Public

Continued Scaling in Semiconductor Manufacturing with EUV Lithography

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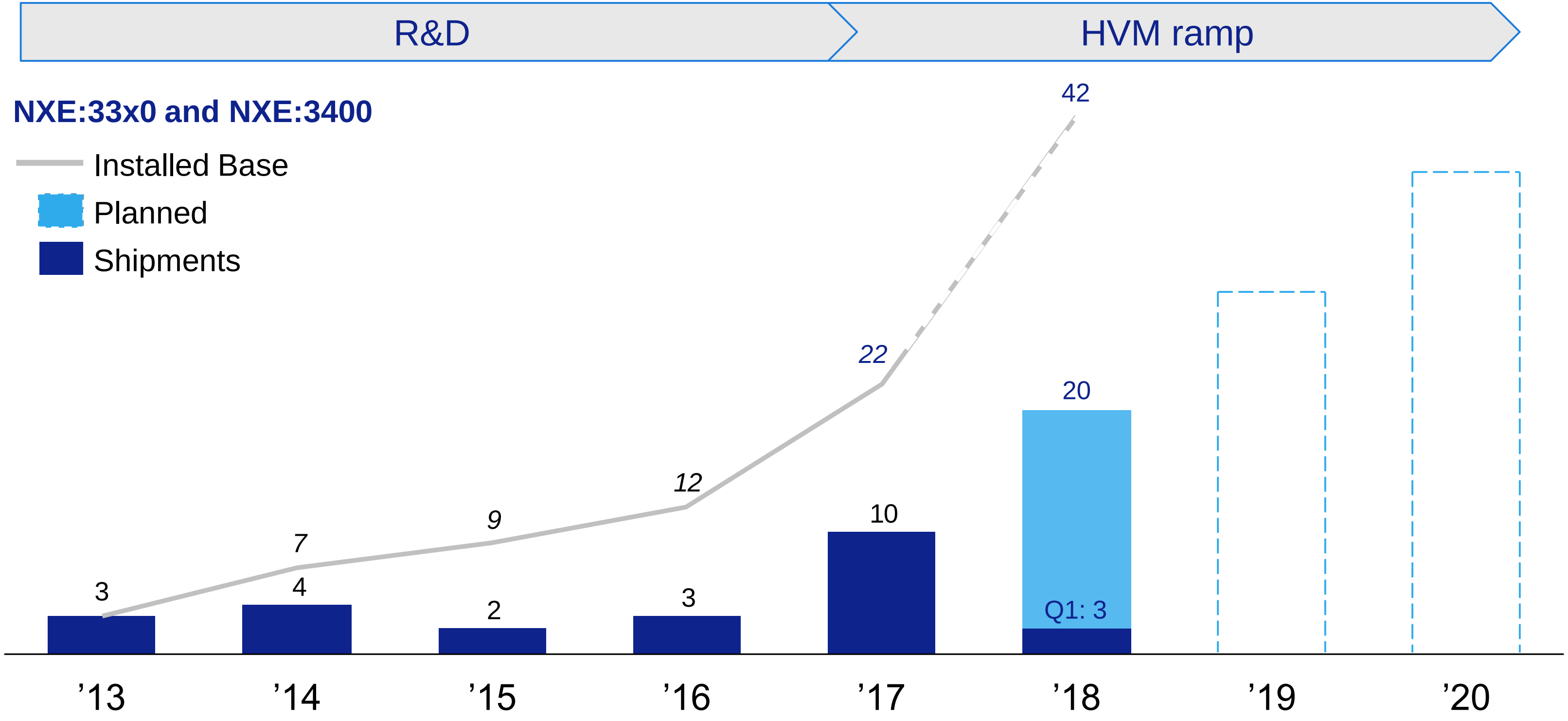
2018
1984

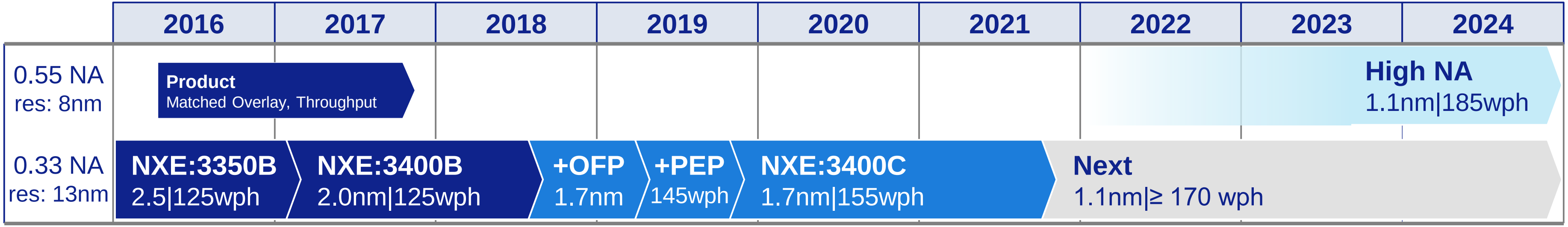
EUV HVM introduction targeted at 7nm is supported by customer shipments and orders

Installed base of EUV systems is expected to double in 2018



TWINSCAN EUV product roadmap

Supports customer roadmaps well into the next decade



3400B uptime improving to >90% for 2018/2019 HVM, extending productivity to >150 W/hr @ 20 mJ/cm²

Current Product status

- Released
- Development
- Definition
- Study

Productivity has been increasing

Secured EUV power is matched with increasing availability

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

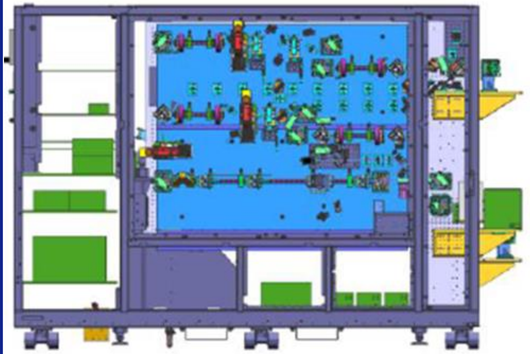
$$\text{EUV Power} = (CO_2 \text{ laser power} \times \text{CE} \times \text{transmission})*(1\text{-dose overhead})$$

Source power **from 10 W to > 250 W**	Drive laser power	from 20 to 40 kW
	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	

EUV 250W source industrialization

From proto to industrialized module in 1 year

Proto



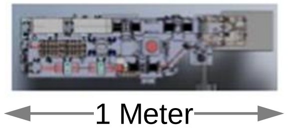
Stand-alone Source
250 Watt demonstrated

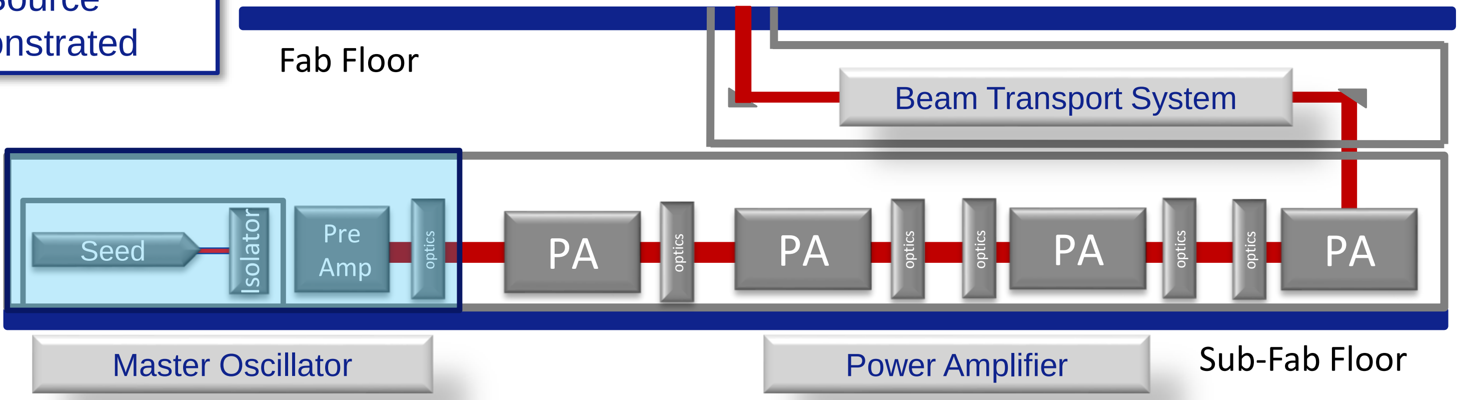
Pre-Pilot

250W integrated on NXE:3400B
125 wph demonstrated

Industrialized module

Final industrialized 250W source, completed Q4-17

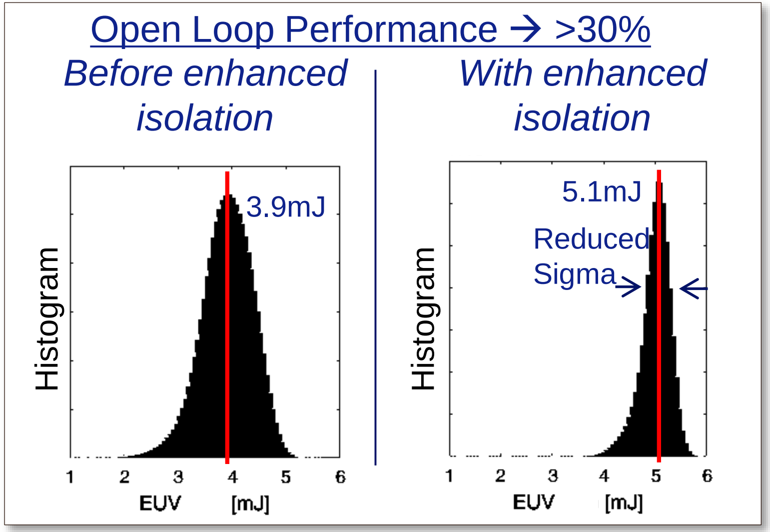


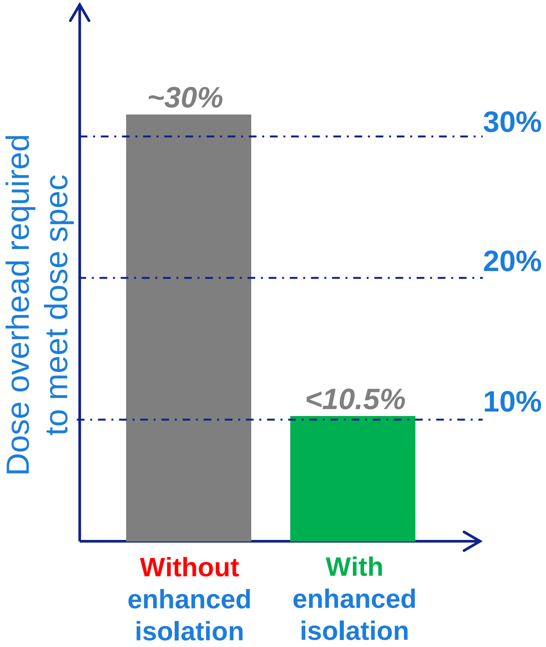


Enhanced laser-target isolation improves performance

Benefits of enhanced isolation:

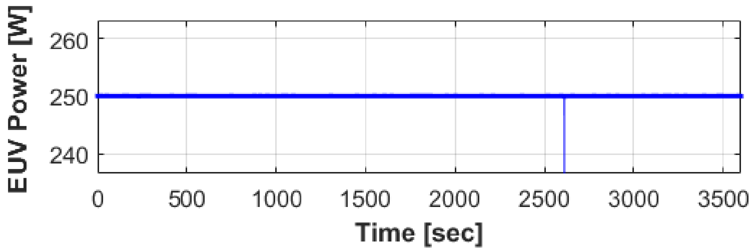
- **Higher, stable CO_2 laser power → lower dose overhead**
- **High conversion efficiency operation → higher pulse energy**

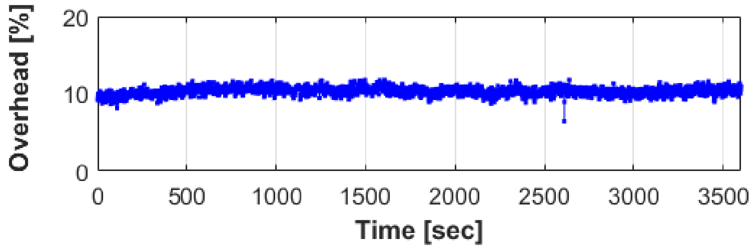


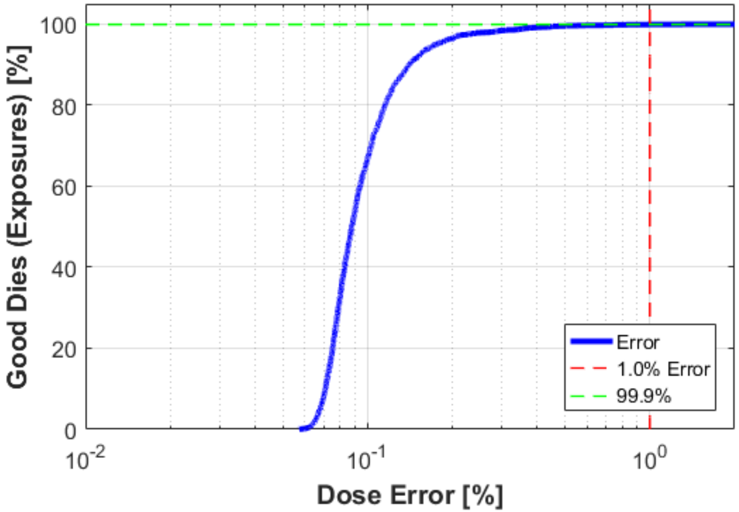


EUV Source operation at 250W

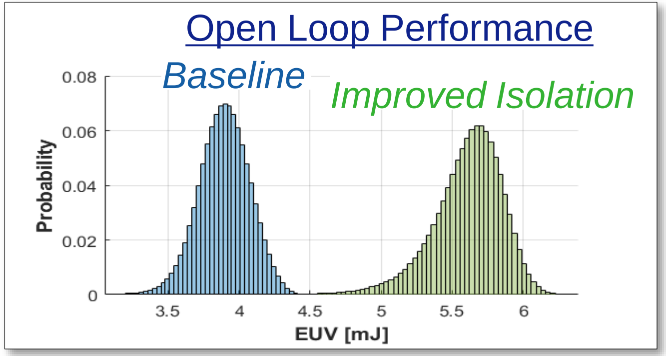
with 99.90% fields meeting dose spec



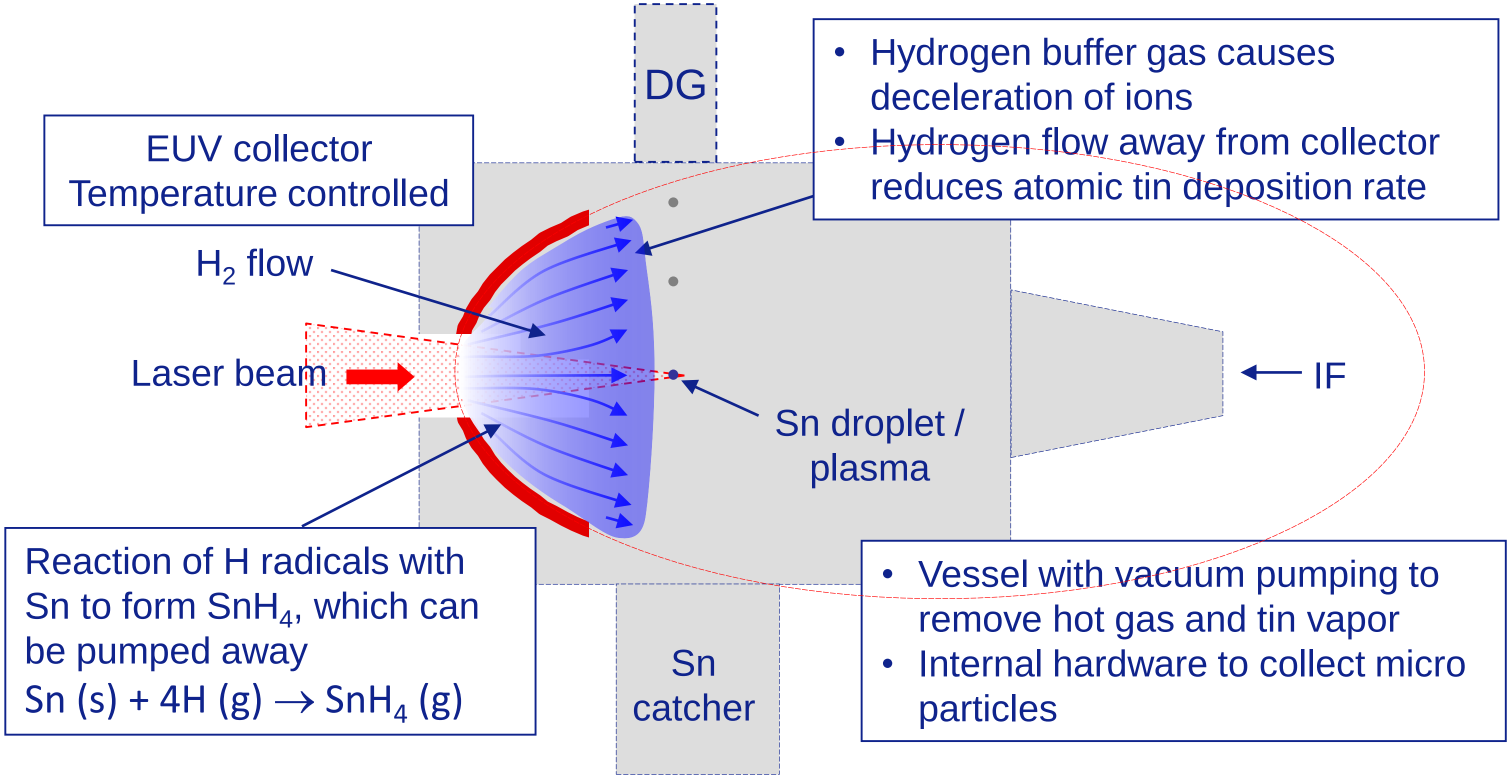




Operation Parameters	
Repetition Rate	50kHz
MP power on droplet	21.5kW
Conversion Efficiency	6.0%
Collector Reflectivity	41%
Dose Margin	10%
EUV Power	**250 W**



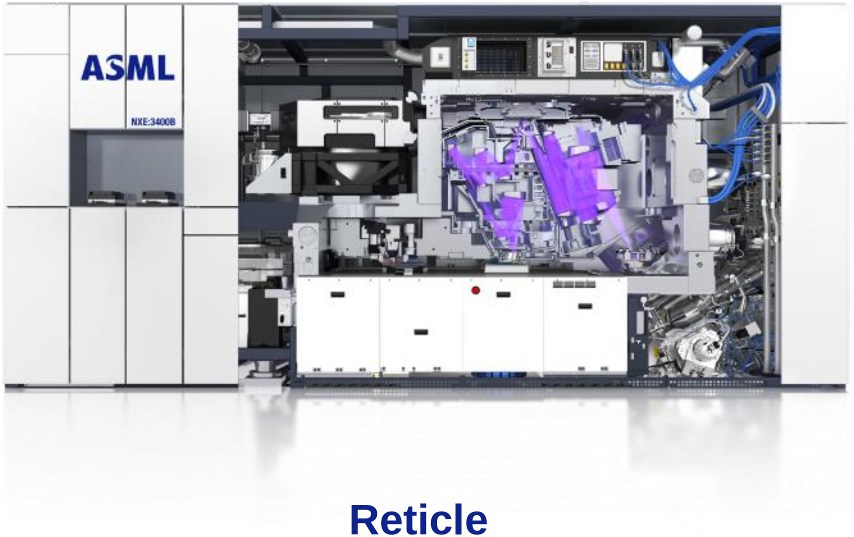
Collector protection by hydrogen flow



Clever collector protection at 250W of source power has been found and is being implemented in the field

Two-fold approach to eliminate reticle front-side defects

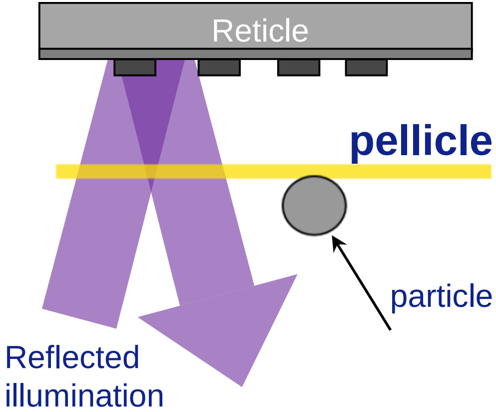
1. Clean system
(without pellicle)

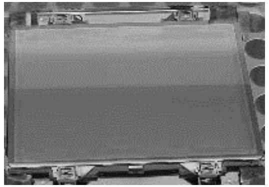


Reticle

2. EUV pellicle

EUV Reticle (13.5nm)

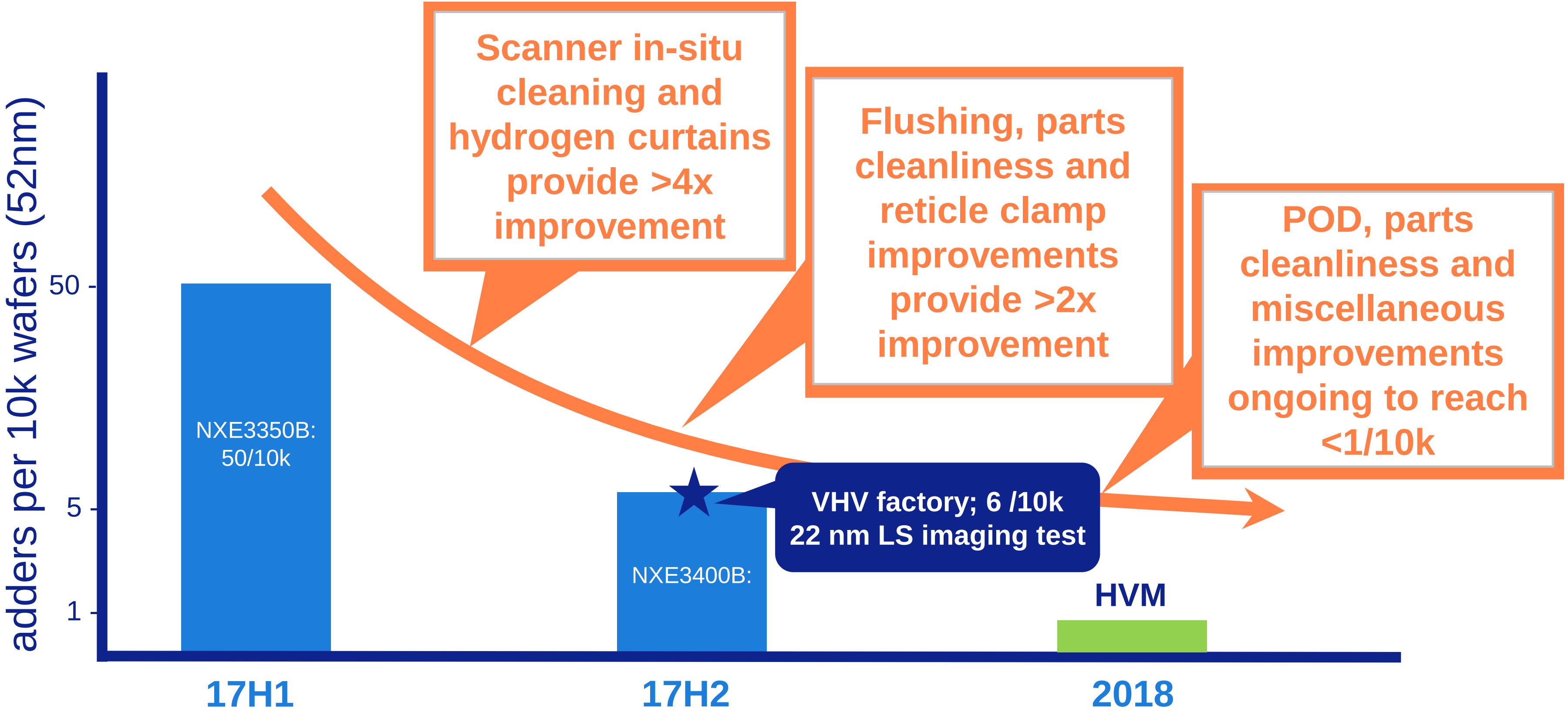




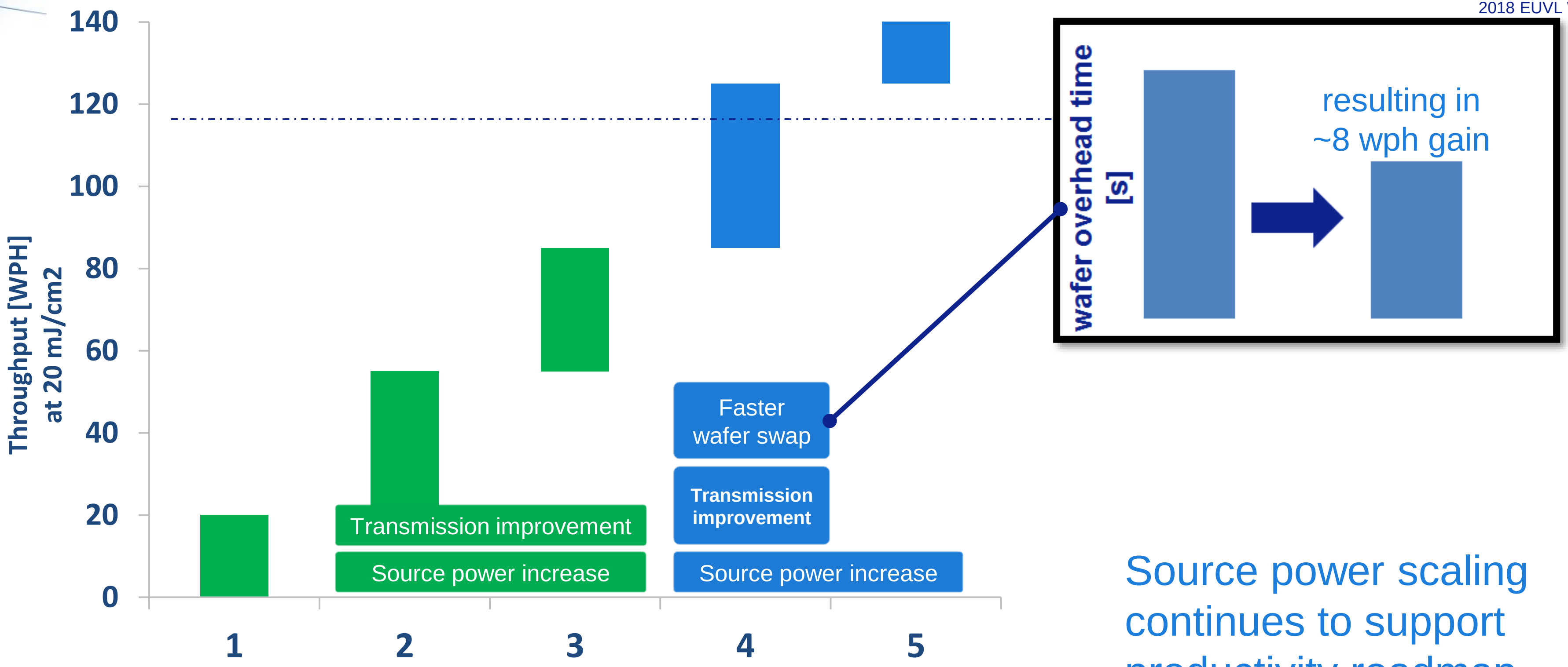
Reticle with pellicle

10x improvement for reticle defectivity in 2017

Further improvement to <1/10k expected in 2018



Productivity roadmap towards >125 WPH in place



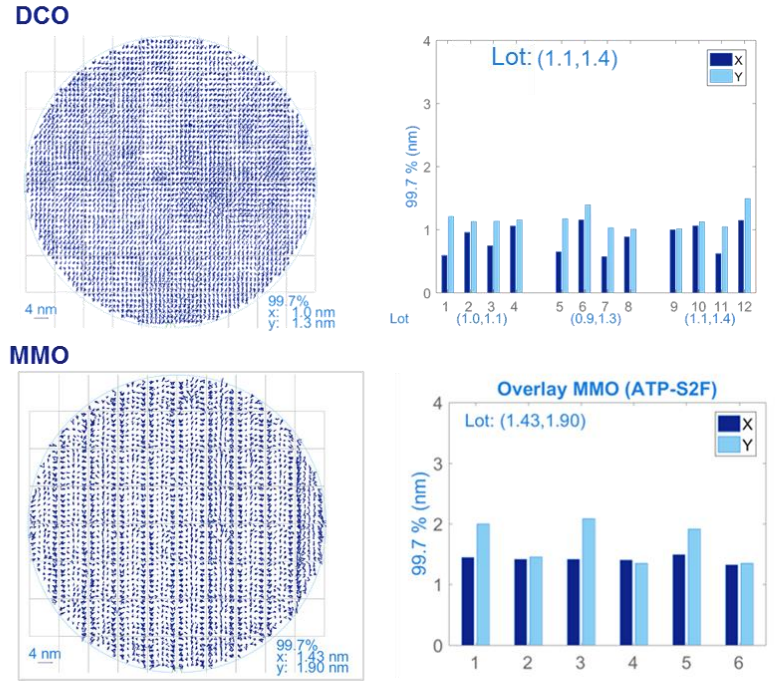
Source power scaling continues to support productivity roadmap

Throughput of 140 WPH achieved at 246W

Matched and single machine overlay meet spec

Overlay in spec at 125 WPH throughput

~200W power at IF with proto version SIM



Throughput of 140 WPH achieved at 246W

Actual: 195W Target: 205W

Throughput without pellicle — **125 WPH**

Full field, 96 fields at 20 mJ/cm^2

Actual: 246W Target: 250W

Throughput without pellicle — **140 WPH**; **Road-map** — **>150 WPH**

Full field, 96 fields at 20 mJ/cm^2

Actual: 246W Target: 250W

Throughput with pellicle+DGLm — **>100* WPH**; **Target** — **125** WPH**

Full field, 96 fields at 20 mJ/cm^2

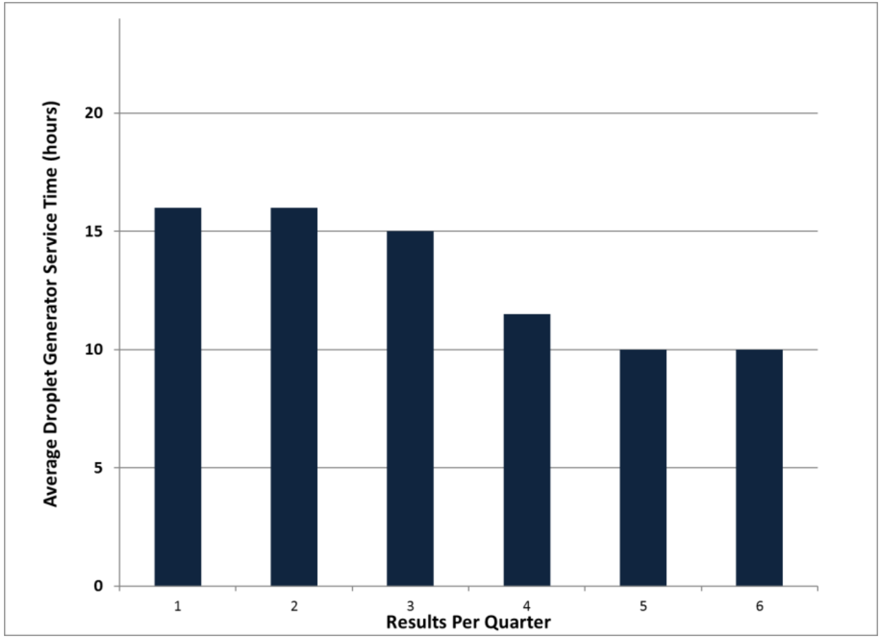
*Measured 116 WPH using pellicle with >83% transmission without DGL membrane. Throughput with membrane is calculated.

**Improvement plan for pellicle transmission to 88% and DGL membrane transmission to 90% included

3rd-gen. droplet generators: average lifetime ~780 hours

Performance parameter	Gen III
Key Features	Restart & Refill capable
Run-time	~780 hours (average) 2700 hours (max)
Start-up yield	>95%
Availability	95%
Droplet diameter	27 µm

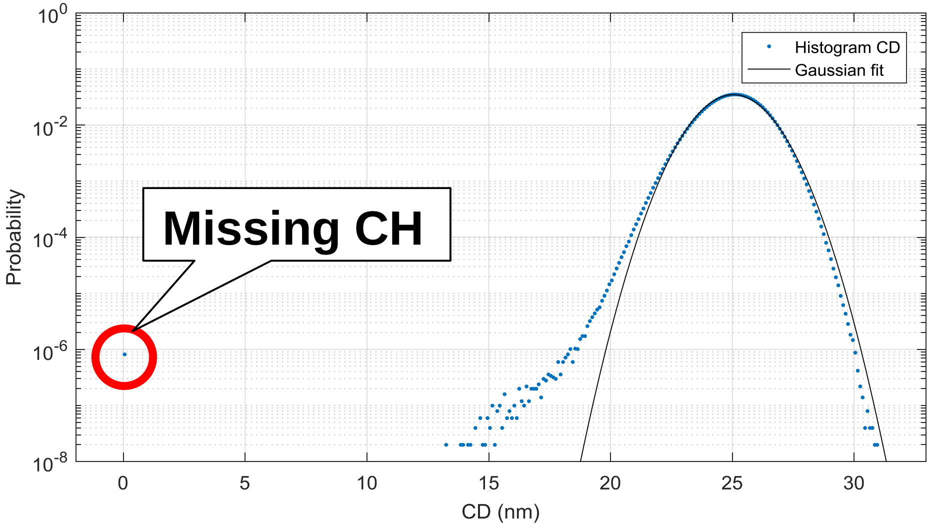
Weekly average service time

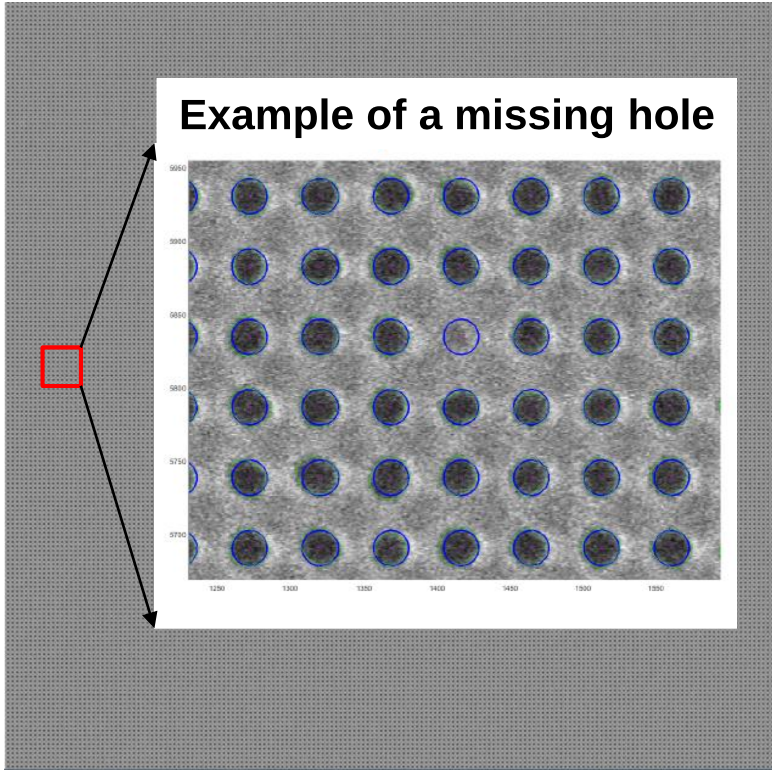


Contact hole measurements with HMI eP5

50 Million measurements to reveal true histogram and failures **within 2 hrs**

Probability plot with Gaussian fit

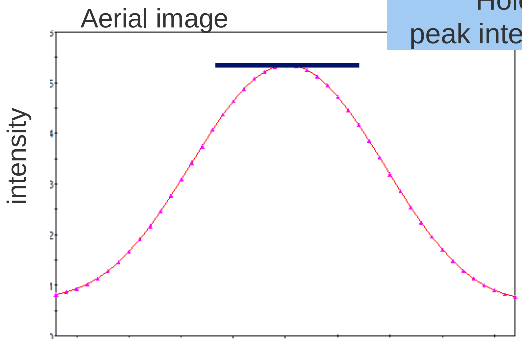


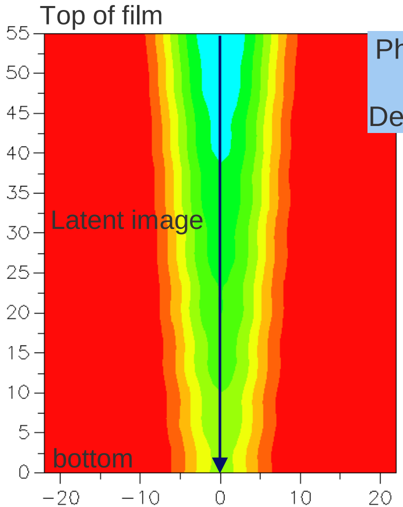


Hole clearing or closing

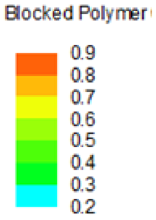
if the process were a continuum

Hole (just) clears when peak intensity = clearing threshold

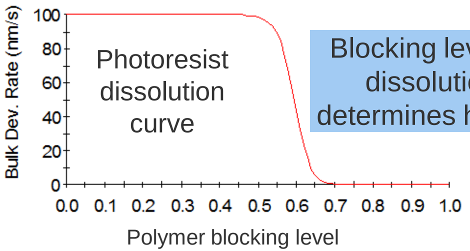




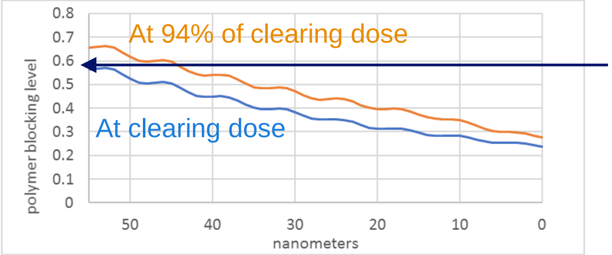
Photoresist, absorbs light, produces acid, acid deblocks polymer; Deblocked polymer becomes soluble



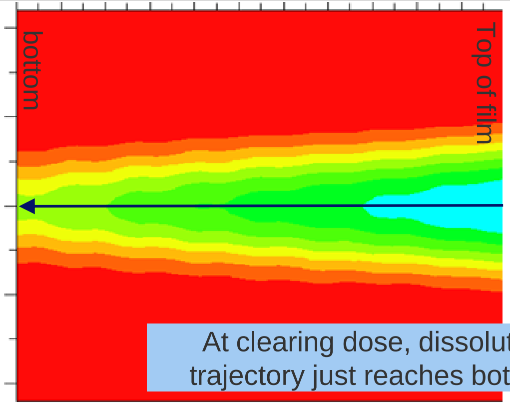
If viewed sideways



Blocking level profile + dissolution curve determines hole clearing



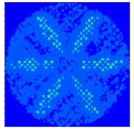
Hole center blocking profile

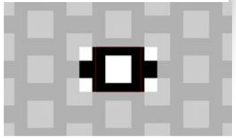


At clearing dose, dissolution trajectory just reaches bottom.

Let’s focus on closed holes

(performed 10000 calculations per dose)





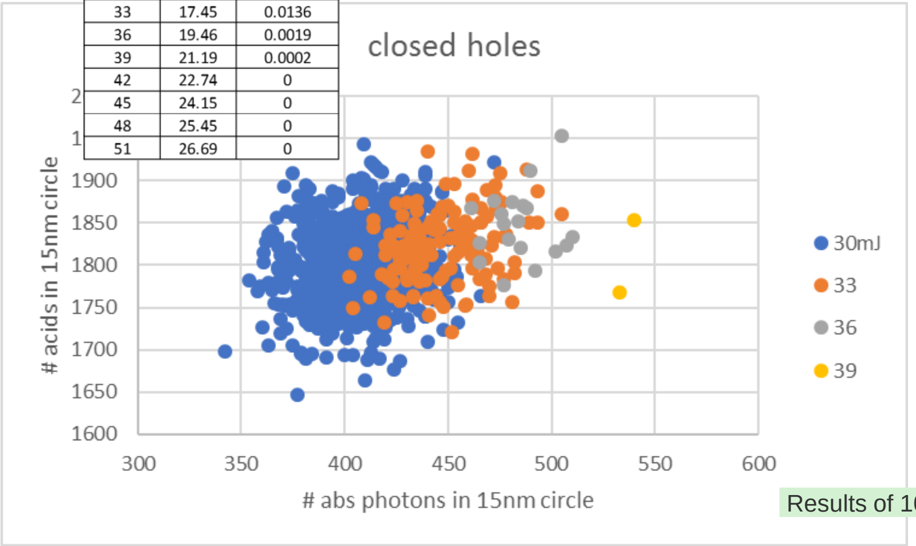
2% flare, 55nm RT

ASML

Photon and acid counts in a hole cylinder* for all closed holes observed

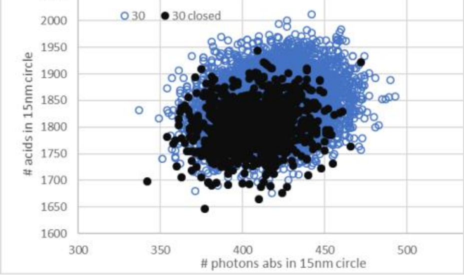
Data for 10000 holes

dose	avg CD	HCR fract closed
30	14.88	0.0884
33	17.45	0.0136
36	19.46	0.0019
39	21.19	0.0002
42	22.74	0
45	24.15	0
48	25.45	0
51	26.69	0

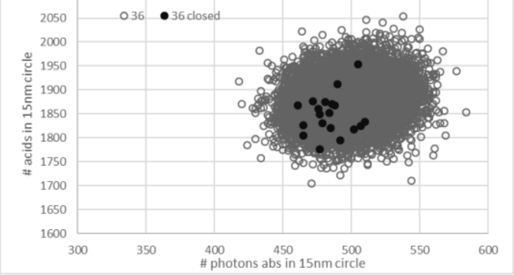


As dose increases, hole closing is less and less due to low photon or acid counts

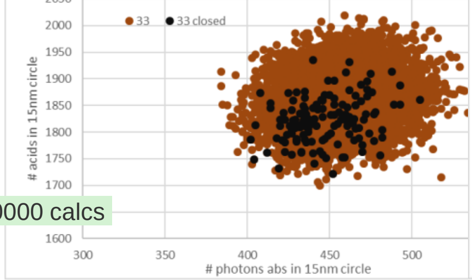
30mJ/cm^2 CD~15nm



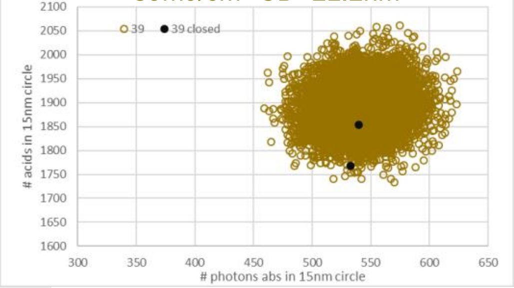
36mJ/cm^2 CD~19.5nm



33mJ/cm^2 CD~17.4nm



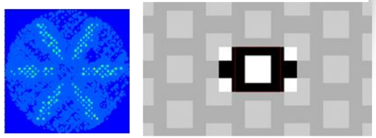
39mJ/cm^2 CD~21.2nm

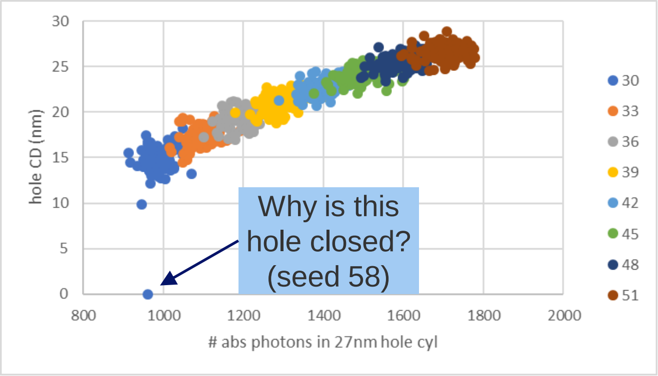


Results of 10000 calcs

* 15nm is approximate CD of holes where closing reaches ~10%

Local effects “beyond dose”

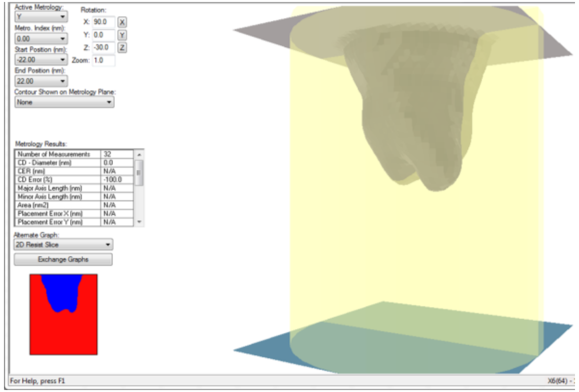

2% flare, 55nm RT



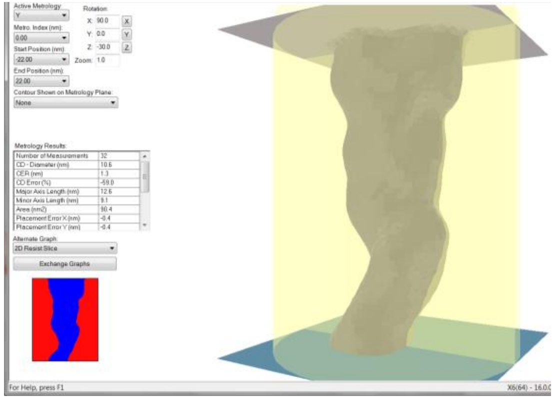
Compare seed 58 with others

			#abs photons in cyl		# acids	
stochastic seed	nom dose mJ/cm2	CD (nm)	27nm	15nm	15nm	
58	30	0	961	378	1799	closed hole
38	30	15.5	913	377	1845	fewer photons but open
43	30	13	971	401	1771	fewer acids but open

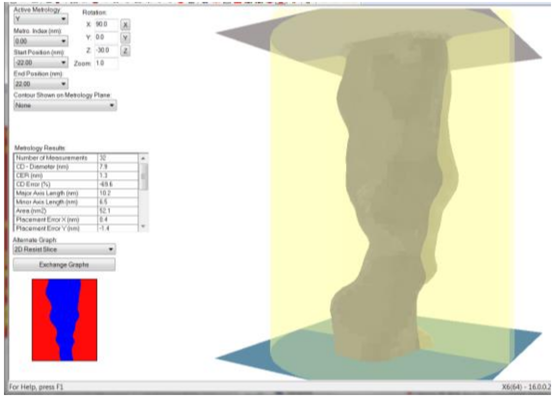
seed 58



seed 38



seed 43

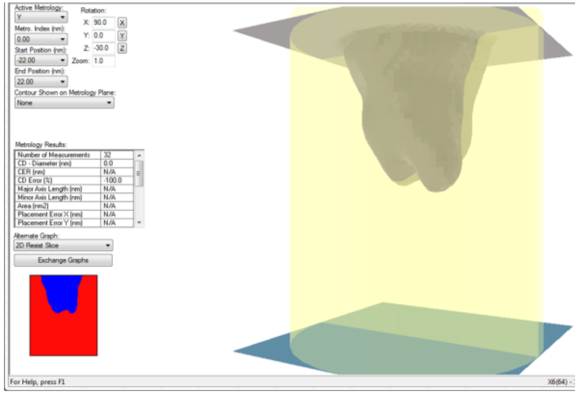


Local effects "beyond dose"

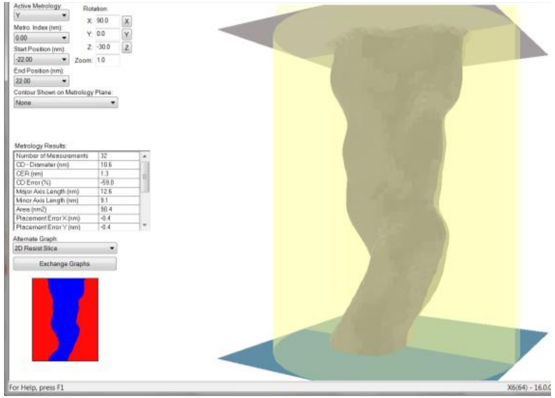
Spatial distribution of components determine hole closing near threshold dose

developed images

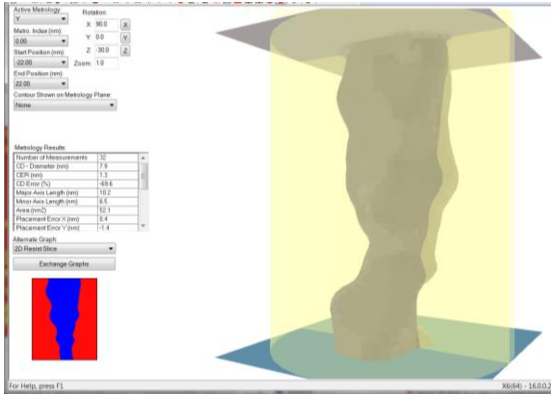
seed 58



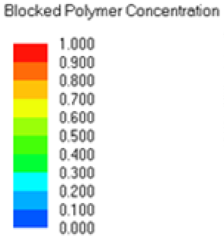
seed 38

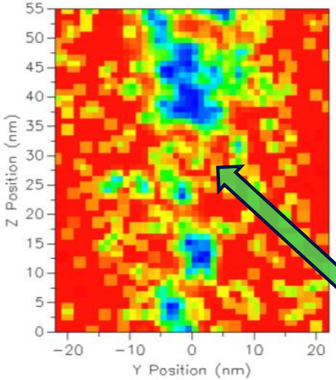


seed 43



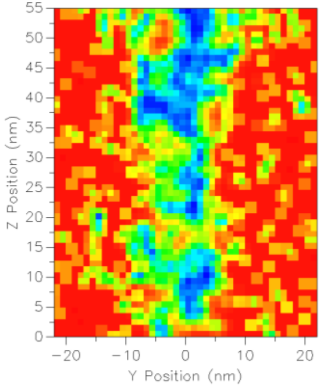
latent images



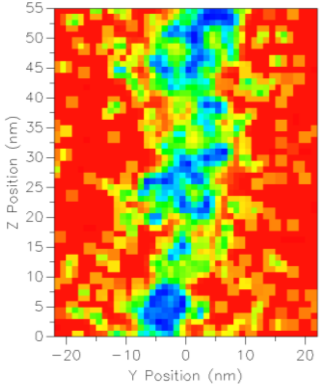


No dissolution path to bottom!

road block



De-blocked polymer profile gives dissolution path to bottom

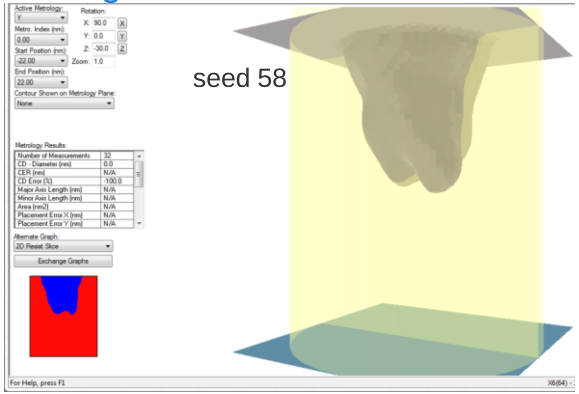


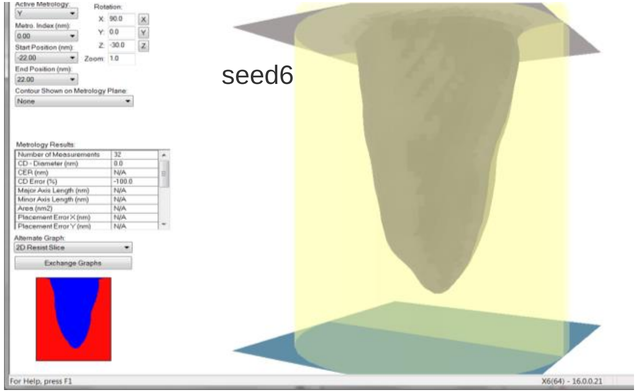
An idea (from Hansen) for extrapolation to low HCR

developed images

Complex CAR model

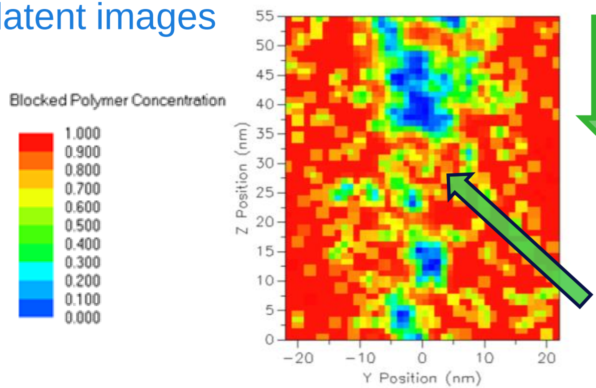
Simplified direct photolysis model with no quencher





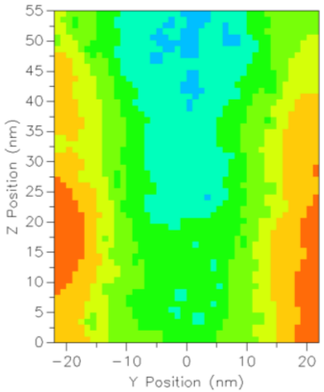
Mechanism for closing is still local fluctuations – lower frequency variation with this simpler, "more deterministic" process

latent images

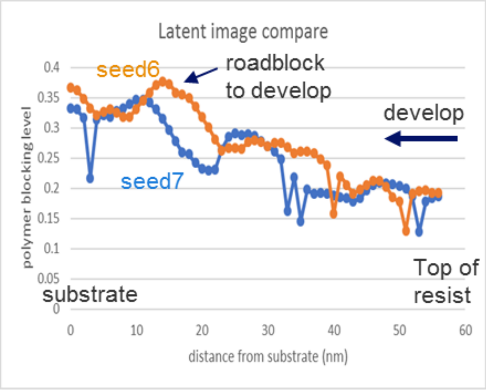


No dissolution path to bottom!

road block



Plot of polymer blocking level at hole center

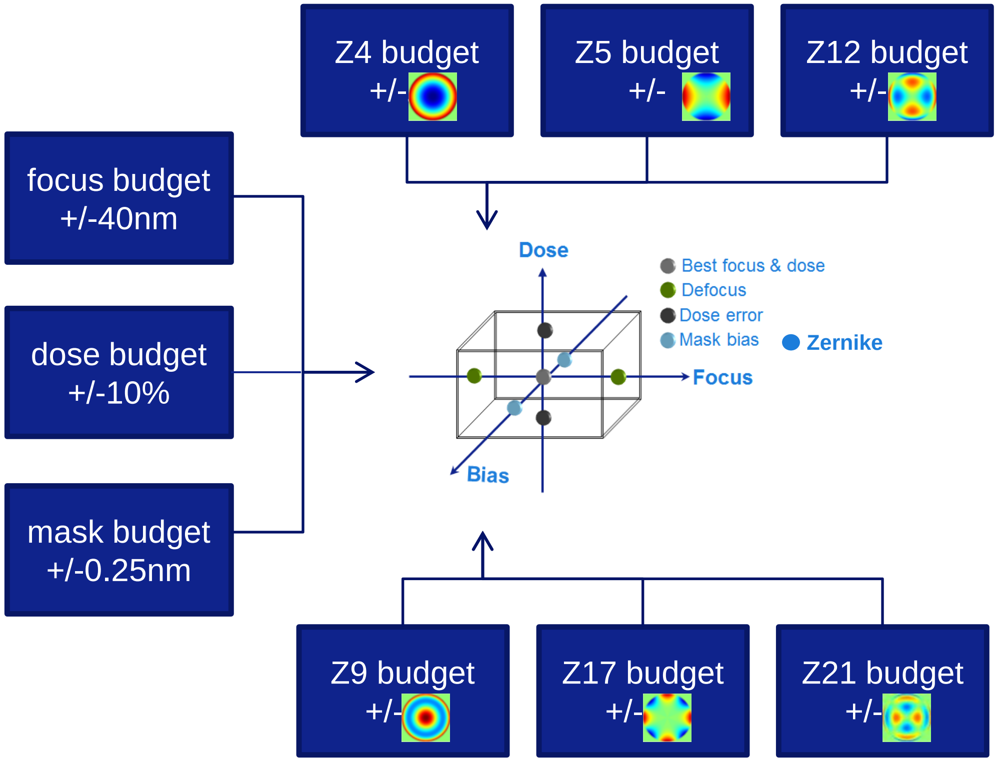


Our findings on EUV resists

- Simulations show that hole closing is not simply explained by local dose variations
- Spatially dependent concentration variations (fluctuations) are also key
  - At a particular dose there will be a mean spatial distribution of blocked polymer with a random variation; every hole is different
  - Changing dose affects the mean level but not the fluctuation amplitude
- Two possible ways to reduce amplitudes of latent image fluctuations and hole closing rates:
  - “Simpler” and/or more uniform resist chemistry
  - Higher acid and/or quencher diffusion (but may limit resolution)

Phase-Control SMO

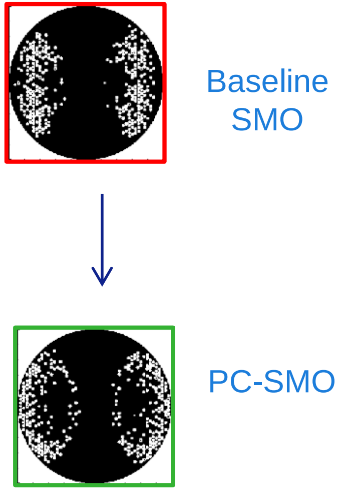
Optimization of source and mask to improve imaging robustness against phase effects from 3D masks and scanner aberrations



Source and mask optimized to be less sensitive to process variations such as focus, dose, mask and aberrations

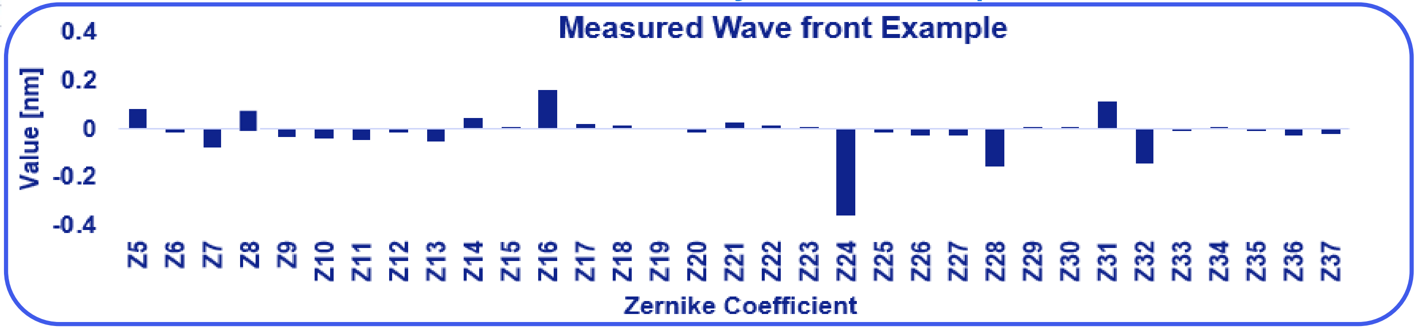
$$\sum_{PW} epe^n$$

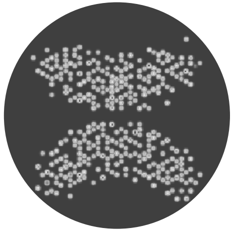
Customized cost function to include aberration impact

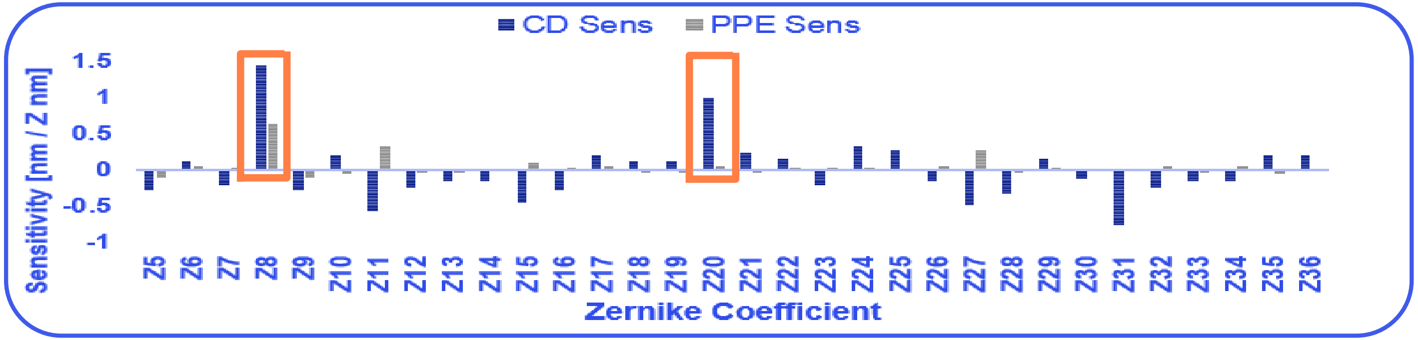


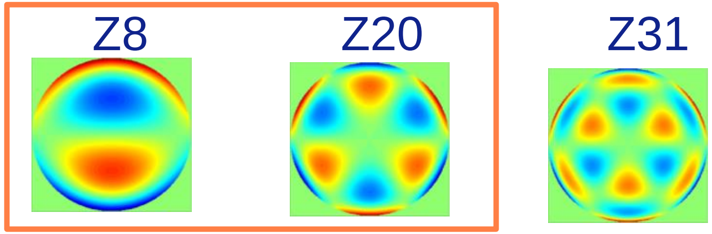
Phase-Control SMO: sensitivity analysis

- Must consider Zernike sensitivity of critical patterns

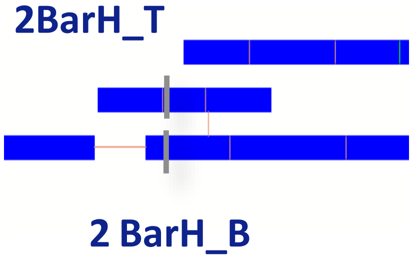








➔ Select Z8, Z20 as most critical



Progression of EUV lithography for logic products

1st Generation (foundry 7-nm node)

- $k_1 \sim 0.45$
- Lithography process relatively straight forward with PC-SMO
- The right time to perfect infrastructure

2nd Generation

- $k_1 \leq 0.4$
- Lithography process becomes more sophisticated

3rd Generation

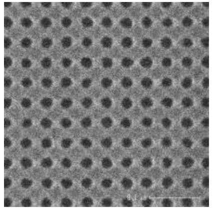
- $k_1 \leq 0.3$
- Process sophistication; DTCO; Double patterning

4th Generation

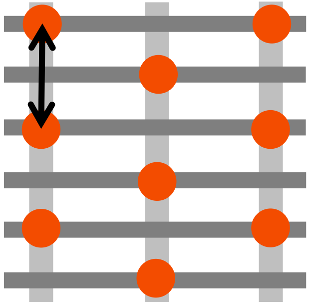
- 0.55 NA

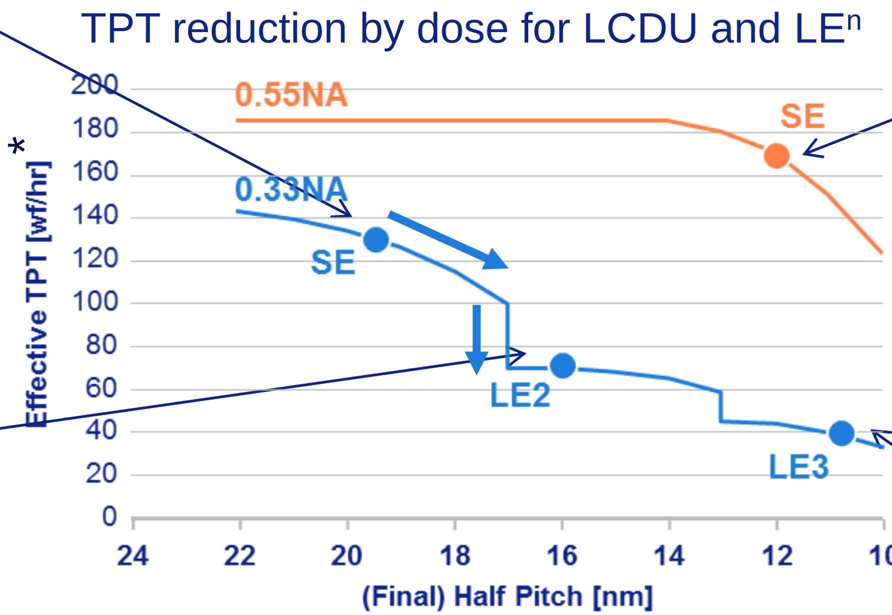
Larger NA results in higher effective throughput

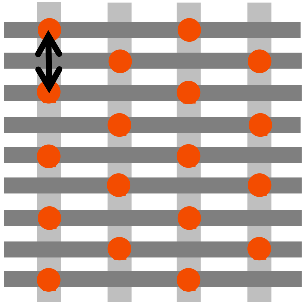
NA limits # of LE steps and dose needed for LCDU

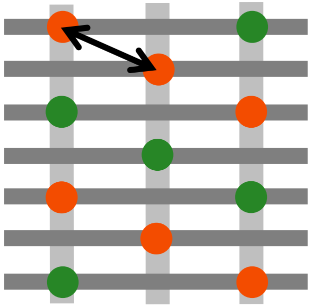


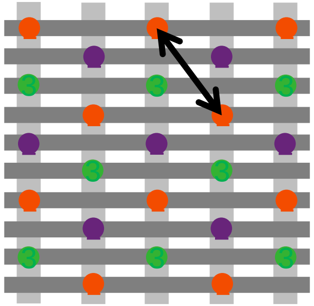
Quasar Illumination











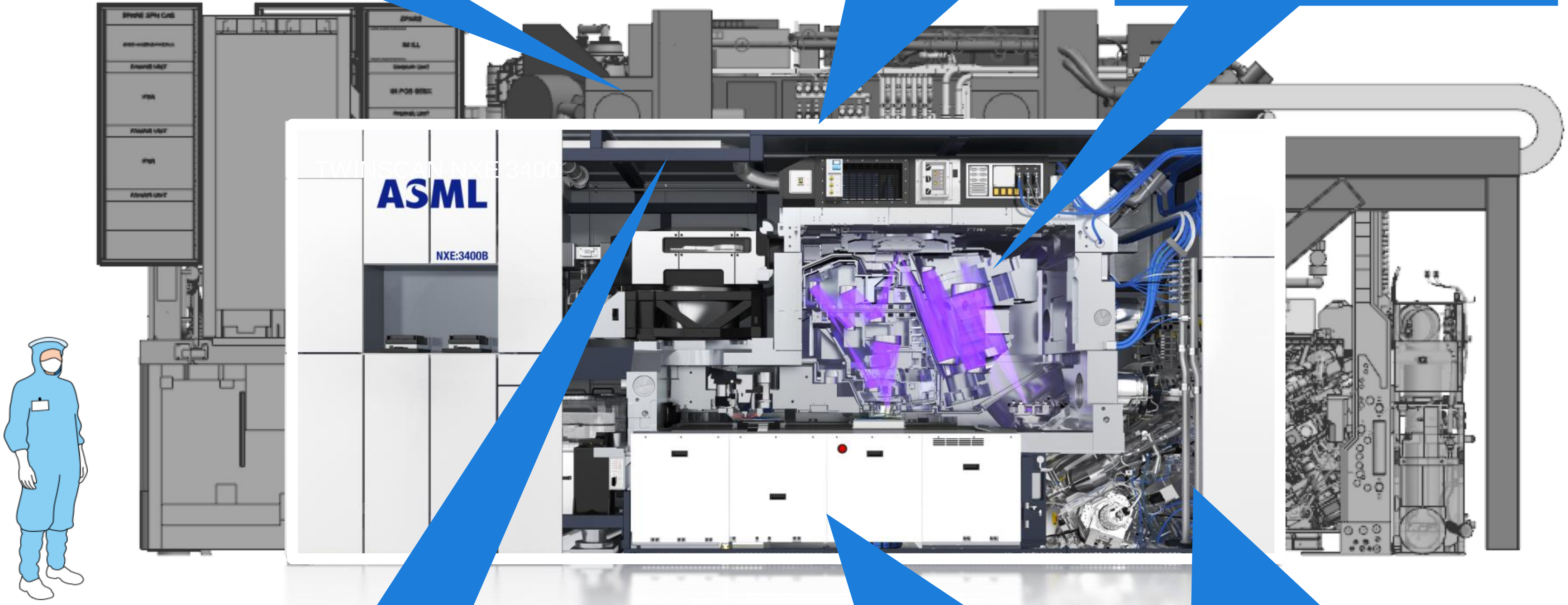
* Effective throughput = throughput / # LE steps

High-NA system architecture available

Improved metrology
2~3x improvement in overlay/focus

Mask Stage
4x increase in acceleration

Lens & illuminator
- NA 0.55 for sub-10nm resolution
- High transmission



New Frames
Improved thermal and dynamic control with larger optics

Wafer Stage
2x increase in acceleration

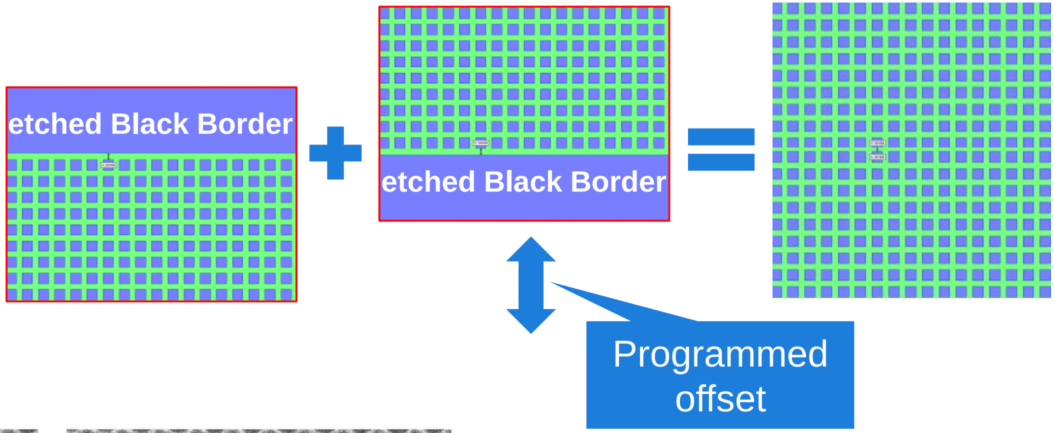
Source
Compatible with 0.33 NA sources, power improvements opportunities over time

Stitching feasibility study ongoing

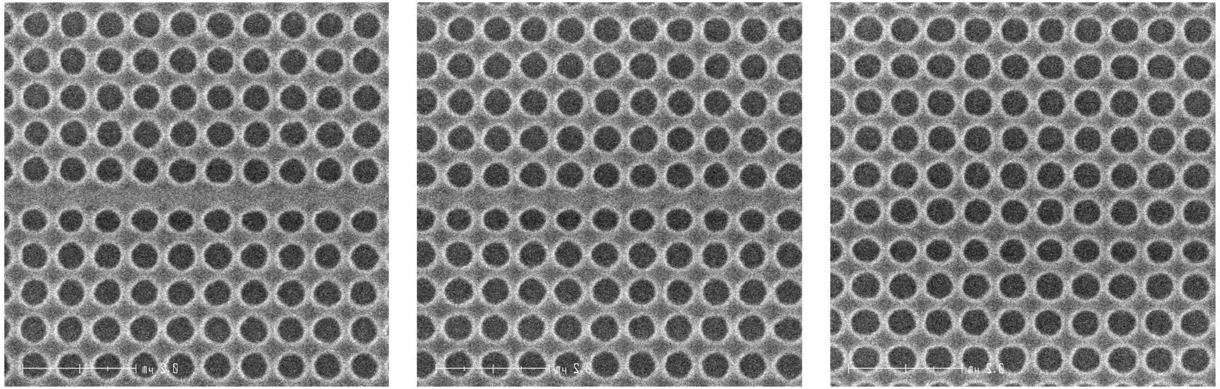
24nm dense holes successfully stitched on NXE:3300 at IMEC

First stitching experiments:

- 24nm Dense CH’s
- Programmed offsets
- JSR 3030



Results for 3 different offsets:



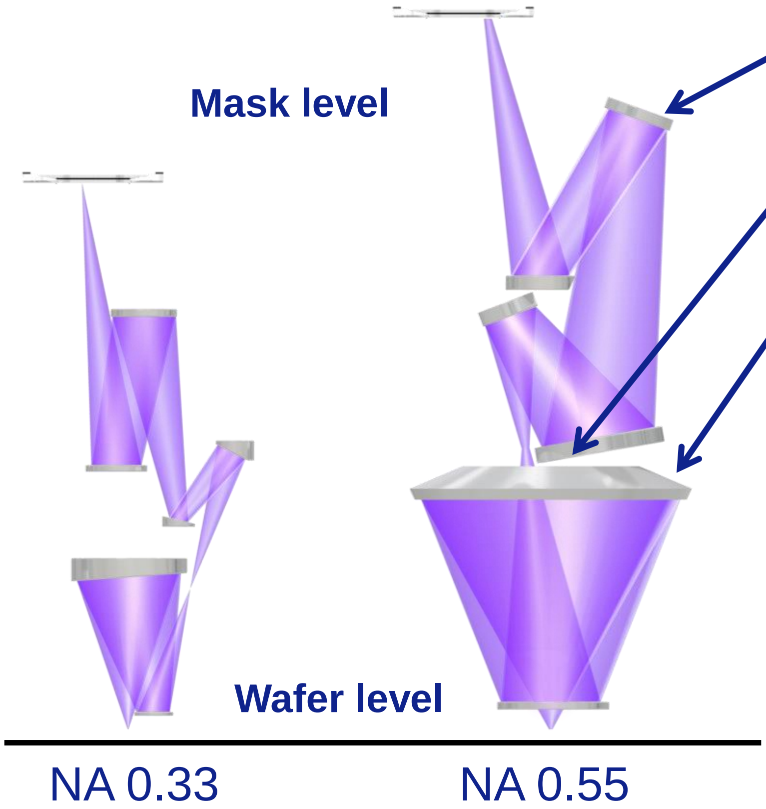
Courtesy Vincent Wiaux, IMEC

Next steps:

- Determine process latitude
- OPC needed?
- Different structures

High-NA projection optics design available

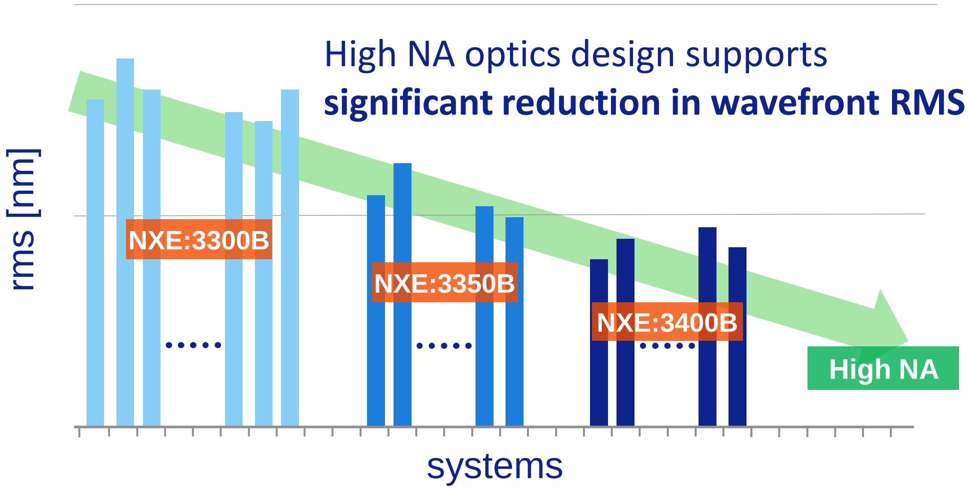
Larger elements with tighter specifications



Extreme aspheres enabling
further improved wavefront / imaging performance

Obscuration enables
higher optics Transmission

Big last mirror driven by
High-NA



Long-lead items getting in place

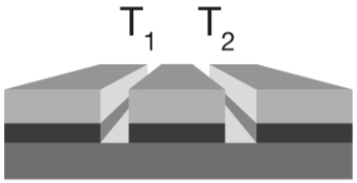
Vessel parts are machined, 1st robots for large mirror handling

Chamber door and vessel

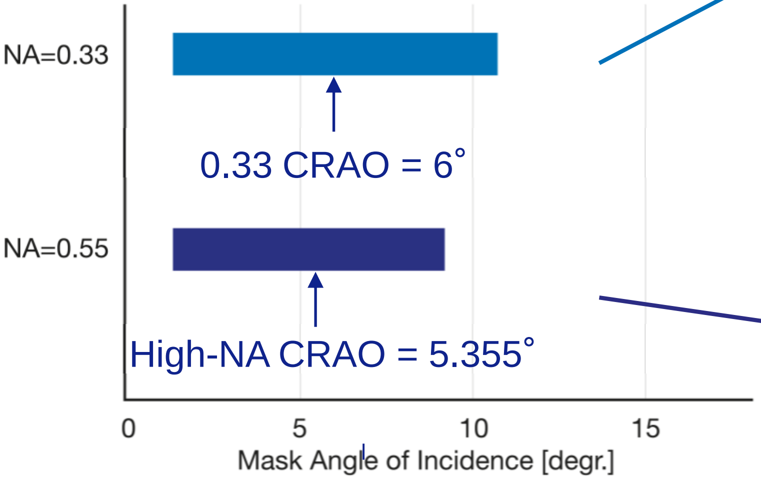
Outer mirror handling robot

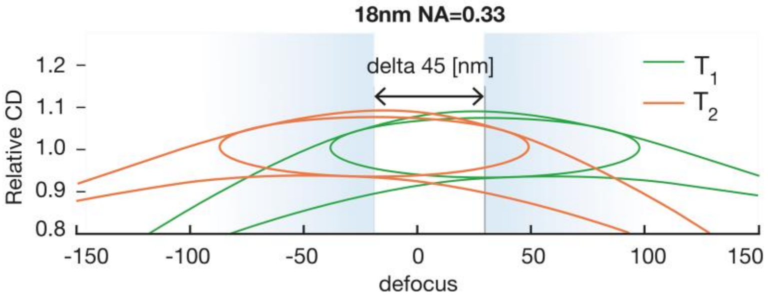
High-NA system has smaller M3D effects than 0.33NA

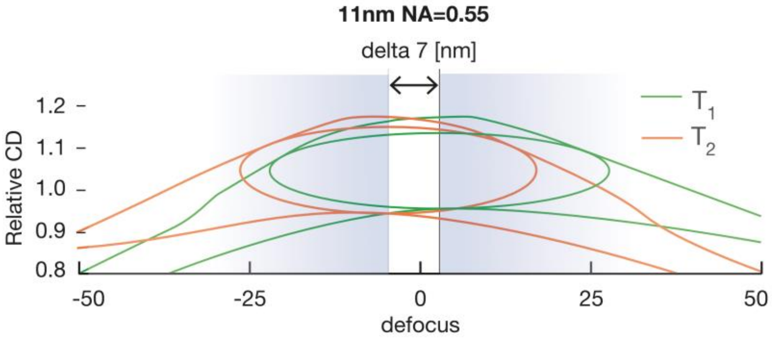
Smaller mask angles of incidence thanks to higher mag and smaller CRAO



Two-bar trenches are a canary for M3D effects



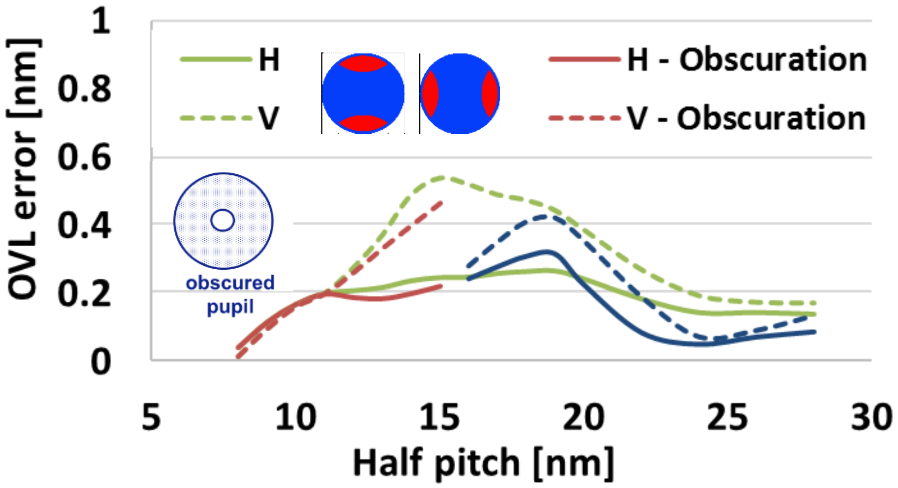




*L. de Winter, Understanding the Litho-impact of Phase due to 3D Mask-Effects when using off-axis illumination, EMLC 2015

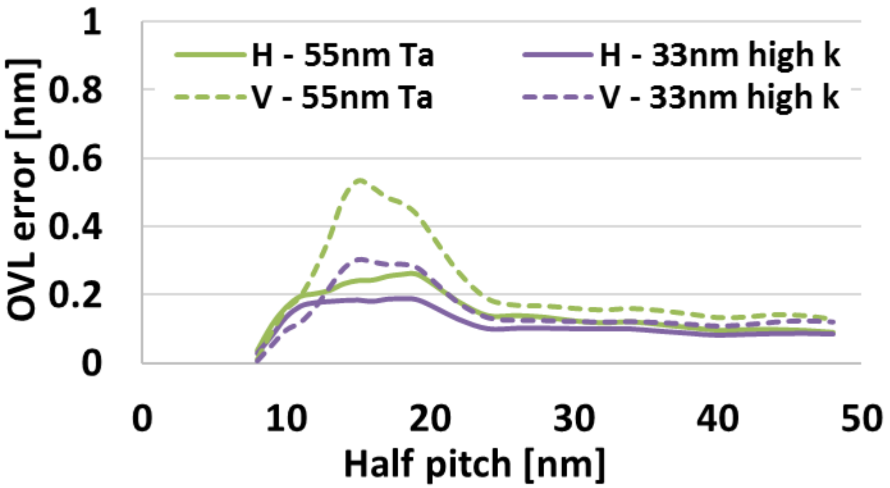
Impact of M3D effects can be mitigated via
SRAF's, M3D-aware SMO, thinner (high-k) absorber

- Using SRAF's
- Using M3D aware SMO



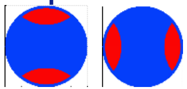
SRAF size adjusted per pitch:
- Horizontal: 20 – 56 nm @mask
- Vertical: 16 – 30 nm @mask

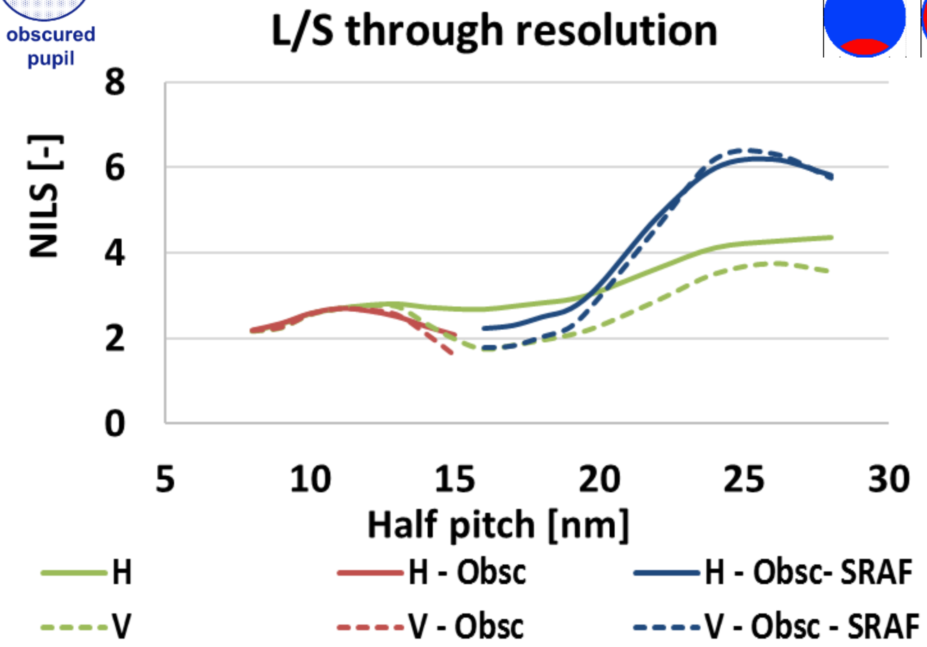
- Using a thinner (high-k) absorber

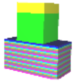


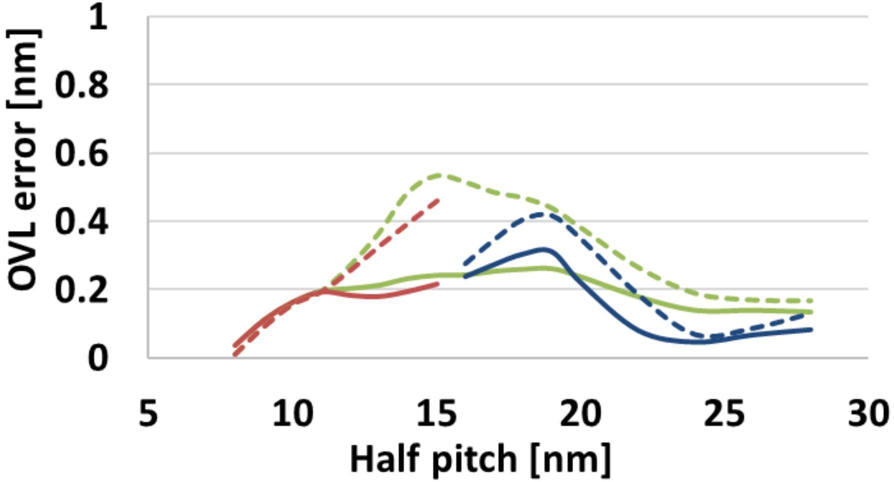
Eelco van Setten et al., EUVL 2017

Sub-resolution assist features recover contrast loss from obscuration and reduce Mask3D overlay





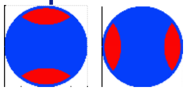


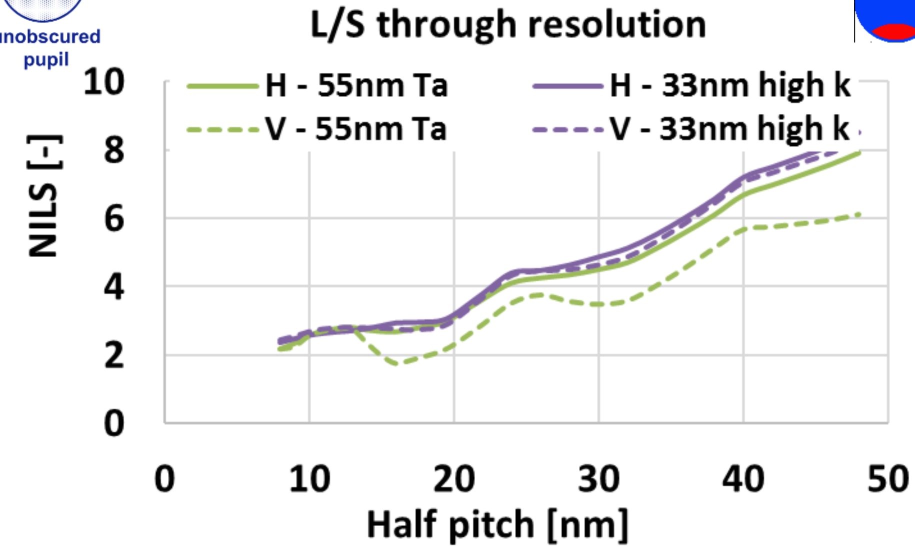


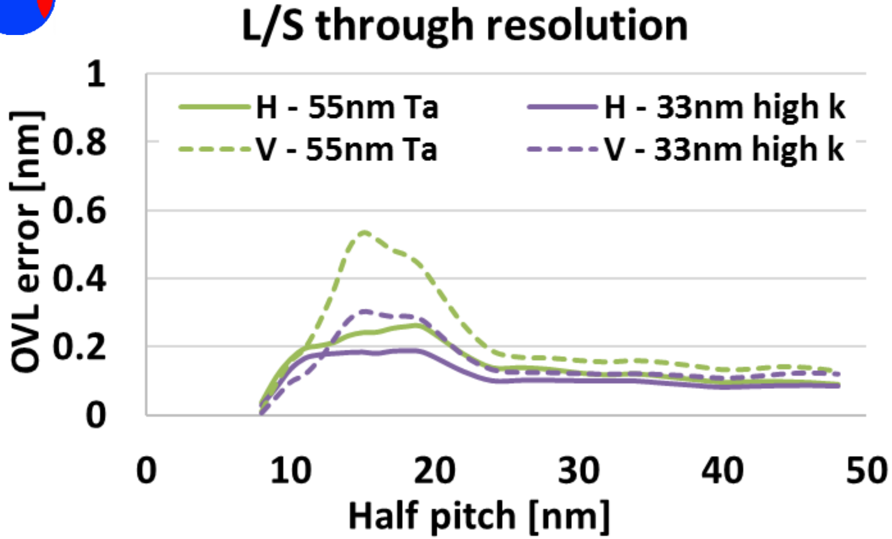
SRAF size adjusted per pitch:

- Horizontal: 20 – 56 nm @ mask
- Vertical: 16 – 30 nm @ mask

High k absorber can increase contrast and reduce Mask3D overlay by ~2x for dipole test case



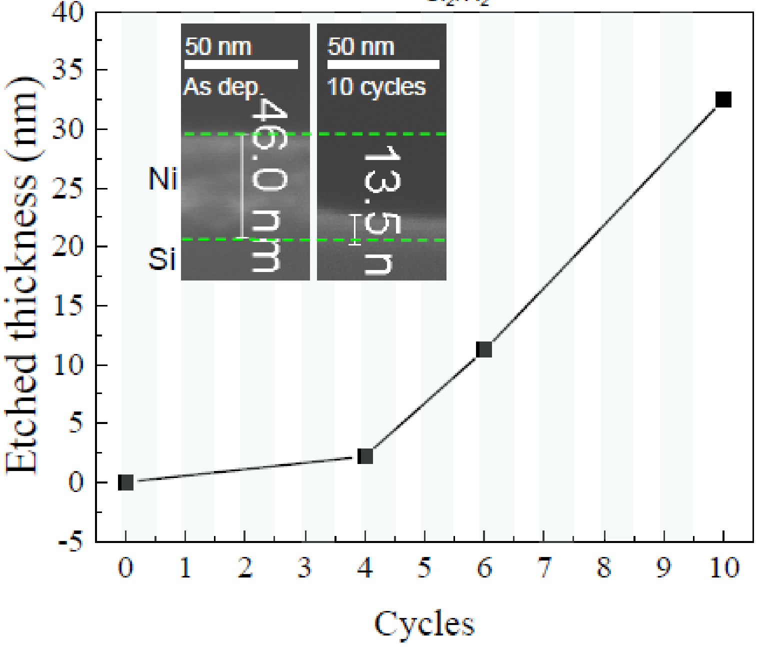


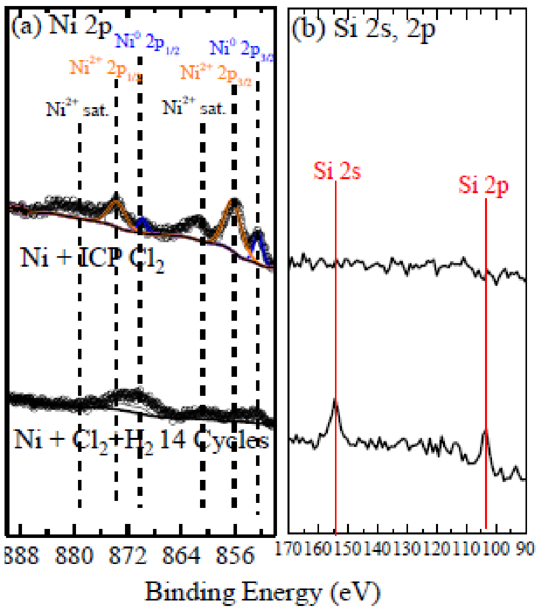


Alternative mask stack:

- 33nm high k material (Ni used)

Summary of RIE Etching of Ni





Ernest Chen

UCLA

- Chlorine plasma was utilized to change metallic Ni to a surface layer of $NiCl_2$, and removed with subsequent hydrogen plasma

Customer commitment to EUV volume manufacturing continues

On 0.33NA Systems

- Shipped 3 systems in Q1 2018
- Received 9 orders in Q1 2018
- Planned to ship 20 systems in 2018
- Production capacity of at least 30 systems in 2019

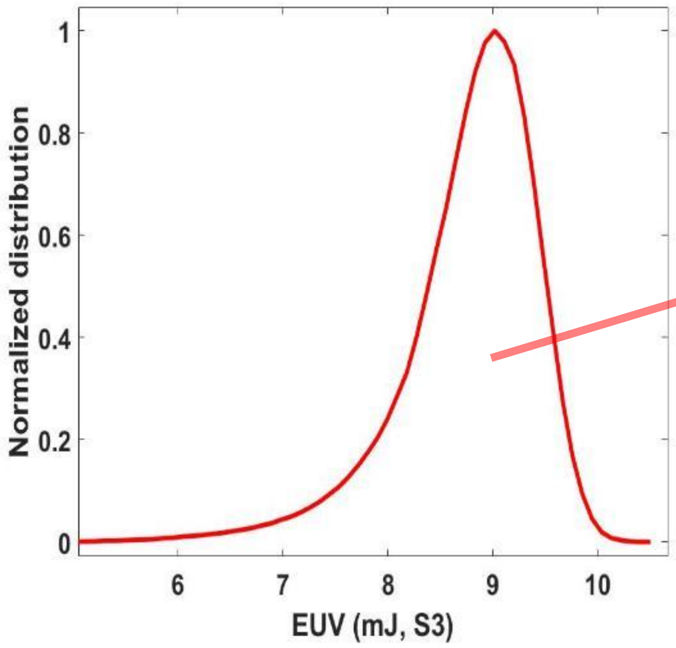
On 0.55NA Systems

- Received 4 orders of R&D systems from 3 customers in Q1 2018
  - targeted to start shipping by end of 2021
- Sold options for 8 early volume systems in Q1 2018
  - targeted to start shipping in 2024

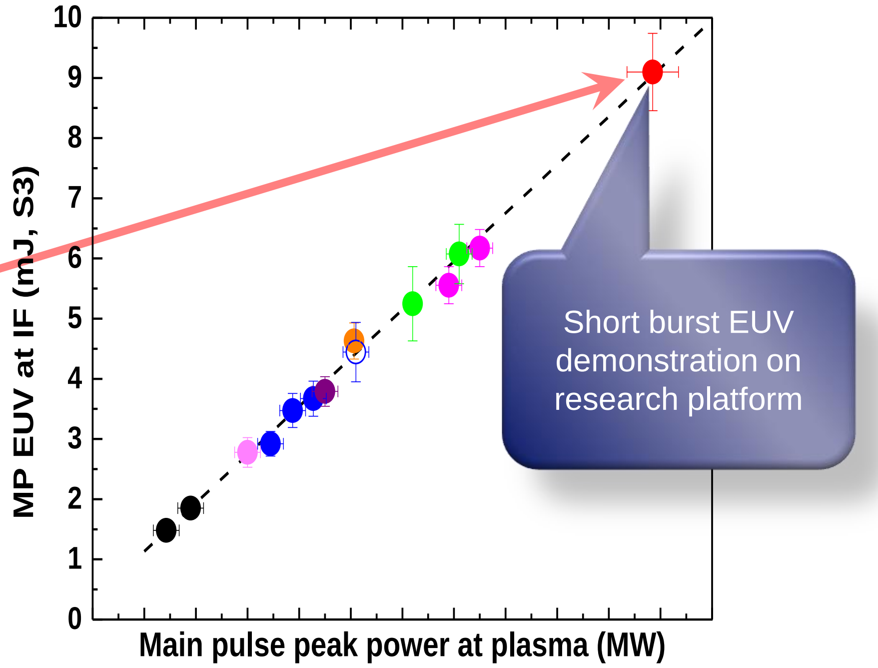
In-burst EUV power of 410 W

Demonstrated IF EUV pulse energy of 8.2 mJ at 50 kHz

Histogram EUV Pulse Energy

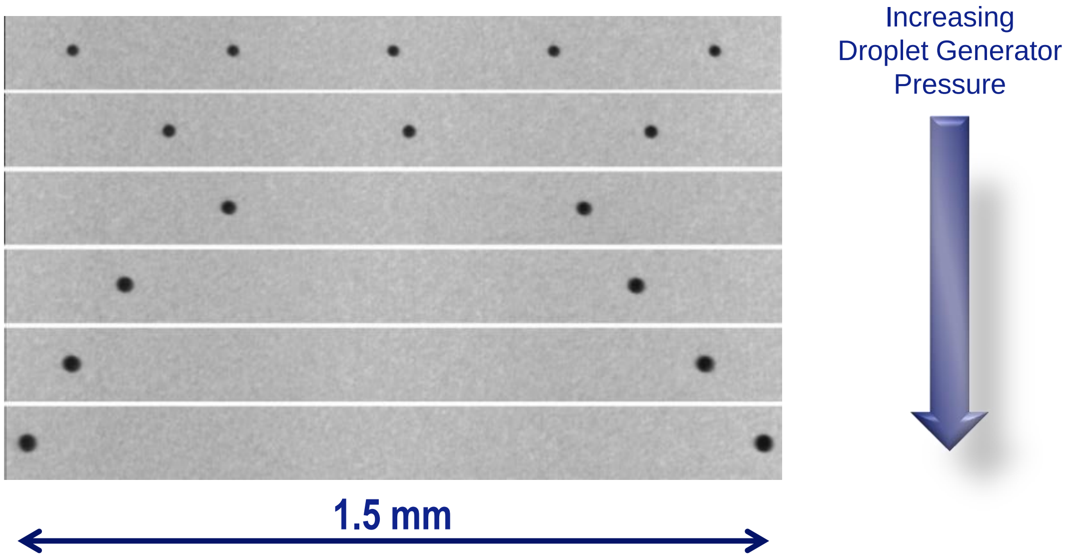


EUV Pulse Energy at IF



On a development EUV source at ASML San Diego
EUV bursts at 3% duty cycle

Droplet generator: principle of operation



Tin droplets at 80 kHz and at different applied pressures
Images taken at a distance of 200 mm from the nozzle

I would like to thank my ASML colleagues for all this work.
In particular, I thank Steve Hansen, Igor Fomenkov, Roderik van Es, Jan van Schoot, Jo Finders, Hans Meiling, and Stephen Hsu whose presentation material I used or with whom I had fruitful discussions.

ASML

Thank you !