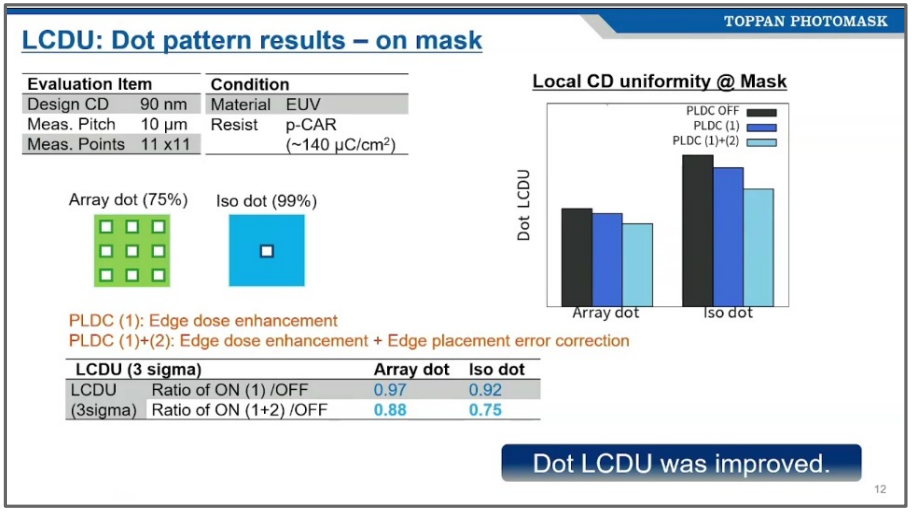
September 10th, 2026 | Abhishek Shendre, Nagesh Shirali and Aki Fujimura

Reduce PEC squishing to improve LCDU and GCDU with no impact on mask write times

Mask Uniformity is As Important As Linearity

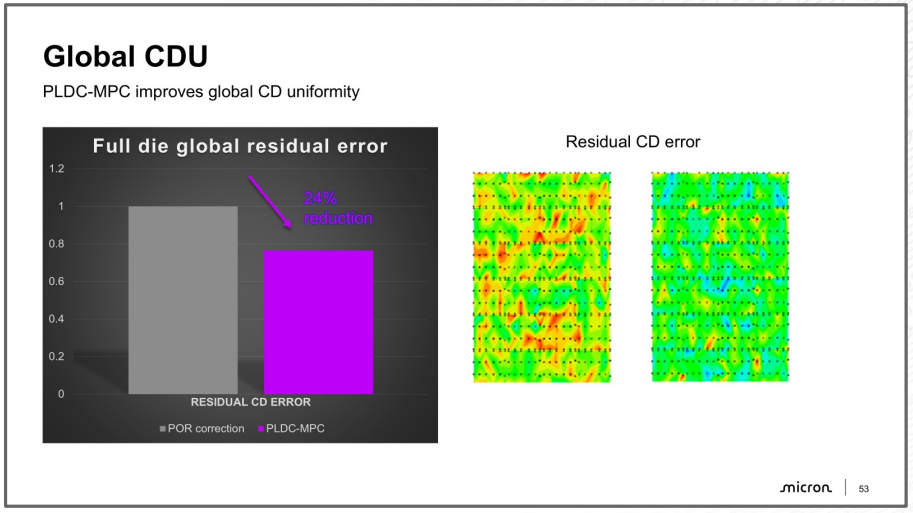
Every variation on mask is a systematic variation on wafer

BACUS 2024 by Tekscend



Mayuko Matsumoto, Naoki Yoshida, Tetsunori Hirata, et al. "Mask performance improvement by pixel level dose correction", Proc. SPIE 13216, Photomask Technology 2024, 132160H (12 Nov 2024); https://doi.org/10.1117/12.3034611

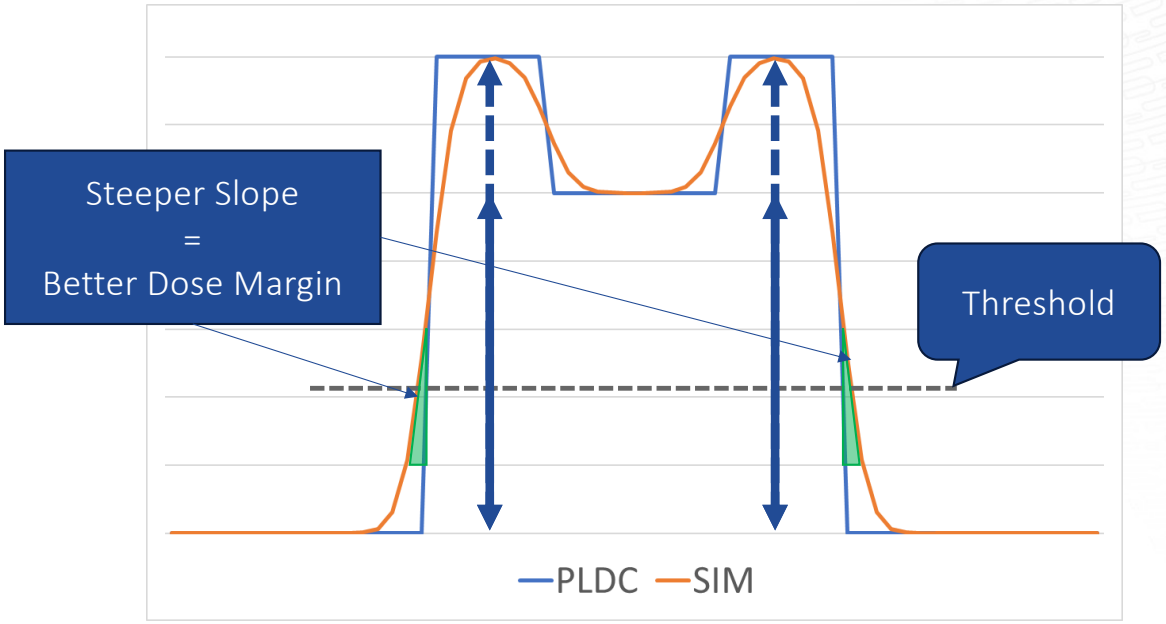
PMJ 2025 by Micron



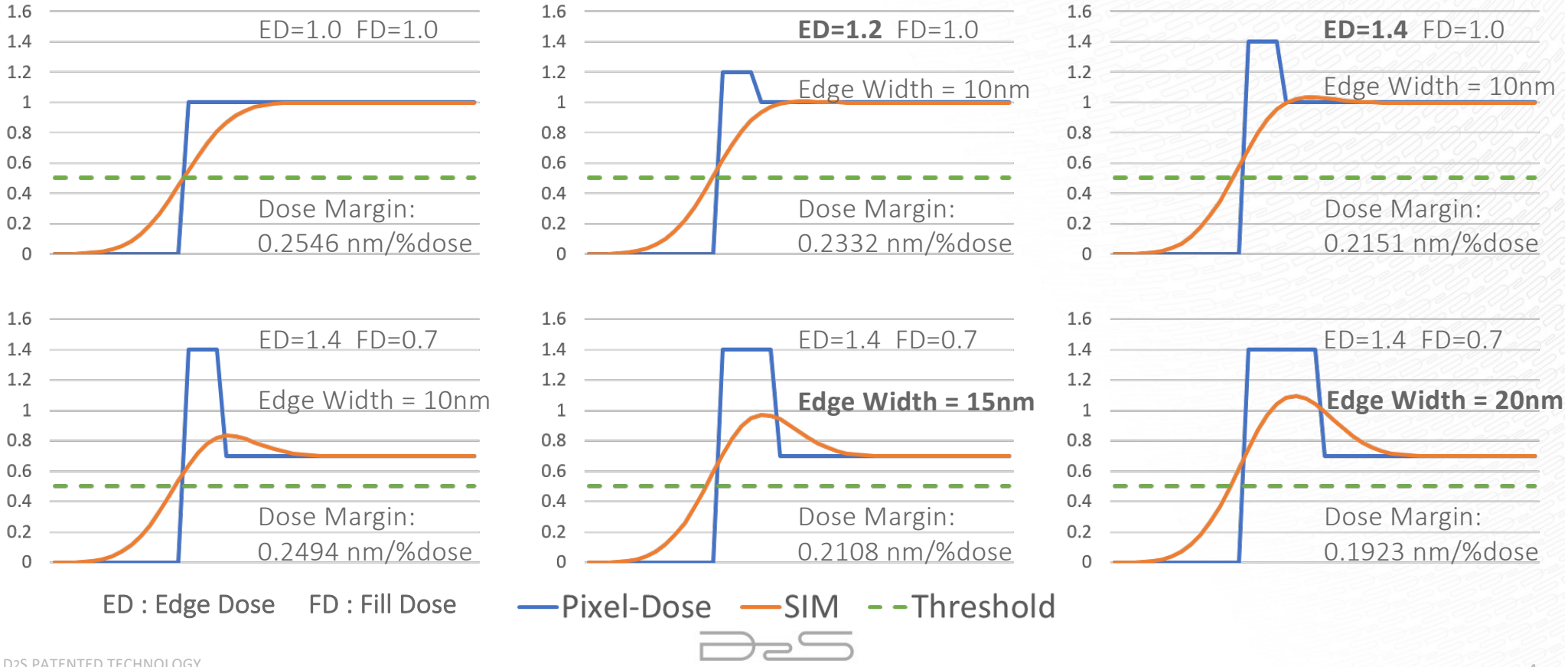
Paris Spinelli, Nagesh Shirali, Kenichi Yasui, et al. "Full reticle curvilinear inline linearity correction including variable bias with zero turnaround time", Proc. SPIE 13427, Novel Patterning Technologies 2025, 1342705 (6 May 2025); https://doi.org/10.1117/12.3051087

Edge Enhancement Improves Mask Uniformity

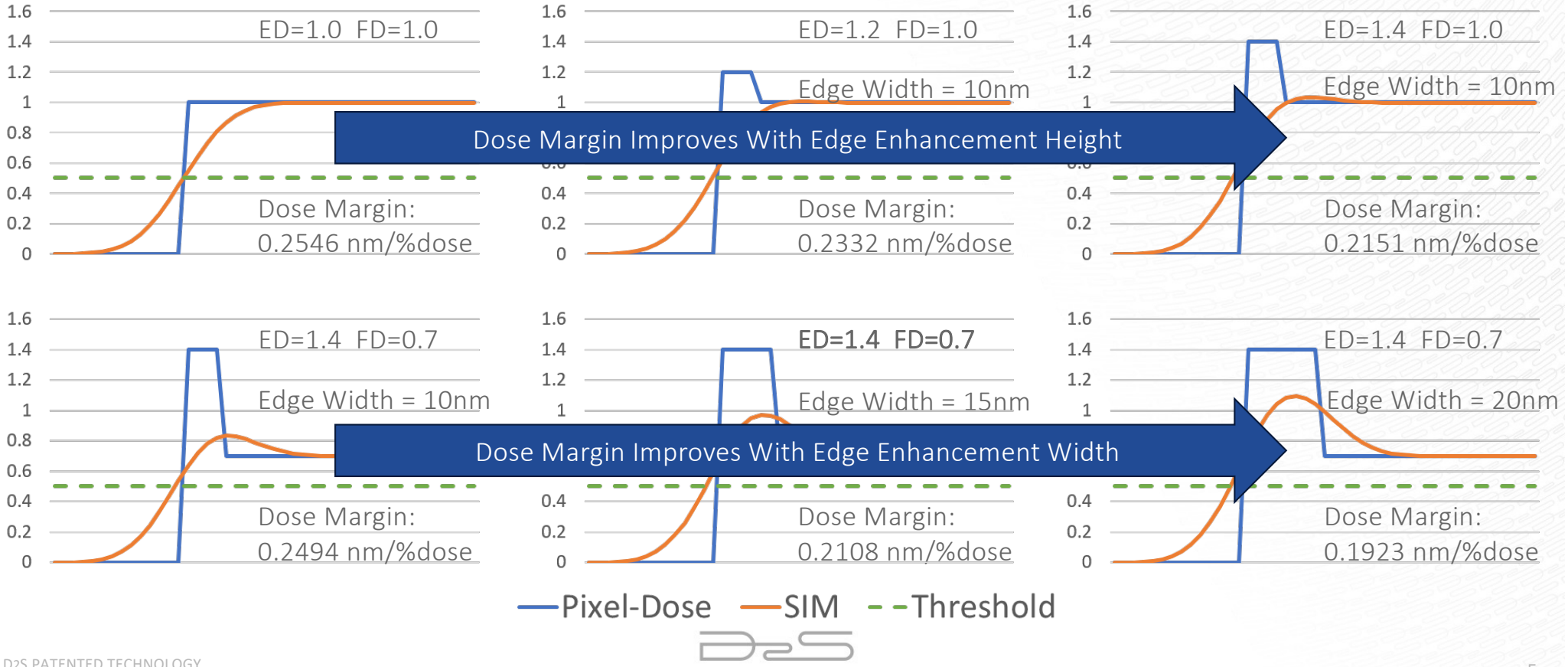
Achieved by improving dose margin



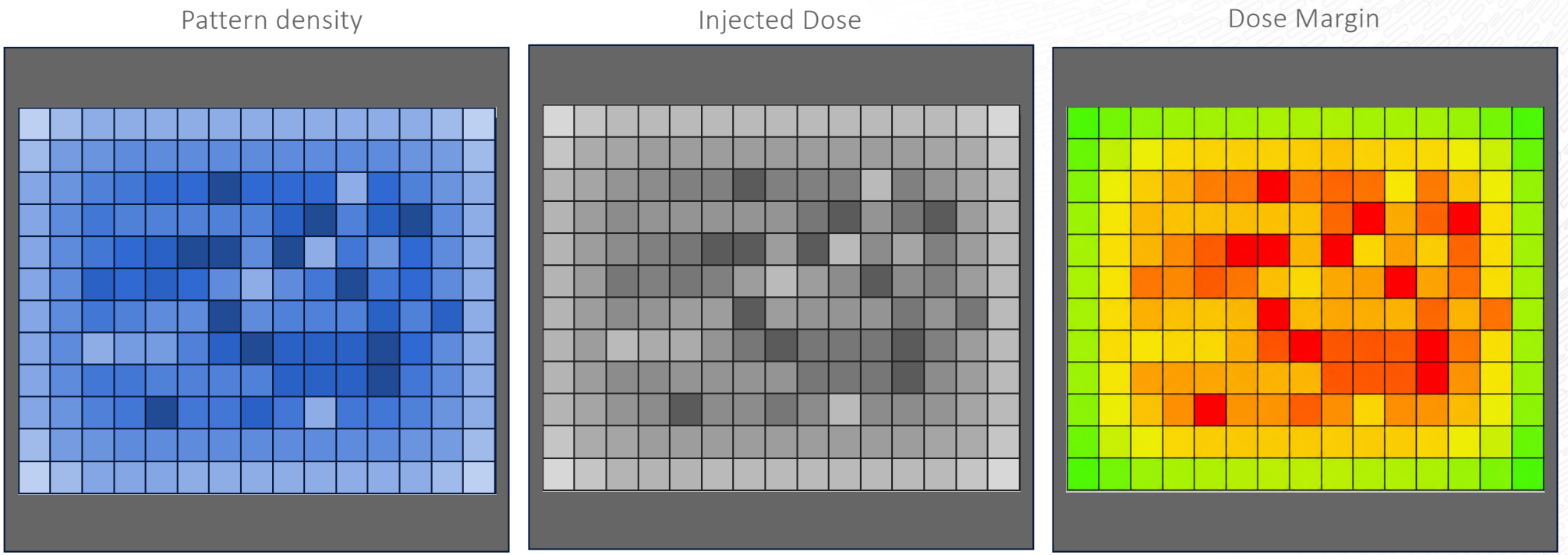
The Edge Enhancement Height and Width Governs Dose Margin For Short Range Effects



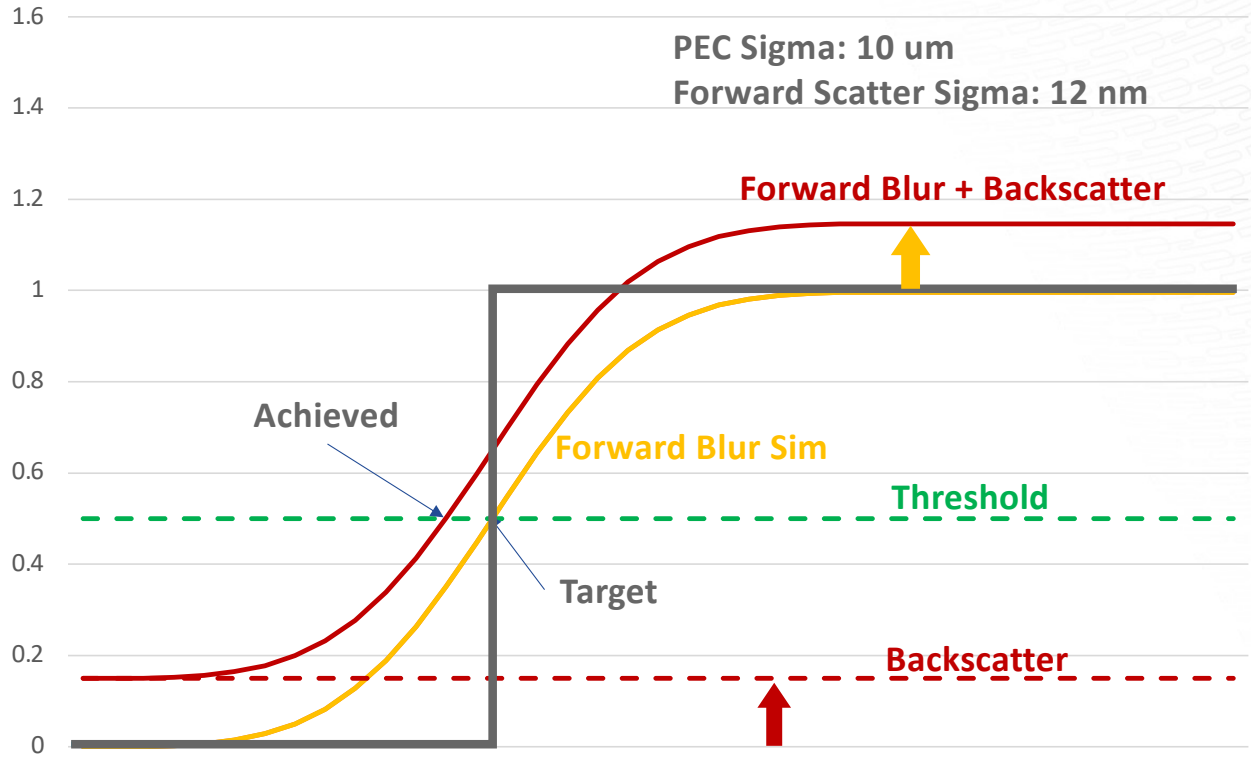
The Edge Enhancement Height and Width Governs Dose Margin For Short Range Effects



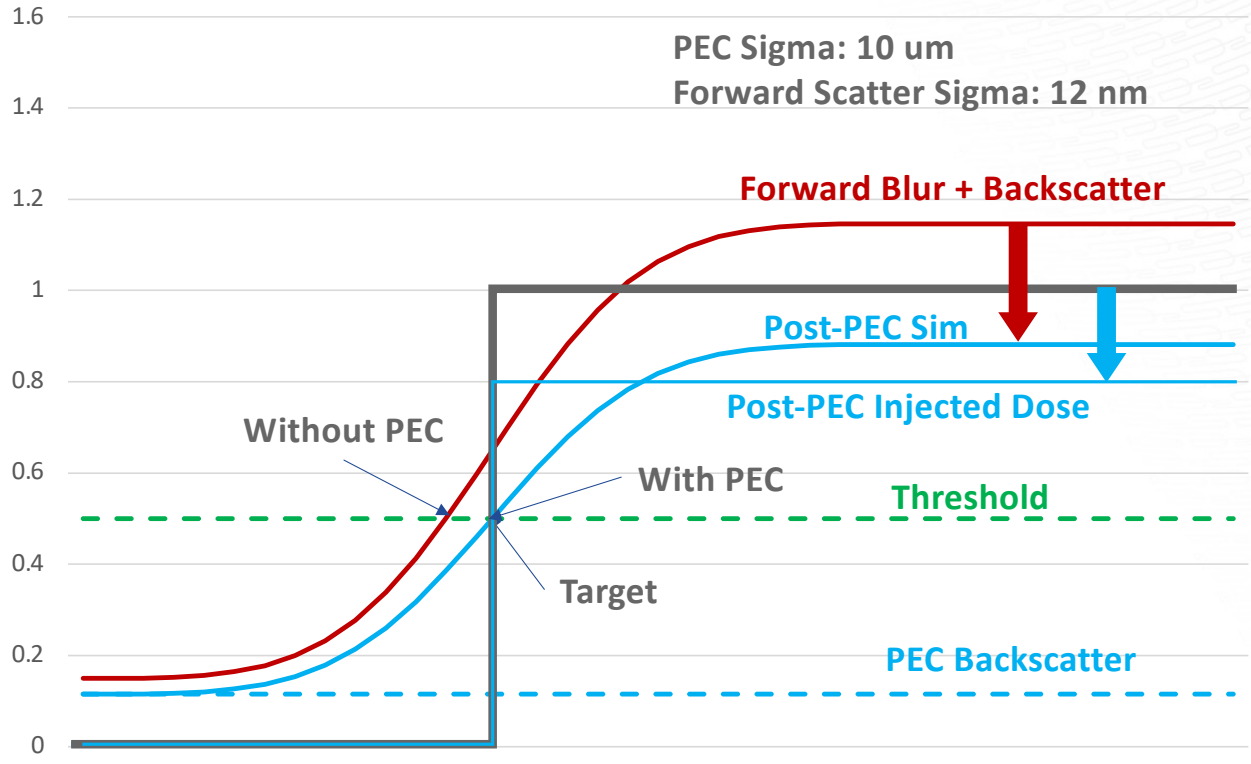
High Pattern Density Regions Have Bad Dose Margin



PEC Involves Correcting For Backscatter

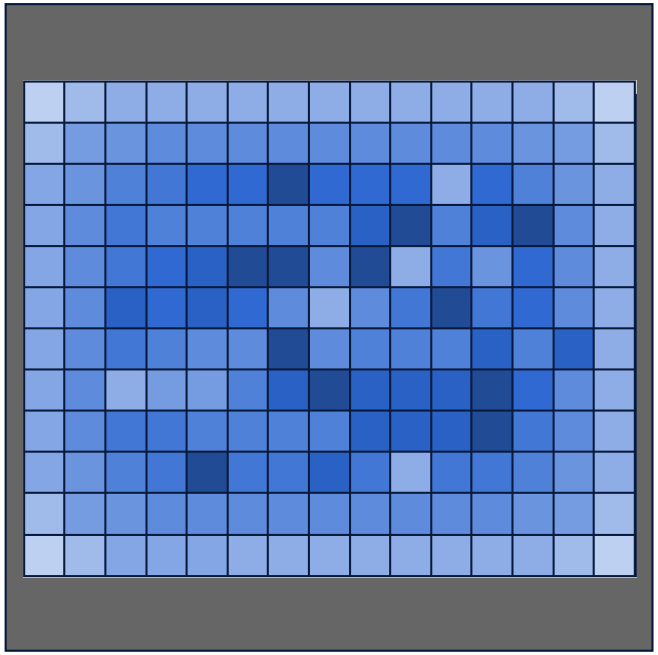


PEC Reduces The Injected Dose

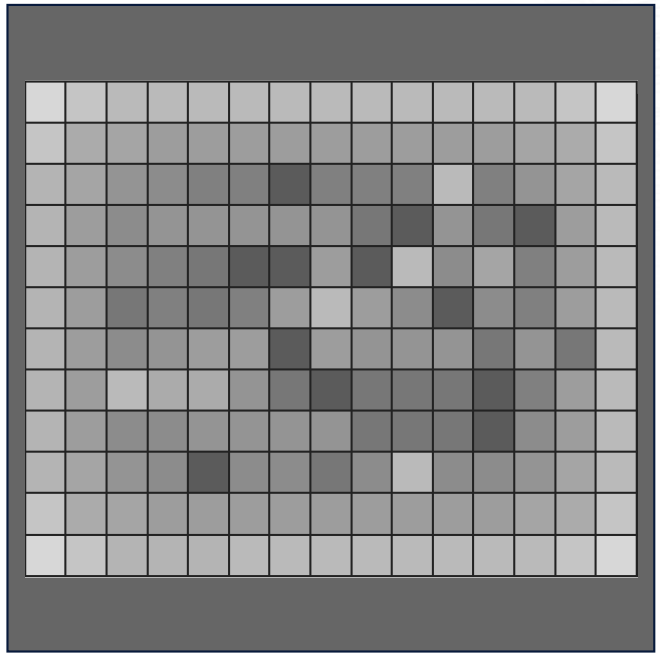


Smaller Injected Dose Produces Bad Dose Margin

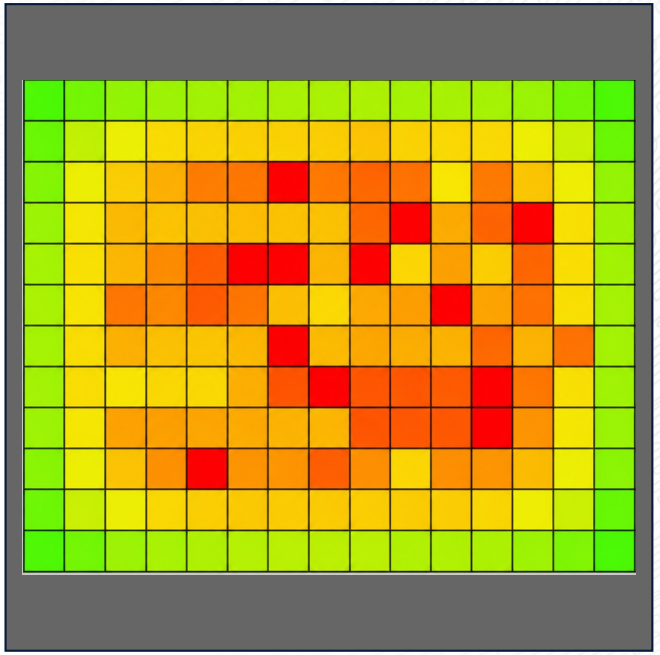
Pattern density



Injected Dose



Dose Margin



Low dose density

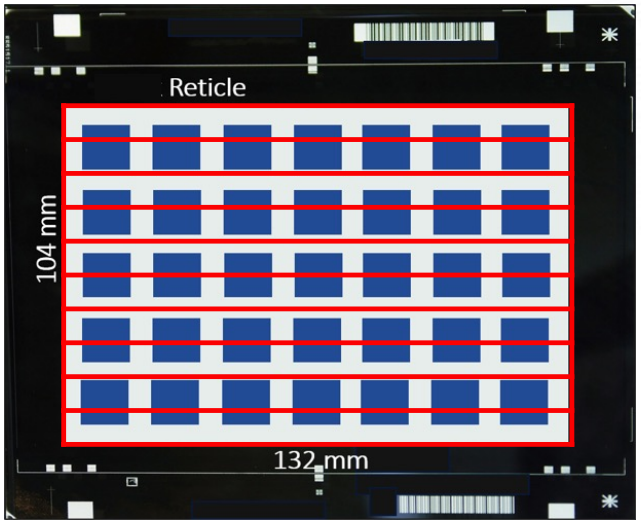
High dose density

High Injected dose → Good Dose Margin

Low Injected dose → Bad Dose Margin

Masks are Written in Stripes with Constant Stage Speed

Stage speed depends on the pattern density



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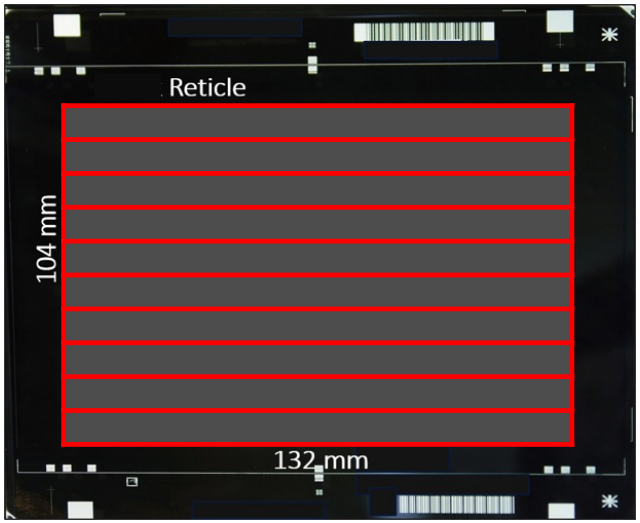

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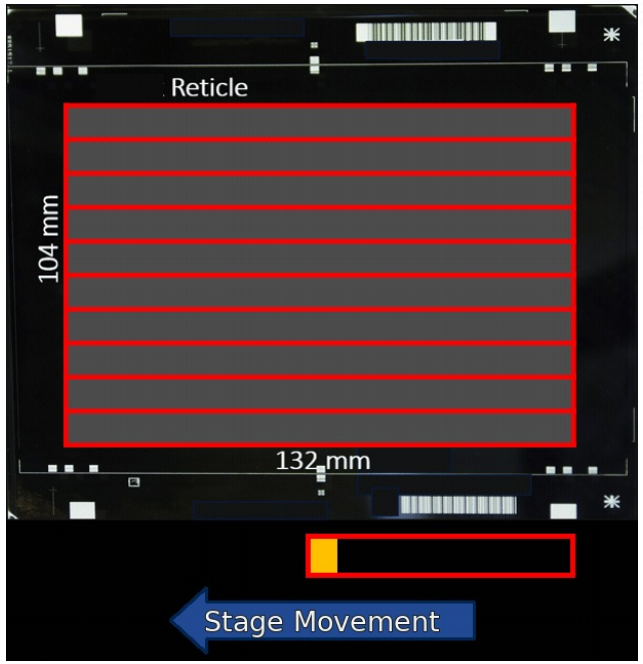
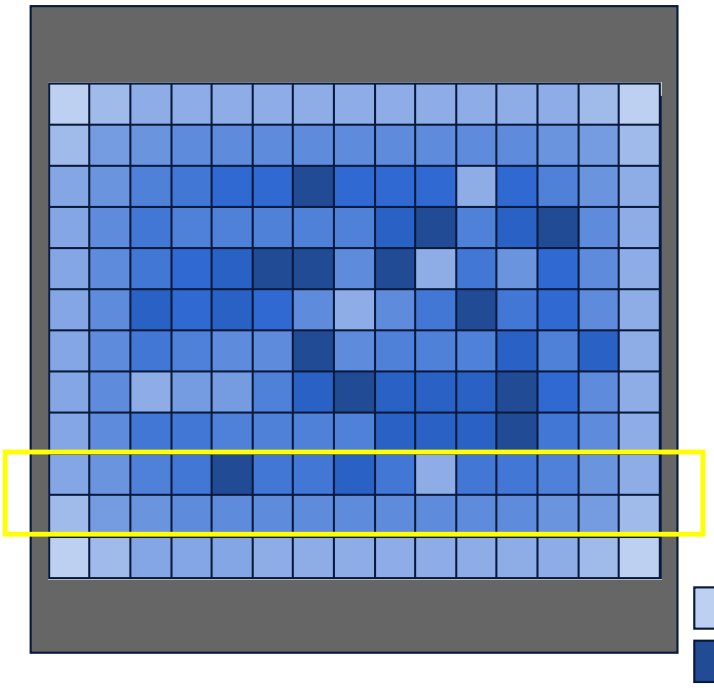


Masks are Written in Stripes with Constant Stage Speed

Stage speed depends on the pattern density

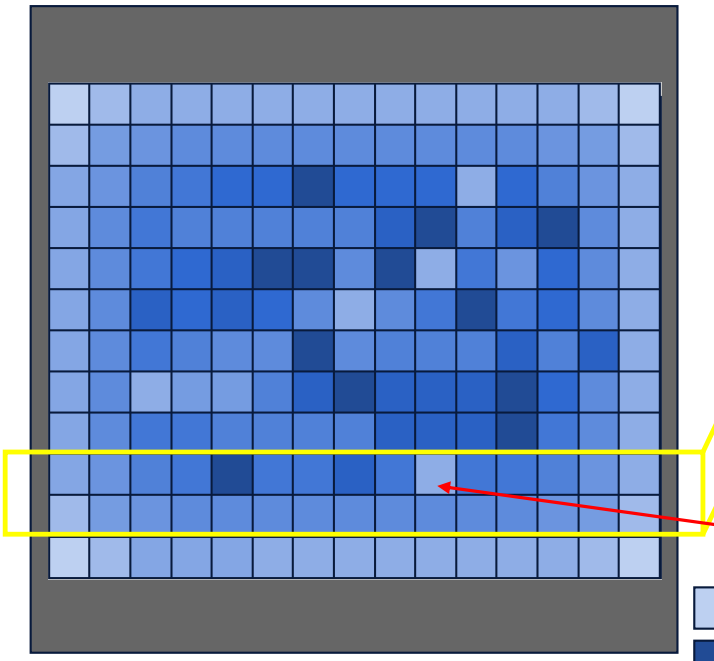


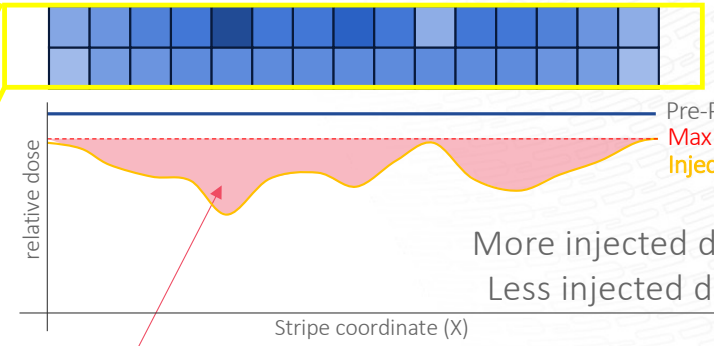
Low dose density

High dose density

Low dose density in PEC neighborhood means higher post-PEC dose cast (see later slide)

Stage Speed is Set by The Max Injected Dose





More injected dose → Slower Stage

Less injected dose → Faster Stage

Dose wasted, since stage is moving based on post-PEC max dose in stripe

More dose squishing for PEC → Less dose margin → Worse CDU

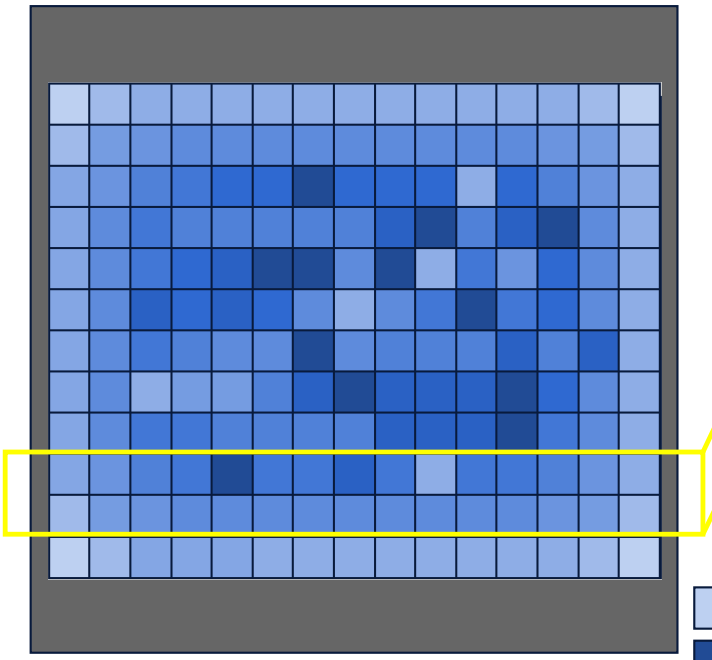
Lowest density region paces speed of the stage

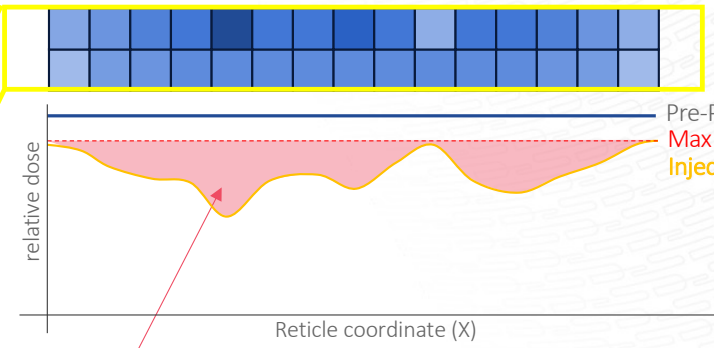
Low dose density

High dose density

Stage Speed is Set by The Max Injected Dose

DMD uses the "wasted time" to improve LCDU in dense regions





Dose wasted, since stage is moving slower than post-PEC max dose

More dose squishing for PEC → Less dose margin → Worse CDU

Low dose density

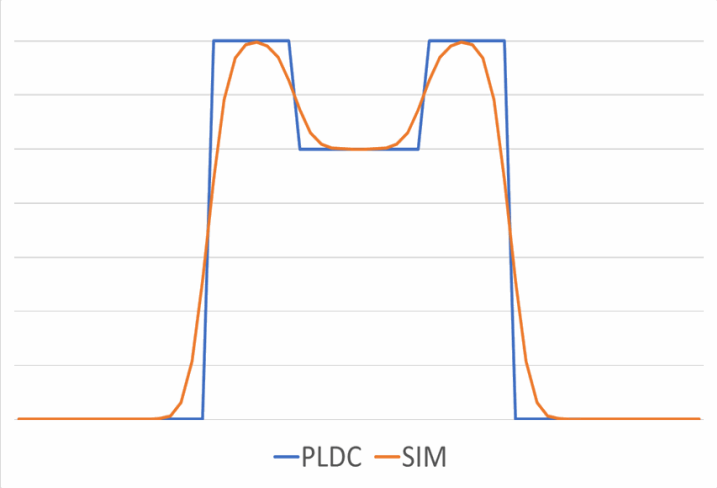
High dose density

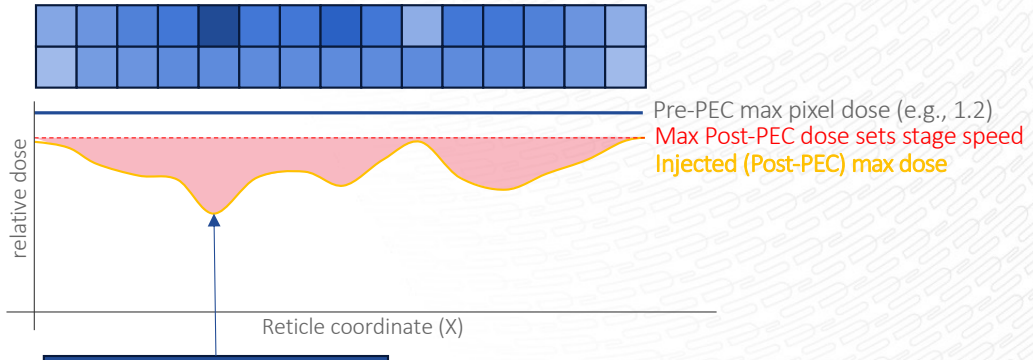
DMD[1] (Dynamic Max Dose) is a mechanism to improve dose margin in high pattern density region using a dynamic Edge Enhancement

1 - D2S Patented Technology: US11756765B2, US12243712B2

Stage Speed is Set by The Max Injected Dose

DMD uses the "wasted time" to improve LCDU in dense regions





DMD does **more** Edge Enhancement

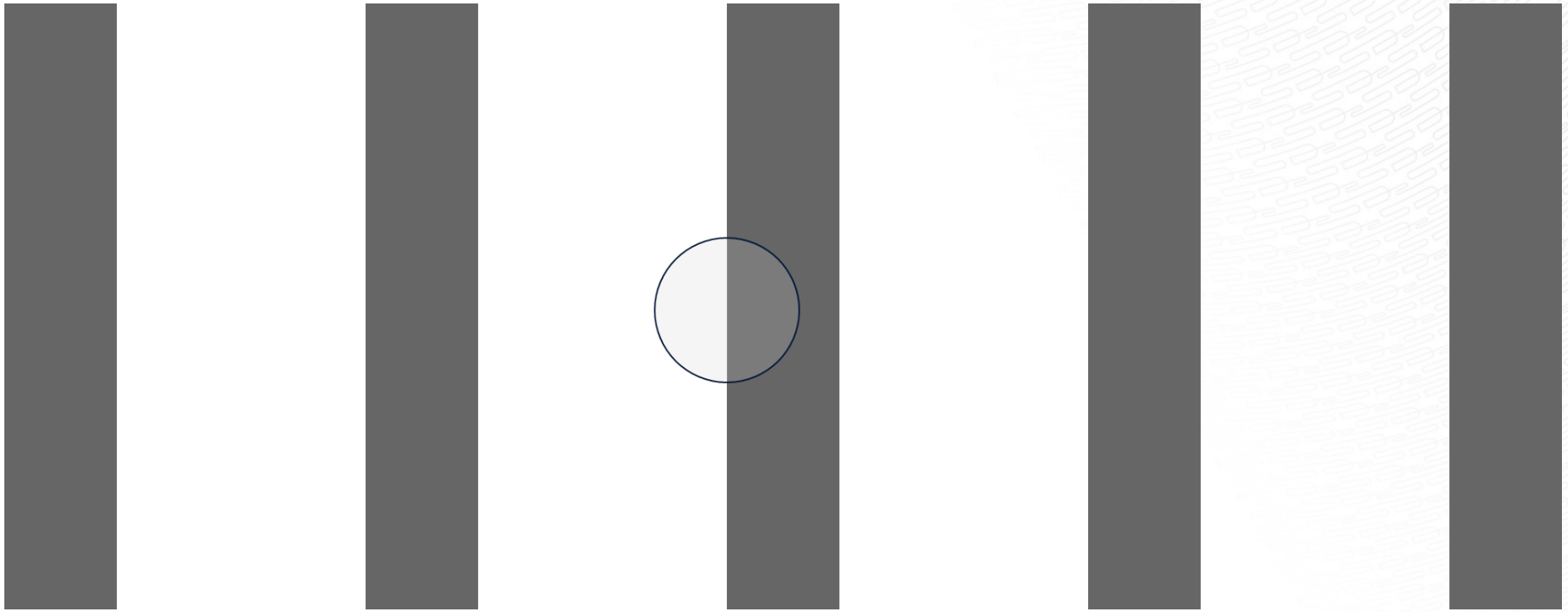
DMD[1] (Dynamic Max Dose) is a mechanism to improve dose margin in high pattern density region using a dynamic Edge Enhancement

1 - D2S Patented Technology: US11756765B2, US12243712B2

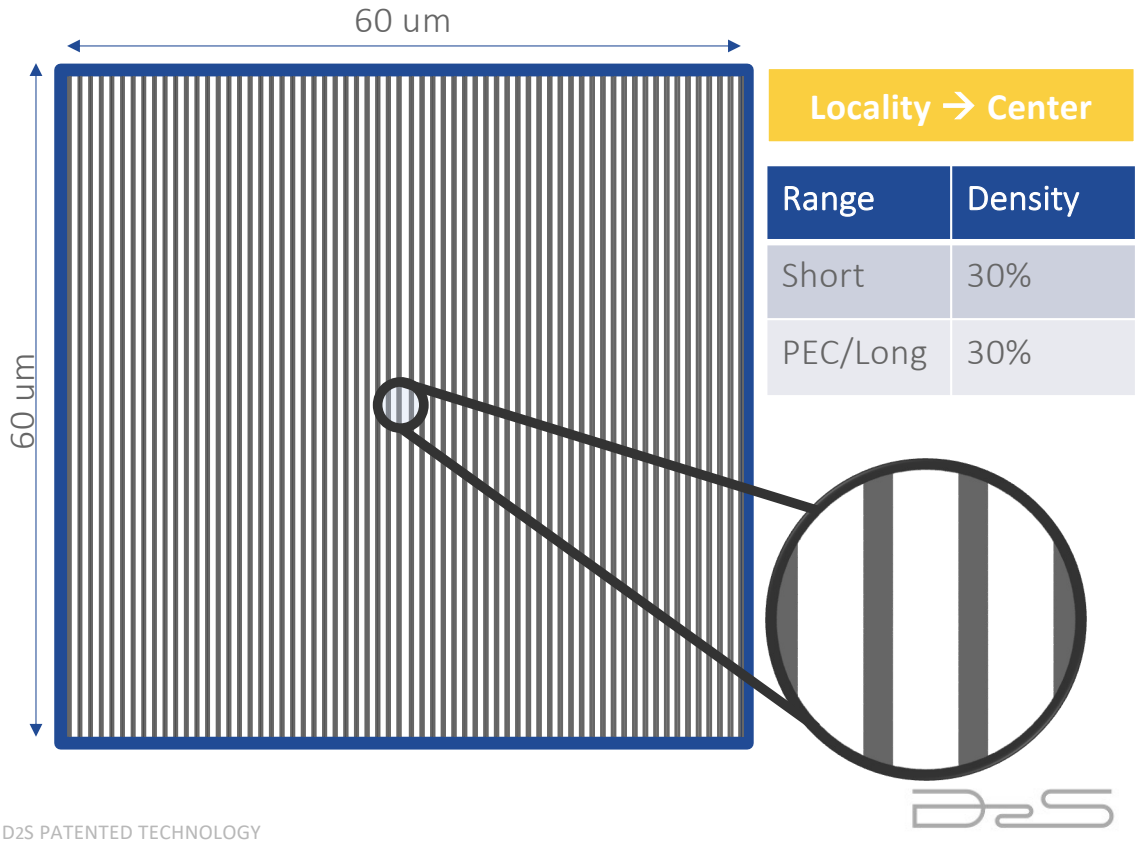
Dose Margin is Affected by PEC Correction

Line Space Pattern: Density = 30% Line Width 100nm

PEC Sigma: 10 um
Short Range Sigma: 12 nm



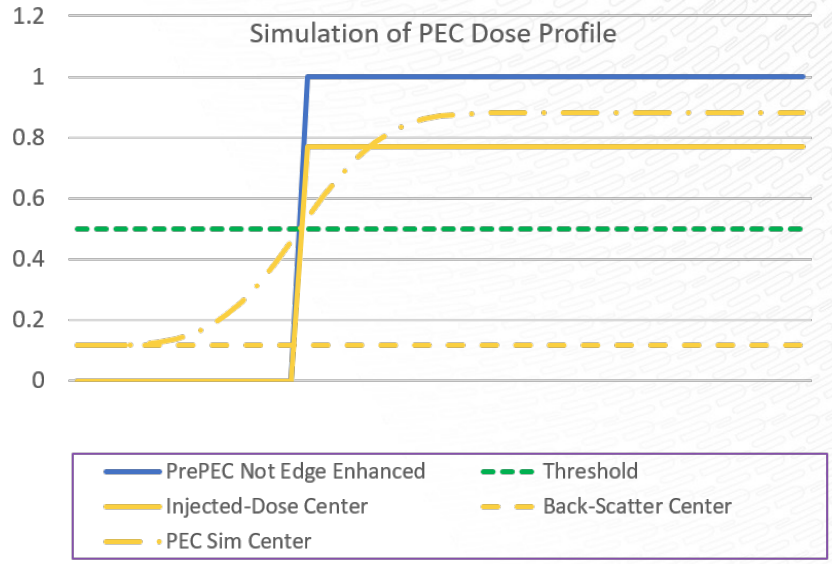
PEC Range Density Varies Depending on the Locality
PEC squishes the injected dose accordingly



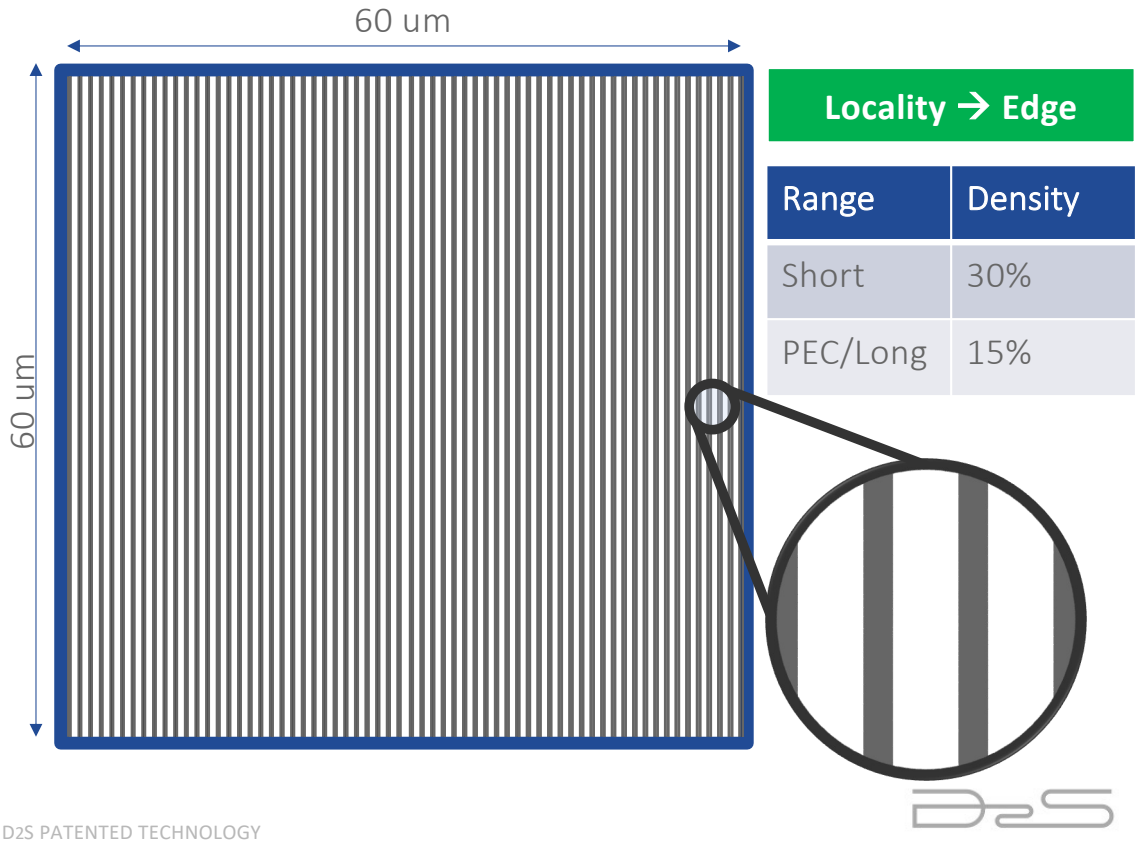
Locality → Center

Range	Density
Short	30%
PEC/Long	30%

PEC Sigma: 10 um
Short Range Sigma: 12 nm



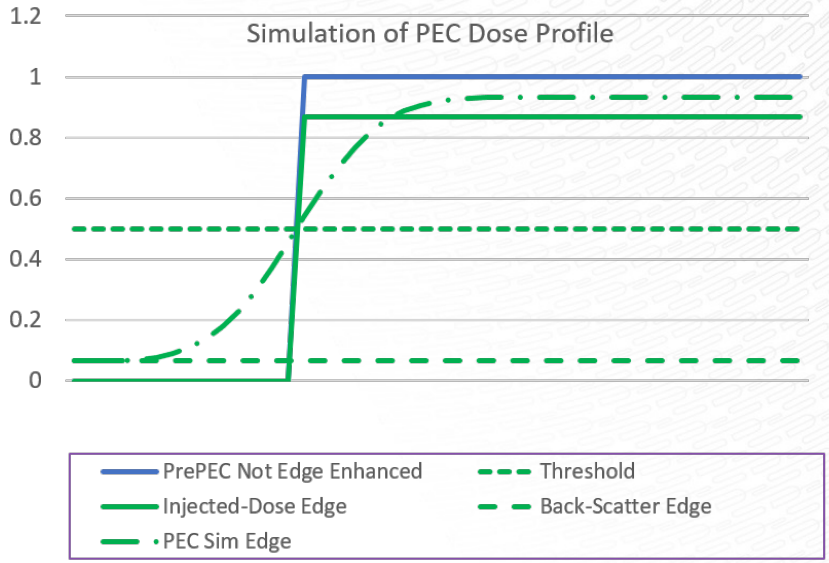
PEC Range Density Varies Depending on the Locality
PEC squishes the injected dose accordingly



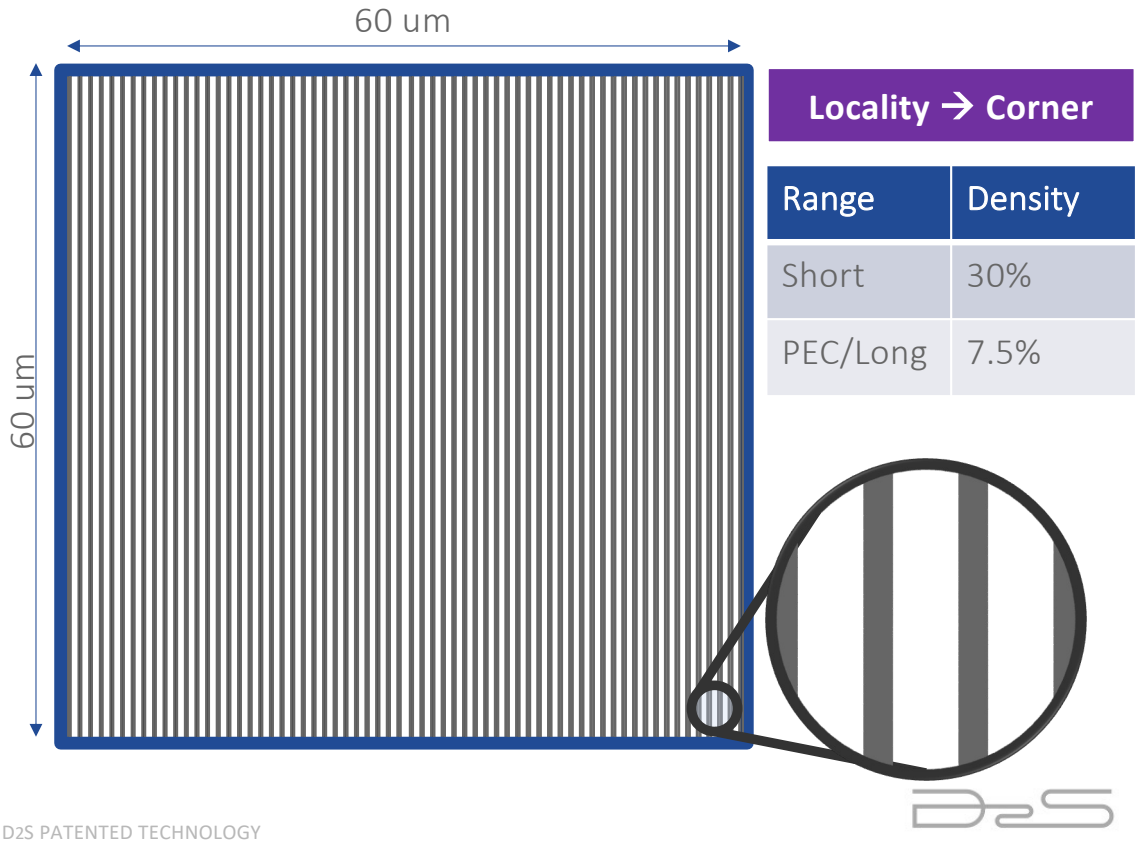
Locality → Edge

Range	Density
Short	30%
PEC/Long	15%

PEC Sigma: 10 um
Short Range Sigma: 12 nm



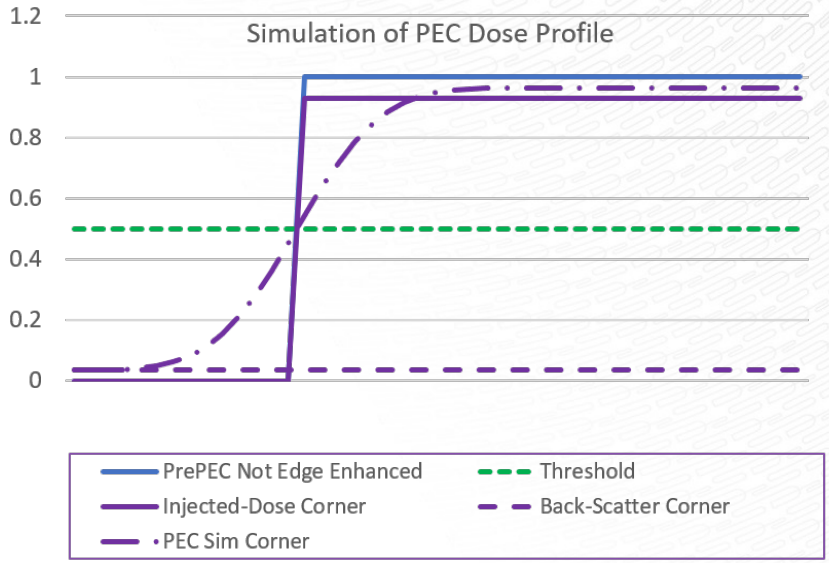
PEC Range Density Varies Depending on the Locality
PEC squishes the injected dose accordingly



Locality → Corner

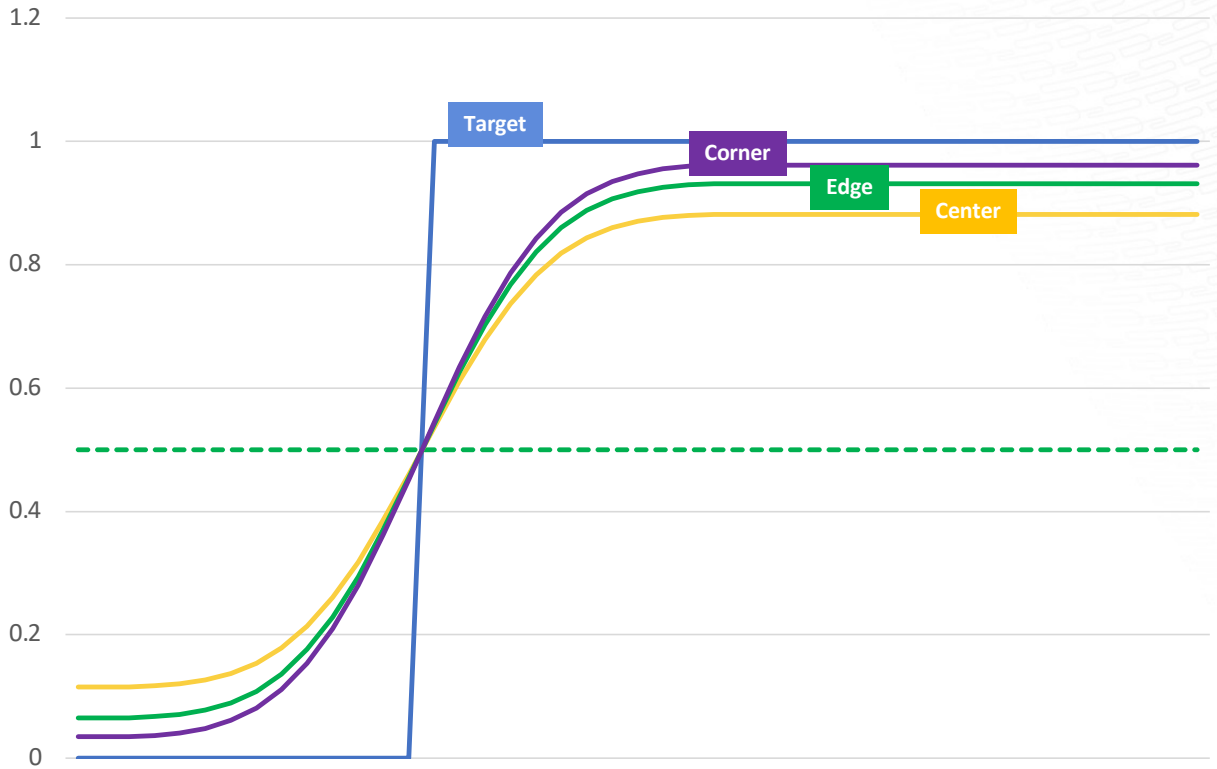
Range	Density
Short	30%
PEC/Long	7.5%

PEC Sigma: 10 um
Short Range Sigma: 12 nm



Dose Margin Degrades As Pattern Density Increases

Dose Margin (nm/%dose)	
Corner	0.2766
Edge	0.3015
Center	0.3579

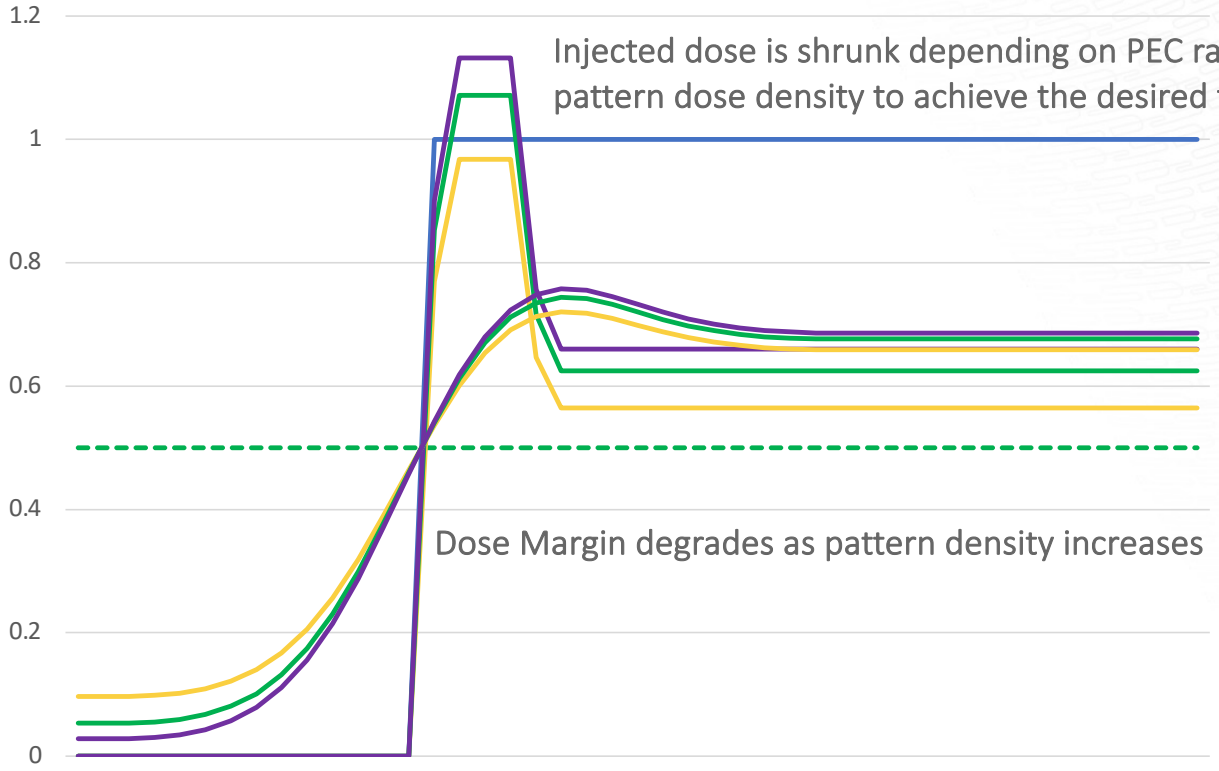


PEC Sigma: 10 um
Short Range Sigma: 12 nm

The Writer Speed is Governed by Max Injected Dose

This provides opportunity to improve dose margin for high density regions

Dose Margin (nm/%dose)	
Corner	0.2847
Edge	0.3042
Center	0.3433



PEC Sigma: 10 um
Short Range Sigma: 12 nm

Dynamic Max Dose (DMD) Uses This Phenomenon to Improve Dose Margin for High Density Regions

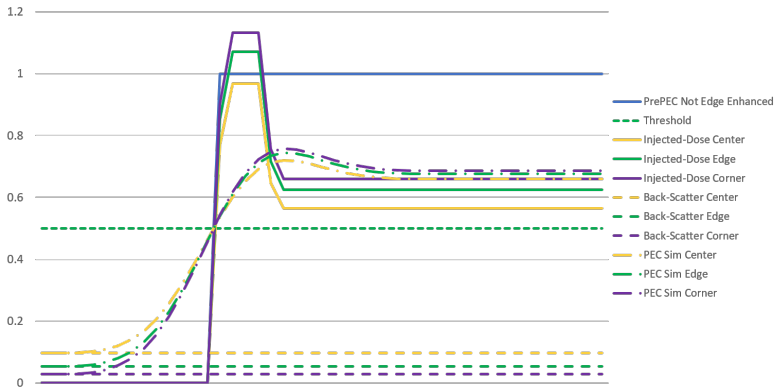
Dose Margin (nm/%dose)	
Corner	0.2764
Edge	0.2856
Center	0.3150

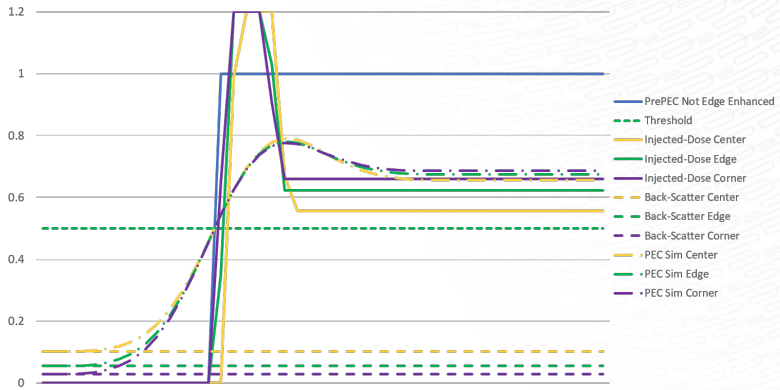
PEC Sigma: 10 um
Short Range Sigma: 12 nm

DMD Uniquely Improves Dose Margin Without Affecting Machine Write Time

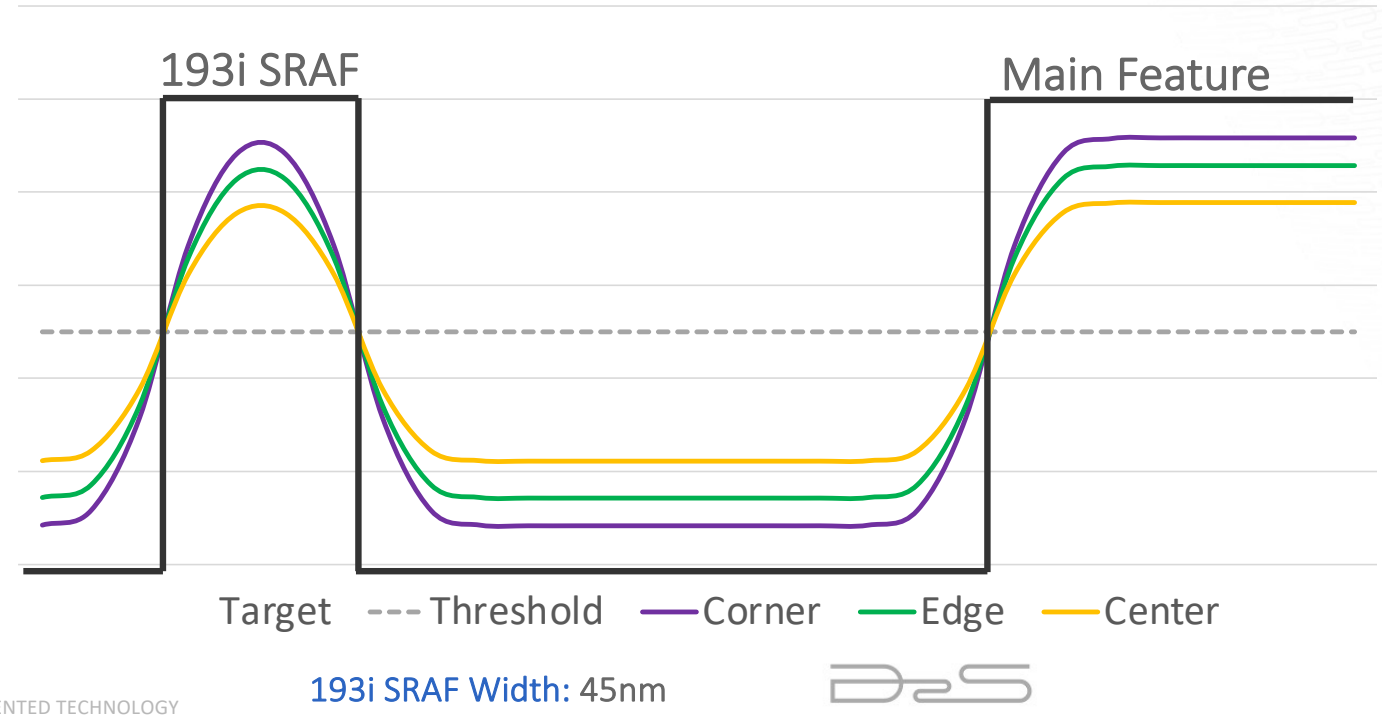
	Dose Margin (nm/%dose)		Dose Margin Improvement
Mode	Without DMD	With DMD	
Corner	0.2847	0.2764	3%
Edge	0.3042	0.2856	6.5%
Center	0.3433	0.3150	9%
Range	0.0586	0.0386	34%

Larger improvement for high-density regions

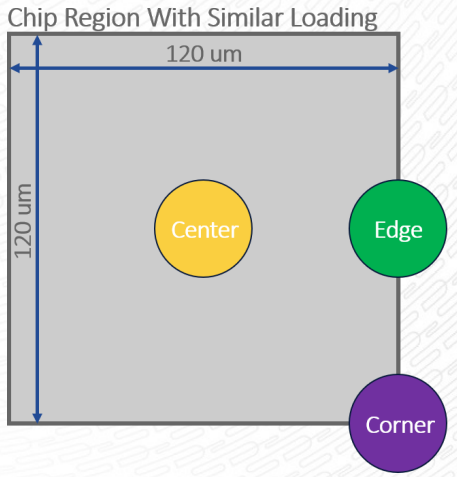


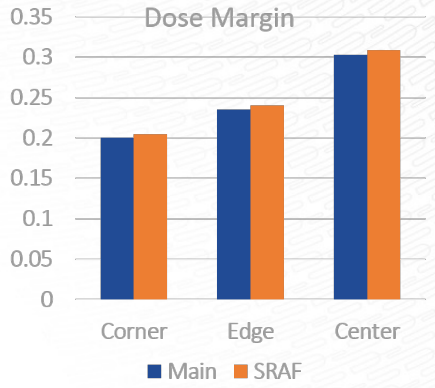


But Geometry Effects like Loading Should be Corrected By Geometric Bias Mechanisms



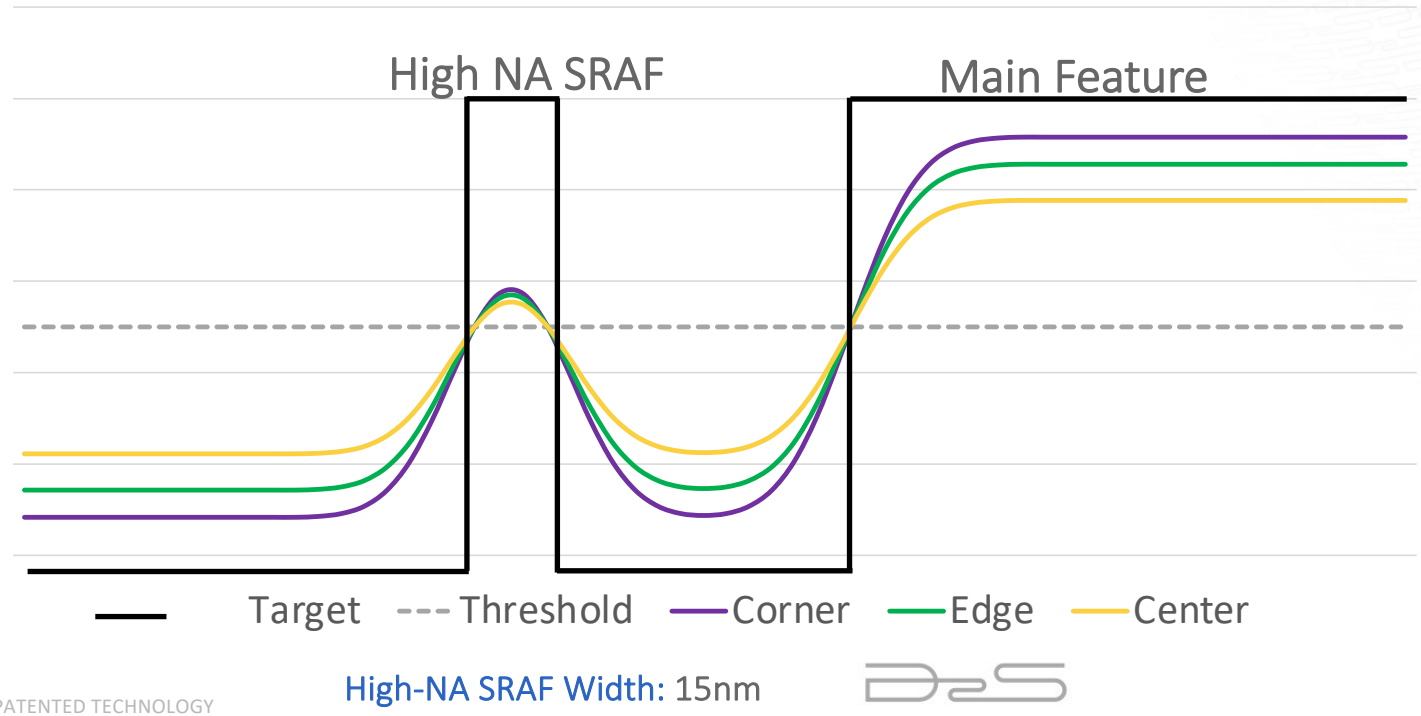
193i SRAF Width: 45nm

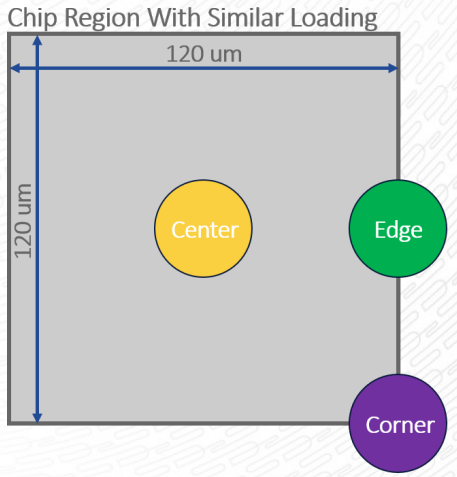


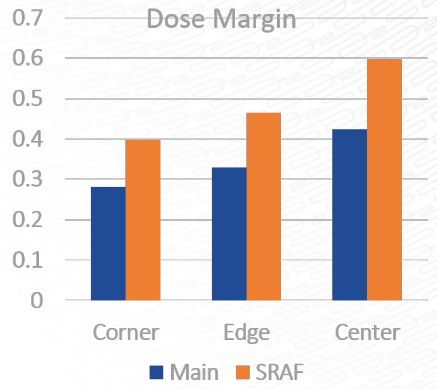


For High-NA, The Dose Margin Variation Is Larger

So, dose-based methods will be more inaccurate

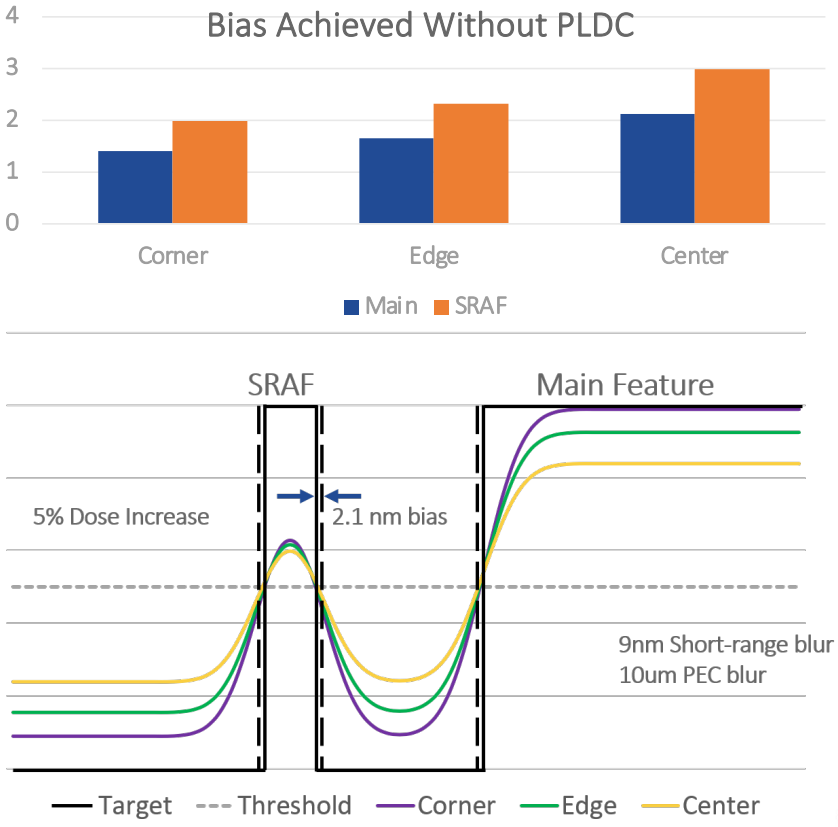


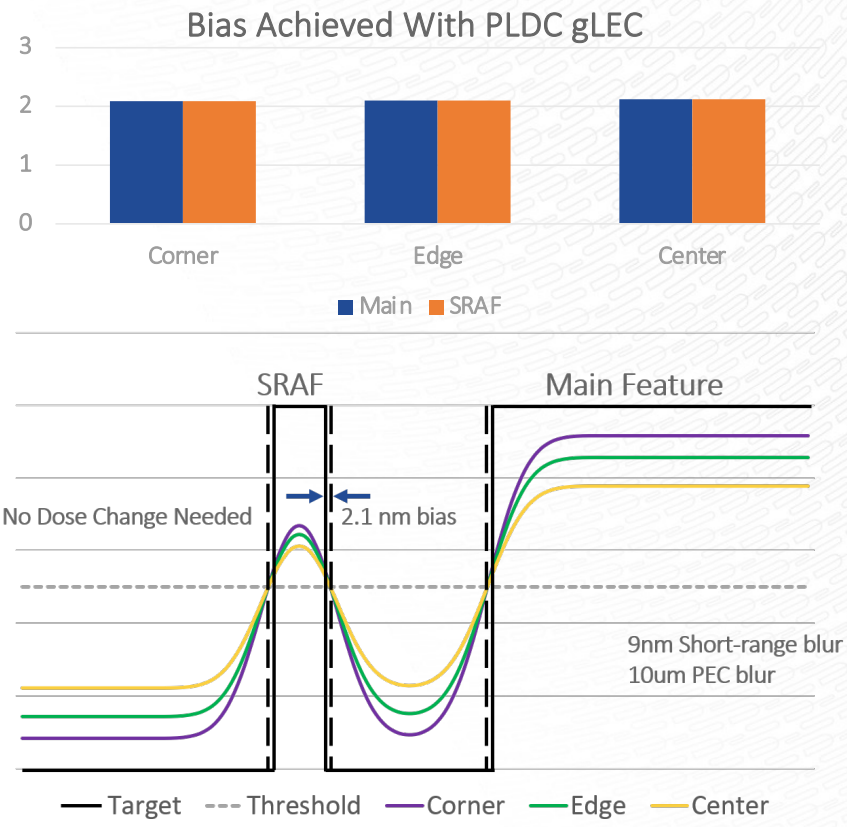




High-NA SRAF Width: 15nm

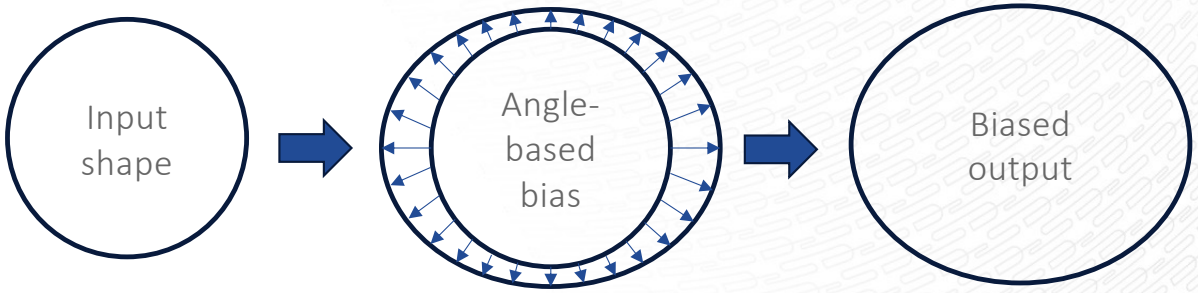
PLDC gLEC Improves CD Uniformity for Geometric Effect



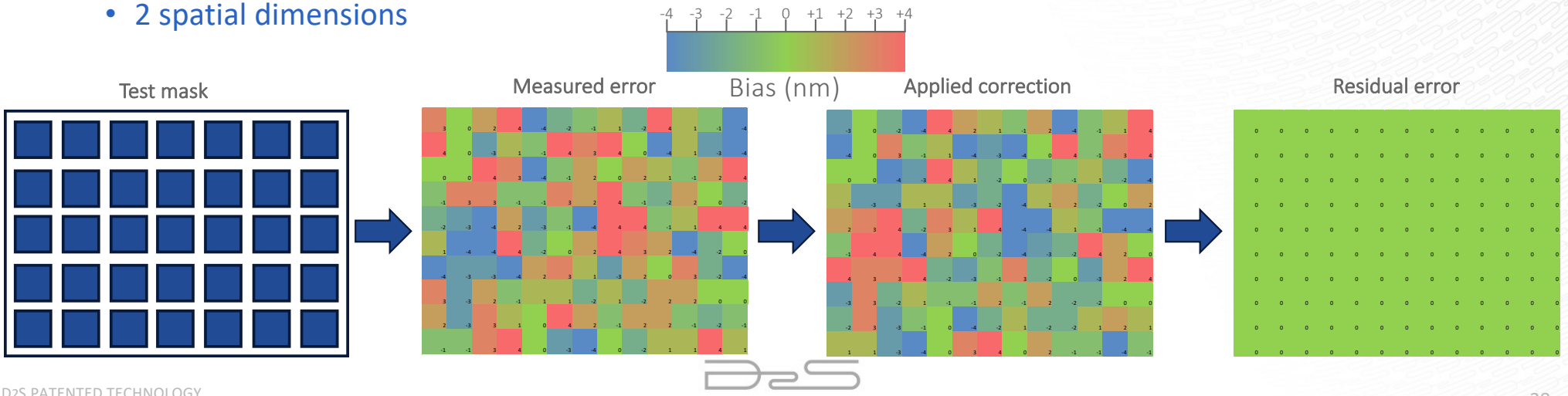


D2S PLDC Has A Regional Radial Bias (RRBias) Correction

gLEC bias is an instance of general geometric bias correction i.e. RRBias

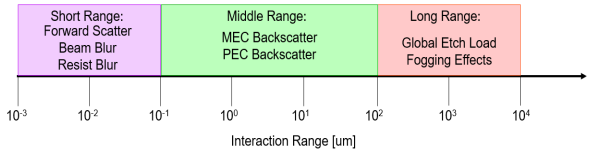


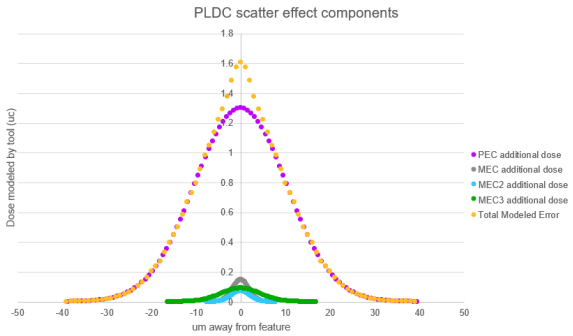
- Geometric bias uses a 3D map
  - 1 dimension for angle
  - 2 spatial dimensions



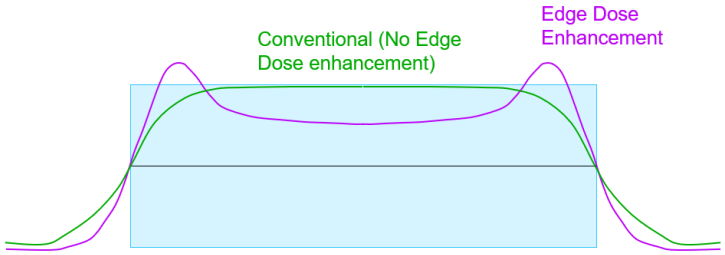
With D2S PLDC
Geometric Effects are Corrected using Geometric Bias
Dose Effects are Corrected using Dose Bias

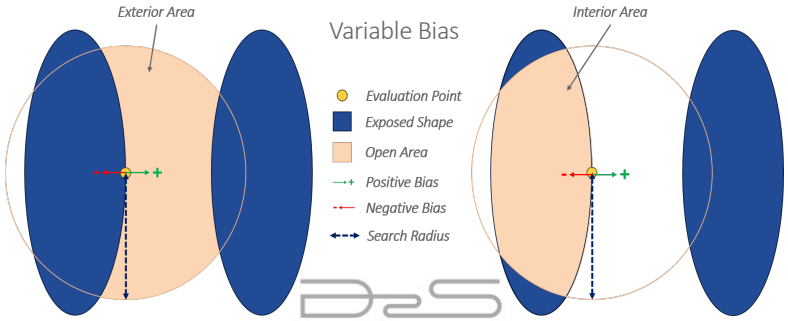
Beam Blur + Edge Dose Enhancement + Dynamic Max Dose + Variable Bias + gLEC / RRBias

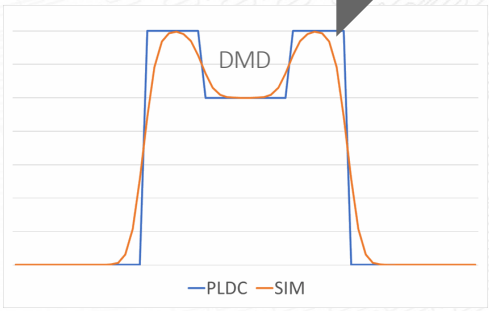


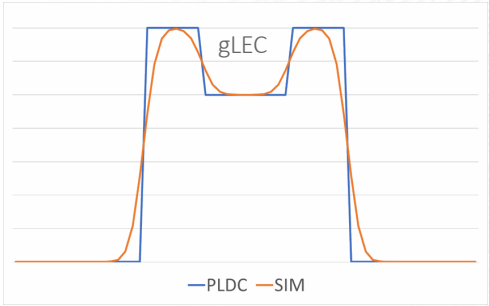


Multi-gaussian Model Based Blur Correction

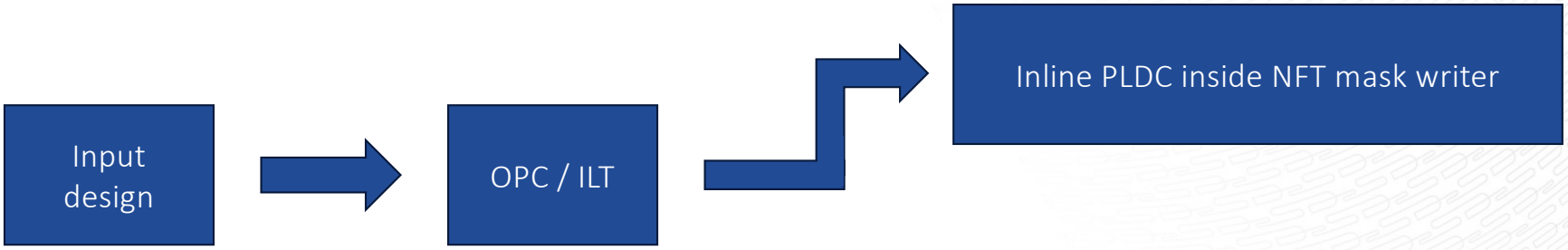




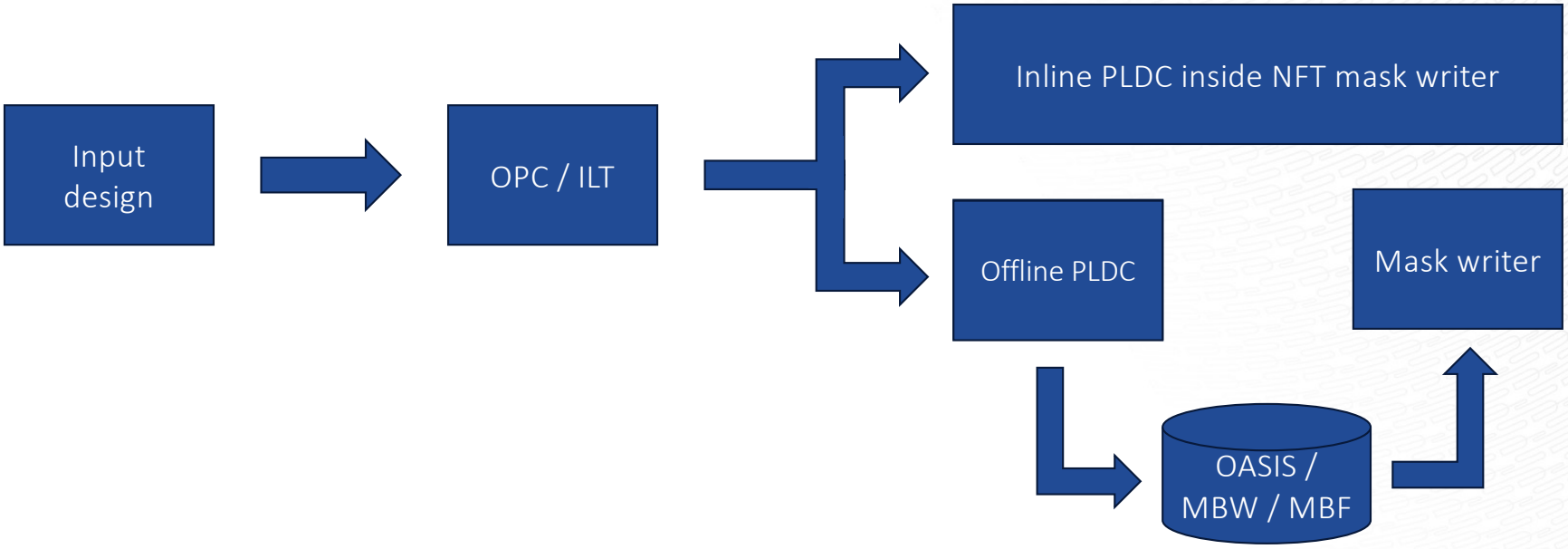




D2S PLDC is Available Inline To Enhance Mask Uniformity and Linearity



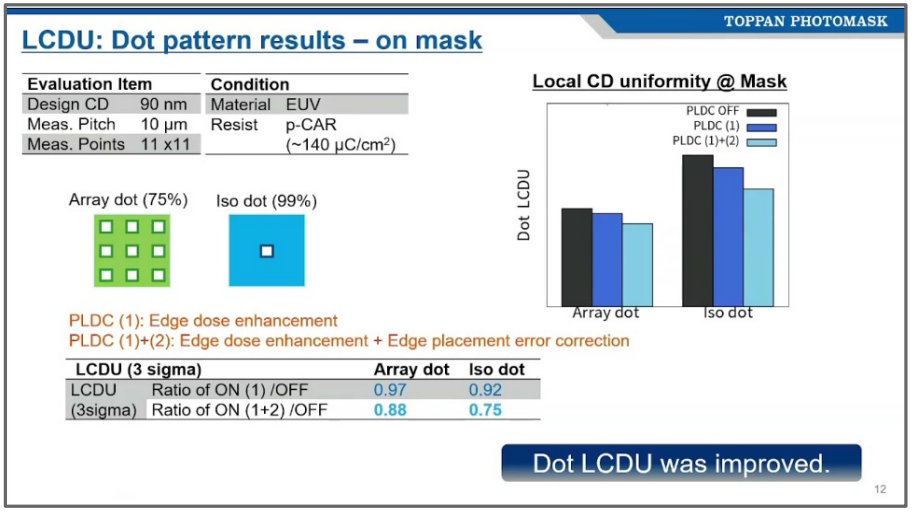
D2S PLDC is Available Inline or Offline To Enhance Mask Uniformity and Linearity



DMD and gLEC with RRBias Improve Mask Uniformity With No Impact On Mask Write Time

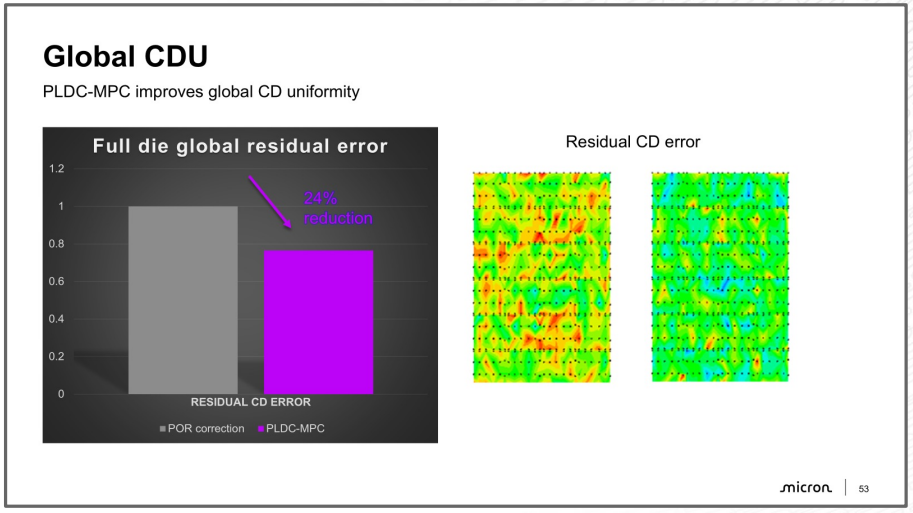
Every variation on mask is a systematic variation on wafer
PLDC improves mask uniformity and thereby wafer CDU

BACUS 2024 by Tekscend



Mayuko Matsumoto, Naoki Yoshida, Tetsunori Hirata, et al. "Mask performance improvement by pixel level dose correction", Proc. SPIE 13216, Photomask Technology 2024, 132160H (12 Nov 2024); https://doi.org/10.1117/12.3034611

PMJ 2025 by Micron



Paris Spinelli, Nagesh Shirali, Kenichi Yasui, et al. "Full reticle curvilinear inline linearity correction including variable bias with zero turnaround time", Proc. SPIE 13427, Novel Patterning Technologies 2025, 1342705 (6 May 2025); https://doi.org/10.1117/12.3051087