Ryan Pearman, P. Jeffrey Ungar, Nagesh Shirali, Abhishek Shendre, Mariusz Niewczas, Linyong Pang, Aki Fujimura, D2S, Inc.

Enhancing ILT process window using curvilinear mask patterning: dual mask-wafer simulation

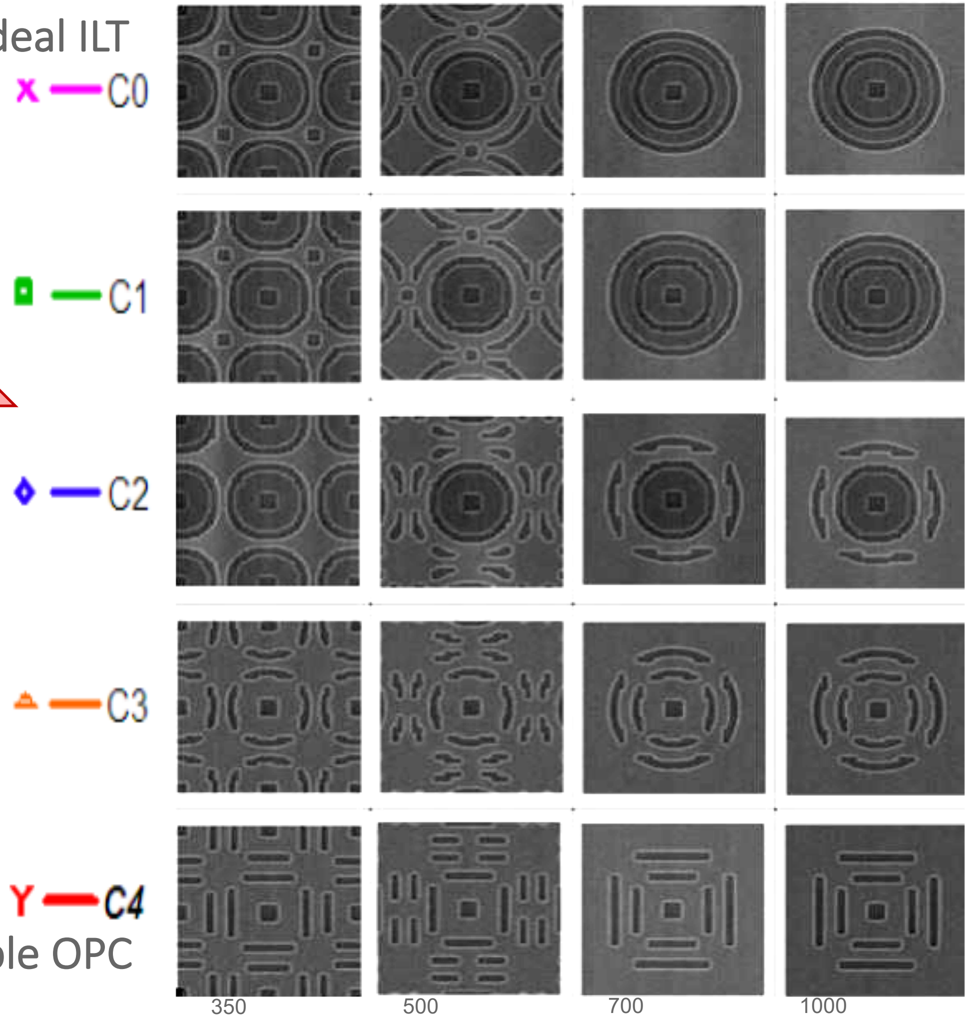
Ryan Pearman, P. Jeffrey Ungar, Nagesh Shirali, Abhishek Shendre, Mariusz Niewczas, Linyong Pang, Aki Fujimura, D2S, Inc.

Why We Prefer Curvilinear Features: A Monte-Carlo Approach

ILT is All About the Mask You Can Make

Ideal ILT

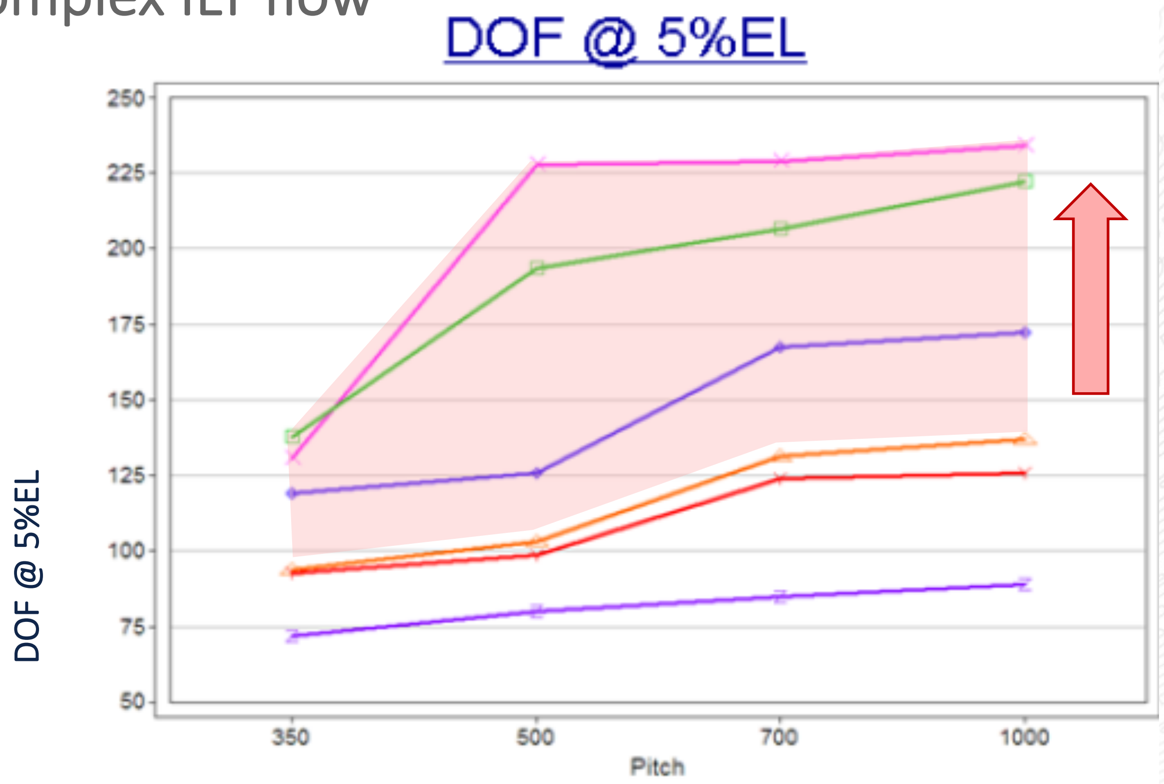
Mask complexity



Simple OPC

Mask manufacturability

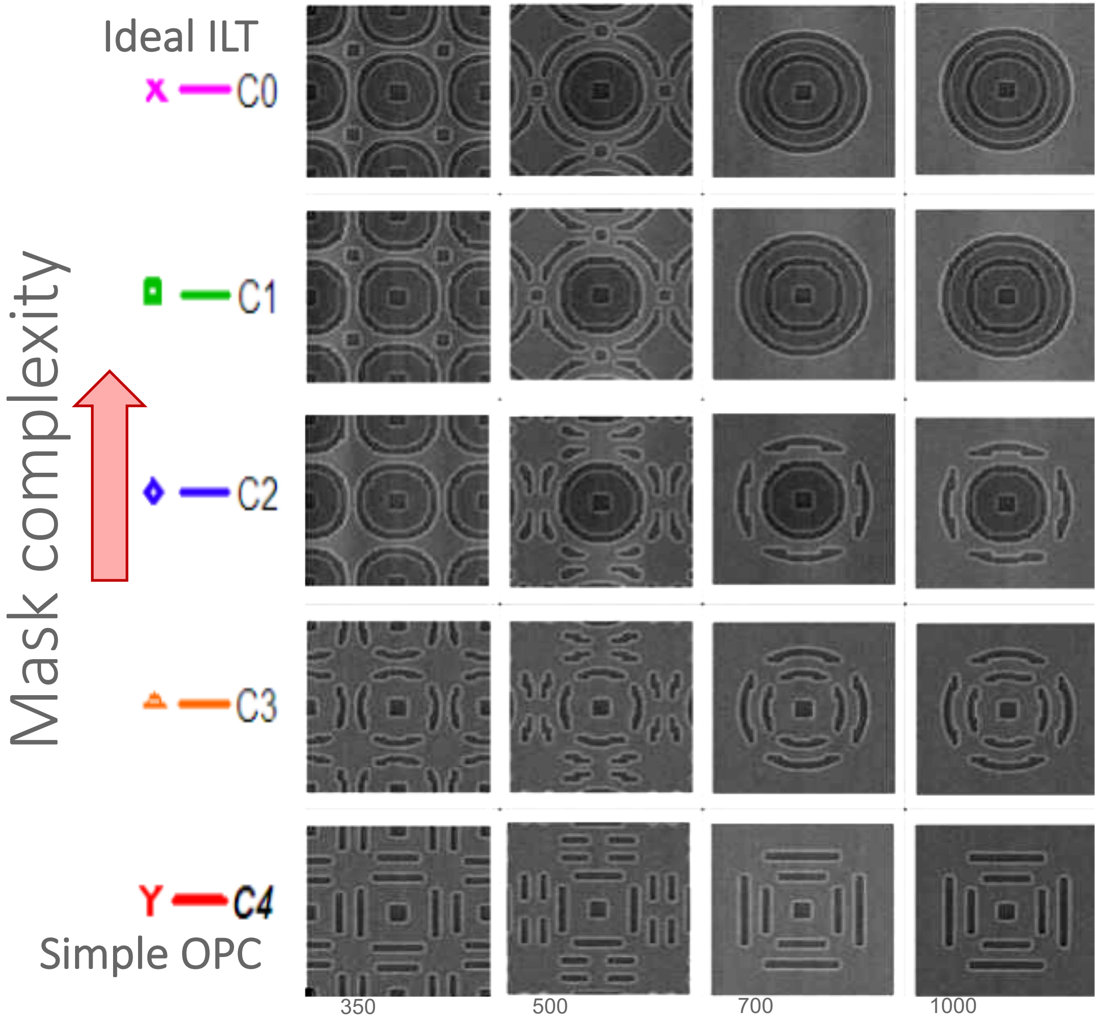
Complex ILT flow



Much better process window is possible with unconstrained shapes

The base study on conventional fracturing is courtesy of Byung-Gook Kim, et al., PMJ 2009

ILT is All About the Mask You Can Make



The base study on conventional fracturing is courtesy of Byung-Gook Kim, et al., PMJ 2009

Complex ILT flow

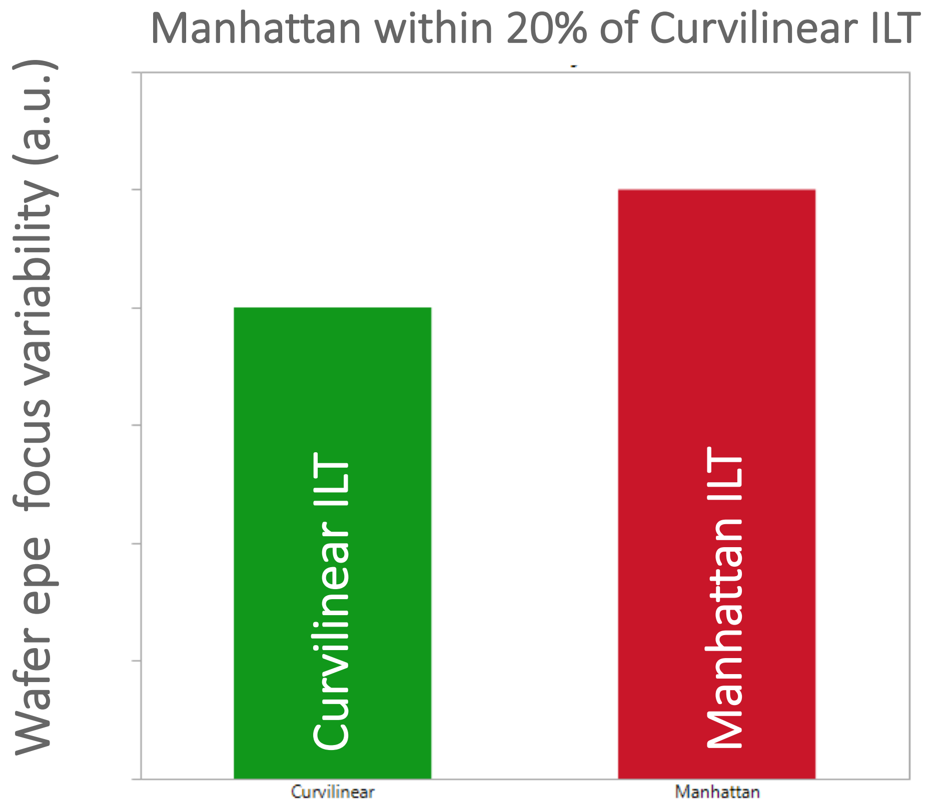
- Ideal ILT generation
- Clean mask with mask rules
- Manhattanization
- Re-optimization of Manhattan Pattern

Hard to implement mask rules in curvilinear space post ILT. >2X slower

"Degrade" the solution, time consuming >2-4X slower

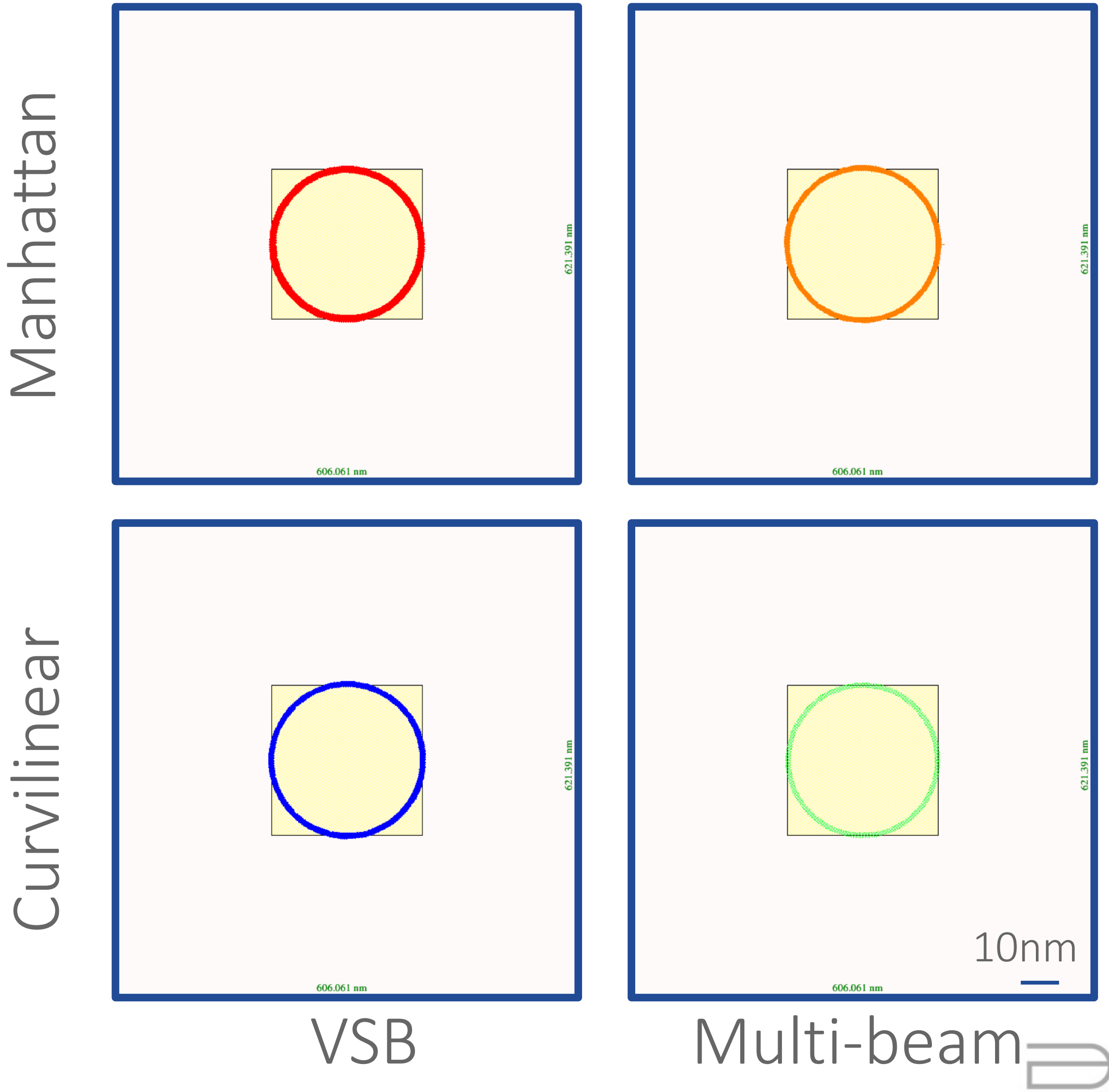
Too slow for full-chip!

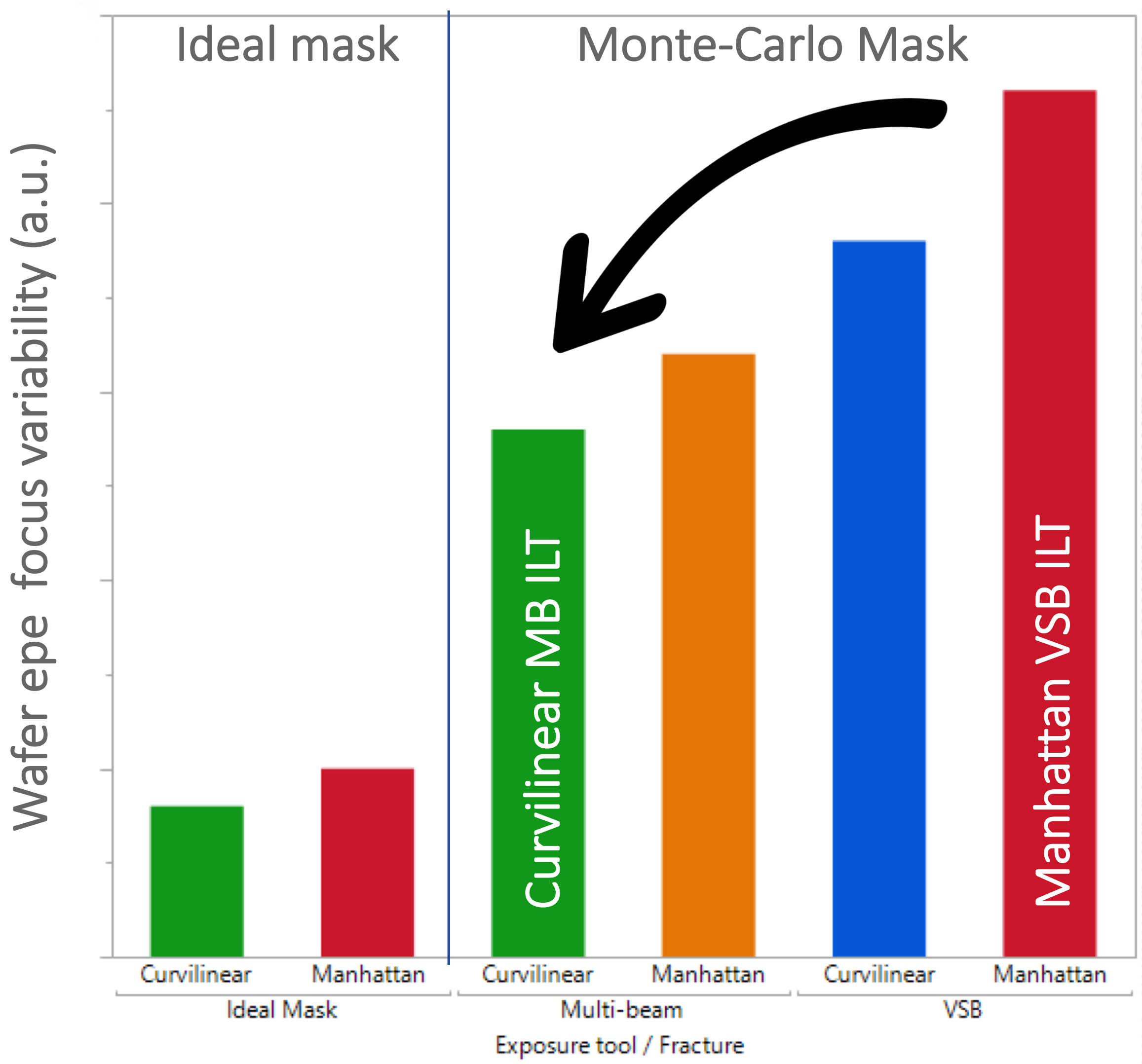
Manhattan is Good Enough, Right?



- Widely held assumption: ILT is better done with curvilinear shapes
  - Level set methods are intrinsically curvilinear
- But mahnattan ILT is “equivalent” and “close enough”
  - Careful manhattanization can get very close to the “ideal” result for 193i lithography
- A simple study agrees with this assessment – on the wafer plane only
  - When mask variability is taken into account, using curved features for ILT can reduce wafer variability by ~40%

No, Curvilinear Shapes Really Are Needed





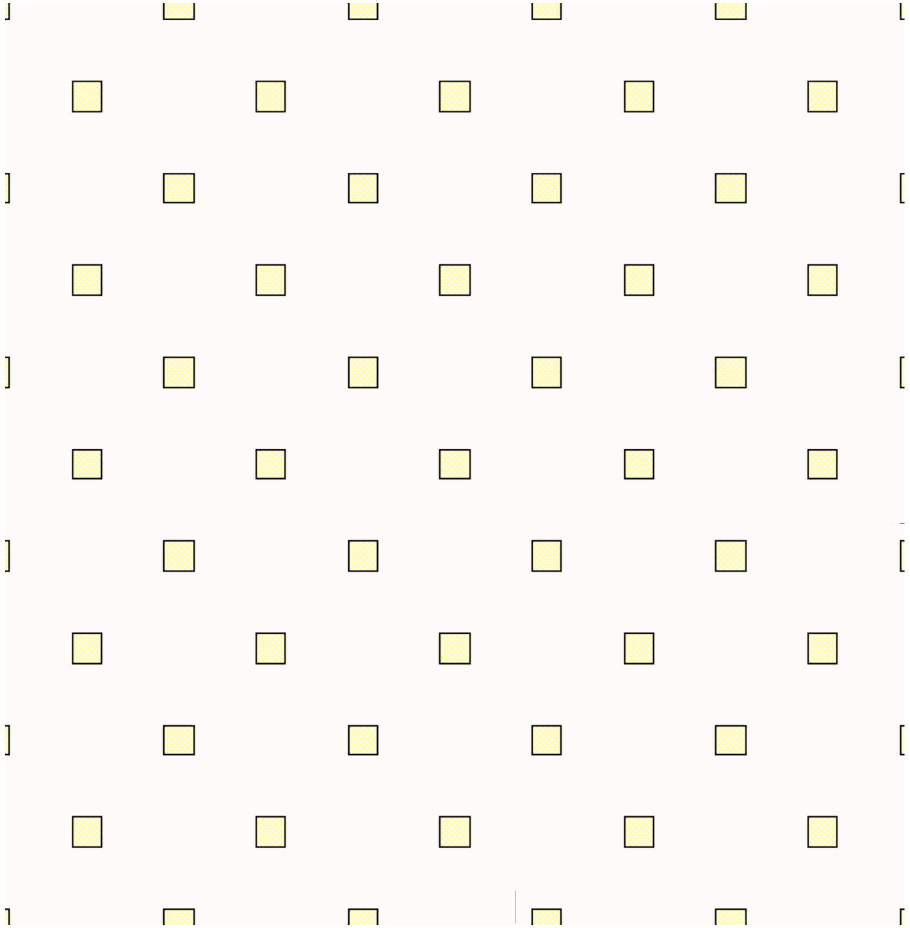
We Will Tell a Story About Immersion ILT

- Demonstrate the conditions under which curvilinear and manhattan masks can give virtually identical process windows
- Review why we have to manhattanize masks in the first place – and why that assumption is now broken
- Discuss why MEEF is not MEEF, and use a Monte-Carlo sampled distribution of possible masks to demonstrate why curvilinear features are necessary for the best process window

How Can Manhattanized ILT and Curvilinear ILT be Equivalent for Immersion Lithography?

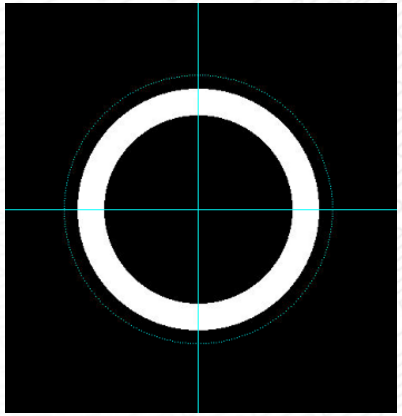
Investigate a Simple System

50nm contact target, staggered array @219.2nm effective pitch



310nm

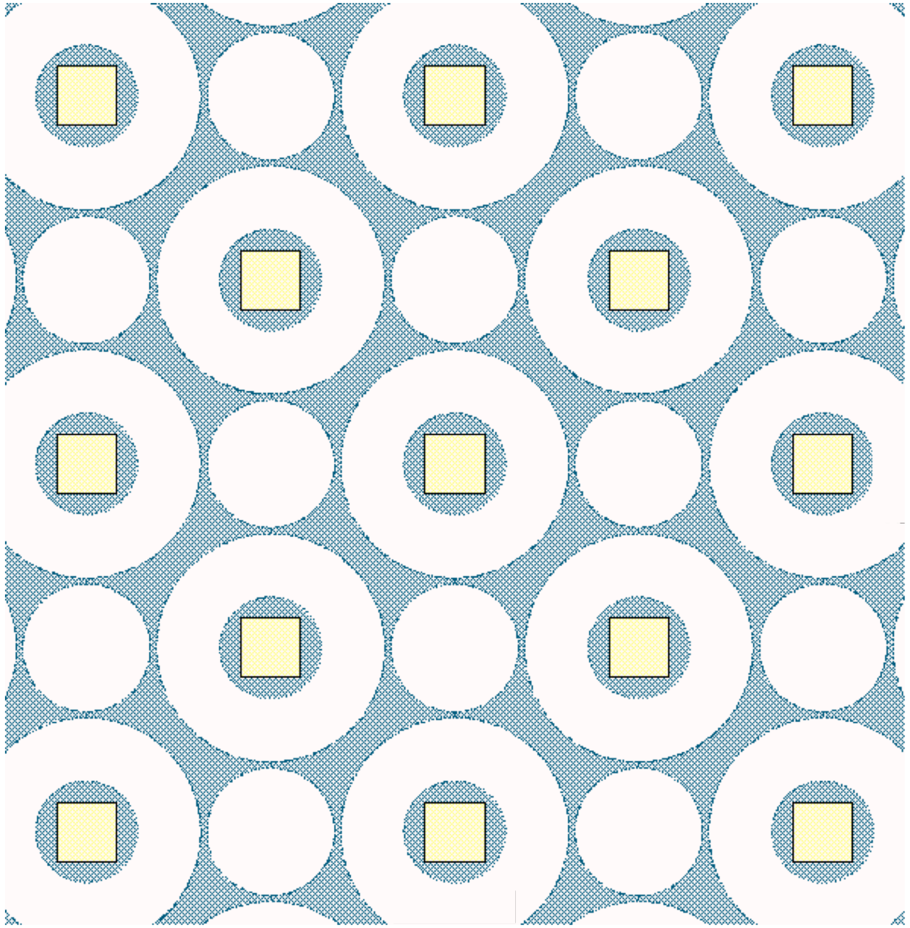
- **Prints to +/-2nm process band without assist features**
- Use a generic source:
  - Annular, 0.9/0.7, TE polarized
  - Looks like a VIA or cut mask



- Ideal pupil function
  - Aberrations won’t change result
- Focus only on the optical image – ignoring all resist effects
  - Ignore resists can enhance process margin
  - Better optics giving smaller variance through focus

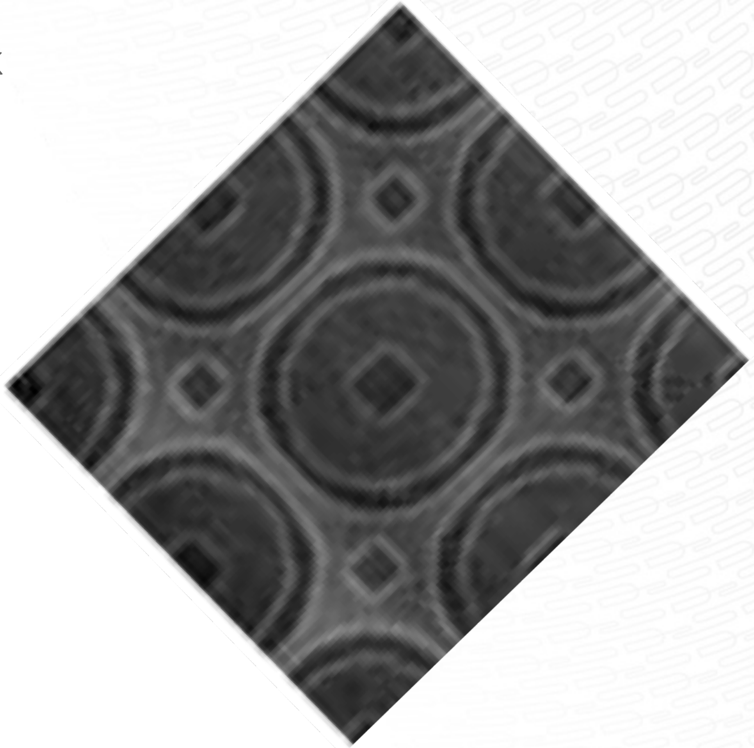
Can do "Analytical" ILT for Contact Holes

"Best" solution looks like sets of concentric circles



310nm

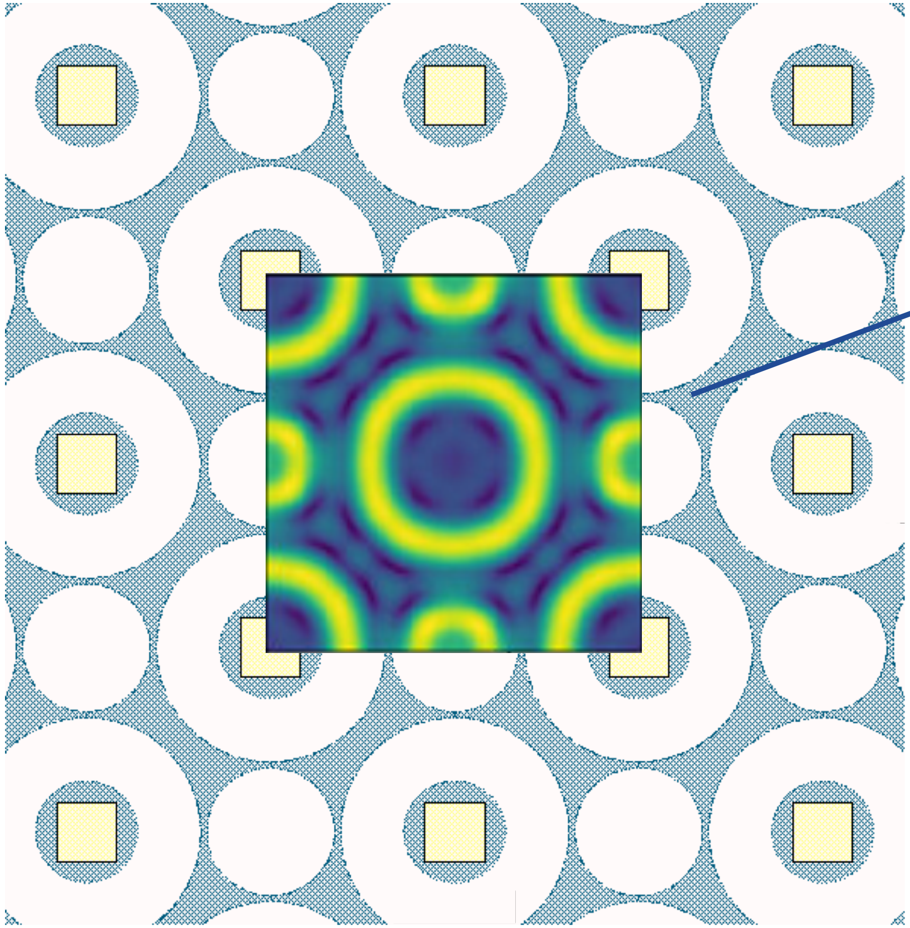
Clear field, 6% mask



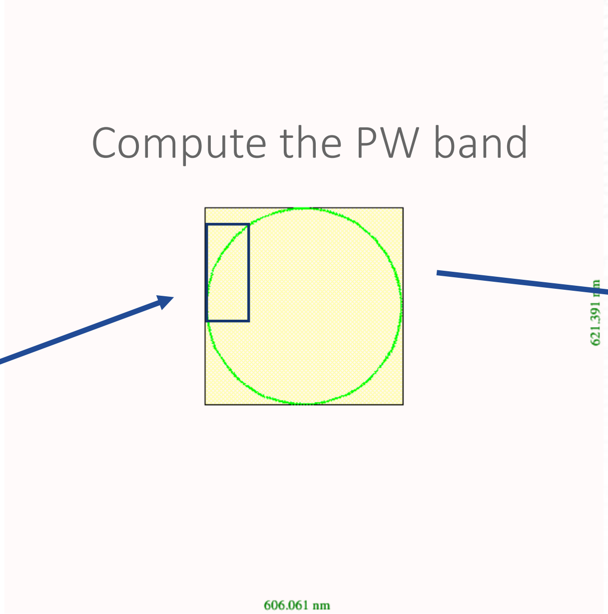
- Manually optimize the rings for best process margin around the target
- Goal: set up a reasonable system to study the effect of mask stochastics

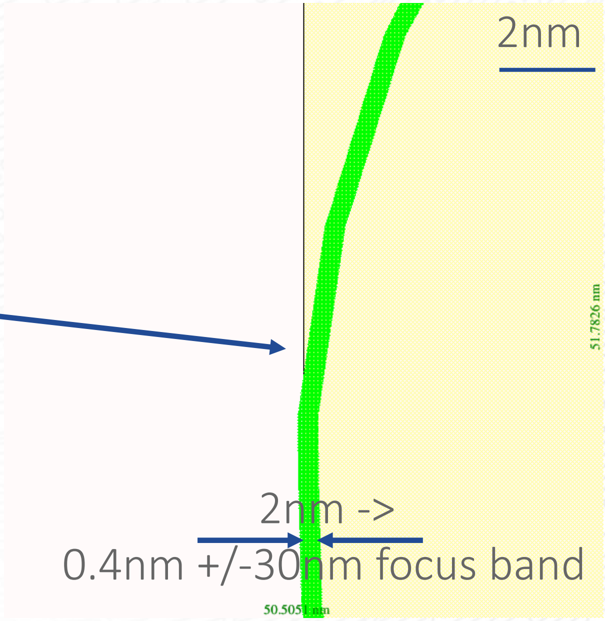
Variance Bands At +/-30nm Are Very Low

Compute the Band-Limited (ctm) Mask



310nm

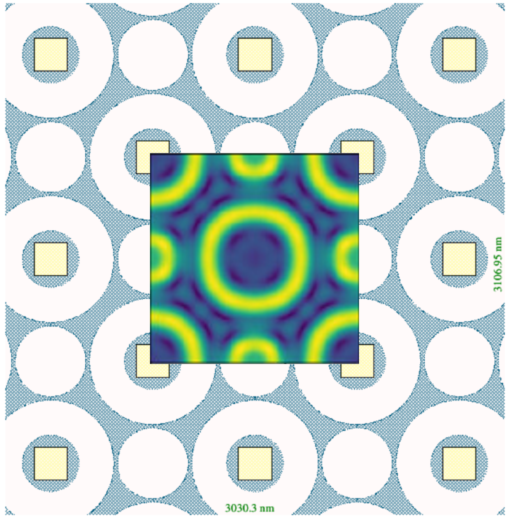




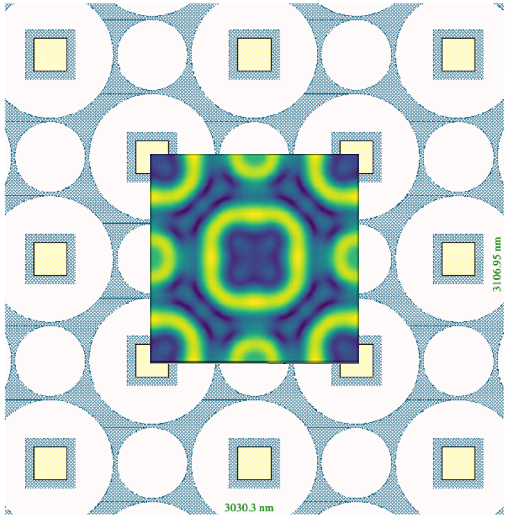
- Optical simulation uses a GPU-accelerated Rigorous Mask 3D simulation on Curvilinear Geometry
- Periodic array 310x310nm – simulation time under 2 seconds.
  - 4 source locations
  - 150nm mask stack, including boundary layers in z
  - 4nm (x,y) 1nm (z) resolution in mask dimensions

D2S

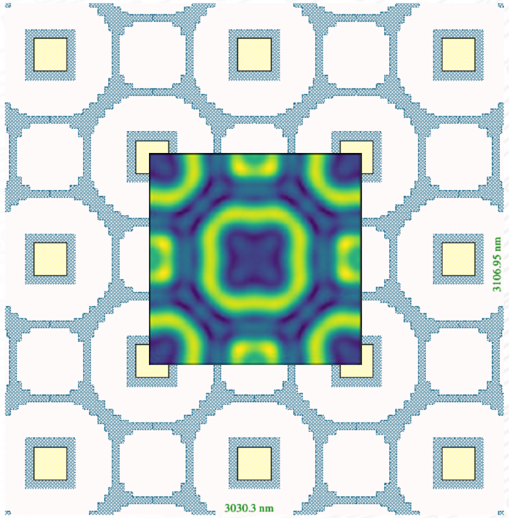
Manhattanizing Works For 193i Lithography



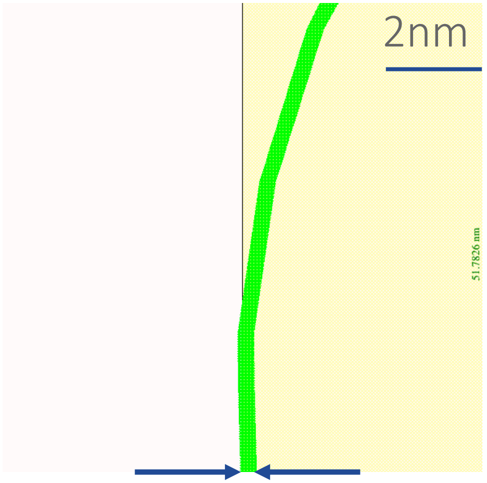
Curvilinear ILT



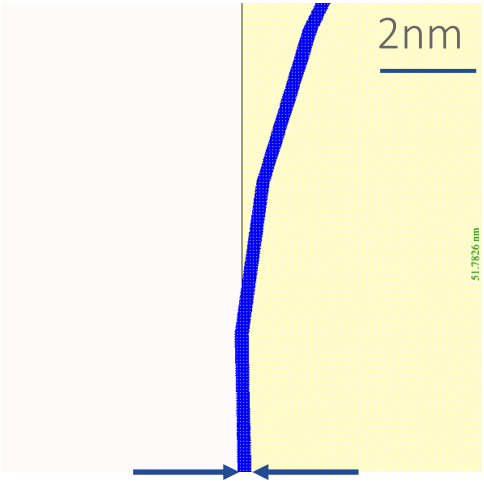
Curvilinear ILT AF, OPC core



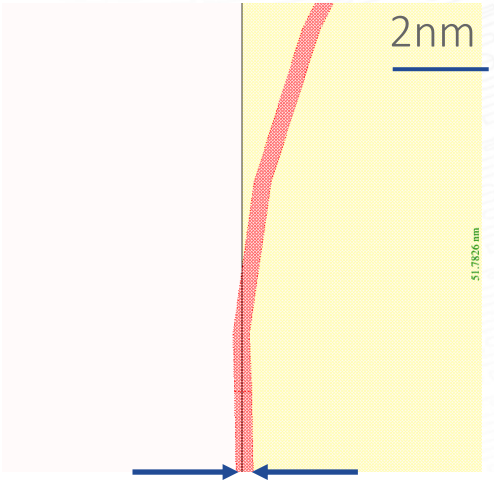
Purely Manhattan ILT



0.4nm +/-30nm focus band



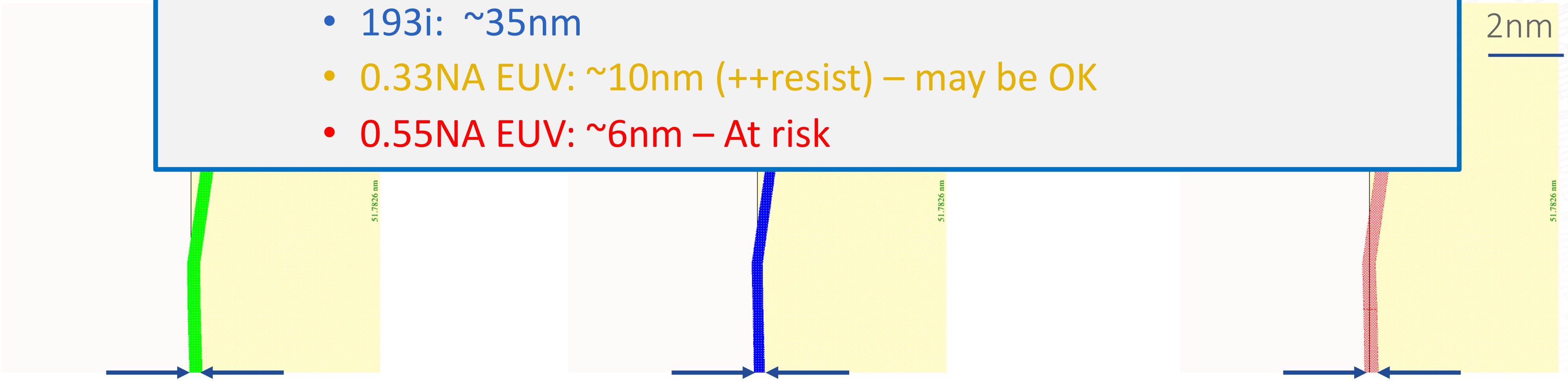
0.4nm +/-30nm focus band



0.5nm +/-30nm focus band

Manhattanizing Works For 193i Lithography

- Infinitely many ILT solutions all have similar band-limited masks:
  - Have features in the similar locations
  - Have area about the same over the same length scale:
    - 193i: ~35nm
    - 0.33NA EUV: ~10nm (++resist) – may be OK
    - 0.55NA EUV: ~6nm – At risk



0.4nm +/-30nm focus band

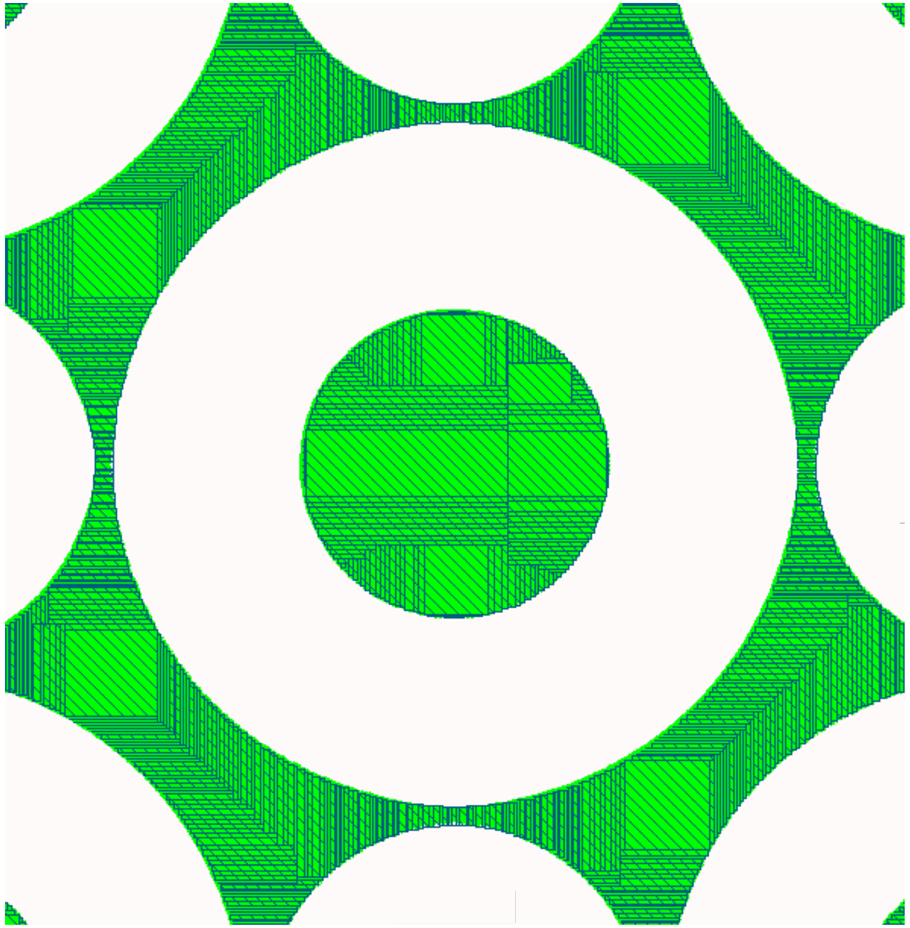
0.4nm +/-30nm focus band

0.5nm +/-30nm focus band

Why Do (Did) We Have to Manhattanize ILT for Immersion Lithography?

Writing Curvilinear Masks Took a Lot of Time

Curvilinear masks have lots of small rectangles



125nm

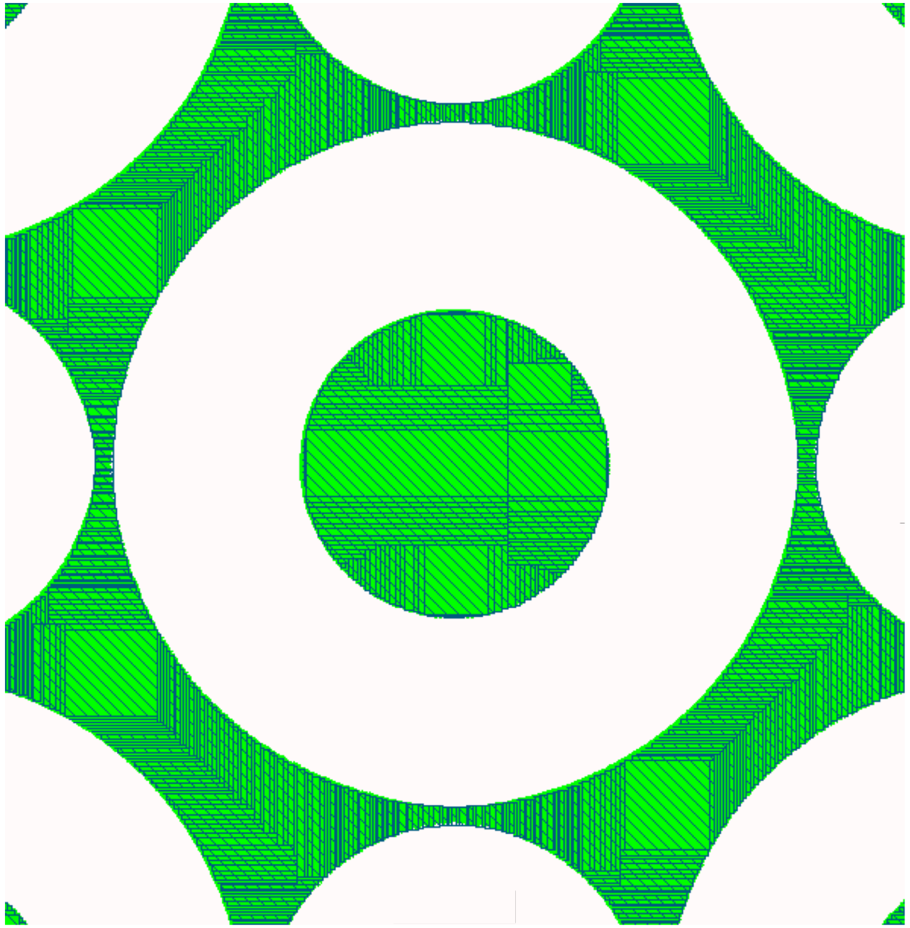
Manhattanized masks have many fewer shots

- How do masks get made?
  - In VSB, we fracture or "break into rectangles"
  - The more curves, the more rectangles you need
- Mask write time is a (linear) function of how many rectangles you use
  - The longer it takes to make the mask the more mask defects you get
  - <24 hours is the typical limit, most companies want less
- The mask on the left is not manufacturable for high-volume production

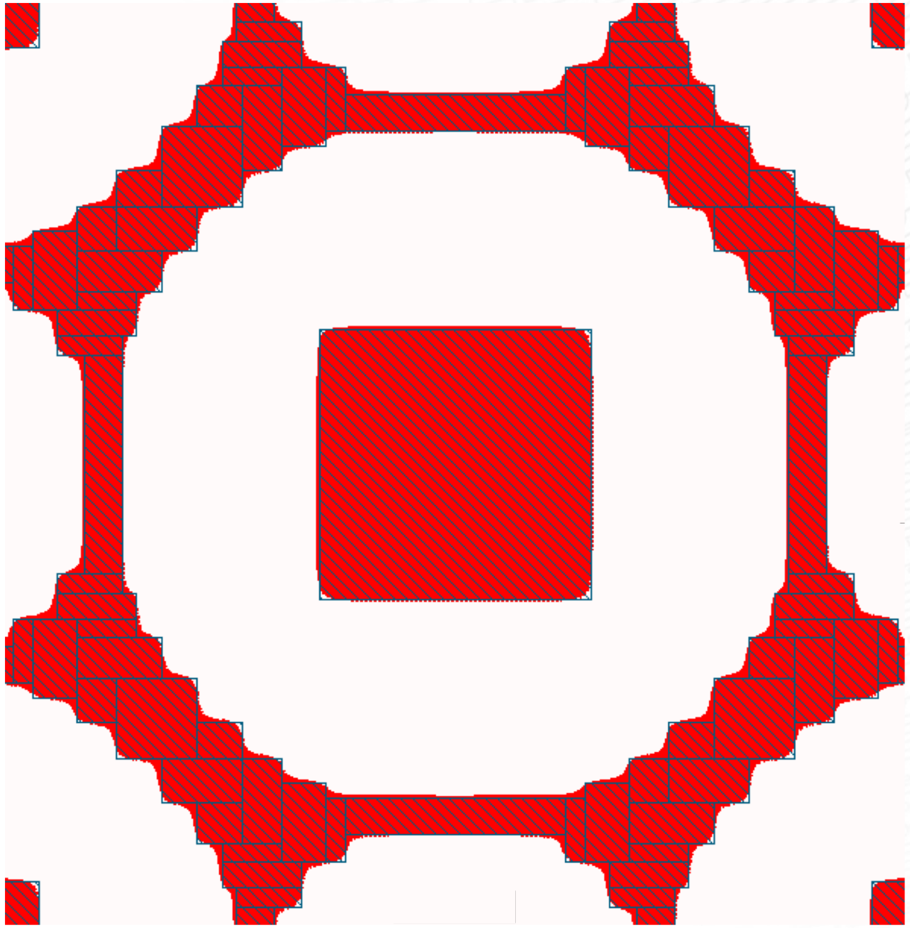
Equivalent process window: tradeoff ILT runtime for mask yield

Writing Curvilinear Masks Took a Lot of Time

Curvilinear masks have lots of small rectangles



Manhattanized masks have many fewer shots

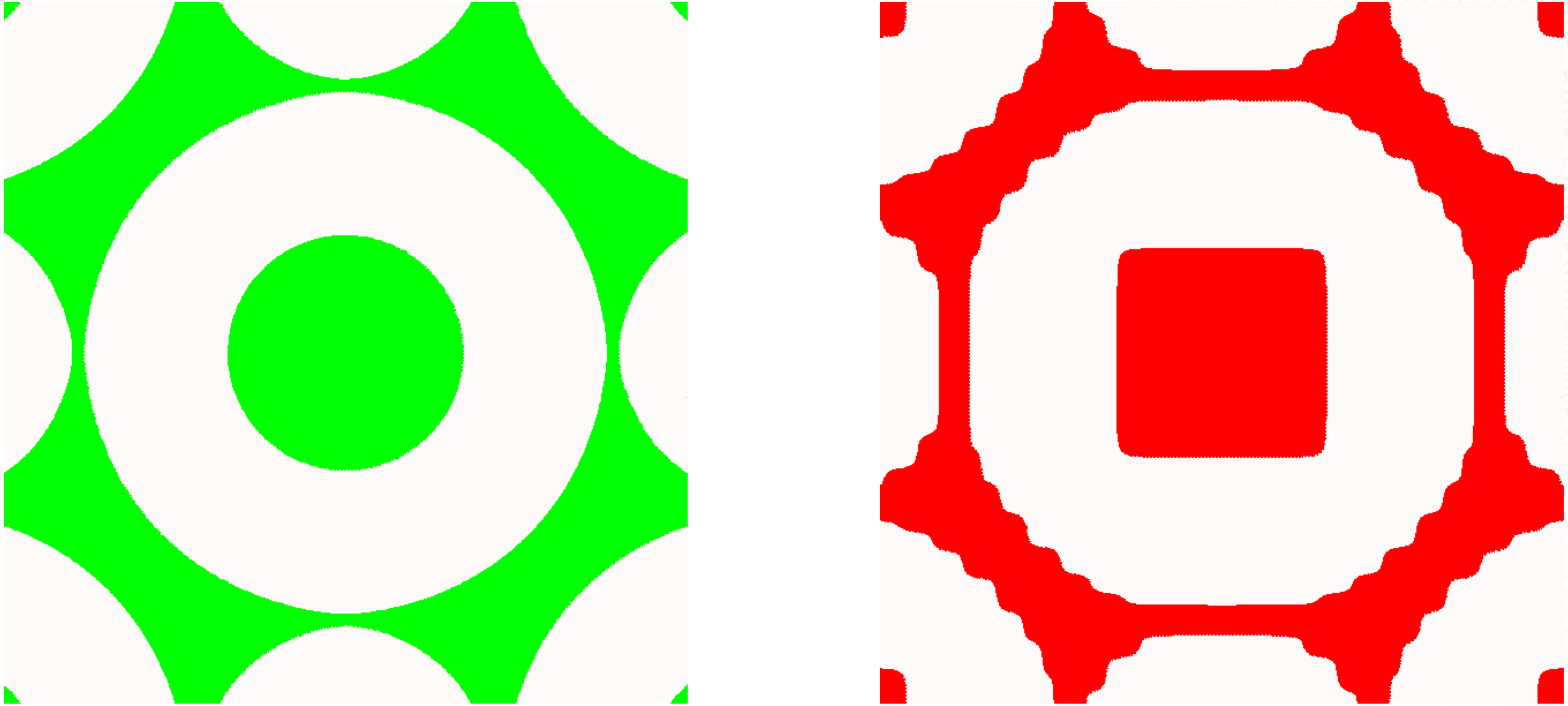


125nm

Equivalent process window: tradeoff ILT runtime for mask yield

Manhattan Masks are Curvilinear

All masks end up curvilinear due to mask process corner rounding

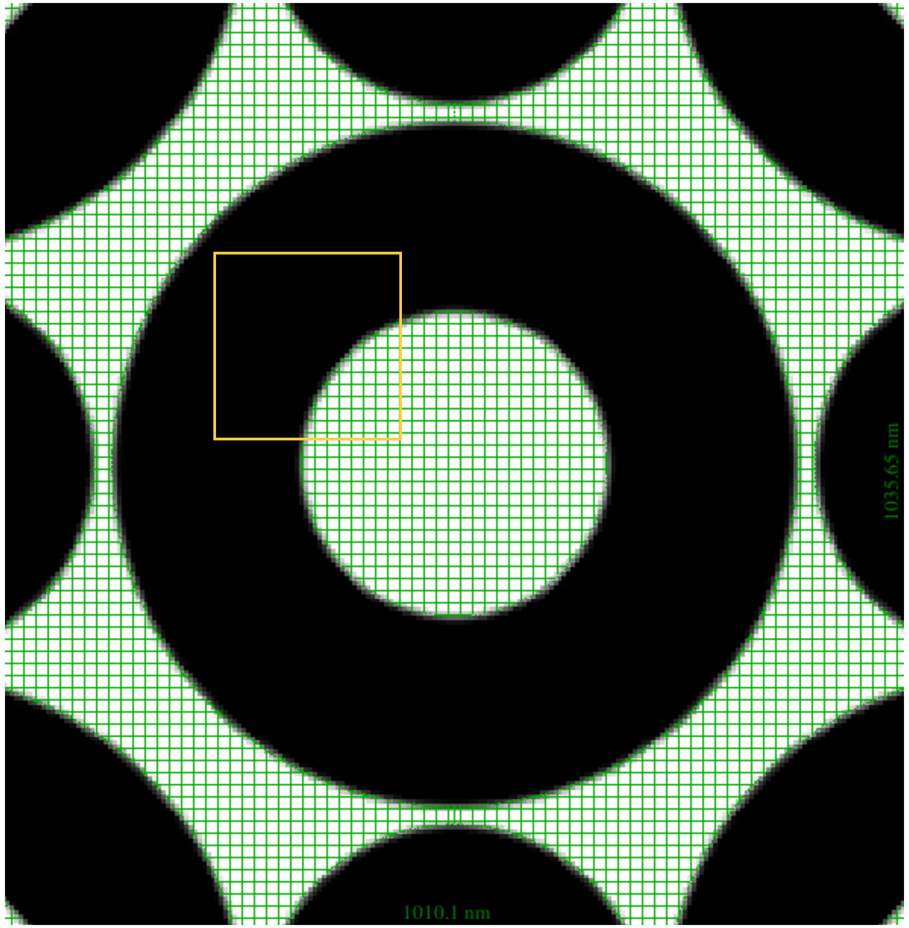


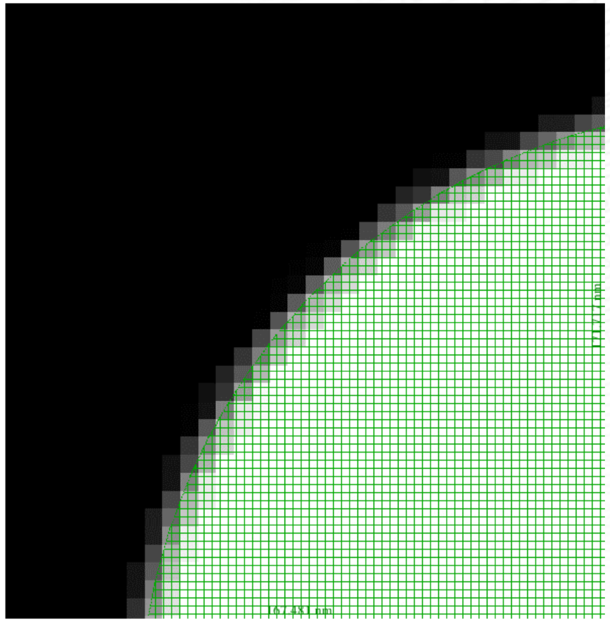
125nm

Additional OPC complexity: Mask Shape Modeling

Writing Curvilinear Masks do not Take Lot of Time

Some Multi-beam Mask Writers Can Even Do MPC for you





125nm

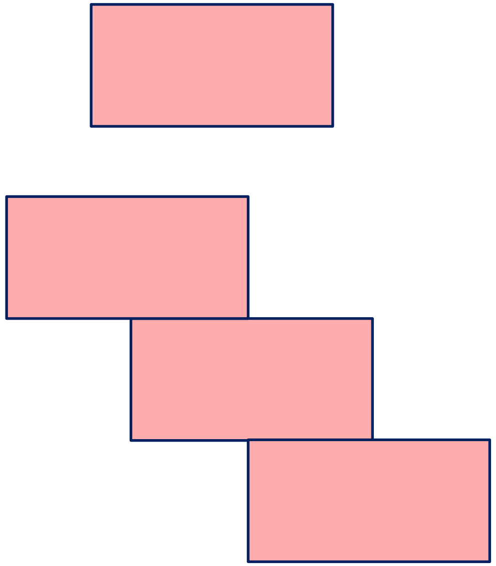
- Multi-beam mask writers can do this today
  - Write time is independent of complexity
- Hundreds of thousands of greyscale pixels.
  - Like a continuous tone mask – for mask manufacturing!
- No longer tradeoff for complex mask shapes

Should We be Continuing to Manhattanize ILT for Immersion Lithography?

Mask Variability Leads to Wafer Variability

But, not by MEEF

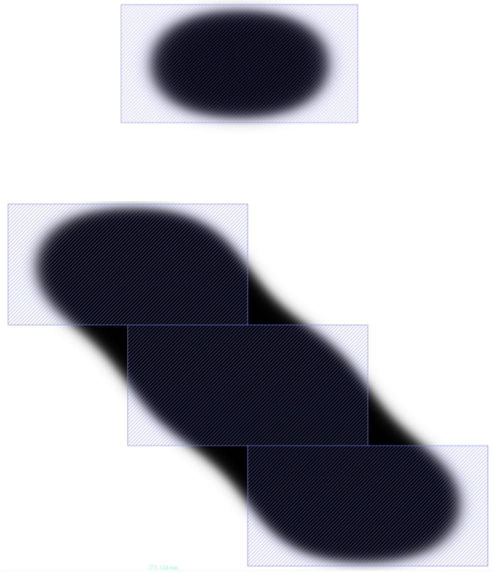
eBeam Shot



Mask Variability Leads to Wafer Variability

But, not by MEEF

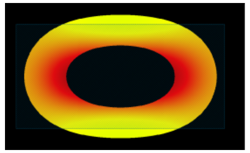
Simulated Image



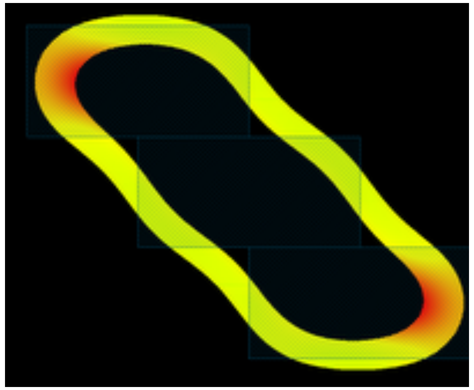
Mask Variability Leads to Wafer Variability

But, not by MEEF

Dose Margin

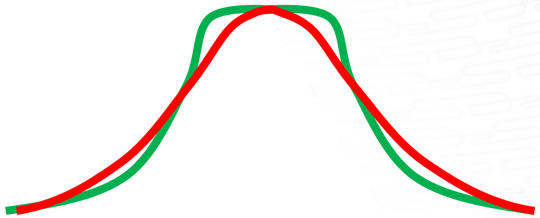


Bad DM
(red -- left and right)

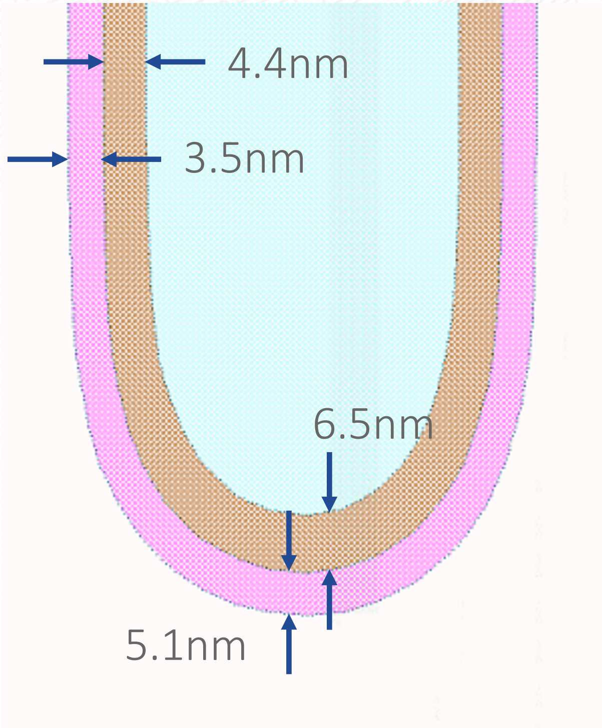


- Dose Margin ~ 1/"ILS"
- Worse dose margin when printed features deviate from eBeam
  - Small features (width or space)
  - Line-ends
  - Sharp corners
- Worse dose margin at higher pattern density

50% more variability on line end



Mask contour variability over 20% dose

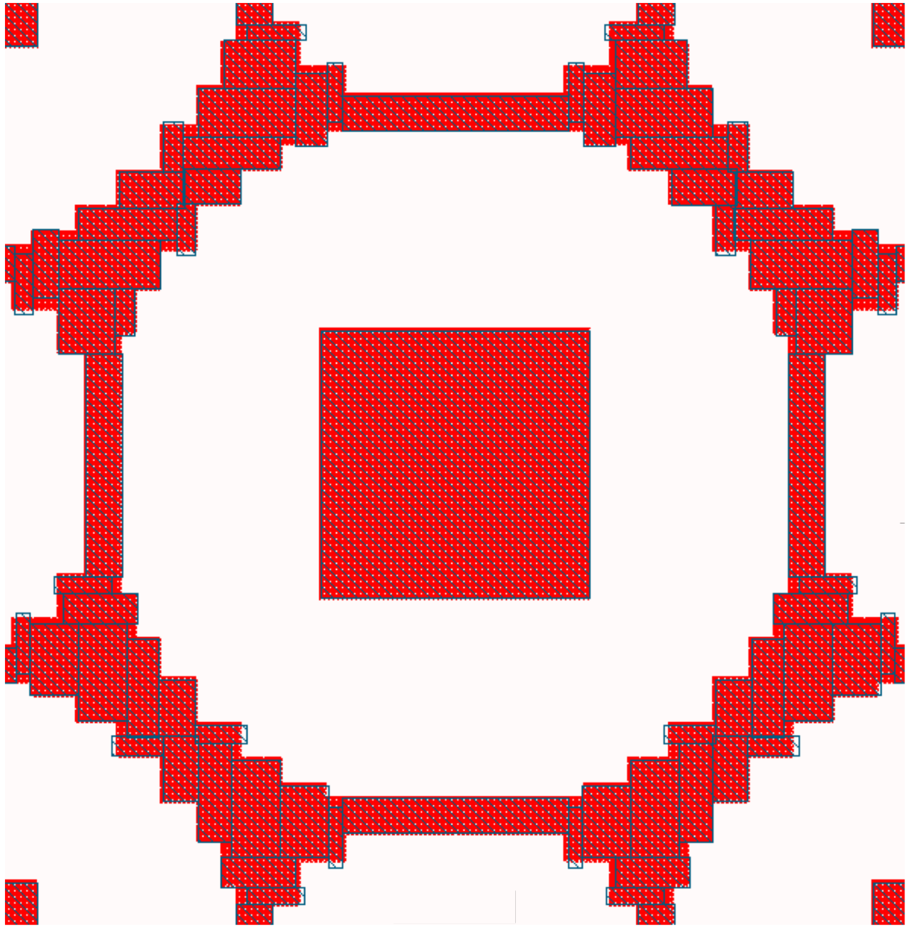


Unfortunate "coincidence":

Worst mask variability typically happens at wafer hotspots

Monte Carlo Analysis for Position and Dose of Every Shot

Manhattanized ILT mask

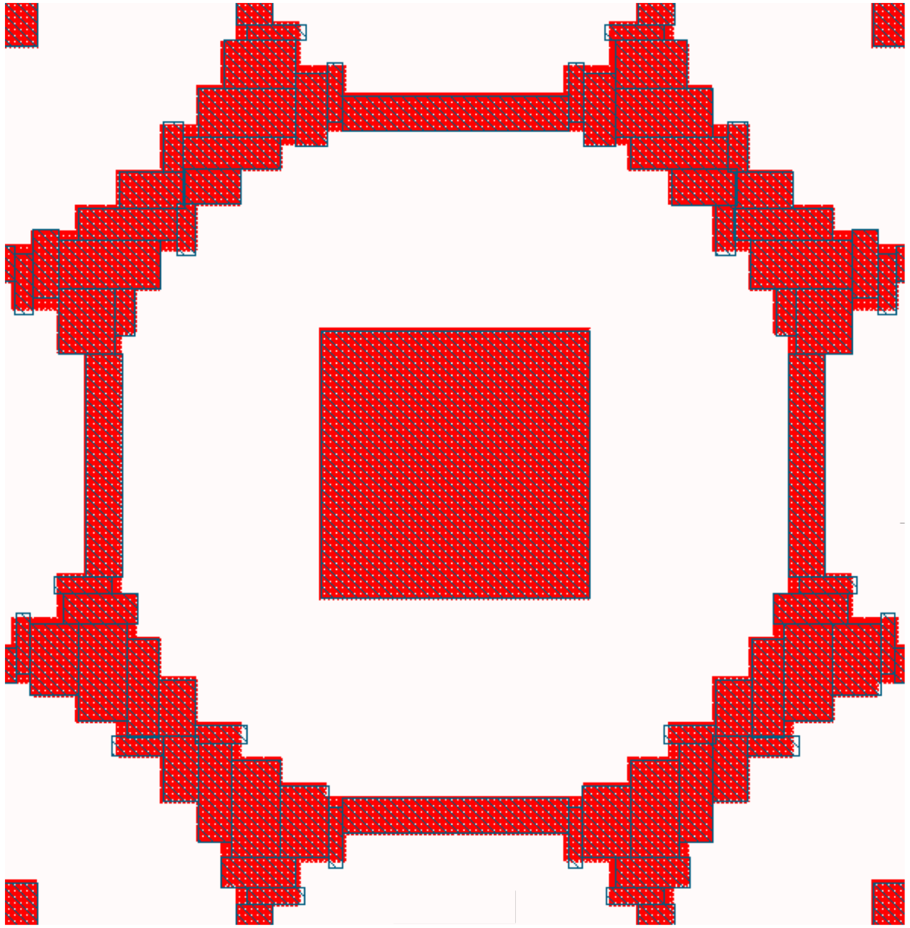


125nm

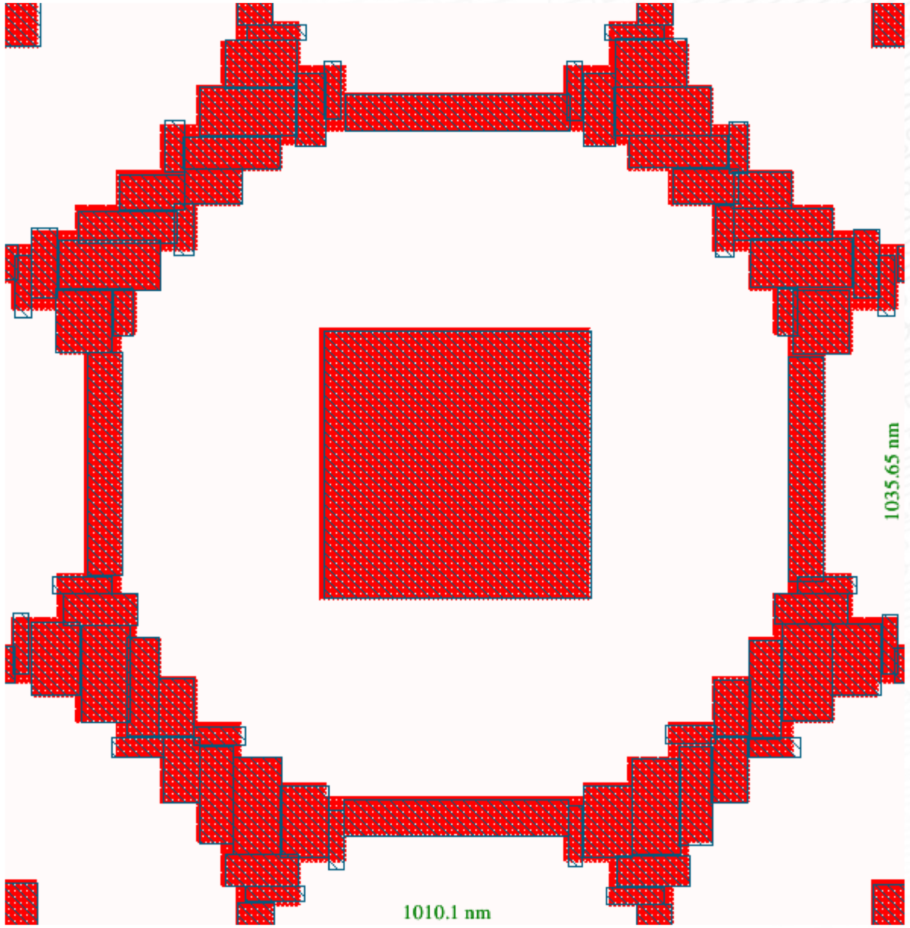
- We do a monte-carlo simulation of mask dose and positional errors
  - +/-5% dose
  - +/-0.2nm position
- Perform >100 perturbations of every shot in the optical simulation window
- Create a set of mask variability bands
  - From which we compute the optical variability bands

Monte Carlo Analysis for Position and Dose of Every Shot

Manhattanized ILT mask



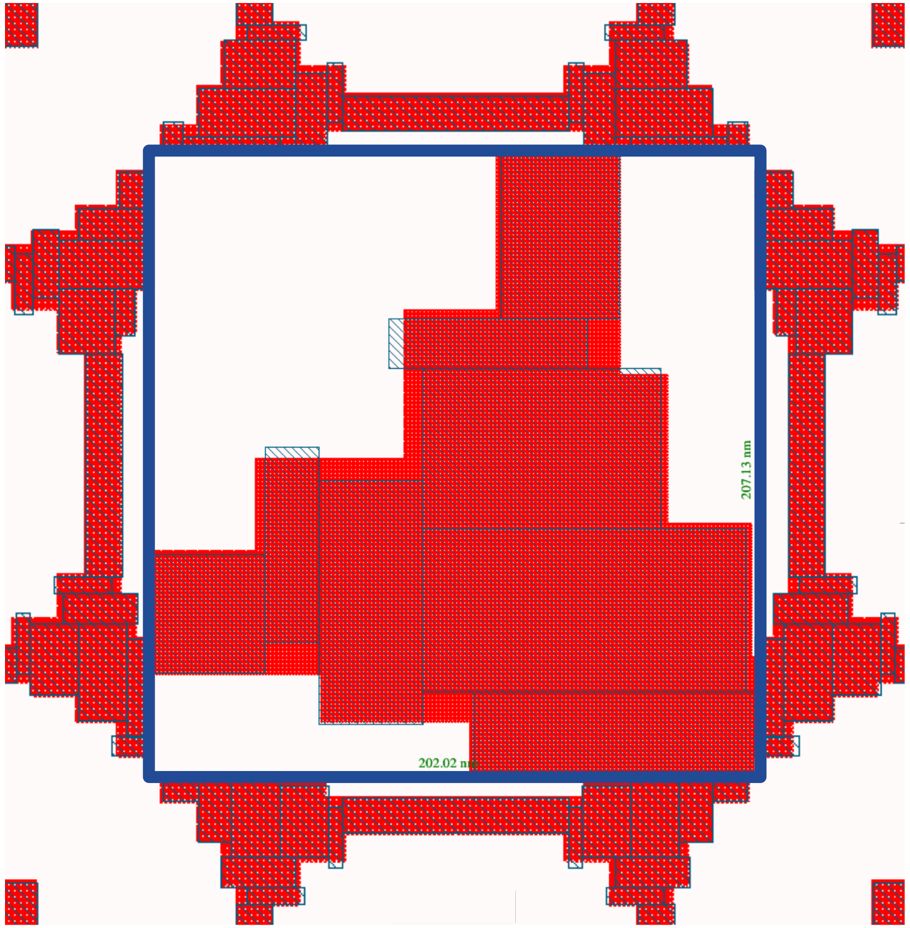
One Monte-Carlo epoch



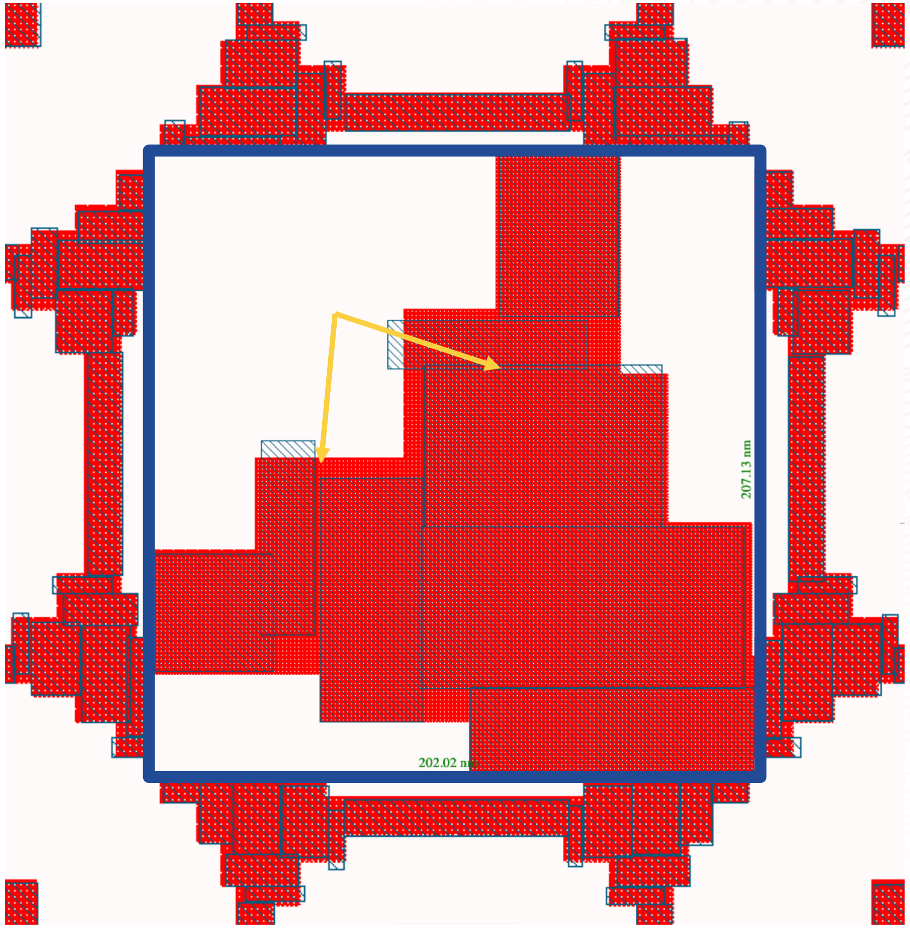
125nm

Monte Carlo Analysis for Position and Dose of Every Shot

Manhattanized ILT mask



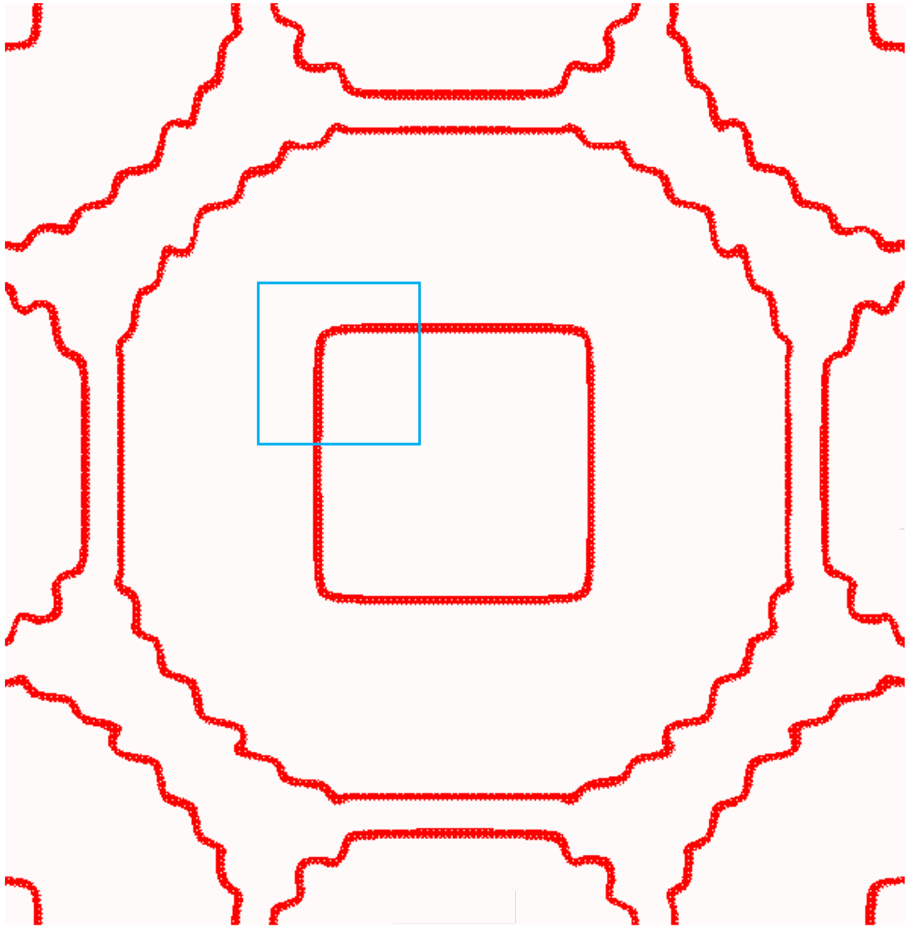
One Monte-Carlo epoch



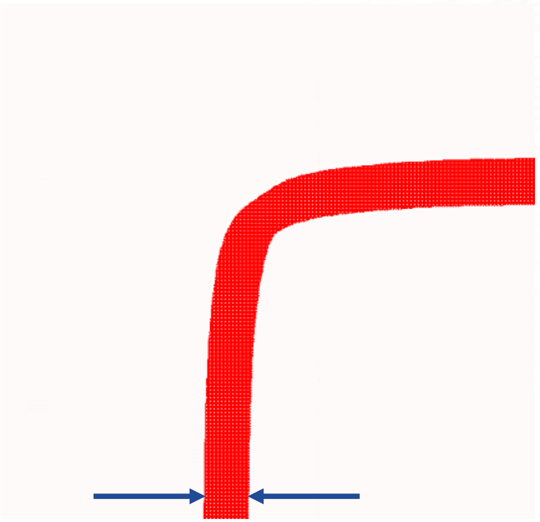
125nm

Monte Carlo Generates Many Masks ...and Many Wafer Contours

Mask variability band

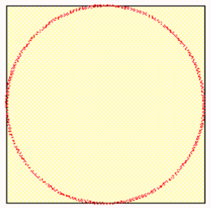


310nm



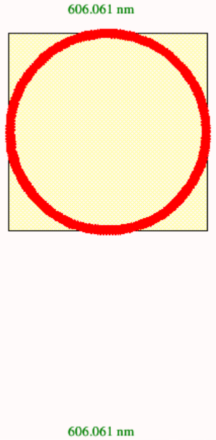
Mask variability band 9nm
Equivalent to 0.3nm/%dose

10nm

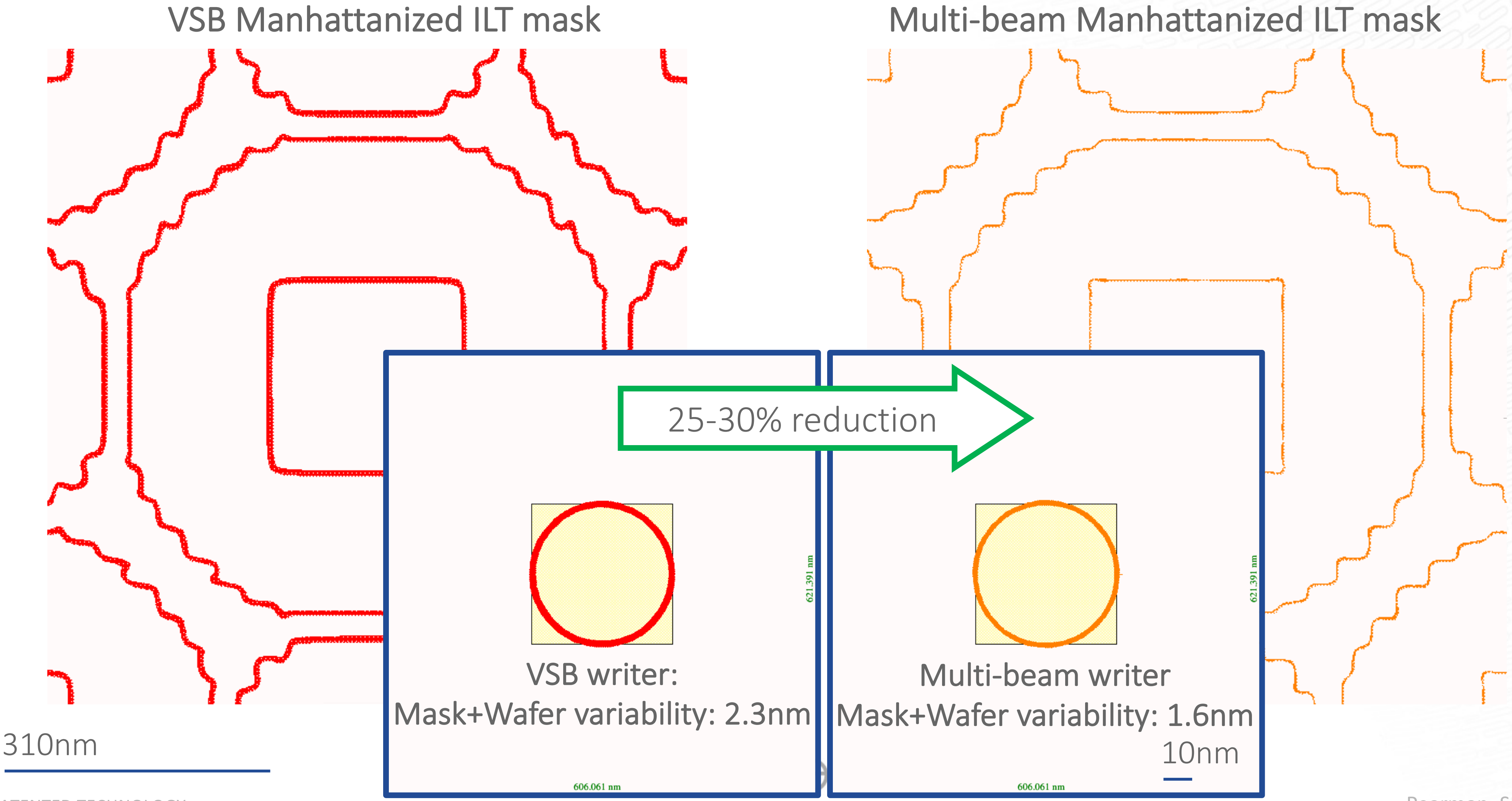


Wafer variability band 0.5nm

Mask+Wafer variability band 2.3nm

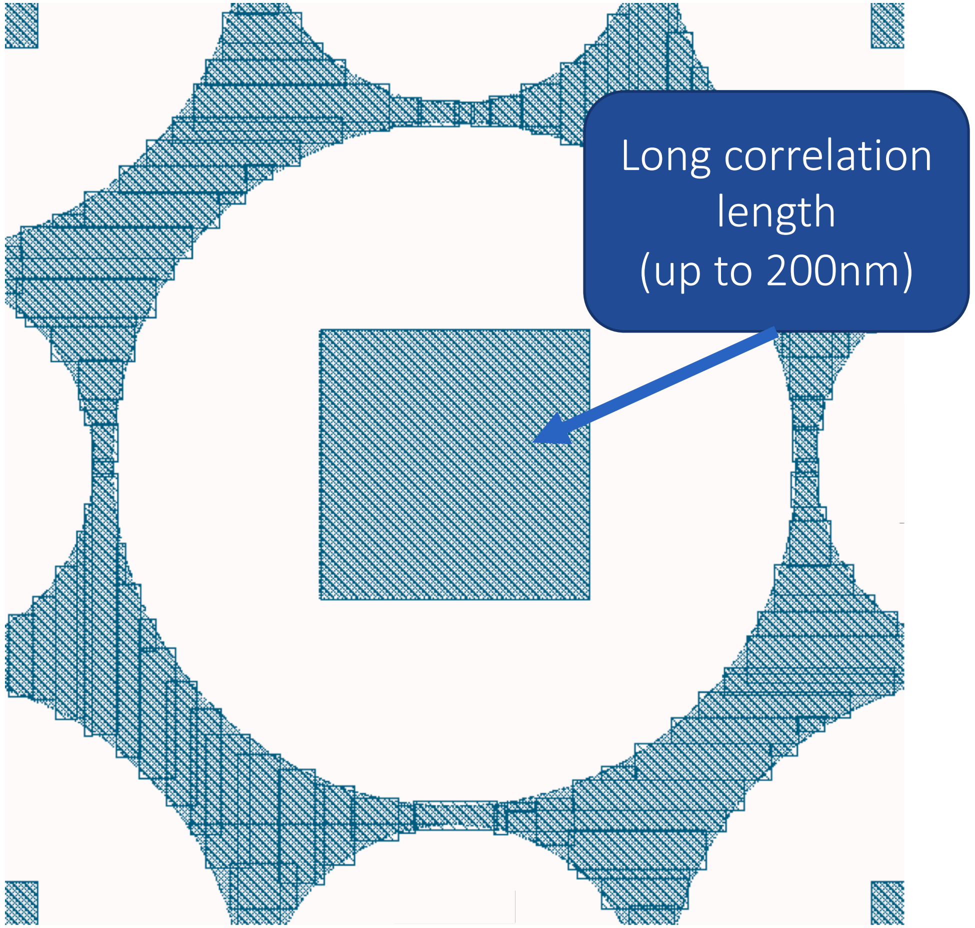


VSB Masks Have More Variability

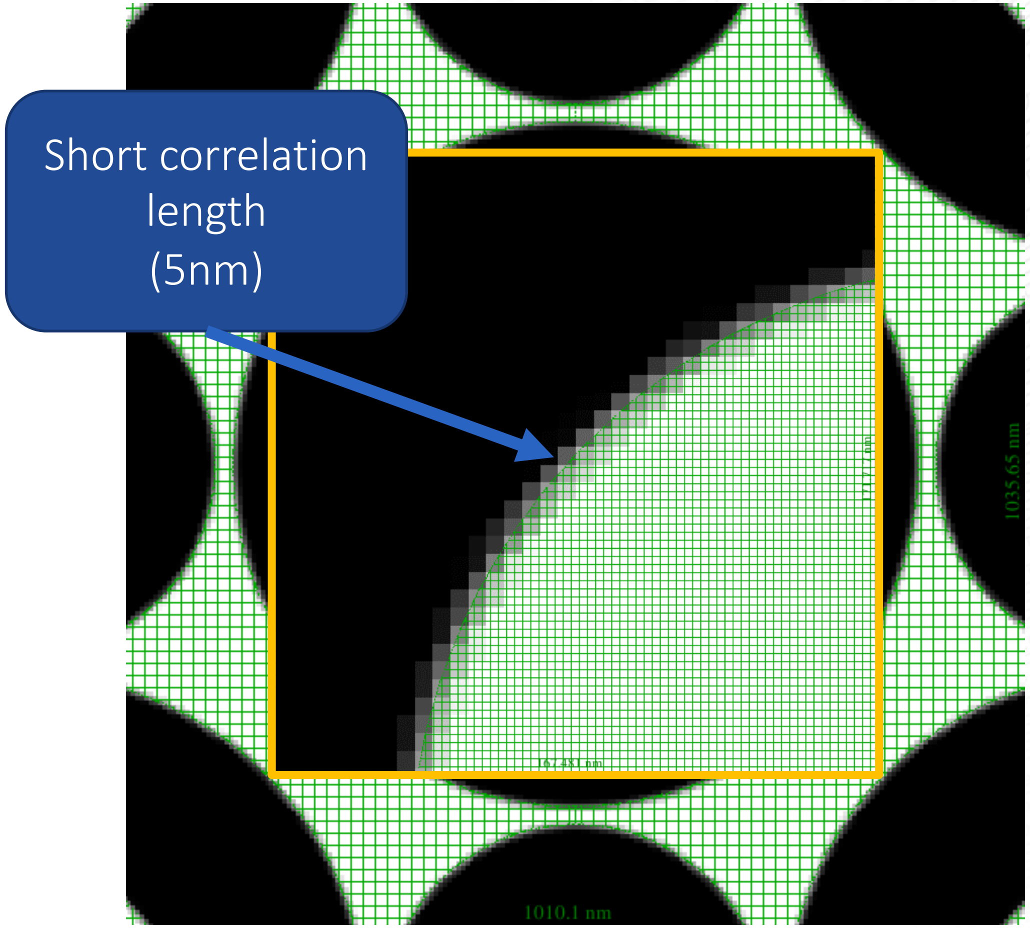


Mask Variability Scales With Number of “Shots”

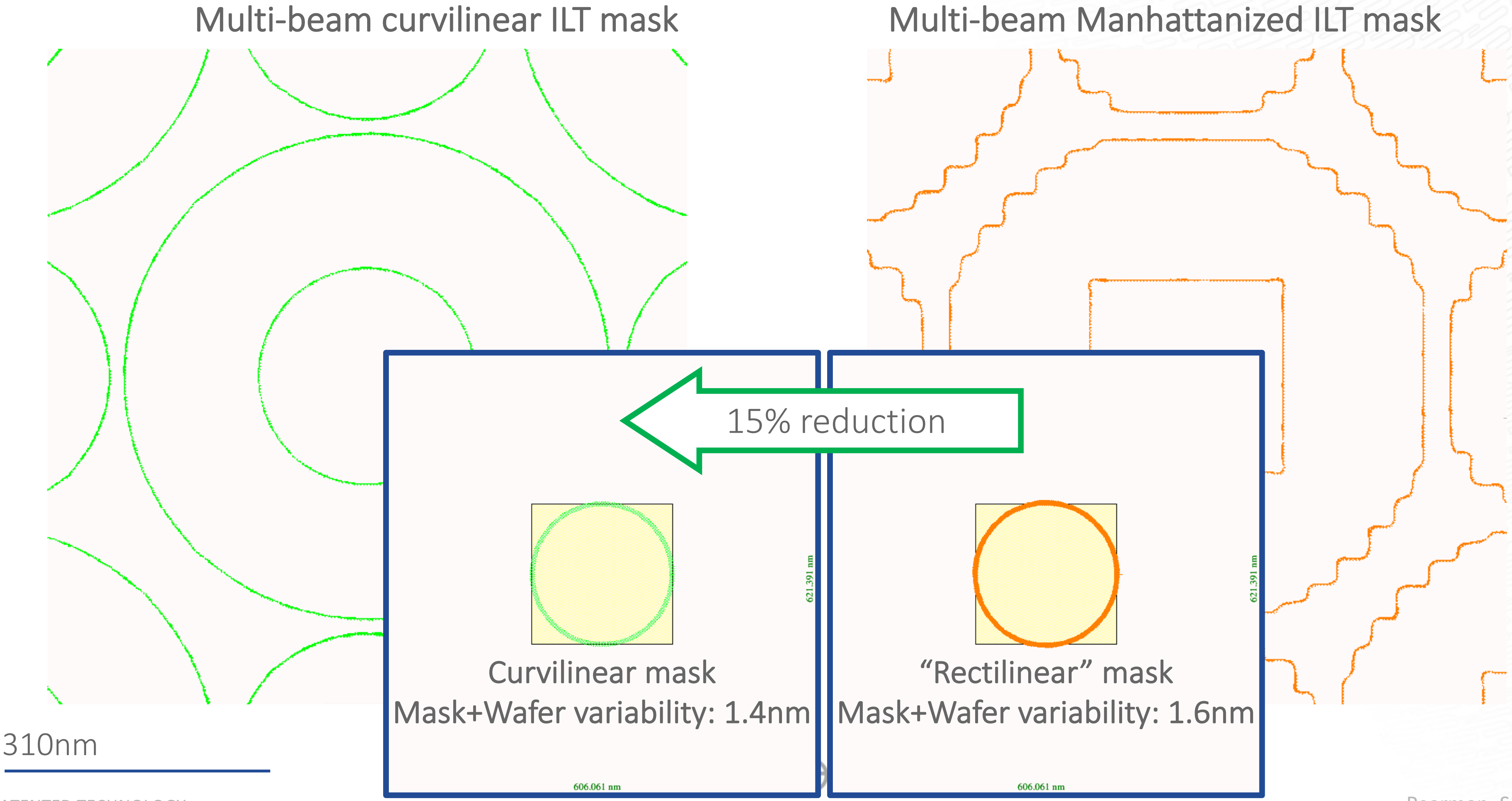
VSB: Tradeoff with write time and variability



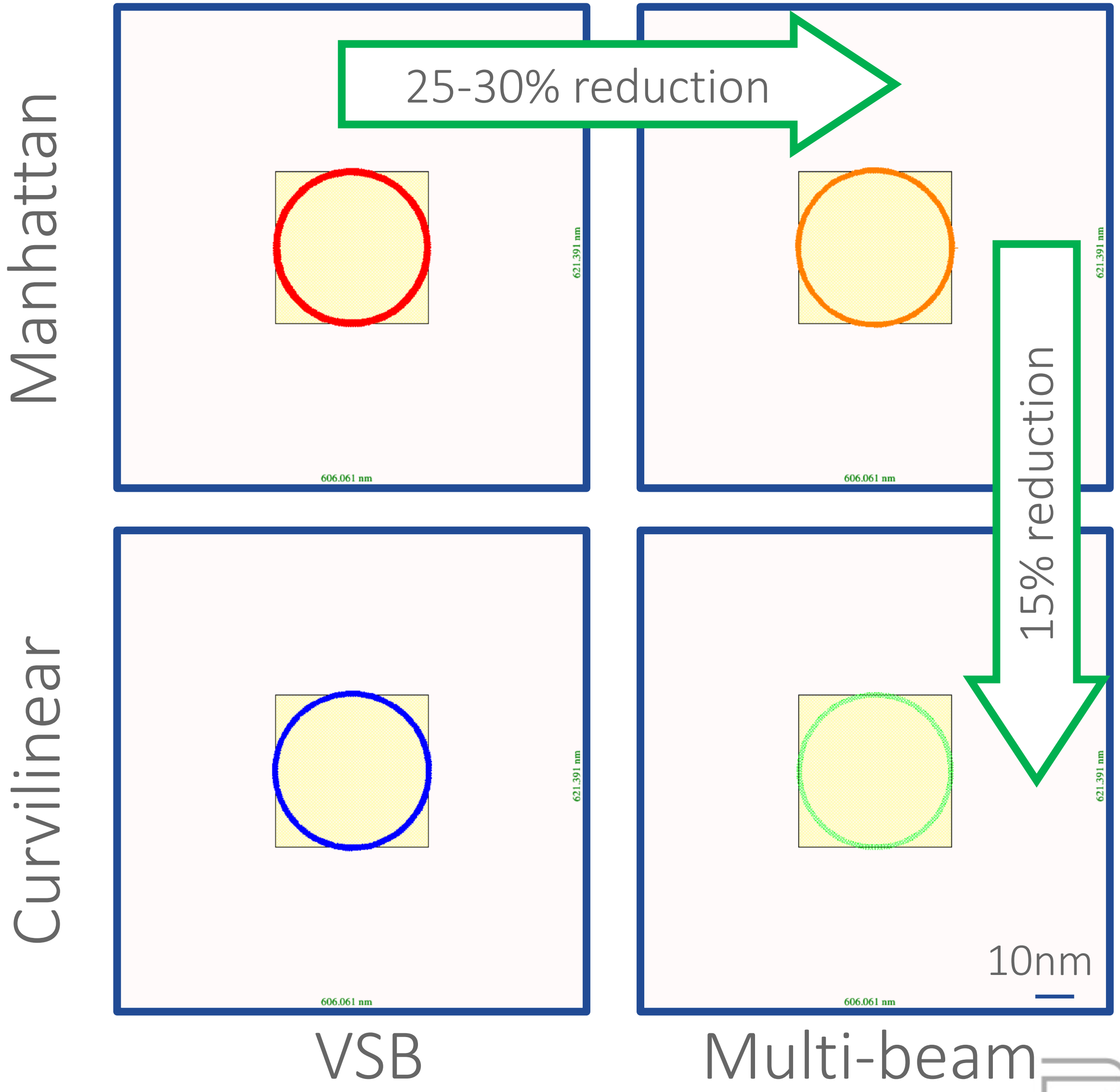
Multi-beam: No such tradeoff

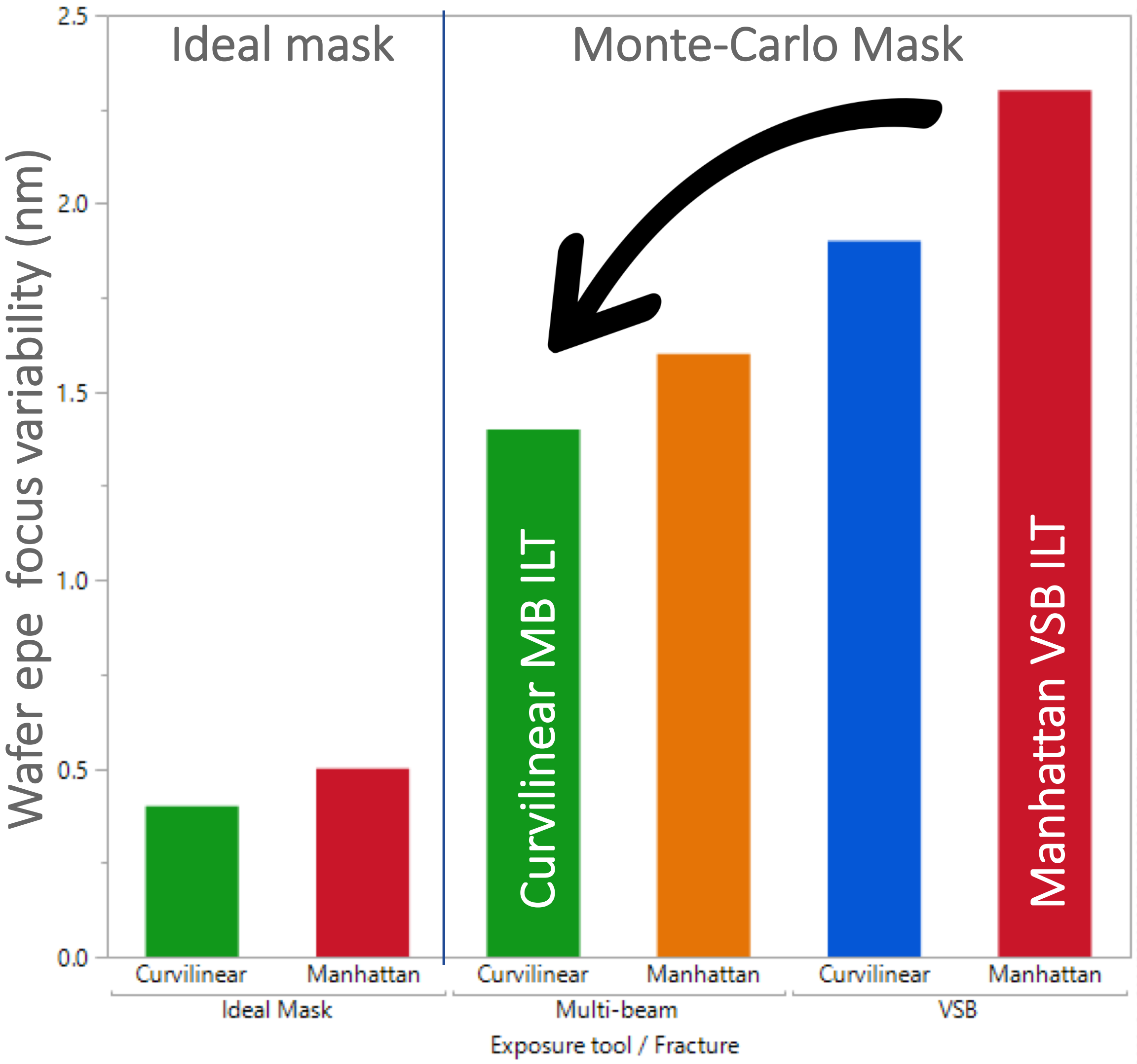


Masks With Constant Dose Margin Print Better



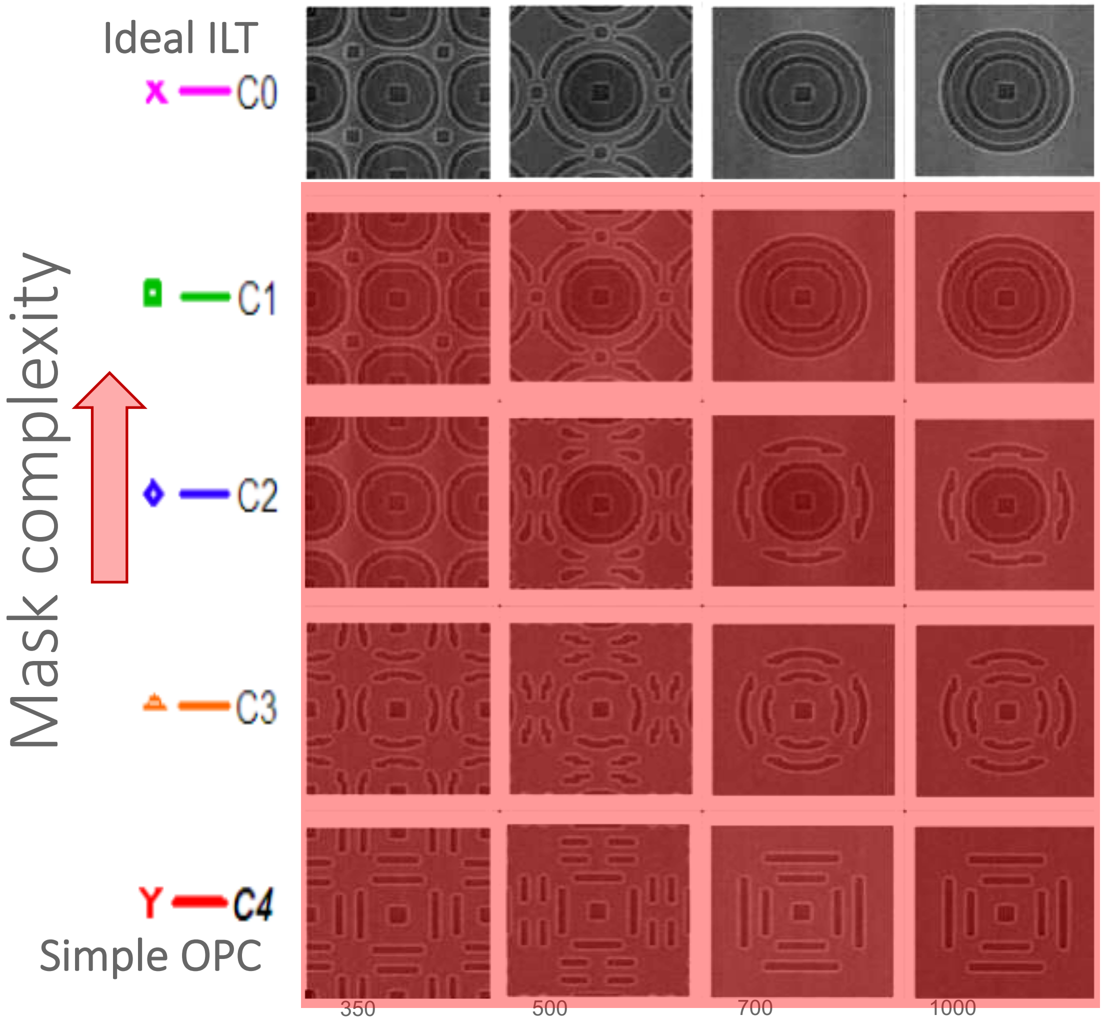
With Real Masks, Curvilinear Shapes are Needed





D2S PATENTED TECHNOLOGY

ILT is All About the Mask You Can Make



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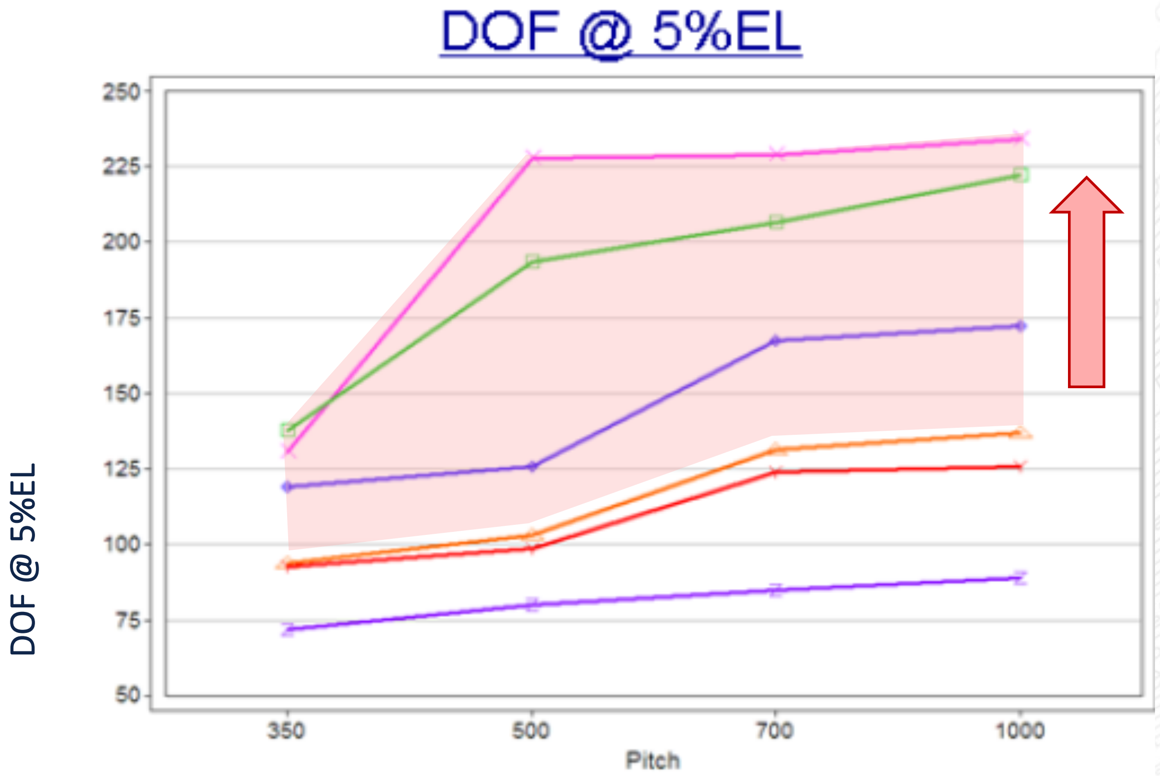

Simplified ILT flow

Ideal ILT generation

Clean mask with mask rules

Everything is Curvilinear, so We Should Act Like It

- Mask variability is a major component to observed process margin
  - Curvilinear = 15% Gain in process window.
- New Multi-beam tools can print native ILT features
  - Significant reduction (>2-4x) in ILT runtime
  - Print features 25-30% more reliably
- Multi-beam tools can perform your data preparation for you
  - Data volume is larger, but manageable
- Removes one uncertainty in process modeling
  - For hotspots, this is even more crucial
- Requires a change in mindset
  - And an update (simplification!) to the Mask Rule Checks
    - We are already using curvilinear checks for intra-layer OPC interactions…
- For EUV, this will even be more true.