Public

EUV lithography industrialization for HVM

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Outline

- NXE Roadmap
- NXE:3400B performance
- Reticle front-side defectivity
- EUV source roadmap
- EUV extendibility

EUV development has progressed over 30 years

from NGL to HVM insertion

1st lithography (LLNL, Bell Labs, Japan)

ASML starts EUVL research program

ASML ships 2 alpha demo tools: IMEC (Belgium) and CNSE (USA)

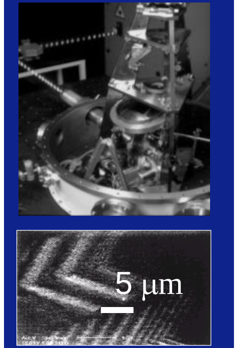
ASML ships 1st pre-production NA 0.25 system NXE:3100

ASML ships 1st NA 0.33 system NXE:3300B

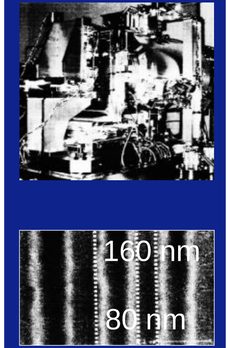
ASML ships 1st HVM NA0.33 system NXE:3400B

’85 ’86 ’87 ’88 ’89 ’90 ’91 ’92 ’93 ’94 ’95 ’96 ’97 ’98 ’99 ’00 ’01 ’02 ’03 ’04 ’05 ’06 ’07 ’08 ’09 ’10 ’11 ’12 ‘13 ’14 ’15 ’16 ’17 ’18

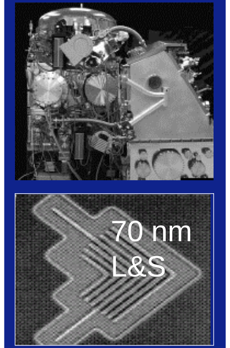
NL



Japan



USA



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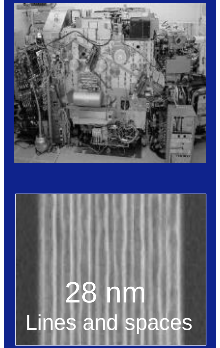

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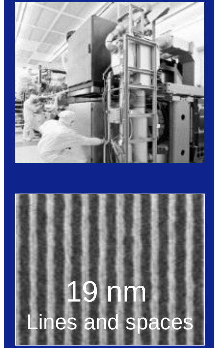

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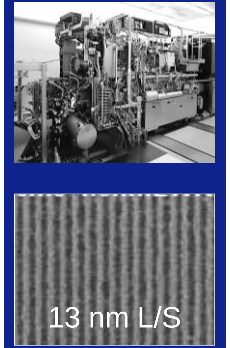

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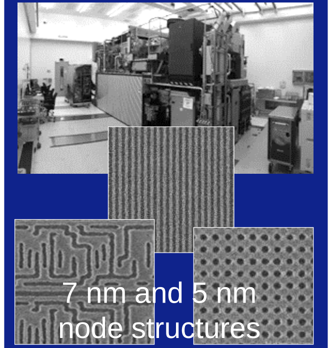
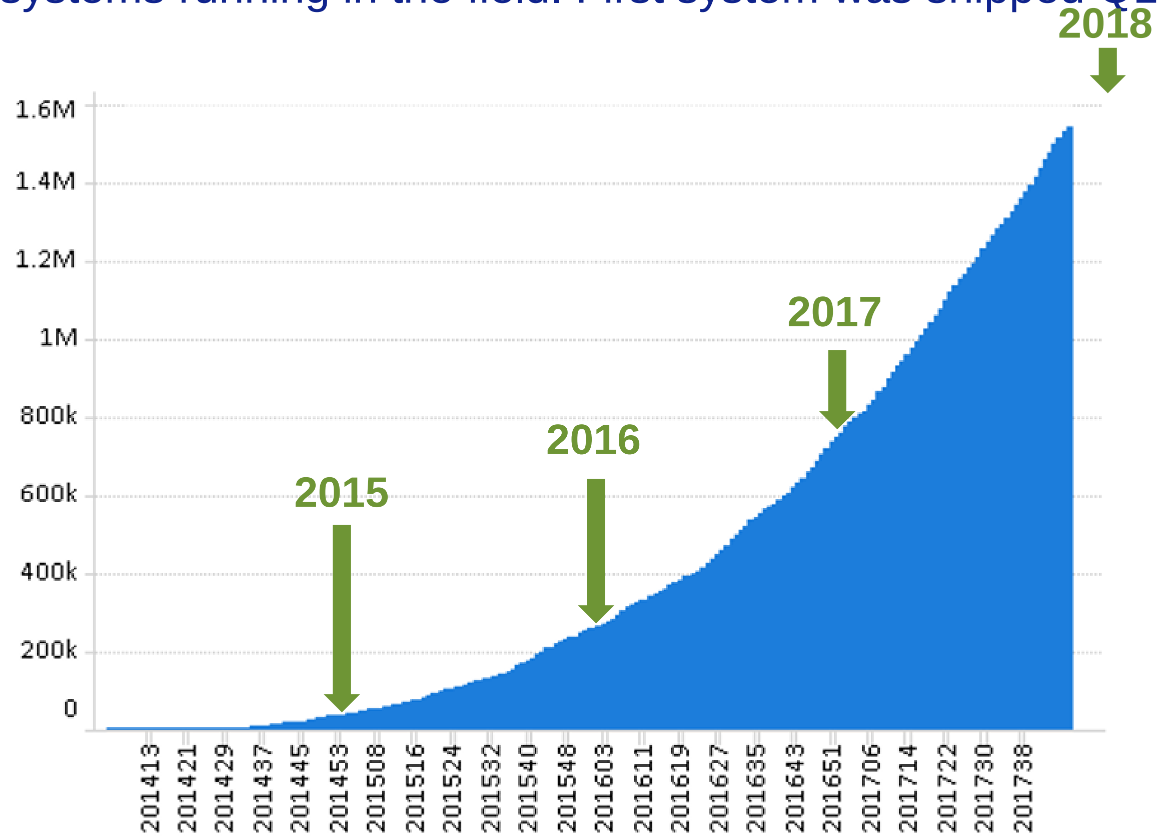


~1.6M wafers exposed on NXE:3xy0B at customer sites

Currently 15 systems running in the field. First system was shipped Q1 2013



EUV extension roadmap

introduction	55 WPH	125 WPH	145 WPH	185 WPH	Overlay [nm]
2013	NXE:33 B				7
2015		350B			3.5
2017		NXE:3400B			3
			NXE:next		<3
				High	<2

At customer upgradable

New platform

products under study

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- NXE Roadmap
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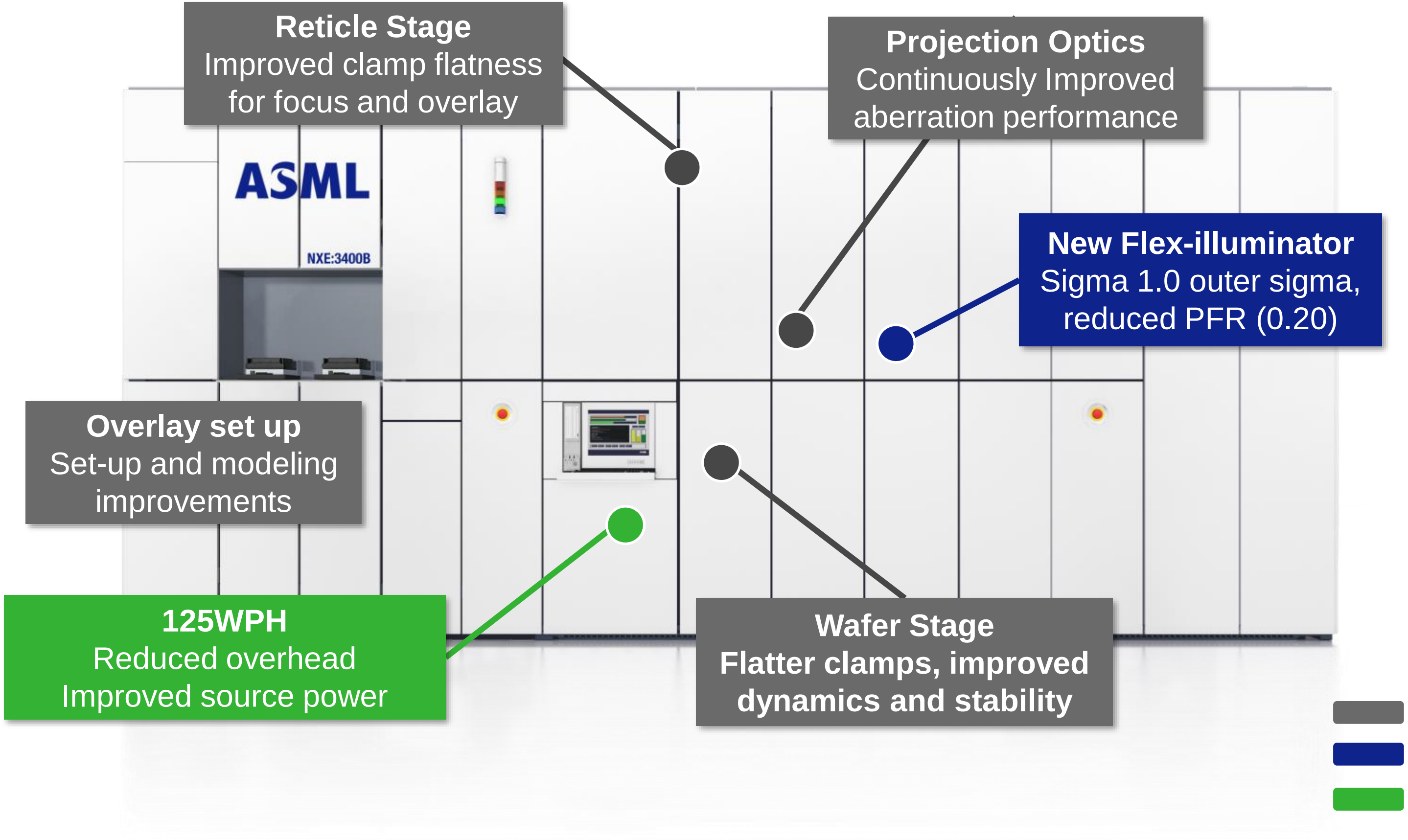
- EUV extendibility

NXE:3400B: 13 nm resolution at full productivity

Supporting 5 nm logic, <15 nm DRAM requirements



Reticle Stage
Improved clamp flatness for focus and overlay

Projection Optics
Continuously Improved aberration performance

New Flex-illuminator
Sigma 1.0 outer sigma, reduced PFR (0.20)

Overlay set up
Set-up and modeling improvements

125WPH
Reduced overhead
Improved source power

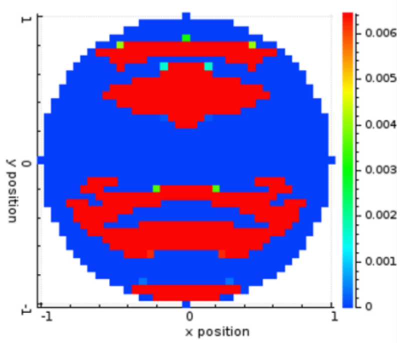
Wafer Stage
Flatter clamps, improved dynamics and stability

Resolution	13 nm
Full wafer CDU	≤ 1.1 nm
DCO	≤ 1.4 nm
MMO	≤ 2.0 nm
Focus control	≤ 60 nm
Productivity	≥ 125 WPH

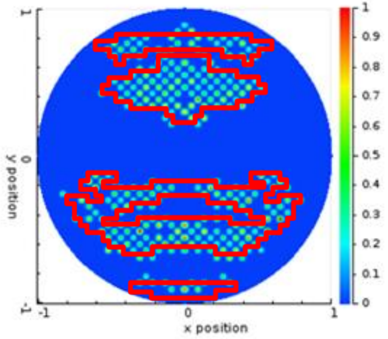
⬛	Overlay
🟦	Imaging/Focus
🟩	Productivity

3400B illuminator: increased pupil flexibility at full throughput

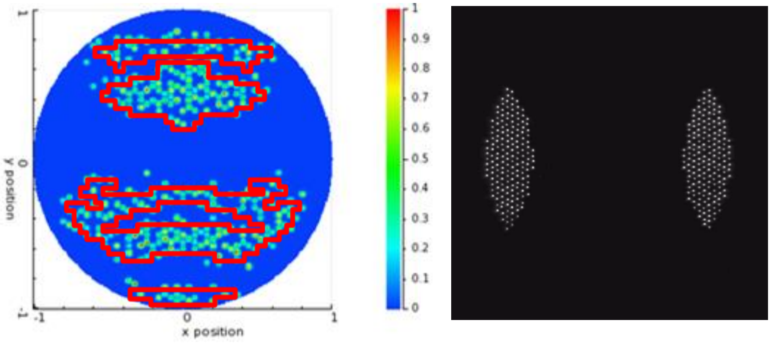
Tachyon



NXE: 3300



NXE: 3400

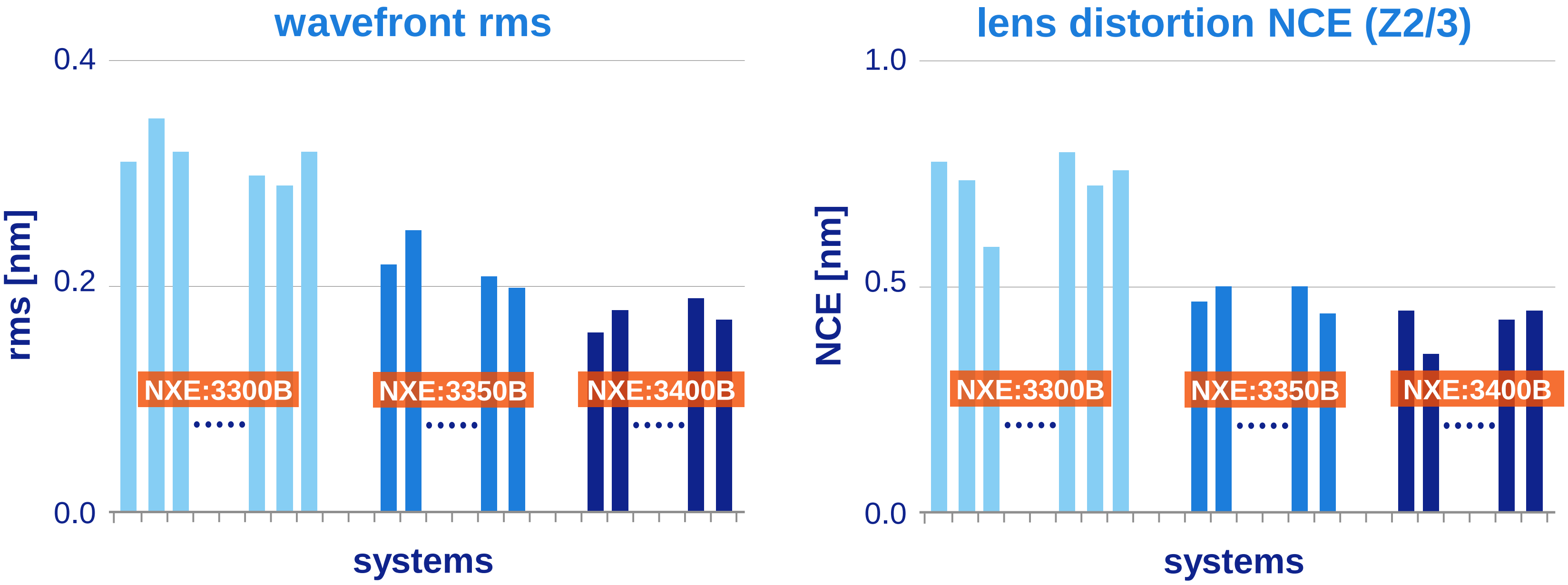


Pupil filling improvement from 3300 to 3400 with approximately 20% higher transmission or 10% higher throughput

Evolutionary improvements in EUV optics

enabling 7 nm and 5 nm nodes for imaging, focus and overlay

Entire 3xy0 population shows wavefront improvements

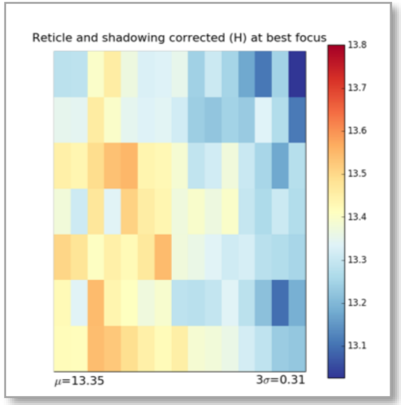


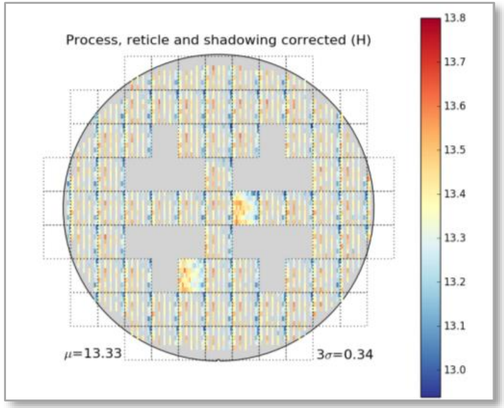
Source: Carl Zeiss SMT AG

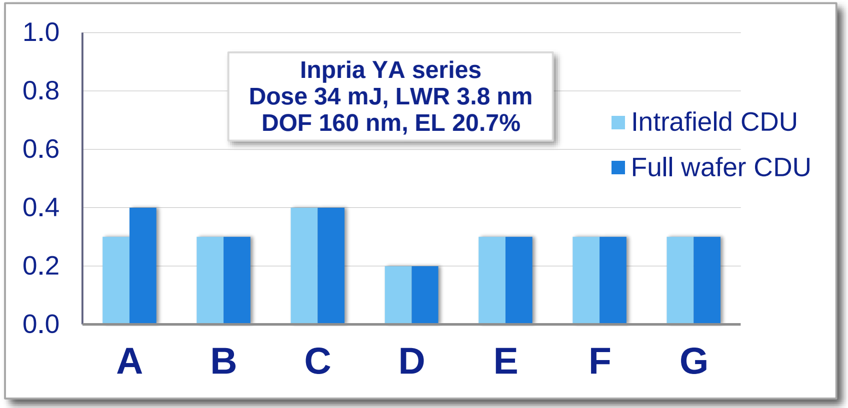
13 nm LS and 16 nm IS: full-wafer CDU **0.3 nm**

meets 5 nm logic requirements, with excellent process windows

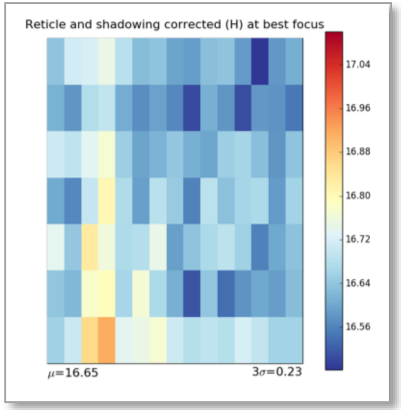
13 nm LS
leafshape dipole

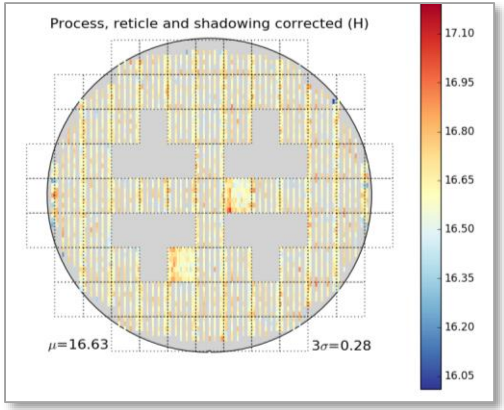


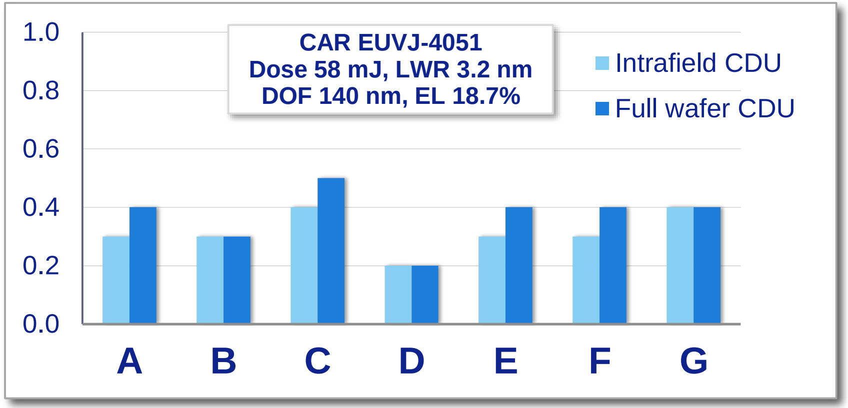



Inpria YA series
Dose 34 mJ, LWR 3.8 nm
DOF 160 nm, EL 20.7%

16 nm IS
small-conventional

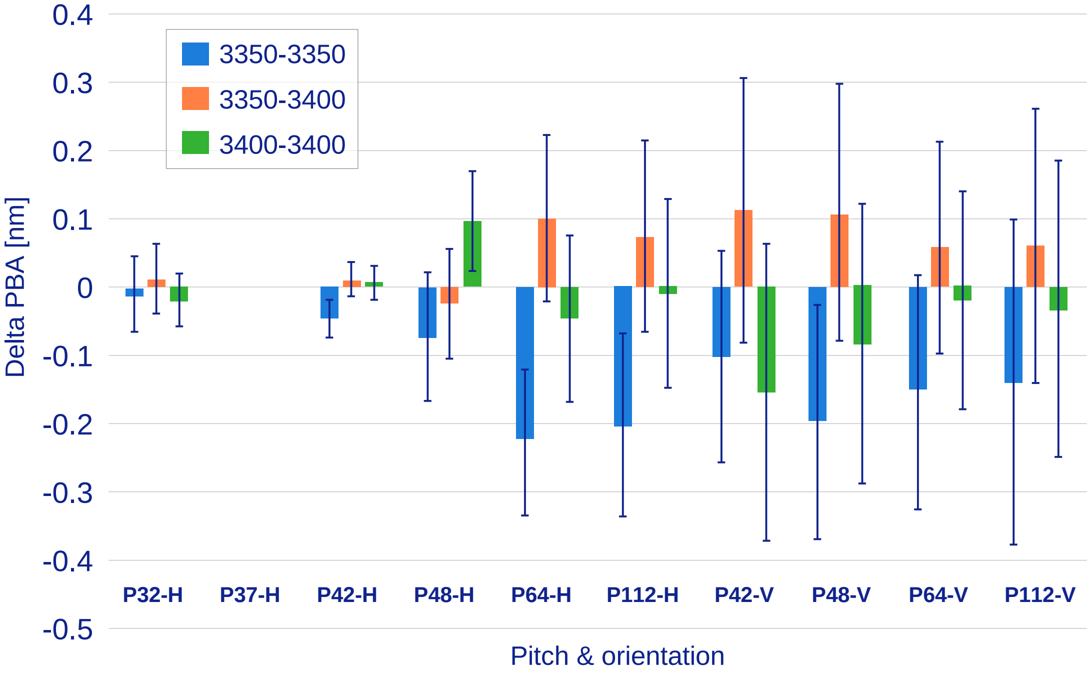





CAR EUVJ-4051
Dose 58 mJ, LWR 3.2 nm
DOF 140 nm, EL 18.7%

Proximity matching 3400-3350 well within specification

Tool-to-tool matching is precondition to HVM



	Test item	Unit	Actual
16 nm PBR	Proximity bias range, 5 pitches, uniformity in slit, 16 nm spaces	nm	**0.4**
16 nm PBA	Proximity bias average, 5 pitches, 16 nm spaces	nm	**0.3**

Higher flexibility of 3400 illuminator can be used to mimic all NXE:3350 settings

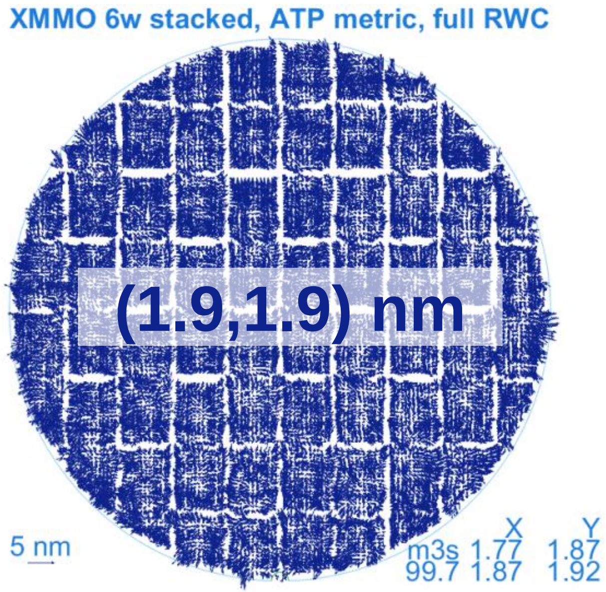
- Plus, throughput loss on NXE:3350 will be recovered for aggressive illumination modes
- Minor differences in lens optics are not significant factors in matching

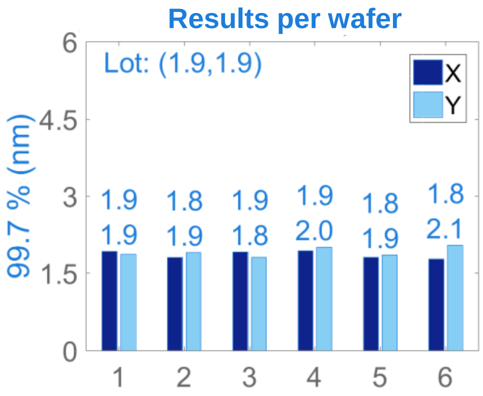
1.9 nm Matched overlay NXT:2000i to NXE:3400B

Champion data including lens fingerprint correction on NXT

- Setup done with new reference wafers (4.2)
- NXT2000i layer exposed with pellicle
- NXT (average population) lens fingerprint correction via Reticle Writing Correction simulated
- NXE at max scan speed (300mm/s)
- Overlay measured to reference (MMO)

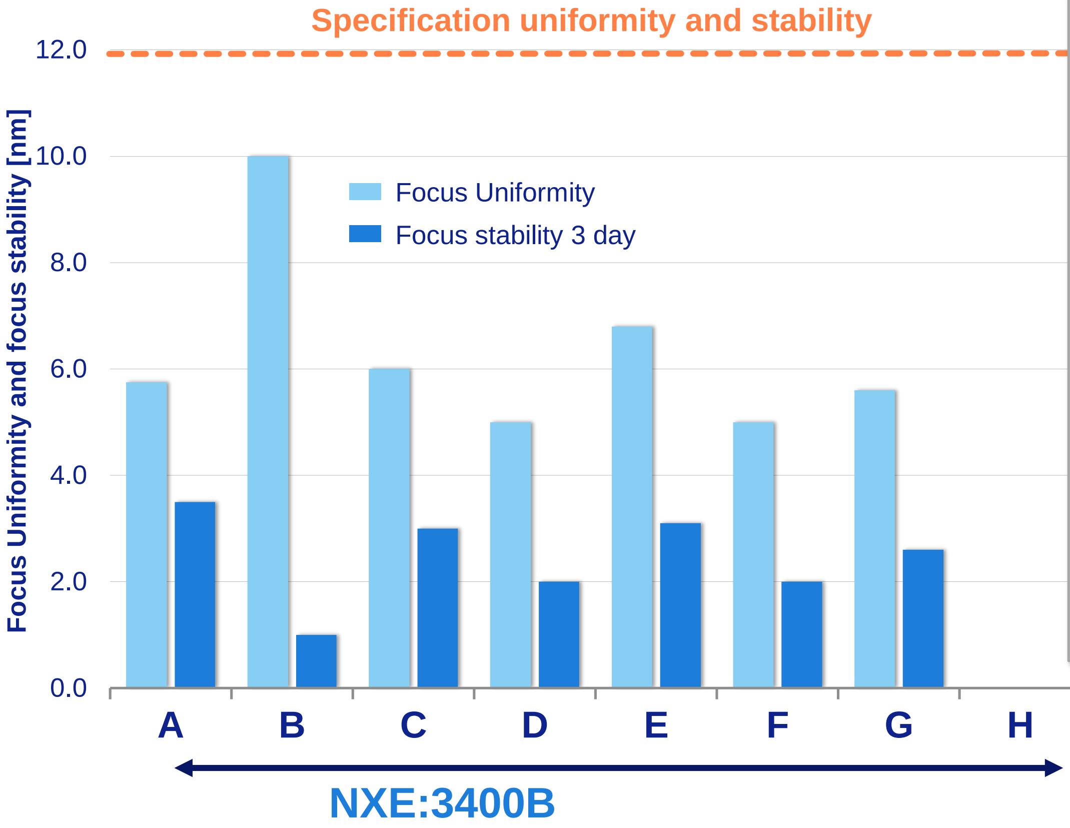
NXT:2000i
NXE:3400B full wafer

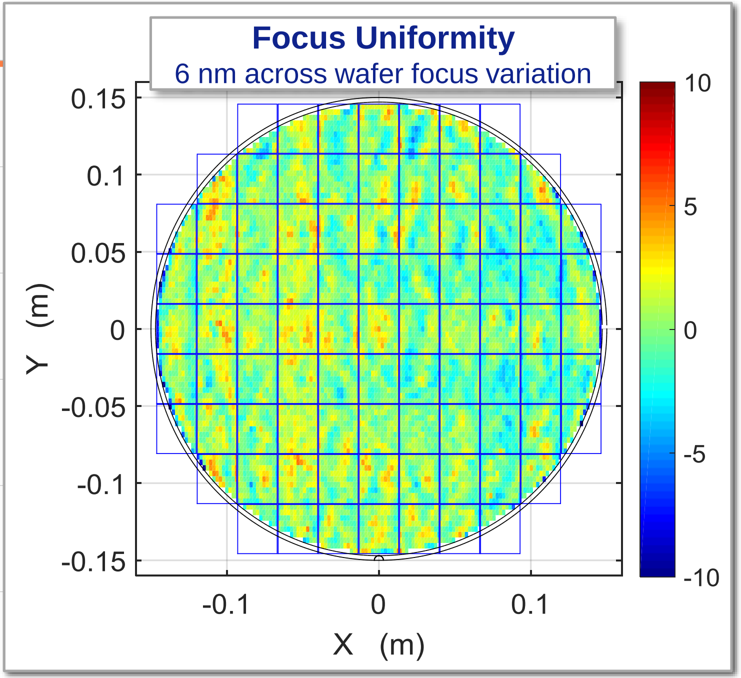




	OVL (X,Y)
NXT:2000 MMO	1.8,1.6 nm
NXE:3400 MMO	1.2,1.3 nm
NXT to NXE matching	1.9,1.9 nm

Multiple machines show < 6 nm focus uniformity





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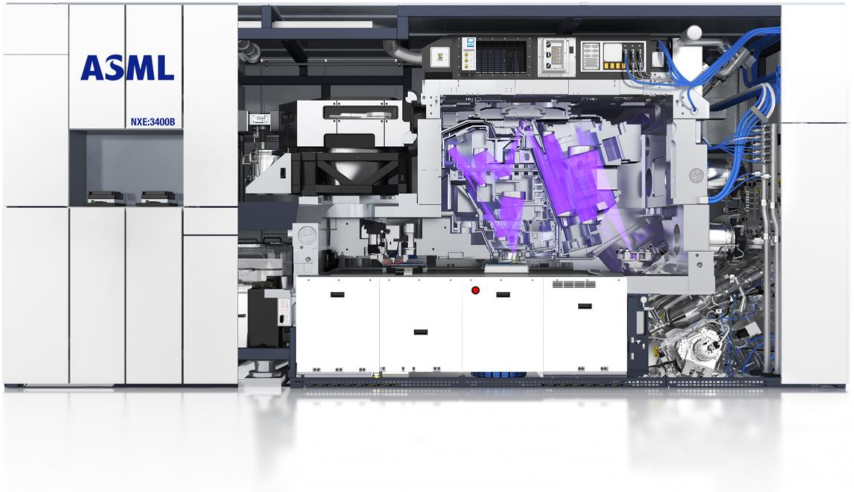
- EUV source roadmap
- EUV extendibility

Two-fold approach to eliminate reticle front-side defects

1. Clean system

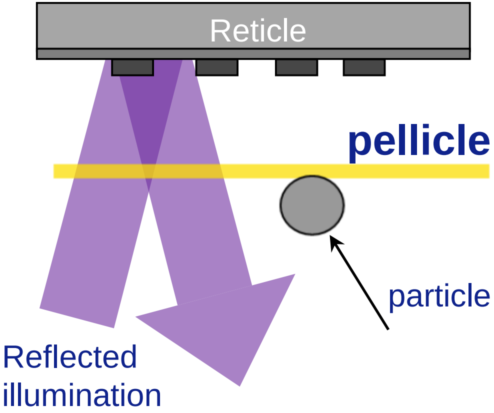
(without pellicle)

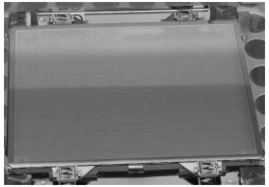


Reticle

2. EUV pellicle

EUV Reticle (13.5nm)

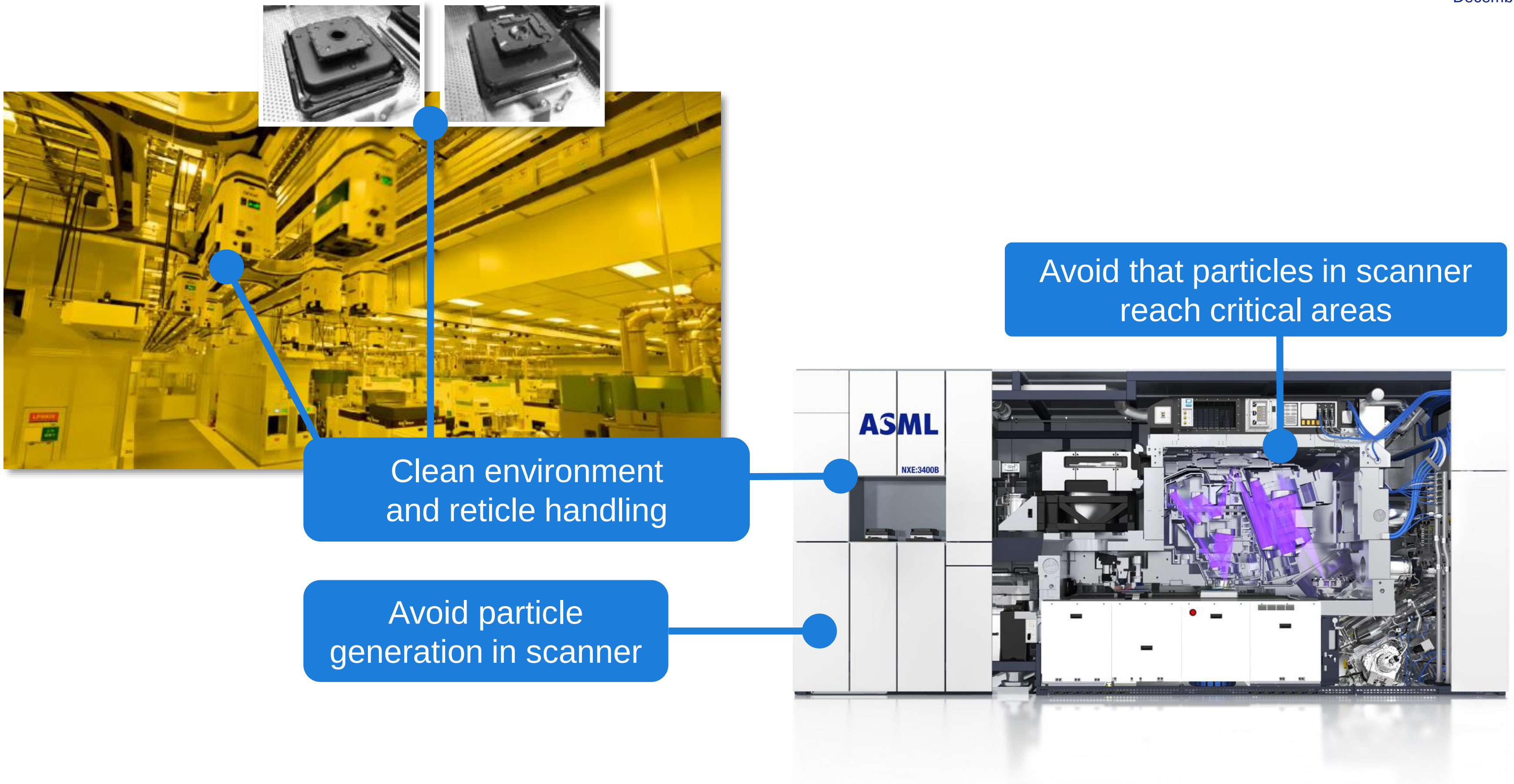




Reticle with pellicle

1. Clean system

Reticle front-side defectivity - Improvement categories



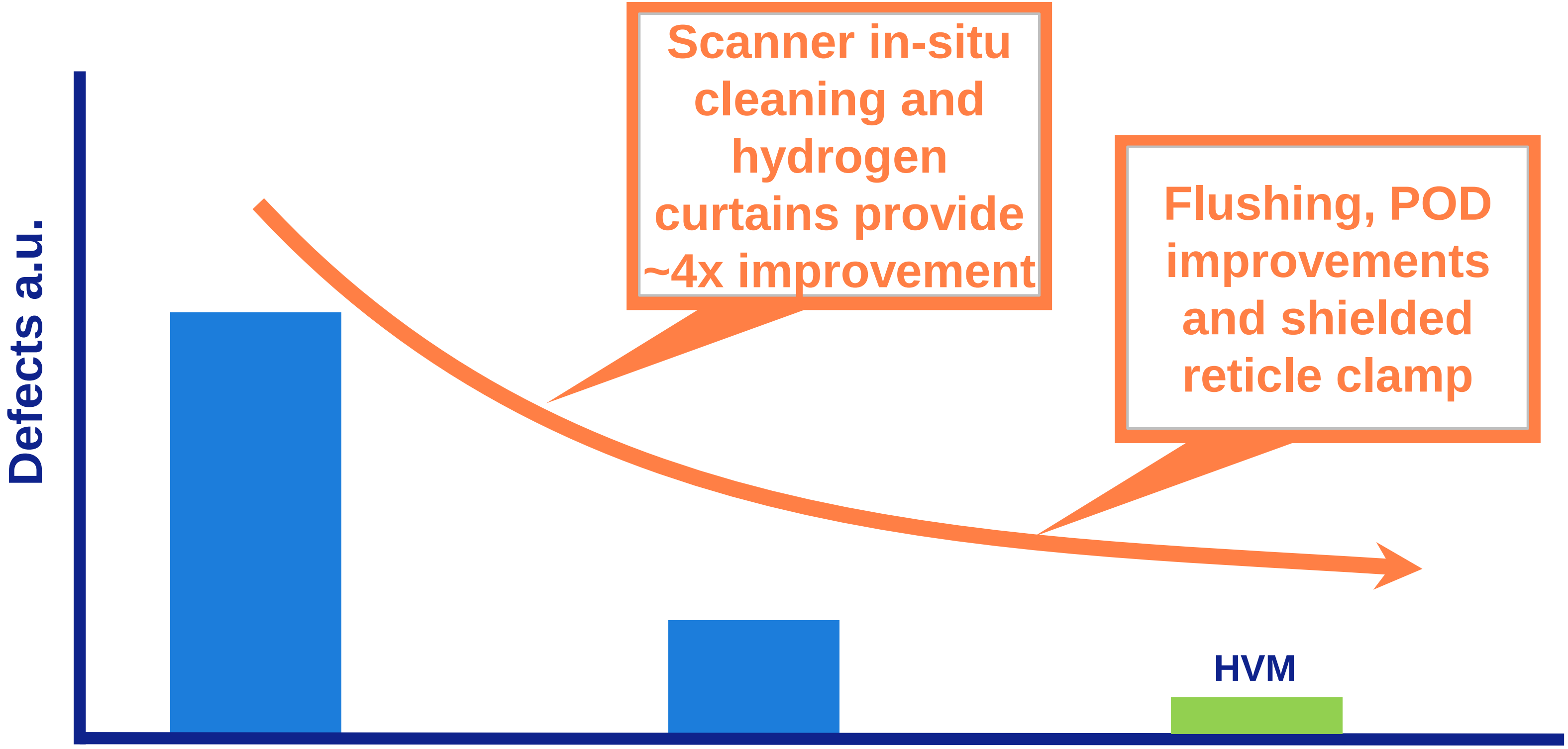
Avoid that particles in scanner reach critical areas

Clean environment and reticle handling

Avoid particle generation in scanner

1. Clean system

4x improvement for reticle defectivity

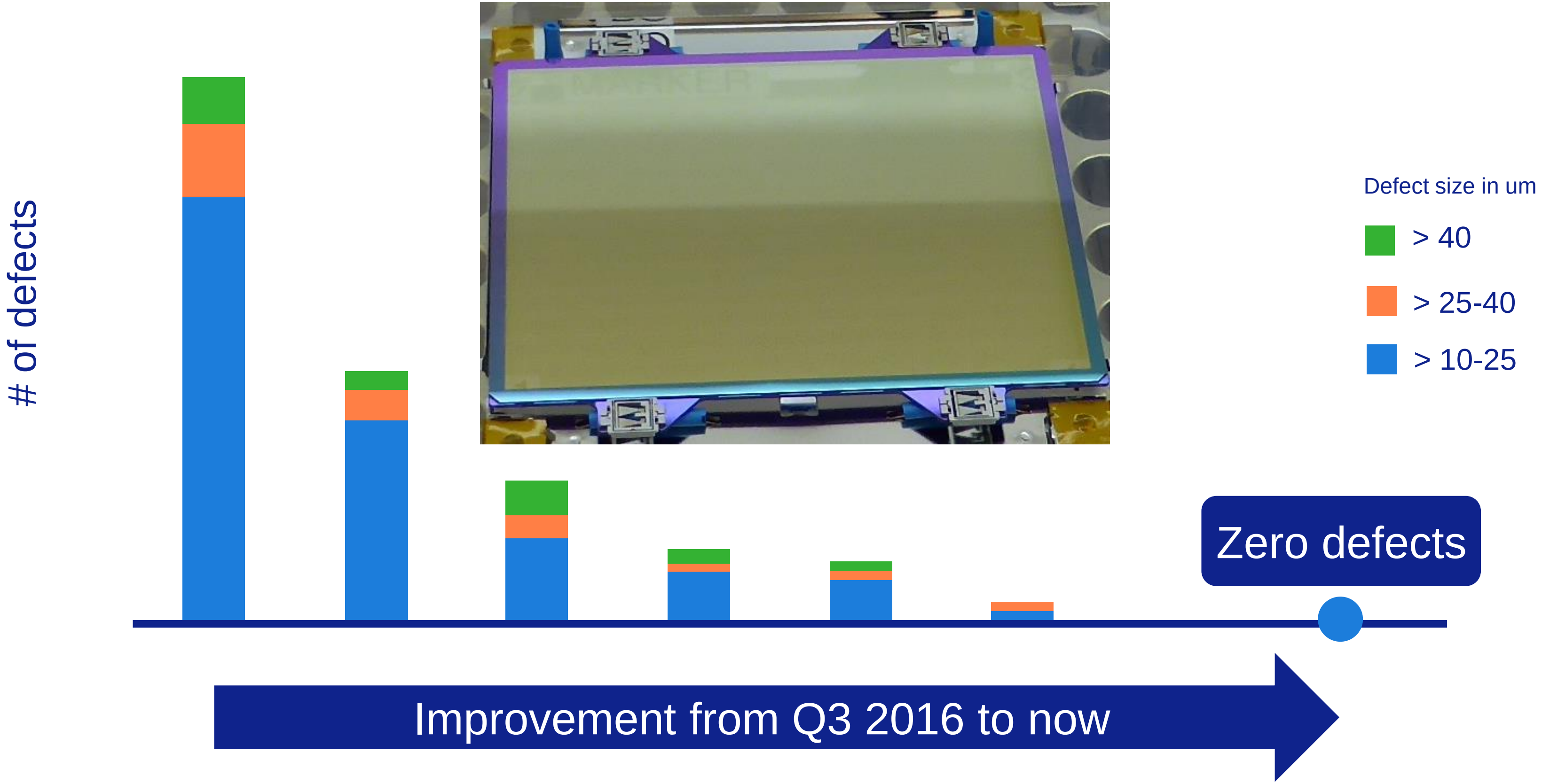


Scanner in-situ cleaning and hydrogen curtains provide ~4x improvement

Flushing, POD improvements and shielded reticle clamp

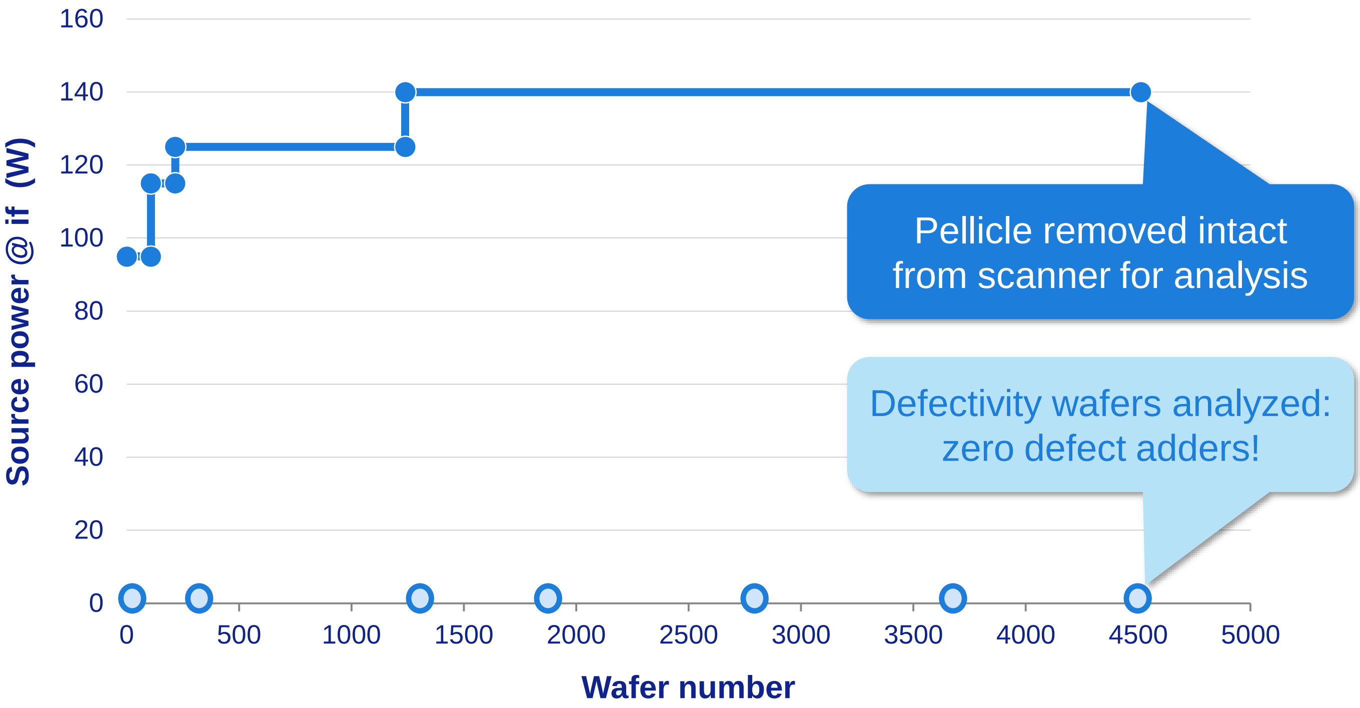
2. EUV pellicle

Today: Pellicle film produced without defects that print



2. EUV pellicle

ASML pellicle capability confirmed to at least 140W



Pellicle removed intact from scanner for analysis

Defectivity wafers analyzed: zero defect adders!

Enhanced cooling enables >200W usage

Defects analyzed at seven instances during marathon run: zero adders

22 nm Patterned Defect reticle exposed on NXE:3400B

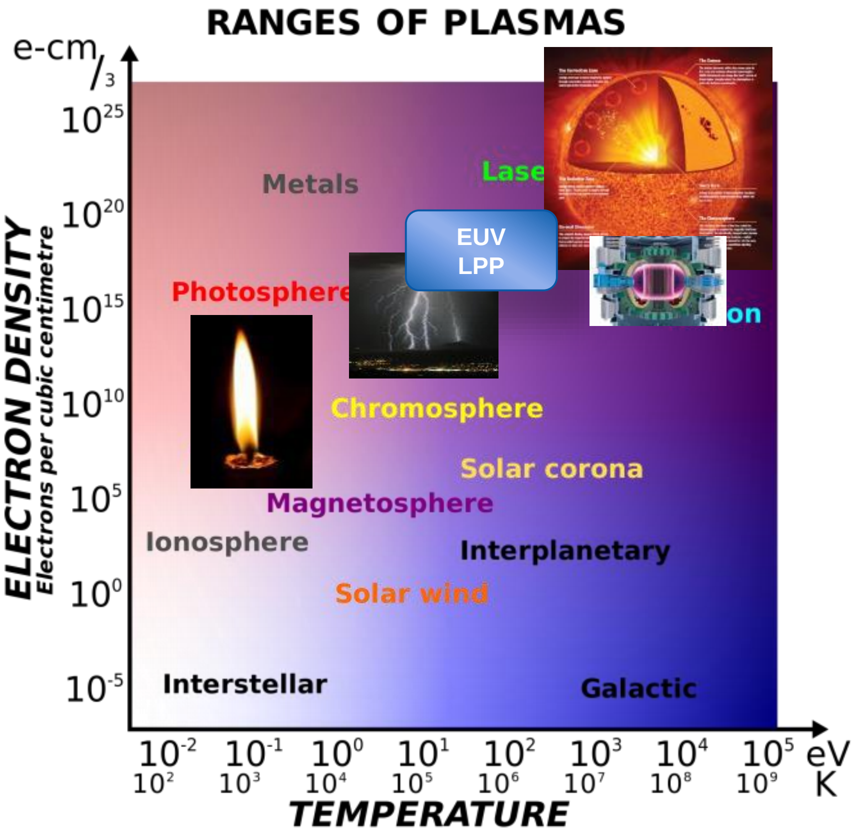
EUV: Principles of Generation

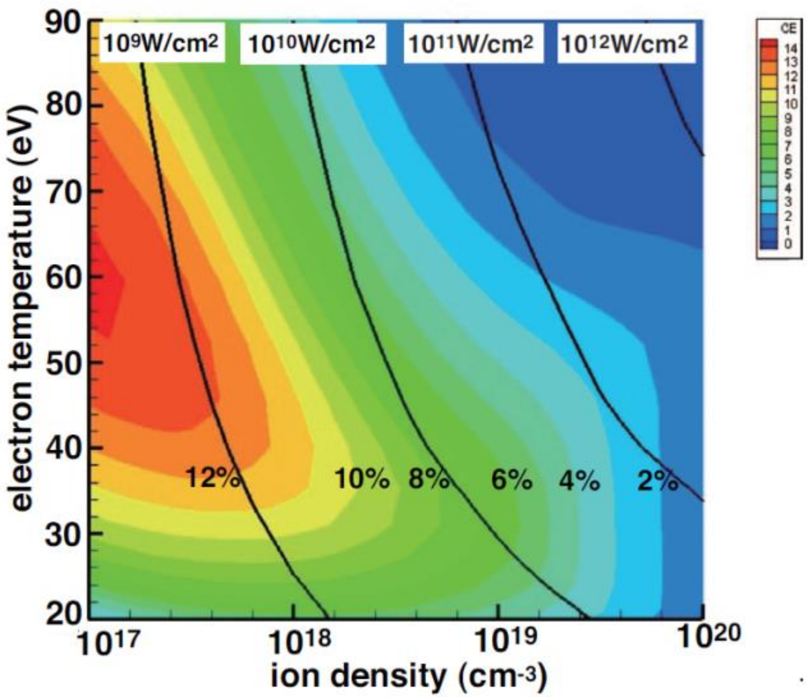
Laser Produced Plasma Density and Temperature

Nishihara et al. (2008)

Ion density ~ $10^{17} – 10^{18}$ #/cm^3

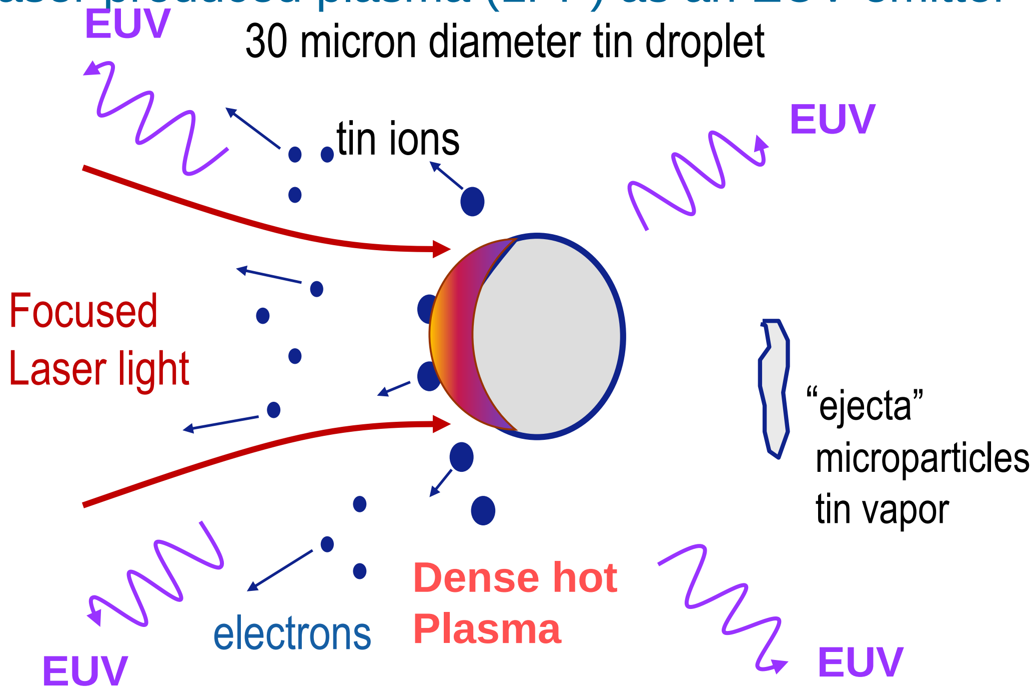
Temperature ~ 30 -100 eV





Fundamentals: EUV Generation in LPP

Laser produced plasma (LPP) as an EUV emitter



EUV

30 micron diameter tin droplet

tin ions

EUV

Focused
Laser light

“ejecta”
microparticles
tin vapor

electrons

Dense hot
Plasma

EUV

EUV

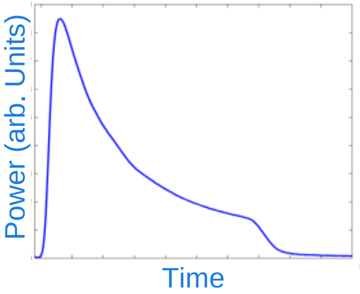
Tin Laser Produced Plasma Image

1. High power laser interacts with liquid tin producing a plasma.
2. Plasma is heated to high temperatures creating EUV radiation.
3. Radiation is collected and used to pattern wafers.

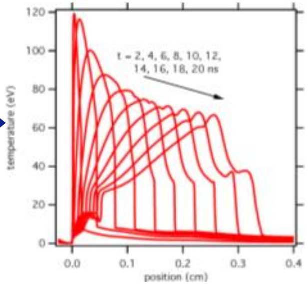
Plasma simulation capabilities

Main-pulse modeling using HYDRA

Main-pulse shape

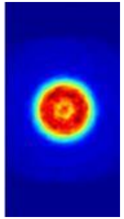


1D:
real pulse shape

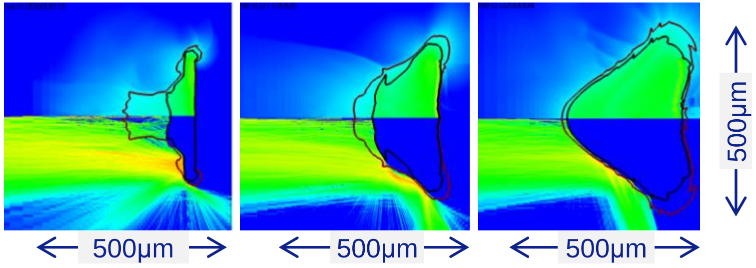


1D simulations are fast and useful for problems that require rapid feedback and less accuracy

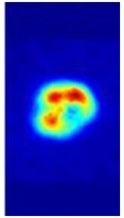
2D:
+ symmeterized beam profile

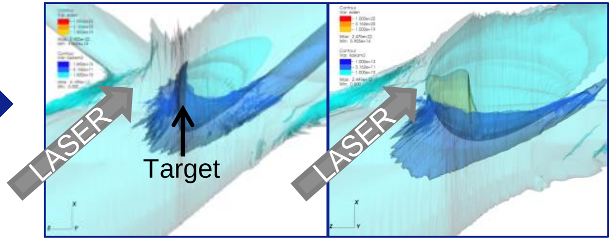


Electron density (top half) with laser light (bottom half)



3D:
+ real asymmetric profile





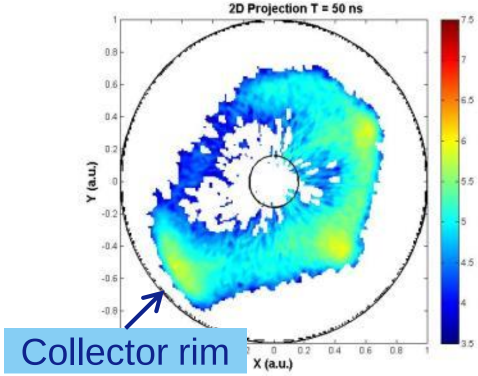
2D and 3D simulations are run for the full duration of the Main pulse. Results include temperature, electron density, spectral emission, etc.

Sn target using a real irradiance distribution

Simulation of the EUV source

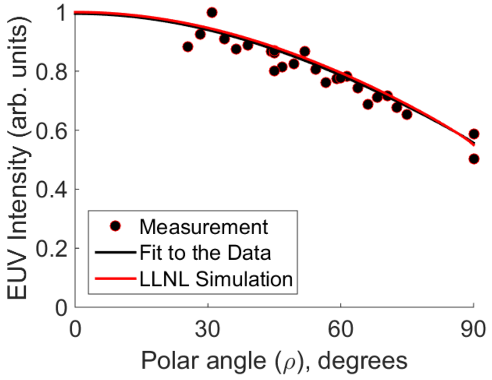
The plasma code's outputs were processed to produce synthetic source data. The comparison to experiments helps to validate the code and understand it's accuracy.

Reflected laser modeling

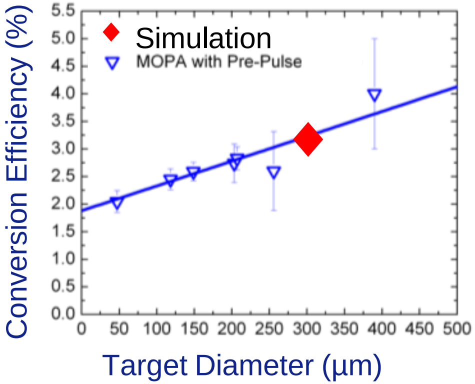


Collector rim

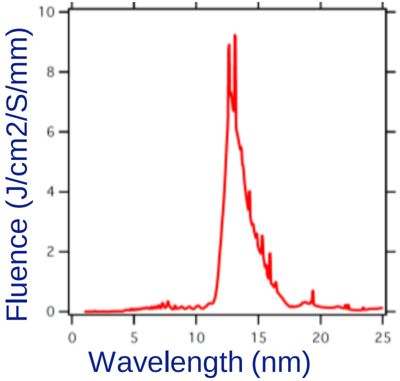
Emission and debris anisotropy



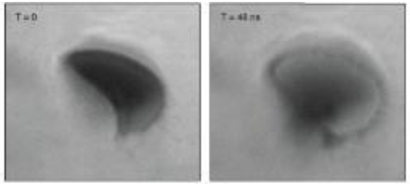
Conversion Efficiency



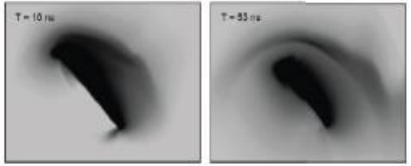
Simulated EUV spectra



Measured Shadowgrams

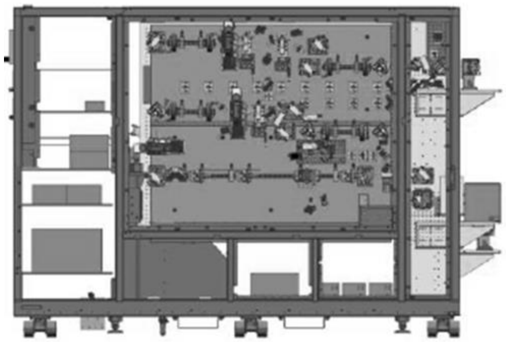


Simulated Shadowgrams



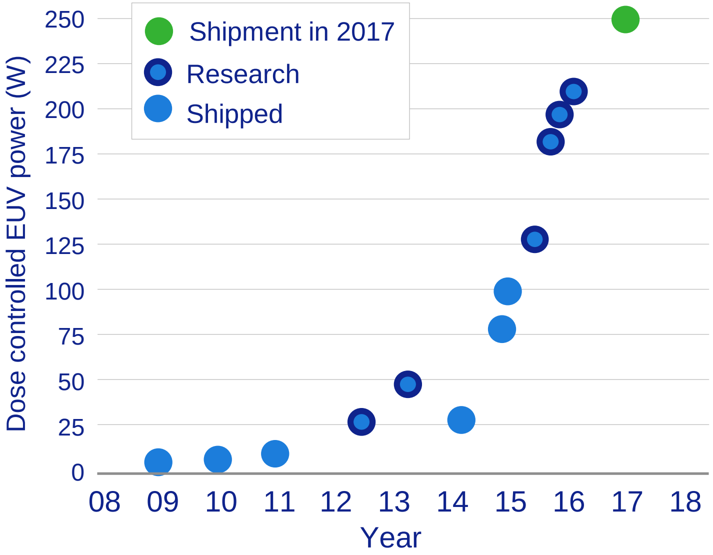
Summary: Path from Technology development with PPIM/MPIM to Industrialized module

Technology Development

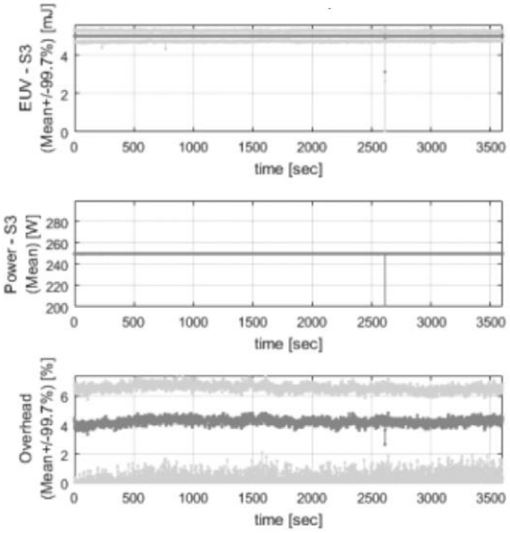


SD Proto: Manufactured and stand-alone test in San Diego 250W achieved

EUV Power History



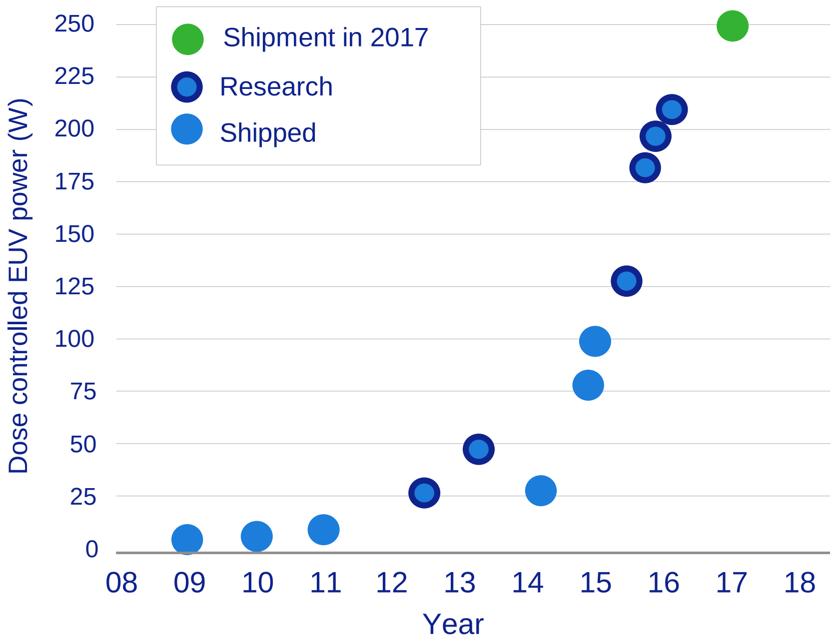
Data: Wk1720



250W with 99% die yield measured

Progress for 2017: 250W demonstrated

EUV power (source/scanner interface, [W]) ∝ **CO$_2$ power [W]** * **Conversion Efficiency [%]** * **1 – Dose Overhead [%]**



>250W is now demonstrated, shipping planned end of 2017

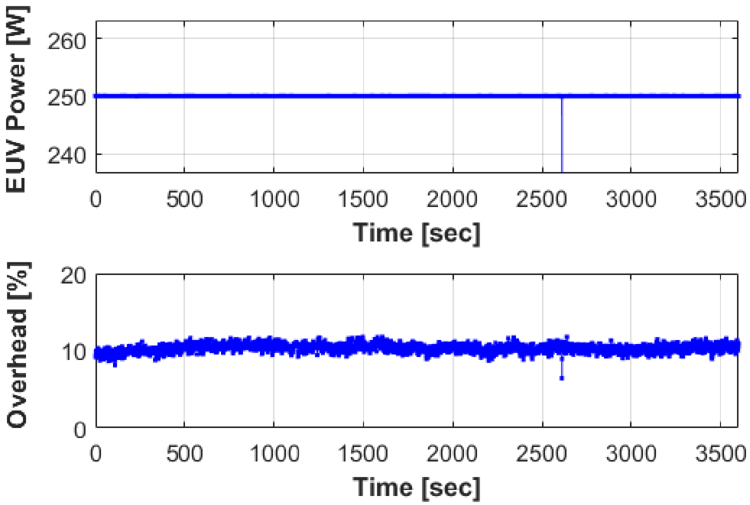
Increase average and peak laser power
Enhanced isolation technology

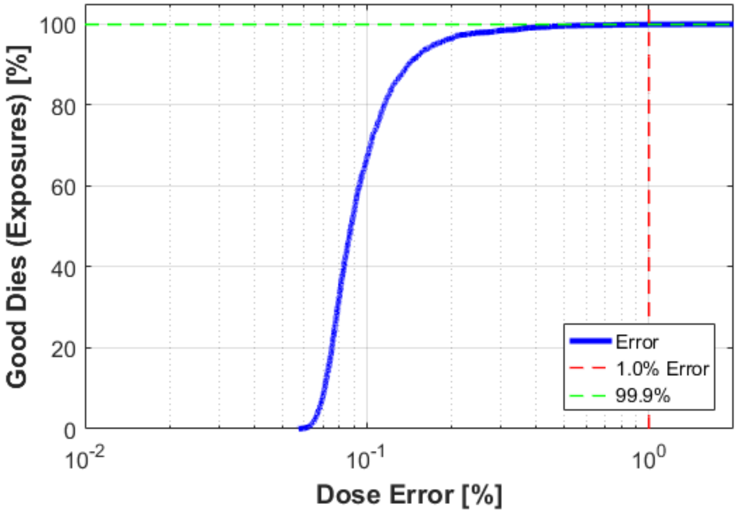
Advanced target formation technology

Improved dose-control technique

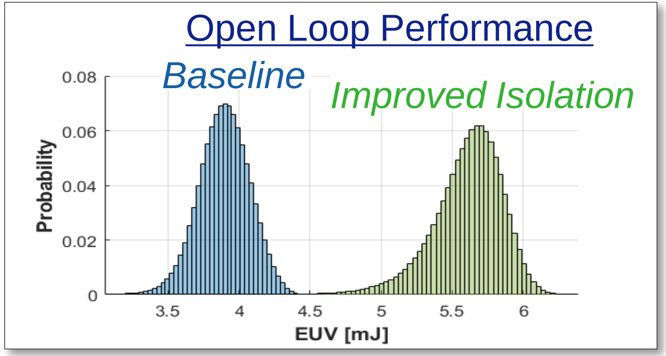
EUV Source operation at 250W

with 99.9% fields meeting dose spec



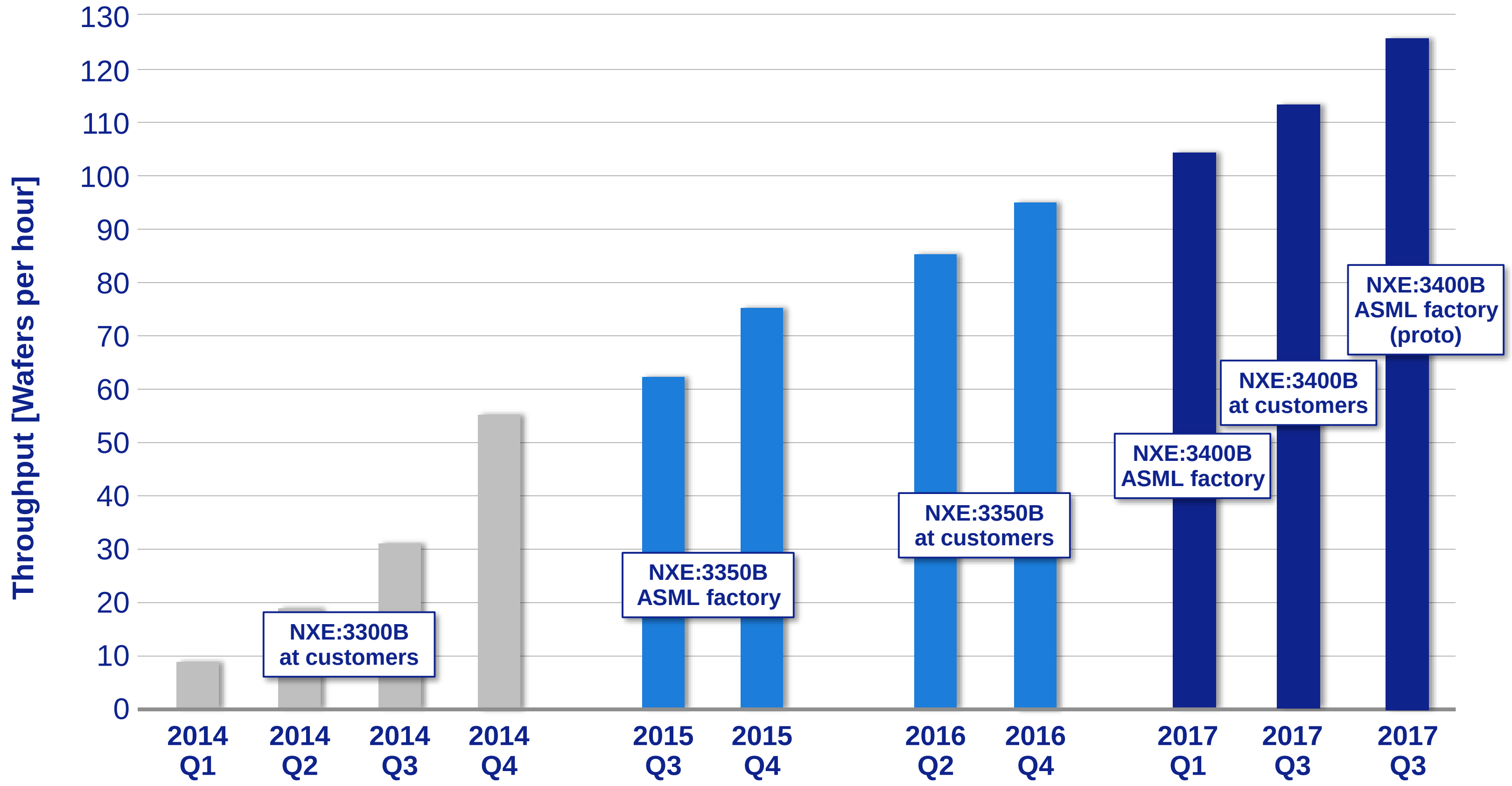


Operation Parameters	
Repetition Rate	50kHz
MP power on droplet	21.5kW
Conversion Efficiency	6.0%
Collector Reflectivity	41%
Dose Margin	10%
EUV Power	**250 W**


Open Loop Performance

NXE productivity above **125** wafers per hour

NXE:3400B, 126 WPH at 207W using proto version Seed table Isolation Module



NXE:3400B ATP test: 26x33mm2, 96 fields, 20mJ/cm2

Productivity increases via source availability

Secured EUV power is matched with increasing availability

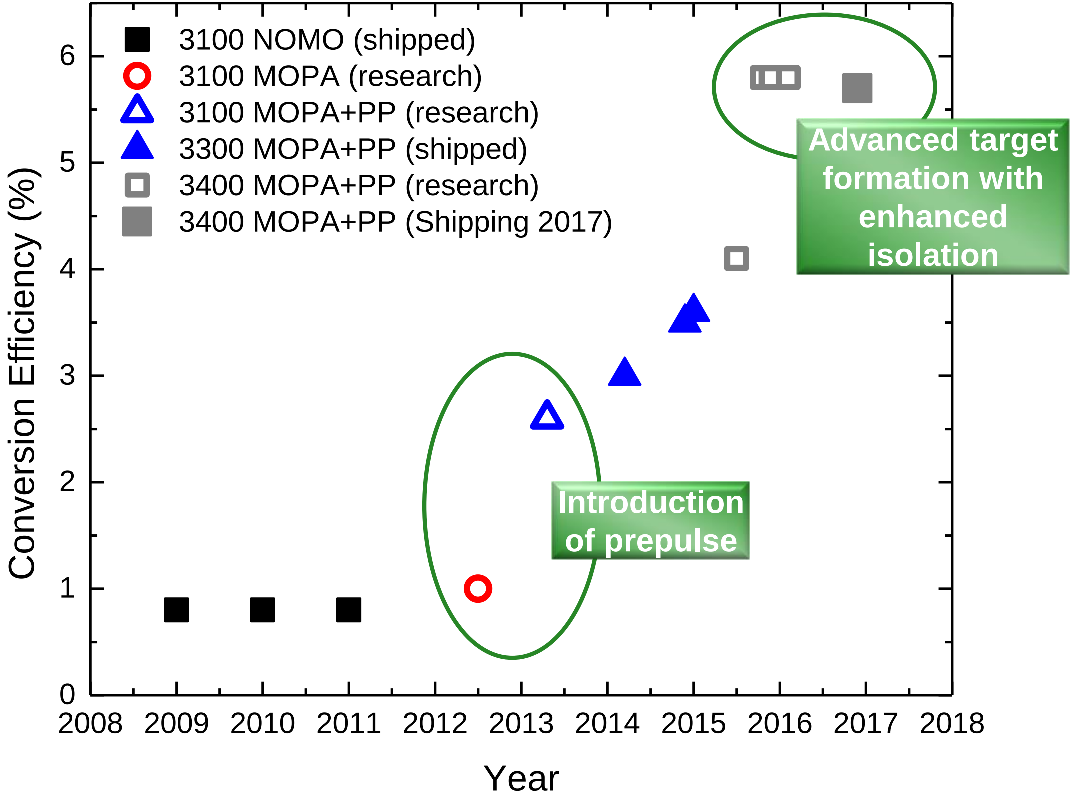
$$\boxed{\text{Productivity} = \text{Throughput}(\propto \text{EUV Power}) \times \text{Availability}}$$

$$\boxed{\text{EUV Power} = (\text{CO}_2\ \underbrace{\text{laser power} \times \text{CE} \times \text{transmission})}_{\text{Raw EUV power}} * (1\text{-dose overhead})}$$

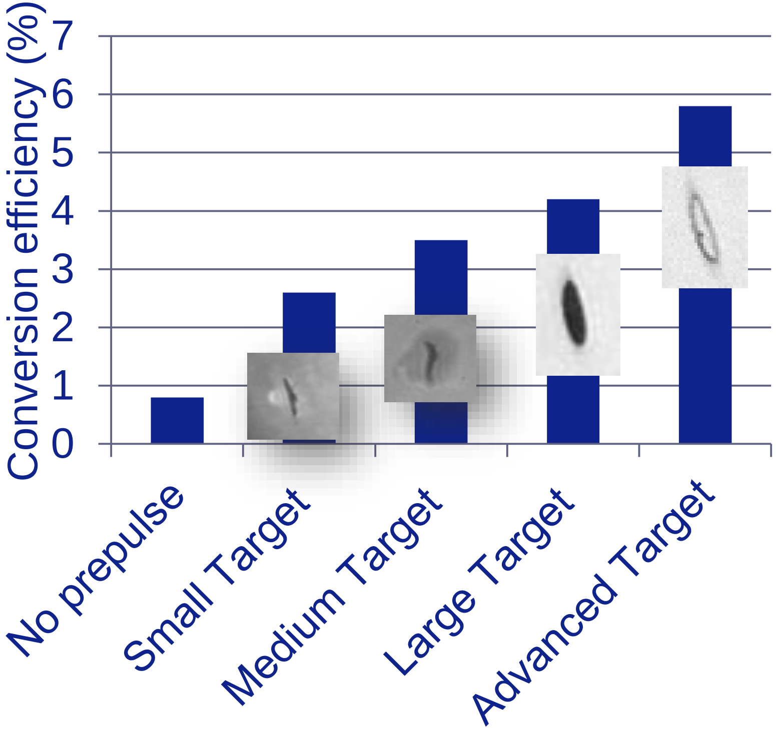
Source power **from 10 W to > 250 W**	Drive laser power	from 20 to >20kW
	Conversion efficiency (CE)	from 2 to 6% (Sn droplet)
	Dose overhead	from 50 to 10%
	Optical transmission	
Source availability	Automation	
	Collector protection	
	Droplet generator reliability & lifetime	
	Drive laser reliability	

Enhanced isolation leads to >205W EUV power

via advanced target formation for high CE



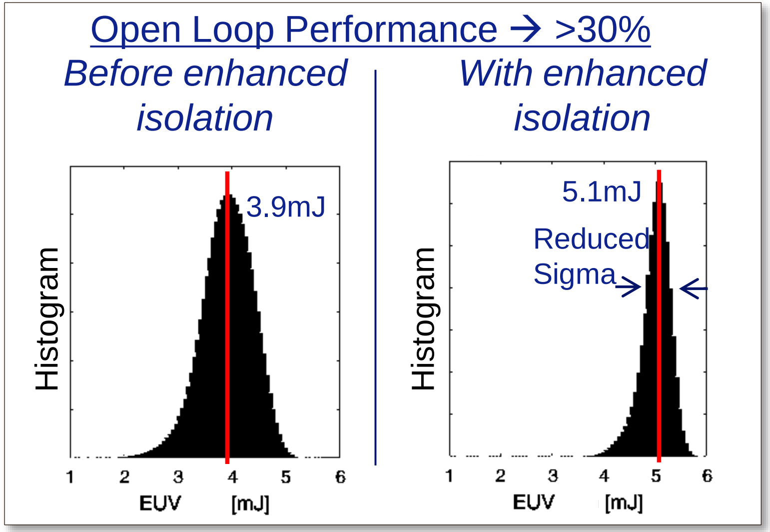
Conversion Efficiency vs target type

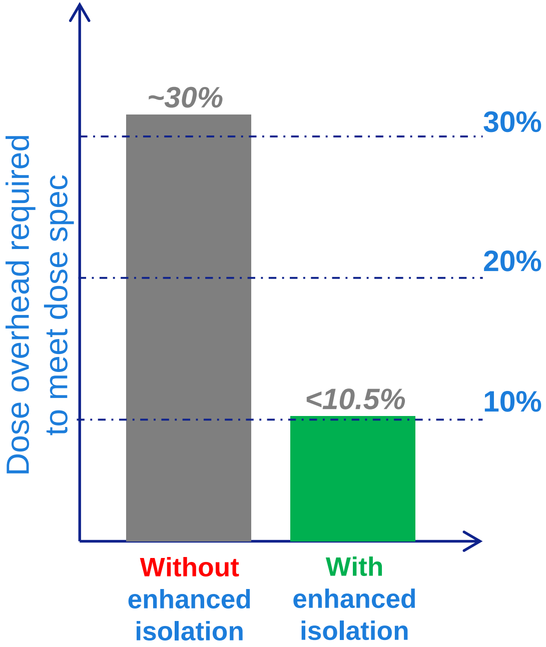


Enhanced isolation improves EUV performance

Benefits of enhanced isolation:

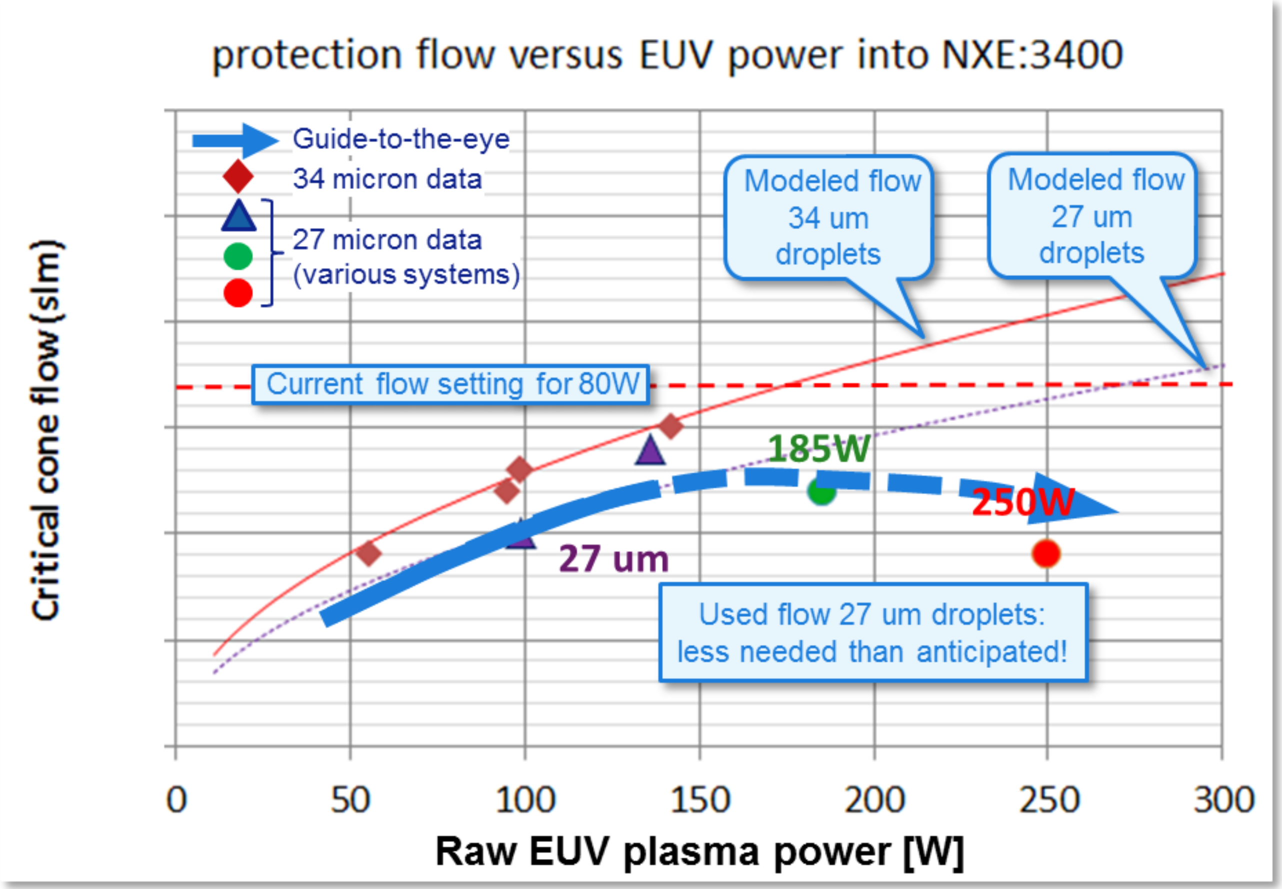
- **Higher, stable CO_2 laser power → lower dose overhead**
- **High conversion efficiency operation → higher pulse energy**





Collector protection secured up to 250 W

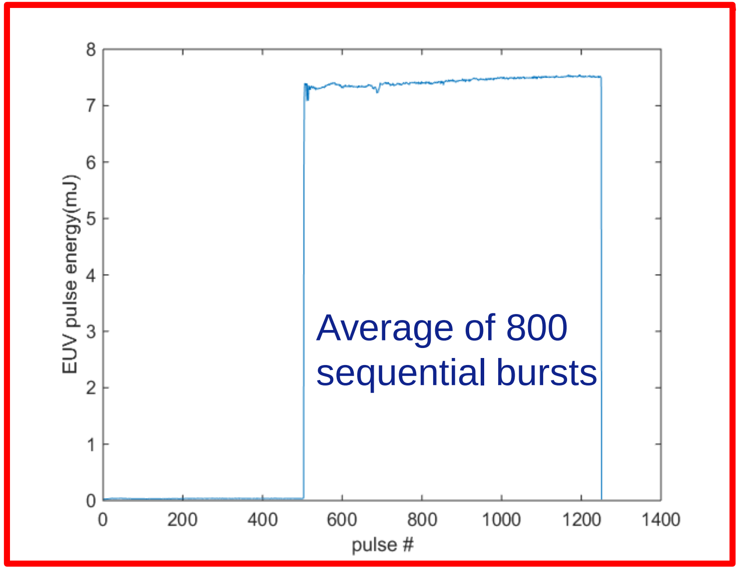
Collector protection demonstrated on research tool



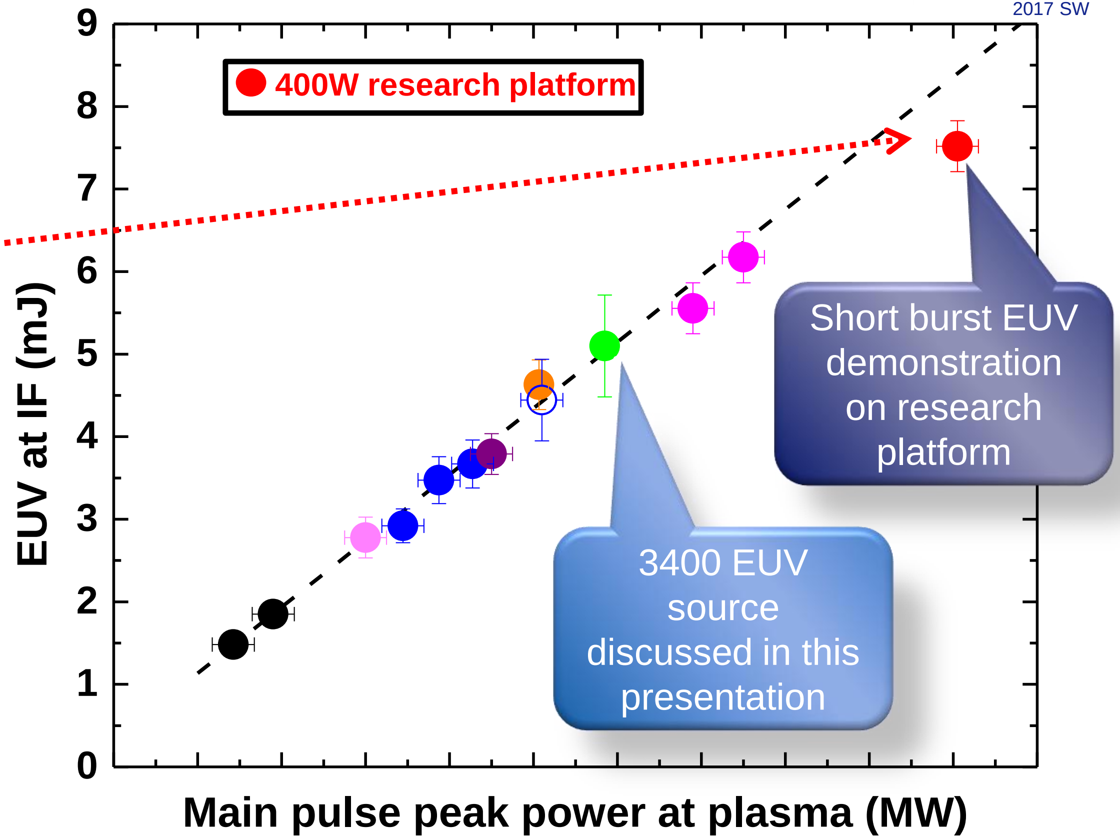
Research progress in EUV source

Demonstrated EUV pulse energy of 7.5mJ

375W in-burst at 50kHz



Average of 800 sequential bursts



Short burst EUV demonstration on research platform

3400 EUV source discussed in this presentation

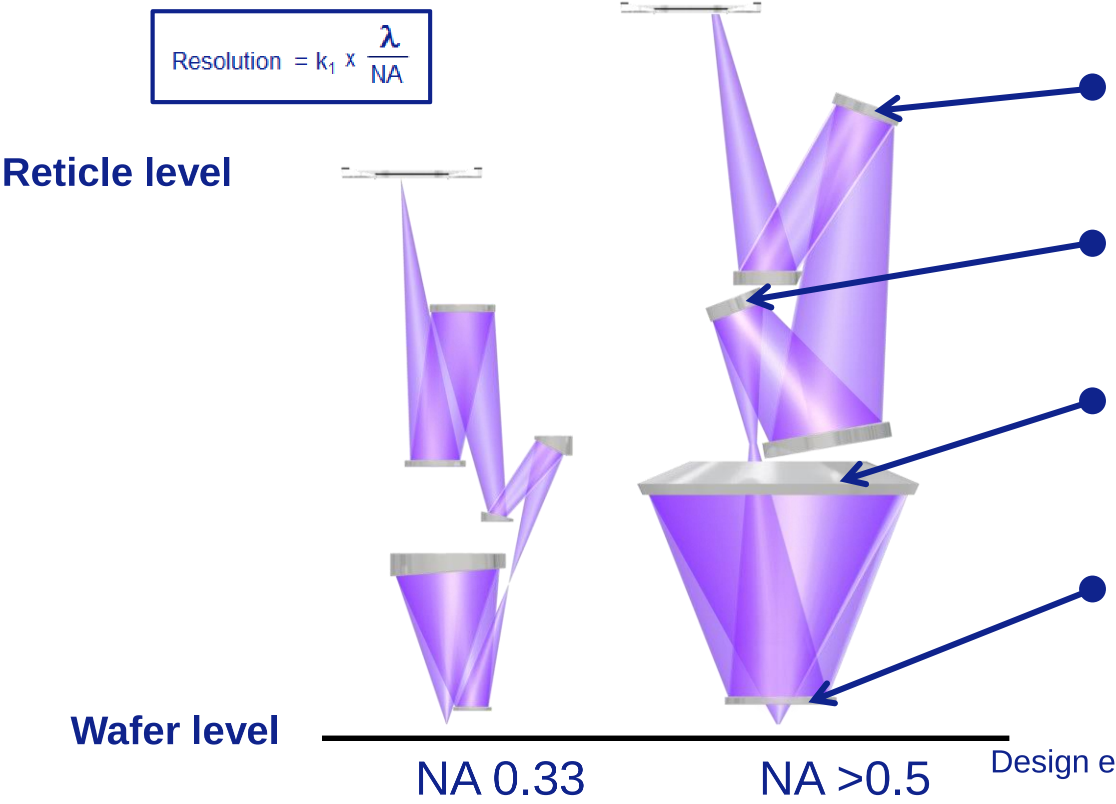
Outline

- NXE Roadmap
- NXE:3400B performance
- Reticle front-side defectivity
- EUV source roadmap
- EUV extendibility

High-NA optics design available

Larger elements with tighter specifications

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



Design examples

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**

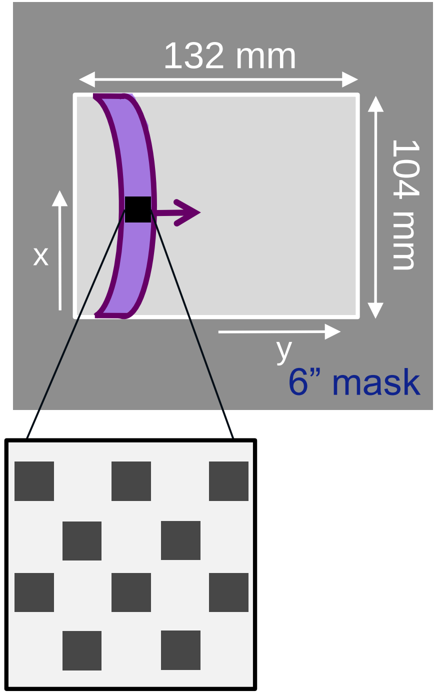
Source: Zeiss, “EUV lithography optics for sub-9 nm resolution,” Proc. SPIE 9422, (2015).

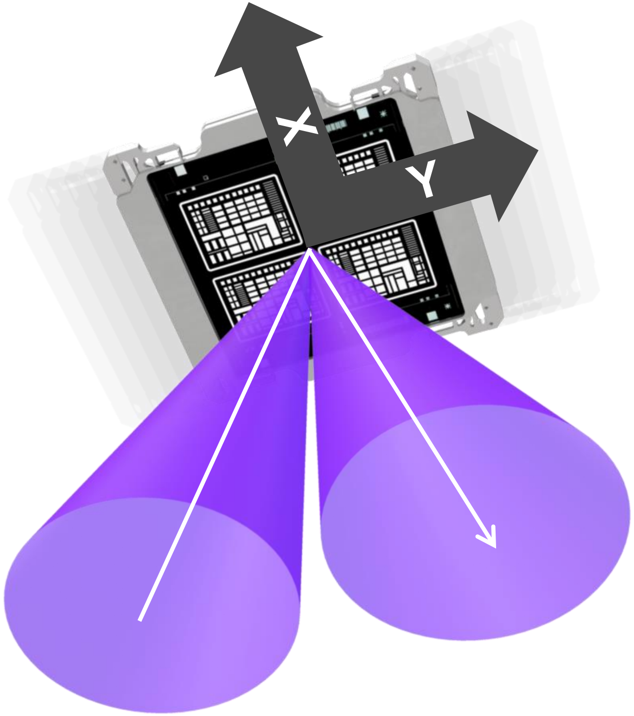
Anamorphic High NA EUV reduces the angles

Enabling a solution with 26 mm slit on 6” masks

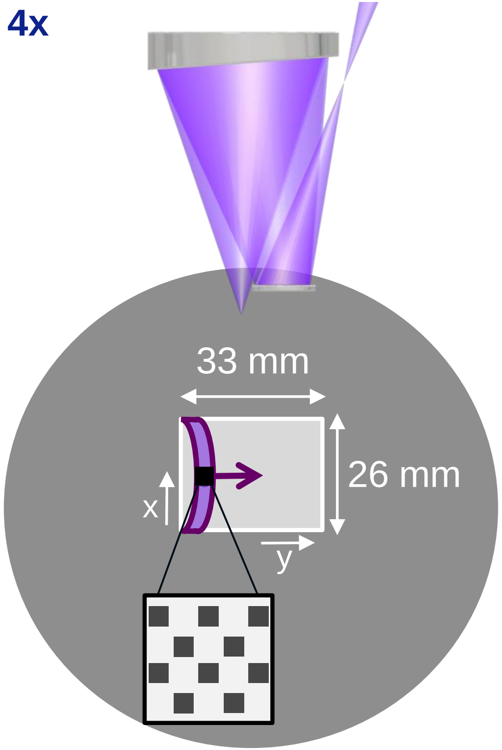
Reticle

Reticle layout compatible with
today 6” mask production





Projection with 0.33 NA
Mag X: 4x
Mag Y: 4x

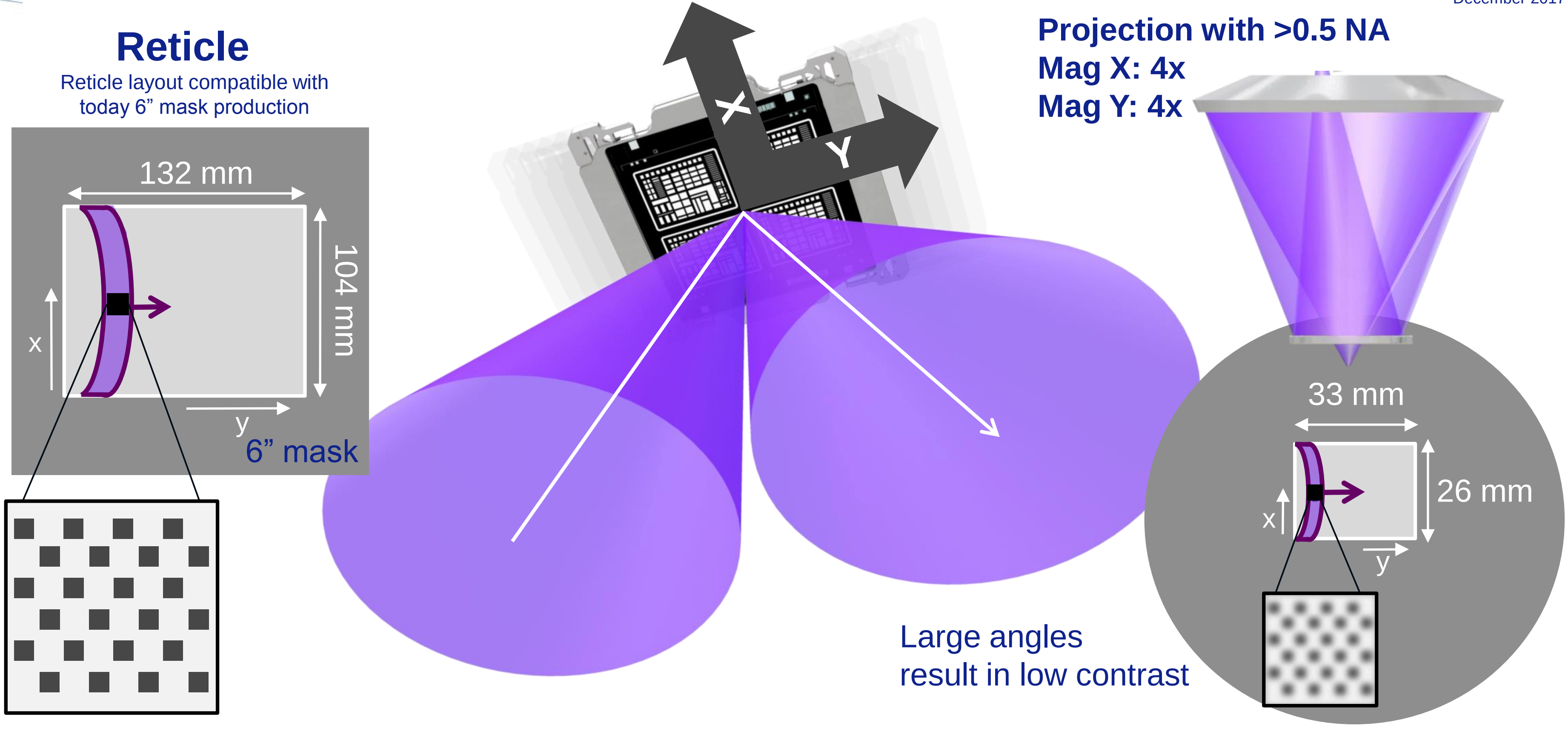


Wafer

Source: Jan van Schoot, ASML, “EUV roadmap extension by higher NA”, 2016 international symposium on EUV, 24 Oct 2016, Hiroshima

Anamorphic High NA EUV reduces the angles

Enabling a solution with 26 mm slit on 6” masks



Reticle

Reticle layout compatible with
today 6” mask production

Projection with >0.5 NA
Mag X: 4x
Mag Y: 4x

Large angles
result in low contrast

Wafer

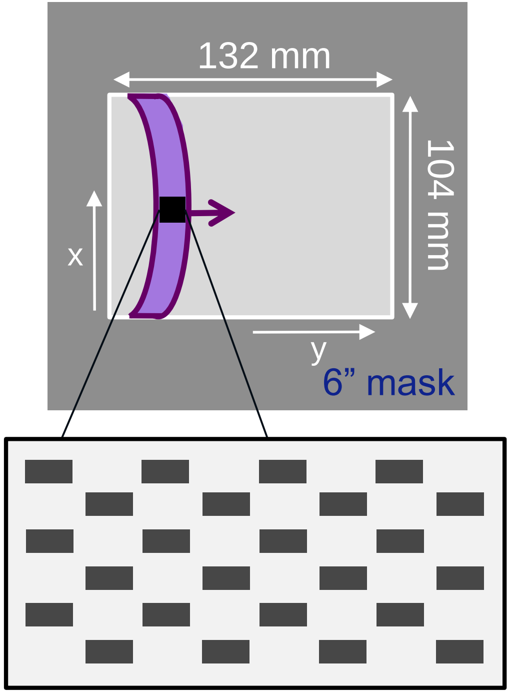
Source: Jan van Schoot, ASML, “EUV roadmap extension by higher NA”, 2016 international symposium on EUV, 24 Oct 2016, Hiroshima

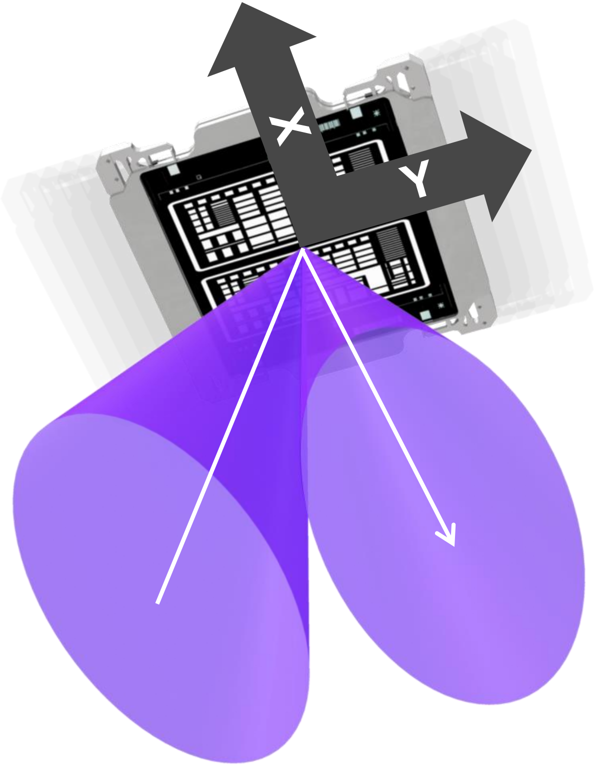
Anamorphic High NA EUV reduces the angles

Enabling a solution with 26 mm slit on 6” masks

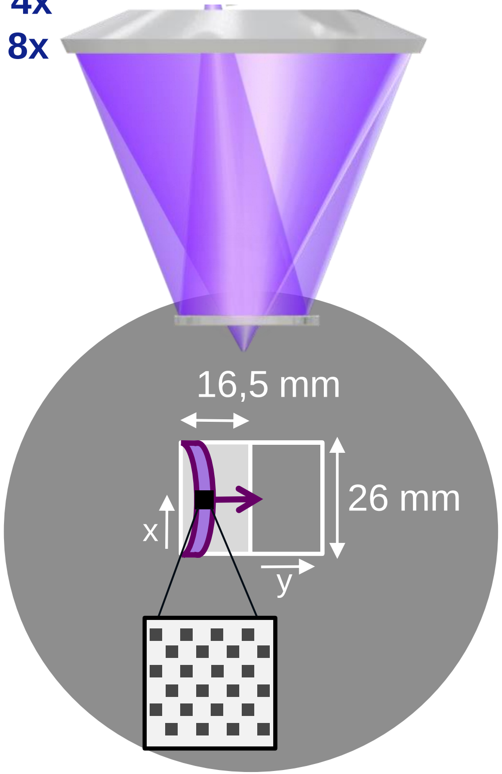
Reticle

Reticle layout compatible with today 6” mask production





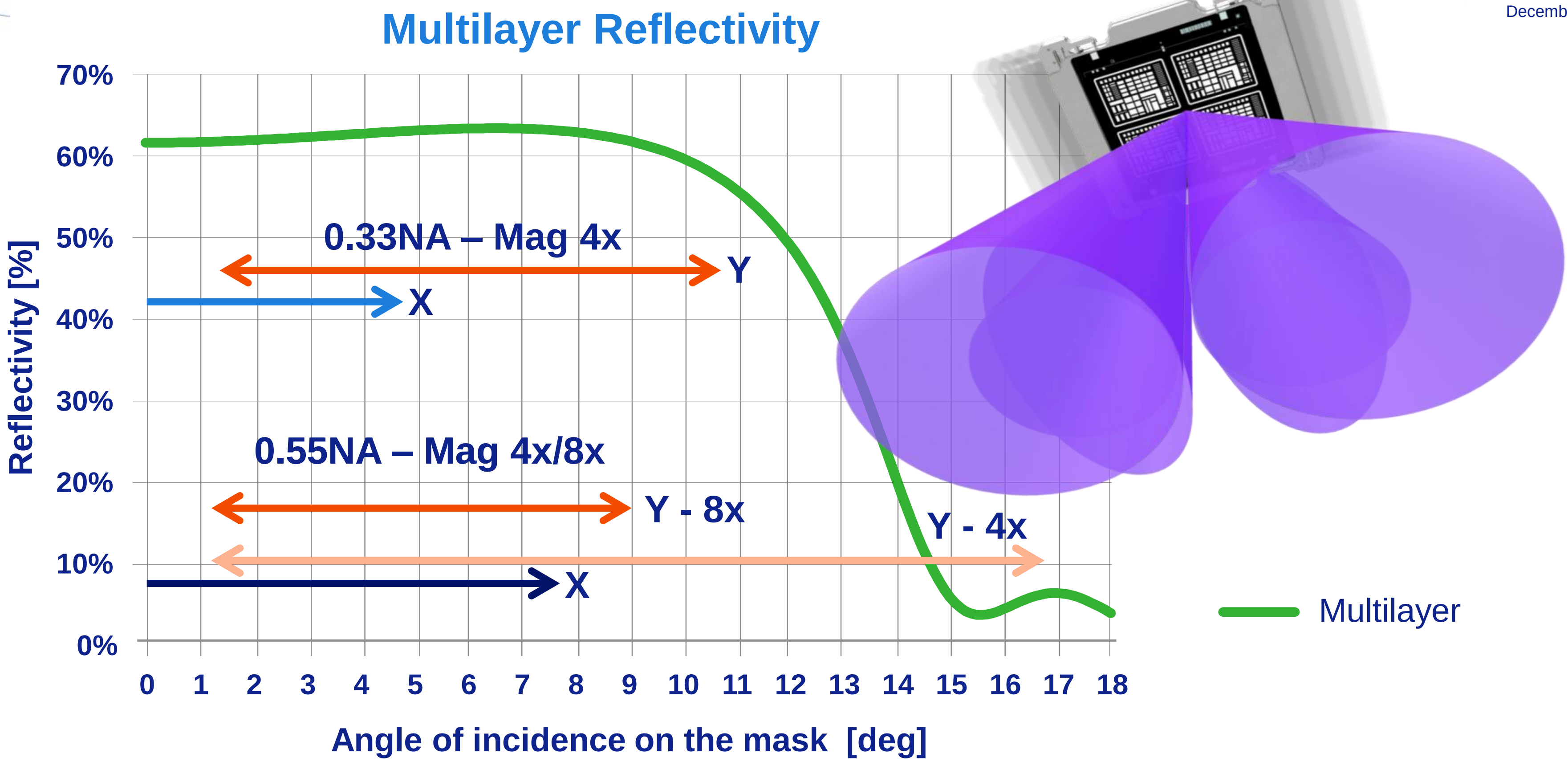
Projection with >0.5 NA
Mag X: 4x
Mag Y: 8x



Wafer

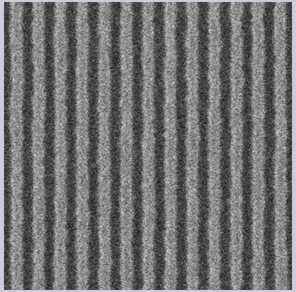
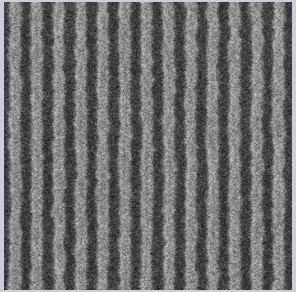
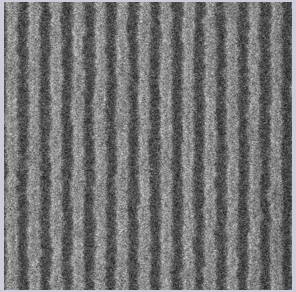
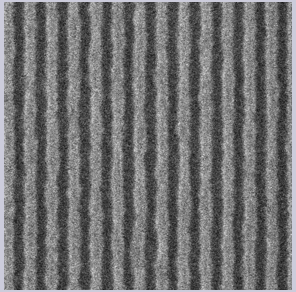
Source: Jan van Schoot, ASML, “EUV roadmap extension by higher NA”, 2016 international symposium on EUV, 24 Oct 2016, Hiroshima

Anamorphic magnification solves the problem at the mask



New CAR Resists: towards 16nm resolution at full throughput

21 mJ/cm^2 achieved with good performance; Z-factor improved by 25%

	Reference	CAR1	CAR2	CAR3
SEM image @BE/BF				
Dose2Size [mJ/cm^2]	42.2	26.3	20.9	20.1
LWR [nm]	4.3	4.8	5.5	5.5
EL_{LQD} [%]	16.5	14.3	14.1	9.1
DOF [nm]	140	115	90	50
Z-factor [mJ/cm^2 * nm^3]	1.6E-08	1.2E-08	1.3E-08	1.3E-08

**** Exposures performed on NXE:3xy0 with Dip90Y illumination***

Conclusion

- Significant progress has been made in all key areas towards insertion in HVM
- >125 WPH demonstrated on NXE:3400B
- EUV lithographic performance results confirmed:
  - Imaging CDU 0.4 nm
  - NXT to NXE overlay matching 1.9 nm
- Roadmap exists to continue to scale productivity

ASML