Curvilinear MPC in Zero Time

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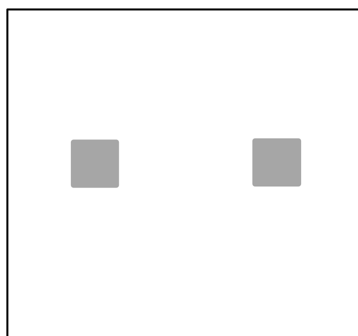
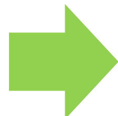
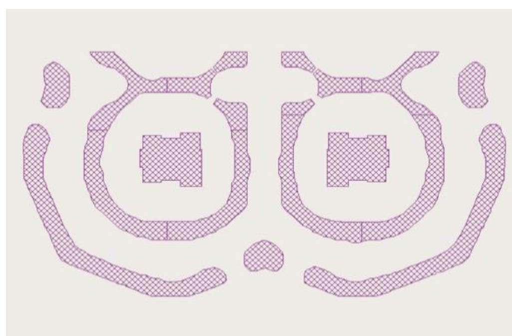
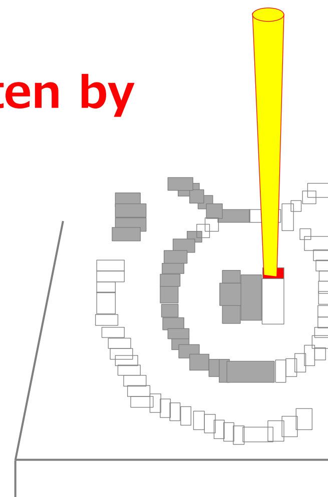
BACUS2022, eBeam Initiative

Single VSB vs. Multi-beam

After Inverse Lithography Technology (ILT) introduction,

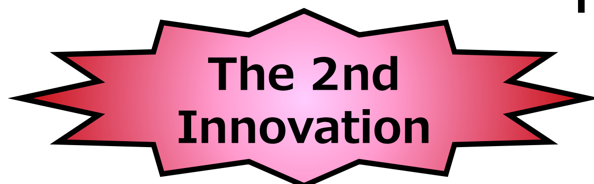
Written by VSB

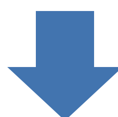


Write time gets too long again!

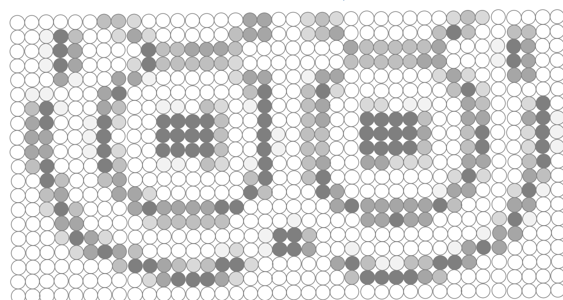
LSI design

LSI design is no longer simple

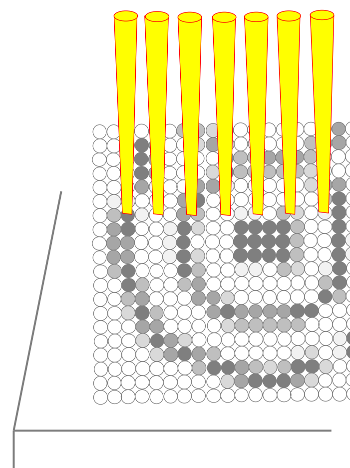




Written by Multi-beam (262K beams)



Rasterized EB data

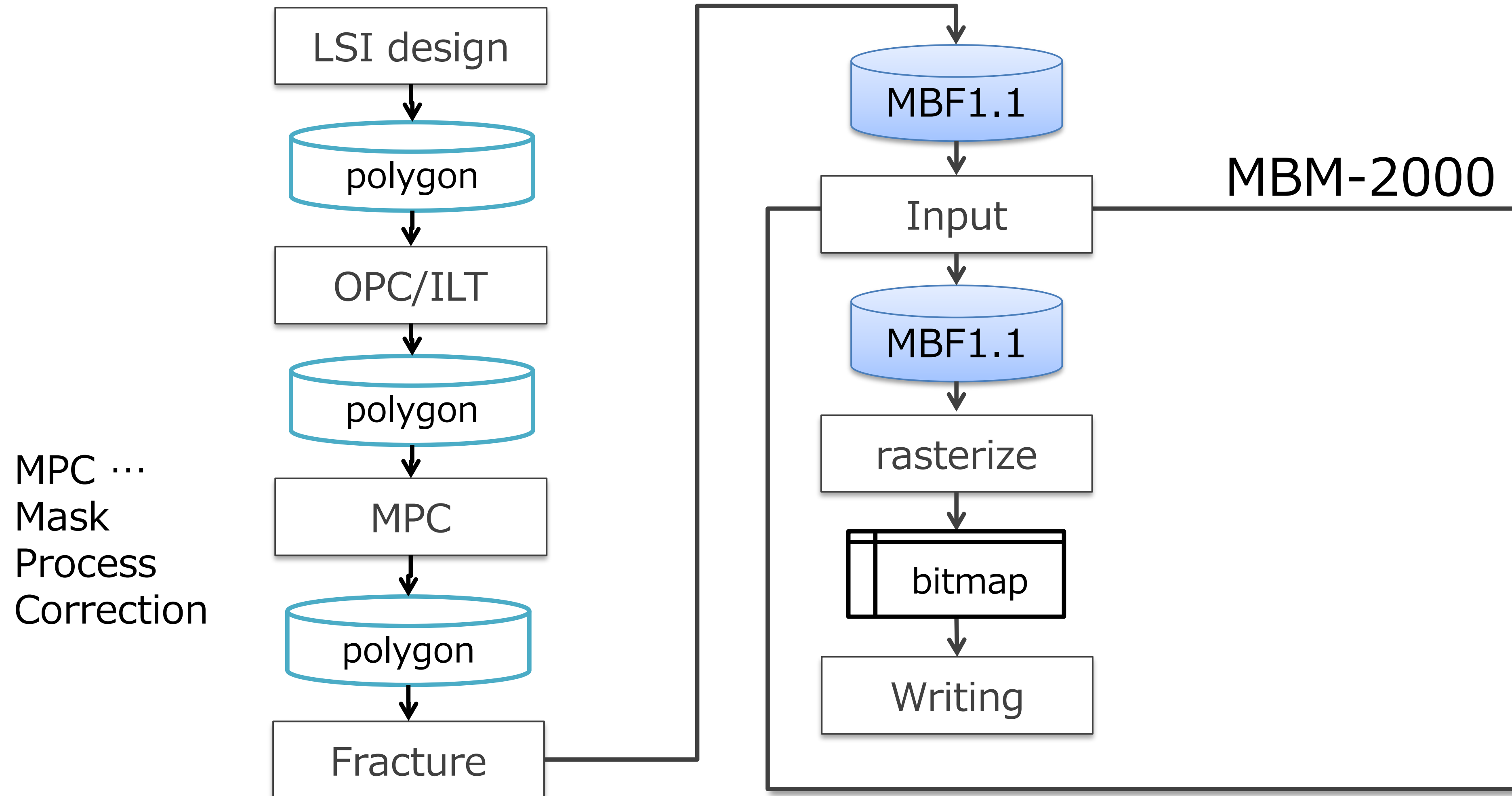


Mask writer has already migrated from shots to pixels

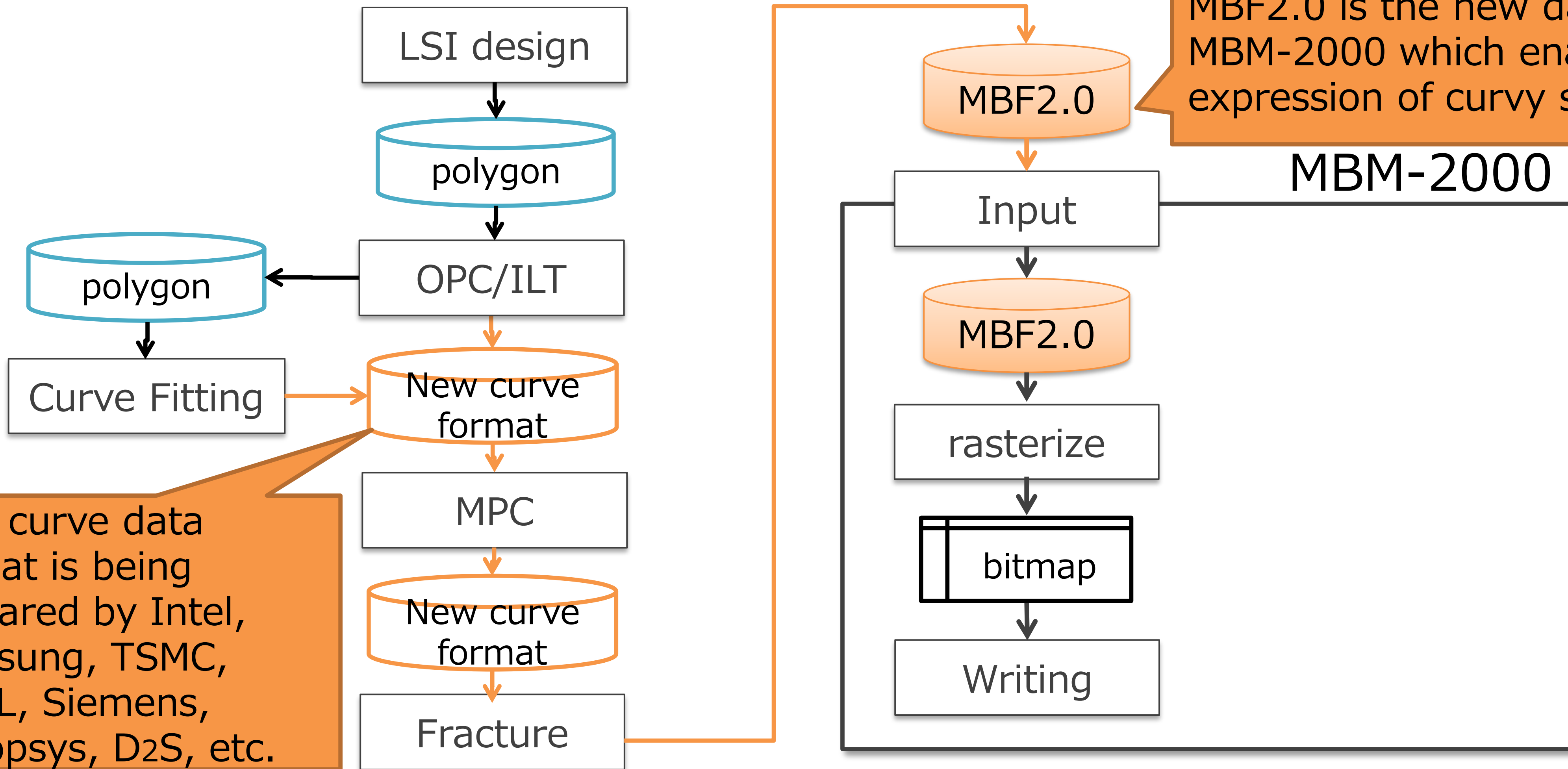
Advantages of Multi-beam Mask Writer

	Single VSB	Multi-beam
Throughput	As patterns get more complex, shot count increases and write time goes up exponentially.	Write time should stay constant for complex patterns.
Accuracy	To reduce write time, it is necessary to increase the current density and keep the pass count as few as possible, which degrades stitching accuracy and resist heating effect.	Same electron current is maintained by low current density by the massive # of beams to keep up with the low sensitivity resist, with less concern for resist heating effect
Dose control	Exposure dose has to be controlled shot-by-shot only. If finer control is necessary, one must reduce the shot size and the throughput will be aggravated.	Exposure dose can be finely controlled at 16nm beam level, which opens the door for the writer to do inline mask process correction (MPC)

Conventional Datapath

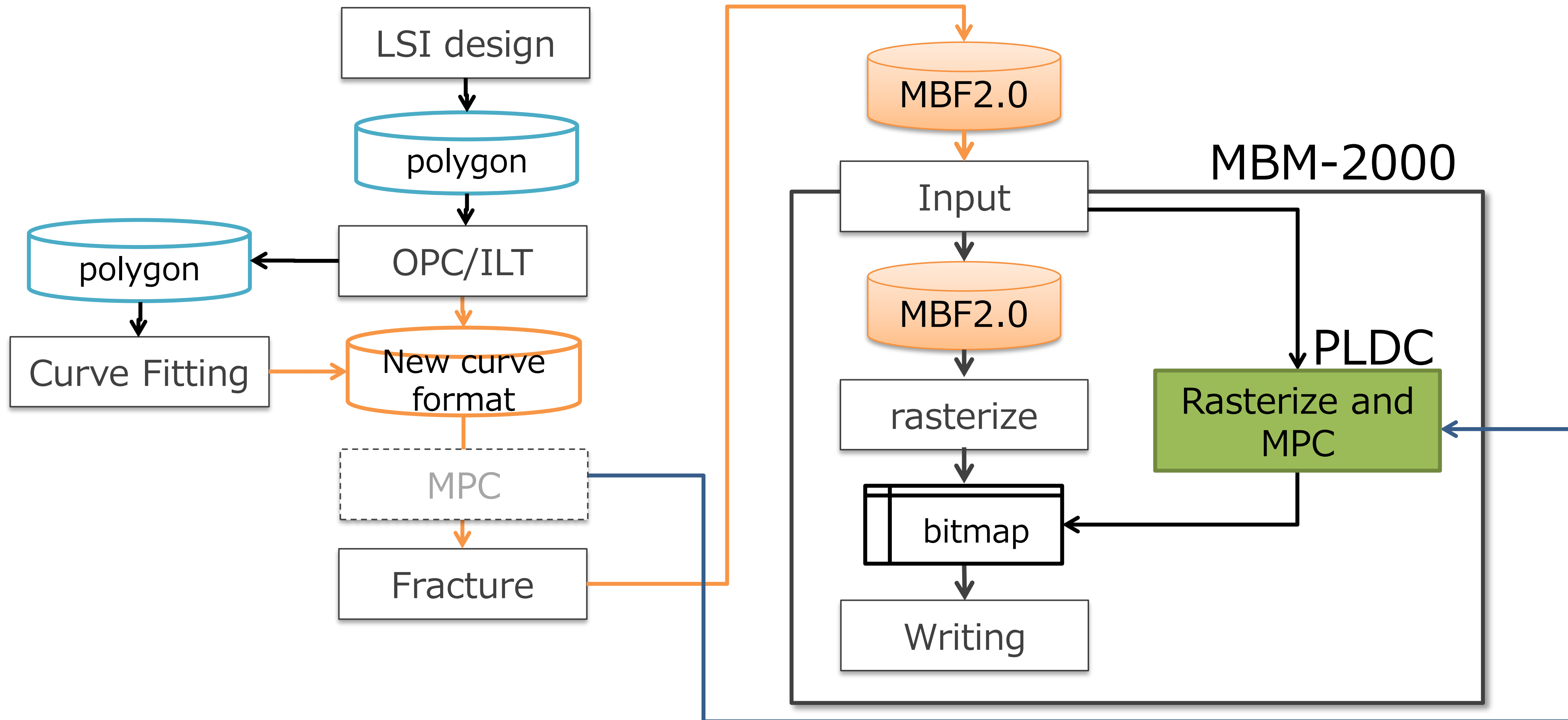


New MPC Flow with Curves (Solution.1)



- File size is kept compact if OPC/ILT outputs Bezier/B-spline curves directly, or
- Curve fitting is performed directly after OPC/ILT
- MPC handles Bezier/B-spline figures

New MPC Flow with Curves (Solution.2)



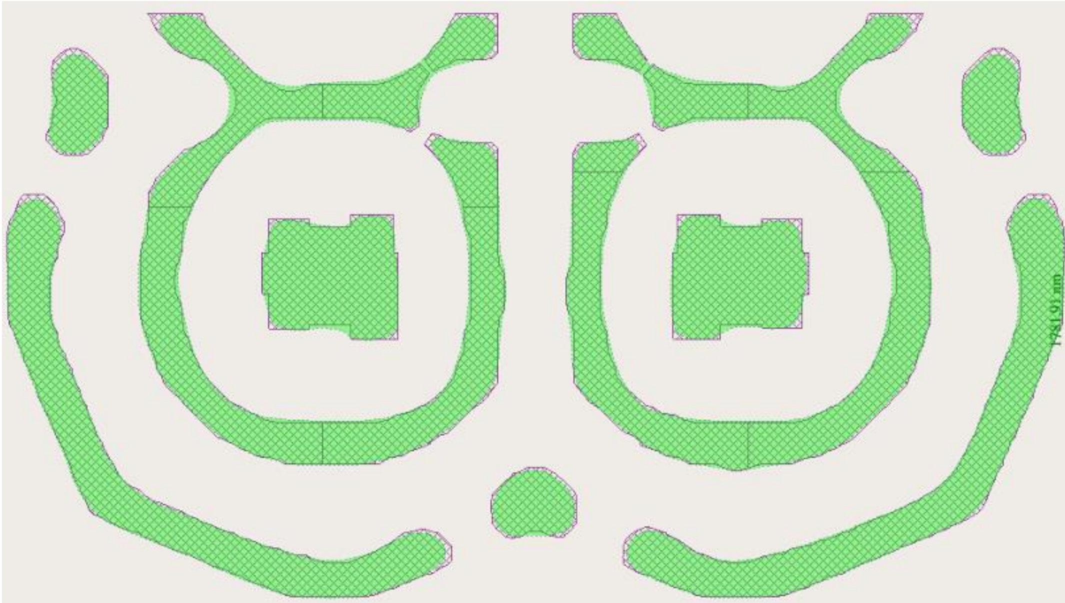
- MPC is moved to writer’s inline software and is handled in pixel domain rather than in geometry domain
- This flow is what NuFlare calls “PLDC”, meaning “Pixel Level Dose Correction”

Advantages of Inline Pixel-based MPC (=PLDC)

	Offline/Pipeline Figure-based MPC	Inline Pixel-based MPC (PLDC)
Turn-around-time (TAT)	As patterns get more complex, figure count increases and MPC time goes up exponentially.	MPC can be processed in the background of writing and the pixel count is constant. There is no additional TAT.
Convergence	Offline MPC has more degree of freedom in size and dose control. This is good in terms of having more combinations of solutions but it often requires more iterations and longer calculation time to find the best one.	Since the beam size is fixed, the dose solution can be obtained through less iterations to keep the calculation time within the machine writing time.
Dose control	Exposure dose has to be controlled by figures. Finest control needs comparable figure size as writer's beam size and figure count increase will be aggravated.	Because inline MPC knows the exact beam grid, it can give precise dose to the pixels.

PLDC works in Pixel domain instead of Geometry domain

Geometry Data



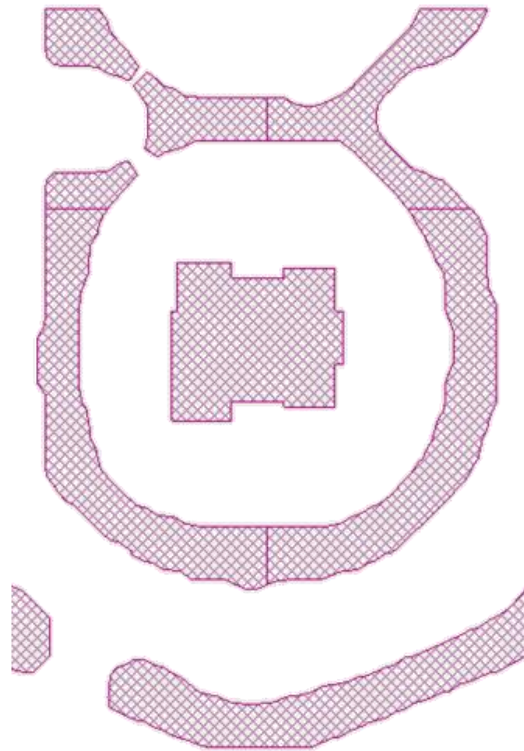
Pixel Data

- Benefit of PLDC
  - Fine dose control by 16nm pixels
  - Improved process margin and pattern fidelity by edge enhancement
  - No additional Turn-around-Time for MPC

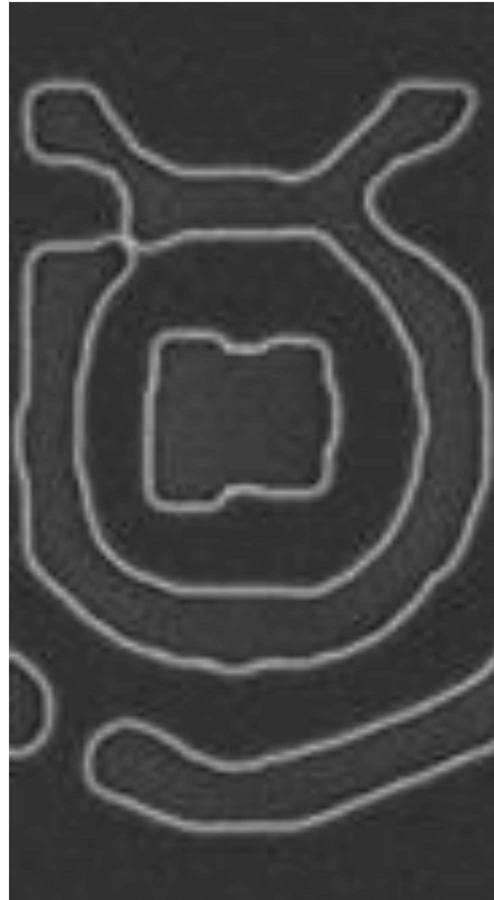
Curvilinear Pattern printed by PLDC

From eBeam Initiative panel in BACUS 2017

Low sensitivity resist (~150 uC/cm2)

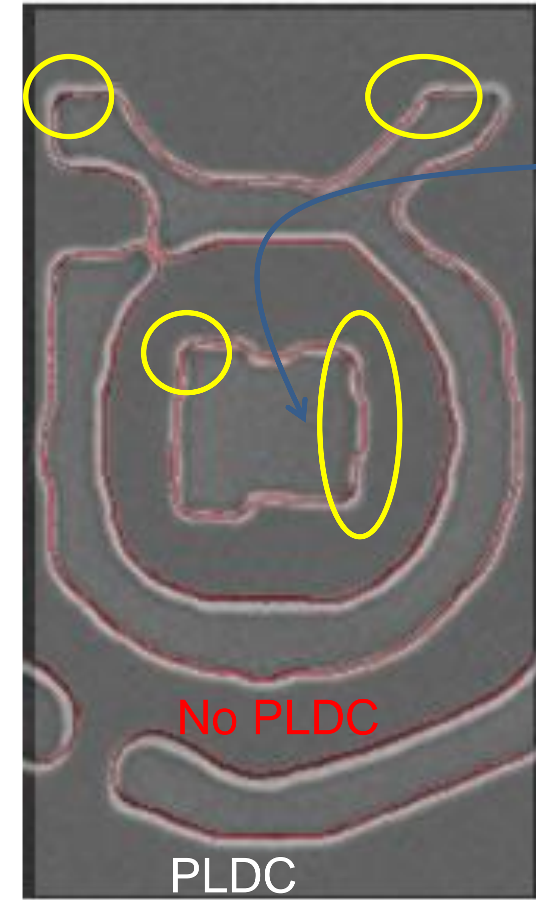


Mask Design



No PLDC

PLDC

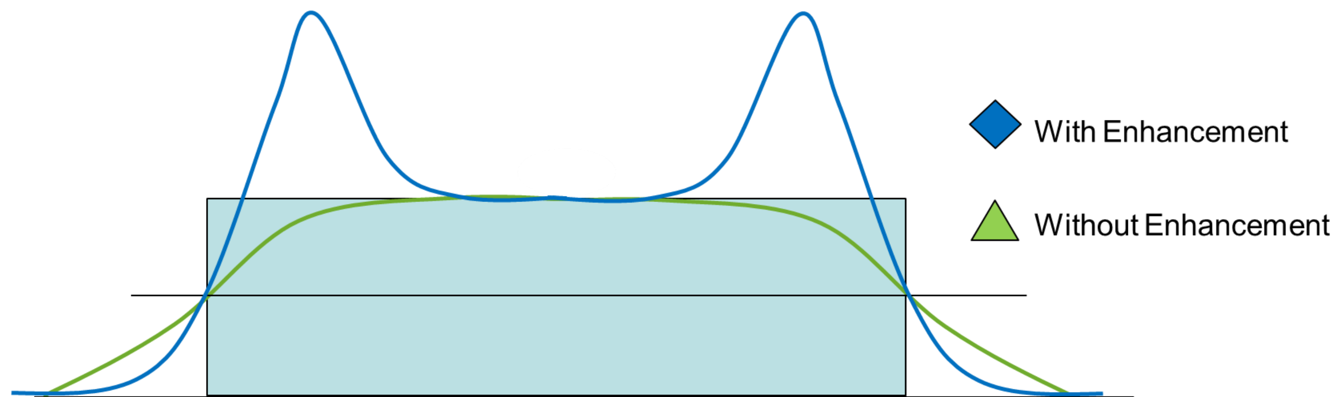


overlay

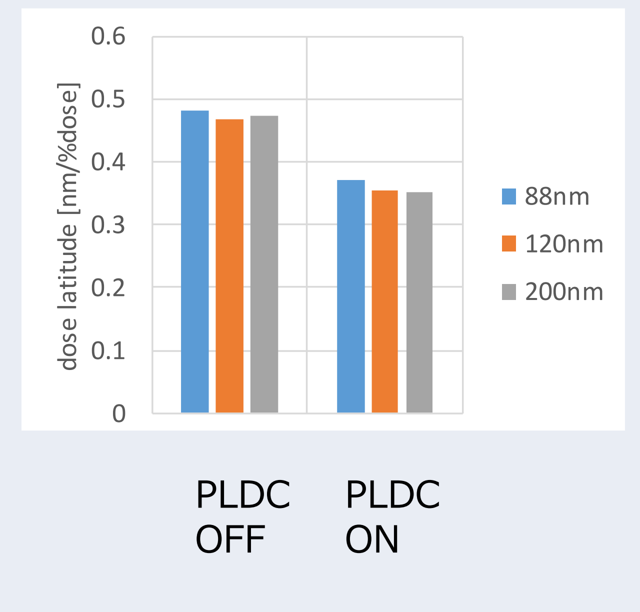
- Improved corner rounding can be confirmed visually

Dose Latitude

Dose Latitude (CD-Dose sensitivity) @ 25% density	pCAR(80uC/cm²)
No PLDC [nm/%dose]	0.48
w/ PLDC [nm/%dose]	0.36
Improvement by PLDC	25%

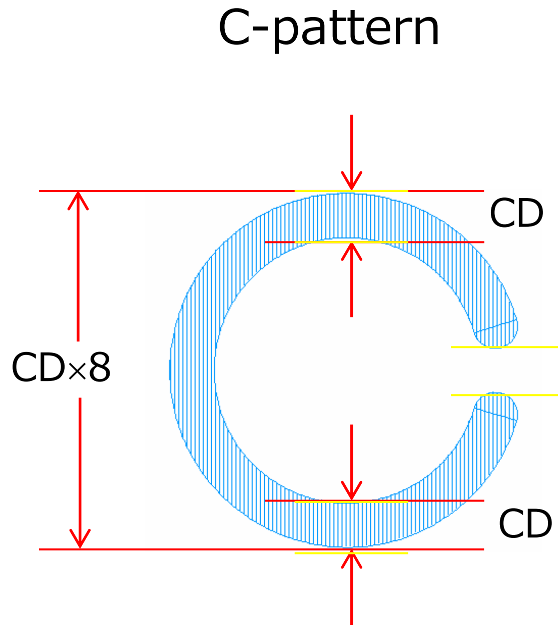


Zable et al. Proc. of SPIE Vol. 10454 104540D-1 (2017)

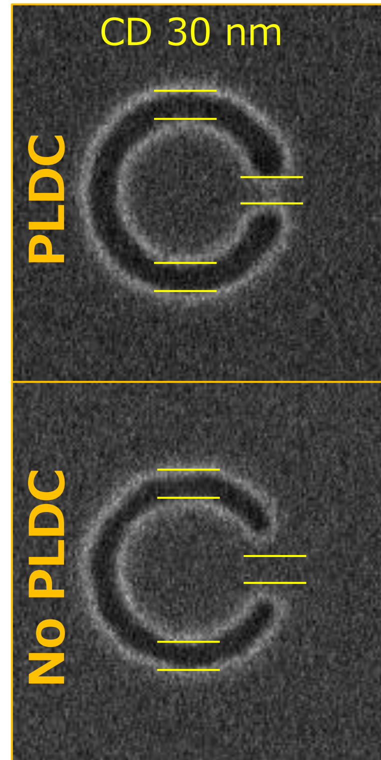


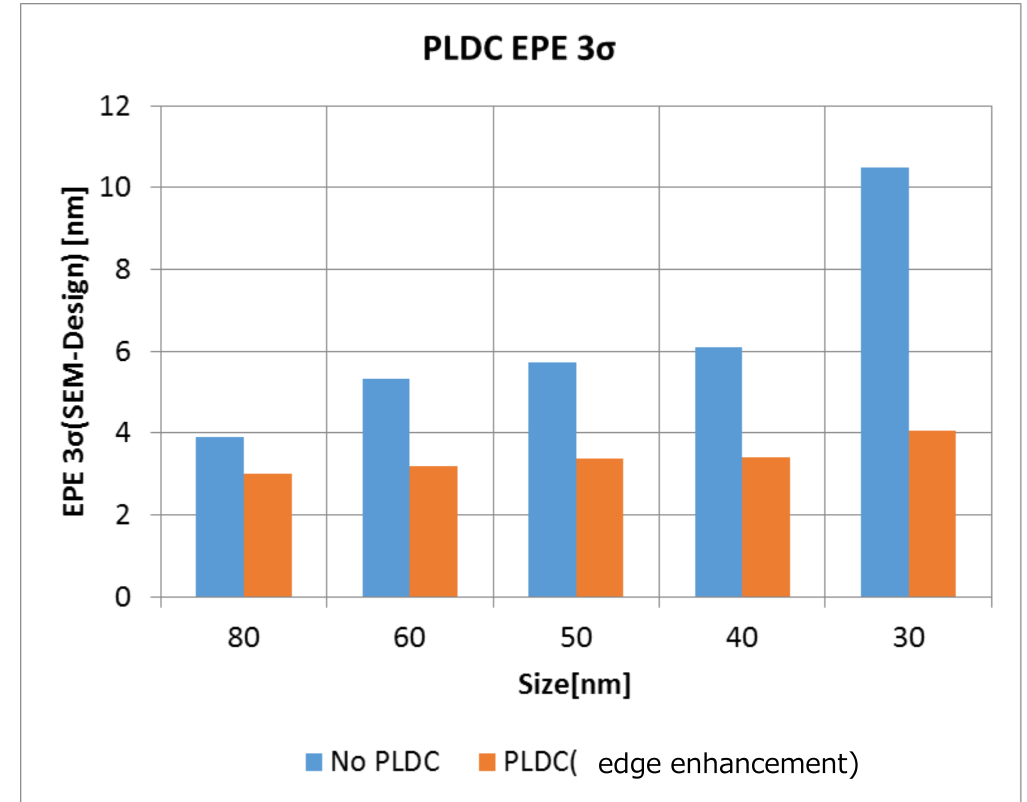
- Dose latitude is improved by PLDC

Edge Placement Error (EPE)



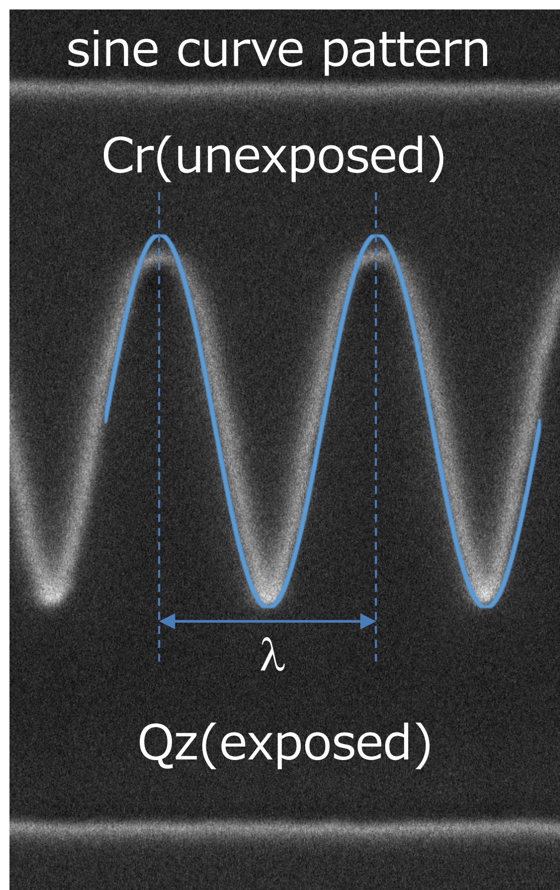
H.Matsumoto et.al, SPIE Vol.11324-20 (2020)



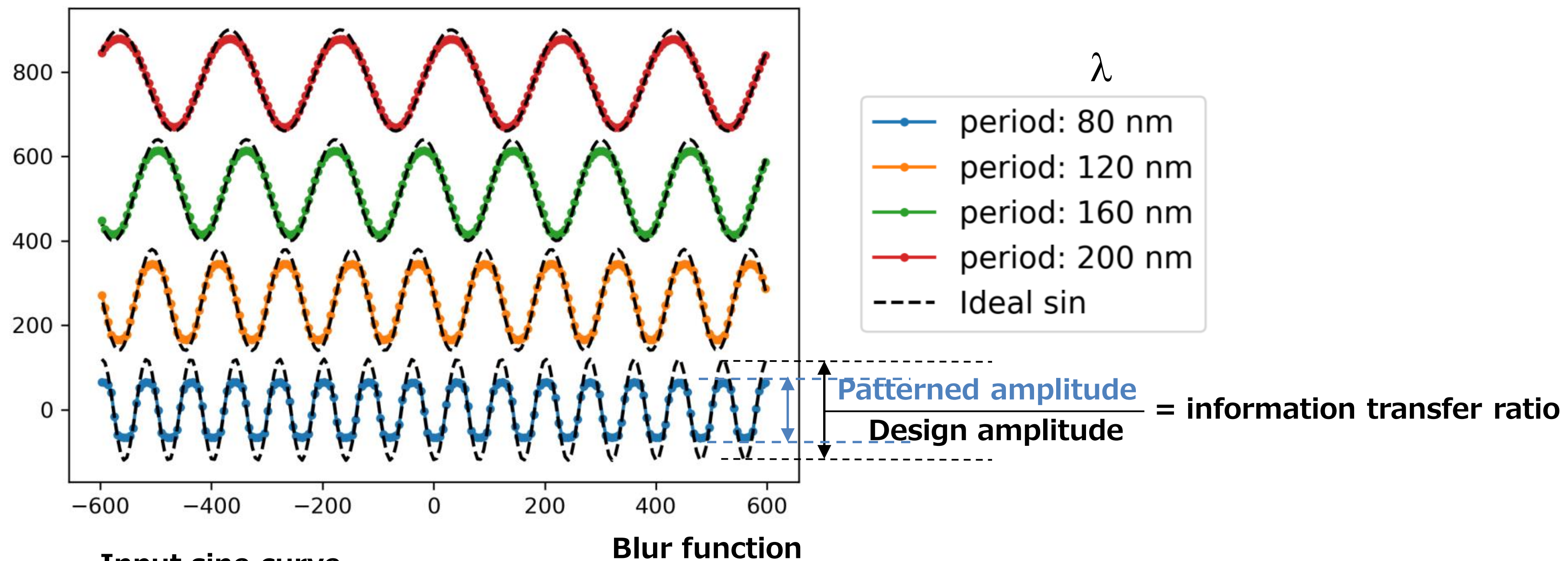


- PLDC keeps EPE of C-pattern at around 3~4nm in 3σ
  - Equivalent to Line Edge Roughness (LER)

Information Transfer Ratio : Theory



Contour results by SEM function (solid) vs. input sine curve (dashed)



Input sine curve

$$f(x) = A\sin\frac{2\pi x}{\lambda}$$

$\otimes$

Blur function

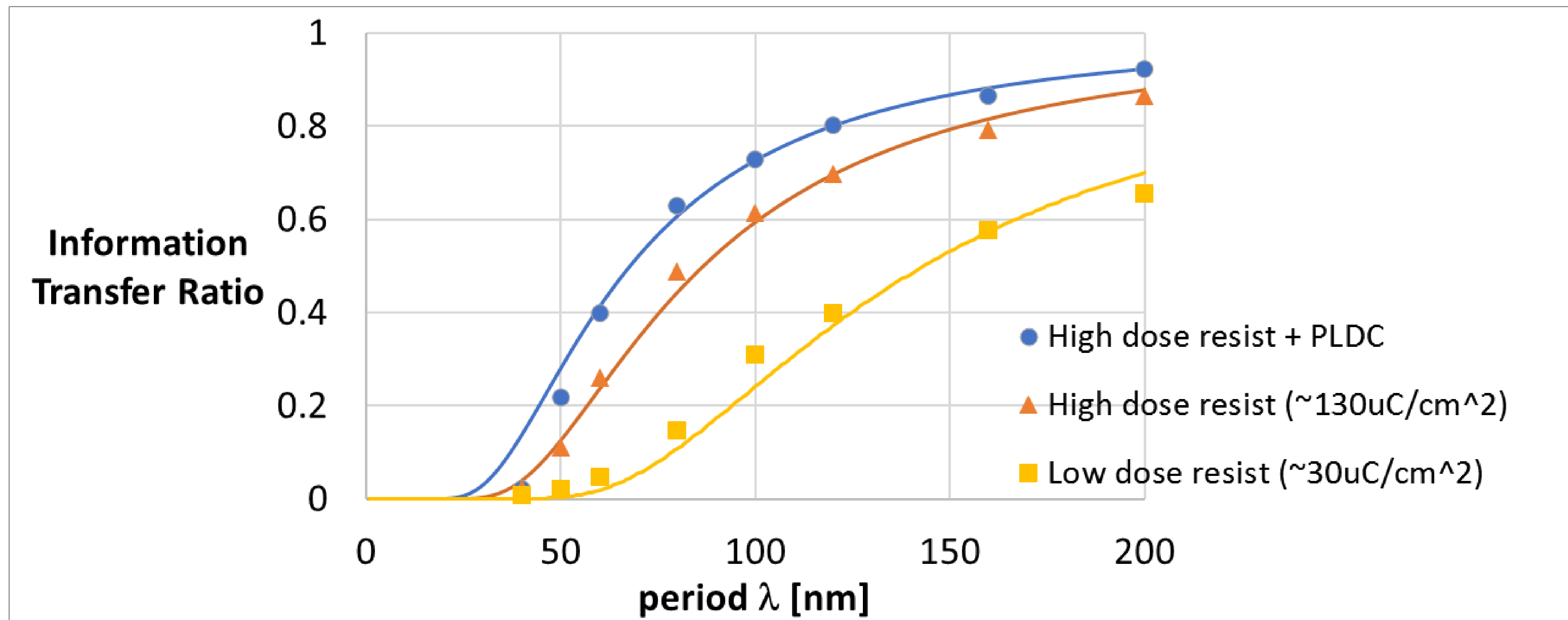
$$g(x) = \frac{1}{\sqrt{\sigma_{\text{edge}}\pi}} e^{-\frac{x^2}{\sigma_{\text{edge}}^2}}$$

$$= e^{-\frac{(\sigma_{\text{edge}}\pi)^2}{\lambda^2}} \cdot A\sin\frac{2\pi x}{\lambda}$$

information transfer ratio

is a function of period λ

Information Transfer Ratio : Results



Patterning Blur $\boldsymbol{\sigma}_{\mathbf{edge}} = \sqrt{\sigma_{\mathrm{gray}}^2 + \sigma_{\mathrm{beam}}^2 + \sigma_{\mathrm{process}}^2 - \sigma_{PLDC}^2}$

- PLDC clearly improves information transfer ratio, i.e. patterning blur

Conclusion

- Multi-beam writer had allowed customer to get away from the problem of shot count increase
- It is regrettable if customer has to face the problem of figure count increase in MPC, again
- But PLDC can set you free from figure count increase by moving MPC to inline datapath, because total pixel count is constant
- Let us help redefining MPC flow to optimize the balance between figure domain’s work and pixel domain’s work, and get away from the figure count increase together