Dry Resist Patterning Readiness Towards High NA EUV Lithography

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2024 EUVL Workshop and Supplier Showcase

Outline



1 Challenges to EUV Patterning

2 Dry Resist Equipment and Process Flow

3 Litho Process Development for High NA Patterning

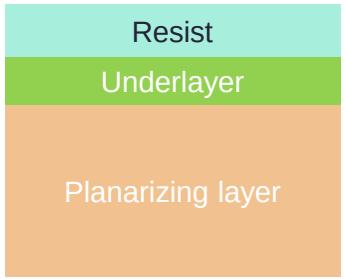
4 Electrical Yield Validation for Dry Resist

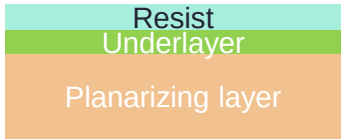
5 Summary

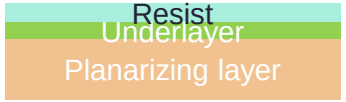
Transition from DUV-> EUV (0.33NA) -> High NA EUV (0.55NA)

Holistic development of tools, materials, processes and metrology is needed

≤ 2017	≥2018	≥ 2024
DUV	**EUV**	**HNA EUV**
Pitch range (nm) for Single Exposure		
80	**28-36**	**≤26**







- **Chemically Amplified Resists (CAR)**
- **Anti reflective coatings**
- **New hardmasks**
- **Planarization layers**
- **Optical defect inspection**

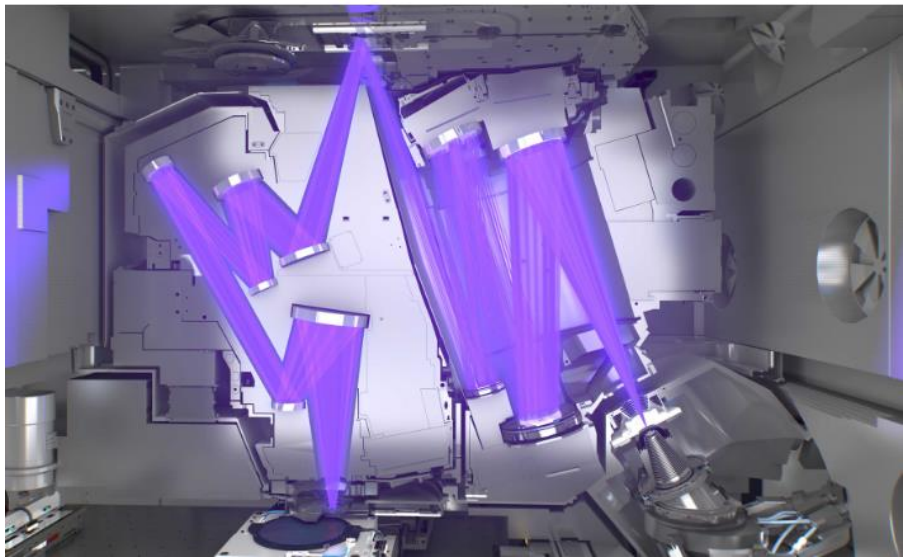
- **CAR, Metal Oxide Resists (MOR)**
- **Lam Dry resist introduction in 2020**
- **Resist underlayer interface dominates**
- **E-beam and optical defect inspection**

Stochastic Era of Patterning

- **Dry Resist, MORs**
- **Thin film scaling**
- **High etch resistance**
- **Lower depth of focus**
- **Defect inspection metrology challenges**

Patterning Challenges in EUV

Radiation Chemistry & Less Photons



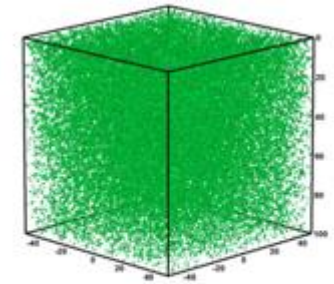
Low conversion efficiency

Low reflectivity

Low % of photons on wafer

ASML is aggressively driving source power improvement

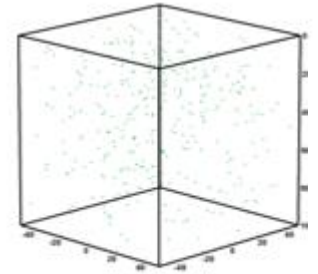
DUV (ArF)



$ArF, 10mJ/cm^2, \alpha = 4/um$

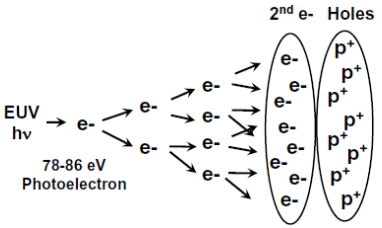
$n_{absorbed} = 366528,\ E_{absorbed} = 2354keV$

EUV



$EUV, 10mJ/cm^2, \alpha = 4/um$

$n_{absorbed} = 25328,\ E_{absorbed} = 2326keV$

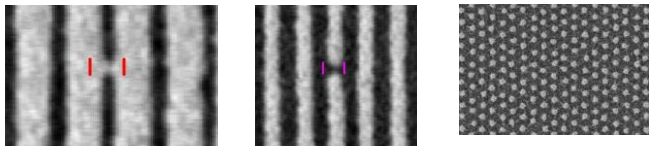


J. Thackery, *Journal of Micro/Nanolithography, MEMS, and MOEMS* 10(3), 033009 (2011).

14x lower number of EUV photons delivered at the same dose compared to ArF -> Photon shot noise

Material variability -> Chemical noise that lowers contrast

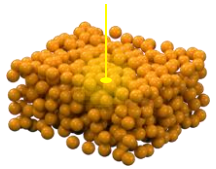
Causes random defects, local CD variation and higher roughness





Resists with high sensitivity, low defectivity and roughness are needed

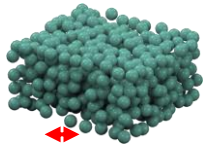
Dry Resist Advantages



Dose Reduction

>3x better EUV absorption than CAR

Organometallics ideal for today and future technology nodes

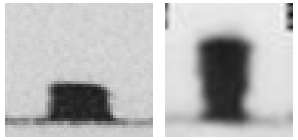


Homogeneity

~6x smaller molecules (~2.5A)

No additives or solvents

Higher etch selectivity



Tunability

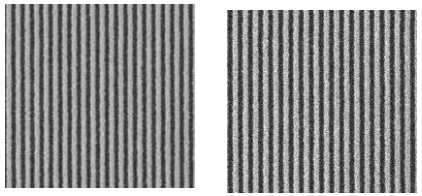
Thickness/conditions scaled by process recipe

No formulation/ampoule changes required



Pattern Collapse

Much wider pattern collapse window with dry development



Defectivity & Roughness

Improved roughness and defectivity at lower dose



Dose to Defect

~3x wider process window compared to other resists

4x-8x fewer in-film particles than CAR or other MOR resists



Stability

>12 months precursor shelf life



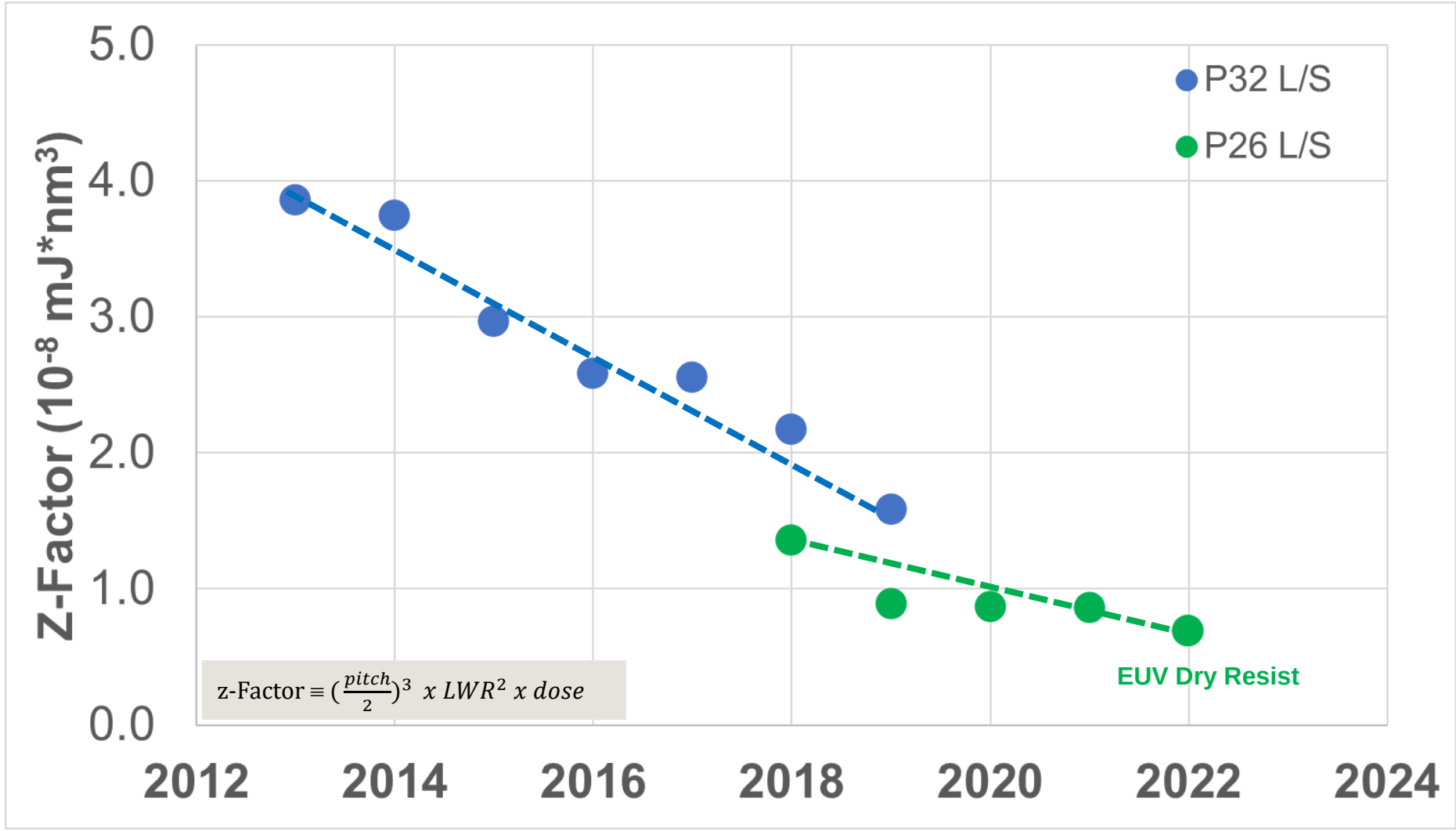
Material Usage

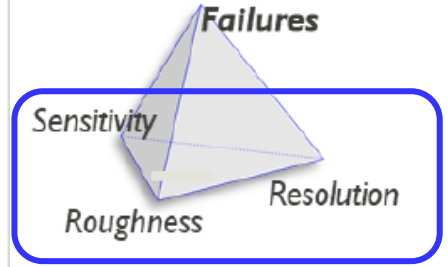
5-10x reduction in material waste, cost

Process step consolidation saves power, CO_2 and water

Lam Dry Resist for the 'Stochastics Era' of Patterning

Best in class z-Factor performance results

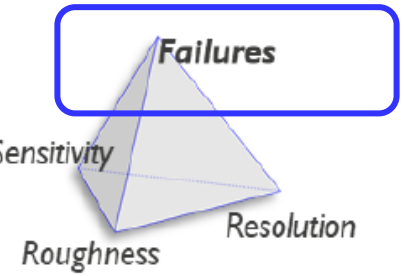


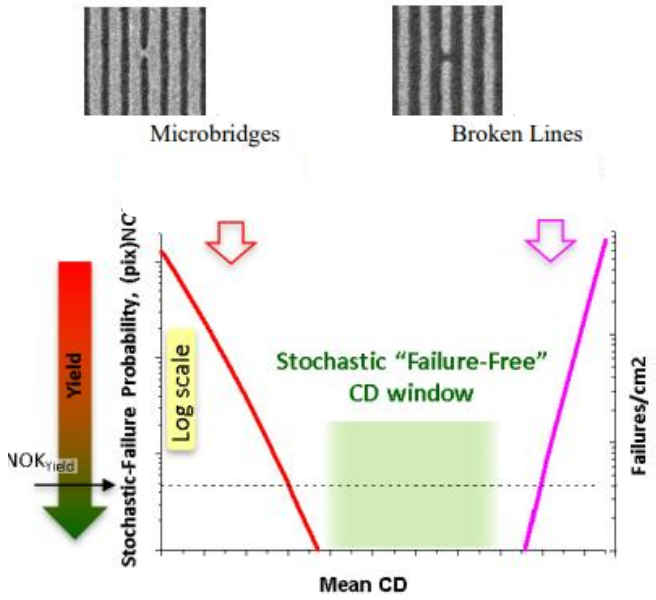


Reference: Jara Santaclara, et al, 2022 SPIE Paper # 12051-7

Stochastic Failures in EUV

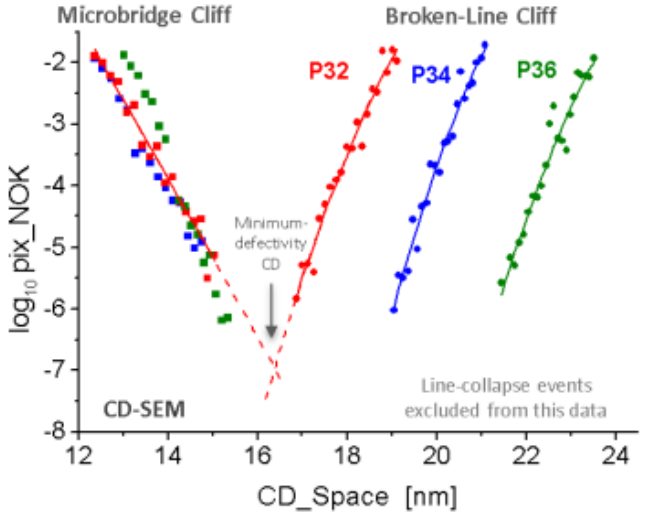
Stochastic failures place a fundamental limit on patterning fidelity and pitch scaling





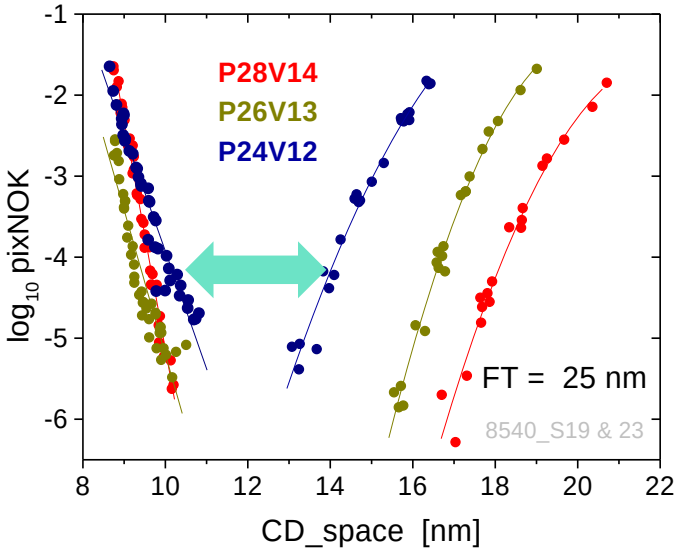
P. De Bisschop, Proc.of SPIE Vol. 10957,109570E (2019)

CAR



Challenge with obtaining a failure free process window with CAR resists limits pitch scaling

Dry Resist



Initial demonstration of dry resist extendibility through failure free window characterization

Stochastic failures caused by photon and chemical components

Photon variability dominates at lower dose

Improving the chemical stochastic with doses that are HVM friendly requires material innovations

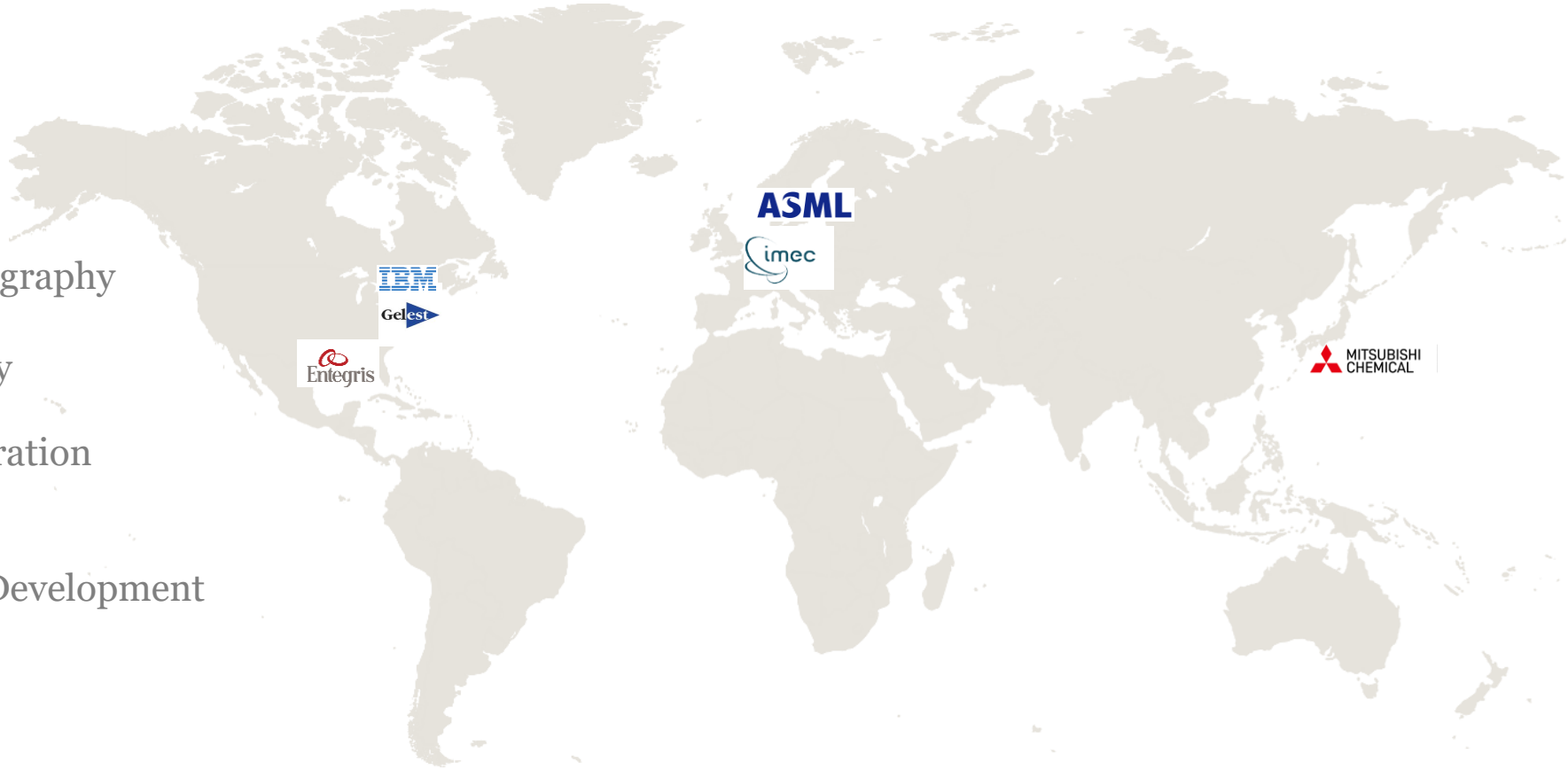
Dry Resist Worldwide Collaborations

ASML Hi-NA EUV Lithography

imec Process Feasibility

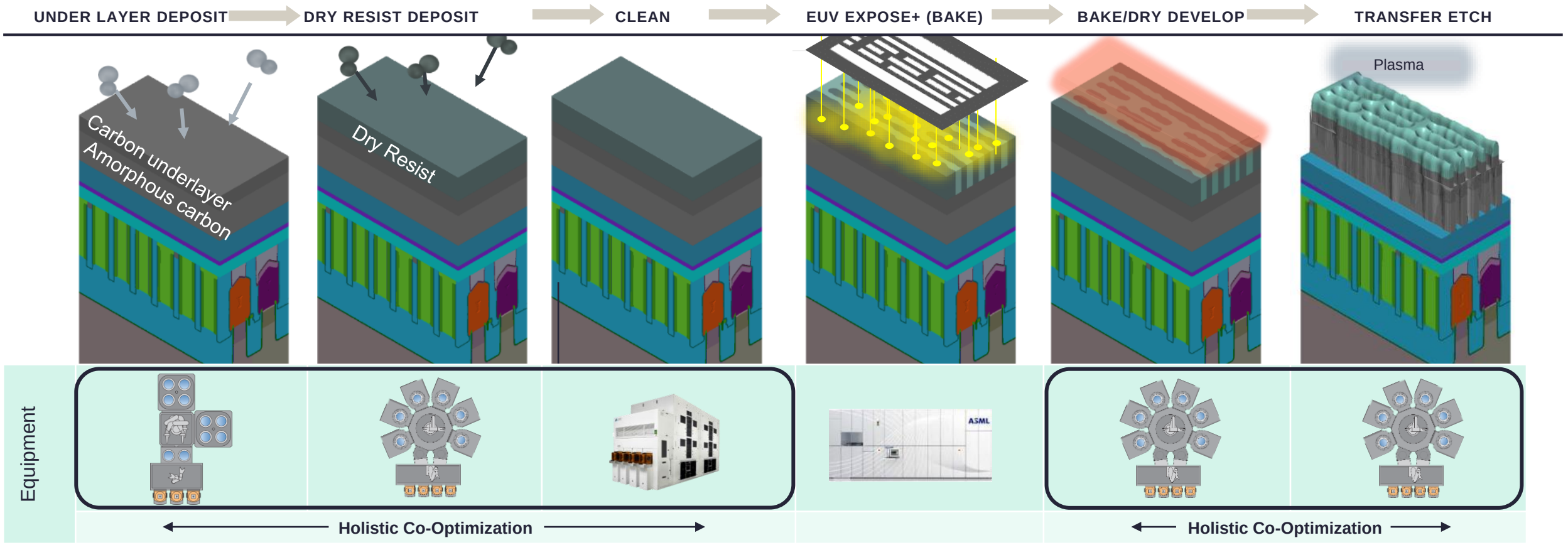
IBM Process Demonstration

Entegris Gelest MITSUBISHI CHEMICAL Novel Precursor Development



Dry Resist Equipment and Process Flow

Dry Resist Equipment and Process Flow

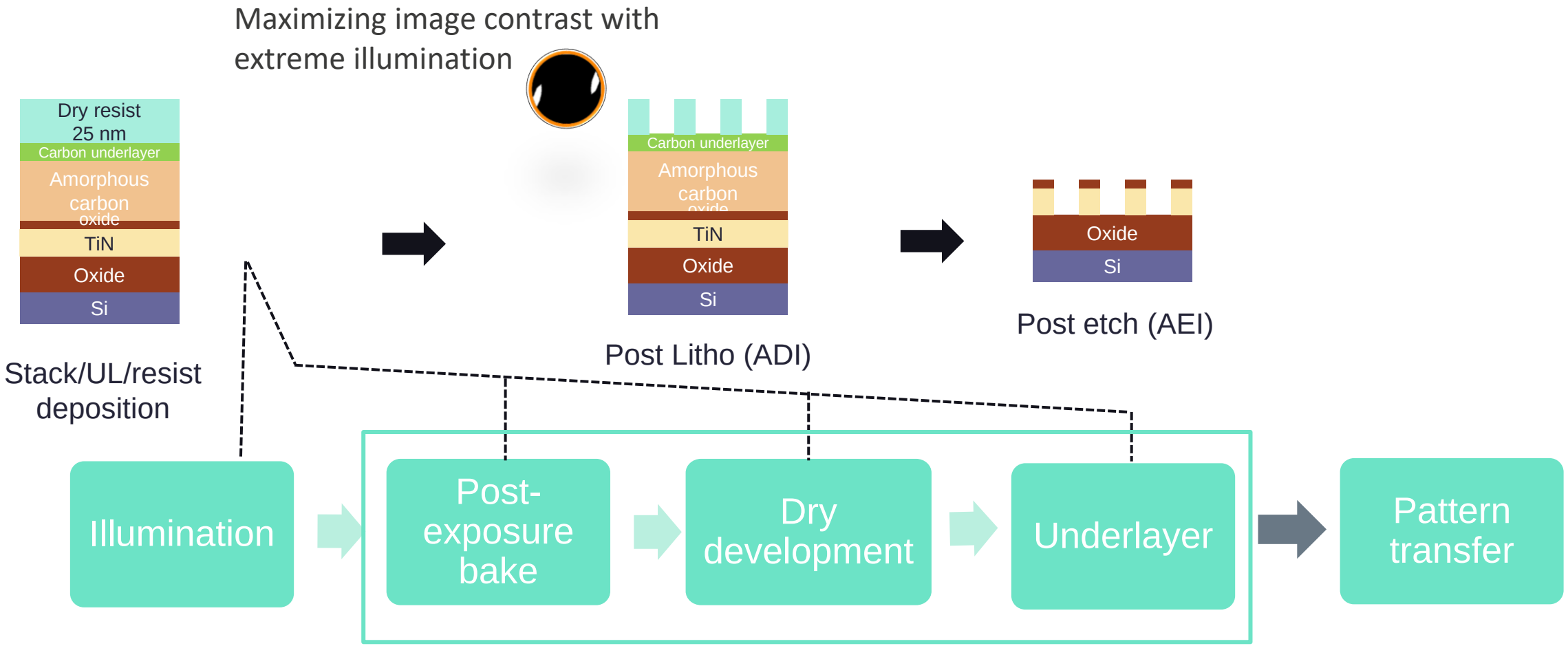


With dry resist processing, holistic co-optimization can be performed at each step pre and post exposure.

Litho Process Development for High NA Patterning

How to study HNA pitch on today's 0.33 NA scanner

Test vehicle evaluating Pitch 24 nm L/S on NXE:3400B with maximum image contrast

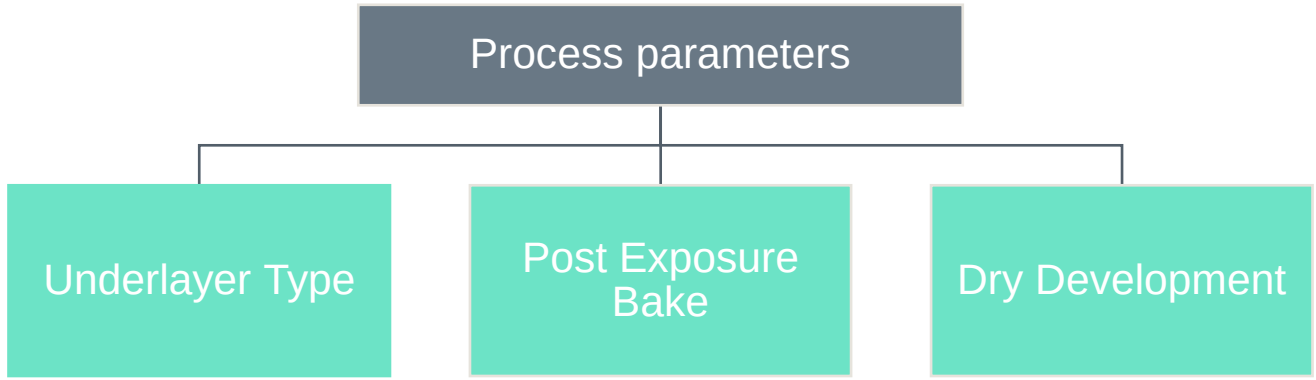


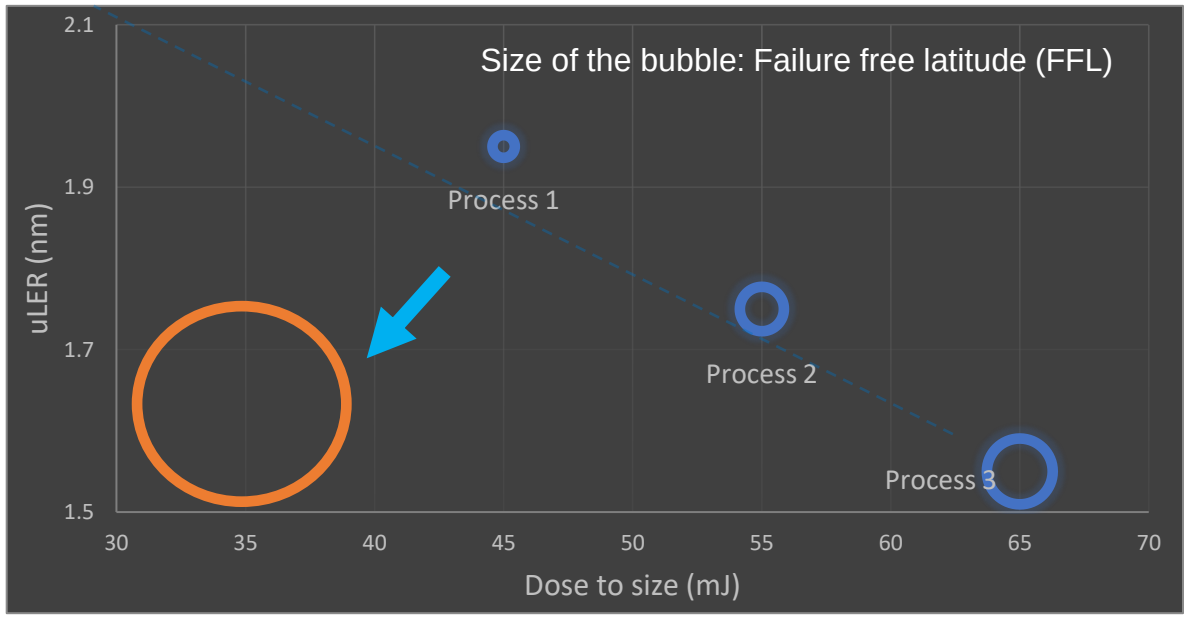
Key metrics for evaluation: Dose-to-size (DtS), unbiased LER/LWR, Failure free latitude (FFL)

Litho Performance Metric Analysis

How can be break the dose vs performance tradeoff?

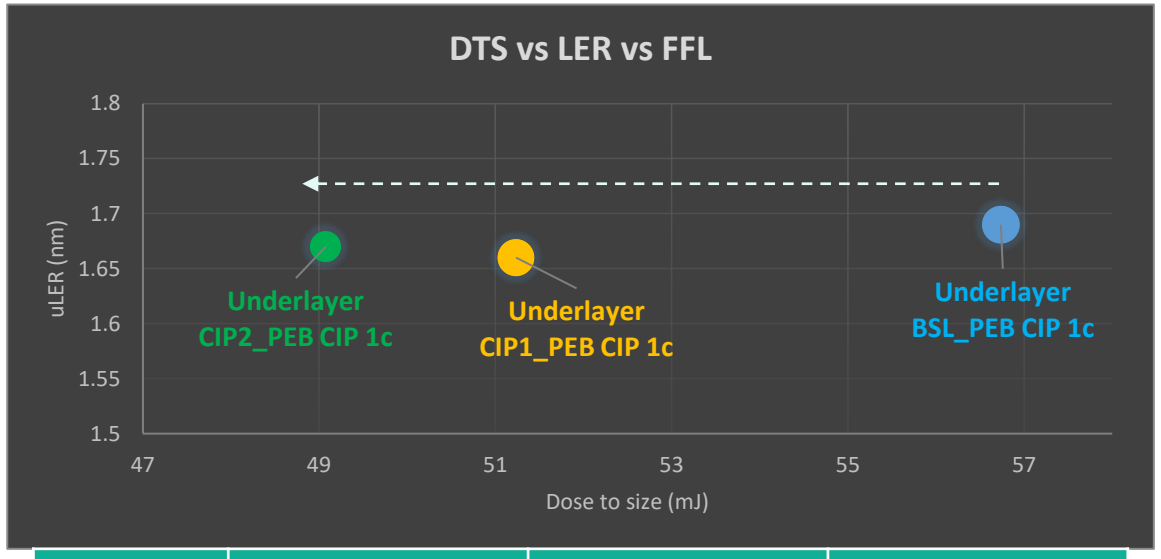


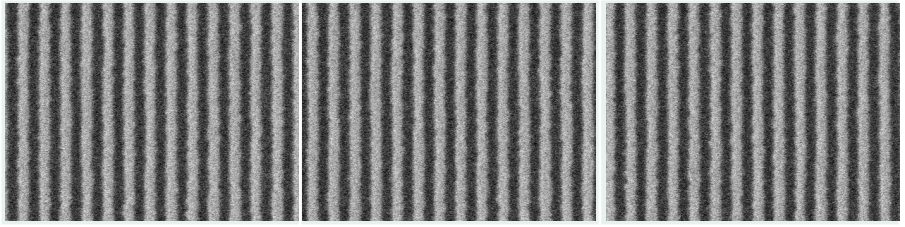




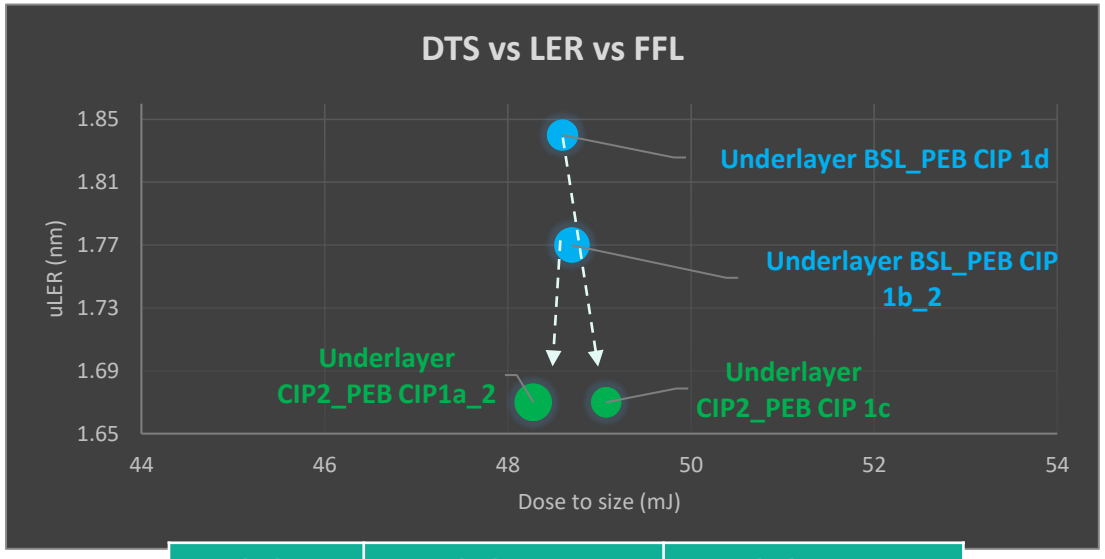
Underlayer and PEB co-optimization for P24L/S

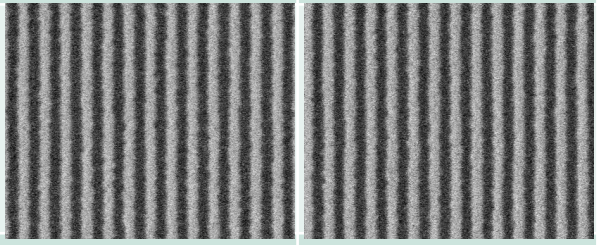
14 % DTS decrease at similar roughness→ Underlayer optimization at fixed PEB



Underlayer	Underlayer BSL	Underlayer CIP1	Underlayer CIP2
PEB	PEB CIP 1c	PEB CIP 1c	PEB CIP 1c
CD-SEM image			
DtS (mJ)	56.80	51.23	49.07
Line CD (nm)	12.03	12.17	12.04
LWR /LER (nm)	2.35 / 1.69	2.29 / 1.66	2.33 / 1.67
Z factor	0.29 (E-08)	**0.24 (E-08)**	**0.24 (E-08)**

11 % Roughness decrease at similar DTS PEB and Underlayer co-optimization



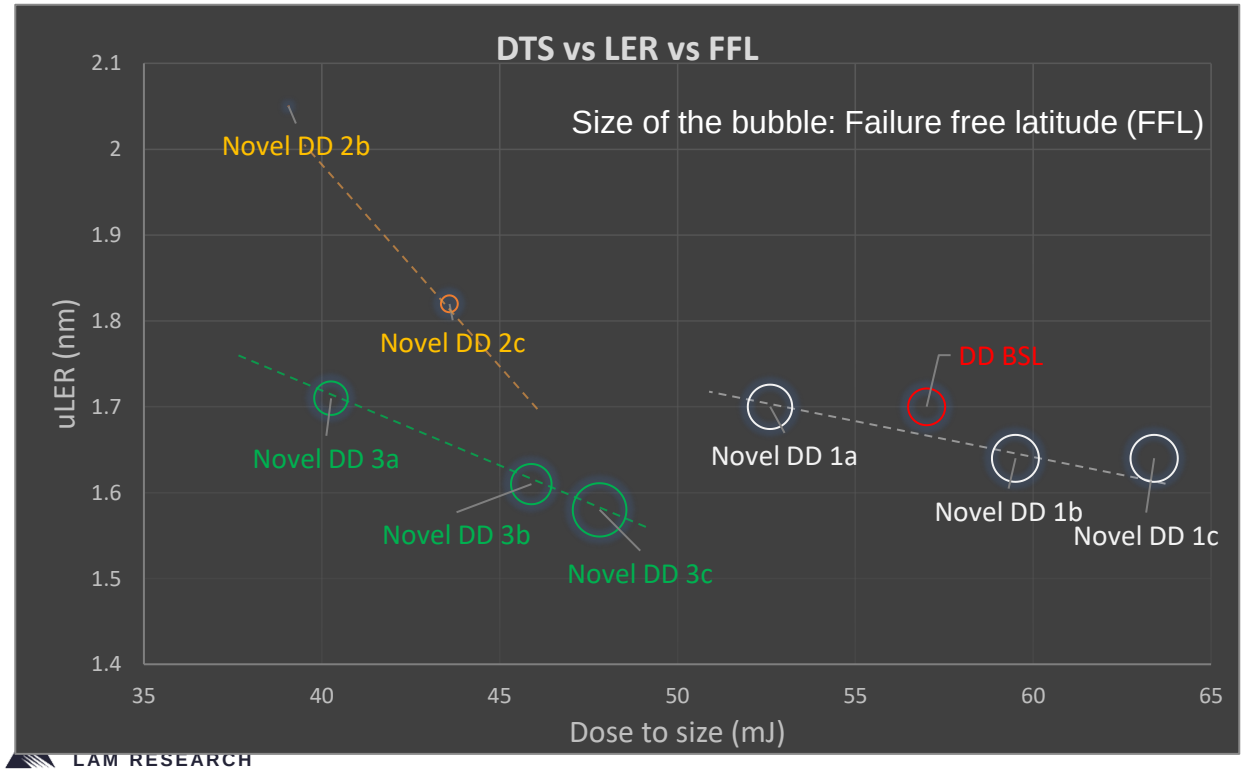
Underlayer	Underlayer BSL	Underlayer CIP2
PEB	PEB CIP 1d	PEB CIP 1c
CD-SEM image		
DtS (mJ)	48.60	49.07
Line CD (nm)	11.90	12.04
LWR /LER (nm)	2.49 / 1.84	2.33 / 1.67
Z factor	0.29 (E-08)	**0.24 (E-08)**

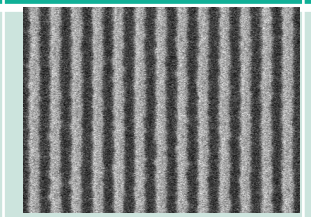
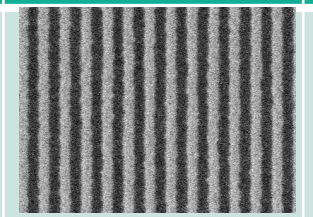
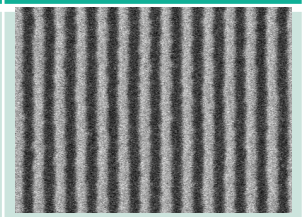
Dry Development Chemistry Evaluation for P24 L/S

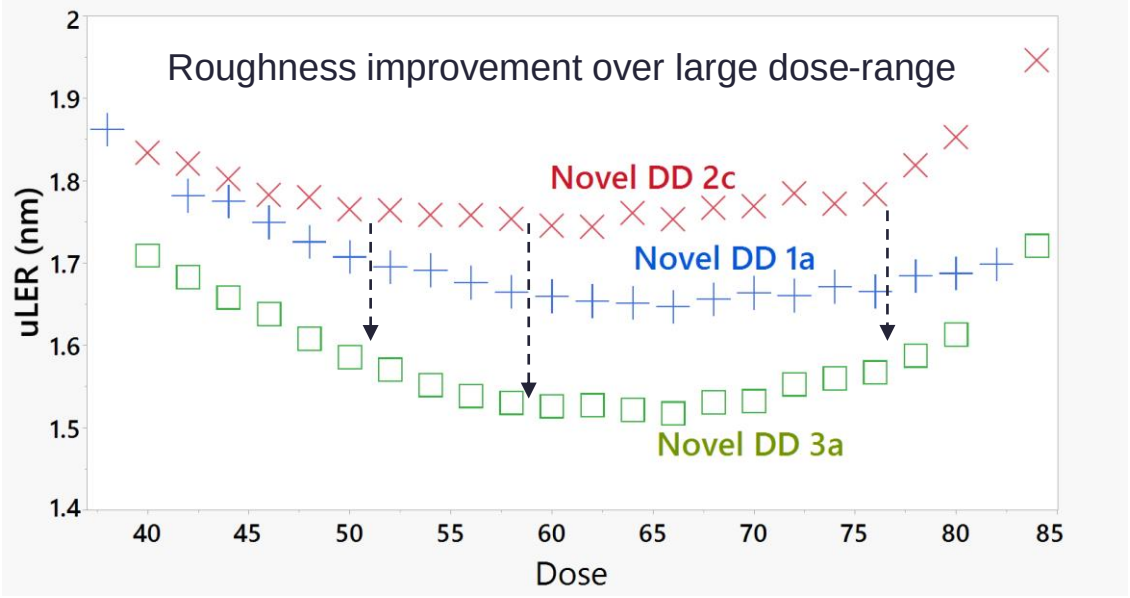
- Breaking dose and roughness tradeoff with Dry-development chemistry optimization
  - **Up to 23 % improvement in Z factor** with Novel DD 3.

Increasing Developer time

Novel DD 1a	Novel DD 1b	Novel DD 1c
Novel DD 2a	Novel DD 2b	Novel DD 2c
Novel DD 3a	Novel DD 3b	Novel DD 3c



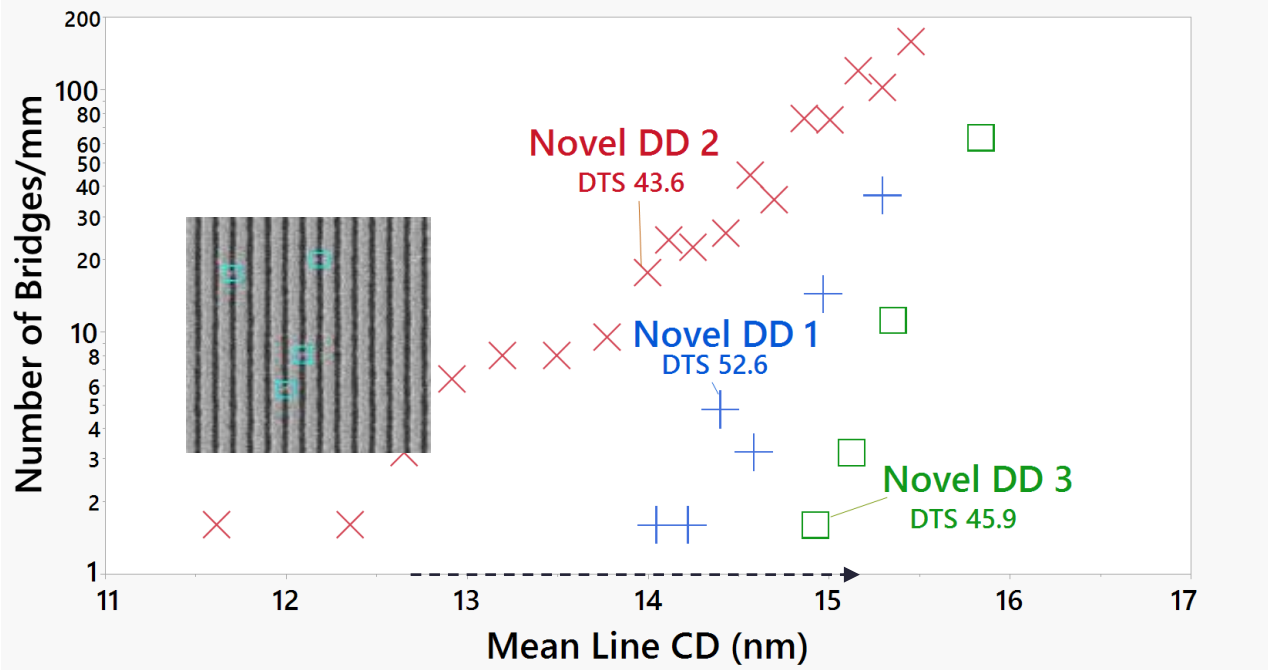
DD	Novel DD 2c	Novel DD 1a	Novel DD 3a
CD-SEM image			
DtS (mJ)	43.59	52.65	**40.26**
Line CD (nm)	11.99	11.93	12.01
LWR /LER (nm)	2.47 / 1.82	2.31 / 1.70	2.37 / 1.71
LER(nm) (LF/MF/HF)	1.13 / 1.37 / 0.39	0.98 / 1.30 / 0.45	1.03 / 1.30 / 0.39
Z factor	0.25 (E-08)	0.26 (E-08)	**0.20 (E-08)**



Post Litho Defectivity Analysis: Bridge Modulation for P24L/S

Bridge window enlargement by optimizing Dry development chemistry

Novel DD 2 → Novel DD3: **Bridge onset from 12.1 to 15.0 nm without increase in dose**

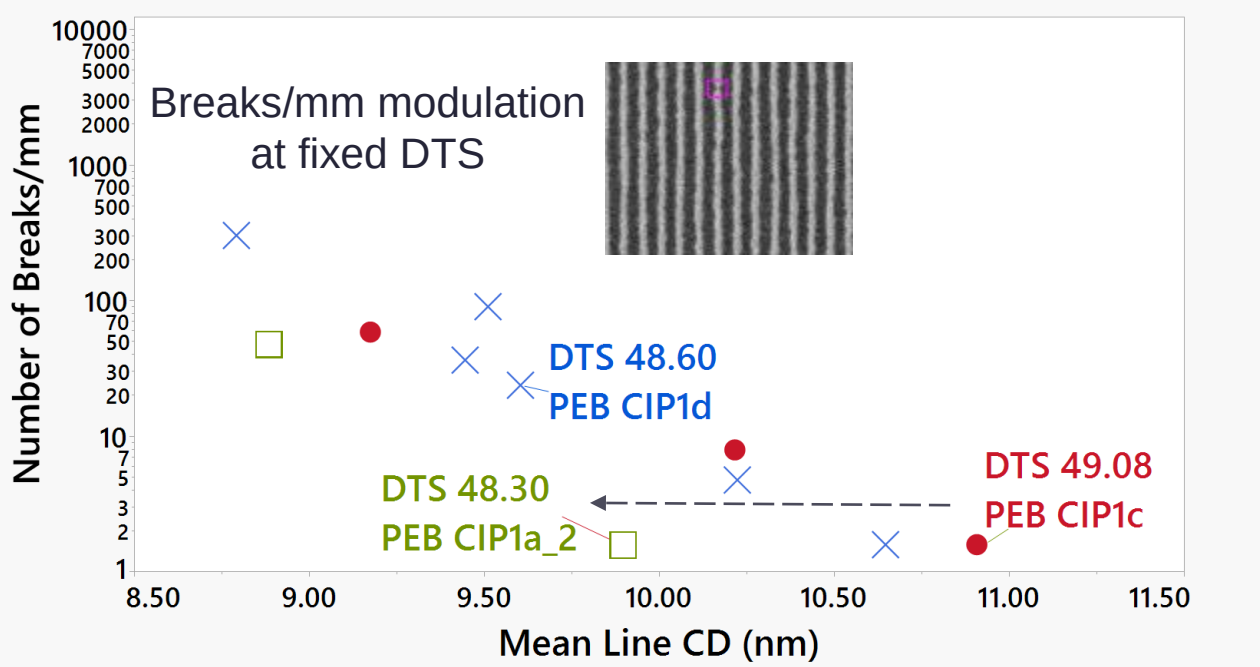


CDSEM based defectivity analysis
16 um^2 area inspection per die

Post Litho Defectivity Analysis: Breaks Modulation for P24L/S

Breaks modulation at similar DTS: Modulation with bake process

Breaks onset from 11 to 10 nm at similar dose by PEB modulation



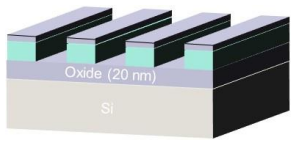
CDSEM based defectivity analysis
16 um^2 area inspection per die

Large Area BBP AEI BF 2935 Inspection for P24L/S

BBP Bright Field 2935 was used for readout of P24L/S defectivity

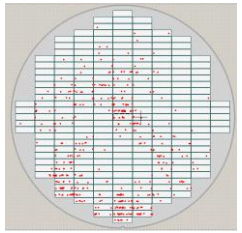
CDU wafers of two down selected process conditions were evaluated at similar post etch line CD

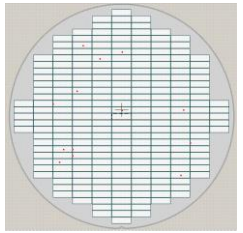
- Bright field recipe (103cm^2)-> bridge sensitive
- Dark field recipe (118cm^2)-> break sensitive

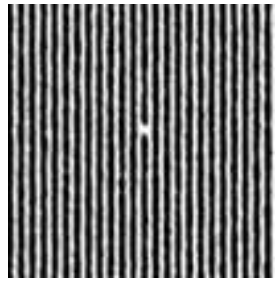


Post TIN HMO (AEI)

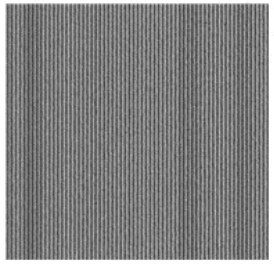
	Bright field recipie	
	Condition 1: PEB1b_2_DD BSL	Condition 2 PEB 1c_DD BSL
DTS	**48**	**54**
LER	**1.77**	**1.75**
Line CD	**12.7**	**12.6**
Total non repeater defects	**`1091**	**411**
Defect density/cm2 (Bright field)	**5**	**<1**







Bridge defects captured by Bright field inspection



Contrast variations captured by Dark field inspection

↓

Correlation to breaks?

↓

39xx demo measurement to confirm and establish the correlations

BBP readout shows bridge defect density modulation and improvement to <1 def/cm^2

LAM RESEARCH imec

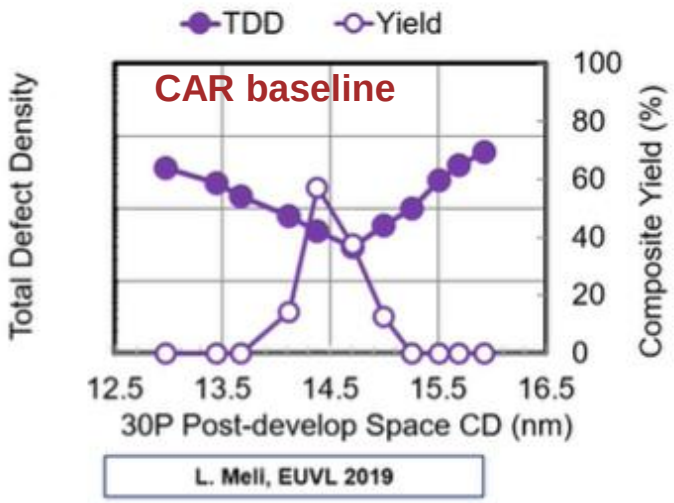
Electrical Yield Validation for Dry Resist

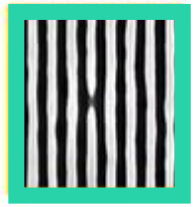
Stochastic Yield Characterization Methodology

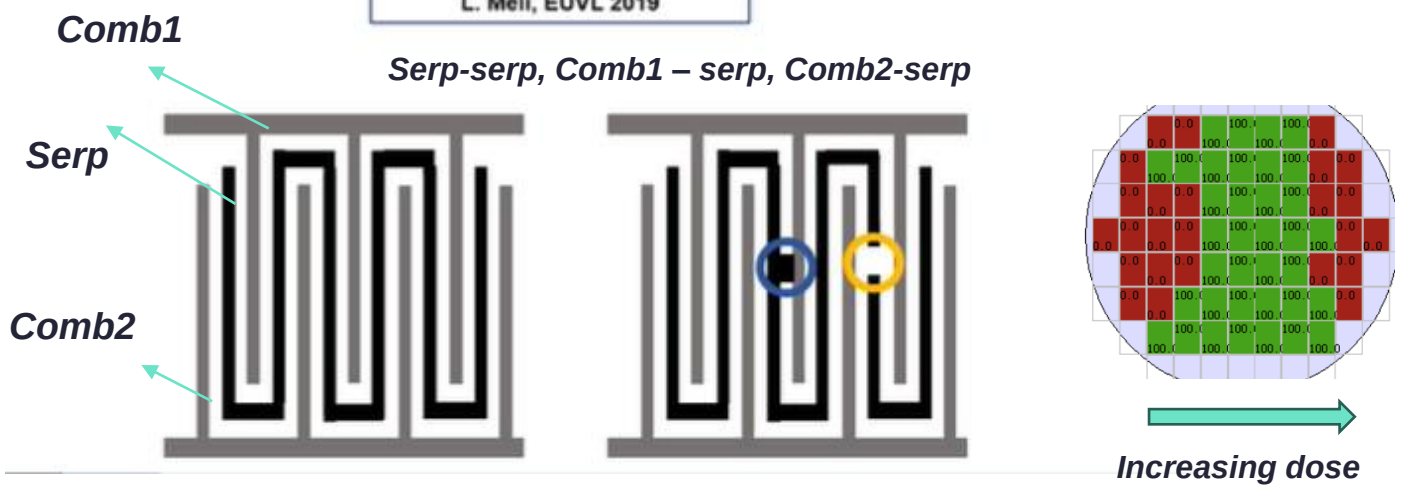
Test vehicle evaluating Pitch 28/26 nm L/S yield on NXE:3400B

IBM









Yield process window, correlated to defect density through dose stripe wafer exposures.

Yield measured on ***Comb-serp*** monitor structures

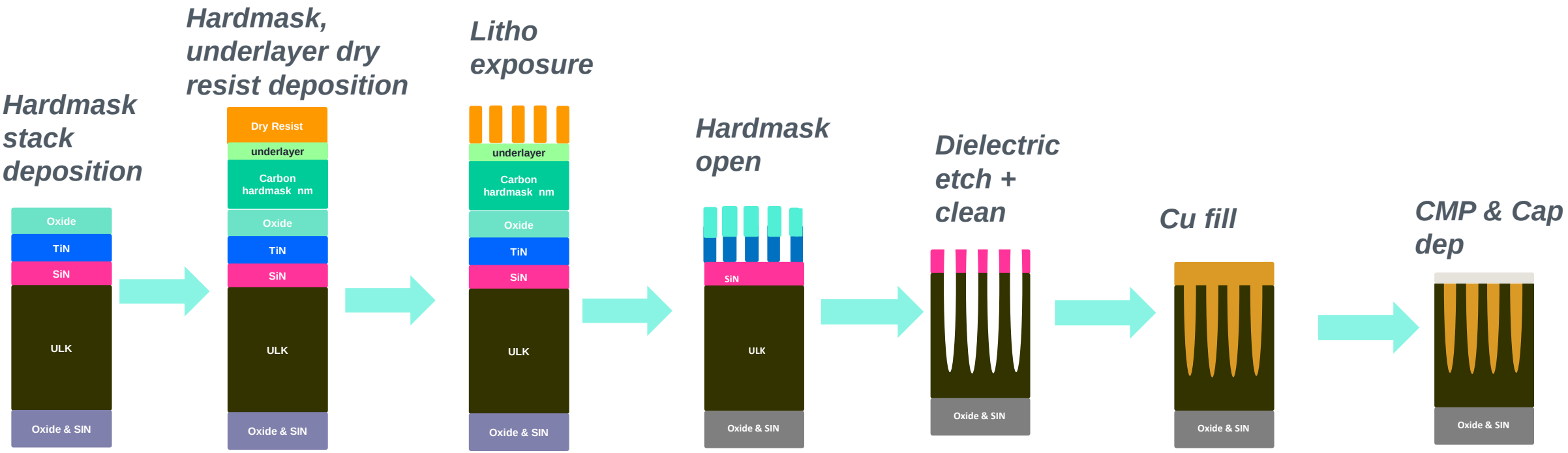
- Detect bridges, breaks combination with minimized chip area/maximized sensitivity.
- **Correlated to defect density with eBI metrology**

L. Meli, Proc.of SPIE Vol. 11609,116090P (2021)
J. Church, Proc of SPIE 12053,1205306 (2022)

Stochastic defectivity is correlated to electrical yield

Dry resist development: Cu Damascene Test Vehicle

Relevant to High NA insertion for <21P interconnect → Expected to be damascene



L. Meli, SPIE Advanced Lithography, 2020

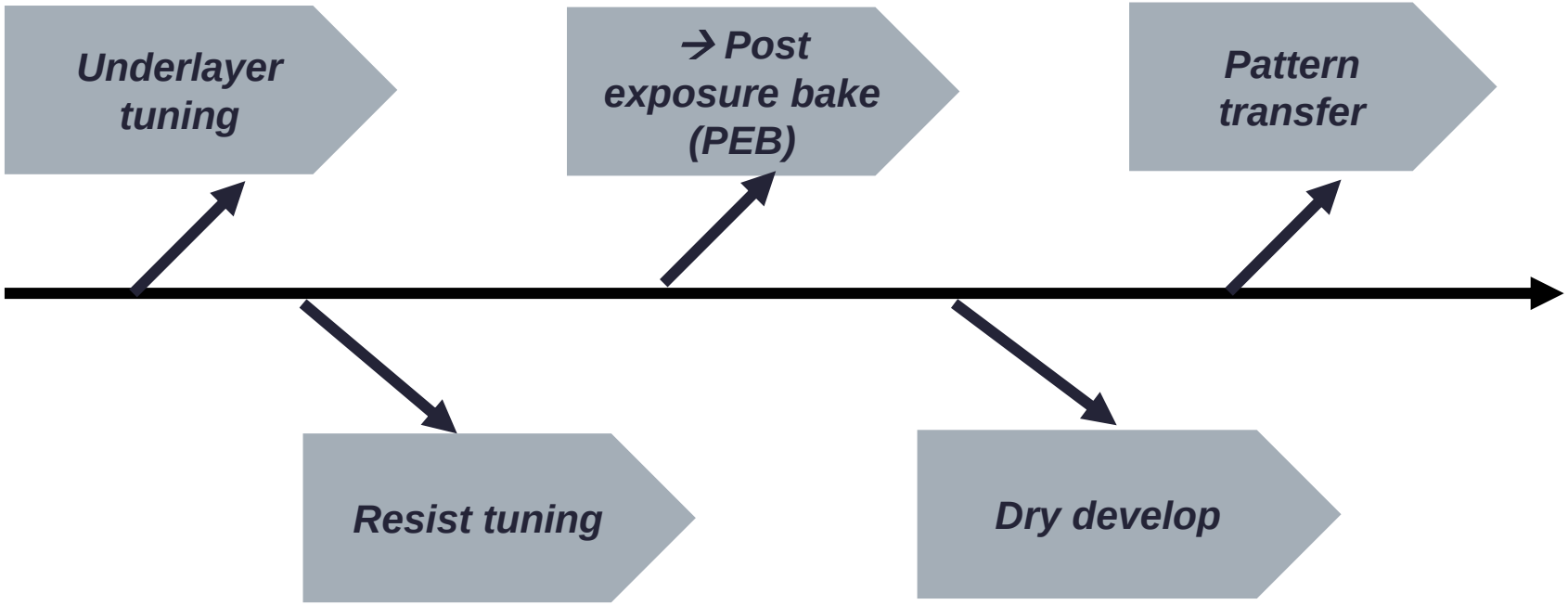
Cu damascene yield vehicle established by IBM Research :

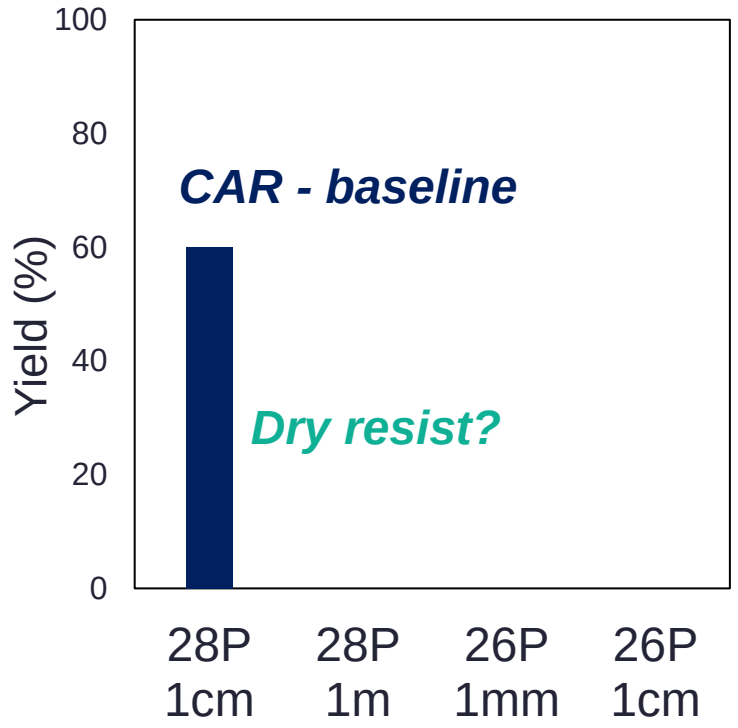
26 – 36nm pitch metal line designs for yield and defectivity testing

Established baseline with CAR resist yield published at 28P-36P -> how will dry resist perform?

Dry Resist Process Optimization for Yield Improvement

Process parameters that can modulate pitch 28/26 nm L/S yield on NXE:3400B

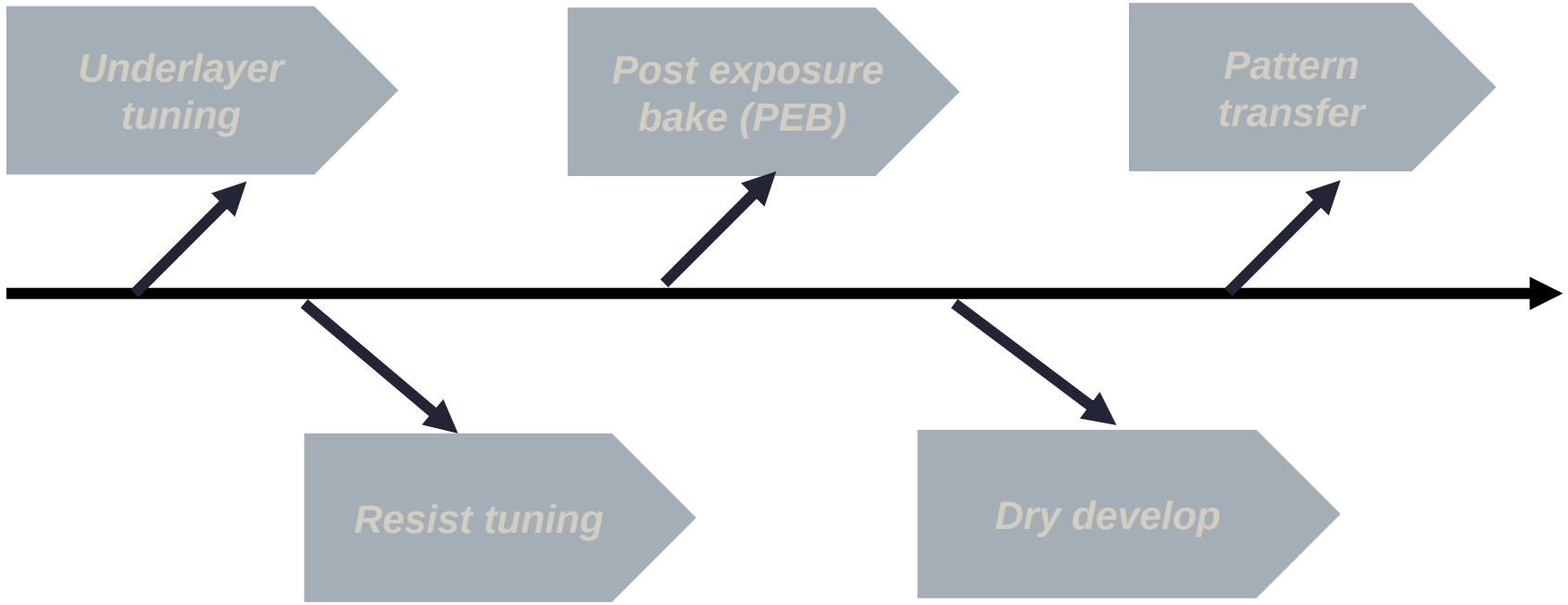


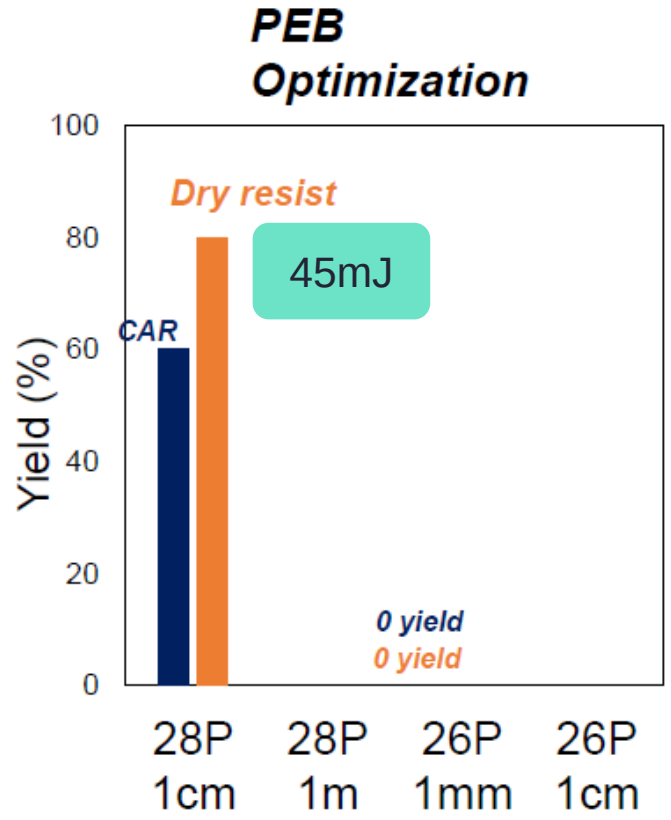


I. Seshadri, Proc. of SPIE Vol. PC12953, PC129530L (2024)

Initial Yield Demonstration for Dry Resist

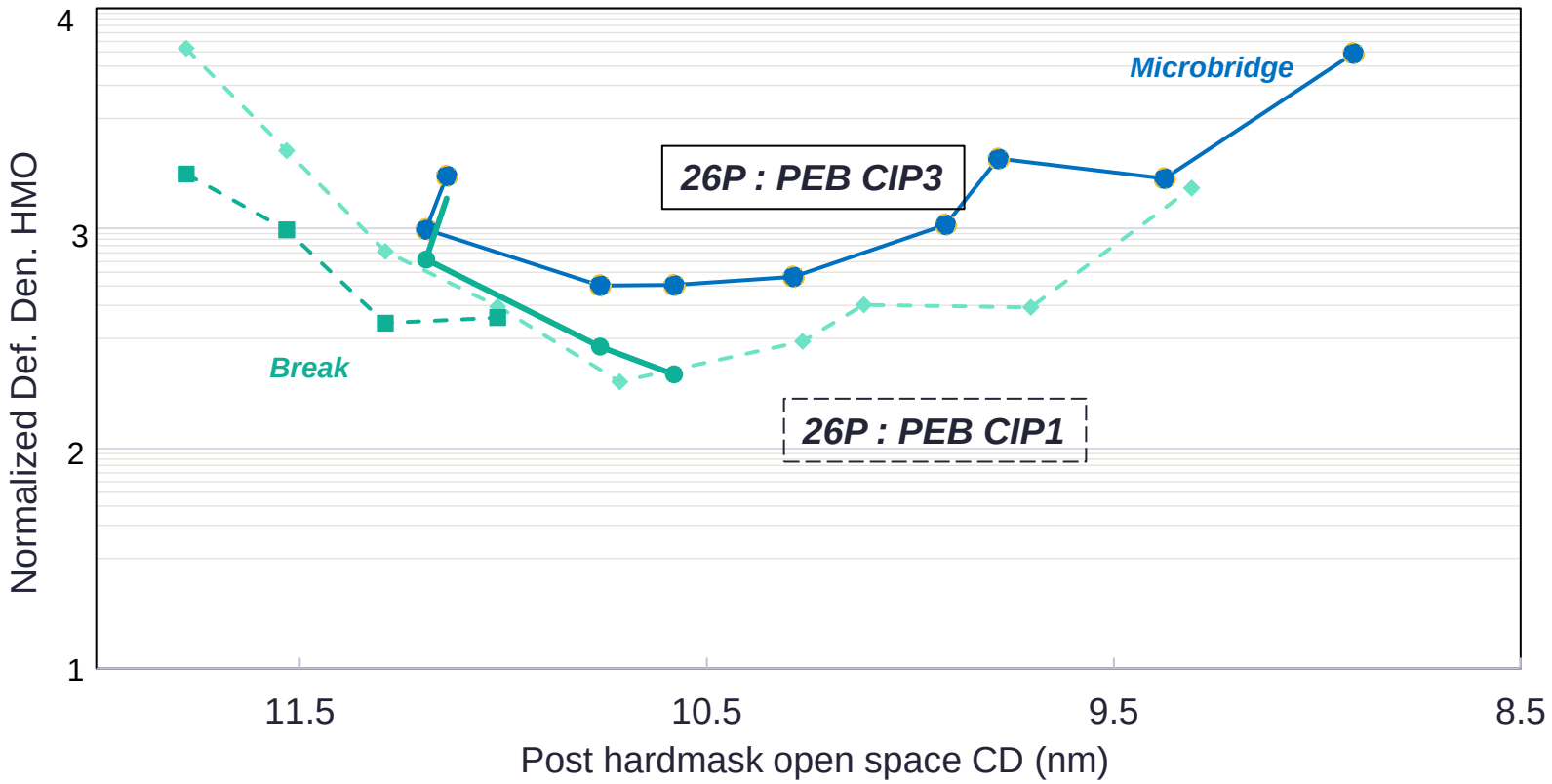
Dry resist demonstrates clear stochastic defectivity and electrical yield advantage over CAR





I. Seshadri, Proc. of SPIE Vol. PC12953, PC129530L (2024)

Bake Process Tuning for Dry Resist Performance



	Post litho trench CD (nm) – 28P	Dose to size (mJ/cm2)	uLWR (3s nm)
PEB CIP3	14.2	***42***	3.1
PEB CIP1	14.6	***60***	2.6

Dose to size is decreased with PEB modulation

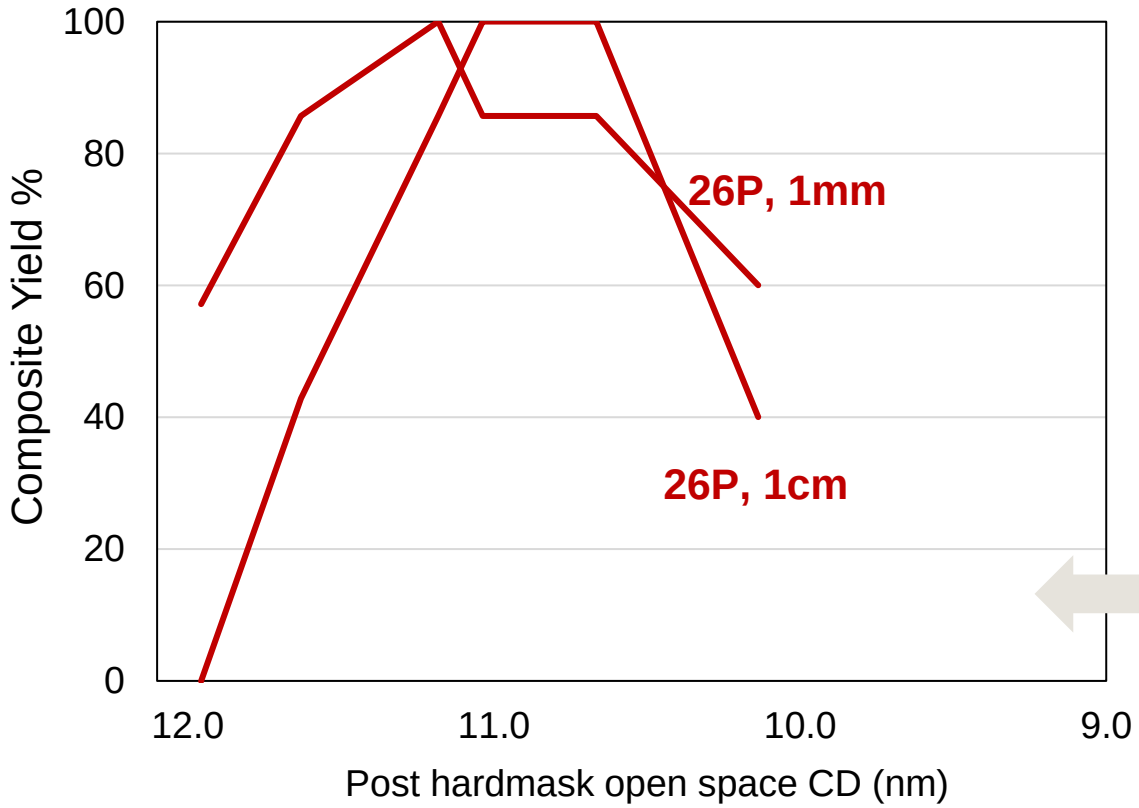
However → LWR and defectivity improves at the cost of dose

Other recovery mechanisms needed to enable lower roughness and higher yield at target DtS of 45mJ.

I. Seshadri, Proc. of SPIE Vol. PC12953, PC129530L (2024)

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Bake and Underlayer Co-Optimization



	Post litho trench CD (nm) – 28P	Dose to size (mJ)	uLWR (3s nm)
PEB CIP3	14.2	***42***	3.1
PEB CIP1	14.6	***60***	2.6
PEB CIP1 + UL CIP2	14.6	***56***	2.6

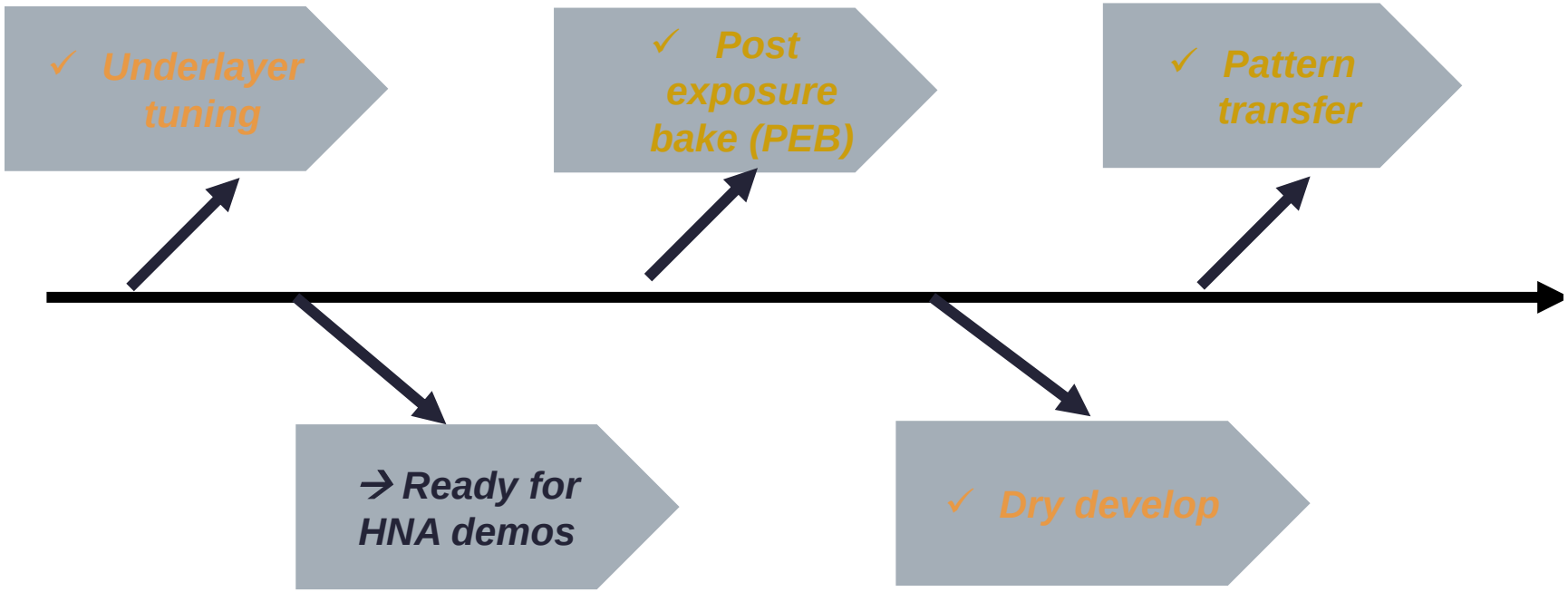
Combining PEB CIP1 with a dose enhancing Underlayer CIP2 results in >80% yield at 26P 1mm, 26P 1cm with >1nm CD range and no LWR degrade. Dose to size is partially recovered

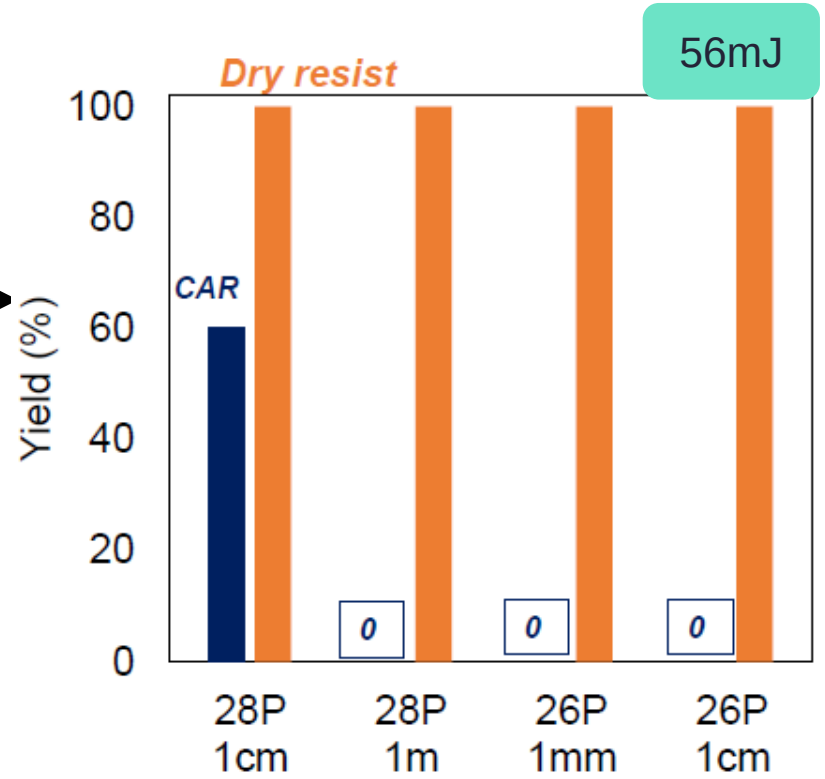
Co-optimization of other parameters (underlayer, dry develop, pattern transfer) is key

I. Seshadri, Proc. of SPIE Vol. PC12953, PC129530L (2024)

Dry Resist process optimization to realize full potential

Dry develop and underlayer co-optimization with PEB shows high yields at pitches 28 and 26nm->without dose compromise





Best in class yield performance demonstrated for 28 and 26nm pitch

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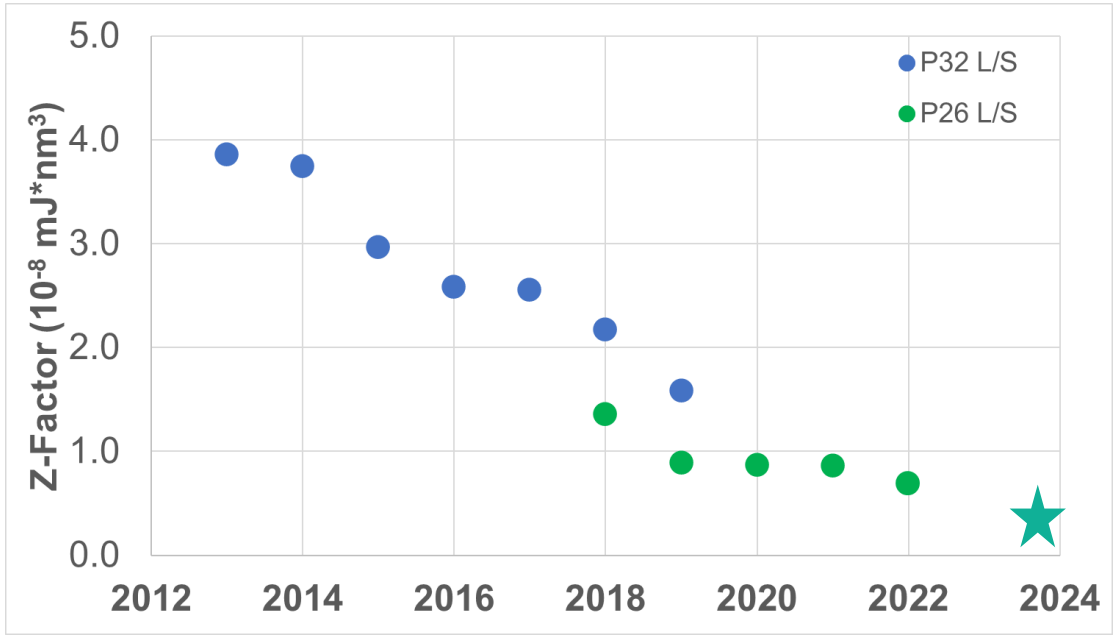
Summary and outlook

Dry resist patterning performance continues to improve at scaled pitch.

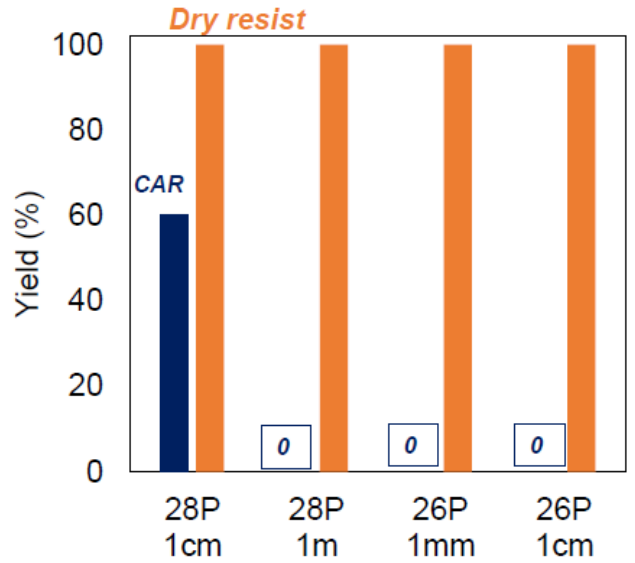
Key to its progress lies in co-optimization of underlayer, post exposure bake, and dry-development processes

Test vehicles are developed through strategic engagements to enhance dry resist development activities

Dry resist is ready for high NA EUV!







Acknowledgments

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imec

ASML

IBM

LAM RESEARCH

Thank You!



