SRC Industry-led Talk

Material and Patterning Innovation: The Foundation for Moore's Law Extension

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EUV Lithography and Novel Materials Research Group

Intel Corporation | Technology Development | Components Research

Hillsboro, OR

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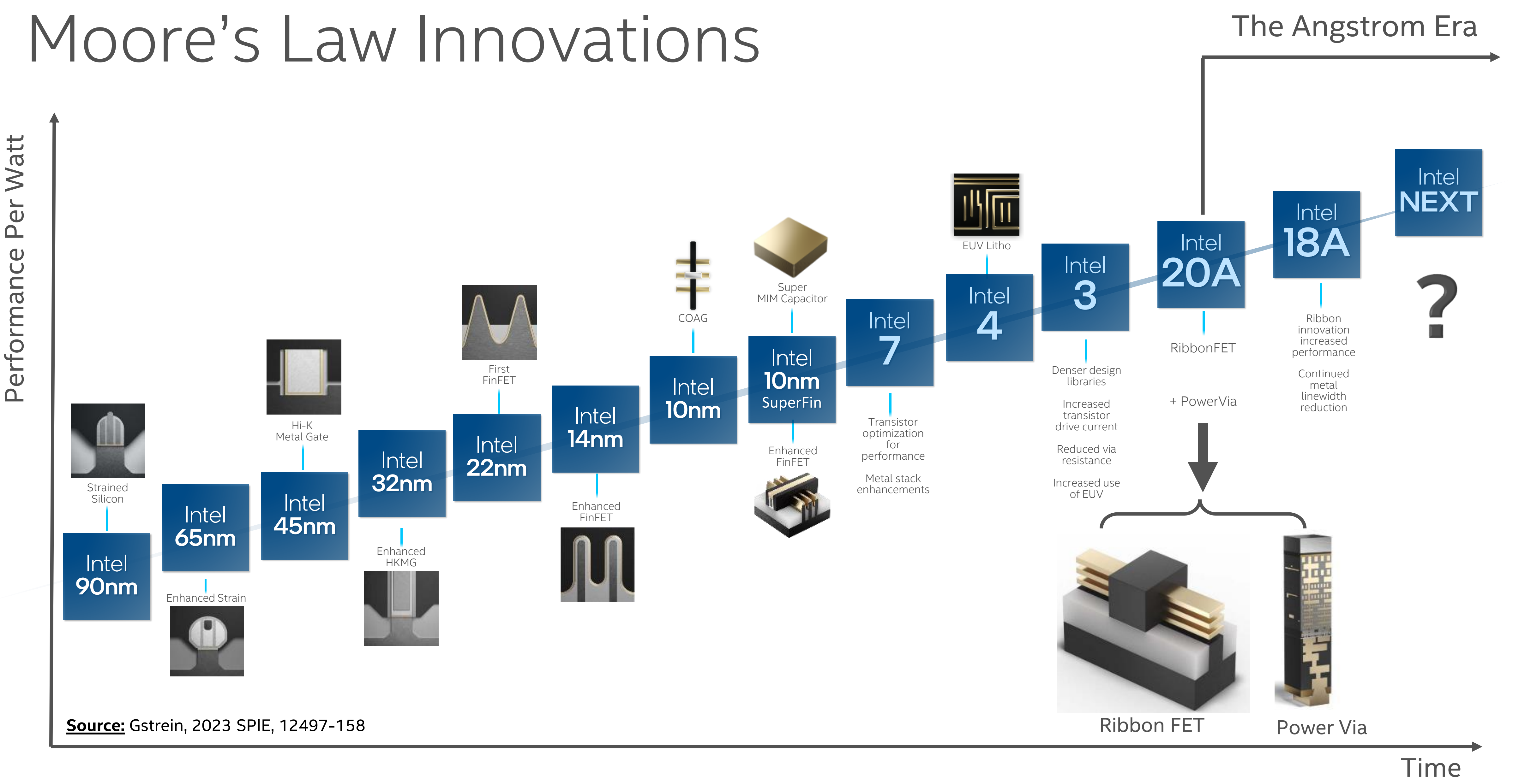
- Our research consortia and university partners

Moore's Law Innovations



Source: Gstrein, 2023 SPIE, 12497-158

Outline

- Cell Size Scaling Trends
  - Importance of Continued Pitch Scaling
- Materials and Patterning Innovations
  - Process variation and Edge Placement Error (EPE)
  - Mitigation of Variation through Novel Resists
  - Mitigation of Variations through Directed-Self Assembly
- Next Gen Materials for Continued Pitch Scaling
- Conclusions and Outlook

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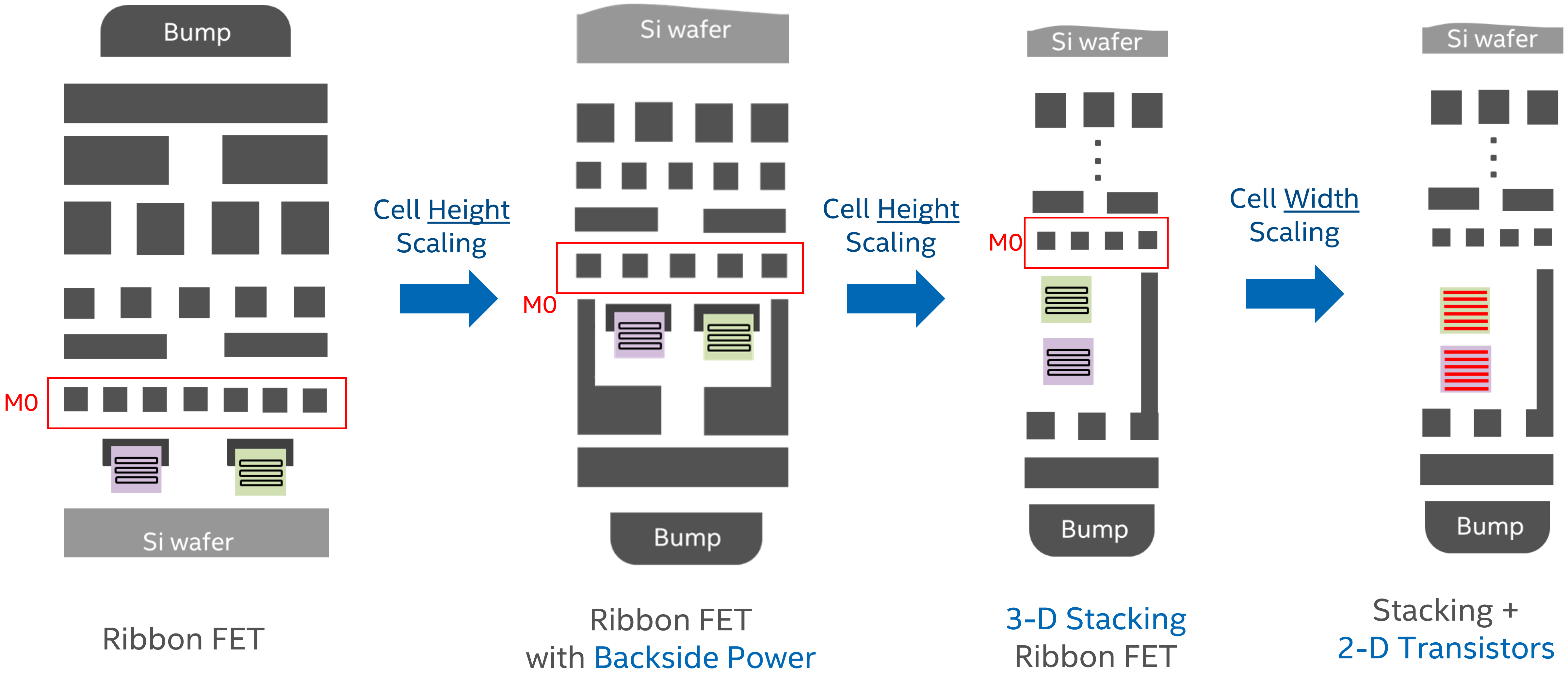
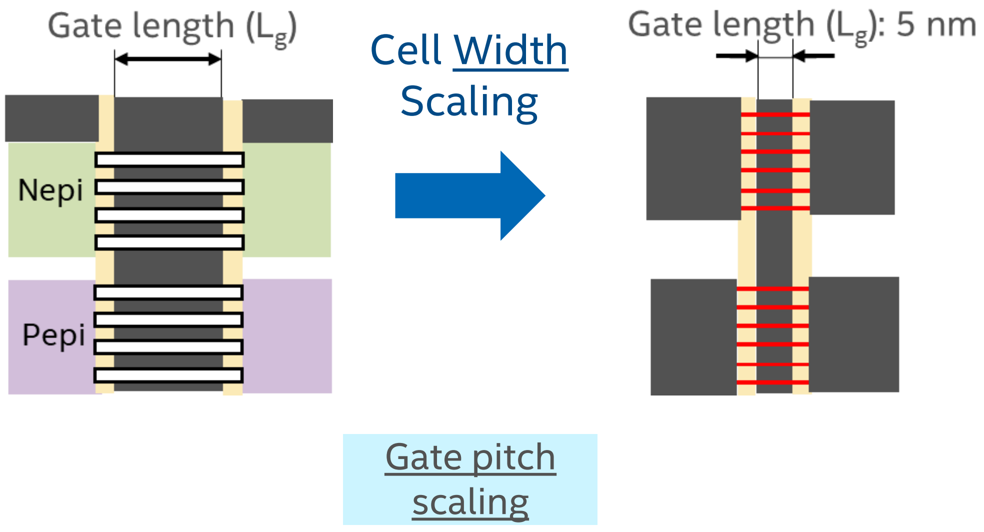
Paradigm Shifts in Cell Size Scaling



Source: 2023 VLSI Papers: W. Hafez and M. Kobrinsky; Gstrein, 2023 SPIE, 12497-158

Paradigm Shifts in Cell Size Scaling

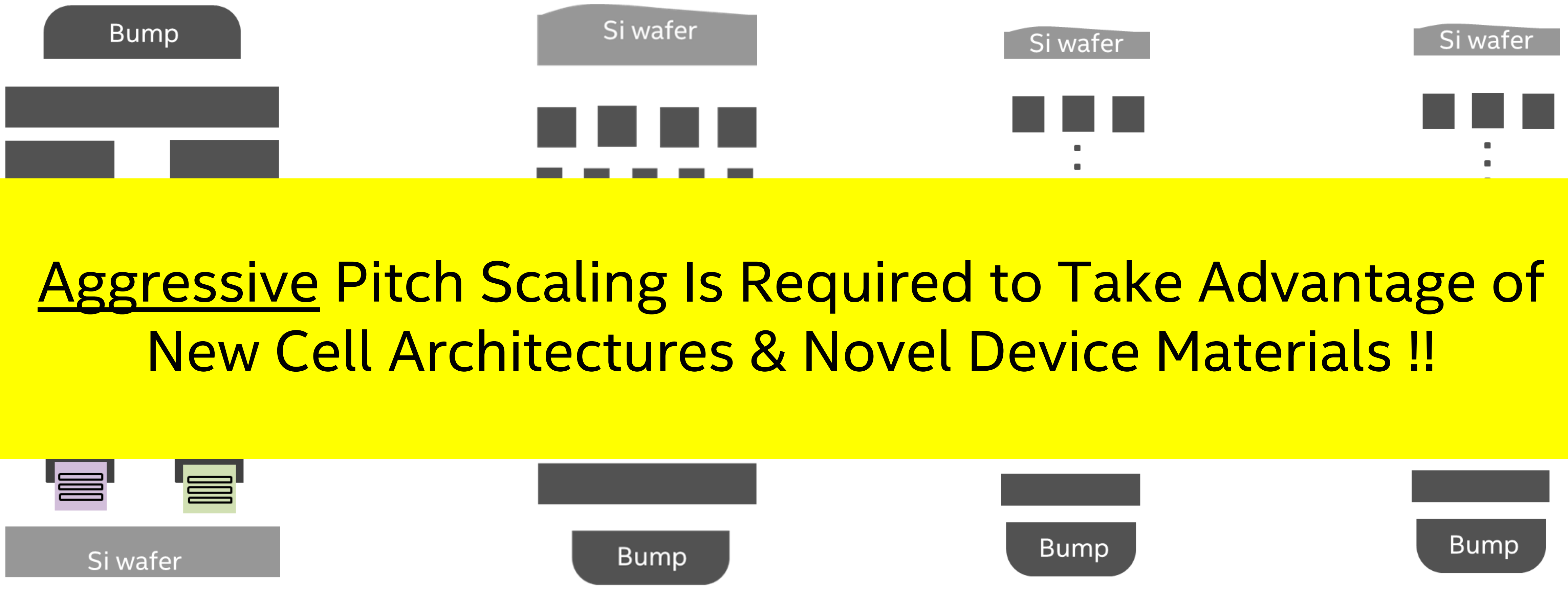


3-D Stacking
Ribbon FET

3-D Stacking +
2-D Transistors

Source: Gstrein, 2023 SPIE, 12497-158

Paradigm Shifts in Cell Size Scaling



<u>Aggressive</u> Pitch Scaling Is Required to Take Advantage of New Cell Architectures & Novel Device Materials !!

Ribbon FET

Ribbon FET
with Backside Power

3-D Stacking
Ribbon FET

Stacking +
2-D Transistors

<u>Source:</u> 2023 VLSI Papers: W. Hafez and M. Kobrinsky; Gstrein, 2023 SPIE, 12497-158

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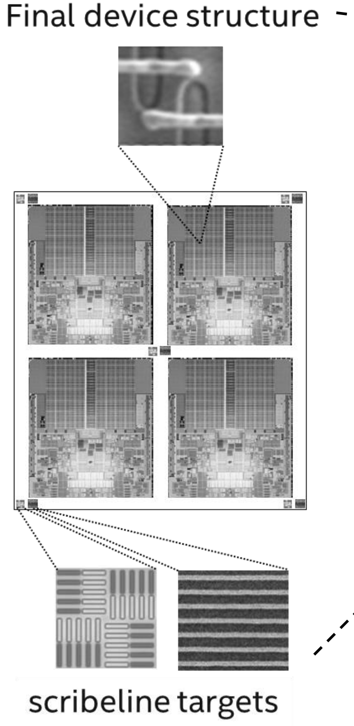
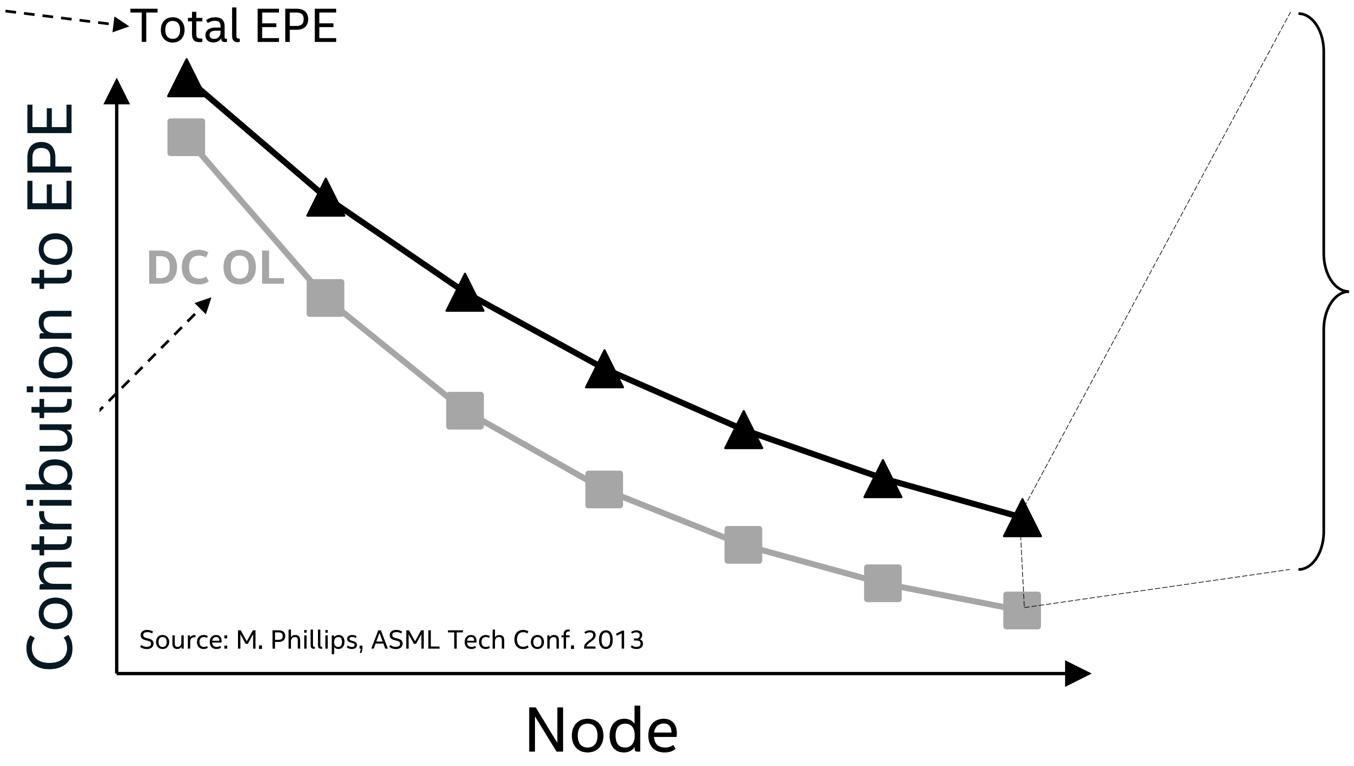
Process Variations → Edge Placement Error

Things that should touch, must. Things that shouldn't touch, can't.





EPE Contributors

- Stochastics
- Wafer bow/flatness
- Reticle error
- OPC modeling error
- Scribeline vs. device Δ*
- Etch
- Delay sensitivity – CD shifts
- Multipass patterning

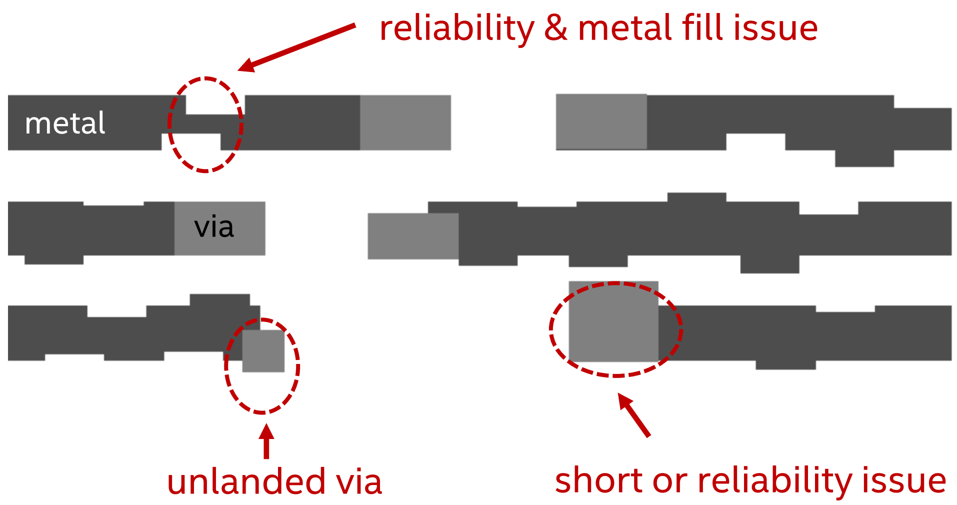
Source:
M. Phillips, ASML Tech Conf. 2013
Gstrein, 2023 SPIE, 12497-158

Scaling Strategies

Target Structure

Source: Gstrein et al., ICPST-39, Invited Paper 2A501, **2022**

Variability Risk



Metal and via size variability is driven by photon shot noise & chemical resist noise

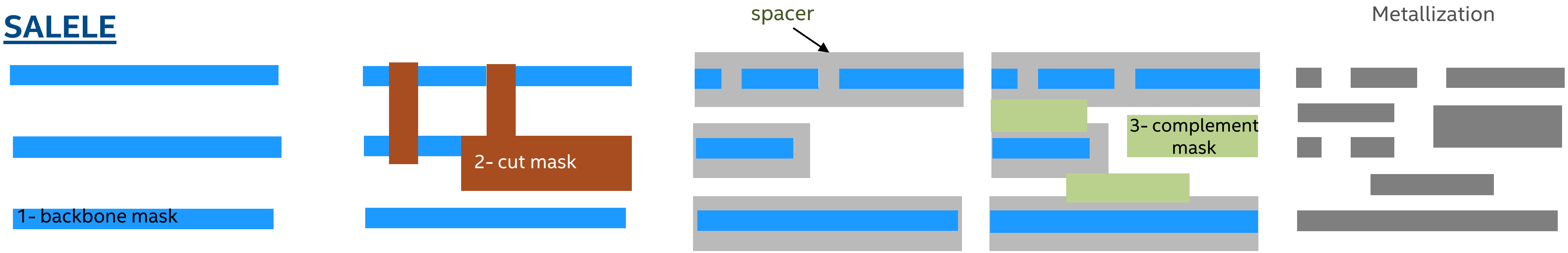
Source: Gstrein, 2023 SPIE, 12497-158

Scaling Strategies

Direct EUV

	Direct EUV	SALELE
Advantages	Efficient & cost effective	• Scalable • Backbone rectification at tight pitch using DSA (DSA-SALELE @ p18)
Technology Requirements	Requires high-NA EUV and novel resist materials <p30	Multiple masks

SALELE



Source: Gurpreet Singh, SPIE2023 12497-29

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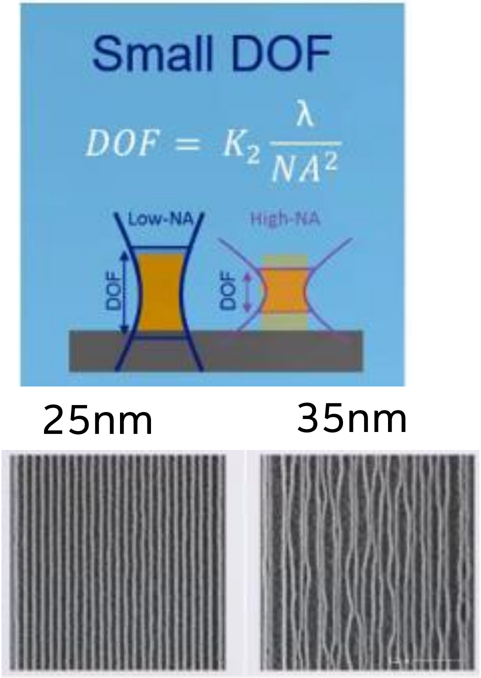
Pitch Scaling with High-NA EUV

Source: Gstrein et al., ICPST-39, Invited Paper 2A501, 2022
Krysak, Regional Innovation Engine Workshop, Invited talk, 2023

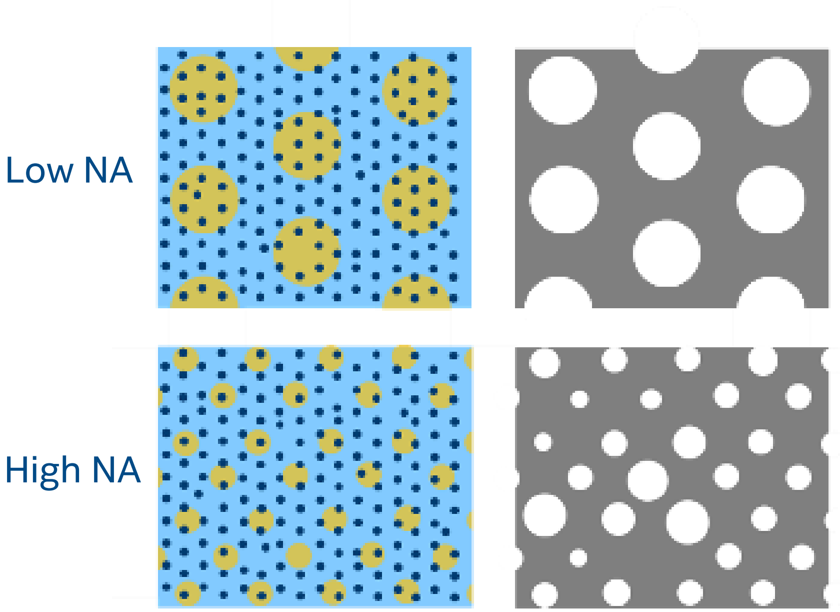
Low NA = 0.33
High NA = 0.55



Source: ASML

Lower depth of focus (DOF) requires thinner resists

Can resist be etch transferred?



We print more & smaller features with high NA

Can we manage stochastics?

Step 1

Resist Synthesis & Formulation

Step 2

On wafer chemical resist characterization

Step 3

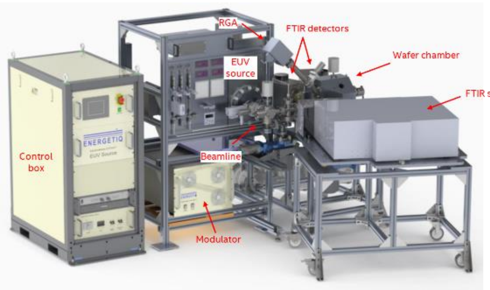
Stochastic Resist Benchmarking

Today: at limit of NXE (0.33 NA)

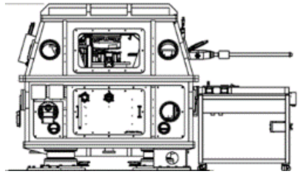
Step 4

Ultimate Resolution Testing

Today: B-MET (0.5 NA)



Advanced Resist Analytics



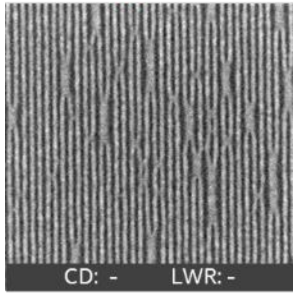
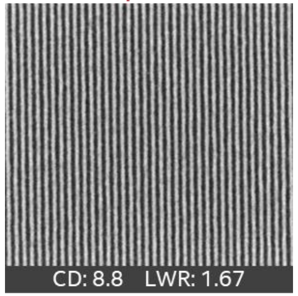
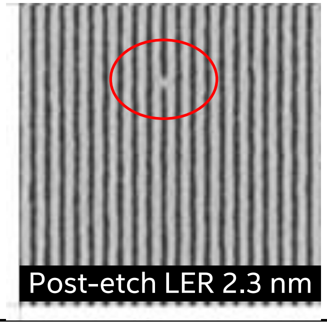
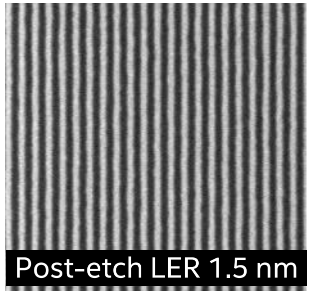
B-MET (0.5 NA)

EUV scanners

Source: Gstrein et al., ICPST-39, Invited Paper 2A501, 2022
Krysak, Regional Innovation Engine Workshop, Invited talk, 2023

Source: Gstrein et al., ICPST-39, Invited Paper 2A501, 2022
Marie Krysak, RIE Workshop, Invited talk, 2023

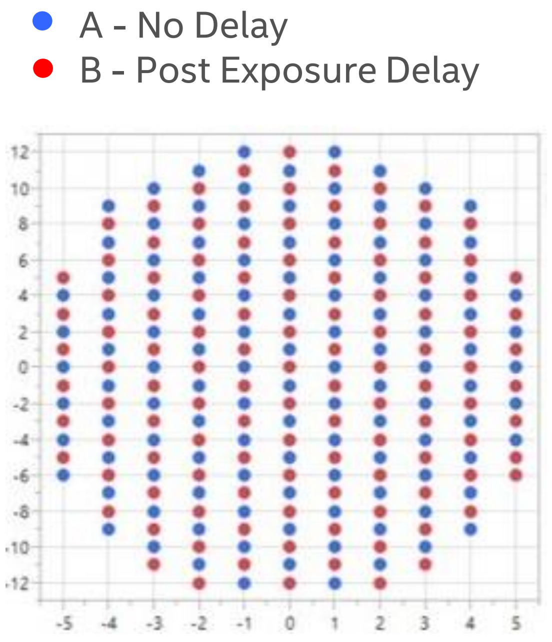
Direct EUV: CARs vs. Metal Oxide Resists (MOx)

0.5 NA MET	Chemically Amplified Resists	0.5 NA MET	MOx Resist Platforms
18 pitch 	• Insufficient contrast • Etch transfer risk • Pattern collapse	*18 pitch* 	• Excellent resolution • High etch resistance • Can be dry developed
0.33 NA scanner	**Chemically Amplified Resists**	**0.33 NA scanner**	**MOx Resist Platforms**
26 pitch 	• High defect levels @ p26 (0.33 NA)	*26 pitch* 	• Lower defect levels @ p26 (0.33 NA) at lower dose than CARs • Sensitive to atmosphere exposure

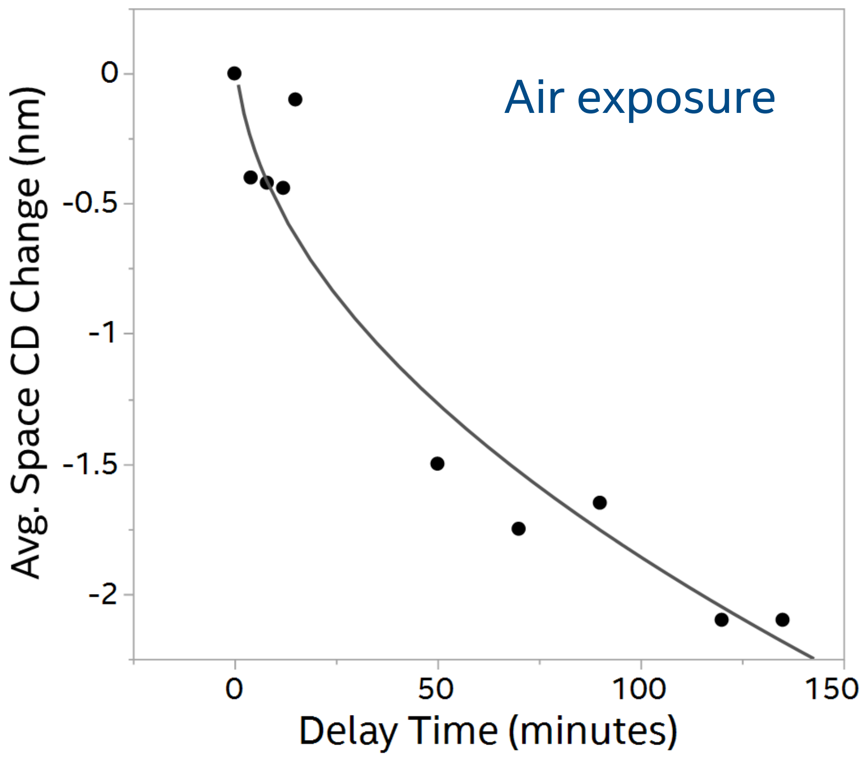
Chemically Amplified Resists need attention
Metal Oxides impress with performance, but are sensitive to air exposure

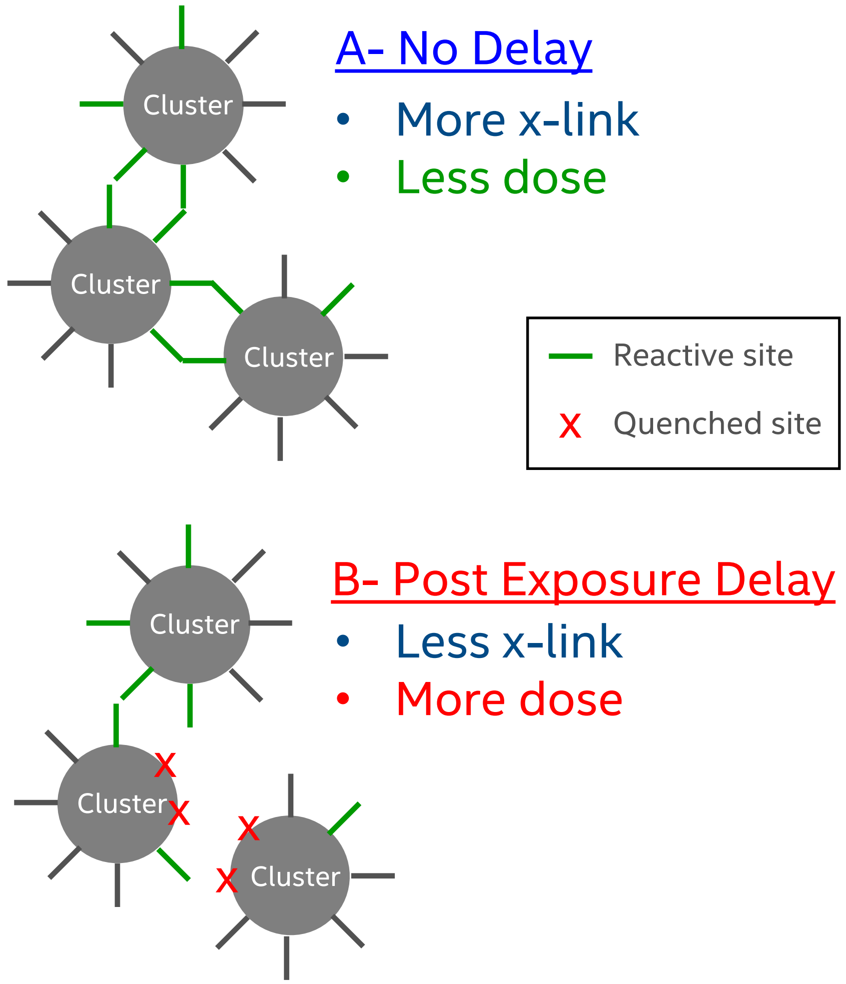
Contact: Tayseer Mahdi <tayseer.mahdi@intel.com>

Delay Sensitivity of Metal Oxide Resist Platforms



High-NA A/B "reticle swap"





A- No Delay
- More x-link
- Less dose

B- Post Exposure Delay
- Less x-link
- More dose

Source: Gstrein, 2023 SPIE, 12497-158

Air exposure can irreversibly quench reactive sites

Scaling Strategies

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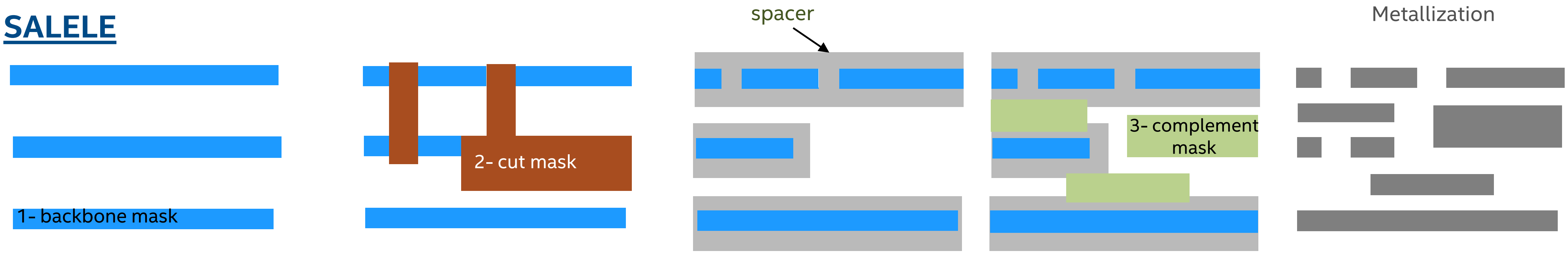
SALELE



Source: Gurpreet Singh, SPIE2023 12497-29

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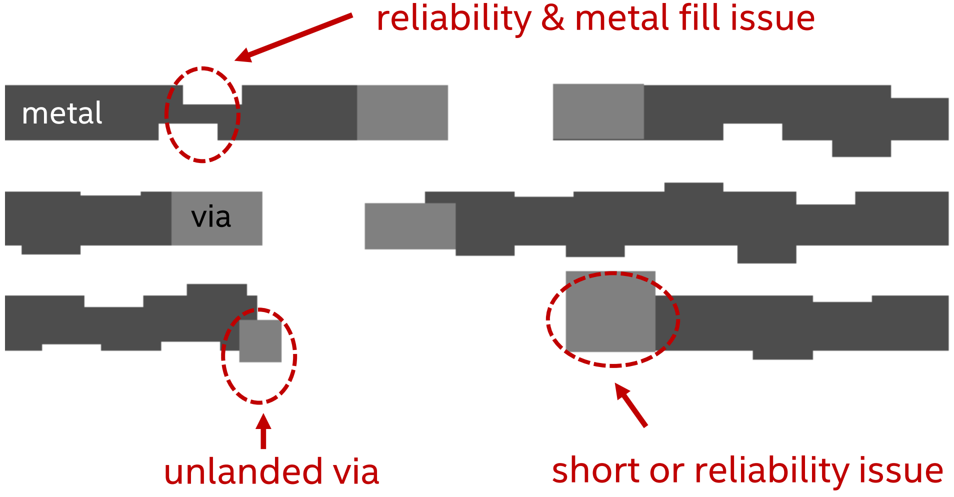
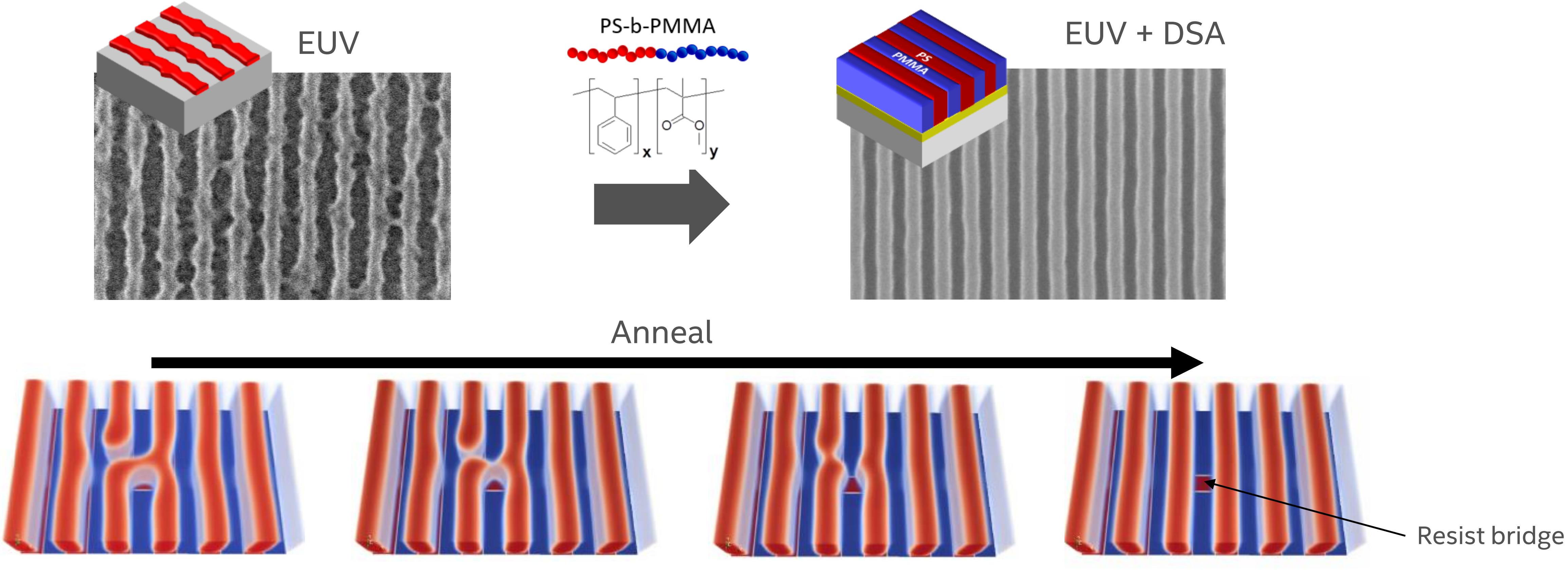


Metal and via size variability is driven by photon shot noise & chemical resist noise

DSA Line/Space Rectification

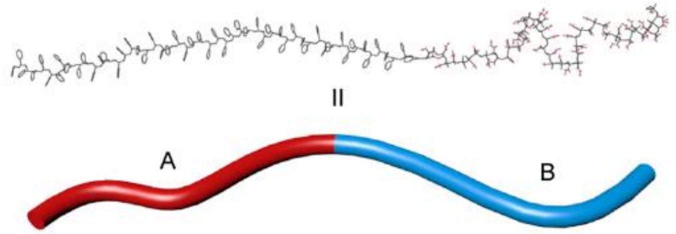


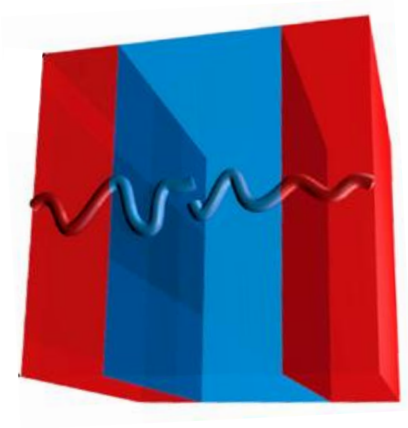
Source: Han et al., 2020 SPIE, 11326-25

DSA fundamentally improves systematic & random variability

DSA heals defects smaller than the pitch

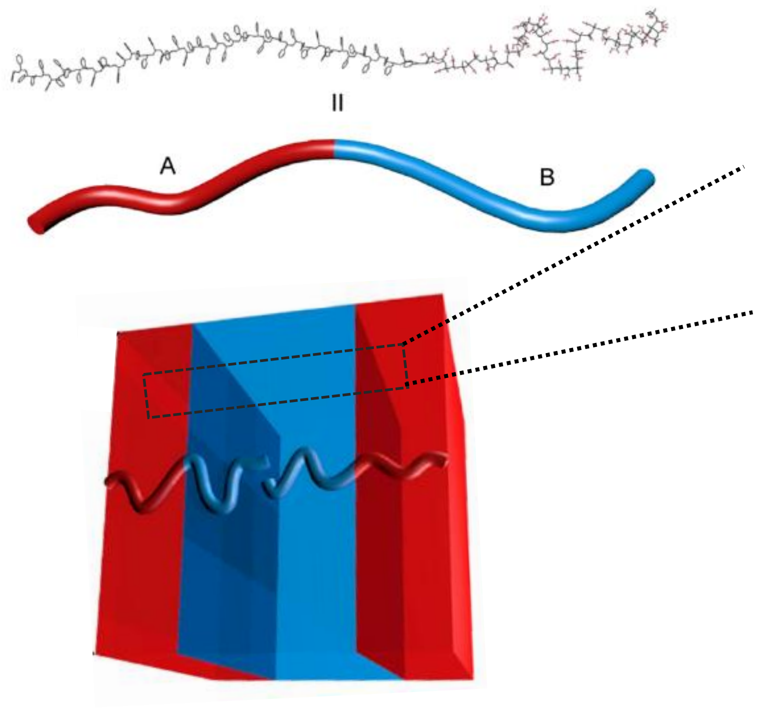
Fundamentals of DSA Rectification



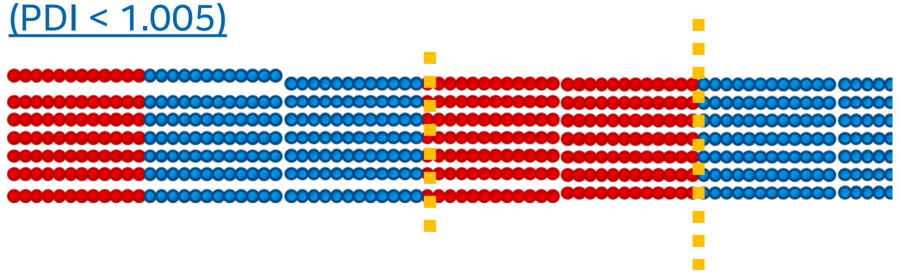


Edges are defined by thermodynamics
Not by lithography

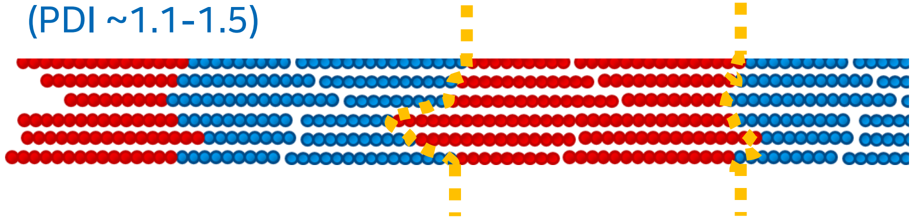
Fundamentals of DSA Rectification



Monodisperse BCP
(PDI < 1.005)



Polydisperse BCP
(PDI ~1.1-1.5)



Edges are defined by thermodynamics
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Narrow Polydispersity → low roughness

Contact: Tayseer Mahdi <tayseer.mahdi@intel.com>

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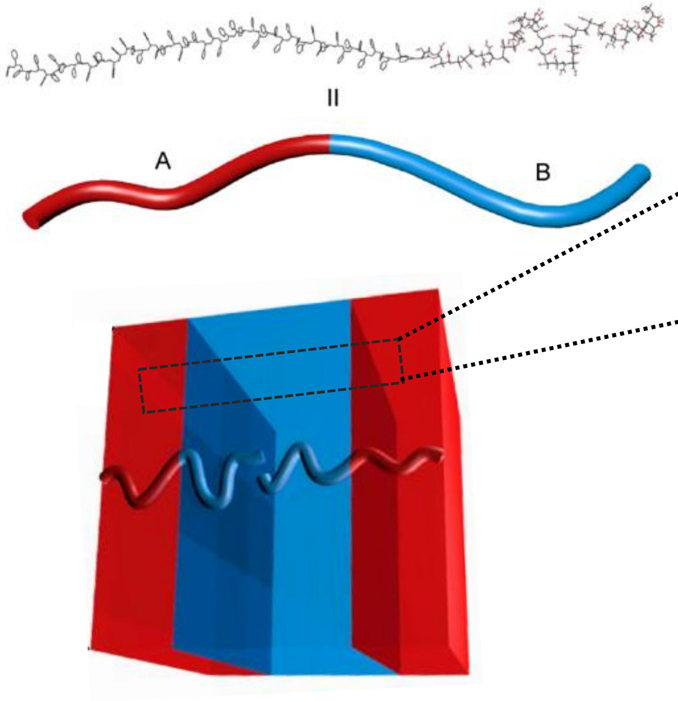

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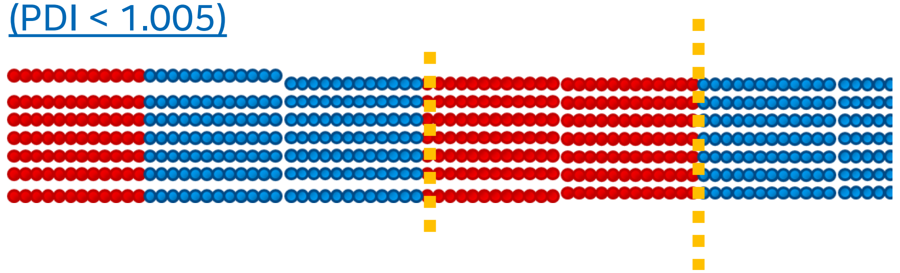

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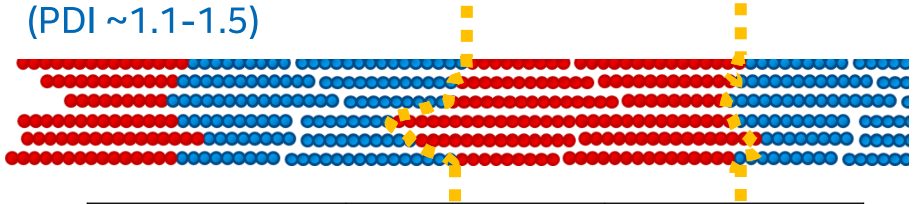

PDI	LER	LWR
1.15	4.8	4.7
+0.05	+1.0	+0.5
1.20	5.8	5.2
+0.04	+0.4	+0.7
1.24	6.2	5.9

Source: Lai et al., 2022 Polymer, Vol 249, 124853

Edges are defined by thermodynamics
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Narrow Polydispersity → low roughness

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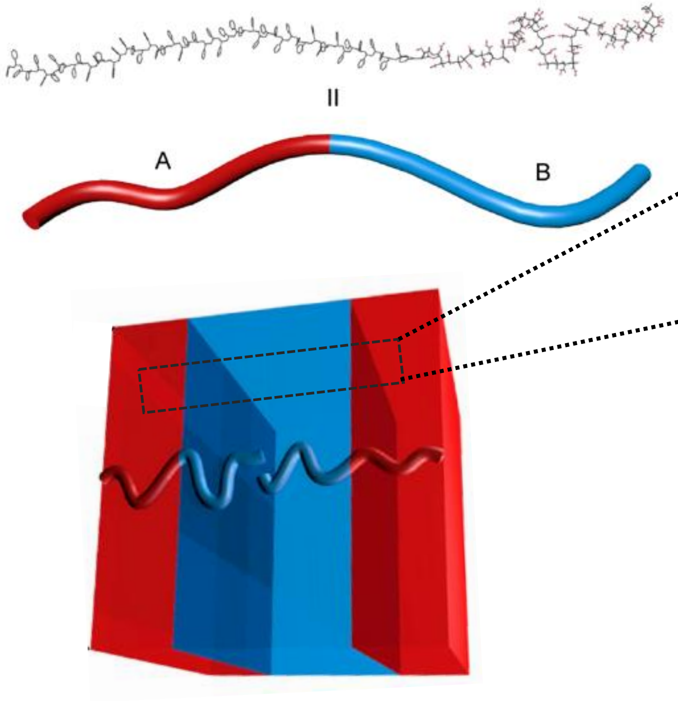

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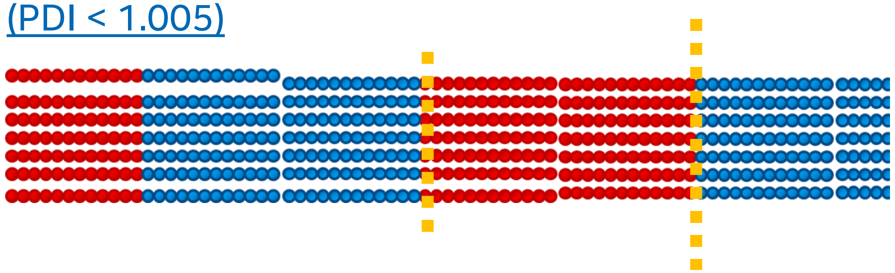

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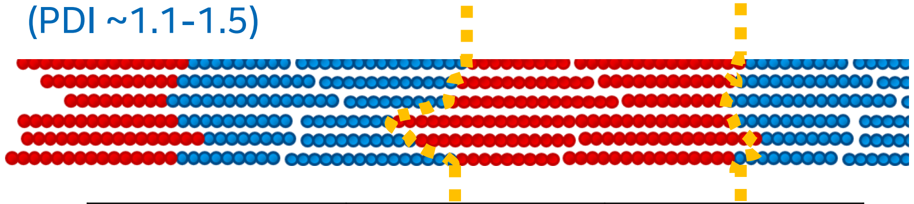

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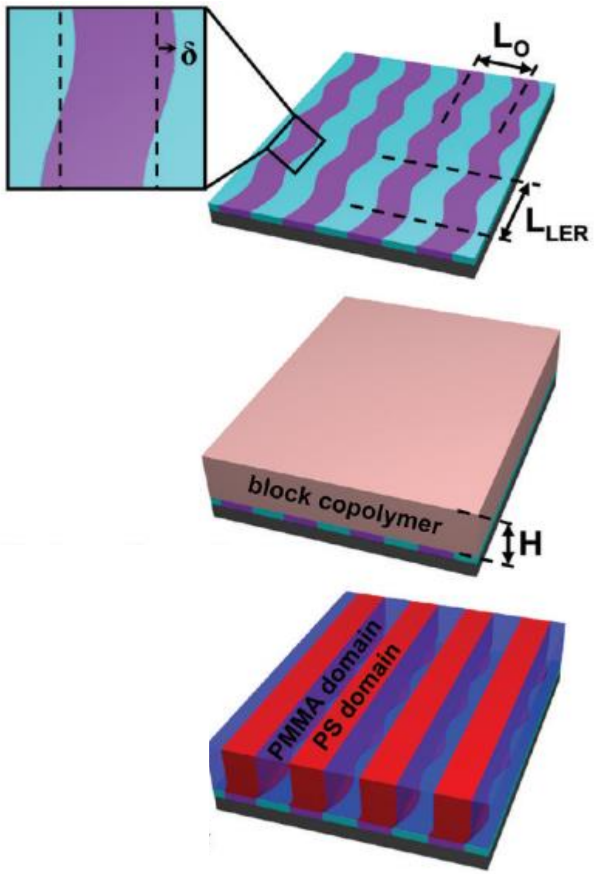


Source: Stoykovich et al., 2010 Macromolecules 2334

Edges are defined by thermodynamics
Not by lithography

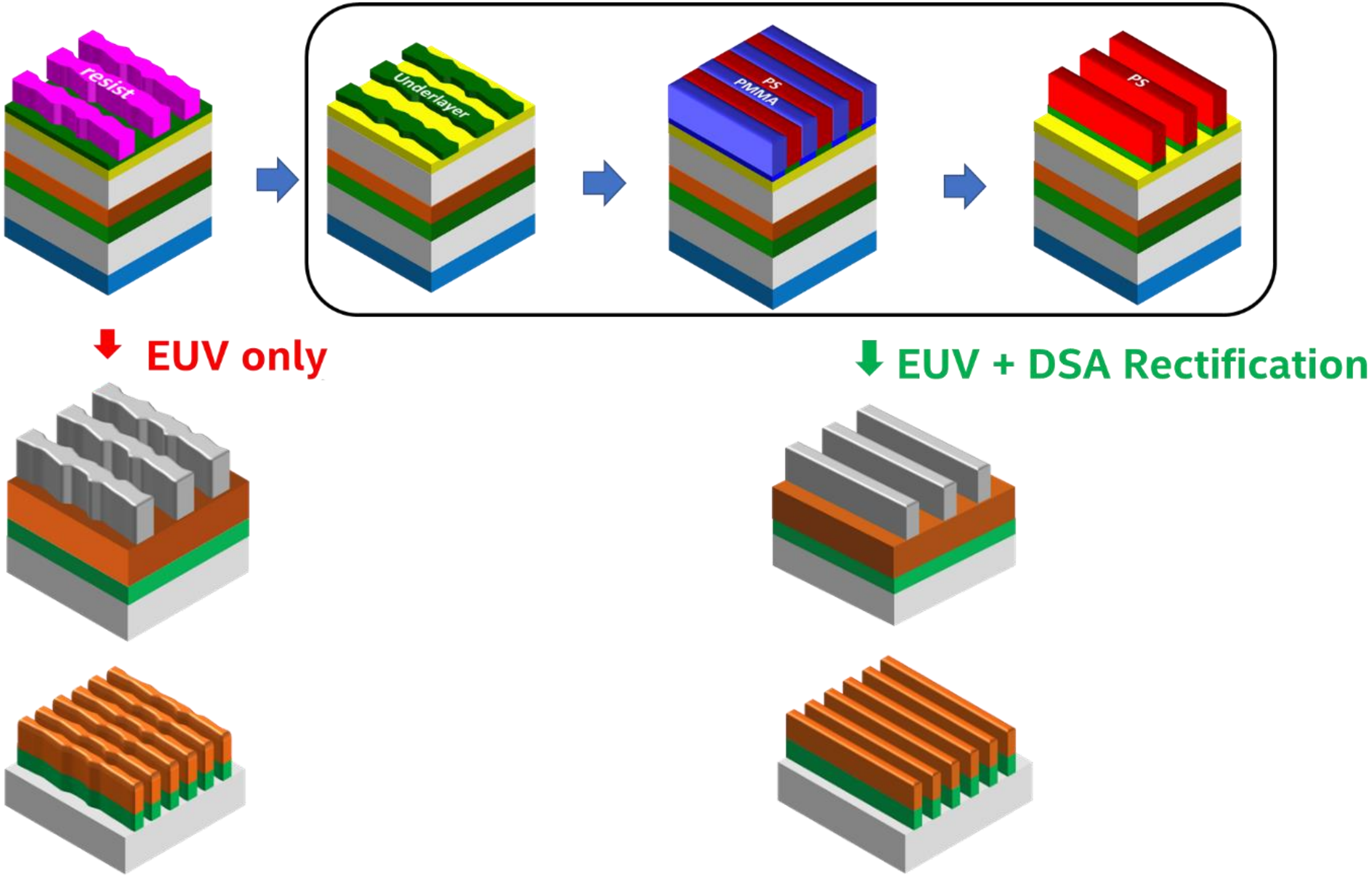
Narrow Polydispersity → low roughness

Guide pattern roughness decays rapidly

Contact: Tayseer Mahdi <tayseer.mahdi@intel.com>

Source: Singh et al., 2022 SPIE, 12054-6

DSA Rectification + Pitch Division

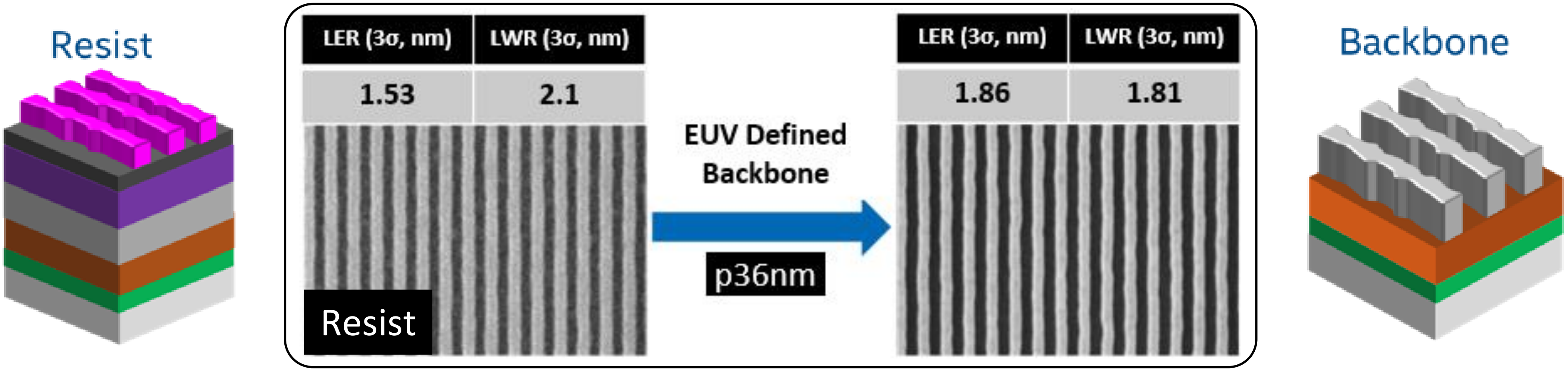


Backbone

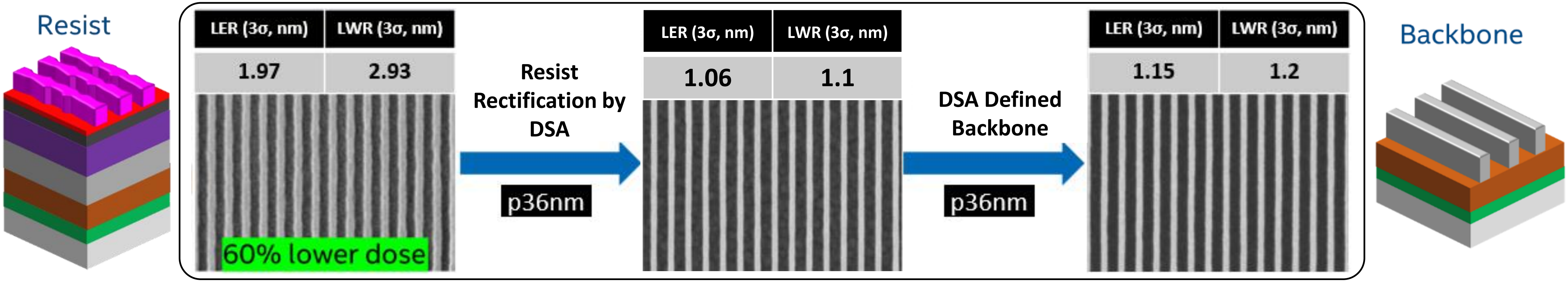
Pitch Division

Addressing variability tails with DSA

Source: Gurpreet Singh, SPIE2023 12497-29



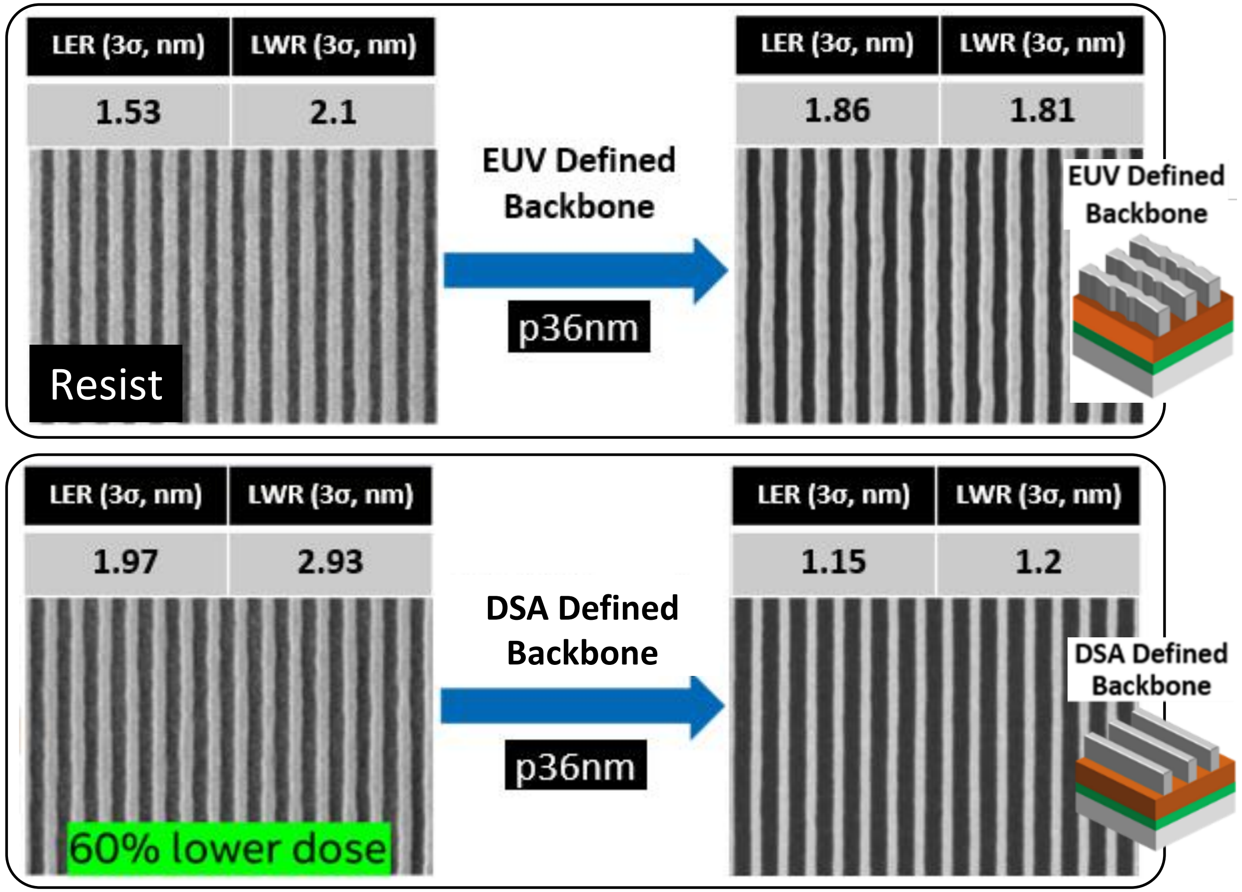
Conventional Flow

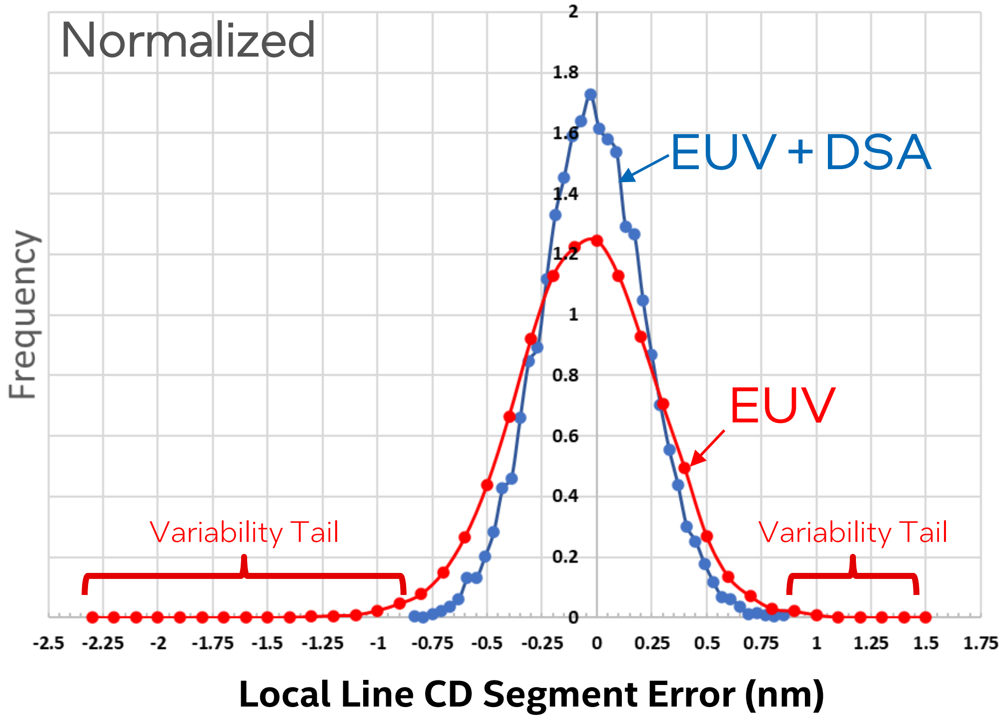


DSA based EUV Rectification Flow

Addressing variability tails with DSA

Source: Gurpreet Singh, SPIE2023 12497-29





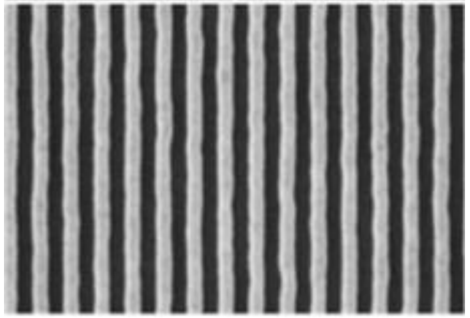
Long tails for EUV backbones largely due to EUV variability (photon noise and resist stochastics)

Variability tails are 'healed' by DSA even with significantly lower EUV dose resist

Addressing variability tails with DSA

EUV Defined Backbone

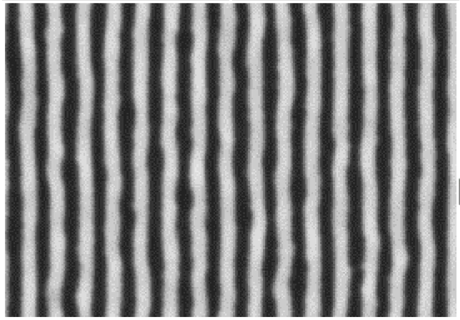
LER (3σ, nm)	LWR (3σ, nm)
1.86	1.81

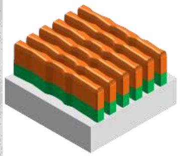


Pitch Halving

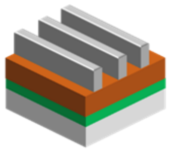
p18nm

LER (3σ, nm)	LWR (3σ, nm)
2.19	1.38

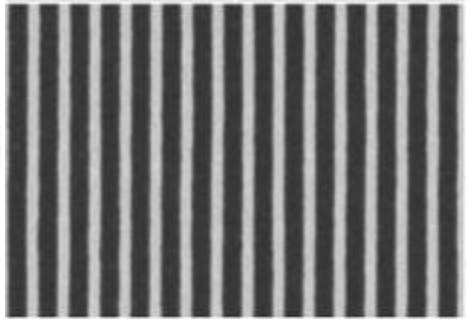




DSA Defined Backbone



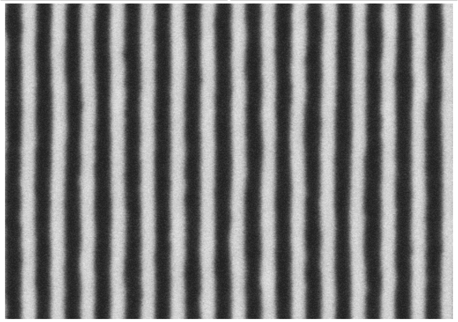
LER (3σ, nm)	LWR (3σ, nm)
1.15	1.2

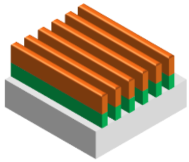


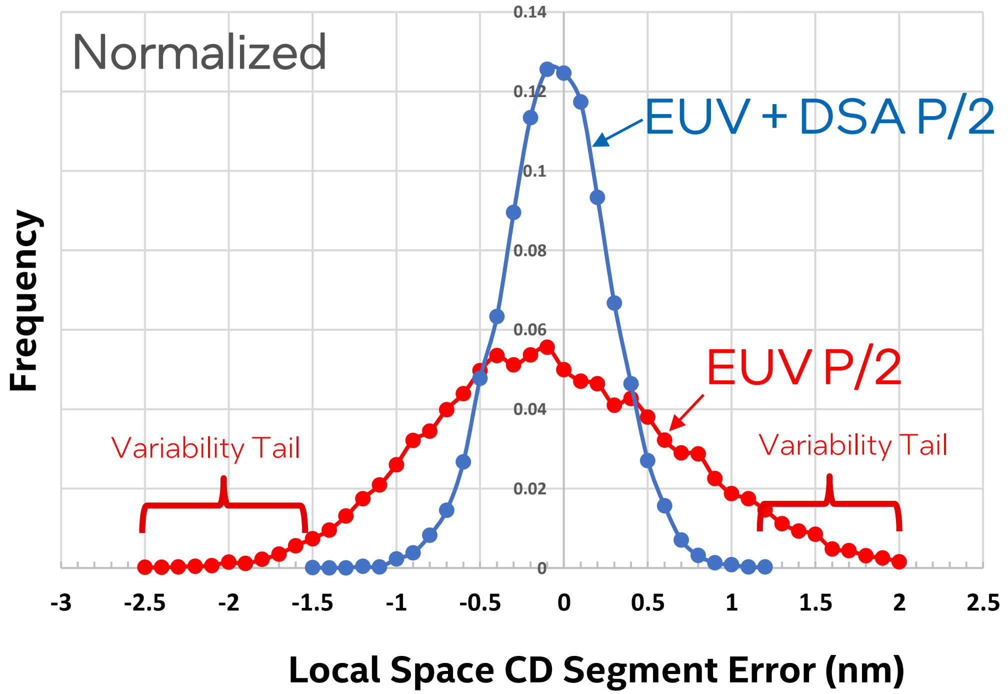
Pitch Halving

p18nm

LER (3σ, nm)	LWR (3σ, nm)
1.25	0.79





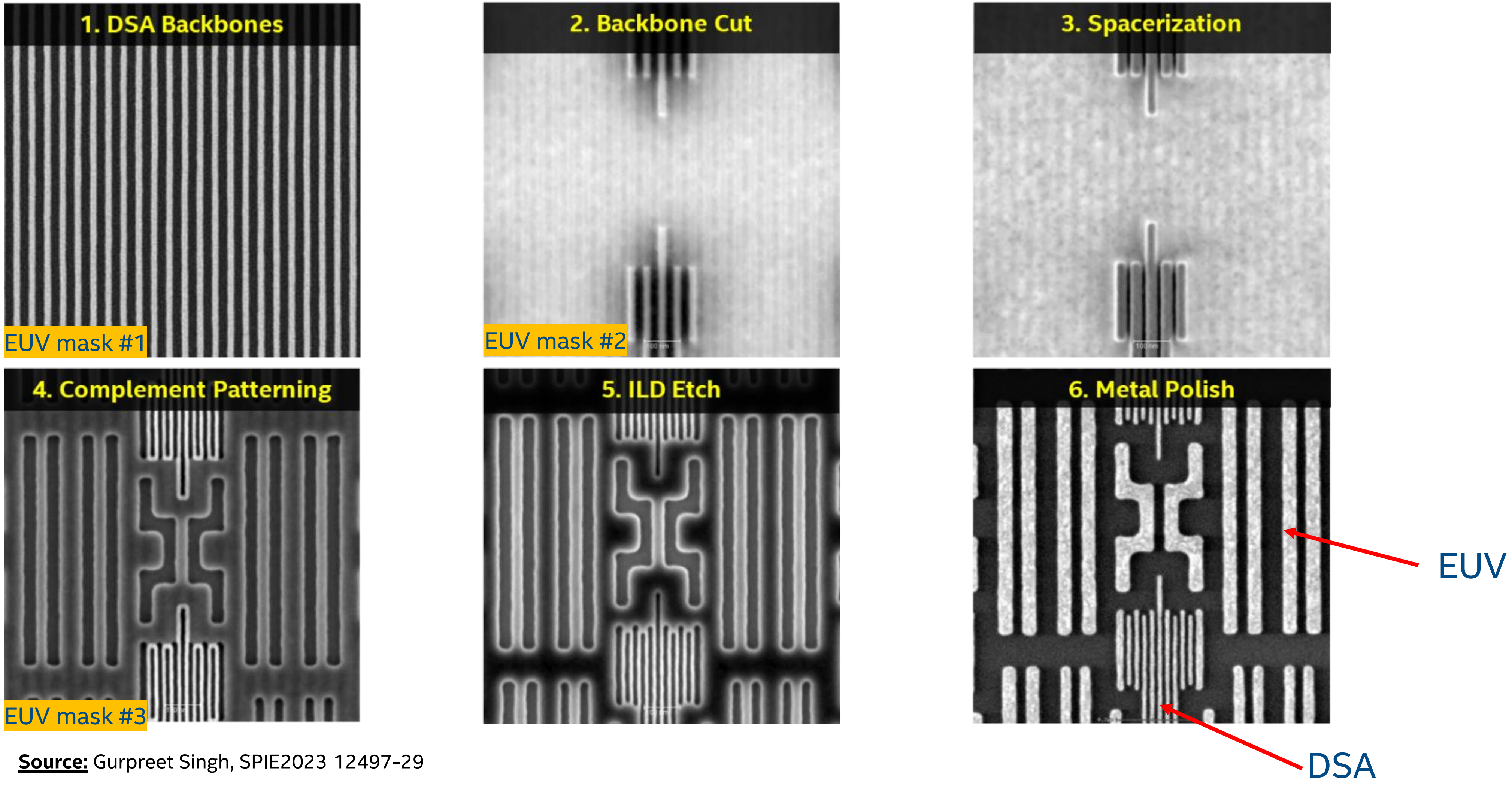


43% lower LER with DSA-EUV P/2 at p18nm

Significant reduction of variability tails

Source: Gurpreet Singh, SPIE2023 12497-29

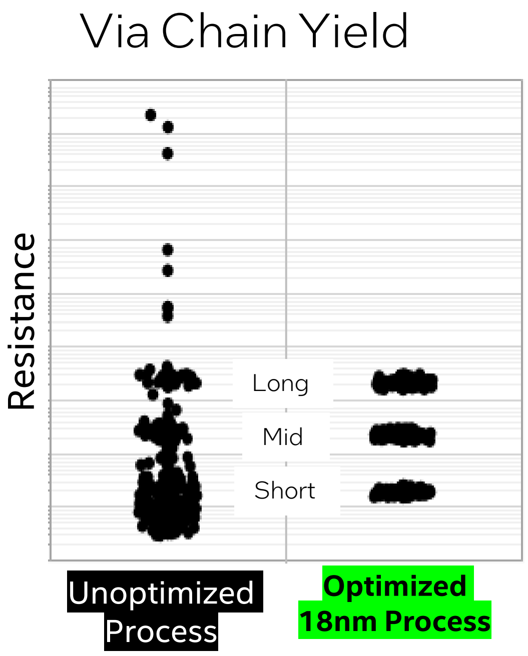
DSA-SALELE - Device Relevant Patterning

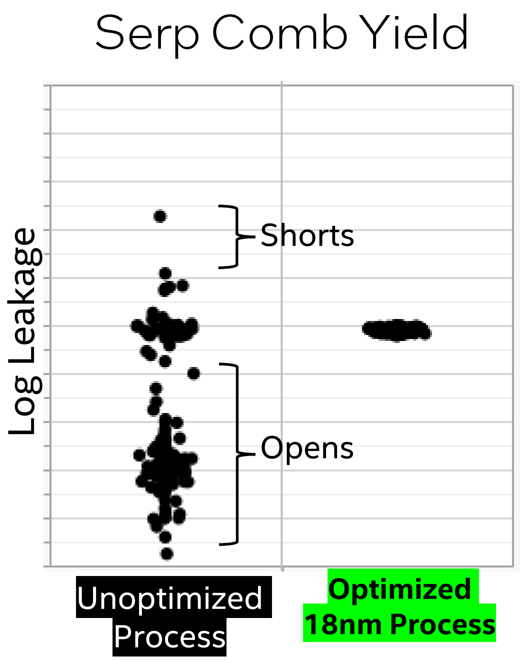


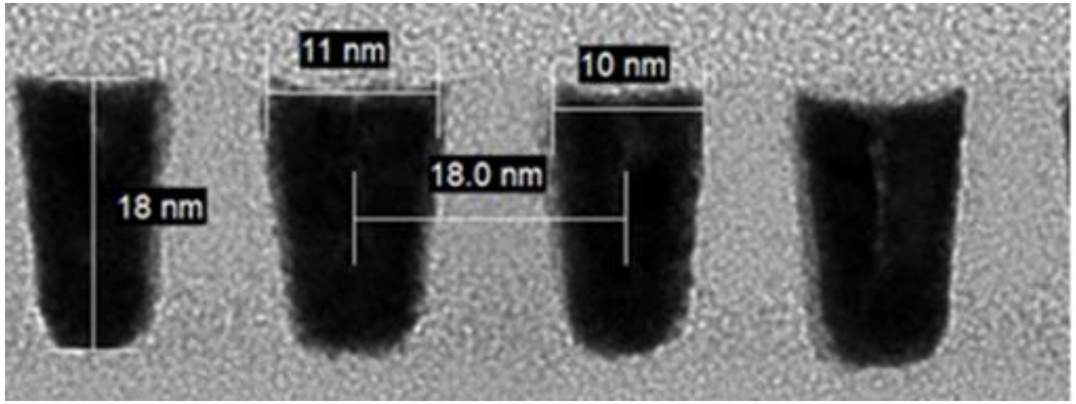
Source: Gurpreet Singh, SPIE2023 12497-29

Minimum pitch defined by DSA looser pitch defined by EUV

DSA-SALELE - 18nm Metal Pitch Electrical Yield





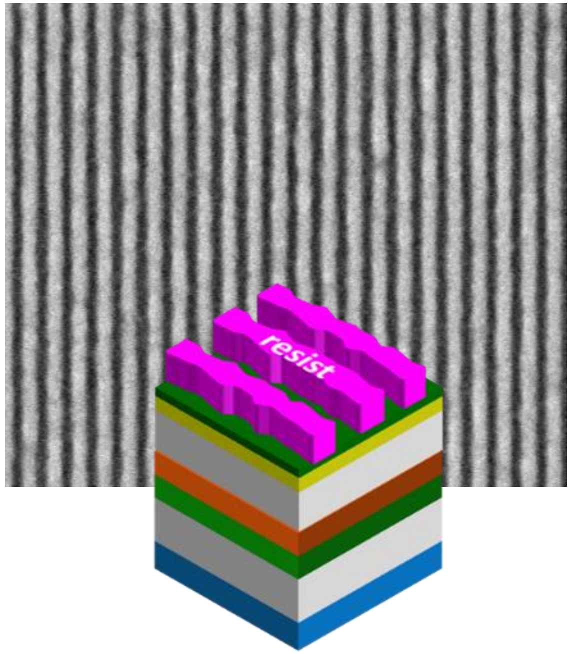


Source: Gurpreet Singh, SPIE2023 12497-29

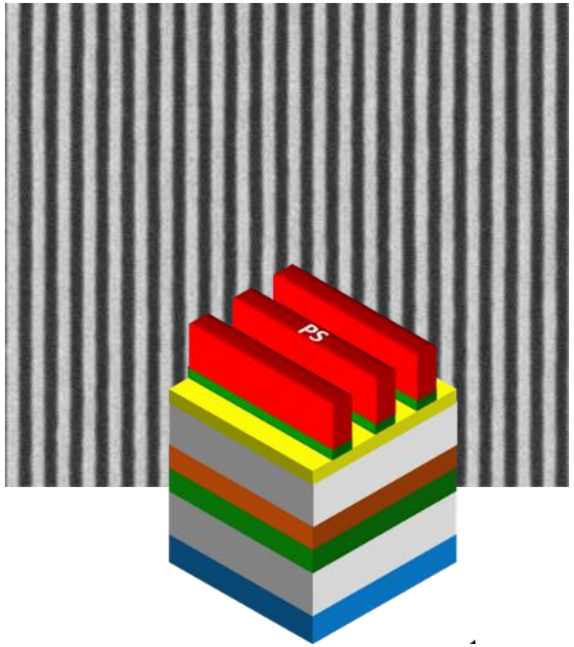
Robust electrical yield achieved at 18nm metal pitch

How far can we extend DSA-SALELE?

p24 EUV Backbone
(CAR resist, 0.33NA)



DSA Rectification



LWR=1.08
LER=1.04
SWR=1.09

To achieve device relevant patterning similar to p18, we need to optimize
- Materials
- Process
- Design rules

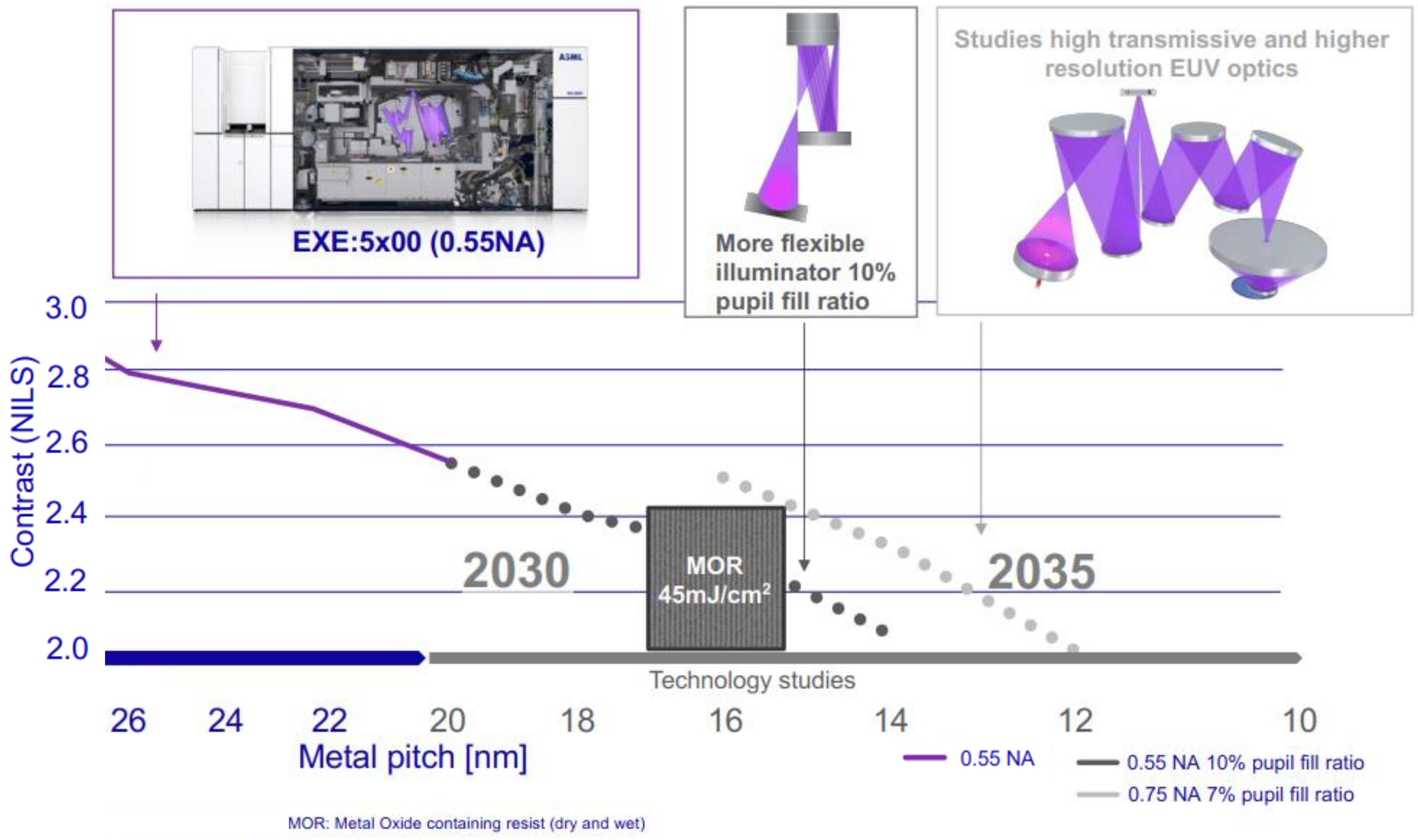
Source: Florian Gstrein, ICPST-40 A3-1-2

Healthy DSA backbones at p24 achieved for subsequent pitch-division to p12

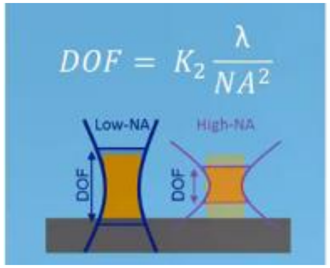
Outline

- Cell Size Scaling Trends
  - Importance of Continued Pitch Scaling
- Materials and Patterning Innovations
  - Process variation and Edge Placement Error (EPE)
  - Mitigation of Variation through Novel Resists
  - Mitigation of Variations through Directed-Self Assembly
- Next Gen Materials for Continued Pitch Scaling
- Conclusions and Outlook

What's Next – Hyper NA



- 0.75 NA will further reduce depth of focus (DOF)



- Resist thickness for line/space applications projected to be 8-12nm

➢ **<u>Need resists with higher EUV absorbance, lower stochastic variation, higher etch resistance</u>**

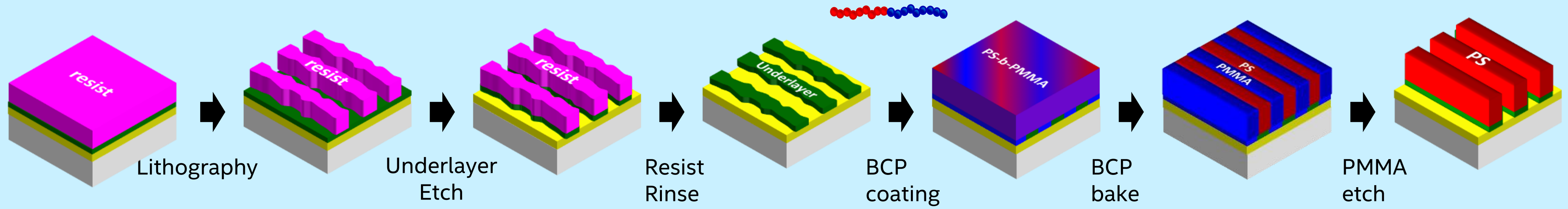
Source: Martin van den Brink, SPIE 2023 Keynote Presentation
Marie Krysak, RIE Workshop, Invited talk, 2023

GRC-NMP Research needs [GRC Research Needs – SRC]
MAPT Roadmap Chapter 4: Digital Processing [*MAPT (srcmapt.org)*]

Next Gen DSA Materials <p24

Source: Gurpreet Singh, SPIE2023 12497-29

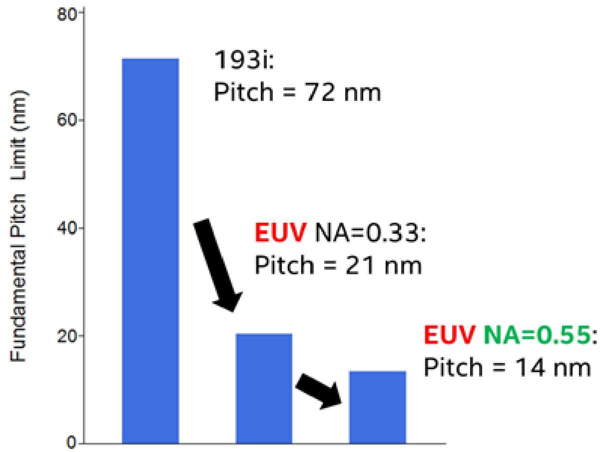
1)



High-NA requires thin resist → less budget for DSA underlayer etch

- ➢ **Require new underlayers that are thin (<5nm) with high etch selectivity to resist *(or directly patternable)***

2)



- ➢ **High chi BCPs required for ≤ p24nm rectification**
- ➢ **High chi BCPs may require novel processing options e.g. Solvent Vapor Annealing, Sequential Infiltration, etc**

GRC-NMP Research needs GRC Research Needs – SRC
MAPT Roadmap Chapter 4: Digital Processing MAPT (srcmapt.org)

Contact: Tayseer Mahdi <tayseer.mahdi@intel.com>

Conclusion and Outlook

- Future of Moore's Law is brighter than ever. Novel materials play a key role.
- Novel process architectures such as stacked transistors and novel device materials require aggressive scaling of metal and via pitches.
- Process variations at every length scale pose a risk.
- Chemically Amplified Resists need attention.
- Metal oxide resist platforms show impressive performance.
- DSA fundamentally improves systematic & random variability in resists.
- Low-variability pitch scaling with highly scalable DSA enhanced EUV p/2.

The investment in the novel material ecosystem must continue.

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