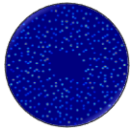
Product status | Released | Development | Definition

Reference:
High NA EUV scanner: obscuration and wave front description, Laurens de Winter, EUVL 2020, 11517-38

Illuminator offers large flexibility

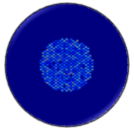
Standard Sources and free form pupils available in Tachyon

High-NA standard pupil shapes


quasi conventional


small annular

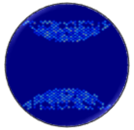

medium annular


small conventional


dipole X


dipole Y


medium dipole X


medium dipole Y

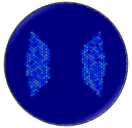

quasar

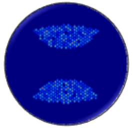

hexapole X


hexapole Y


leaf hexapole X


leaf hexapole Y

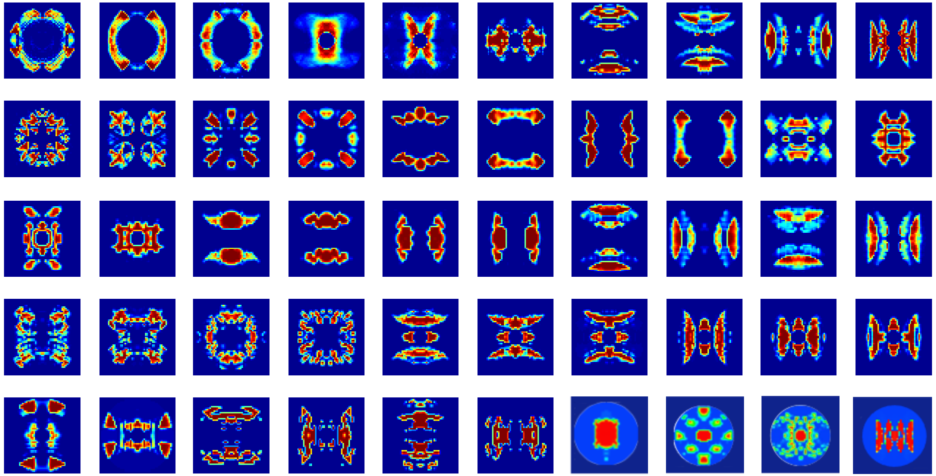

small dipole X


small dipole Y


slim dipole X


slim dipole Y

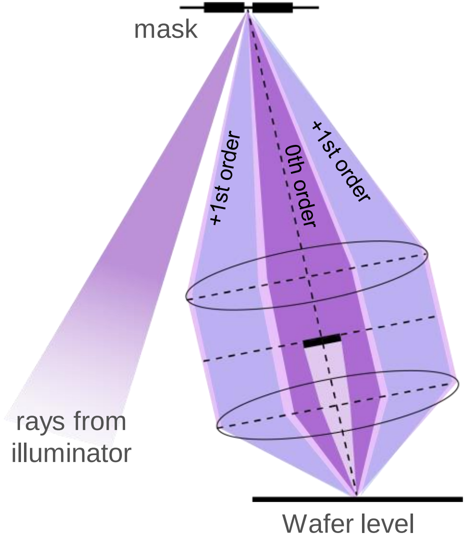
High-NA examples from Tachyon SMO

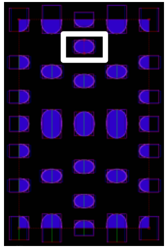


Obscuration aware SMO can gain contrast

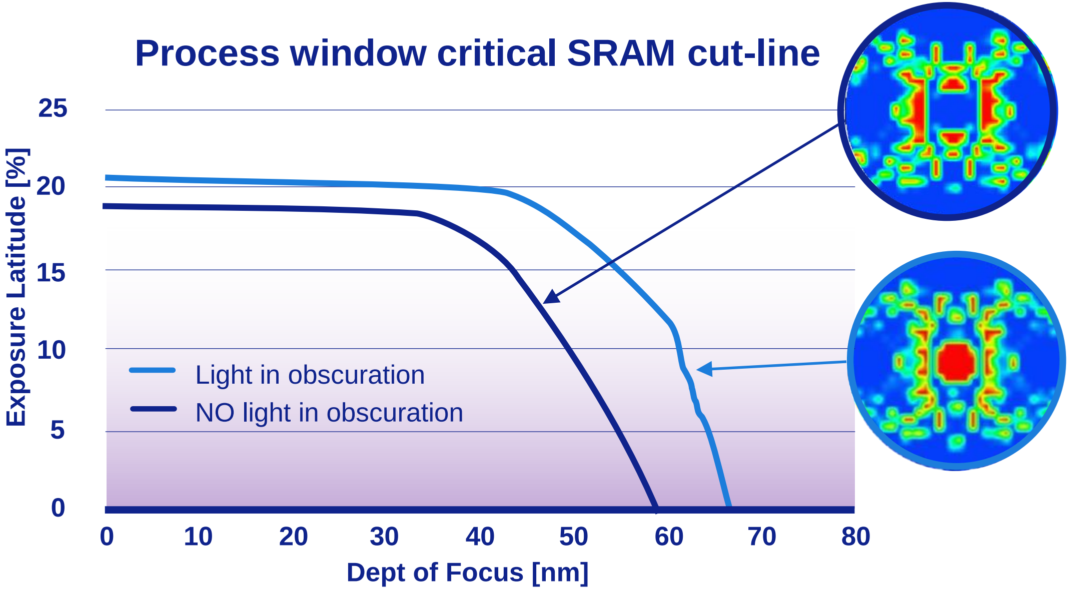
By blocking 0th order light from the illumination pupil

dark-field illumination





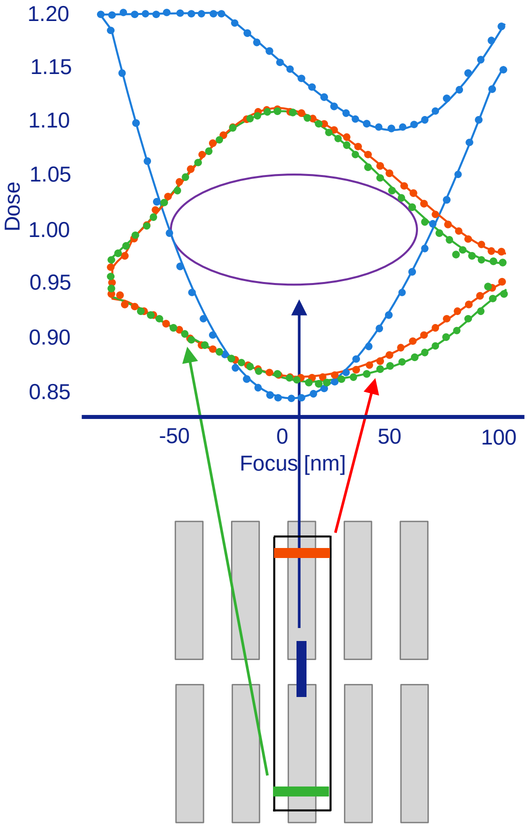
Mask 55nm Ta-based

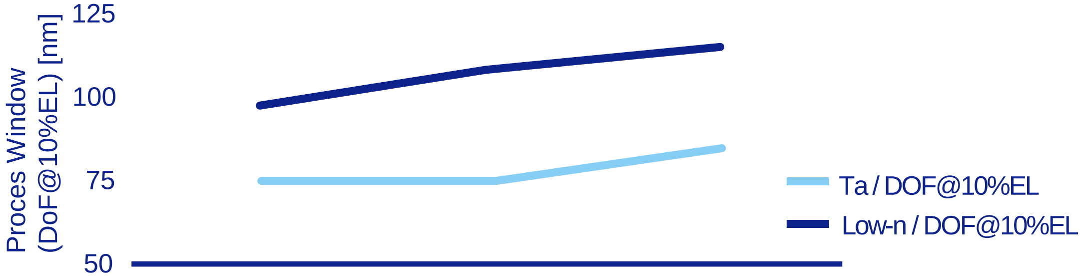


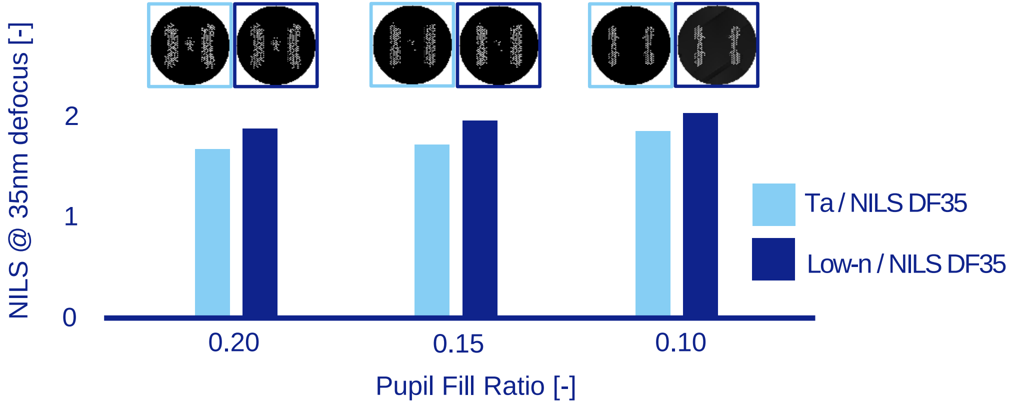
Ref: E. van Setten et al, 'High-NA EUV lithography: Next step in EUV imaging', Proc. SPIE. 10809 (2018)

Holistic optimization: pupil & mask

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







Outline

EUV is here: Status 0.33NA

What's next? Towards High-NA

- Contrast
- **Dose**
- Resist

High-NA progress

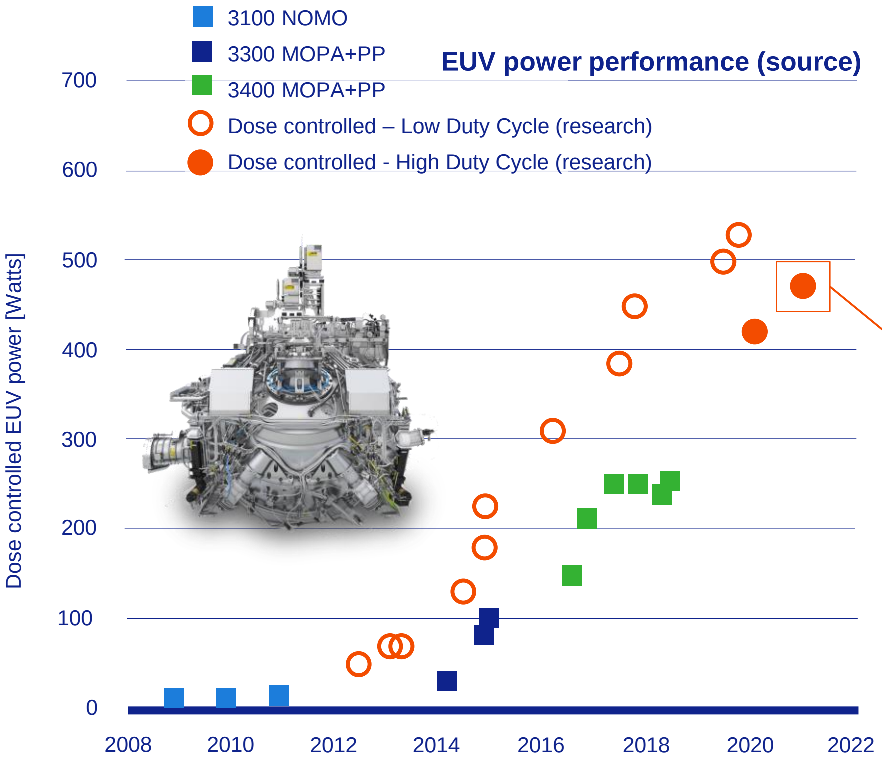
- Architecture
- Industrialization

Summary

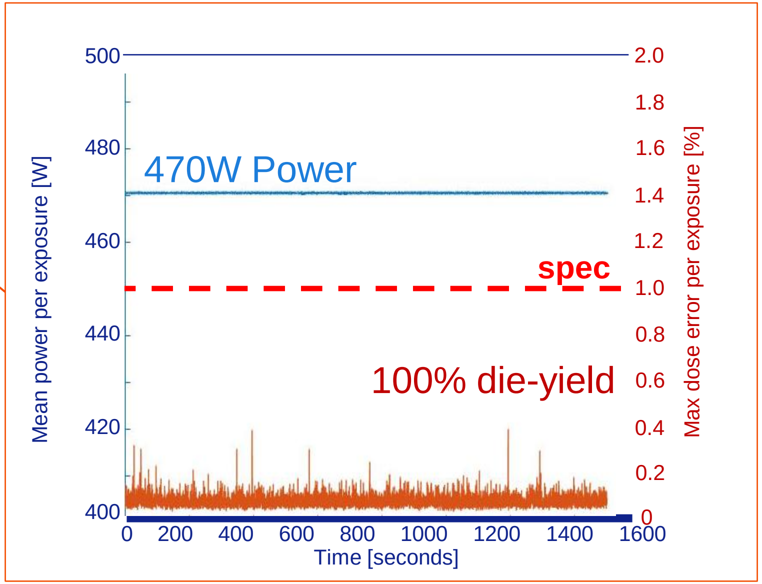
Research demonstration of >400W dose controlled EUV

… and higher powers demonstrated in the lab

EUV power performance (source)



470W in-spec[1] dose controlled EUV power demonstrated at full EUV duty cycle



---

[1] Performance for use on NXE:3800

Outline

EUV is here: Status 0.33NA

What's next? Towards High-NA

- Contrast
- Dose
- **Resist**

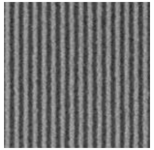
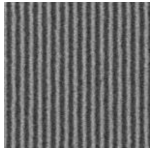
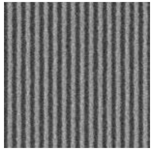
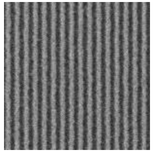
High-NA progress

- Architecture
- Industrialization

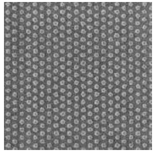
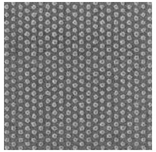
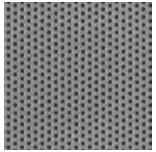
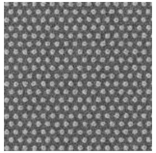
Summary

Continuous resist improvement for multiple use cases

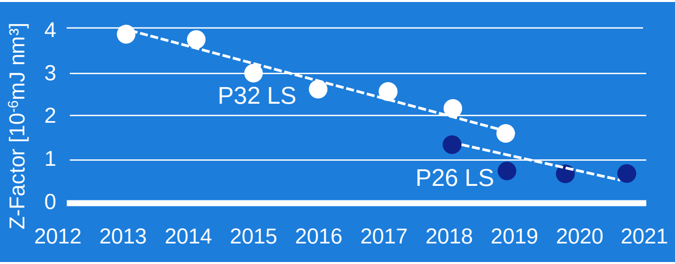
Progress is needed moving forward

	2018	2019	2020	2021
Resist type	**Non-CAR[1]**	**Non-CAR**	**Non-CAR**	**Non-CAR**
Resolution: (P26 LS)				
Dose $[\text{mJ/cm}^2]$	57	45	47	50
LWR_{unb} [nm]	3.1	3.0	2.9	2.8
Z-factor $[10^{-6}\text{mJ nm}^3]$	**1.2**	**0.9**	**0.87**	**0.86**

Lines and Spaces

	2018	2019	2020	2021
Resist type[1]	**Non-CAR**	**Non-CAR**	**CAR**	**Non-CAR**
Resolution: (P40 Hexagonal Pillars/CH)				
Dose $[\text{mJ/cm}^2]$	66	65	61	53
LCDU [nm]	2.7	2.2	2.1	2.0
Z-factor $[10^{-6}\text{mJ nm}^3]$	**3.8**	**2.5**	**2.3**	**1.7**

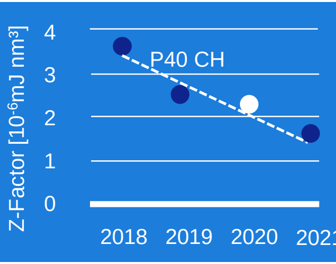
Contact Holes



$$\text{*}\textbf{Z-factor} = \text{Res}^3 \times \text{LWR}^2 \times \text{Dose}$$

Z-factor comparison only valid at equal contrast

● Non CAR ○ CAR



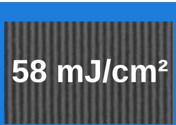
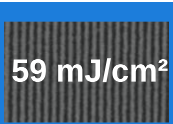
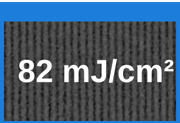
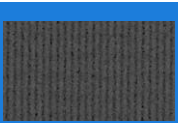
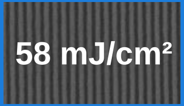
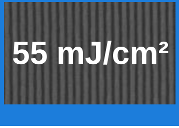
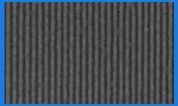
---

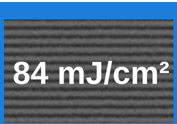
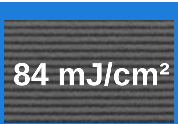
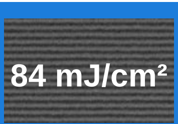
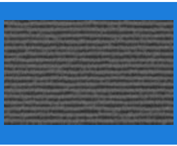
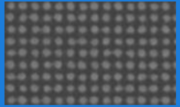
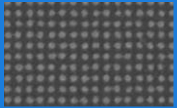
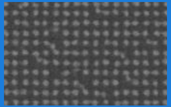
[1] CAR Chemical Amplified Resist

Reference: Jara Garcia SantaClara: Today's scorecard for tomorrow's photoresist. 11612-2

PSI and BMET5 screenings towards ultimate resolution

Interference Litho (PSI) and frequency doubling (BMET5) for resist testing

Resolution [hp]	**13nm**	**12nm**	**11nm**	**10nm**	**9nm**	**8nm**
Inorganic Resist	 62 mJ/cm²	 58 mJ/cm²	 75 mJ/cm²	 59 mJ/cm²	 82 mJ/cm²	
Chemically Amplified Resist (CAR)	 58 mJ/cm²	 55 mJ/cm²				

Resolution [hp]	**13nm**	**12nm**	**11nm**	**10nm**	**9nm**	**8nm**
Dry Dev. Inorganic Resist Lines and Spaces			 84 mJ/cm²	 84 mJ/cm²	 84 mJ/cm²	
Inorganic Resist Regular Pillars						

Reference: Jara Garcia SantaClara: Today's scorecard for tomorrow's photoresist. 11612-2

Outline

EUV is here: Status 0.33NA

What's next? Towards High-NA

- Contrast
- Dose
- Resist

High-NA progress

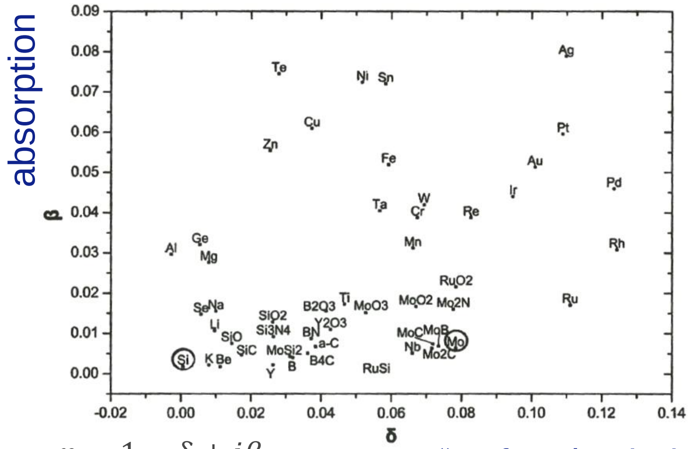
- **Architecture**
- **Industrialisation**

Summary

The basics for High-NA EUV are found in the elements

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

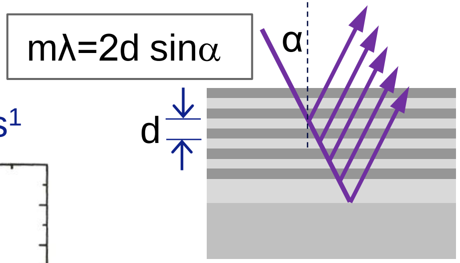
Optical properties of materials[1]

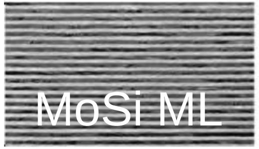


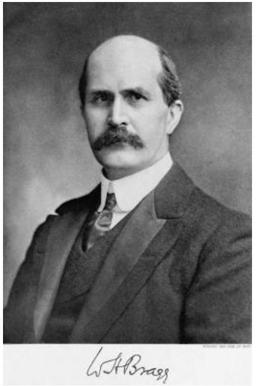
$n = 1 - \delta + i\beta$

"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].

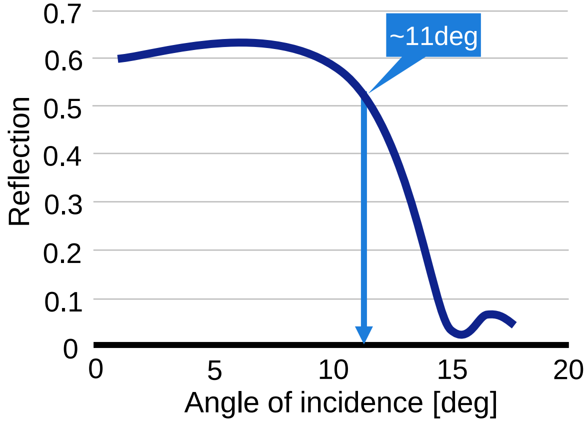

$m\lambda = 2d \sin\alpha$





William Bragg

ML reflection



Absorption:

- Mirrors
- Vacuum
- Source powers

Refractive index:

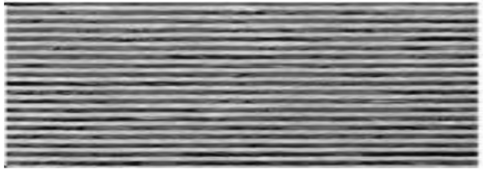
- Bragg reflectors (Multi-layers, ML)
- Angular dependency

---

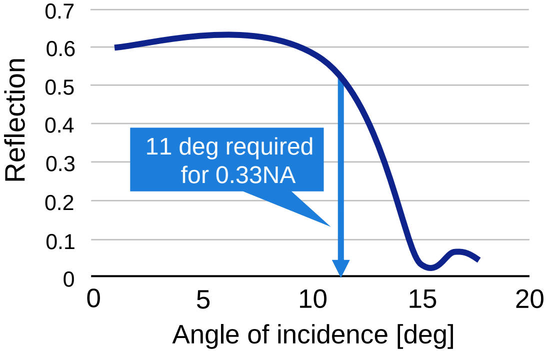
[1] Chart is from Eric Louis, Physics and technology development of multilayer EUV reflective optics, PhD thesis, University of Twente, The Netherlands, 2012

EUV High-NA requires an anamorphic lens

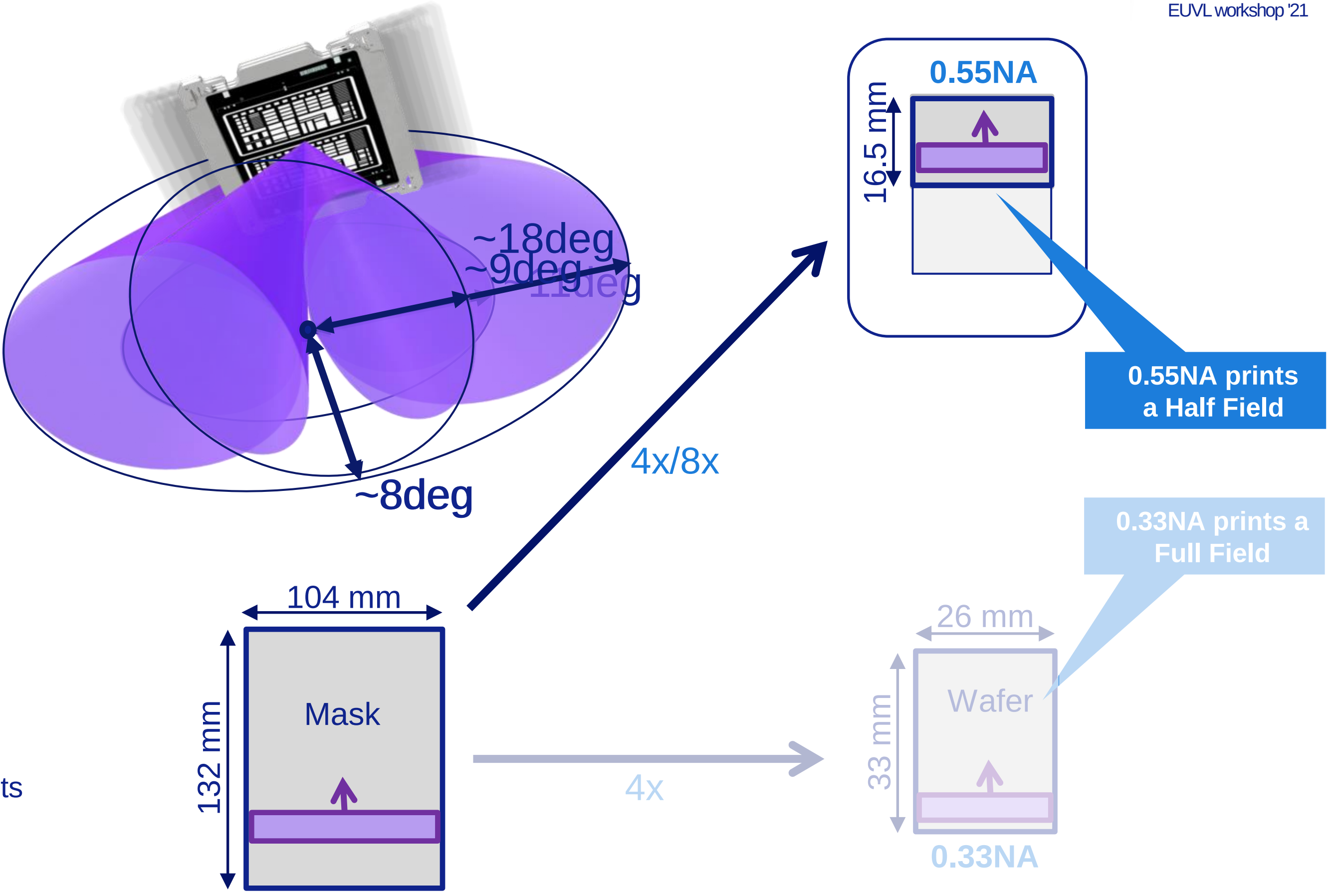
Mask MoSi Multilayer



ML reflection



11 deg required for 0.33NA



0.55NA prints a Half Field

0.33NA prints a Full Field

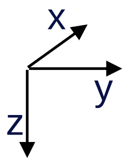
Note: for simplicity M3D effects are ignored, only multi-layer effect taken into account

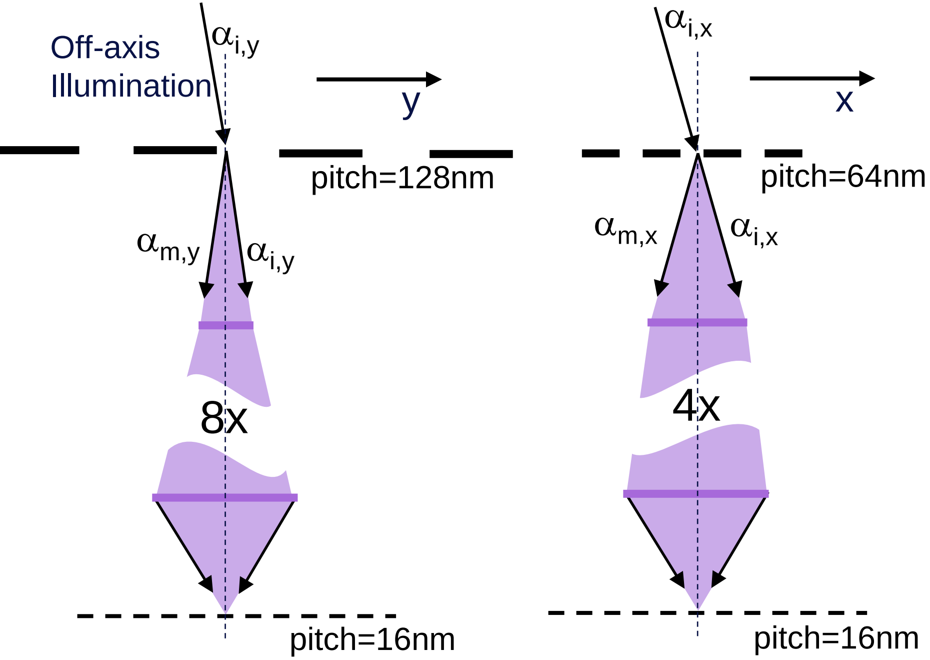
Anamorphic projection lens has same resolution in x & y

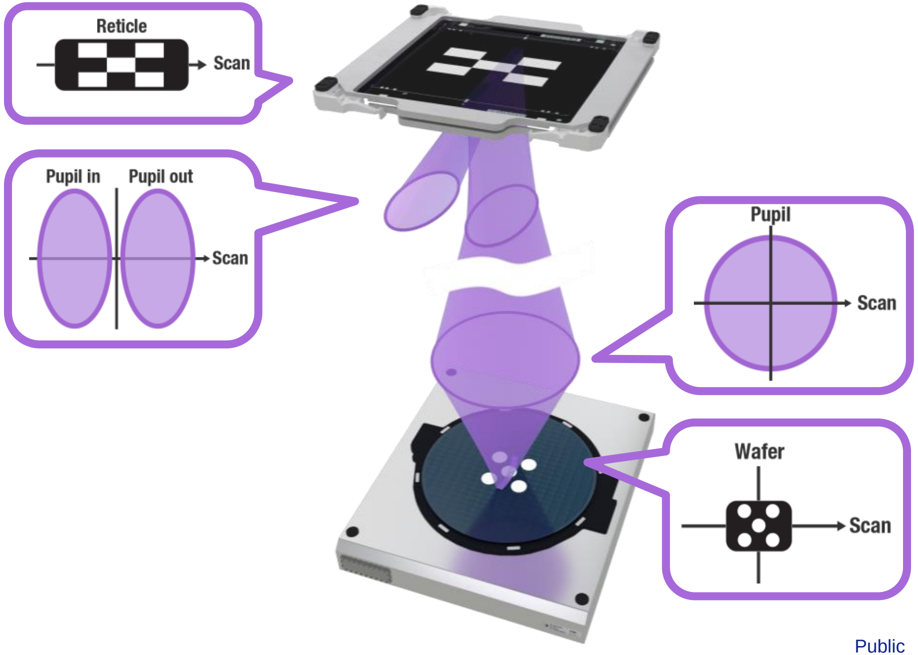
Elliptical illumination pupil is transformed in a round exit pupil

$$(\sin\alpha_i - \sin\alpha_m) = \frac{m\cdot\lambda}{pitch}$$

(m integer) 'Bragg Condition'

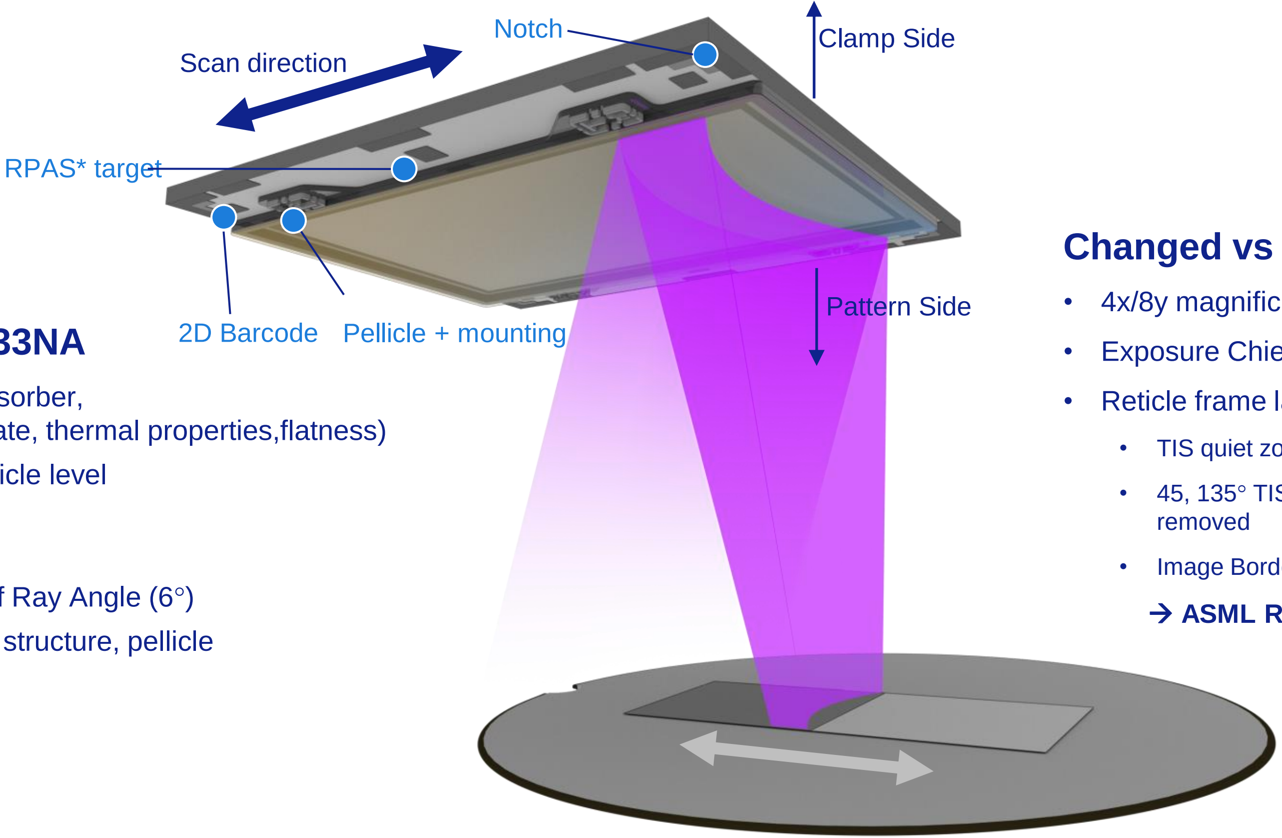






The ASML High-NA Reticle Design

The ASML Reticle Design Manual for High-NA is available and describes the changes w.r.t 0.33NA



Unchanged vs 0.33NA

- Reticle blank (ML, absorber, capping layer, substrate, thermal properties,flatness)
- Image field size at reticle level (104 x 132 mm)
- Exposure wavelength
- Mask metrology Chief Ray Angle (6°)
- Pellicle, pellicle infra- structure, pellicle relevant mask layout
- EUV pod
- Backside coating

Changed vs 0.33NA

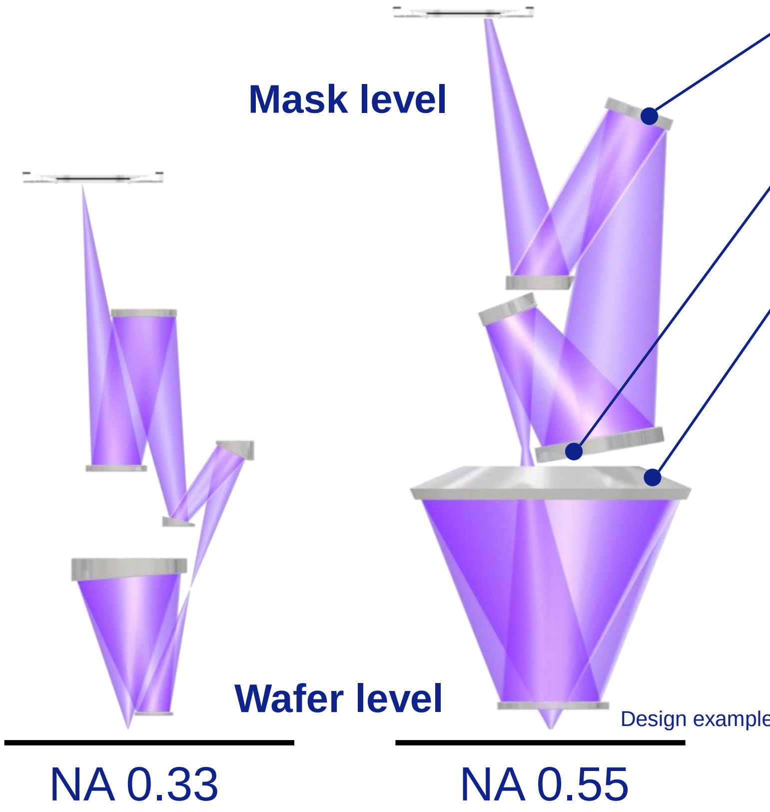
- 4x/8y magnification
- Exposure Chief Ray Angle (~5.3°)
- Reticle frame layout
  - TIS quiet zone dimension in Y
  - 45, 135° TIS RBA gratings obsolete & removed
  - Image Border size in X & Y direction

→ **ASML Reticle Design Manual**

*Reticle Pre-Alignment Sensor

High-NA projection optics design available

Larger elements with tighter specifications

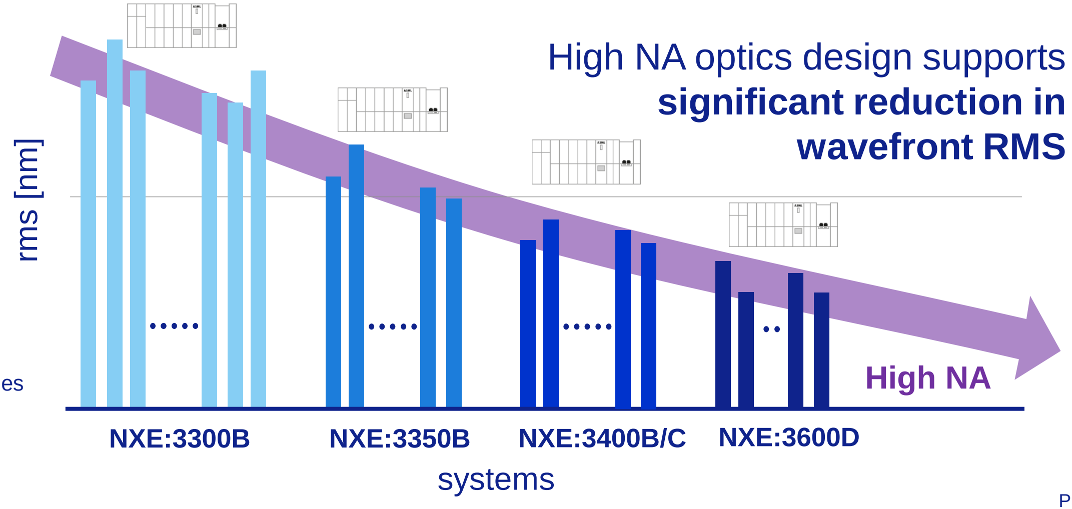


Design examples

Extreme aspheres enabling
further improved wavefront / imaging performance

Obscuration enables
higher optics Transmission

Big last mirror driven by
High-NA

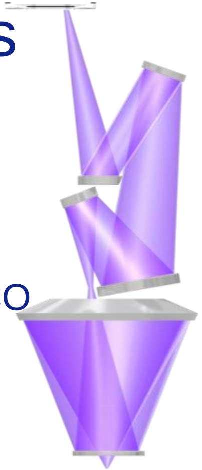


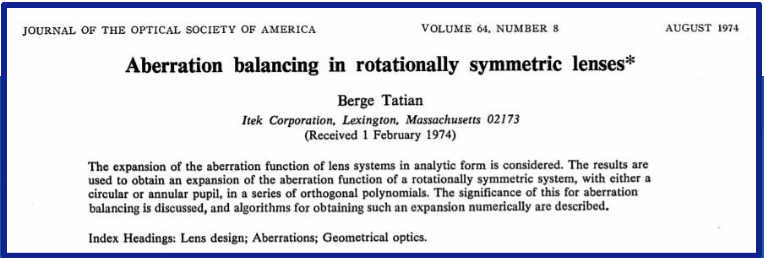
High NA optics design supports
significant reduction in
wavefront RMS

Zernike wave front description replaced by Tatians

To account for central obscuration in High-NA

- Zernike is a well-known basis to expand wavefronts
- For high-NA machines, projection lens has a central obscuration (CO)
- Tatian (or annular-Zernike) is a basis that ASML uses to express aberration with CO
- Tatian description implemented in Tachyon





JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 64, NUMBER 8 AUGUST 1974

Aberration balancing in rotationally symmetric lenses*

Berge Tatian
Itek Corporation, Lexington, Massachusetts 02173

(Received 1 February 1974)

The expansion of the aberration function of lens systems in analytic form is considered. The results are used to obtain an expansion of the aberration function of a rotationally symmetric system, with either a circular or annular pupil, in a series of orthogonal polynomials. The significance of this for aberration balancing is discussed, and algorithms for obtaining such an expansion numerically are described.

Index Headings: Lens design; Aberrations; Geometrical optics.

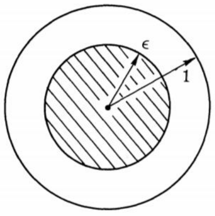
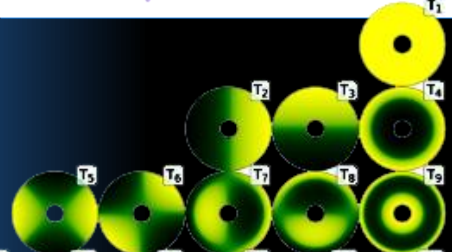
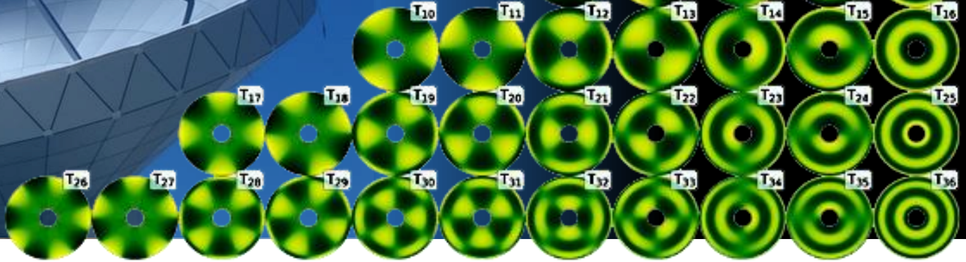


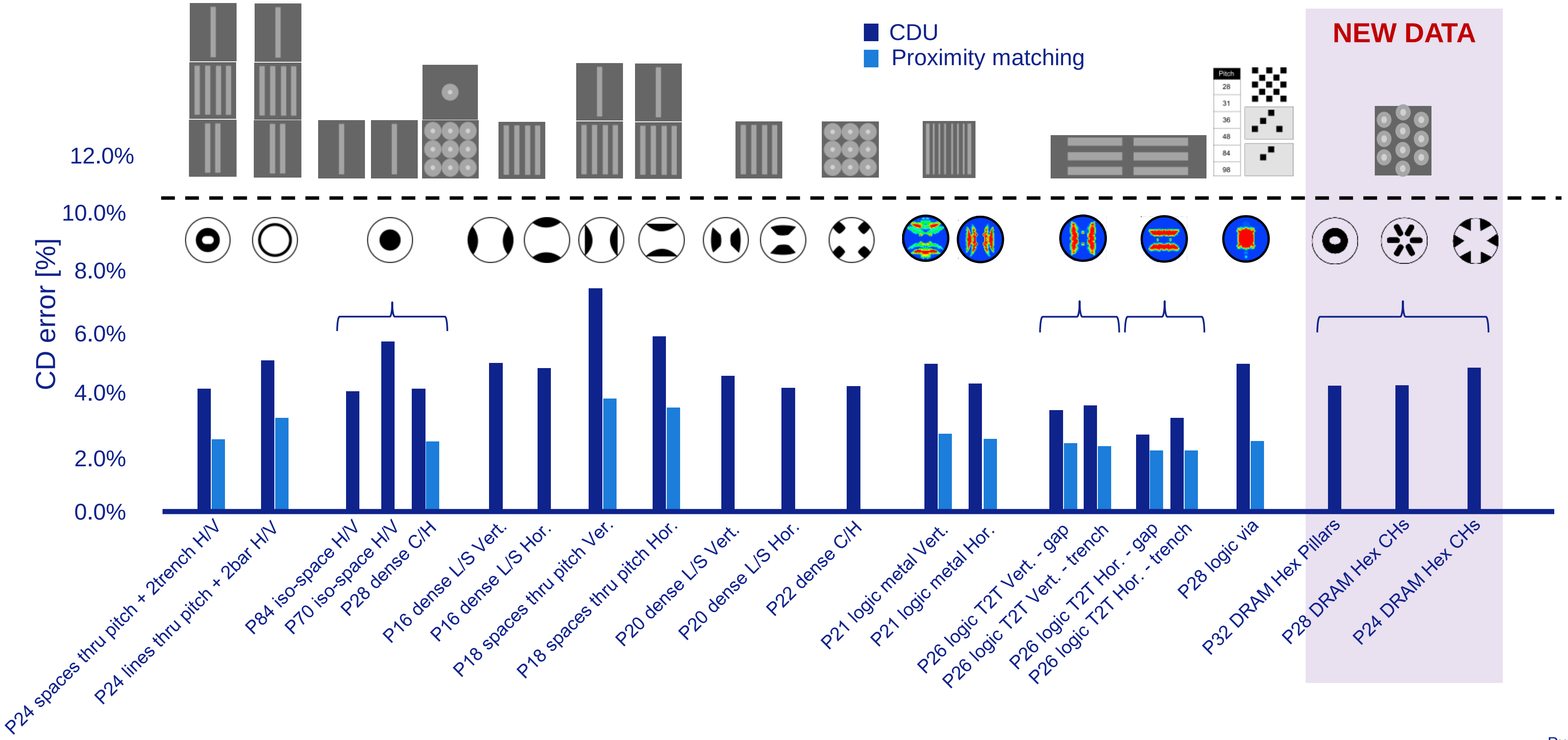
FIG. 2. Annular aperture with a relative obstruction value, ε.

Reference:
High NA EUV scanner: obscuration and wave front description, Laurens de Winter, EUVL 2020, 11517-38

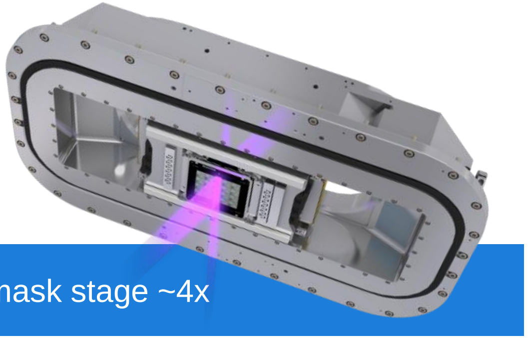
Full wafer and tool-to-tool CD control well below 10% CD

Balanced performance budgets for many different use-cases and pupils

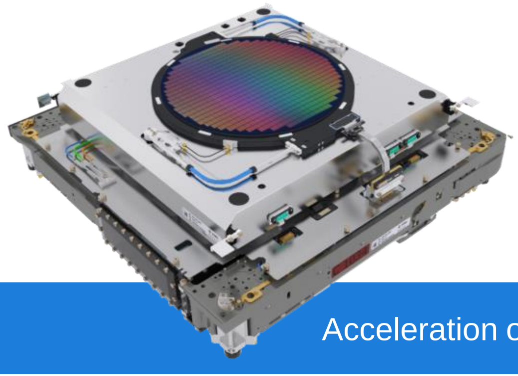


High-NA and fast stages enables throughput 185 wph

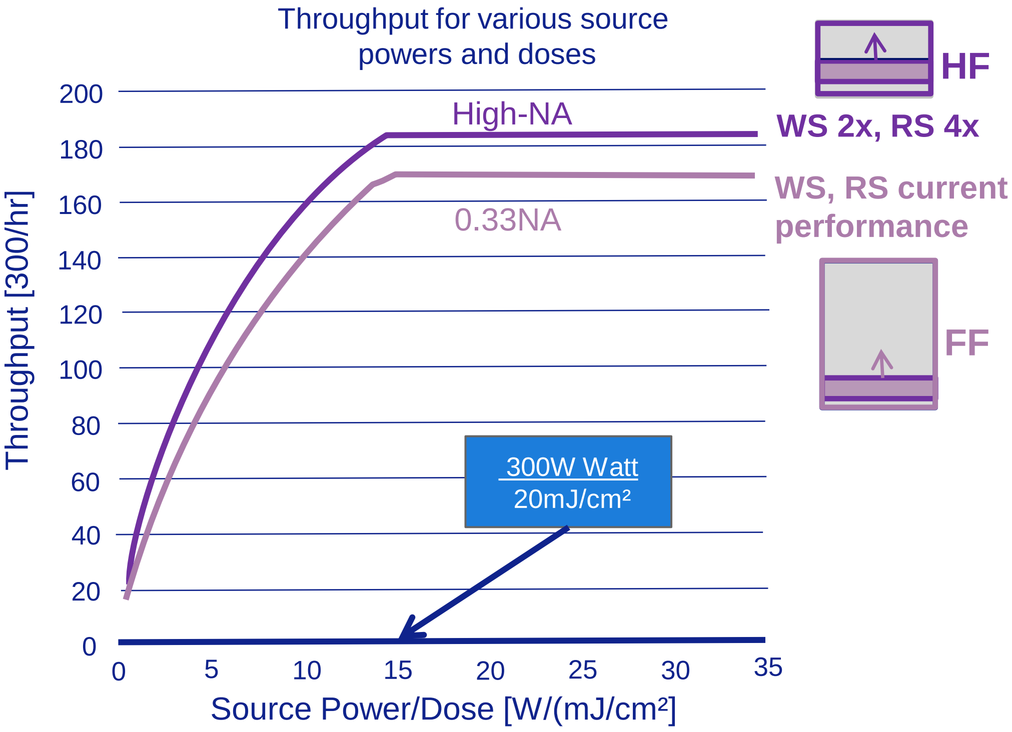
188 half fields per wafer



Acceleration of mask stage ~4x

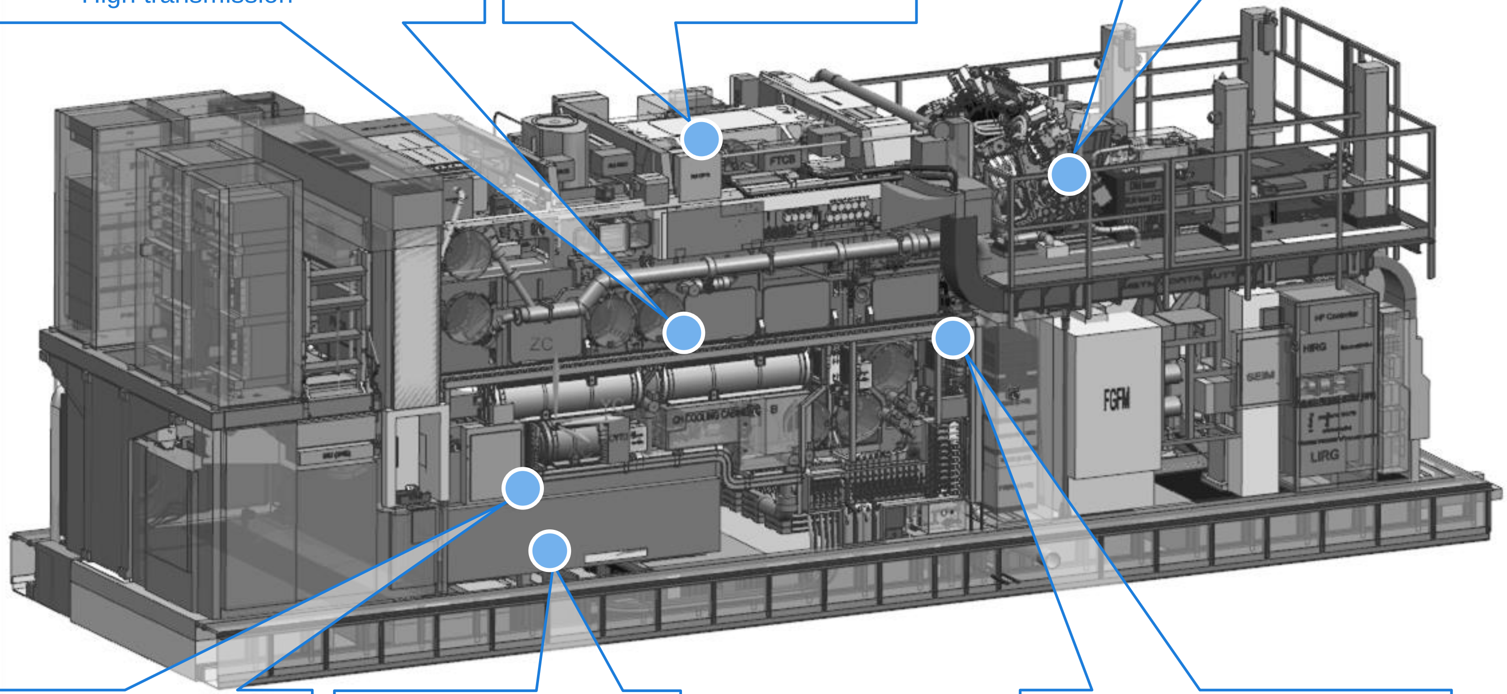


Acceleration of wafer stage ~2x



High-NA system architecture finalized

High-NA system architecture finalized



Lens & illuminator
- NA 0.55 for high contrast
- High transmission

Mask Stage
4x increase in acceleration

Improved Source position
Allows for larger transmission, compatible with 0.33 NA

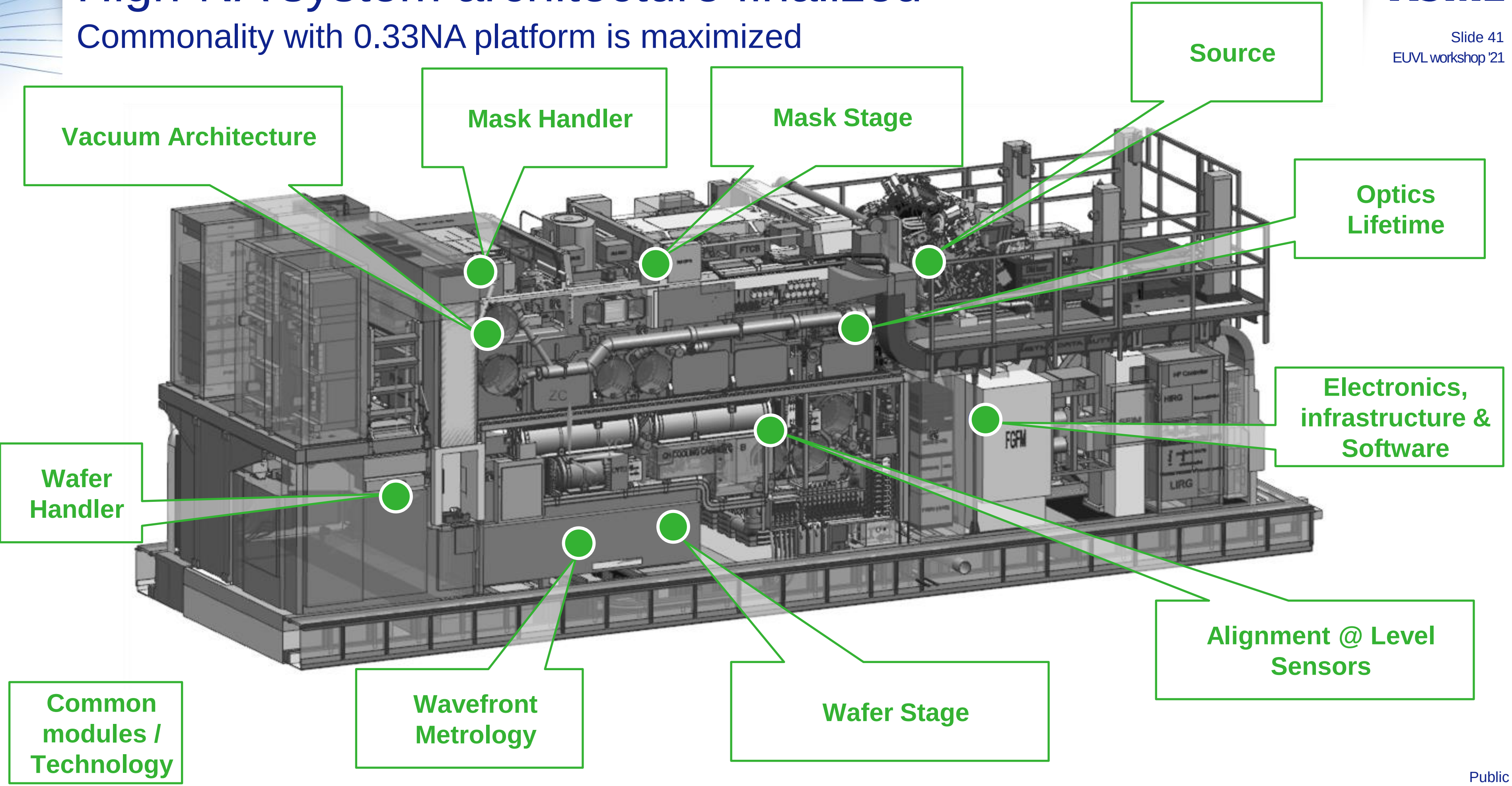
Improved metrology
2~3x improvement in overlay/focus

Wafer Stage
2x increase in acceleration

New Frames
Improved thermal and dynamic control with larger optics

High-NA system architecture finalized

Commonality with 0.33NA platform is maximized



Vacuum Architecture

Mask Handler

Mask Stage

Source

Optics Lifetime

Electronics, infrastructure & Software

Wafer Handler

Alignment @ Level Sensors

Wafer Stage

Wavefront Metrology

Common modules / Technology

Outline

EUV is here: Status 0.33NA

What's next? Towards High-NA

- Contrast
- Dose
- Resist

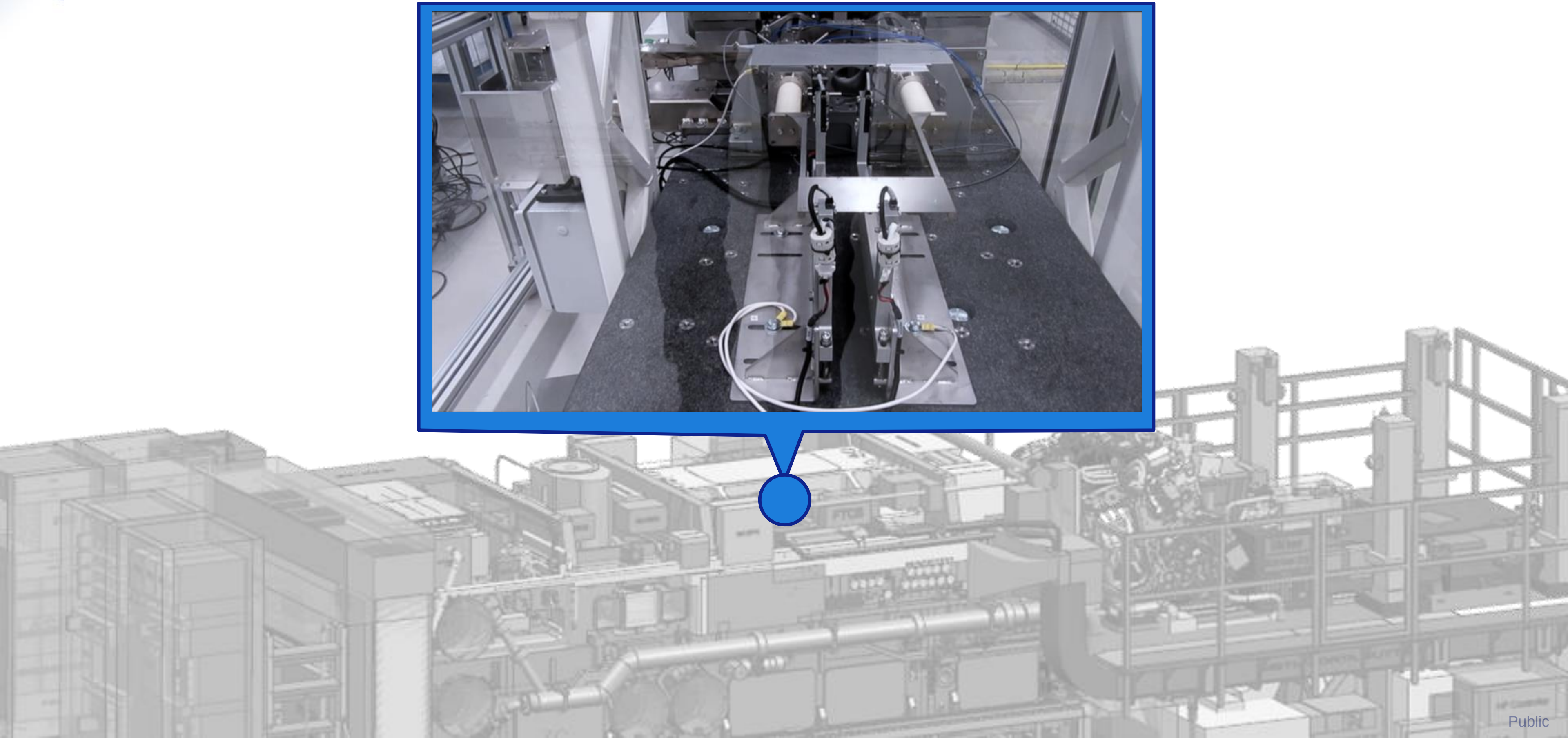
High-NA progress

- Architecture
- **Industrialisation**

Summary

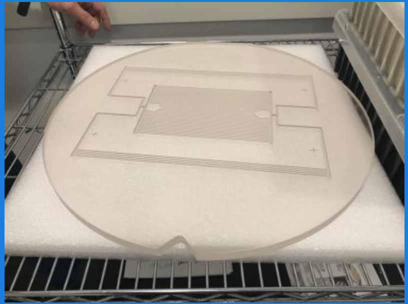
Reticle Masking first tests executed succesful

Currently being tested at 65% of final acceleration



Reticle stage short stroke module manufacturing progressing

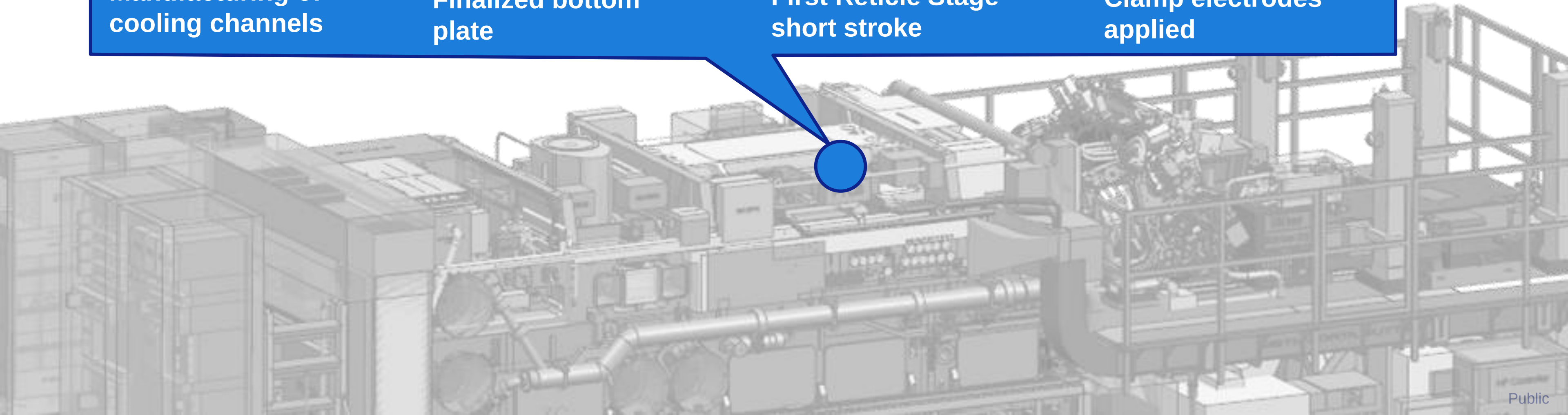
Manufacturing of cooling channels



Finalized bottom plate

First Reticle Stage short stroke

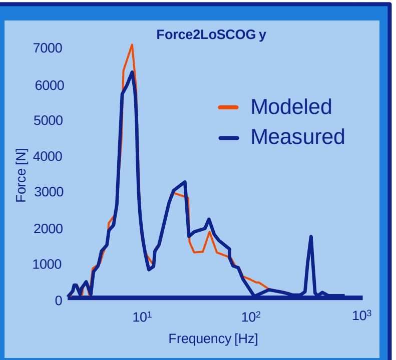
Clamp electrodes applied



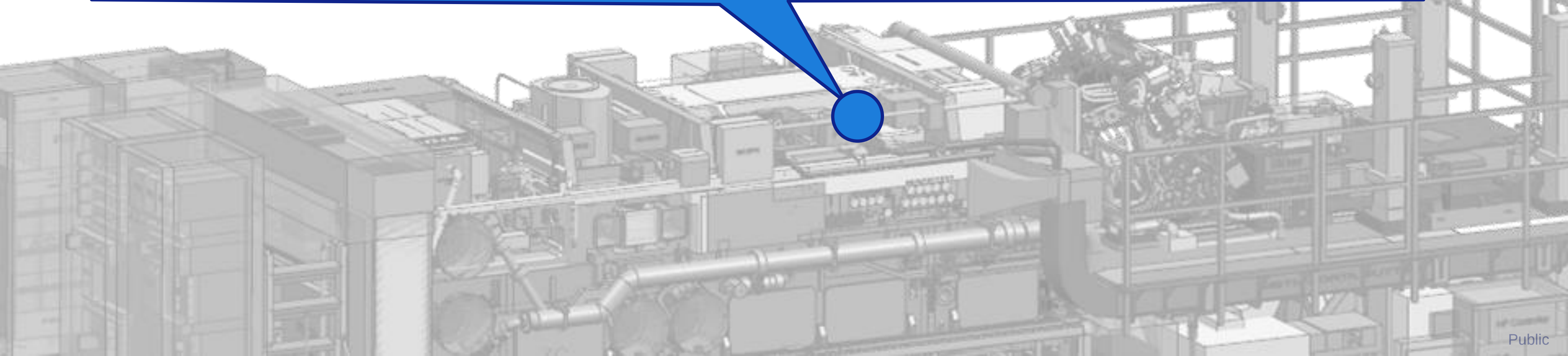
Long stroke motor mask stage risk build-down

Moving at NXE:3400 profile

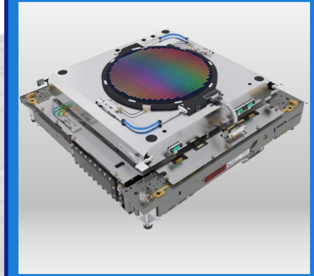
Moving at EXE:5000 profile (4x)



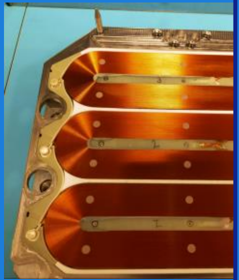
Model verification



Wafer stage modules being manufactured

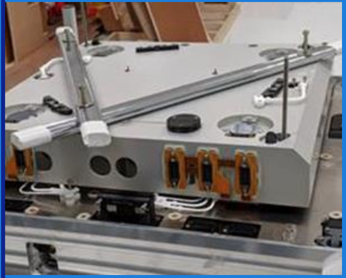


Wafer stage design ready

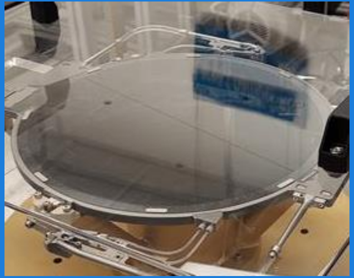


Actuator Coils for testing

Wafer stage module housing



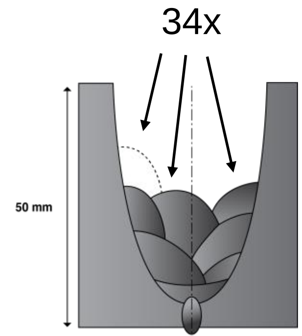
ror block



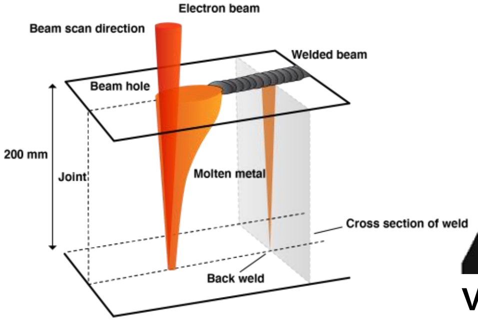
Wafer Clamp

Base Frame pre-milling of sections completed

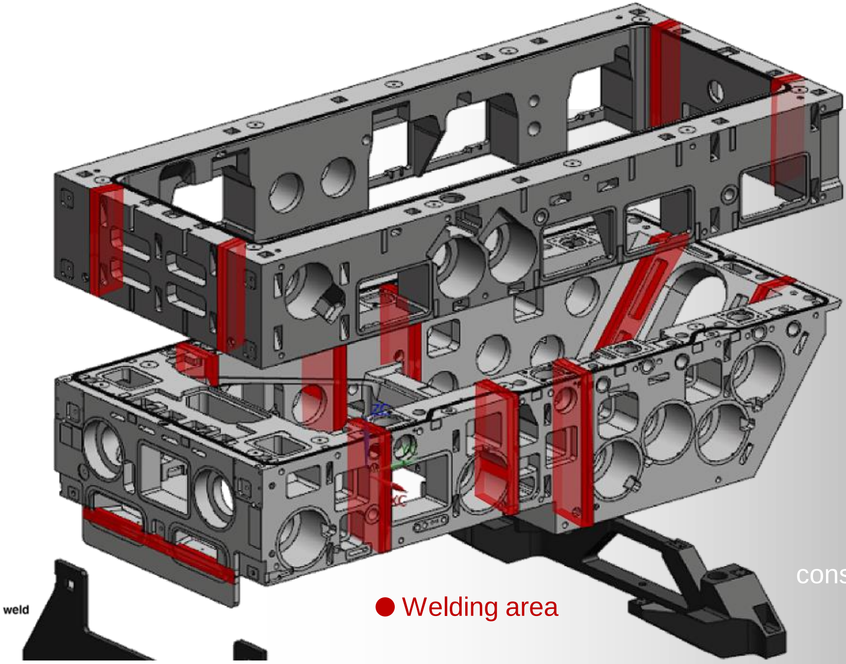
e-beam welding in progress



Conventional welding

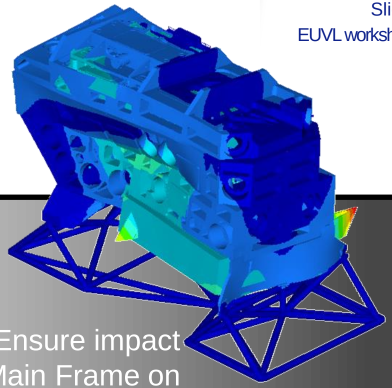


Robotized E-beam welding:
3 days / frame



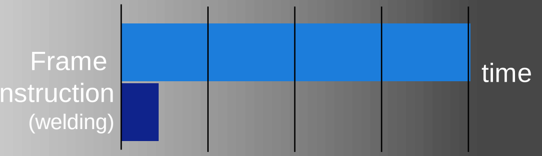
● Welding area

Volume: 6m x 2.5m x 2.5m
Weight: ~21,000kg



Ensure impact of Main Frame on POB in spec

Traditional welding: 4 weeks / frame

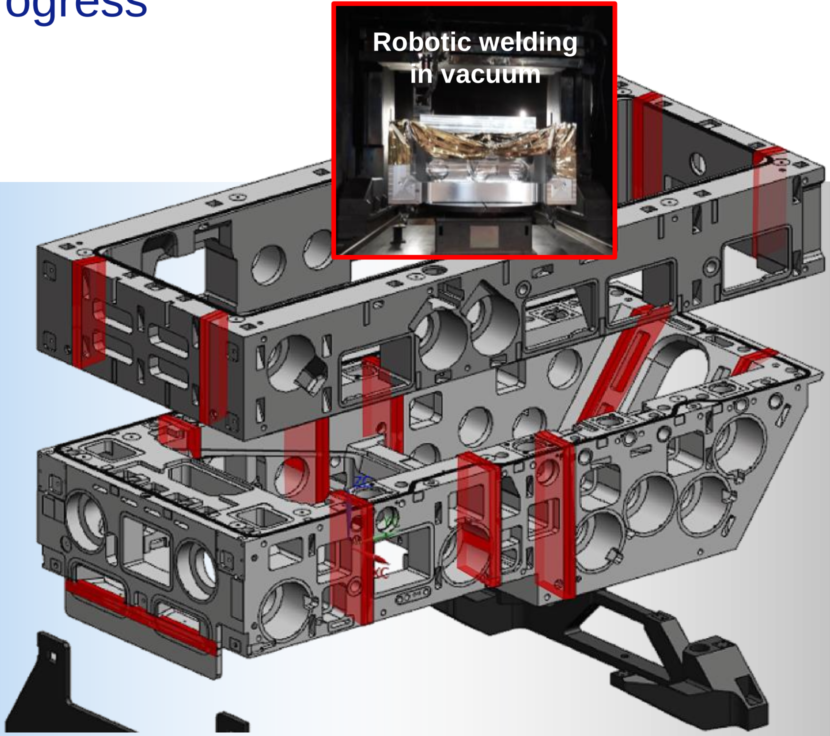


Base Frame pre-milling of sections completed

e-beam welding in progress

Milling

Pre-milling of frame sections has been completed



Robotic welding in vacuum

Volume: 6m x 2.5m x 2.5m
Weight: ~21,000kg

Welding

E-beam welding of sections in progress

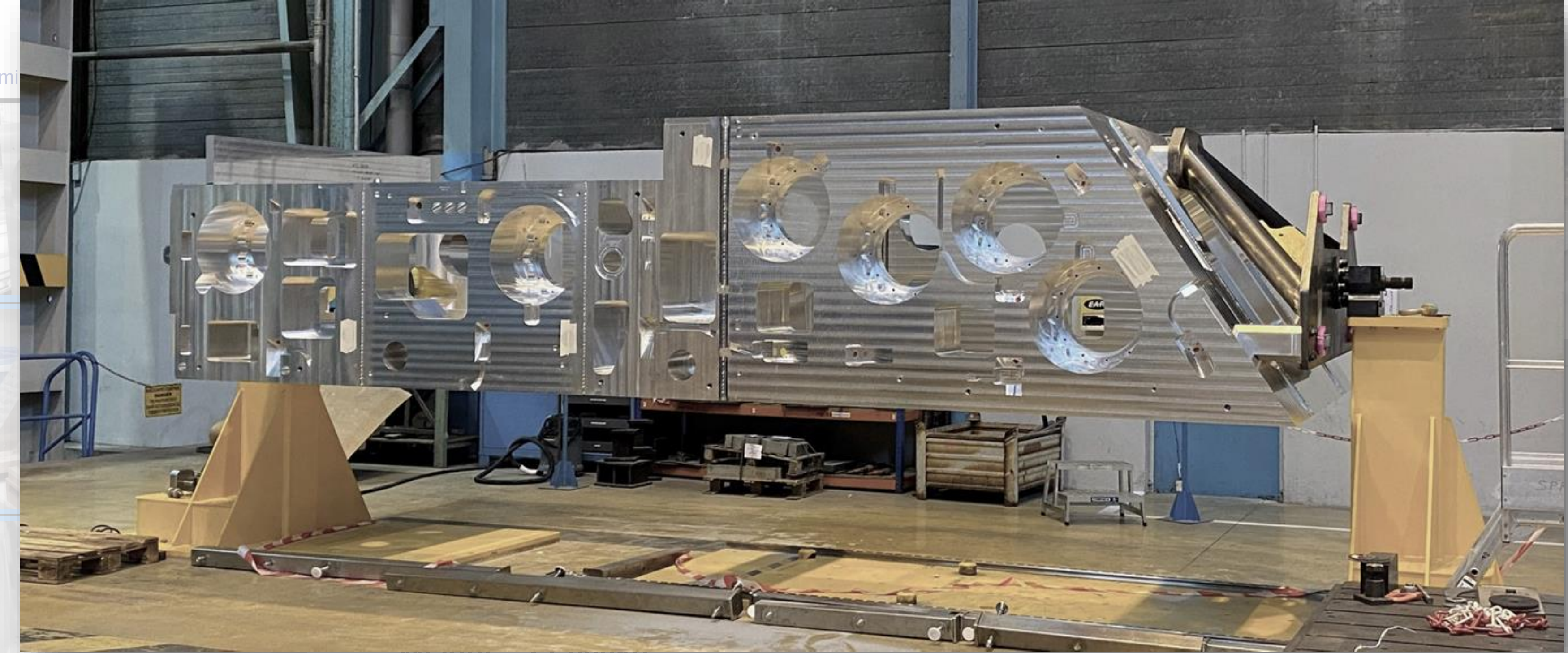
Four sections ready for welding

After welding

Base Frame pre-milling of sections completed

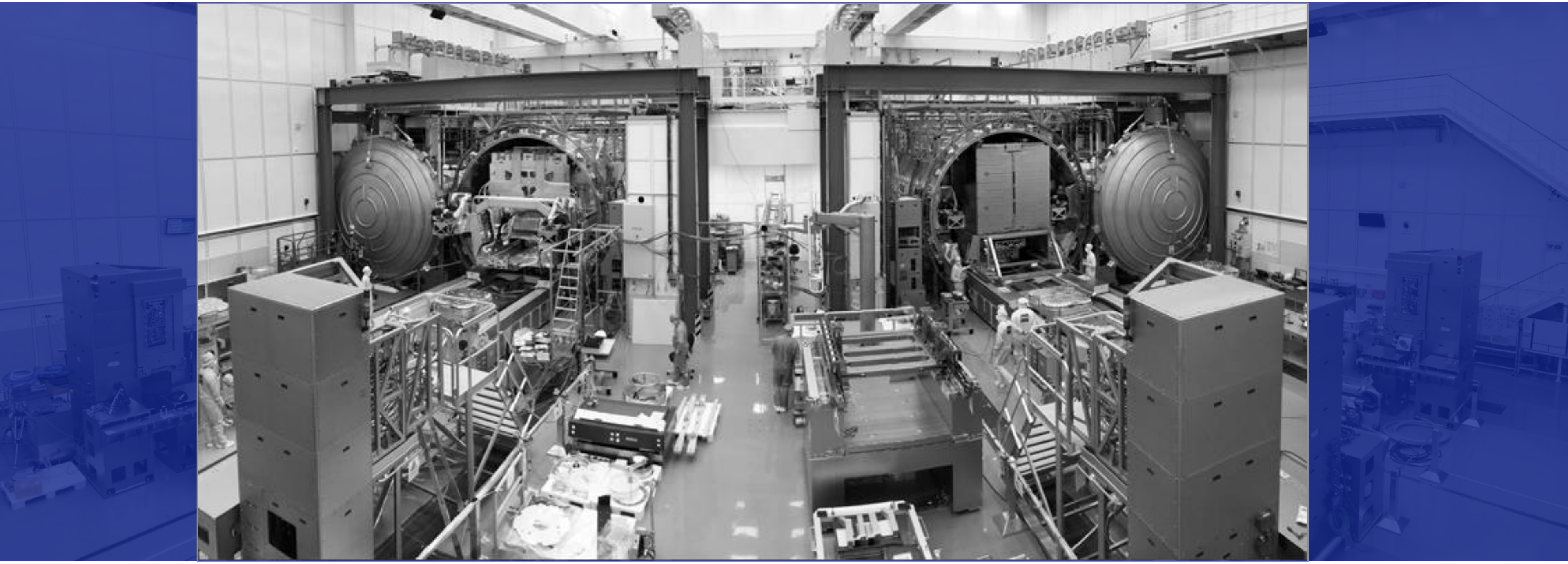
e-beam welding in progress

Robotic welding



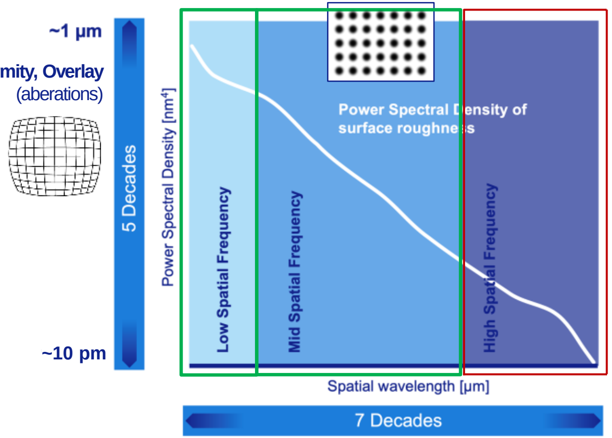
Mirror metrology systems are operational

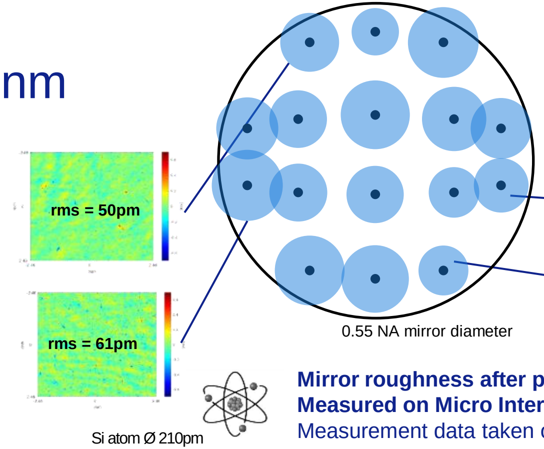
and support mirror polishing loops

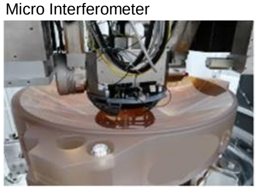


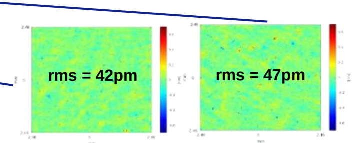
Mirror Metrology results

Figure performance now below 1nm



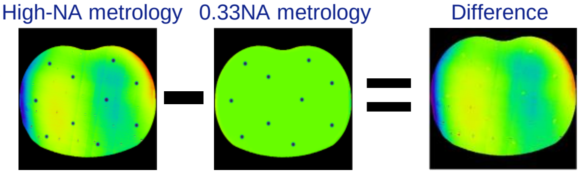


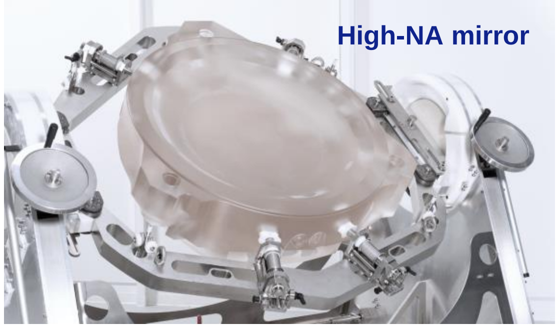


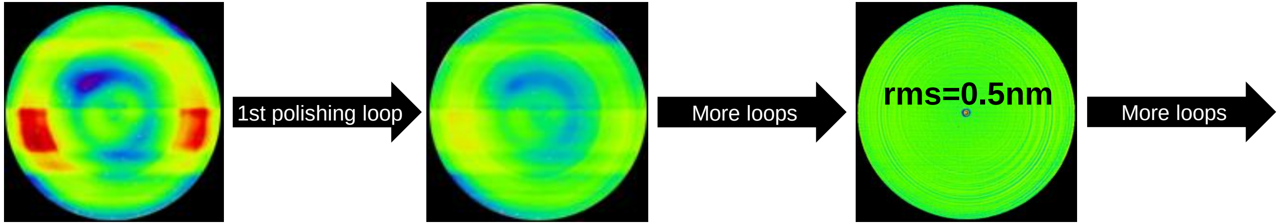


Mirror roughness after polishing <61pm for all measurement points.
Measured on Micro Interferometer (Field of View ~5mm)
Measurement data taken on sample positions (no full surface coverage)

1st crosscheck with known 0.33NA mirror





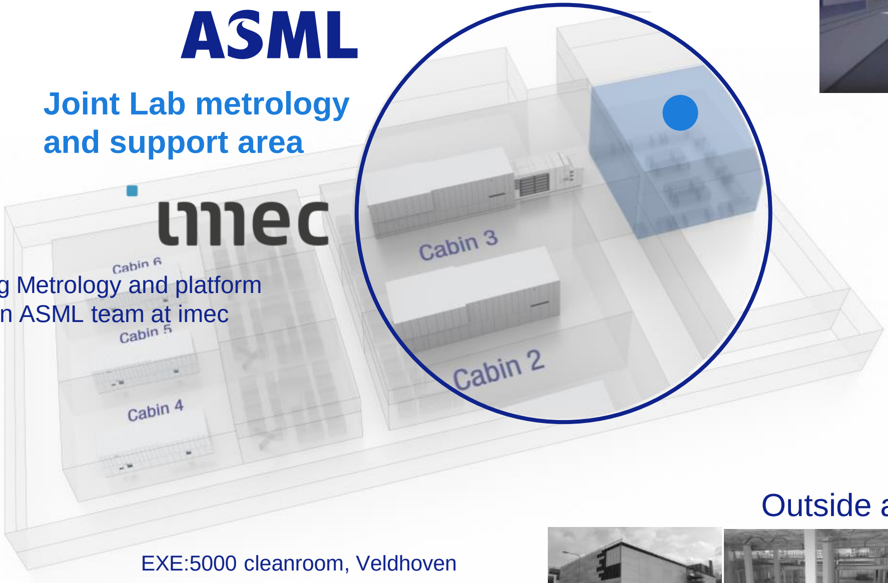


Ref: Lars Wischmeier, this workshop

EXE facilities on track for first High-NA proto

Will also house the ASML-IMEC Joint Lab

Joint development integrated track and metrology imec team at ASML → start in H1’23

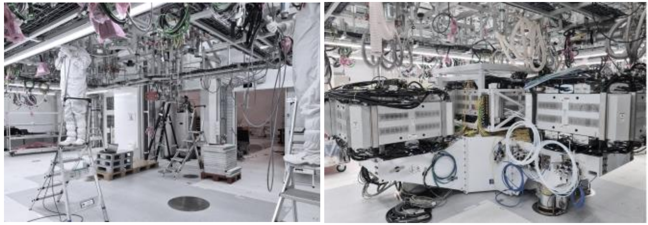


Joint Lab metrology and support area

Patterning Metrology and platform integration ASML team at imec

EXE:5000 cleanroom, Veldhoven

Equipment install for manufacturing cabins



Cabin equipment

Drive Laser

Outside almost fully closed; facilities inside in progress

High-Na Wilton (USA) facilities on schedule for fabrication top module EXE

Facilities for integration of High-NA in progress

Facilities for integration of High-NA in progress

Heaviest module test, successfully loaded in B747

28 Tons

@ Airbridge Cargo Schiphol Airport

Outline

EUV is here: Status 0.33NA

What's next? Towards High-NA

- Contrast
- Dose
- Resist

High-NA progress

- Architecture
- Industrialisation

Summary

Summary

High-NA is logical roadmap extension by improving contrast

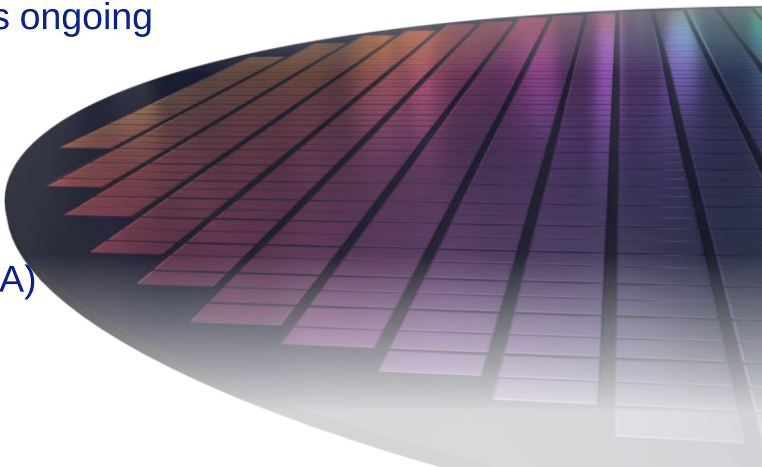
- LCDU and defect print rate reduced by improved contrast, dose and resist
- Contrast is improved by a new anamorphic lens; imaging well controlled
- Throughput maintained by stage accelerations, transmission and source power
- Economical printing for both intermediate pitches (low dose) and tight pitches (avoid DE)

High-NA EUV Scanner realization is in full progress

- Feasibility of stages, sensors and many more demonstrated
- System design available, manufacturing of multiple modules ongoing
- Optics design finalized, mirror metrology in place, manufacturing has started

Timely availability of high-NA ecosystem is needed

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



Summary

High-NA is logical roadmap extension by improving contrast

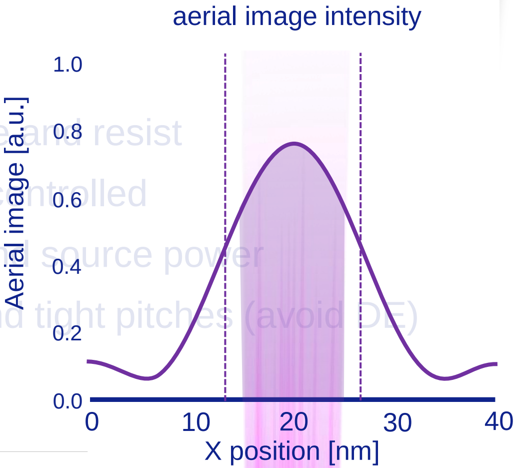
- LCDU and defect print rate reduced by improved contrast, dose and resist
- Contrast is improved by a new anamorphic lens; imaging well controlled
- Throughput maintained by stage accelerations, transmission and source power
- Economical prin dose) and tight pitches (avoid DE)

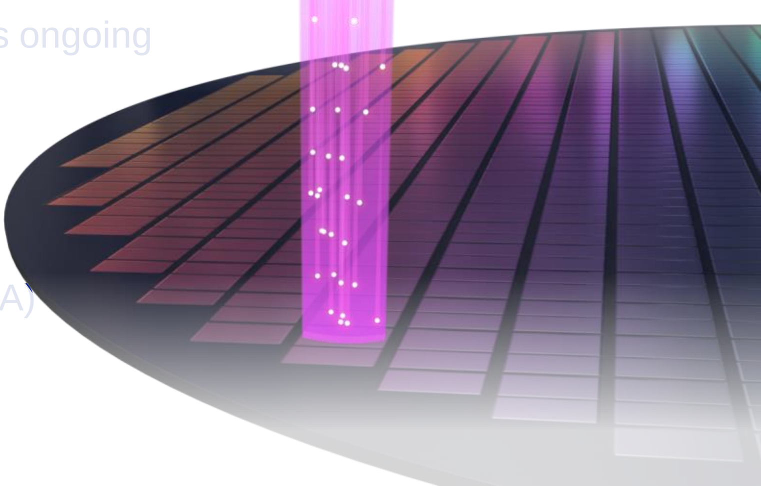
High-NA EUV Scan

- Feasibility of stages, sensors and many more demonstrated
- System design available, manufacturing of multiple modules ongoing
- Optics design finalized, mirror metrology in place
- manufacturing has started

Timely availability of high-NA ecosystem is needed

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





High contrast puts the photons where you need them

Thank you for your attention

Special thanks goes to:

- Jara Garcia Santaclara
- Joost van Bree
- John McNamarra
- Pieter de Groot
- Jason Steward
- Joost van Bree
- Chrysostomos Batistakis
- Bernardo Oyarzun
- Rob van Ballegoij
- Claire van Lare
- Rik Hoefnagels
- Lidia van Lent
- Zuhal Tasdemir, PSI
- Patrick Naulleau, CXRO
- Chris Anderson, CXRO
- Paul Graeupner
- Gijsbert Rispens
- Gerardo Bottiglieri
- Harry van der Schoot
- Jeannot Driedonkx
- Peter Kuerz
- Thomas Stammler
- Winfried Kaiser
- Sjoerd Lok
- Eelco van Setten
- Ruben Maas
- Kars Troost
- Rudy Peeters
- Jo Finders
- Judon Stoeldraijer
- Jos Benschop

And the High-NA teams in Wilton,
San Diego, Oberkochen, and Veldhoven

This work was funded by the European Commission and the Federal Ministry of Education and Research (Germany) by the ECSEL JU Grant Agreement SeNaTe (662338, FKz 16ESE0036K), TAKE5 (692522, FKz 16ESE0072K), TakeMi5 (737479), and TAPES3 (783247, FKz 16ESE0287K).