Progress and Outlook towards High-NA EUV Resist

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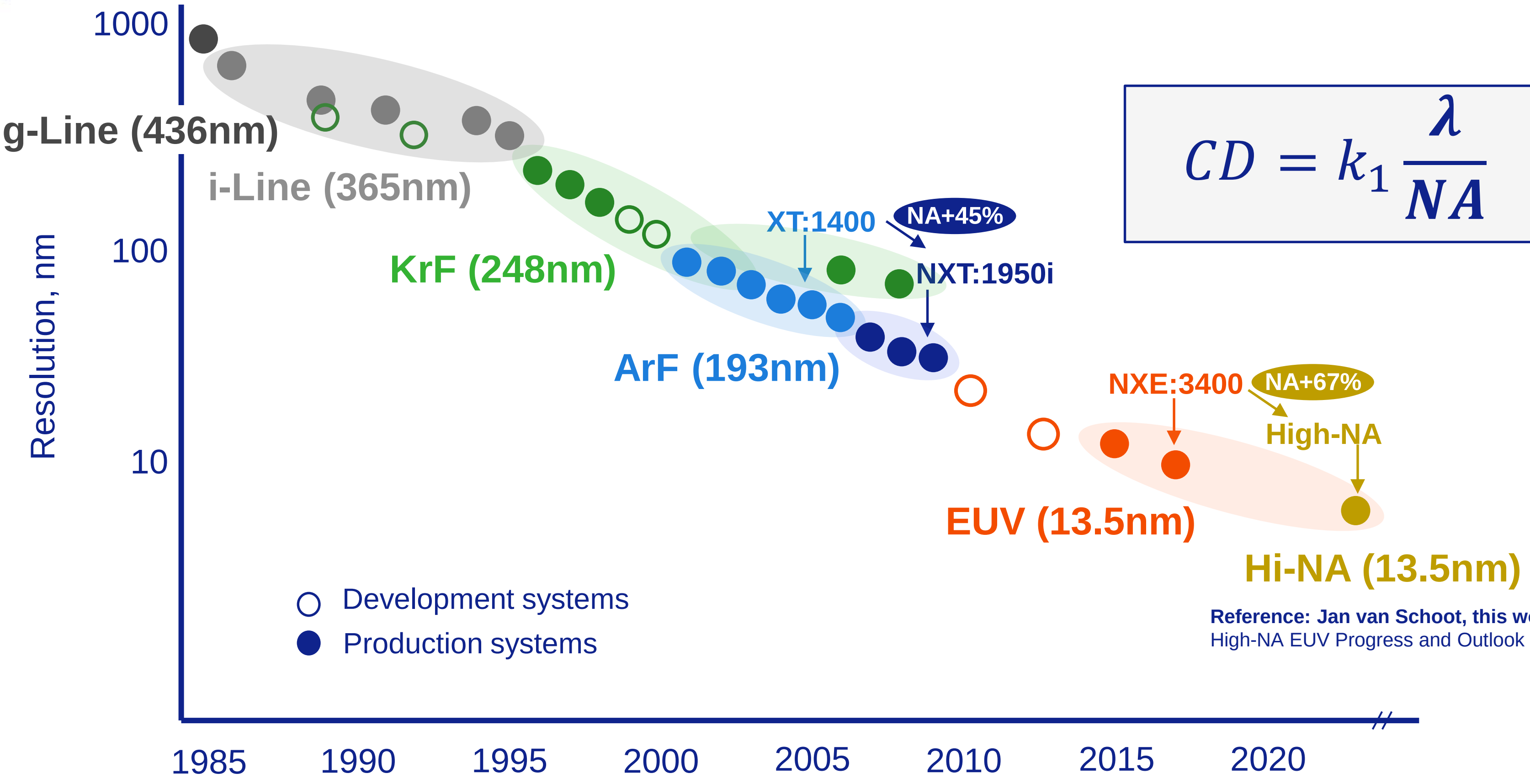
Yasin Ekinci (PSI); Kevin Gu, Da Li, Tim Weidman (Lam)

High-NA: next generation EUV lithography



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

Reference: Jan van Schoot, this workshop
High-NA EUV Progress and Outlook

Timely availability of high-NA ecosystem is needed

Holistic optimization driven by stochastics, high resolution and low thickness

Motivated by anamorphic imaging with tightened resolution and novel absorbers

High-NA resist requires holistic optimization driven by stochastics, high resolution and low thickness

Co-optimization of resist and post processing to improve defectivity and LWR

1

2

Low thickness to support high resolution

3

Reduce blur & chemical (acid, quencher, small building blocks) contributions to stochastics

High-NA resist requires holistic optimization driven by stochastics, high resolution and low thickness

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Low thickness to support high resolution

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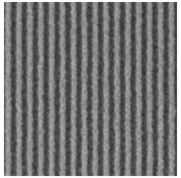
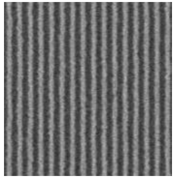
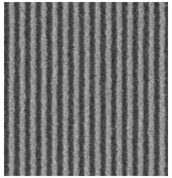
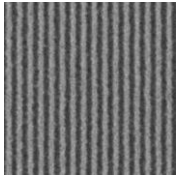
Reduce blur & chemical (acid, quencher, small building blocks) contributions to stochastics

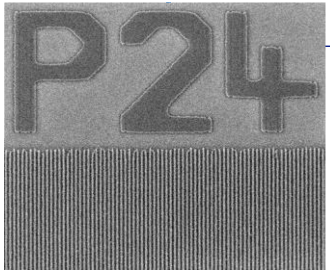
Resolution improvements shown with NXE:3400

P24 Single exposure achieved at imec

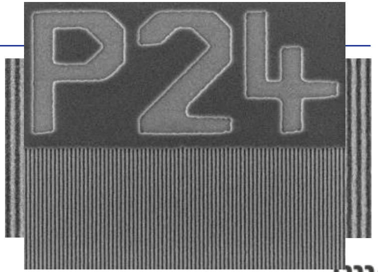
Metric	NXE:3x00 (imec & customer site)
Imaging Principle	Projection 0.33 NA • Free form pupil
Source	Sn Laser Produced Plasma
Proven resol.	12nm LS
Processing infrastructure	Track: 300mm wafer

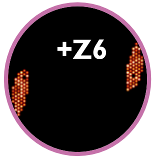
	2018	2019	2020	2021
Resist type	Non-CAR	Non-CAR	Non-CAR	Non-CAR
HP13nm Lines and Spaces				
Dose [mJ/cm²]	57	45	39	32
LWR$_{unb}$ [nm]	3.1	3.0	2.9	3.2

After etch



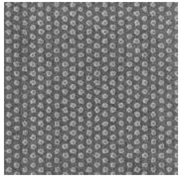
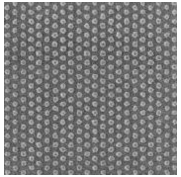
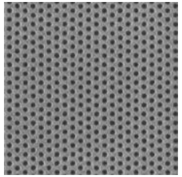
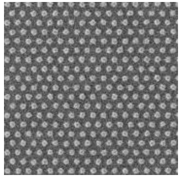
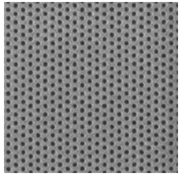
After tone inversion



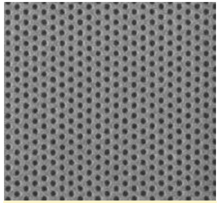
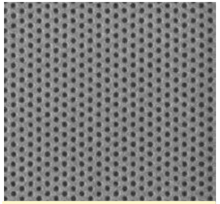
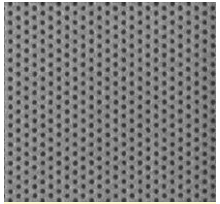
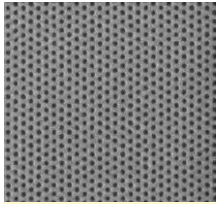
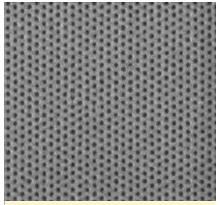
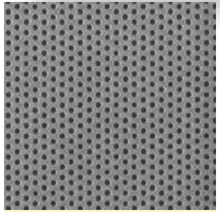
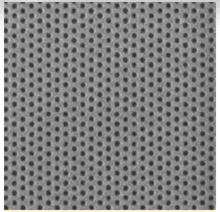
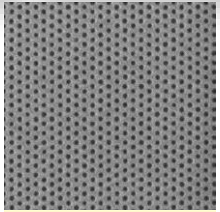
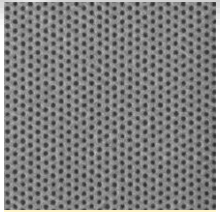
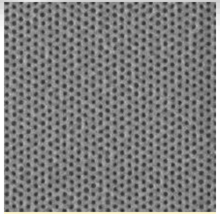
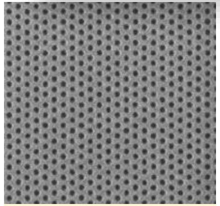
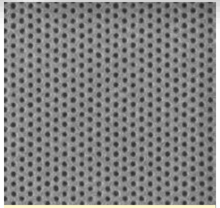
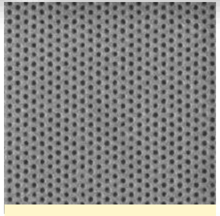
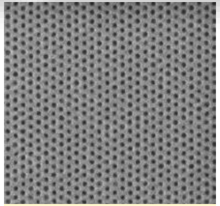
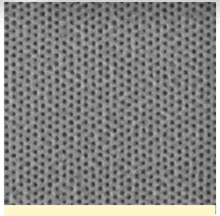


Continuous resist improvement for Hex. Pillars/CH

Progress needed in order to improve both Dose & LCDU performance

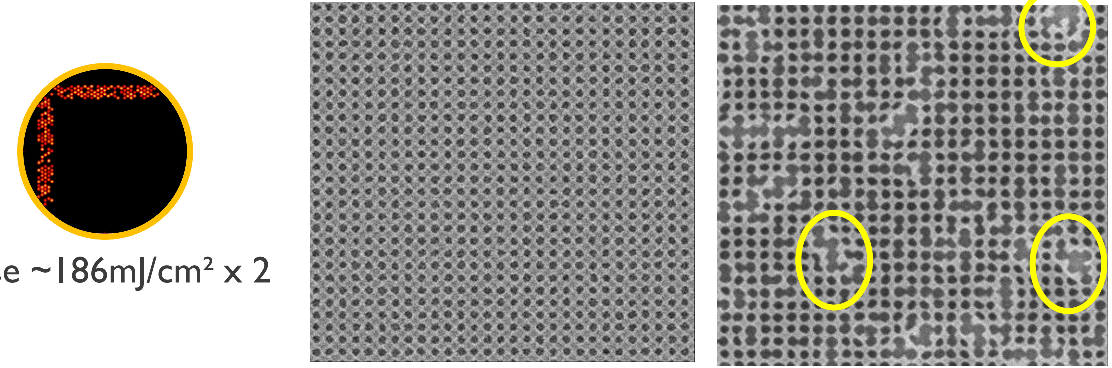
	2018	2019	2020	2021	
Resist type	Non-CAR	Non-CAR	CAR	Non-CAR	CAR
P40 Hexagonal Pillars/CH					
Dose [mJ/cm²]	66	65	61	53	35
LCDU [nm]	2.7	2.2	2.1	2.0	2.6

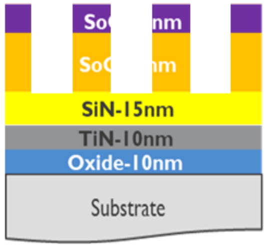
Resist screening / optimization for high resolution CH

	P40	P38	P36	P34	P32
Low LCDU Resist	 59mJ/cm² | 2.4nm	 59mJ/cm² | 2.6nm	 63mJ/cm² | 2.9nm	 65mJ/cm² | 3.1nm	 67mJ/cm² | 3.5nm
Reference Resist	 52mJ/cm² | 2.6nm	 52mJ/cm² | 2.7nm	 55mJ/cm² | 3.0nm	 56mJ/cm² | 3.4nm	 59mJ/cm² | 4.2nm
Low Dose Resist	 35mJ/cm² | 2.6nm	 34mJ/cm² | 3.1nm	 36mJ/cm² | 3.2nm	 36mJ/cm² | 3.5nm	 38mJ/cm² | 4.3nm

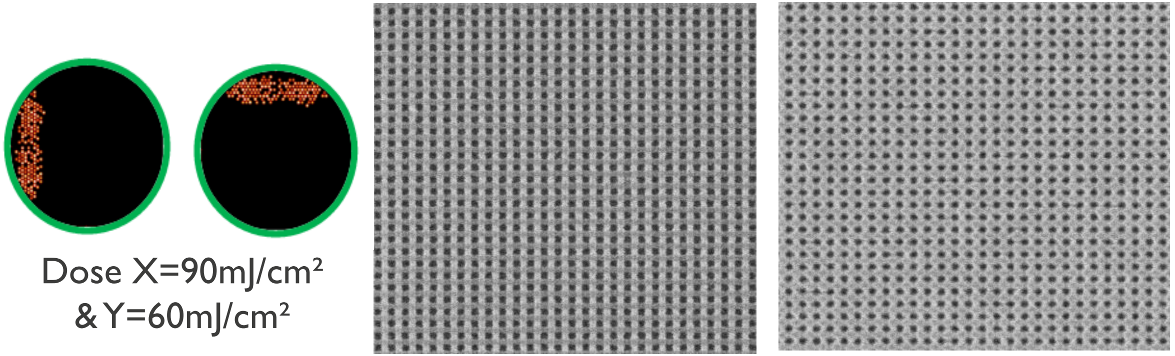
P28 CH etch demonstration on NXE towards High-NA

Best performance achieved by double exposure LS optimized pupils





Dose ~186mJ/cm² x 2



Dose X=90mJ/cm² & Y=60mJ/cm²

Exposure tools overview

Berkeley MET5 and PSI IL tools allow ultimate resolution resist testing

Metric	NXE:3x00 (imec & customer site)	Berkeley MET5 (US)	PSI (Switzerland)
Imaging Principle	Projection 0.33 NA • Free form pupil	Projection 0.5 NA • Free form pupil • Central obscuration	Interference • 'Unlimited' DoF • Regular features only
Source	Sn Laser Produced Plasma	Synchrotron	Synchrotron
Proven resol.	12nm LS	7.5nm LS	6nm LS
Processing infrastructure	Track: 300mm wafer	8" track (Sokudo, 200mm wafer)	Manual processing: max. 200mm wafer

PSI and BMET5 screenings towards ultimate resolution

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

PAUL SCHERRER INSTITUT PSI

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				

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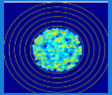
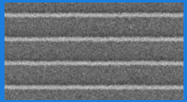
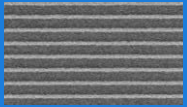
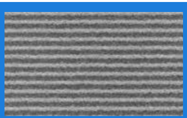
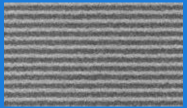
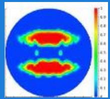
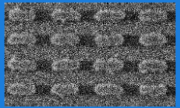
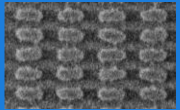
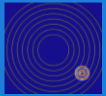
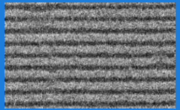
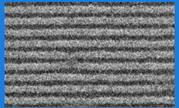
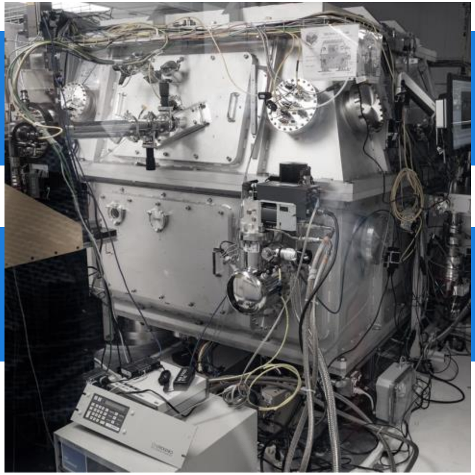
Resolution [hp]	13nm	12nm	11nm	10nm	9nm	8nm
Dry Dev. Inorganic Resist Lines and Spaces			84 mJ/cm²	84 mJ/cm²	84 mJ/cm²	
Inorganic Resist Regular Pillars						

BMET5 allows for resist screening for multiple usecases

Resist evaluation using state-of-the-art illumination conditions

Resist & Feature	Illumination					
			12P80	12P50	12P30	12P27
Inorganic Resist Through Pitch		Small conv.				
inpria			14P35	14P28		
Inorganic Resist Tip-2-Tips		SMO				
			13P26	12P24		
CAR Lines and Spaces		MP				



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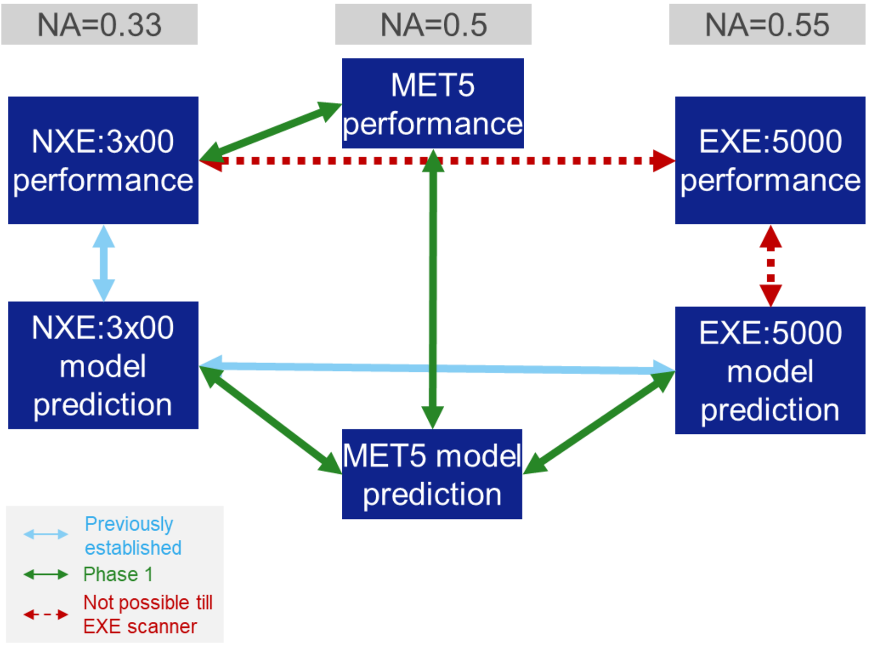
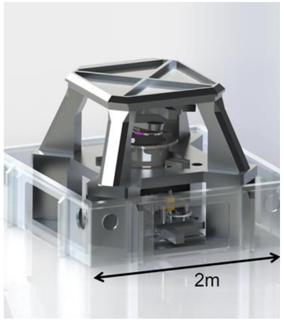
BMET5 bridges Low-NA and High-NA ASML scanners

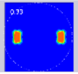
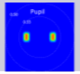
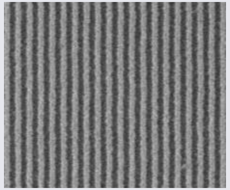
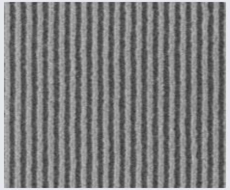
Link between BMET5 simulations and on wafer results



MET5

- NA = 0.5
- Mag = 5
- CRAO = 6°
- Resolution limit = 8 nm
- Synchrotron source



P32LS	NXE 0.33NA	BMET5 0.5NA
NILS	 2.46	 2.41
$LWR_{unbiased}$ @BE/BF	3.3nm	3.2nm
Dose (mJ/cm^2)	31.0	27.0
BE/BF picture		

Round Robin on exposure tools for High-NA

PSI, Berkeley MET5, NXE:3400 and Intel MET5 tools benchmarking

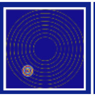
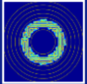
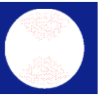
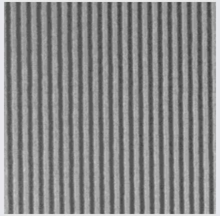
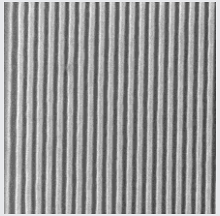
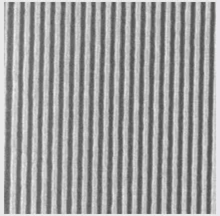
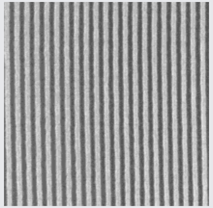
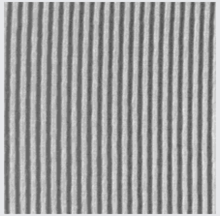
Materials
- Same materials (resist batch) and processing at each site

Exposures
- Imaging wafers: different illuminations proposed by PSI, Berkeley MET5, NXE, Intel MET5

Wafer results
- Contrast understanding: CD SEM measurements done at PSI

Ongoing exposure tools benchmarking 16P32 LS

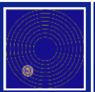
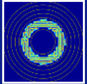
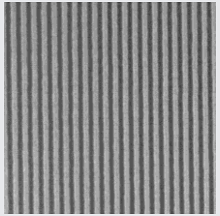
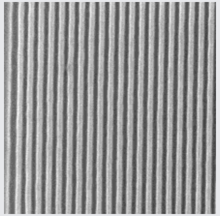
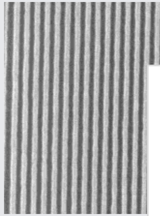
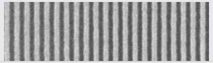
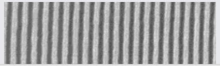
LWR scaling with contrast for the different tools

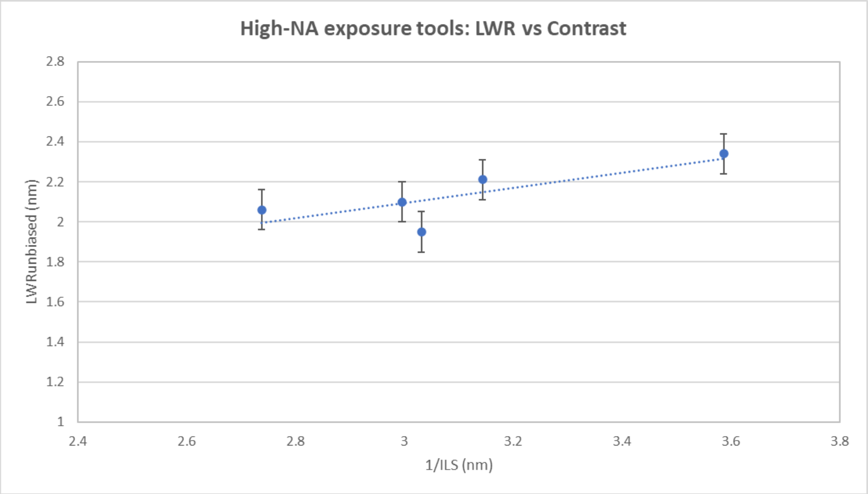
	PSI	BMET5		NXE:3400	
Illumination	n/a	Monopole 	Annular σ=0.35-0.55 	Leaf Dip 	Dip90Y 
Simulated Contrast	0.93	0.84	0.81	0.85	0.71
Image					
DtS (mJ/cm^2)	58.3	68.7	65.3	69.5	70.1
LWR_{unb} (nm)	2.1	1.9	2.2	2.1	2.3

Follow-up: LWR scaling through pitch across the different exposure tools

Ongoing exposure tools benchmarking 16P32 LS

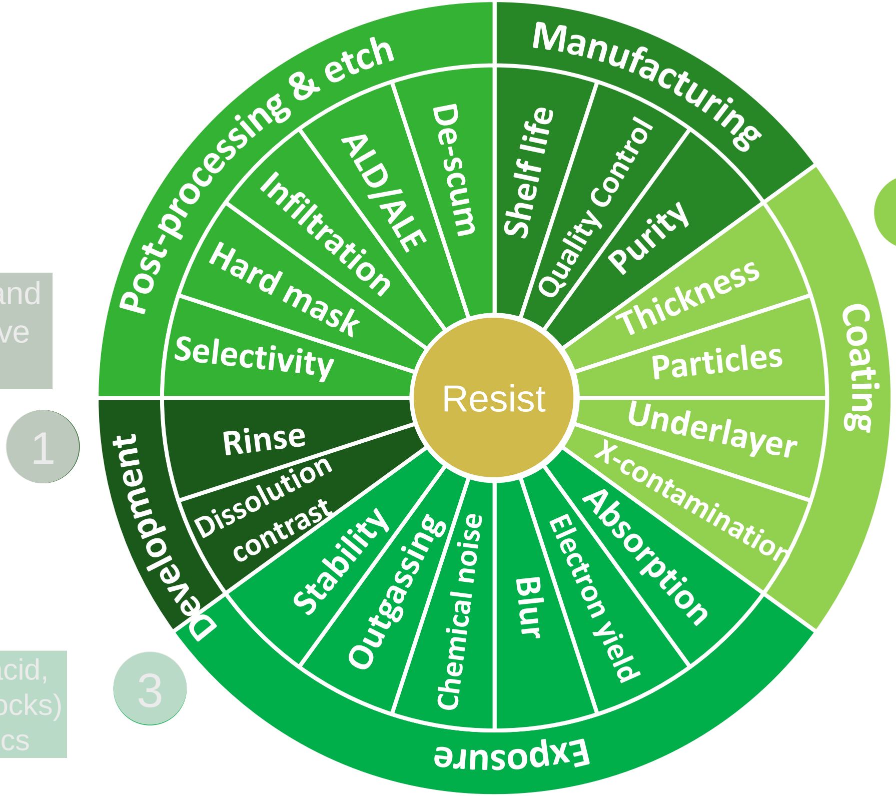
LWR scaling with contrast for the different tools

	PSI	BMET5		NXE:3400	
Illumination	n/a	Monopole 	Annular σ=0.35-0.55 	Leaf Dip 	Dip90Y 
Simulated Contrast	0.93	0.84	0.81	0.85	0.71
Image					
DtS (mJ/cm^2)	58.3	68.7	65.3		
LWR_{unb} (nm)	2.1	1.9	2.2		



Follow-up: LWR scaling through pitch across the different exposure tools

High-NA resist requires holistic optimization driven by stochastics, high resolution and low thickness



Low thickness to support high resolution

Co-optimization of resist and post processing to improve defectivity and LWR

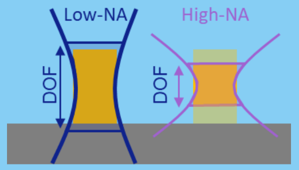
Reduce blur & chemical (acid, quencher, small building blocks) contributions to stochastics

High-NA film thickness requirements (DOF-based)

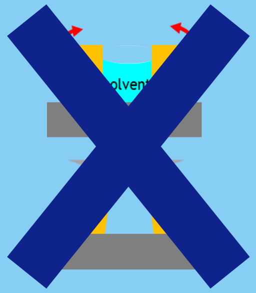
Pattern collapse for 0.5NA exposures on dry developed resist

Small DOF

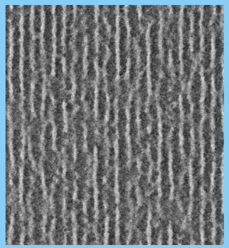
$$DOF = K_2 \frac{\lambda}{NA^2}$$

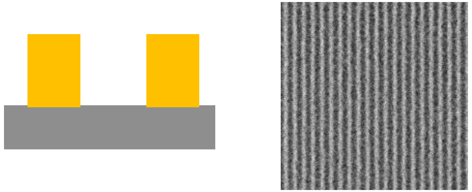


Capillary forces



Pattern collapse

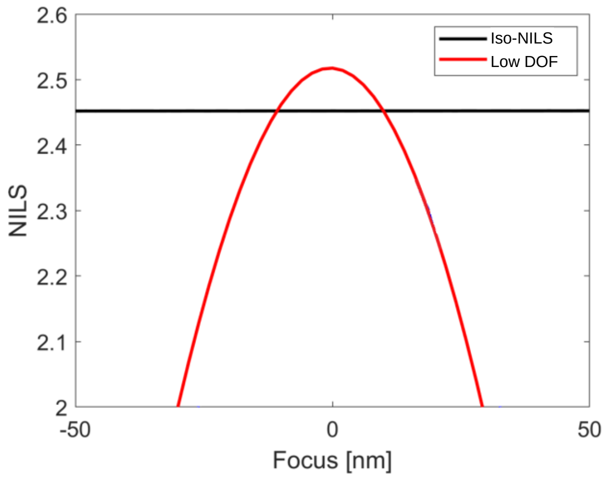




Dry deposited & Dry developed Lam resist prevents mechanical collapse

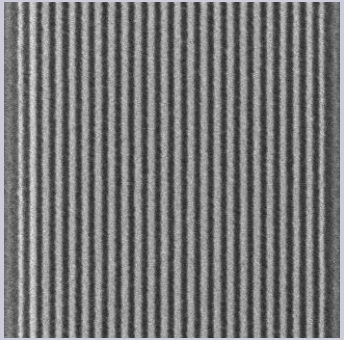
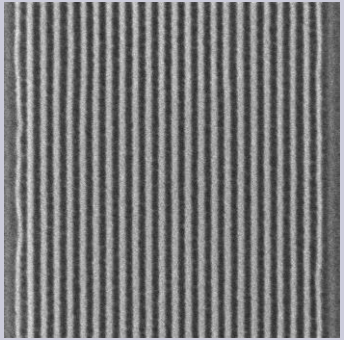
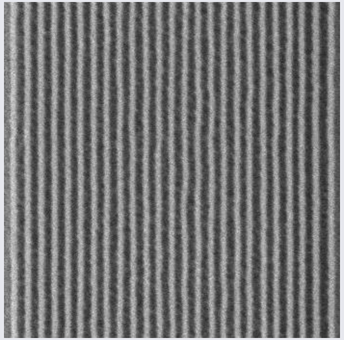
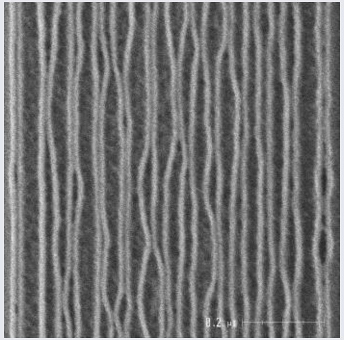
High-NA film thickness requirements (DOF-based)

P32nm LS exposures done using pupils with different NILS through focus behavior



2 Pupils

- Iso-NILS pupil → flat through focus
- Low-DOF pupil → higher peak NILS, low DOF

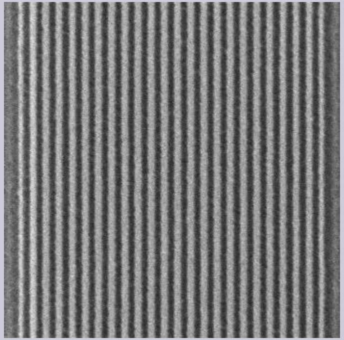
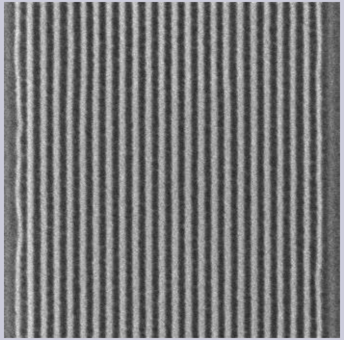
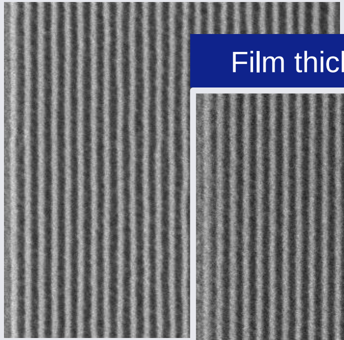
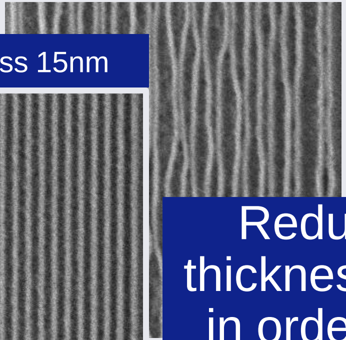
Pupil	Film thickness 25 nm	Film Thickness 35 nm
Iso-NILS		
Low DOF		

High-NA film thickness requirements (DOF-based)

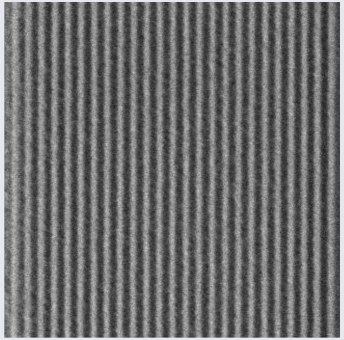
P32nm LS exposures done using pupils with different NILS through focus behavior

Optimization including:

- Resist film thickness
- Peak NILS vs NILS through focus trade-off

Pupil	Film thickness 25 nm	Film Thickness 35 nm
Iso-NILS		
Low DOF		

Film thickness 15nm



Reduced film thickness required in order to avoid line wiggling

High-NA resist requires holistic optimization driven by stochastics, high resolution and low thickness

Co-optimization of resist and post processing to improve defectivity and LWR

1

2

Low thickness to support high resolution

3

Reduce blur & chemical (acid, quencher, small building blocks) contributions to stochastics

Stochastic resist model translates aerial image to 3D resist geometry

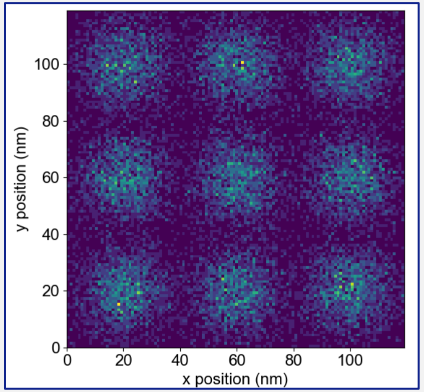
Use-case definition → 3D photoabsorption → PAG activation model → Acid & quencher reaction-diffusion → Resist development → 3D resist geometry

Application to Chemically Amplified Resist (CAR)

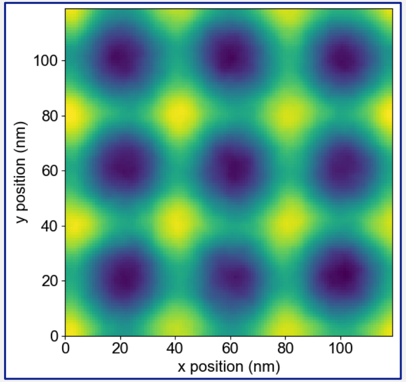
Locally absorbed dose

Chemical variability

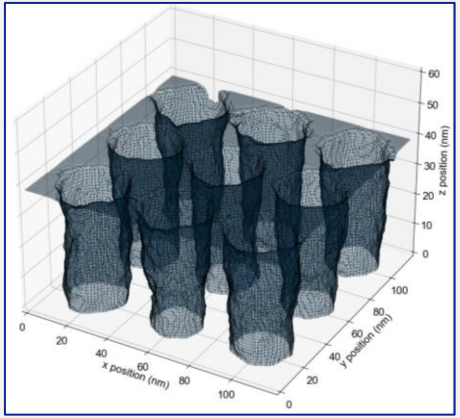
Photon absorption (nm^{-2})



Slice of latent image after reaction-diffusion



Resist geometry after development



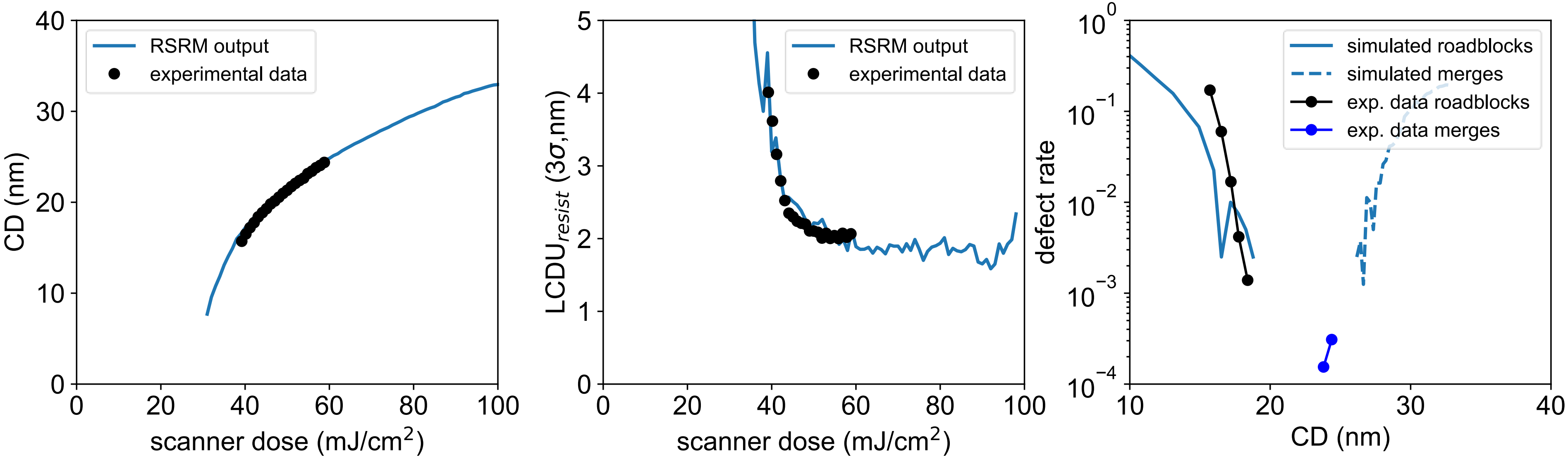
PAG= Photo Acid Generator

Reference: Ruben Maas, this workshop
A Stochastic Resist Model Based Comparison of 0.33NA and 0.55NA Lithography

Good matching of model output and experimental data

0.33NA model calibration on CAR P40 CH

ASML



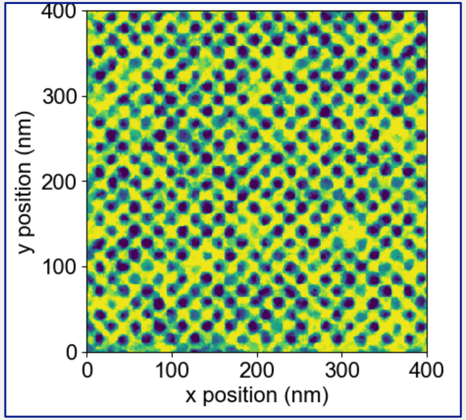
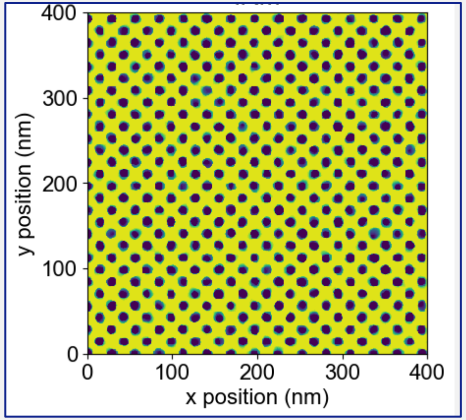
Notes:

- Model calibration did not include experimental failure rates
- Assuming $CD_{SEM\_bias} = 3.3$ nm, $LCDU_{SEM+mask} = 0.7$ nm (3σ)

14nm CH's: Chemical noise limits 0.55NA potential

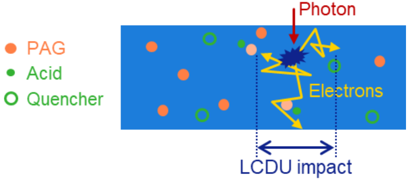
Reducing chemical noise contribution critical for enabling 0.55 NA SE

0.55NA model use-case

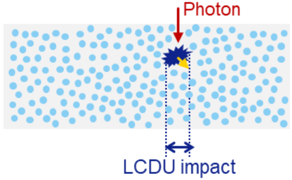
Chemically Amplified Resist (CAR) *Chemical noise & limited absorption*	Isotropic resist *Reduced chem. noise & high absorption*
	
40nm thickness, $\alpha = 5\ \mu m^{-1}$	20nm thickness, $\alpha = 15\ \mu m^{-1}$

0.55NA mitigates photon shot noise, but chemical noise limits final performance

CAR



Isotropic Resist



Reference: Ruben Maas, this workshop
A Stochastic Resist Model Based Comparison of 0.33NA and 0.55NA Lithography

Conclusions

Holistic optimization driven by stochastics, high resolution and low thickness

- Resists are improving (RLS): 0.33NA and ultimate resolution exposures
- Film thickness should be optimized with illumination (DOF challenge)
- Reduction of chemical noise is critical
- Stochastics resist modeling is key in order to drive improvements towards High-NA

Call to resist modeling groups for collaboration towards High-NA ecosystem development

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