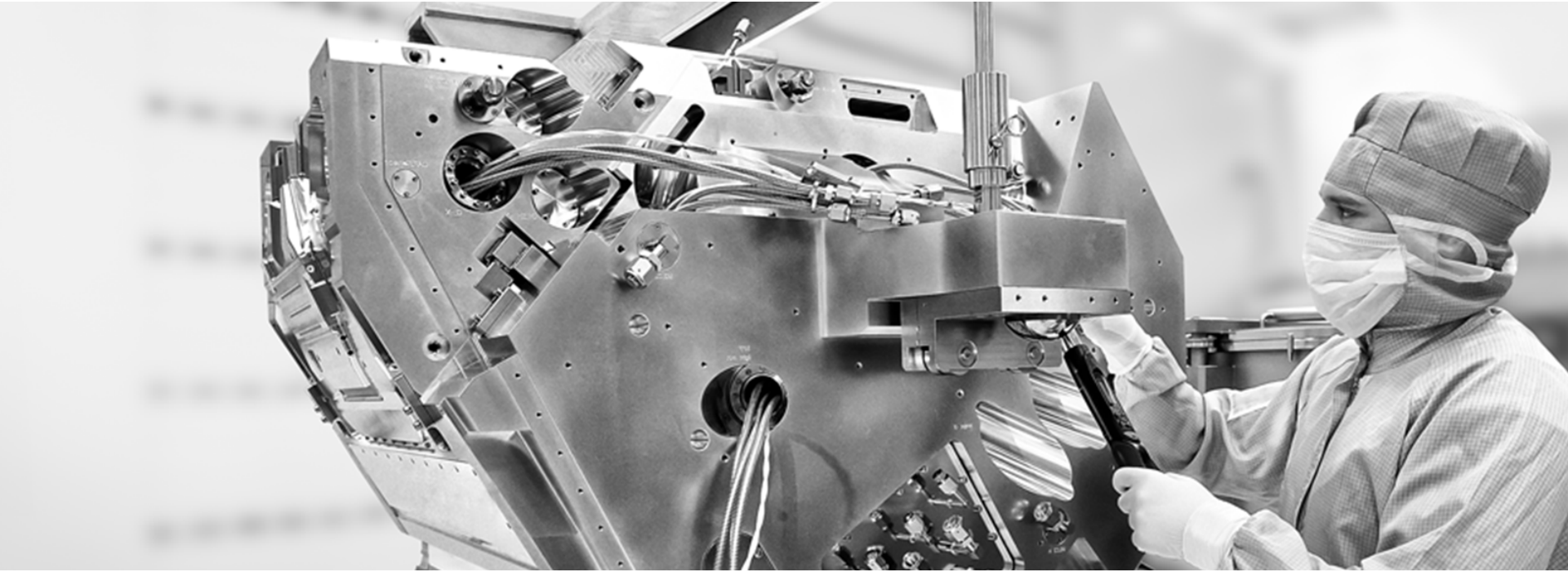
EUV Optics: Achievements and Future Perspectives



Winfried Kaiser

International Symposium on Extreme Ultraviolet Lithography 2015

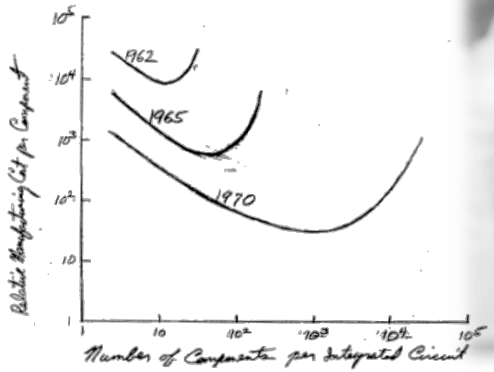
October 7th, 2015

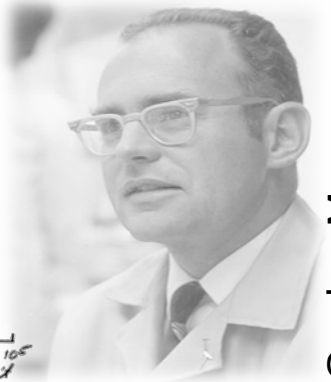
Maastricht

Photo: Bernd Geh

Moore‘s Law and how it relates to optics

Moore‘s Law (1965)





Gordon Moore

Moore‘s Law drives the requirements on the optical system.

“Transistor density doubles every 24 months.“

Abbe Equation (1873)

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

CD … Resolution / Critical Dimension

k_1 … Process Factor (Contrast)

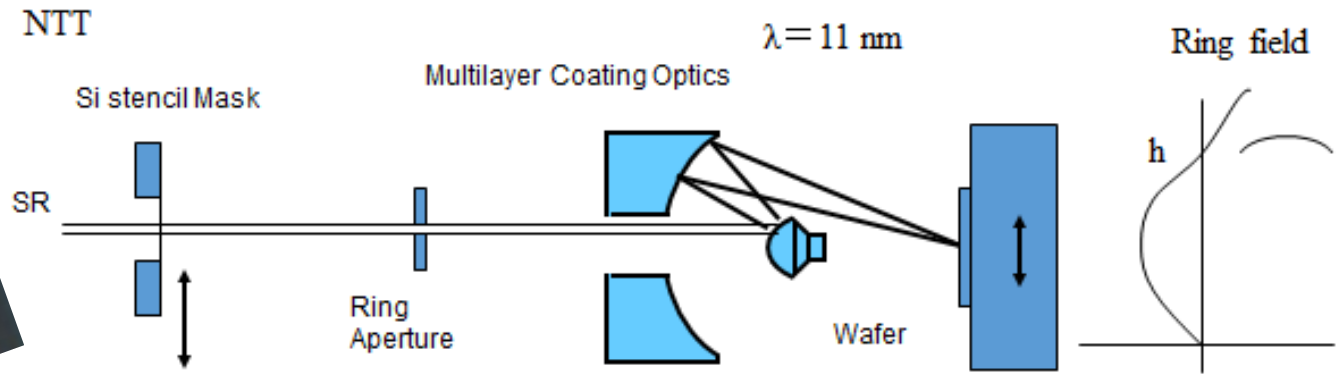
λ … Wavelength

NA … Numerical Aperture

Ernst Abbe

“Optics resolution improves ~30% with each new generation.“

Prof. Kinoshita “invented“ EUVL 30 years ago



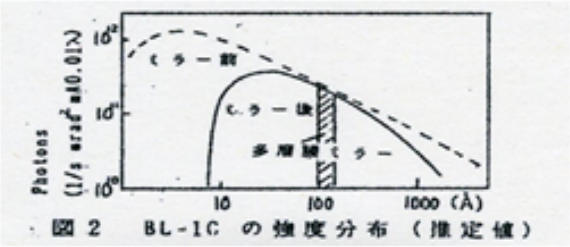


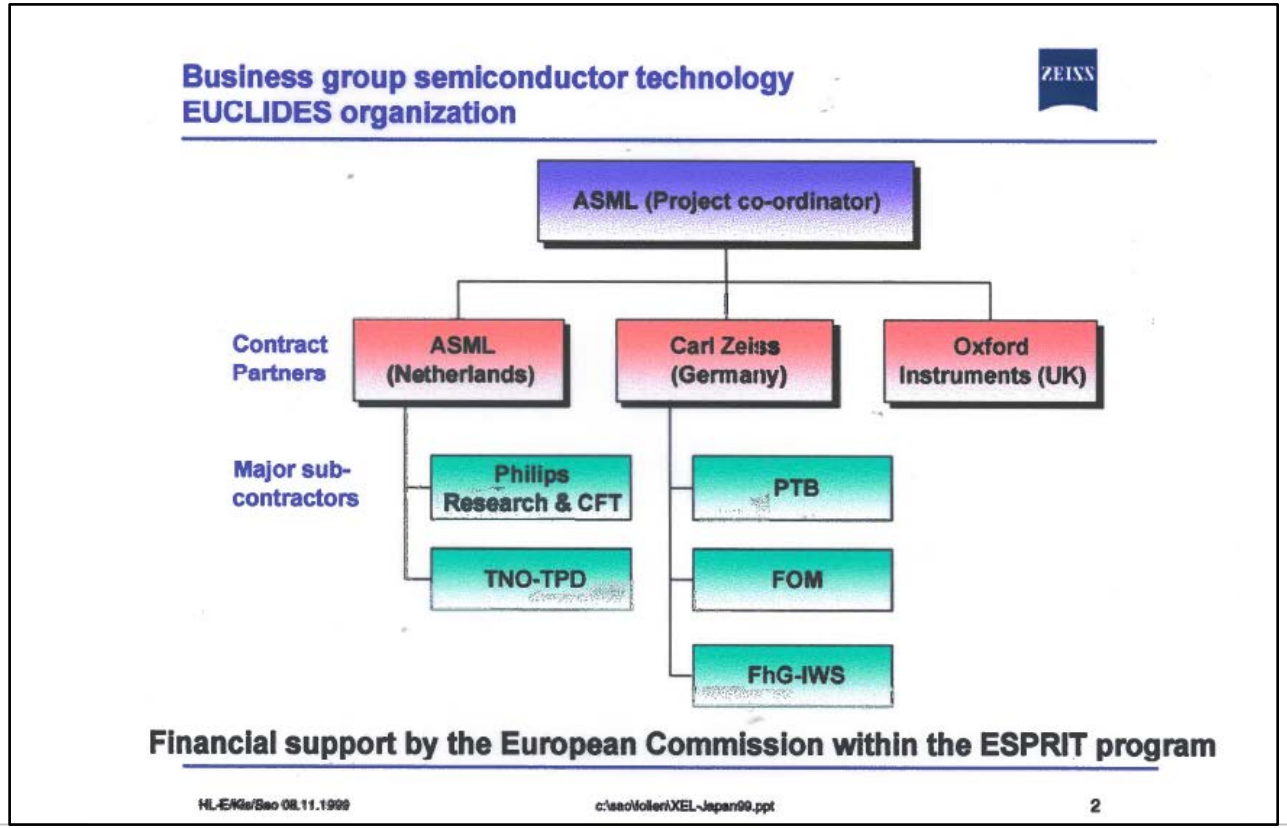
図 2　BL-1C の強度分布（推定値）

図 3　露光パターン例　PMMA(0.2um)/Si

(J. Vac. Sci. Technol. B7(6), Nov/Dec 1989)

EUV Workshop | November 13th/14th, 1995

EUCLIDES was the 1st European EUV research project (1997 – 2000)



In search of the Next Generation Lithography („NGL“): Optics Issue #1 for EUV

Critical Issues of Advanced Lithography Technologies (EPL and EUV Issues from Dec ’98 NGL Task Force)

Alternative	193nm + O.E.	157nm	EUV	EPL
Critical Issue #1	Progress on exposure tools to support 100nm node	Feasibility of a pellicle solution	Full Field Optical Design	Beam blur relation to D, TPT, and IP vs. feature size
Critical Issue #2	Progress on masks to support the 100nm node	Incorporation of purging into exposure tool design	Defect free mask mfg. at 65nm	Wafer heating
Critical Issue #3	Progress on resists to support the 100nm node	Timing / Risk of production tools for the 100nm node	Defectivity and thermal mgmt. of ULE masks	Dynamic stitching vs. throughput
Critical Issue #4	Assessment of 193nm Lithography to do 100nm node	Feasibility of 157nm resists	Specifications & CoO for debris free source	Defect free mask mfg. at 65nm
Critical Issue #5	------	Quality and scale-up of modified fused silica supply	Defect density scaling vs. size to 55nm	Electron proximity correction
Critical Issue #6	------	CoO of 157nm vs. 193nm with optical extensions	Defectivity of thin layer imaging (TLI)	Alignment capability

Advanced Lithography Critical Review Task Force Assessment of

The best asphere in the world in 1998 …

M3 is the best EUV normal incidence element ever fabricated

Coated M3 Figure Error Measured with PSDI at LLNL

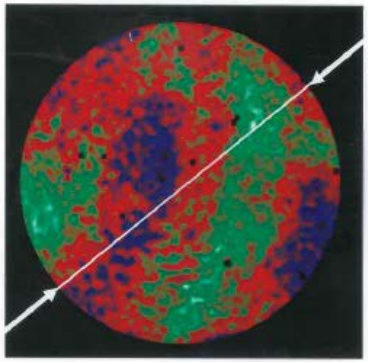
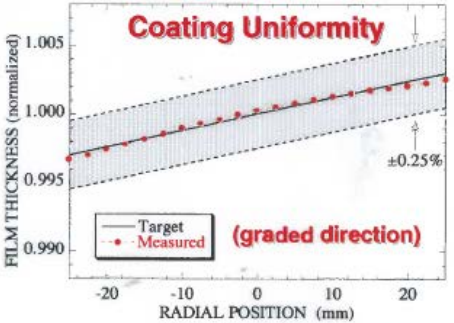


Figure = 0.38 nm rms
MSFR = 0.22 nm rms
HSFR = 0.14 nm rms
Mo/Si Fig. Error = 0.013 nm rms
Reflectance = 65%

M3 with Mo/Si Coating

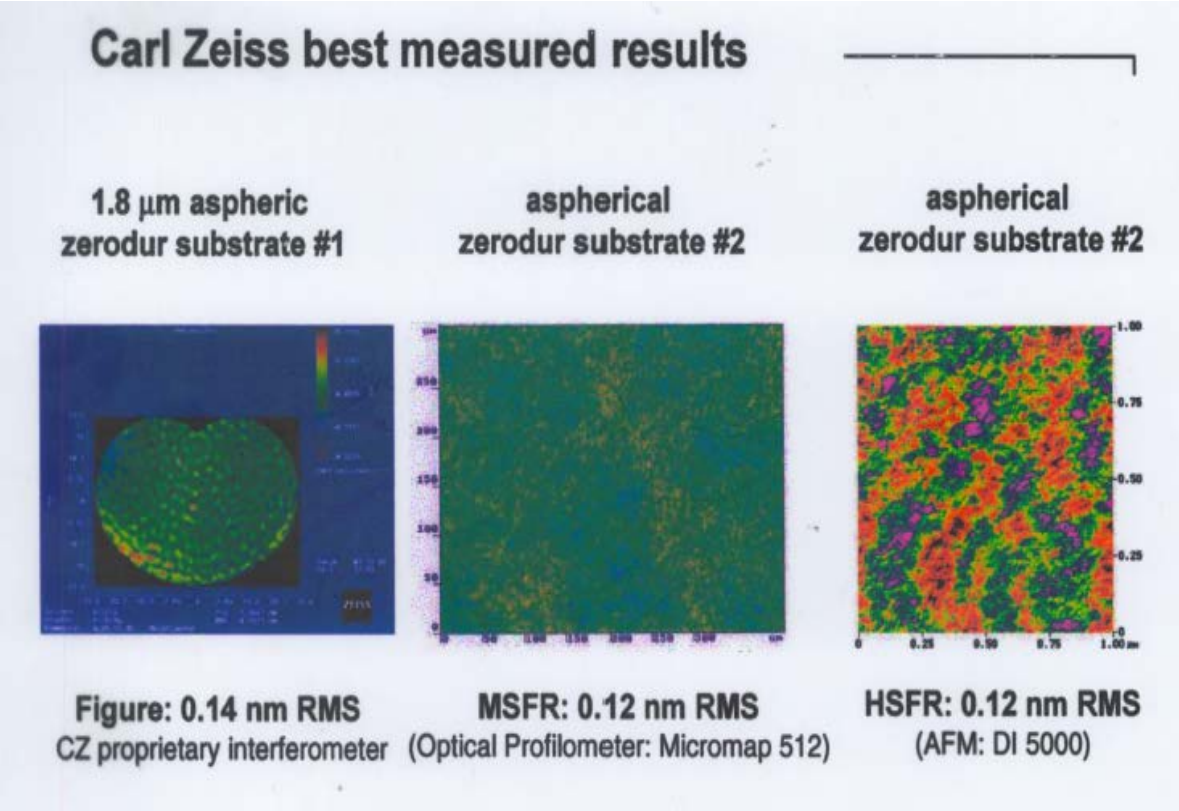


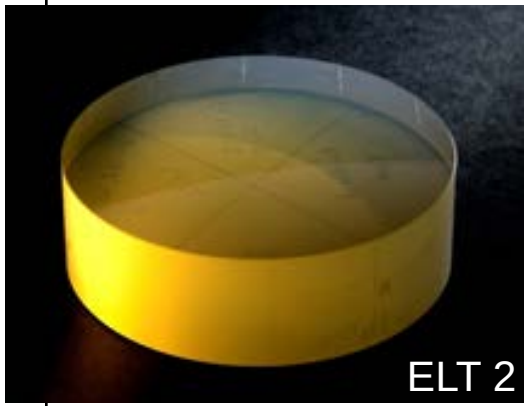
John S. Taylor
M9801258

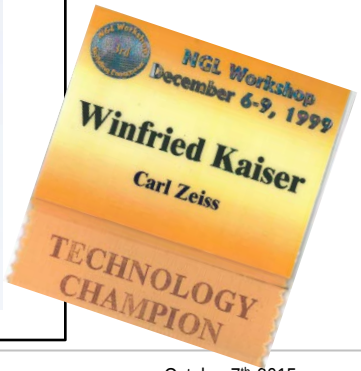
EUV LLC Business Sensitive
3

EUV LLC Quarterly Review
December 15, 1998

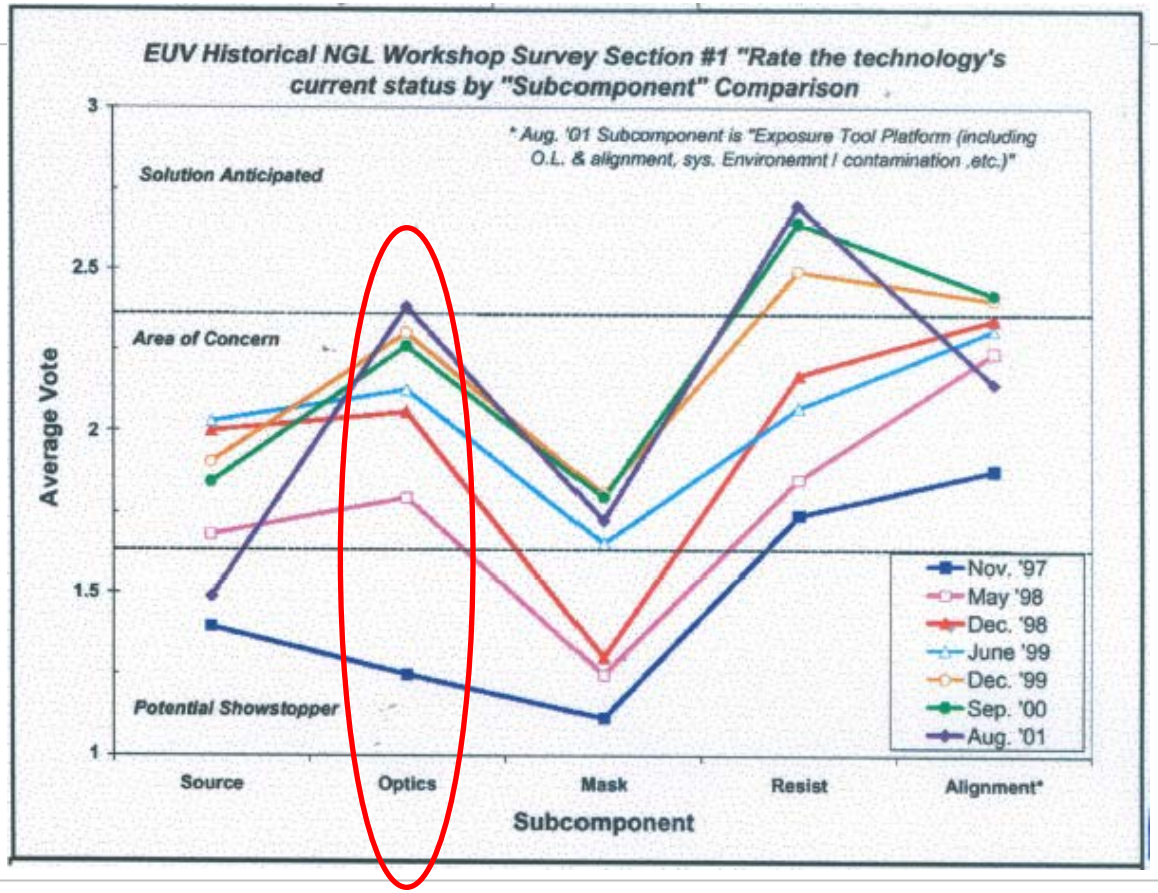
… and in 1999:


Carl Zeiss best measured results
1.8 µm aspheric
zerodur substrate #1
aspherical
zerodur substrate #2
aspherical
zerodur substrate #2
Figure: 0.14 nm RMS
CZ proprietary interferometer
MSFR: 0.12 nm RMS
(Optical Profilometer: Micromap 512)
HSFR: 0.12 nm RMS
(AFM: DI 5000)

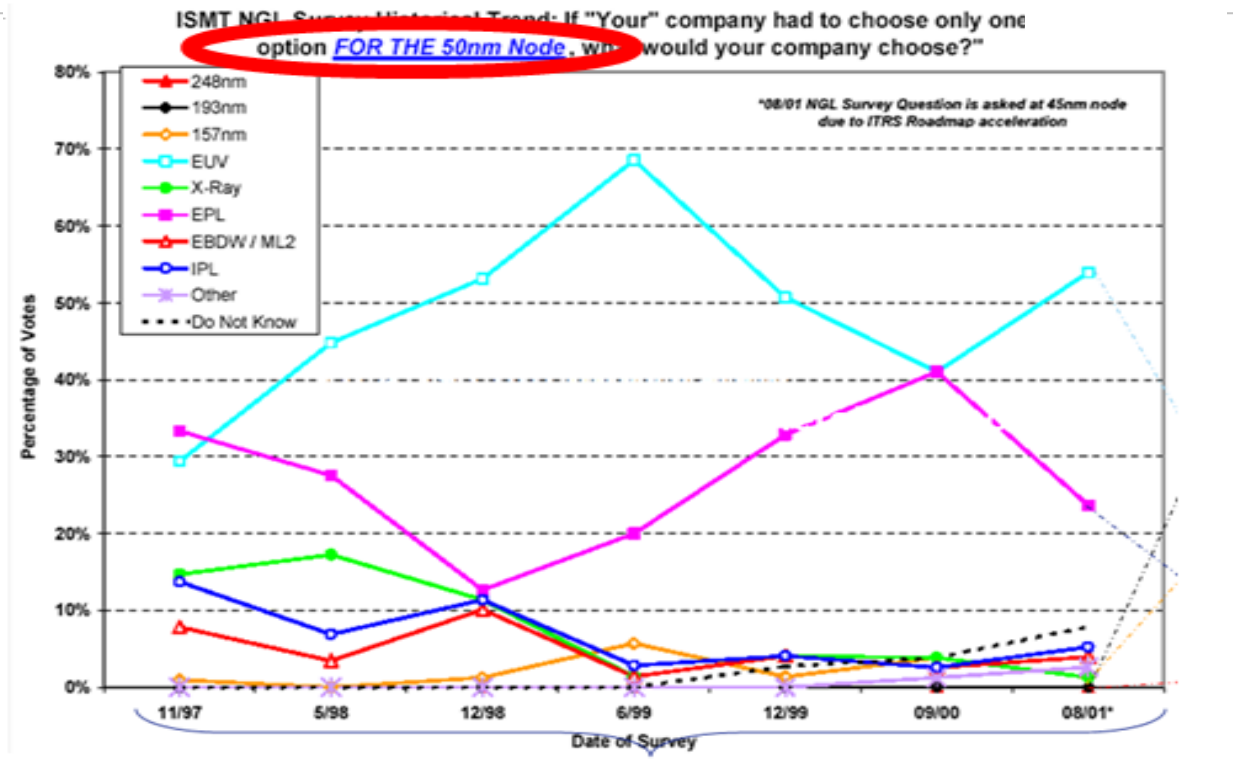

ELT 2


NGL Workshop
December 6-9, 1999
Winfried Kaiser
Carl Zeiss
TECHNOLOGY
CHAMPION

Optics ranking improves from “showstopper“ to “solution“



EUVL became the winner of the NGL race



The 1st ZEISS EUV optics system: a small field system for the Micro Exposure Tool (“MET”)

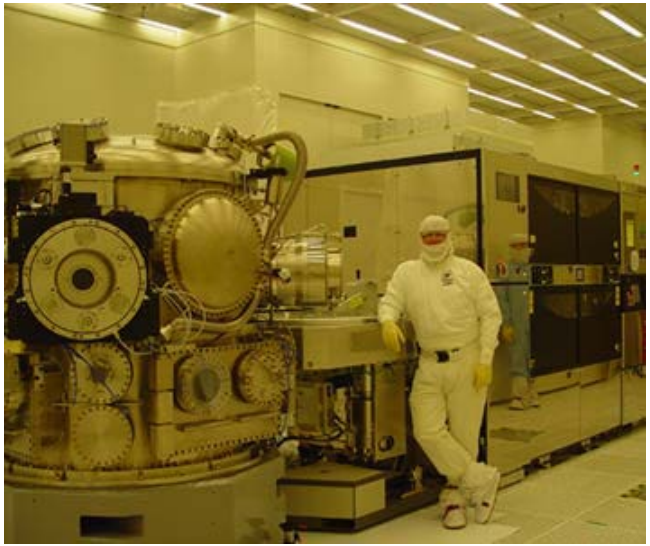
Production readiness achieved

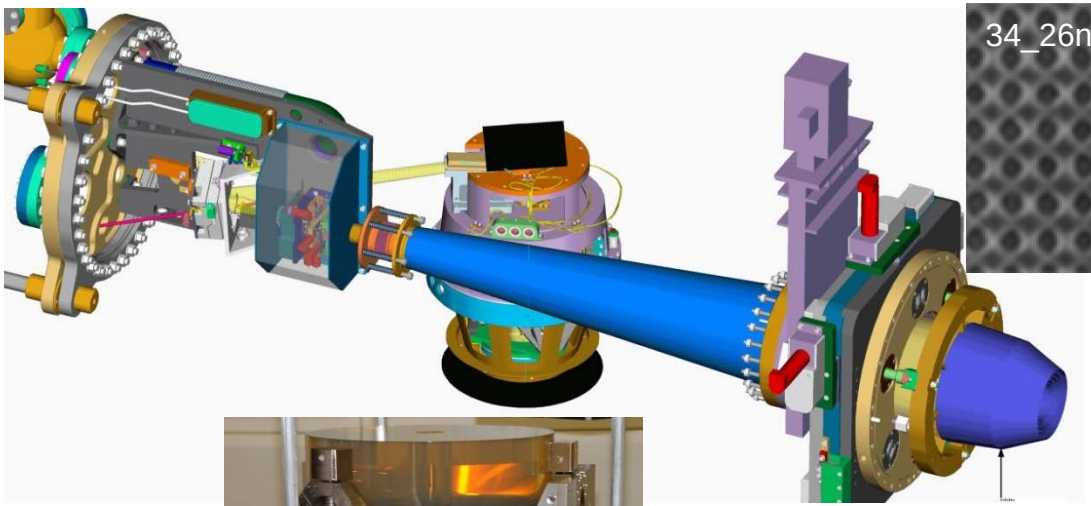
Development phase ongoing

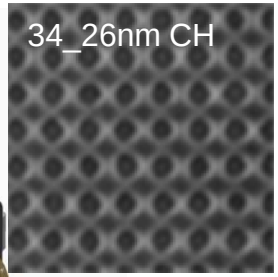
1995 — 2003 — 2006 — 2009 — 2012 — 2015 — 2018

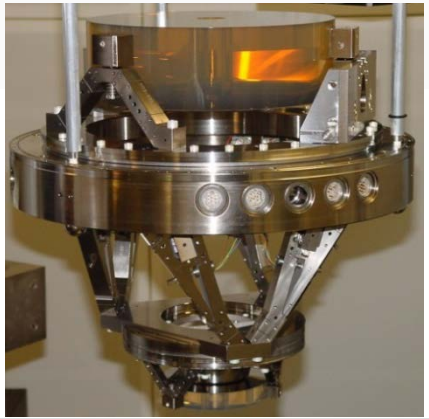
MET
Micro Exposure Tool

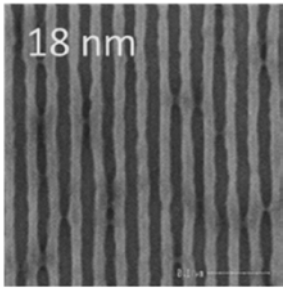
The Micro Exposure Tool is supporting EUV research since 12 years

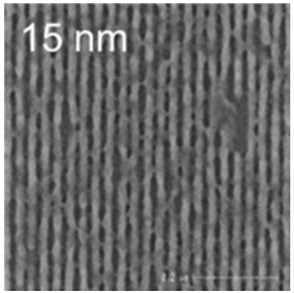












EUV Microstepper Optics (MET) developed in cooperation with LLNL and LBNL
2003: First Microstepper operating in Berkeley
2004: Exitech Microsteppers
2010: Illuminator upgrade with 0.9 sigma
2015: “MET 5” redesign with 0.5NA (Zygo/ZEISS)

Source (resist prints images): Sematech

The 1st EUV full field system: Optics for ASML ADT/ NXE: 3100

Production readiness achieved

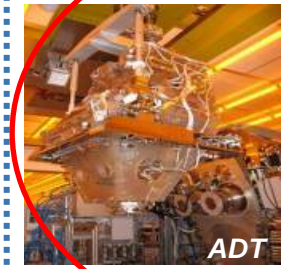
Development phase ongoing

1995 | 2003 | 2006 | 2009 | 2012 | 2015 | 2018

MET
Micro Exposure Tool

ADT
(α-Demo Tool)

Starlith® 3100

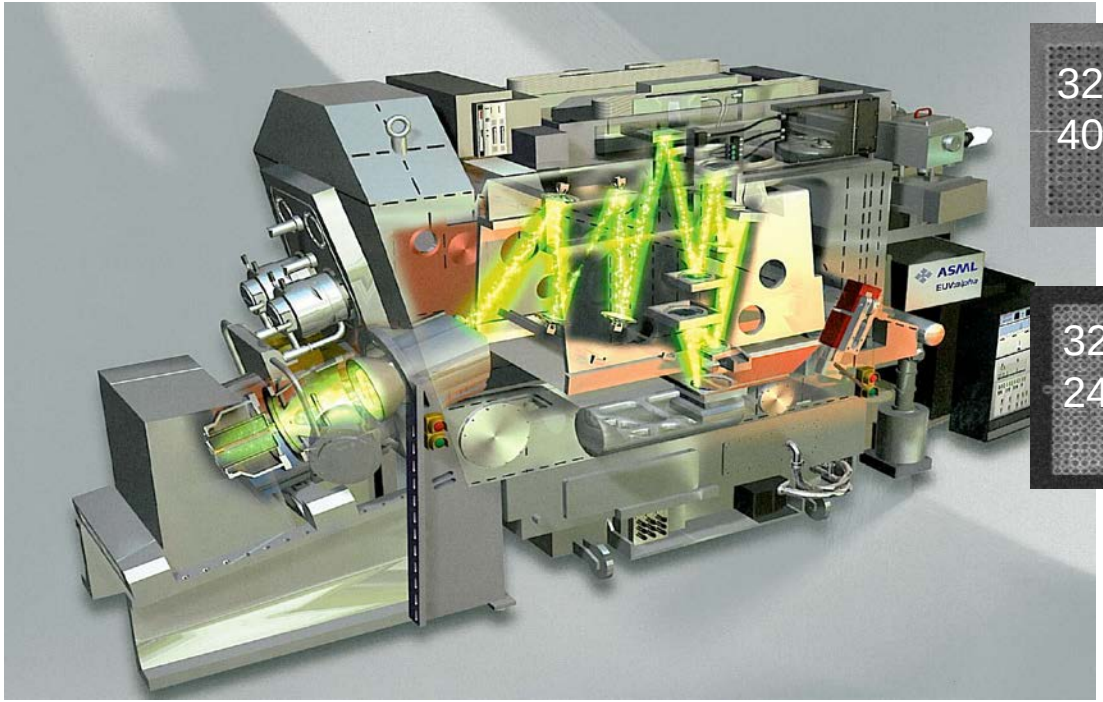


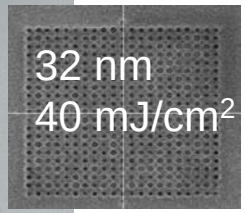
The 1st EUV full field system: Optics for ASML ADT/ NXE: 3100

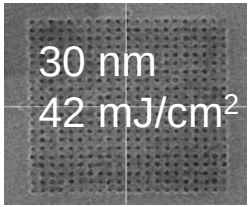
λ	13.5 nm
NA	0.25
Field	26 x 33 mm²
Mag.	4x
Res	32/27 nm

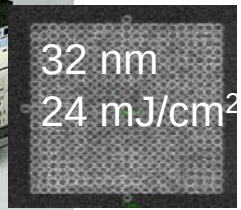
design scheme

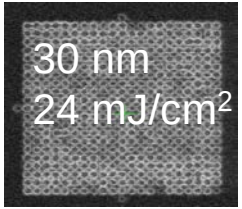
A sketch of the Status Alpha Demo Tool, the 1st EUV full field scanner …











1st scanner able to print dense features in single exposure

... and the ASML NXE: 3100 in full size with improved POB and upgraded illuminator

Starlith® 3300 and 3400 are designed for HVM

Production readiness achieved

Development phase ongoing

1995 2003 2006 2009 2012 2015 2018

MET
Micro Exposure Tool

ADT
(α-Demo Tool)

Starlith® 3100

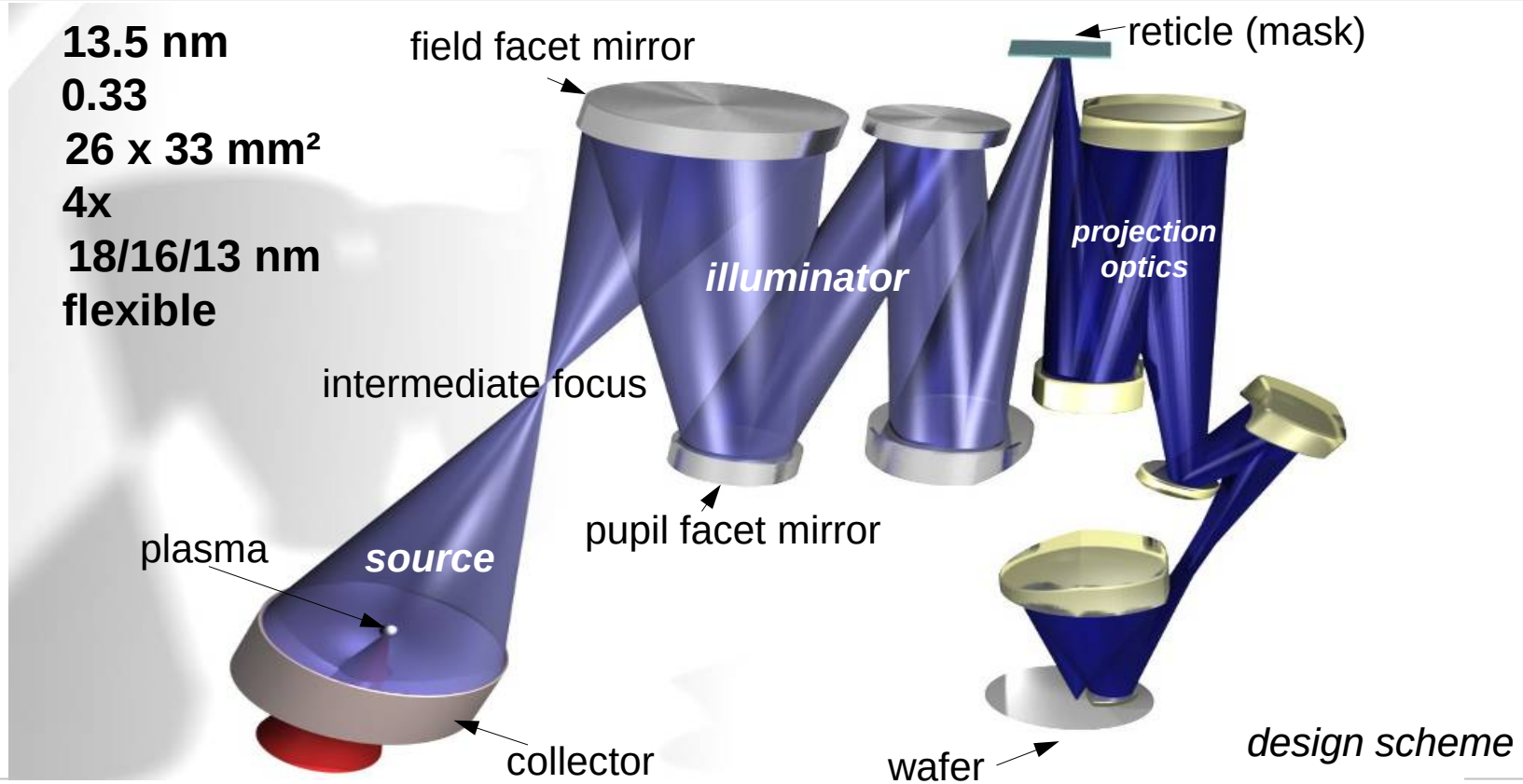
Starlith® 3300

Starlith® 3400

High NA

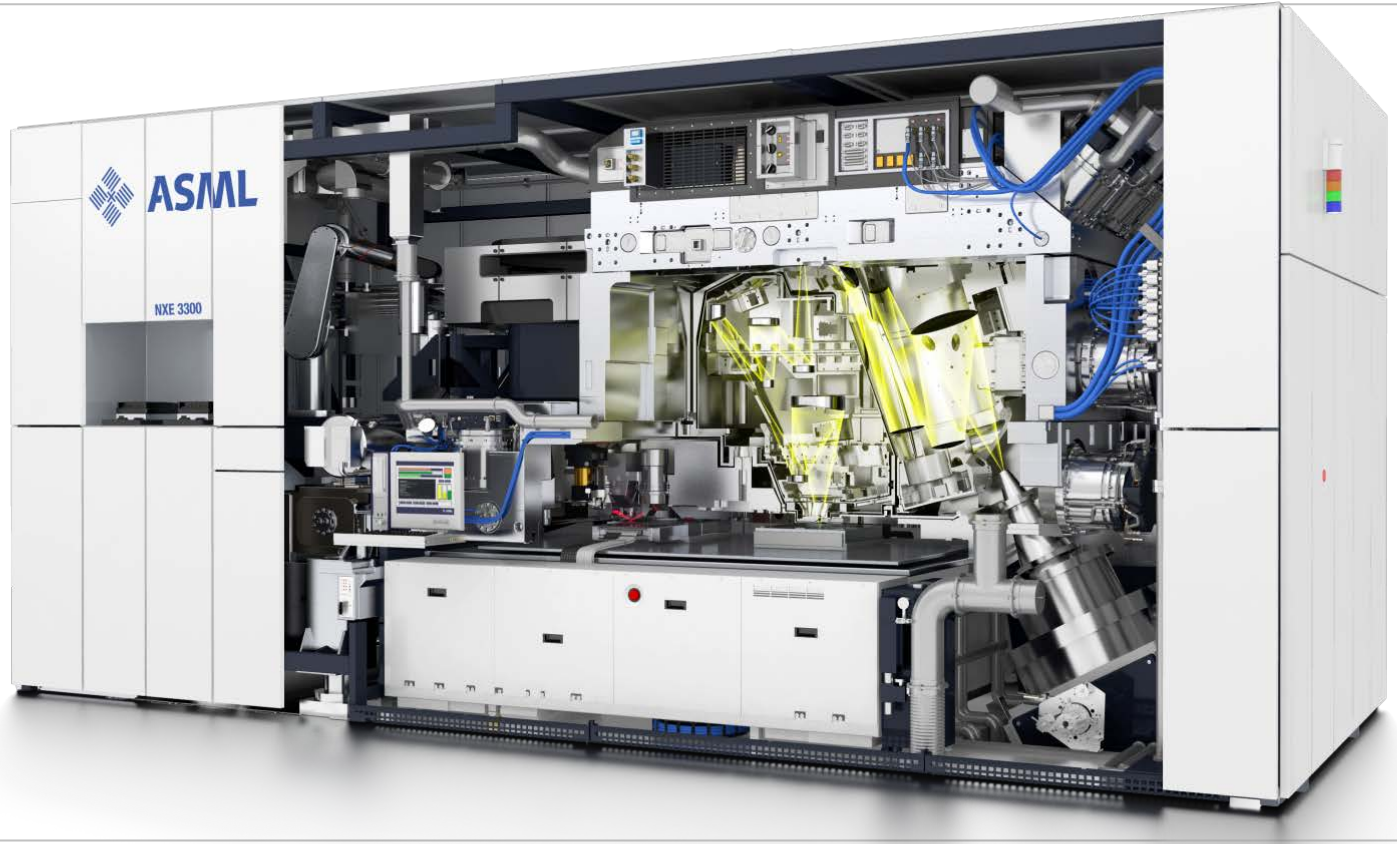
The solution for volume production: Starlith® 3300/3400

λ	13.5 nm
NA	0.33
Field	26 x 33 mm²
Mag.	4x
Res	18/16/13 nm
Illu	flexible

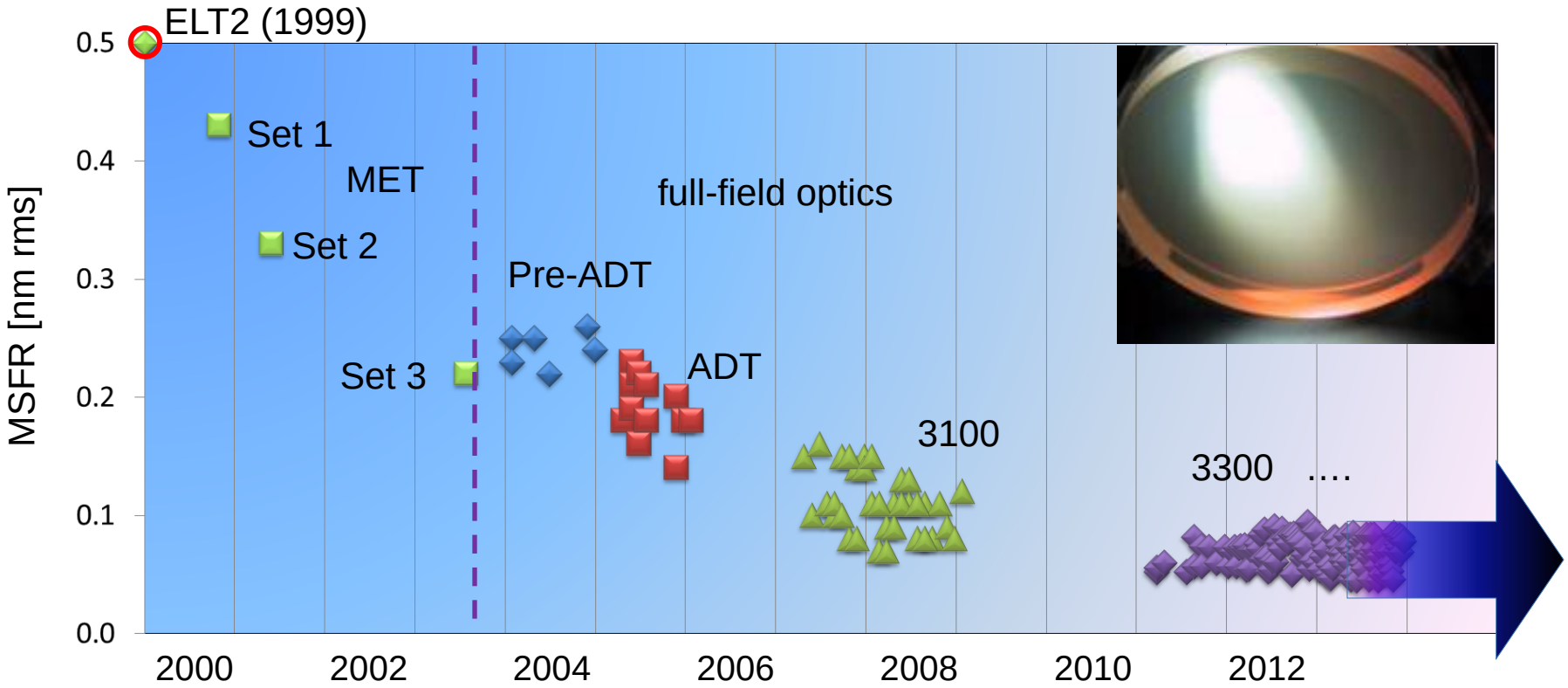


design scheme

… for the ASML NXE: 3300B

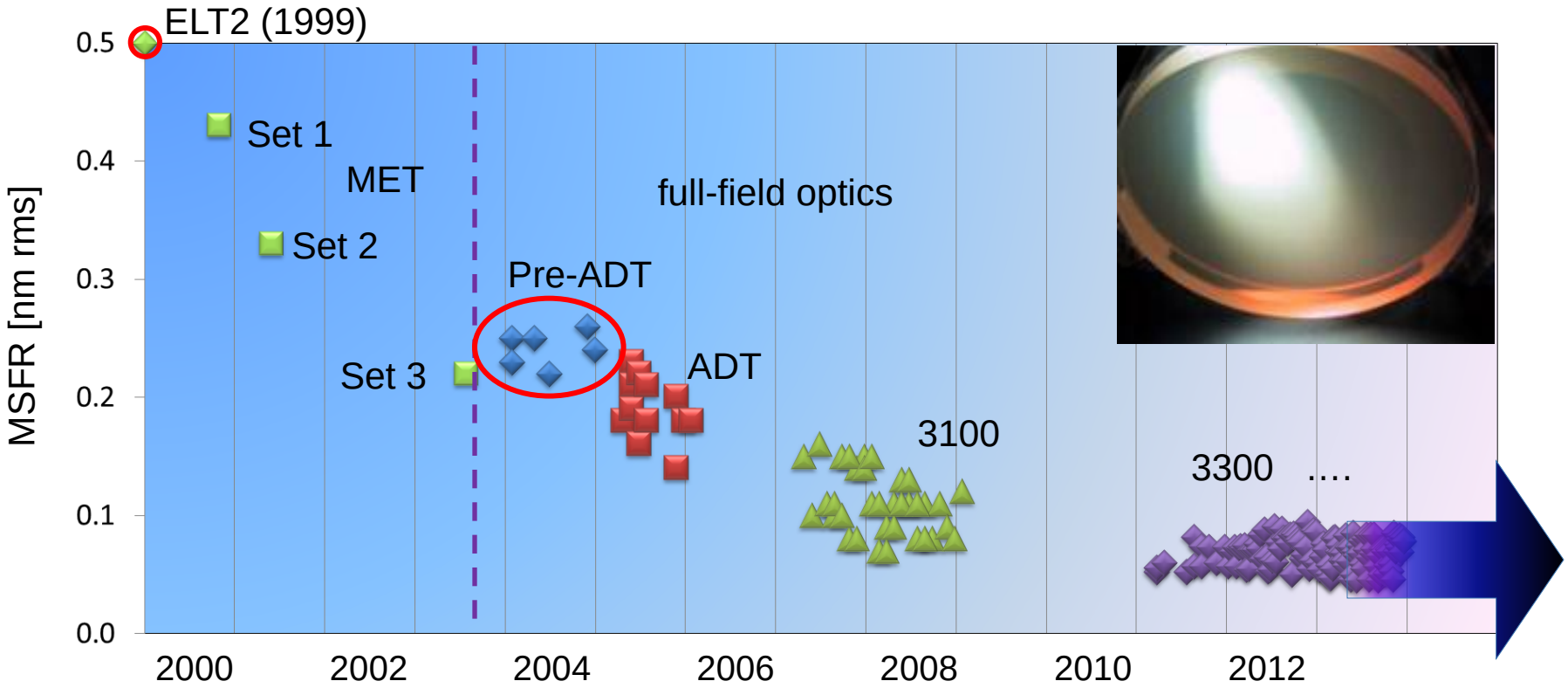


MSFR improved significantly…



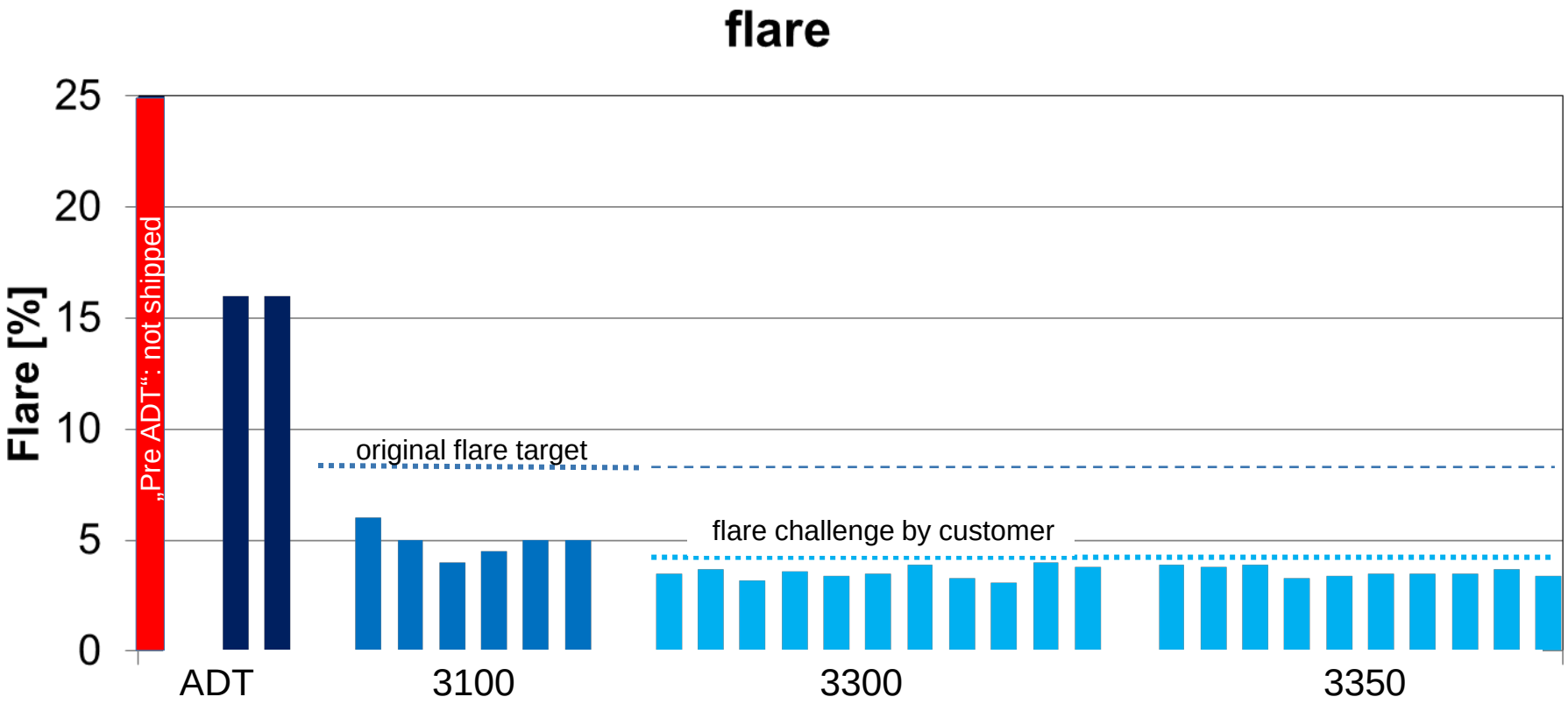
Note: all MSFR values here are based on the same definition as for 3100/3300

MSFR improved significantly …

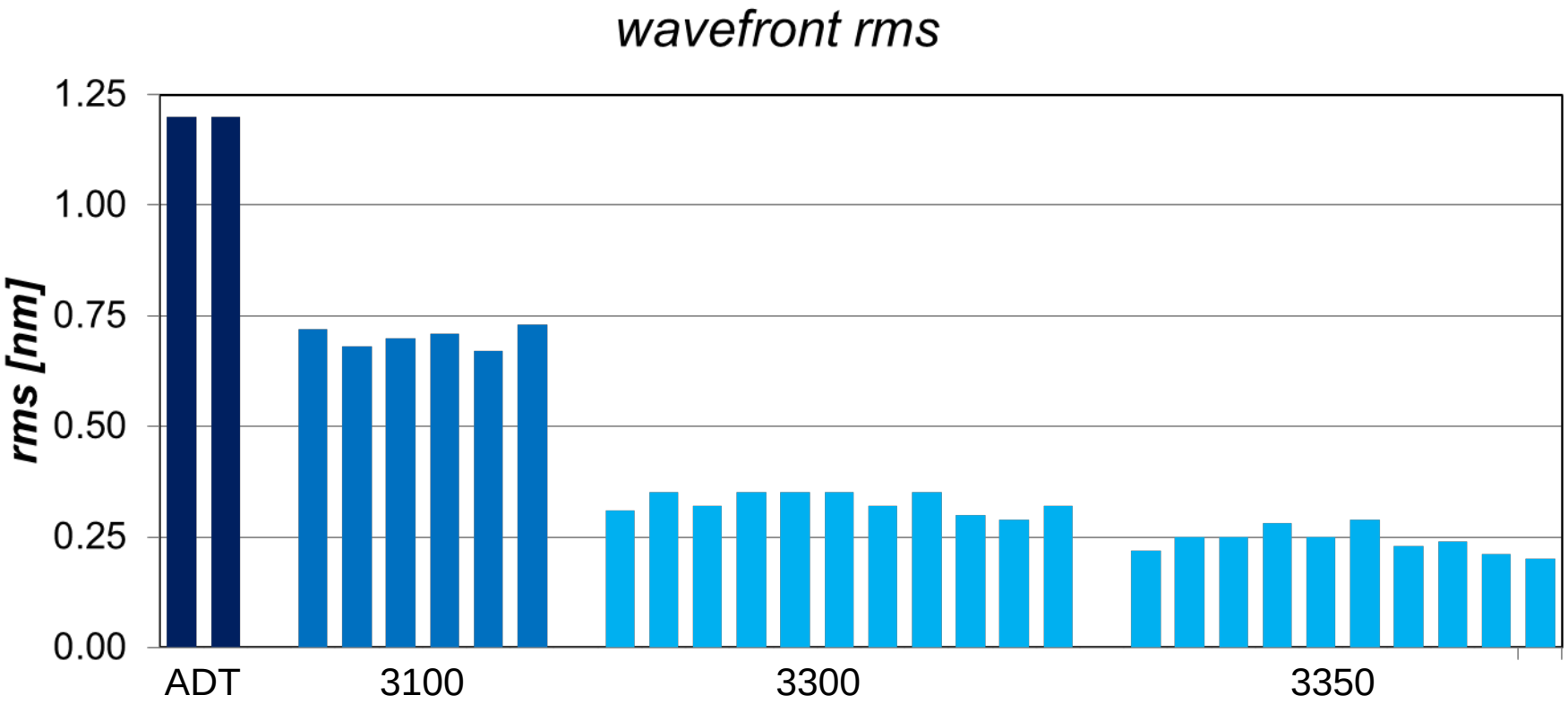


Note: all MSFR values here are based on the same definition as for 3100/3300

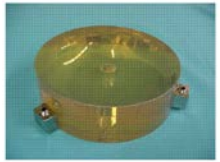
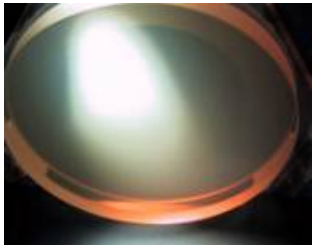
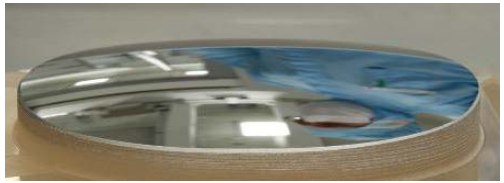
… and reduced flare to satisfying levels meeting a challenging target



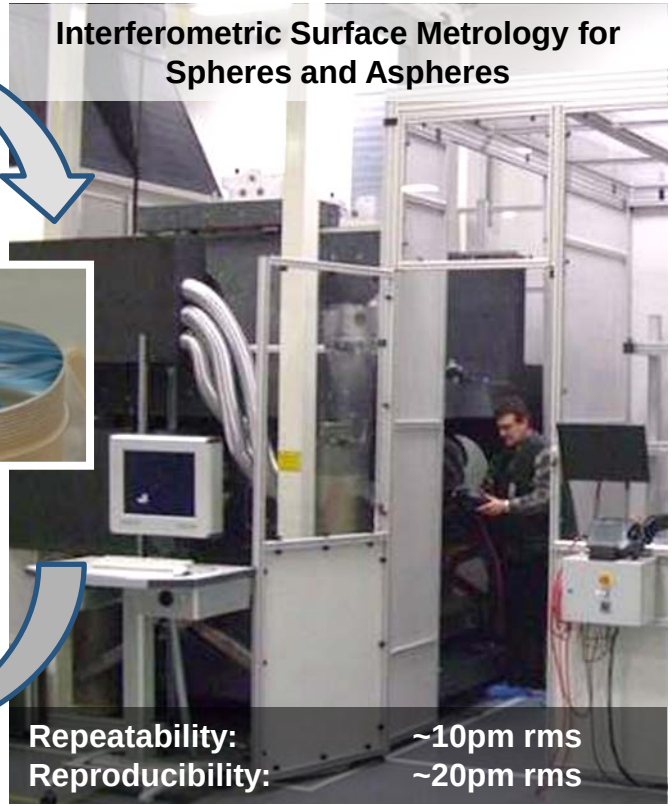
Also wavefront performance was strongly improved



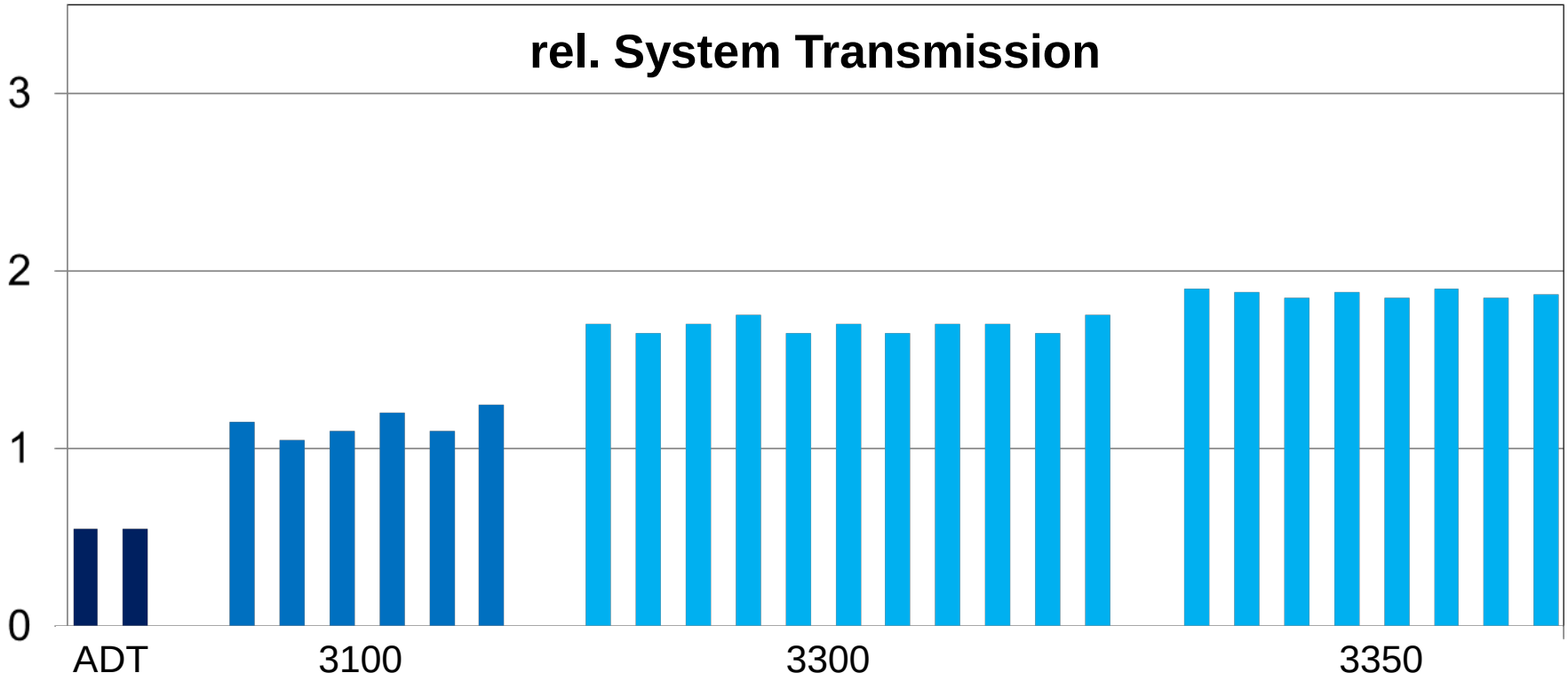
Mirror fabrication: The sizes and challenges get bigger with each generation of EUV tools enabled by …

	MET	ADT	3100	3300
Photos show relative mirror size				
Figure [pm rms]	350	250	140	~75 → aberrations
MSFR [pm rms]	250	200	130	~100 → flare
HSFR [pm rms]	300	250	150	~100 → light loss

… manufacturing technologies and metrology closing the loop for figure control on atomic level

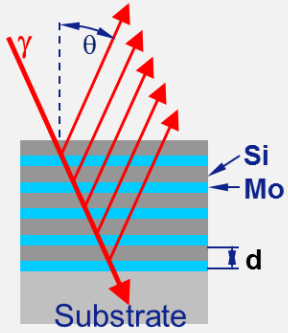


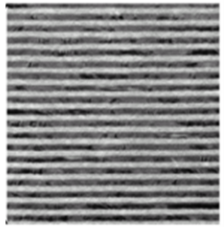
Transmission improved by reduced mirror roughness, optimization of the optic design and…



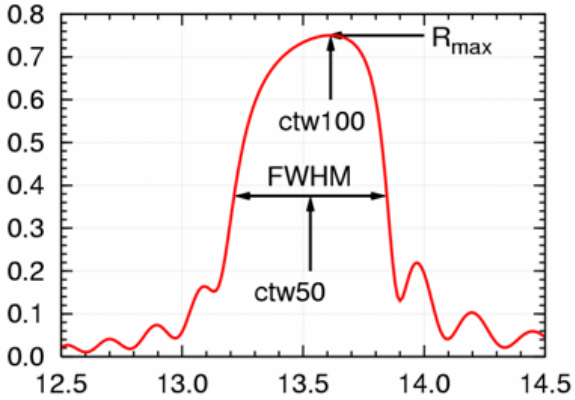
… coating technology:
the multi-layer coating defines EUV and needs…

EUV Coating:
Mo/Si
Bragg Reflectors





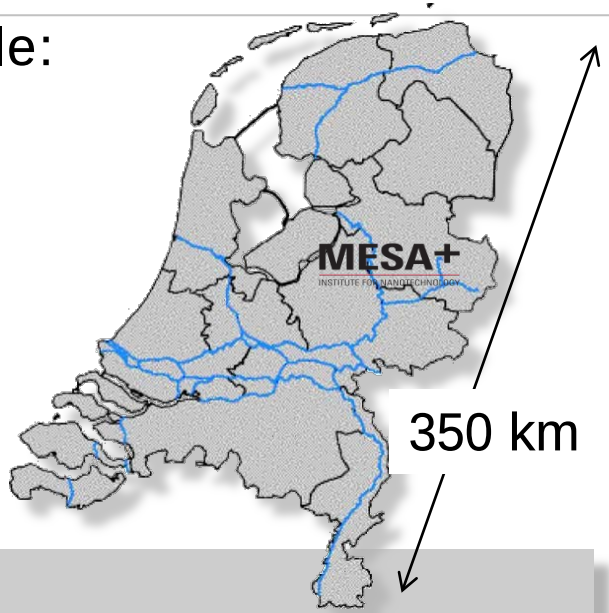
> 50 Bi Layers



Reflectivity	>67%, high bandwidth
Layer thickness control	<0.2%
Lateral uniformity	<0.2%
Coating stress	100 MPa
Thermal stability	200°C

…Sub-atomic coating accuracy

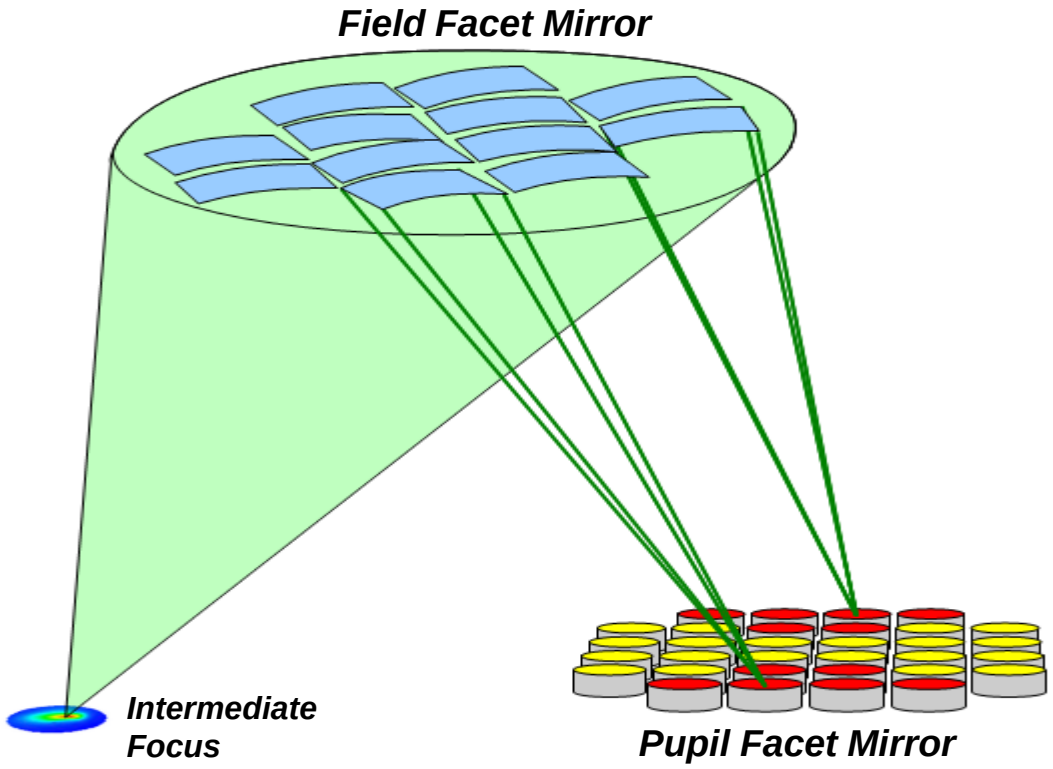
Deposition accuracy on a macroscopic scale:



Cover The Netherlands by 0.5 m of asphalt,
with a reqd accuracy of the thickness of 7 sheets of letter paper
> achieved an accuracy of the thickness of a single sheet …

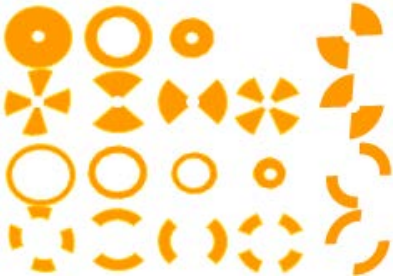
Courtesy Fred Bijkerk, MESA+ Institute, Twente

EUV Flex Illuminator allows lossless changes of settings for the optimization of image contrast



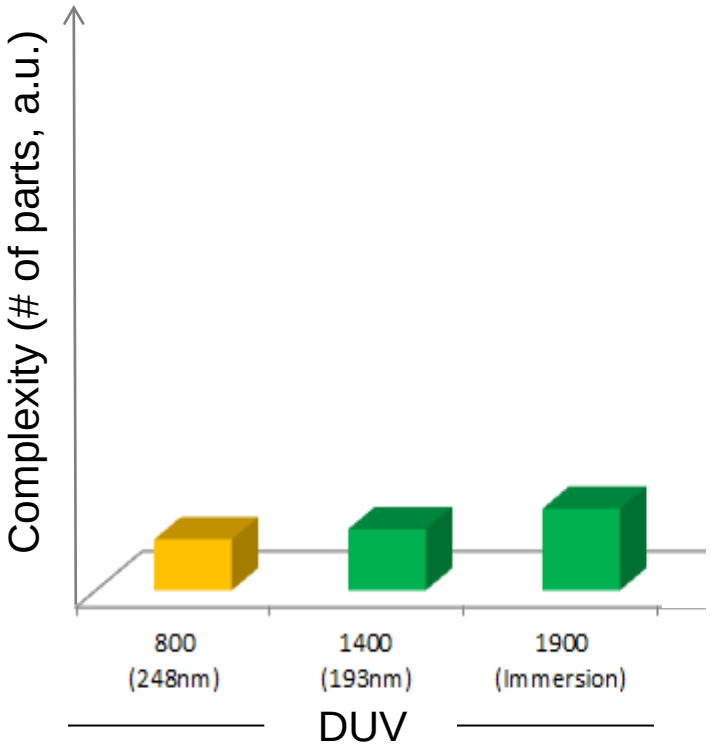
3300:
one field facet can address two pupil channels

3400:
one field facet can address many pupil channels
Smaller pupil fill ratio
Larger sigma

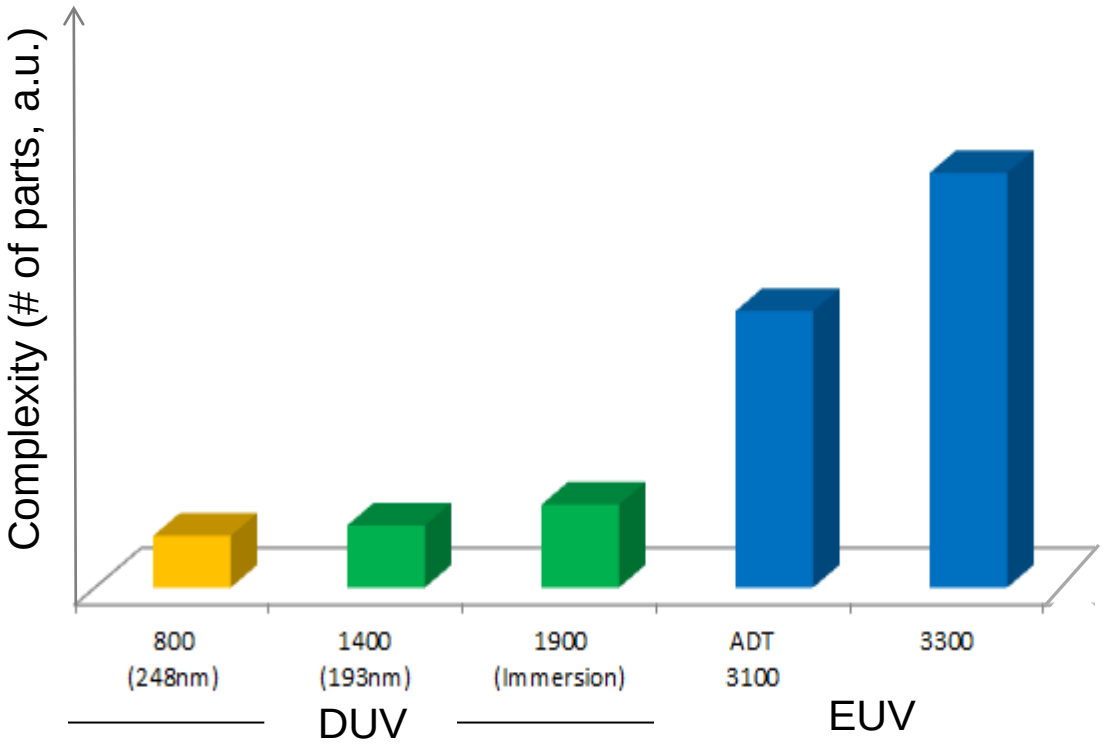


and many more …

Complexity normally grows with performance ...

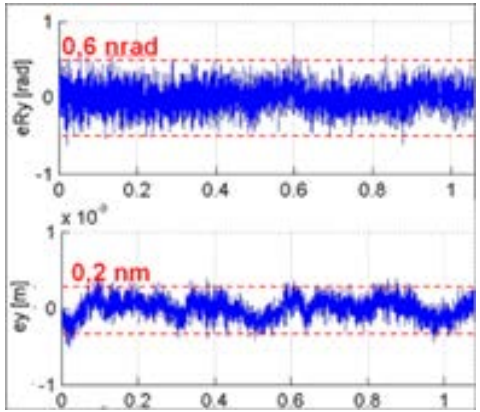


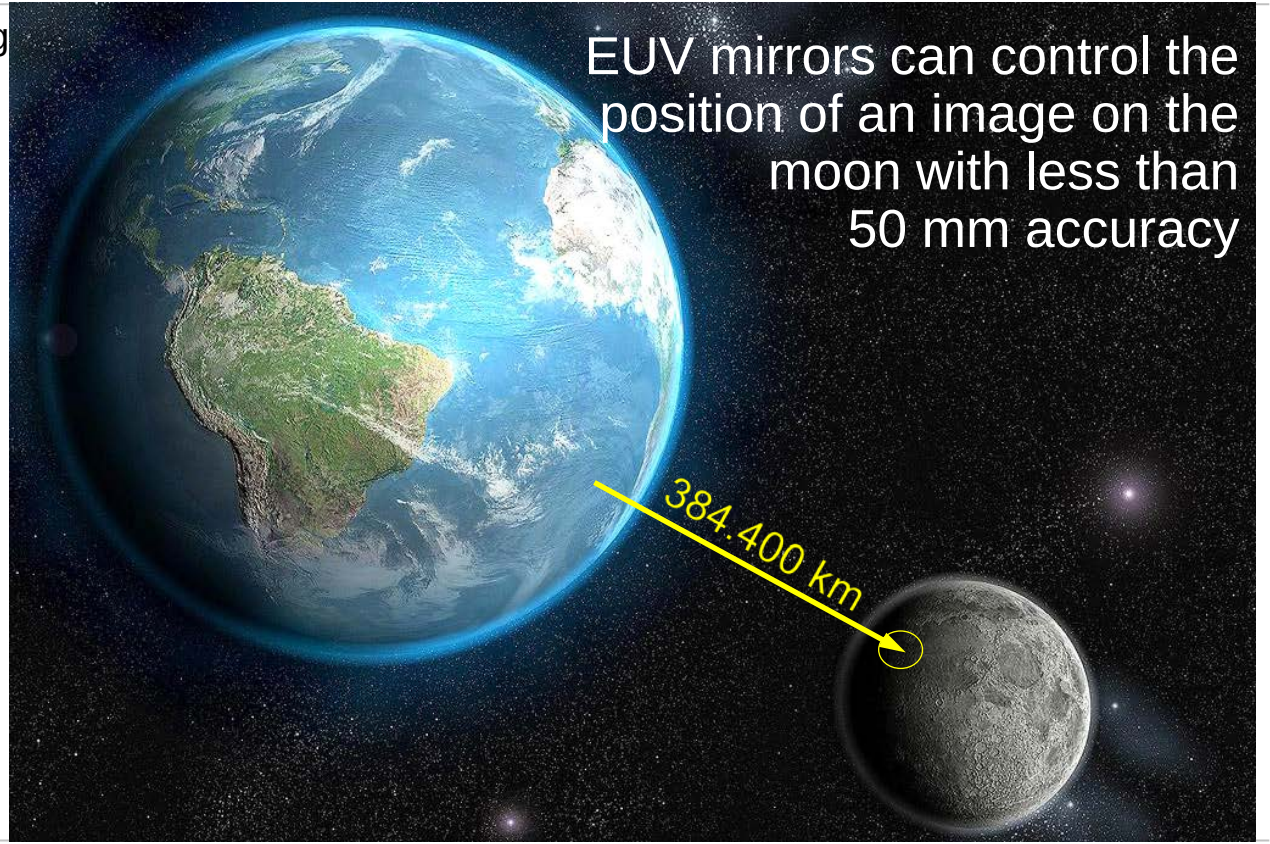
… but complexity of EUV systems was a real surprise!



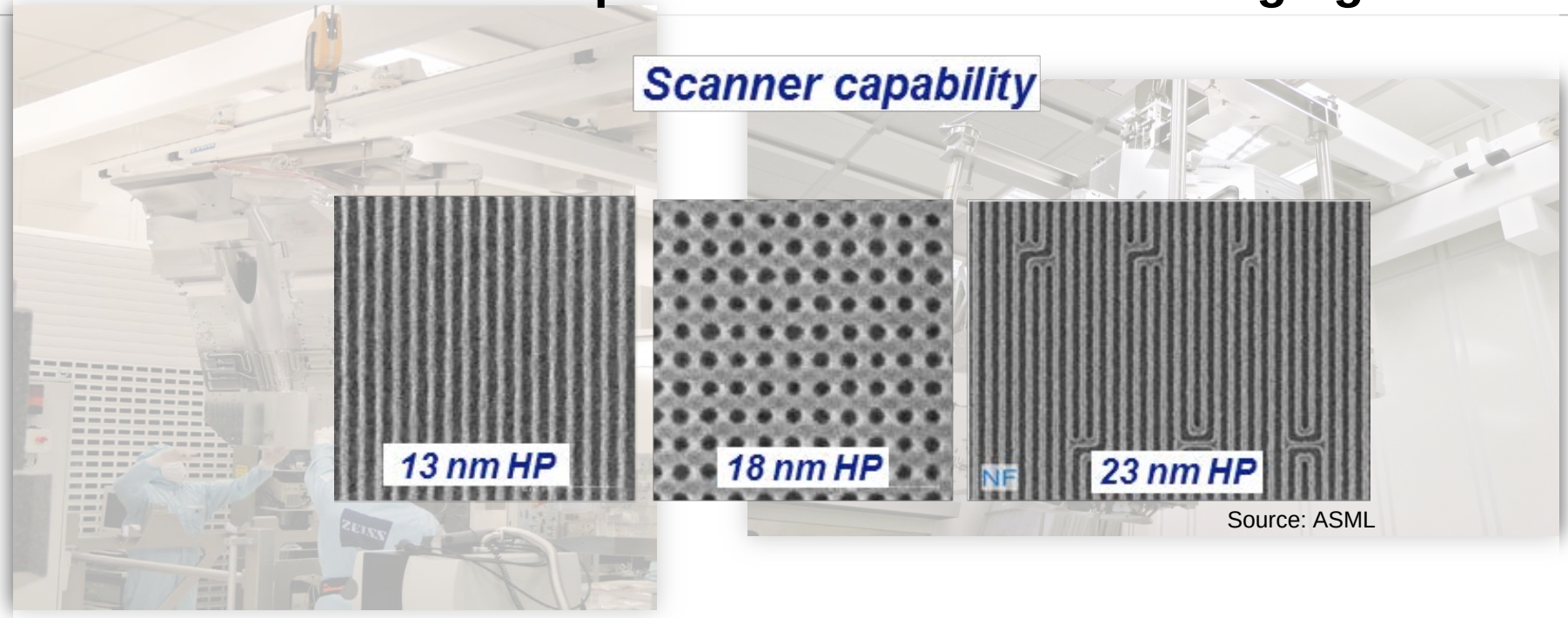
EUV mirror tilts must be controlled with sub-nrad accuracy to enable sub-nm image placement

Test module for EUV mirror positioning





The final result:
ZEISS Starlith ® 3300 optics delivers excellent imaging



Source: ASML

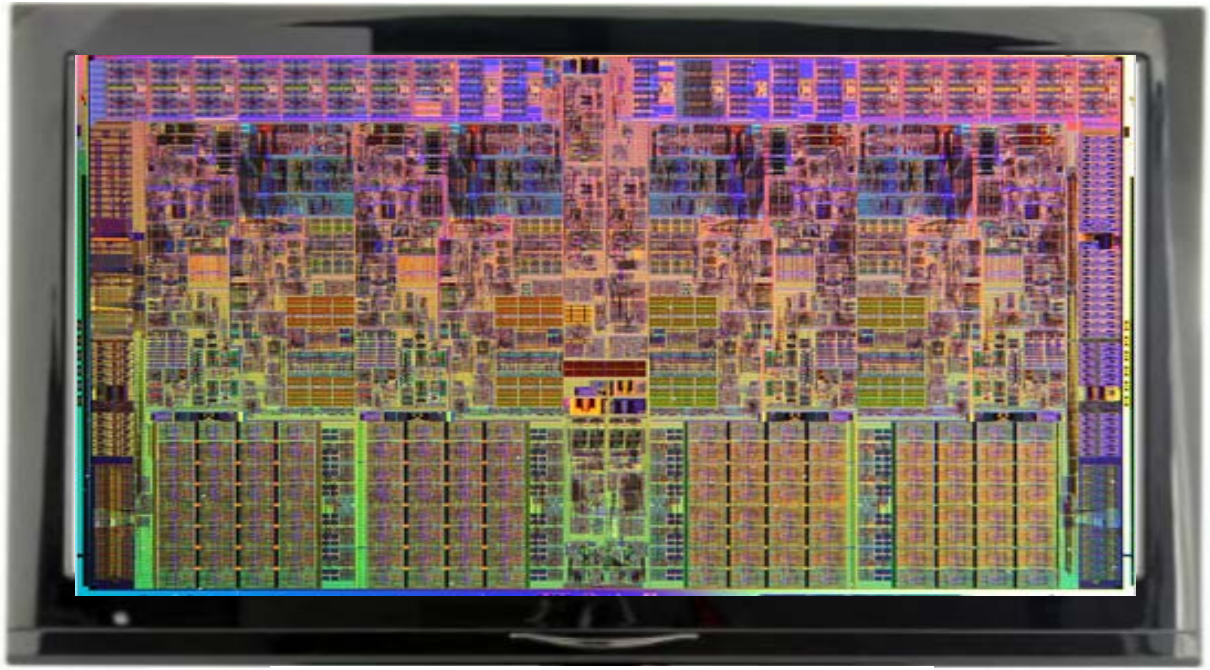
Illuminator

POB

Displaying the information content of the 3300 EUV POB requires 1,616,512 HD screens …

.... corresponding to a gigantic screen of 778 m height and 1038 m width

Burj Khalifa
828 m
From Wikipedia



Intel Core I7 layout

High NA EUV: In search of the optics for the ultimate lowest cost/pixel printing machine

Production readiness achieved

Development phase ongoing

1995 2003 2006 2009 2012 2015 2018

MET
Micro Exposure Tool

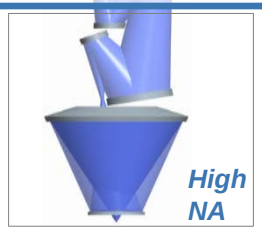
ADT
(α-Demo Tool)

Starlith® 3100

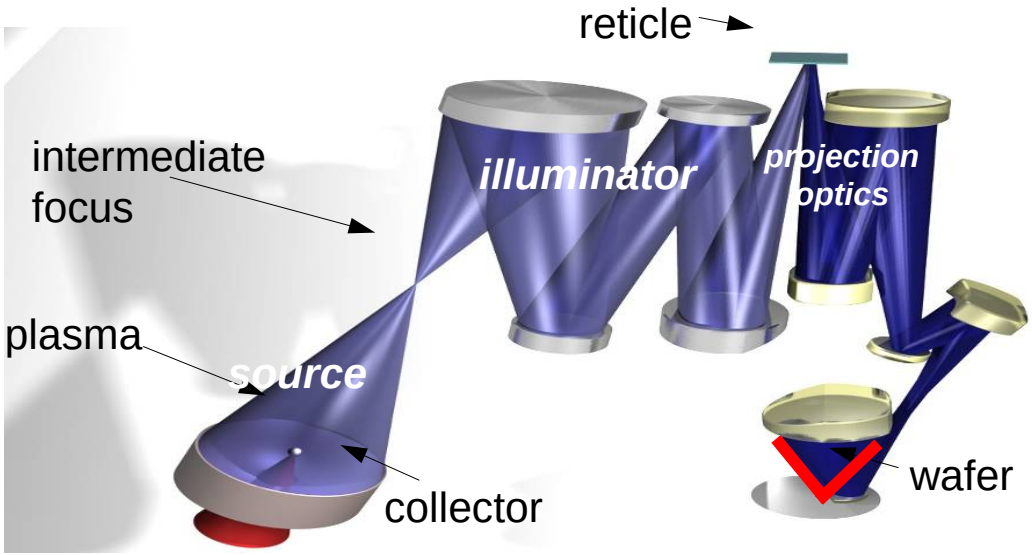
Starlith® 3300

Starlith® 3400

High NA EUV



“High NA EUV” is targeting the highest (practical and economical) resolution by significant increase of NA



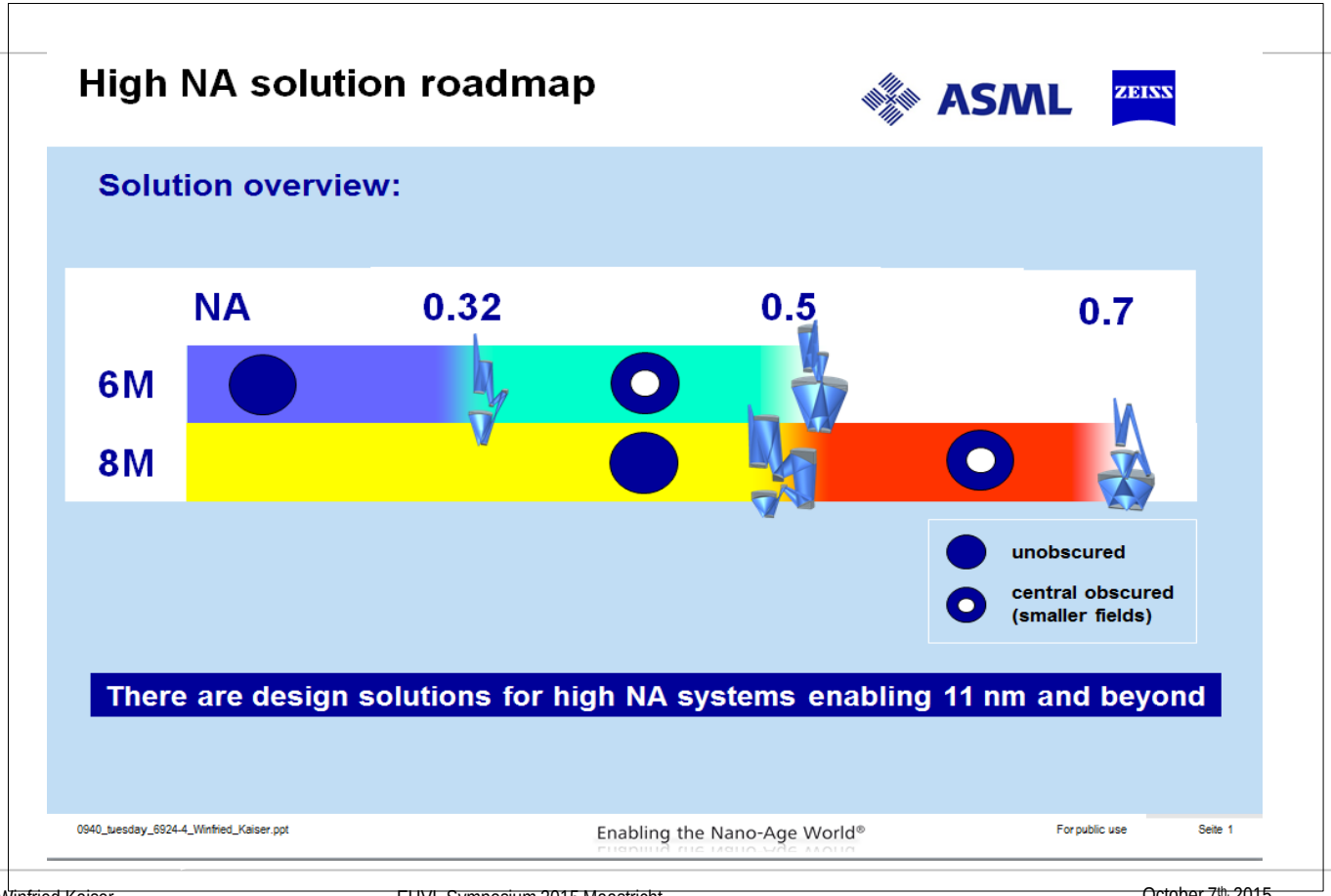
EUV 13.5 nm

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

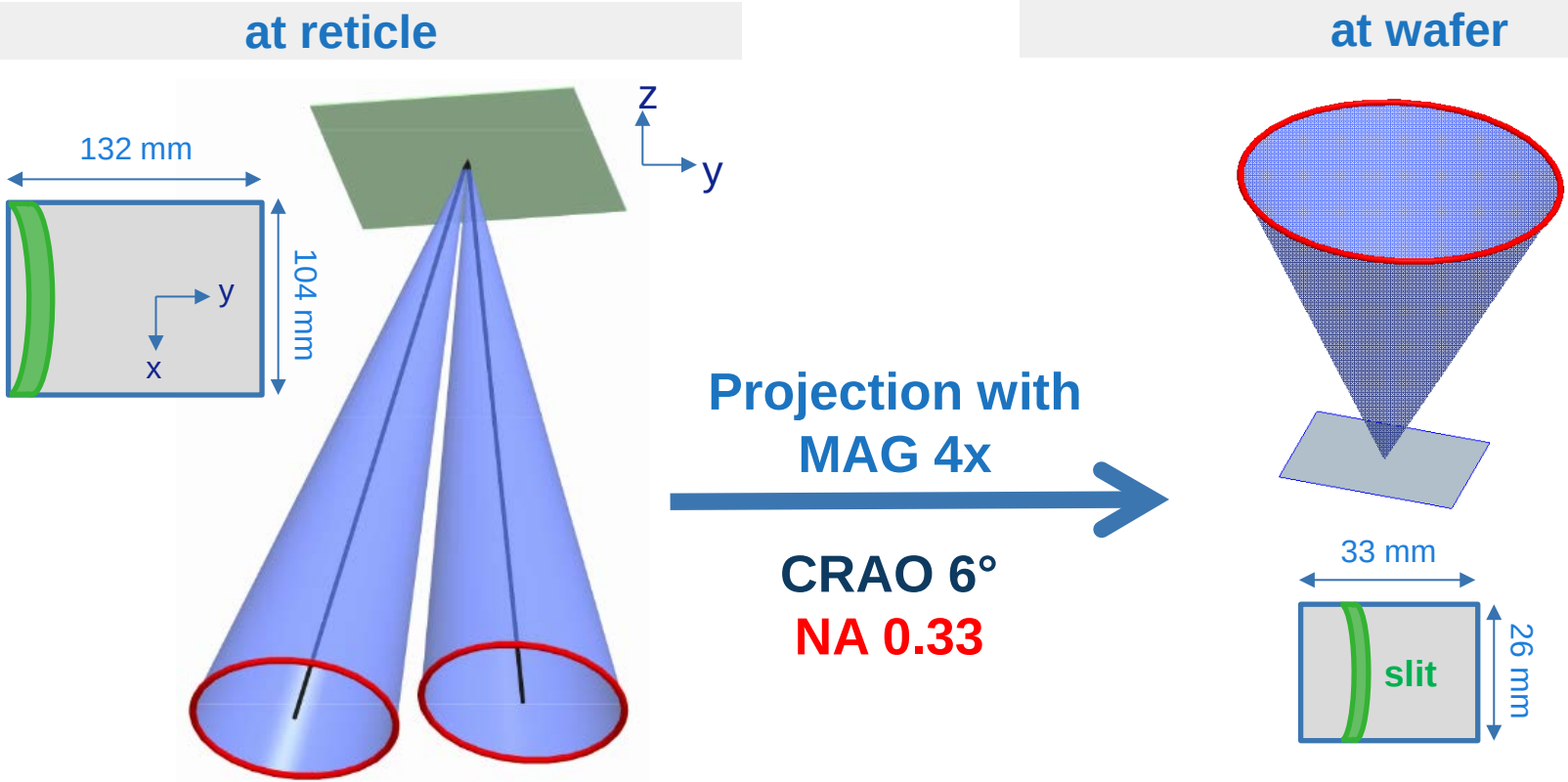
High-NA

NA	0.33	…	0.45	0.5	0.55	0.6
Resolution @ k1=0.3 single exposure / nm	12.3	…	9.0	8.1	7.4	6.8

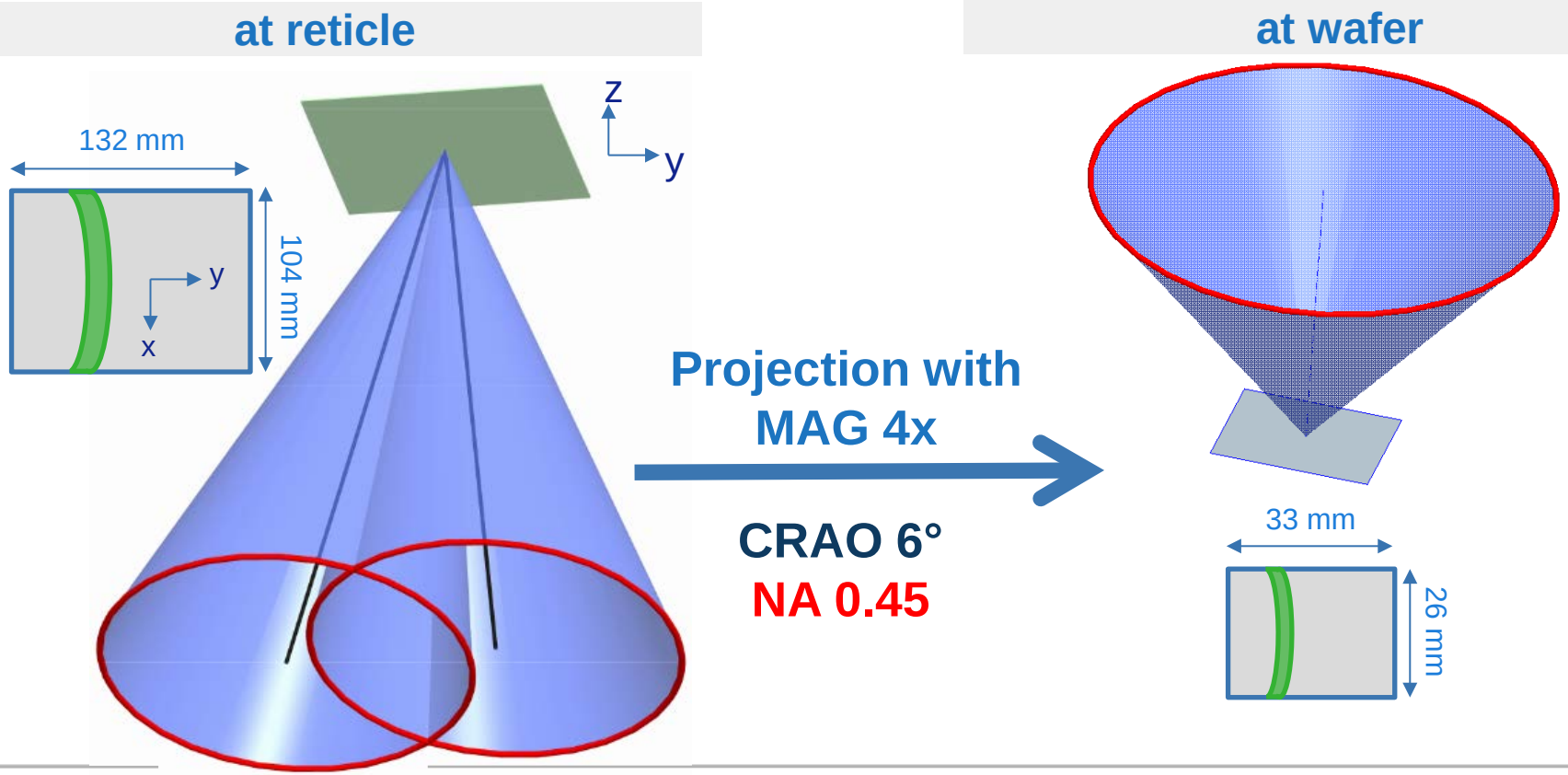
SPIE 2008: Potential solution space for High NA EUV



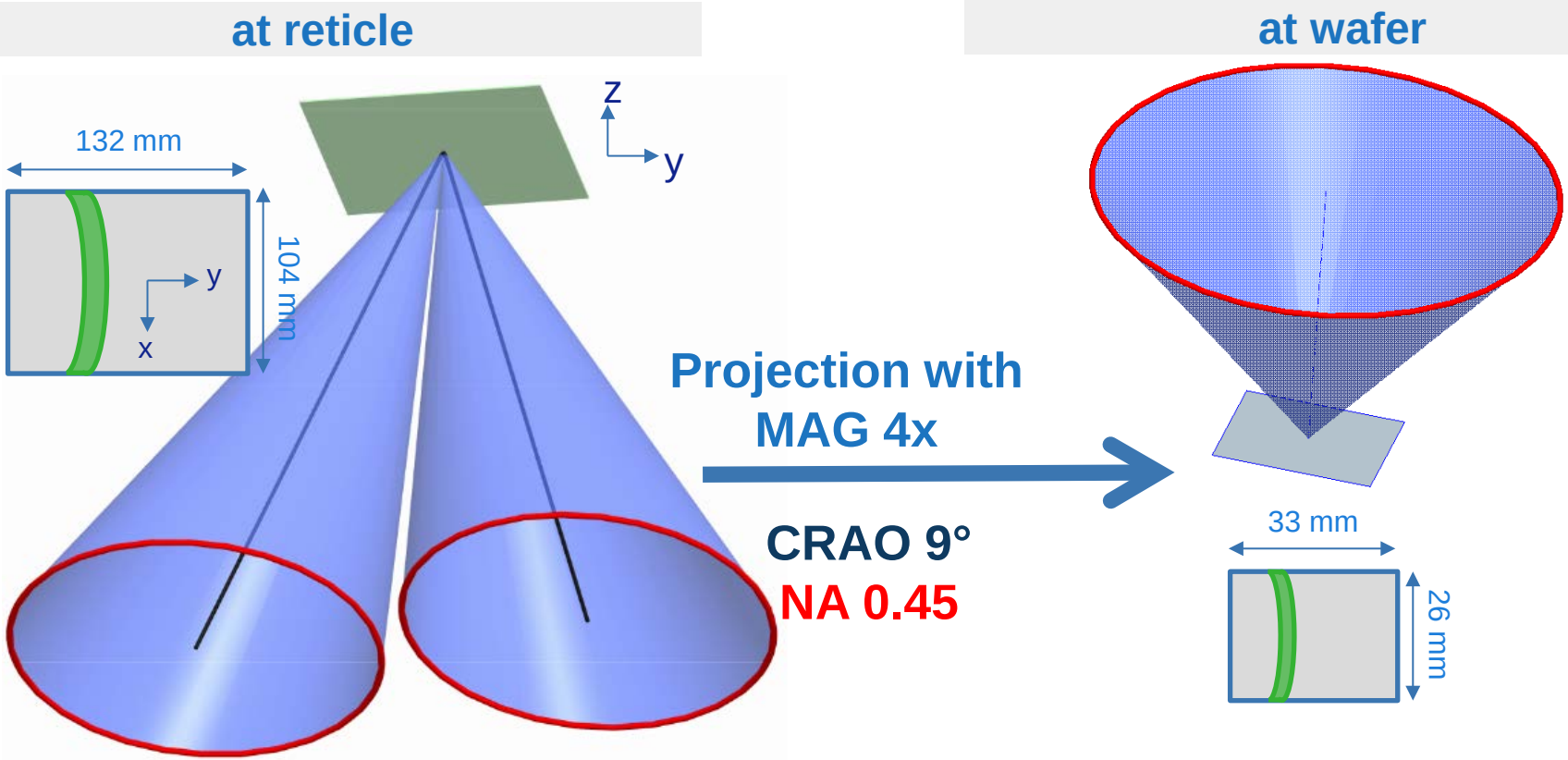
Fields and light cones at reticle and wafer are connected via MAG



Increasing NA, light cones at reticle start to overlap

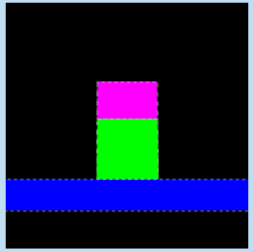


To separate light cones, CRAO must be increased



SPIE 2008: No understanding of CRAO increase

Impact of CRAO change (2)



Source: Samsung

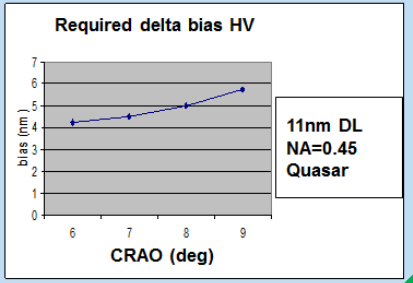
Att PSM Stack (11nm)

17nm TaN (magenta)

21nm Ru (green)

11nm Si (blue)

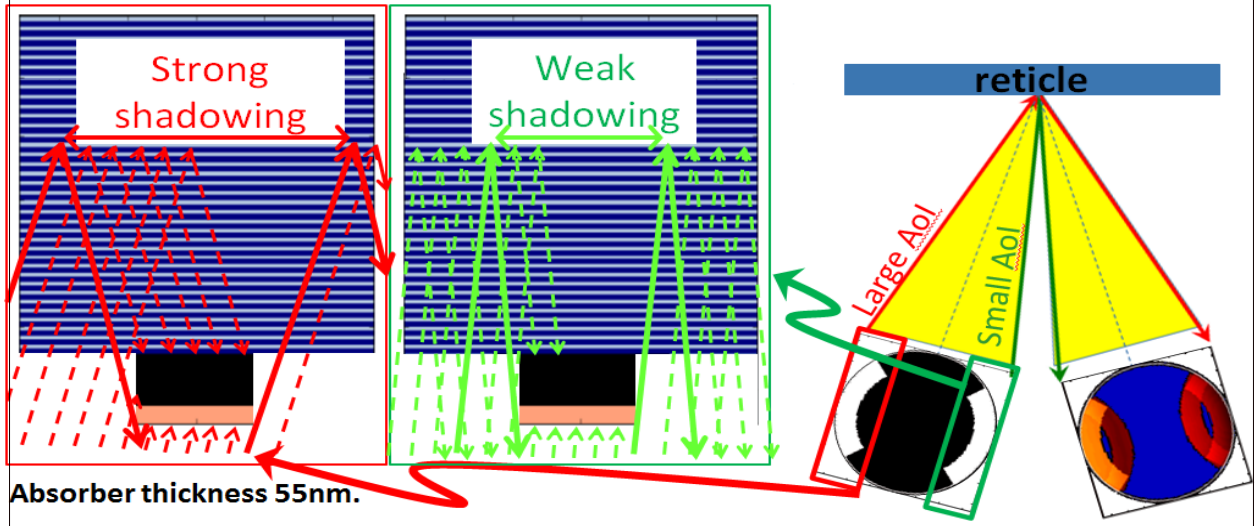
40 MoSi bilayer



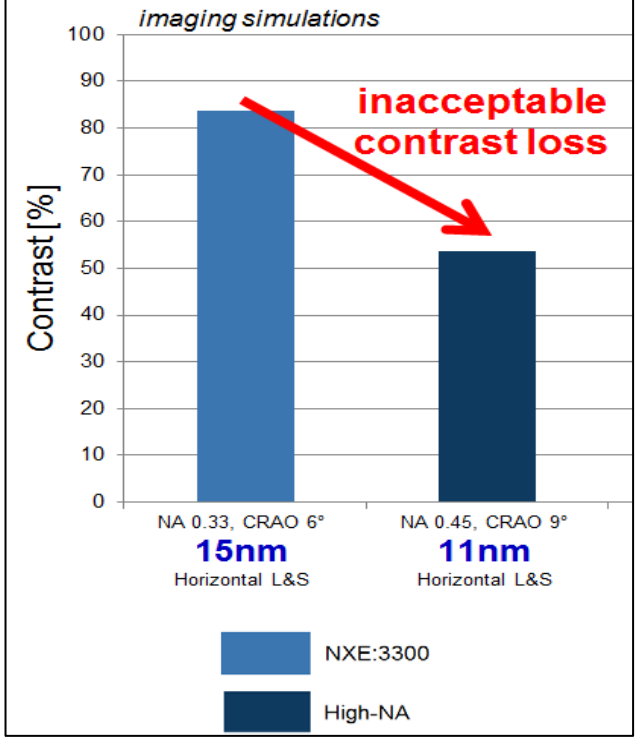
The impact of a change of CRAO is not well understood today in full extent.
Our view is that there are no showstoppers for an increase to 9 - 10° allowing full field optics with NA ≈0.5 The actual assumption is that there will be mask stacks where on the effect on imaging by larger CRAOs can be compensated by biasing without critical impact.
The only alternative for NA > 0.4 would be to go to higher Mag (5x, 6x, 8x) which would limit the usable field size in 2 dimensions with significant impact on productivity or require larger mask sizes.

0940_tuesday_6924-4_Winfried_Kaiser.ppt Enabling the Nano-Age World® For public use Seite 2

2012: The insight: angle dependent shadowing deep in the multi-layer causes this inacceptable contrast loss



J.T. Neumann, EUVL 2012



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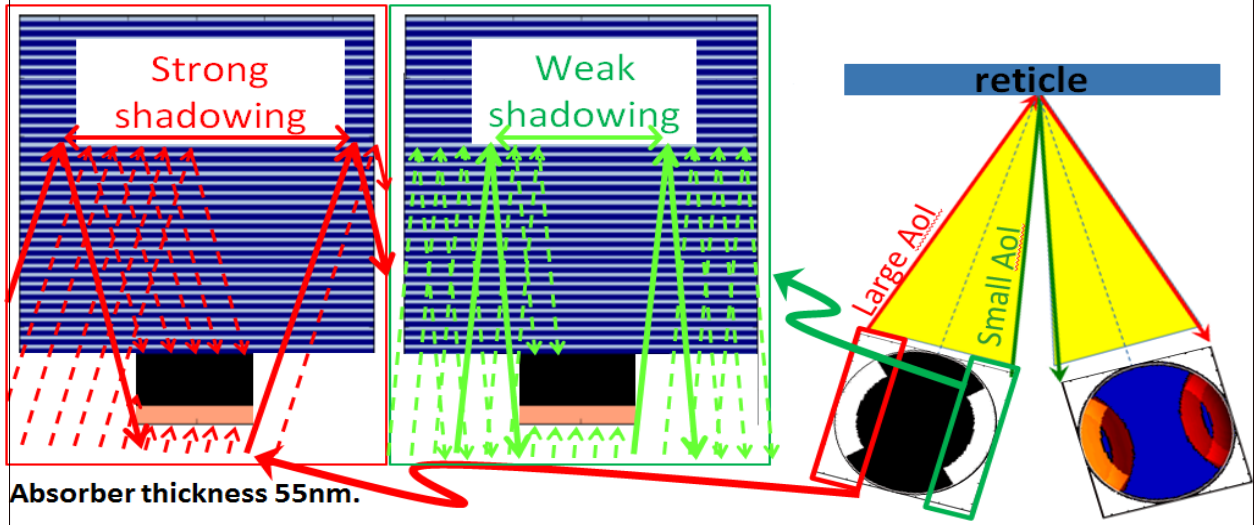
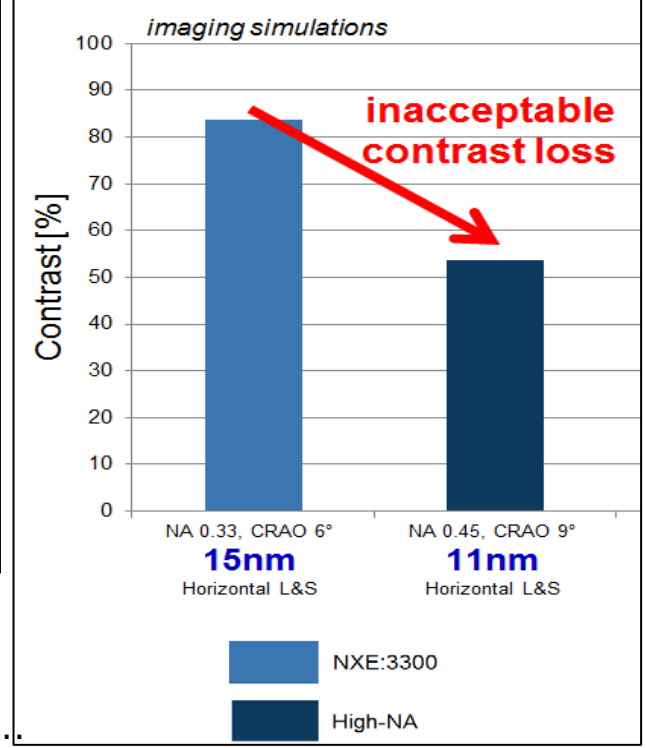


J.T. Neumann, EUVL 2012



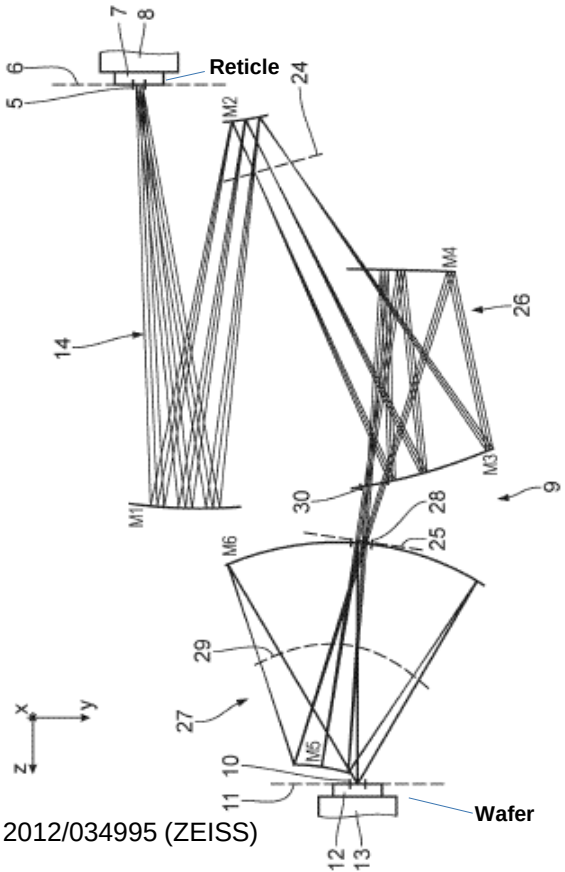
Even before the issue was fully understood, an idea came up in 2010…

Anamorphic lenses – ZEISS is doing this in movie making …

“The Master Anamorphic lenses open up new creative opportunities, making shots possible that would have been considered impossible before.”

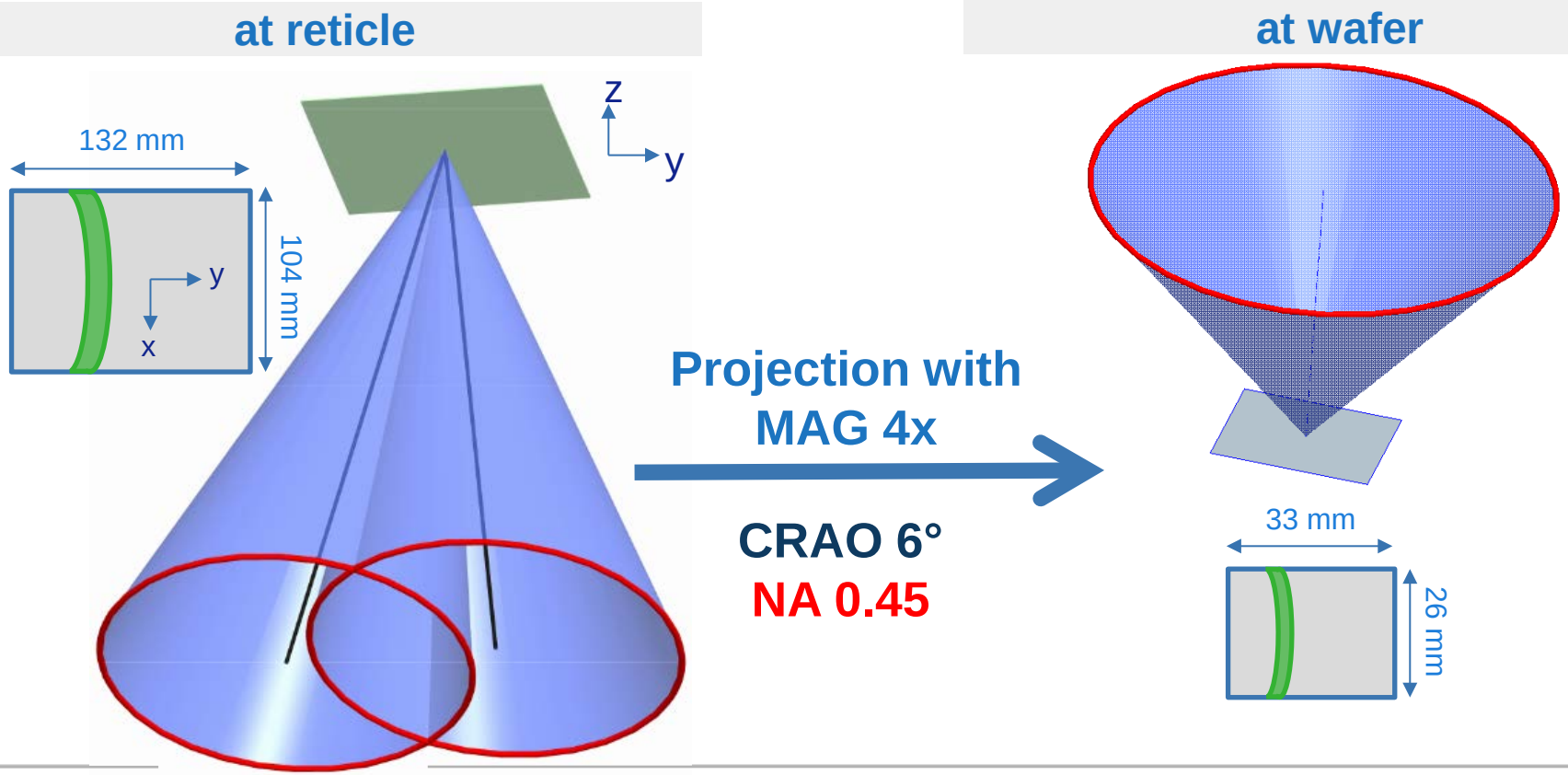
… and now in lithography!

“The Master Anamorphic lenses open up new creative opportunities, making shots possible that would have been considered impossible before.”



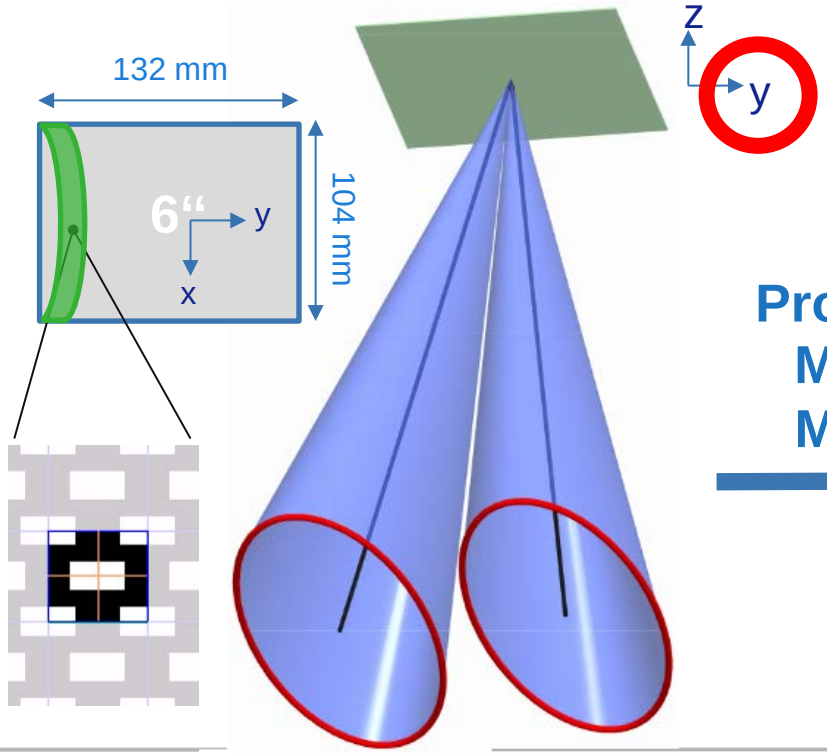
WO 2012/034995 (ZEISS)

So the solution for the conflicting light cones is…



The anamorphic High NA EUV reduces the angles in one direction which enables a solution with 26 mm slit on 6” masks

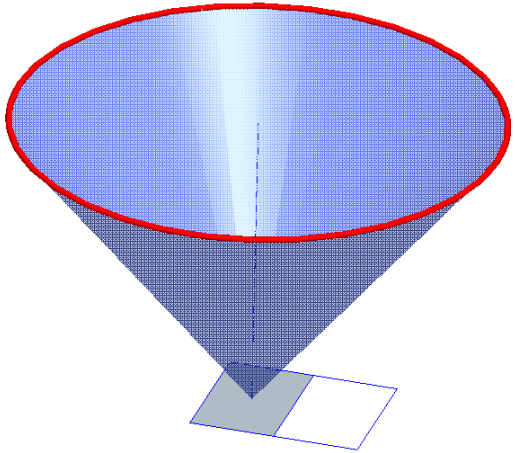
@ reticle

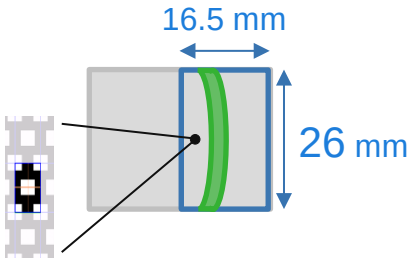


Projection with
MAG 4x in x
MAG 8x in y

CRAO 6°
NA >0.5

@ wafer

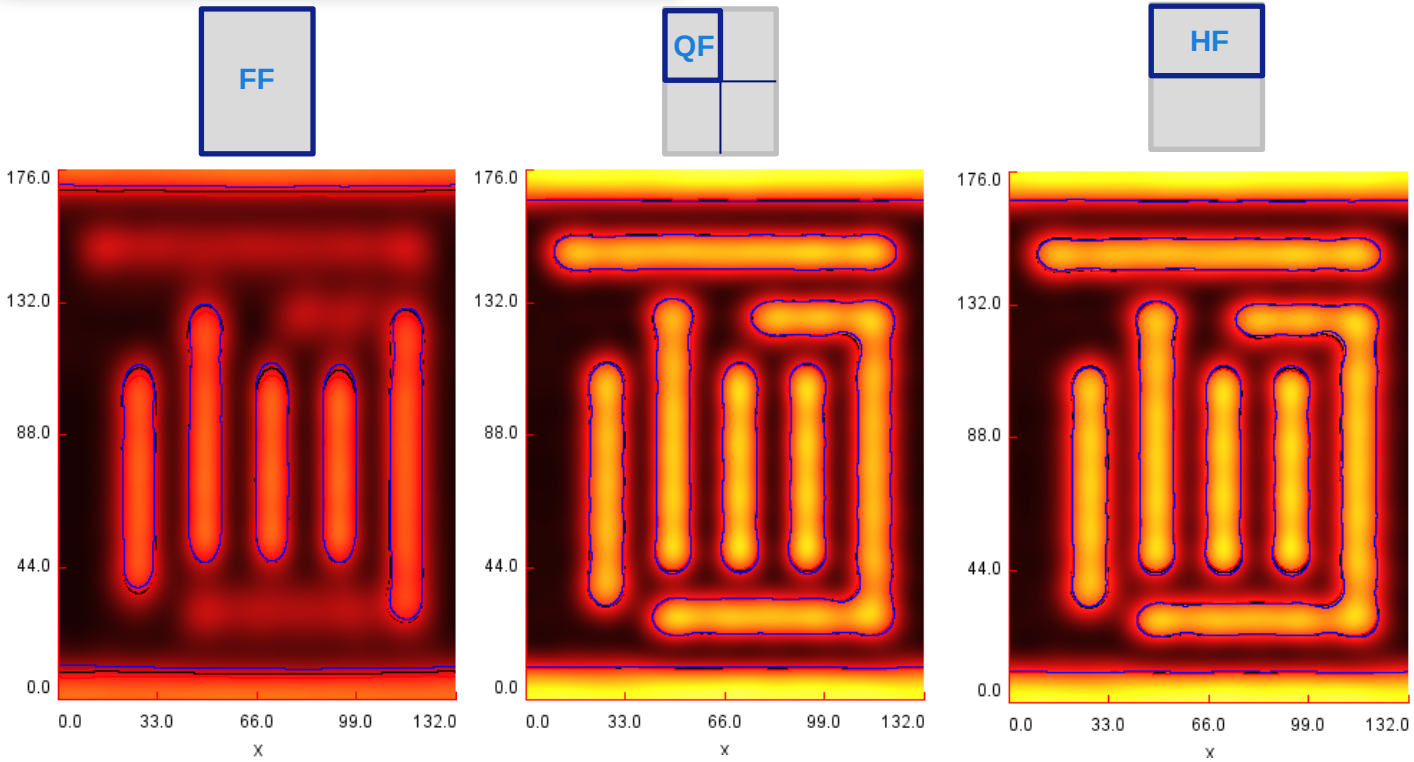


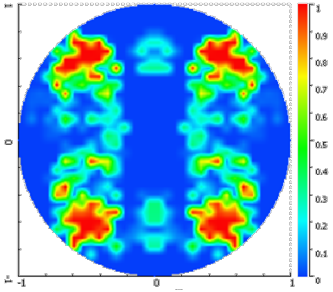


Imaging verification of the new Half Field concept

Logic N5 clip Metal-1, 11nm lines Aerial Image Intensity in Hyperlith

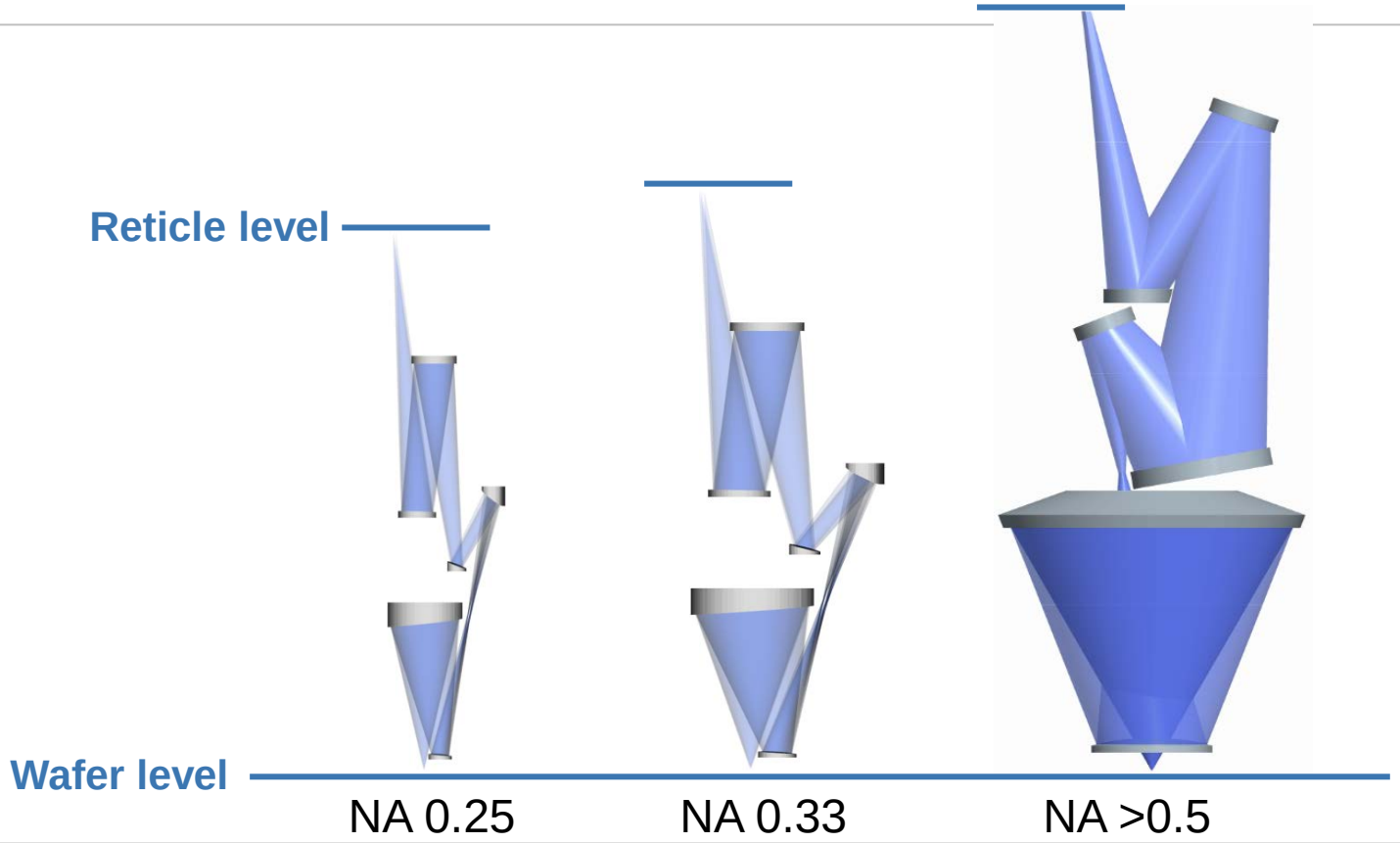
Note: pictures at same scale, smaller mask reflection is also visible





Gerardo Bottiglieri, ASML

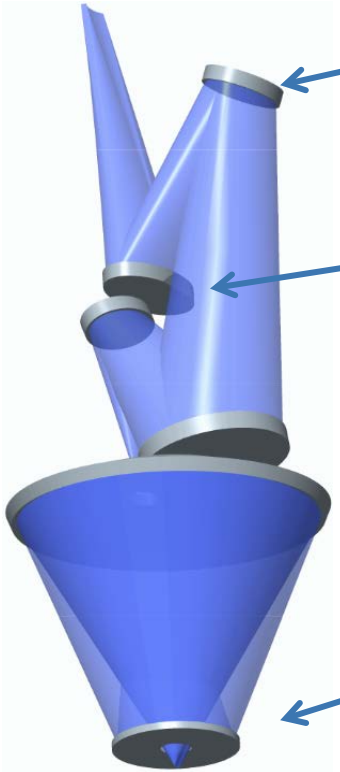
EUV design evolution



Design examples

Big optical system with very large mirrors and extreme aspheres at increased accuracy requirements

Large overall size of optical system



Extreme aspheres enabling **further improved wavefront / imaging performance**

Tight surface specifications enabling **low straylight / high contrast imaging**

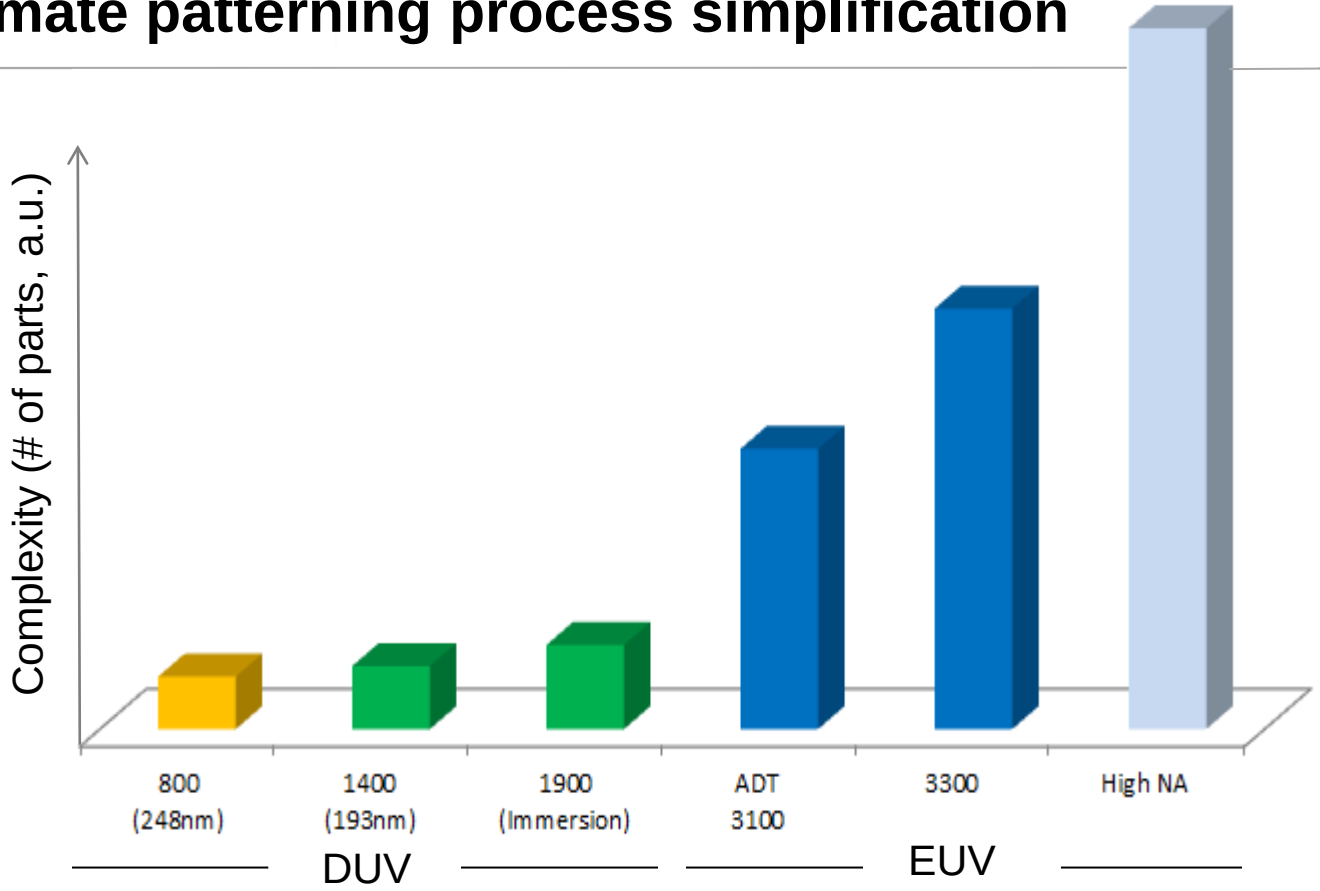
Big last mirror driven by **High NA**

Obscuration enables **higher optics transmission**

→ Big challenge for optics technology and manufacturing

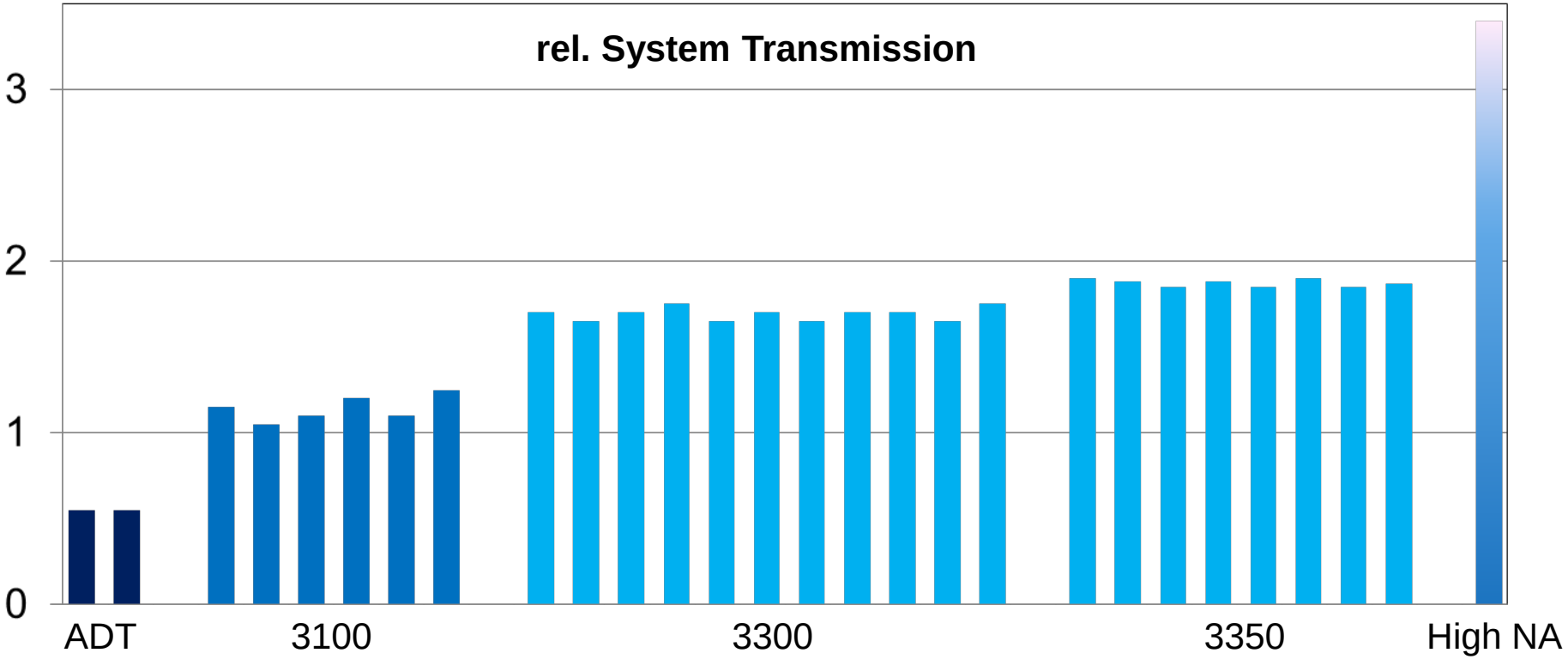
→ No fundamental limits

Another step in complexity for ultimate patterning process simplification



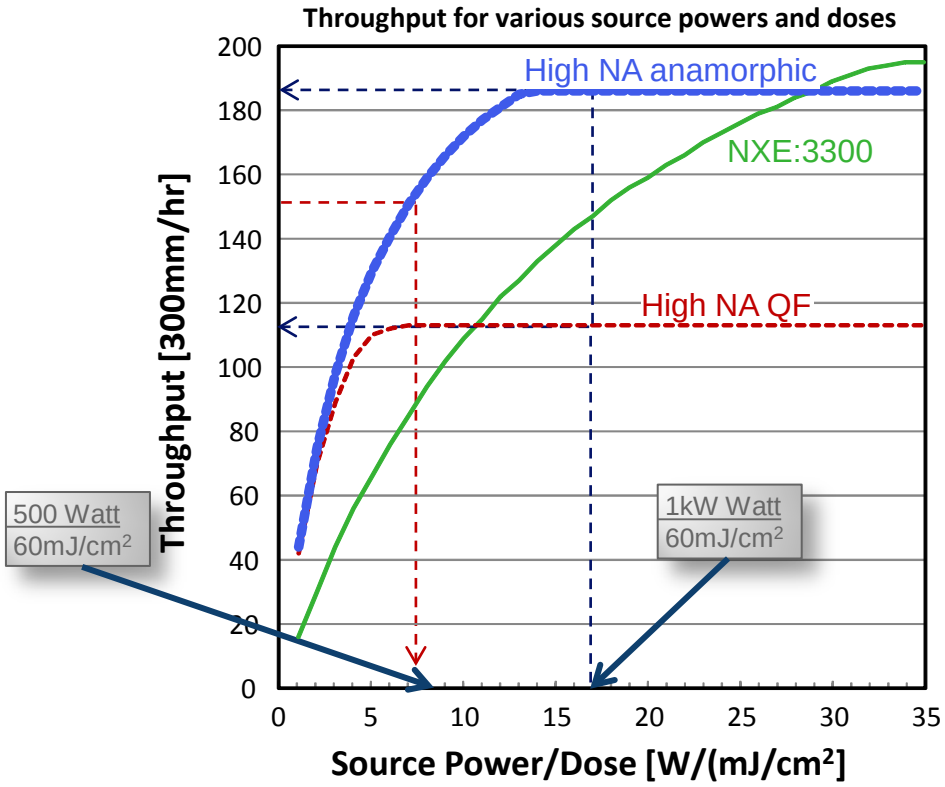
Fab expansion in Oberkochen: prepared for High NA EUV

In parallel we strive for a significant increase in transmission to enable highest productivity



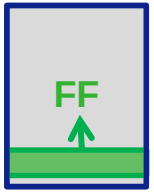
High-NA Field and Mask Size productivity

500W enables throughput of 150wph with anamorphic HF

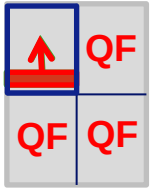


WS, RS current performance

WS 2x, RS 4x



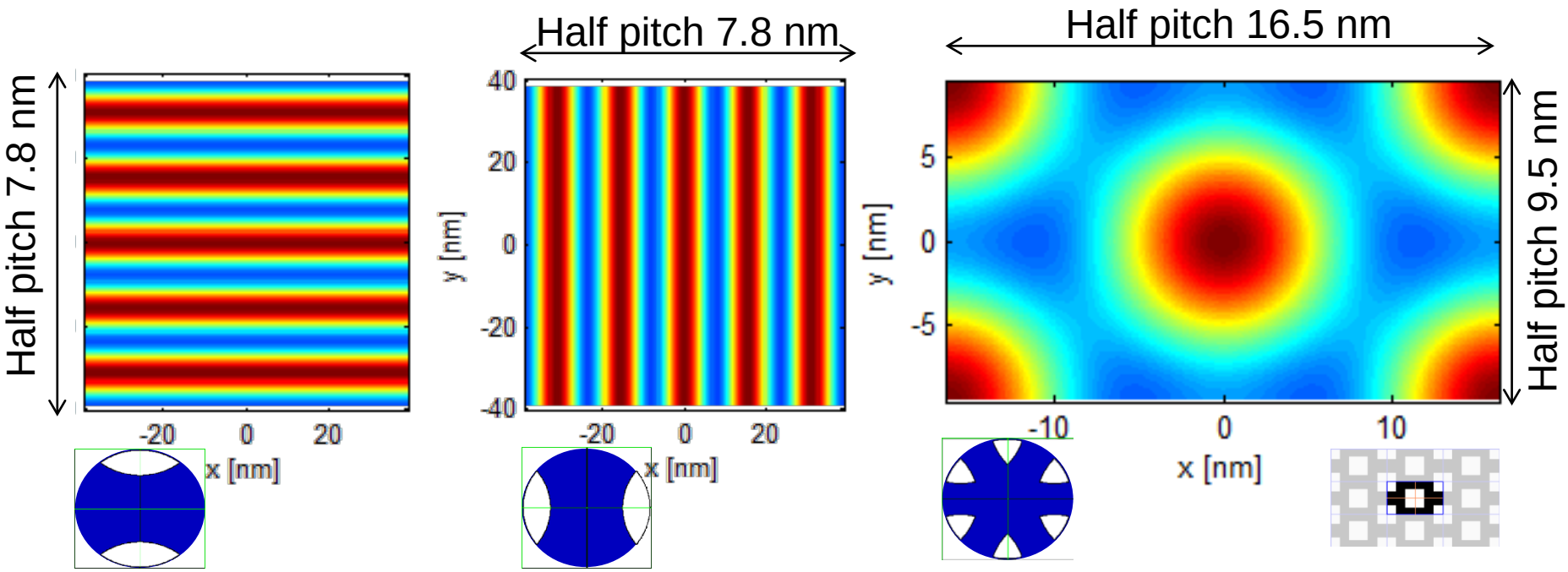
WS 2x, RS 4x



High-NA Half Field scanner needs 500W for 150wph at 60mJ/cm²

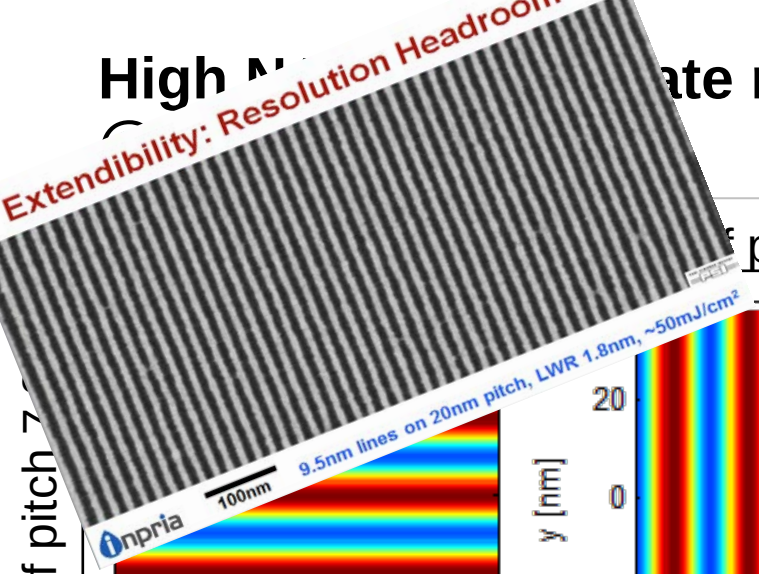
(see J.v. Schoot)

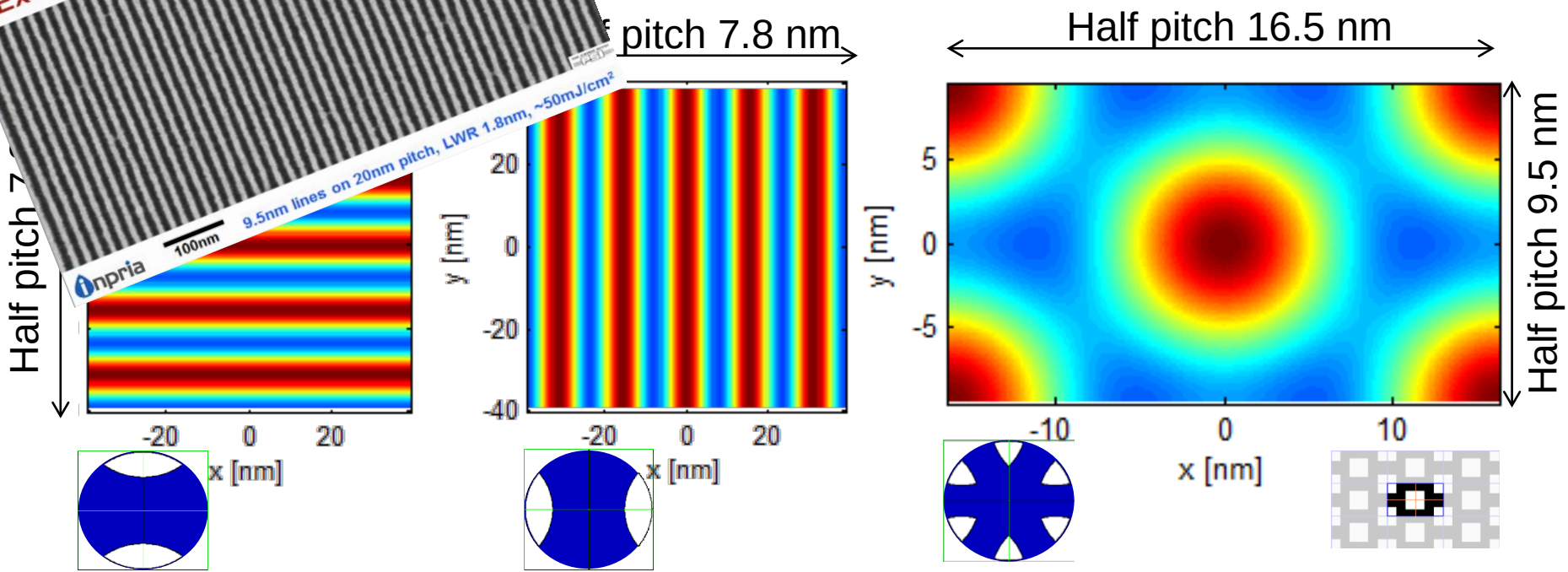
High NA EUV: Ultimate resolution power at single exposure



With its suprior resolution and highest productivity potential the High NA EUV system offers the chance for the ultimate lowest cost/pixel printing machine!

High N ate resolution power





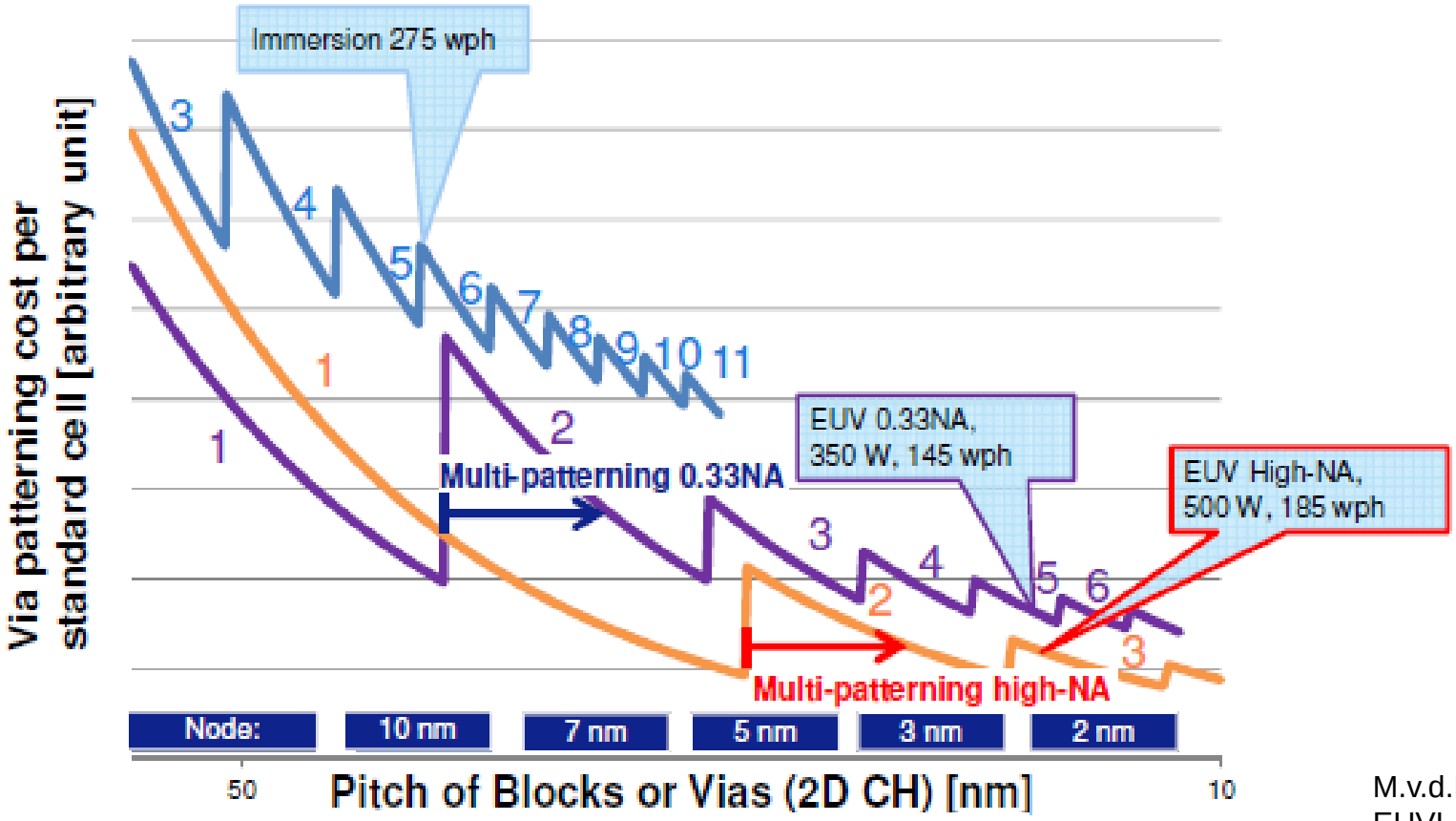
With its suprior resolution and highest productivity potential the High NA EUV system offers the chance for the ultimate lowest cost/pixel printing machine!

EUV will ensure continued cost and complexity reduction

Up to 5-10x EUV *vs.* Immersion, 2x high-NA vs 0.33 NA complexity reduction

ASML

Public
Slide 37
5 Oct 2015



M.v.d.Brink
EUVL 2015

Summary and Acknowledgement

- **The quality and performance of EUV optics has improved over two decades in orders of magnitudes to a level where excellent imaging and image positioning (distortion) is demonstrated by systems from serial production.**

- **High NA EUV will be again another very big challenge! This system will enable highest resolution for patterning process simplification combined with highest productivity potential – and it looks feasible:** ***The optical system for the ultimate lowest cost/pixel printing machine!***

Many thanks to:

- **The big teams of ZEISS, ASML and our partners**

- **BMBF (Germany) and EU for continuous support of the EUV development**


NO
Show
Stoppers
Wynn
LAS VEGAS

ZEISS

We make it visible.