EUV Modeling in the Multi-beam Mask Writing Era

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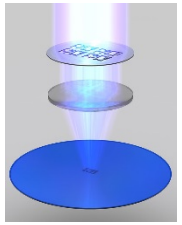
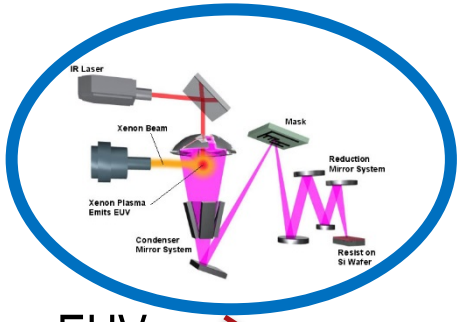
D2S, Inc.

D2S Patented Technology

Mask Modeling is Ready for the EUV Multi-beam Era

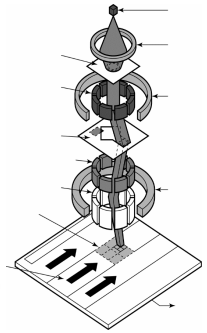


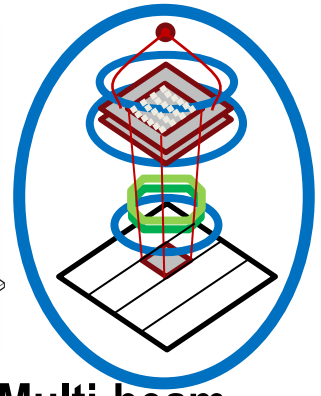


ArF or EUV

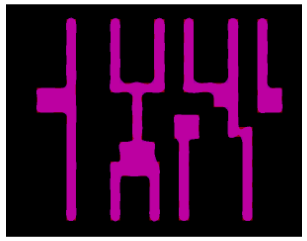
IMS Nanofabrication

NuFlare





VSB or Multi-beam

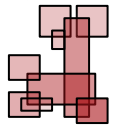


1D or 2D Shapes

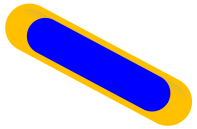
TrueModel®

Positive or Negative Resist

Overlapping Shots



Dose Modulation



Shape-based Effects

Talk flow… What is challenging about EUV multi-beam modeling:

- Review the challenges about the multi-beam era
- Review the challenges about the EUV era
- Demonstrate that the two challenges can co-exist
  - But only with help from GPUs!

Reviewing the Complexities in the Multi-beam Era

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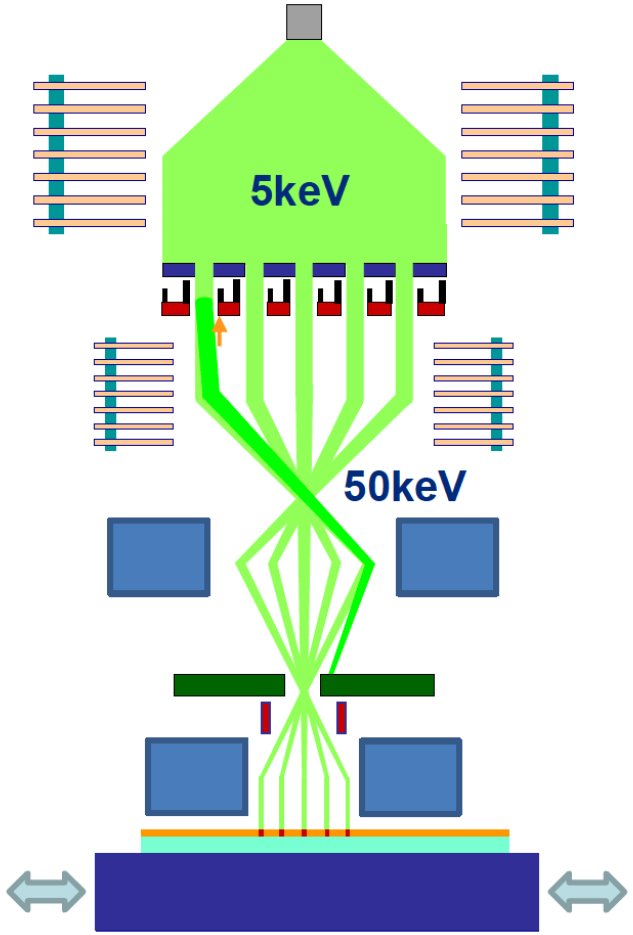
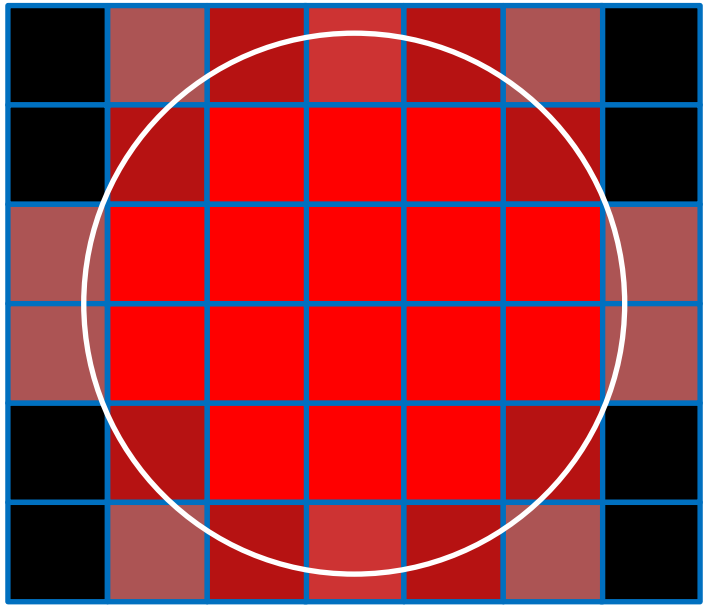
Multi-beam Uses Many Beamlets in Parallel



Source: IMS Nanofabrication

Many beamlets means patterns are rasterized

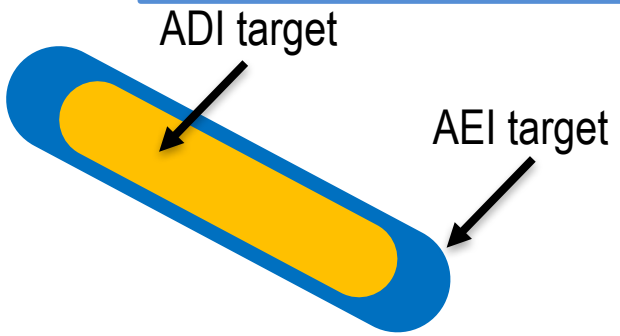


Dose profiles are more complex than for VSB

Multi-beam Era is More Complicated

VSB era	Multi-beam era
Dose profiles are “simple”	Dose profiles will be complex
Typically only “1 or 2” doses assigned	Many dose values to predict [“0” … “2”]
Can use dose terms to assist bias terms.	Dose terms no longer degenerate to Etch terms; more complex dose models are needed
Etch done by constant bias	Etch needs to be done on curvilinear shapes

Curvilinear geometry transformations ideally suited for GPU!



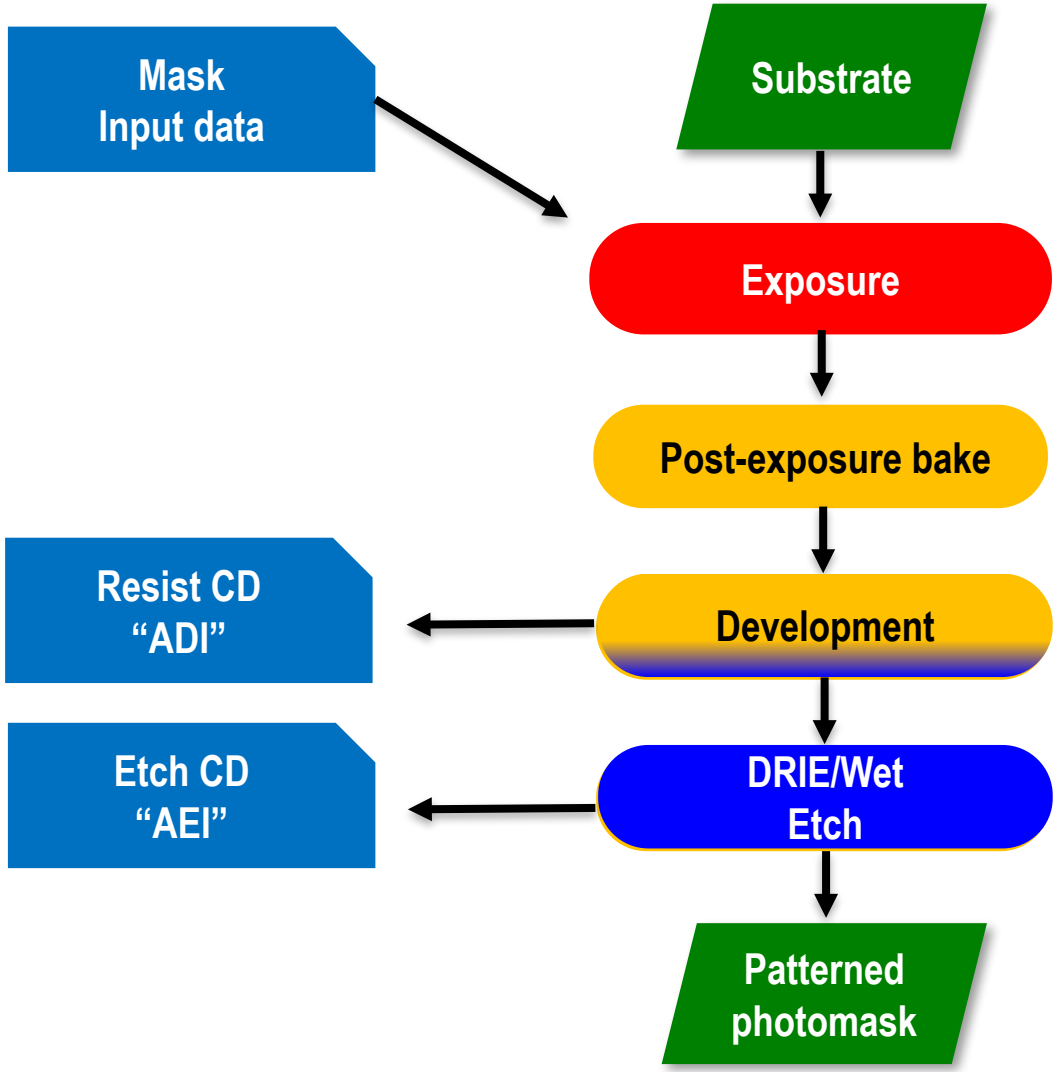
Shape effects are now curvilinear!

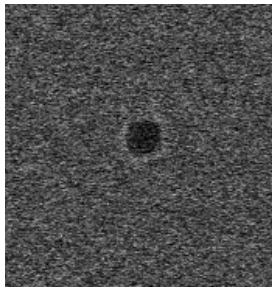
Shape effects depend on:

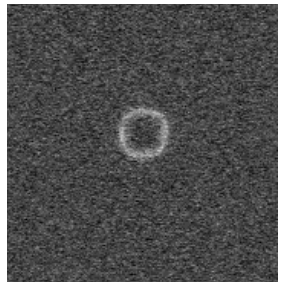
- Open area “shadowing”
- Local pattern density “loading”
- Local radius of curvature

A good etch model needs to encompass a wide variety of 2D features

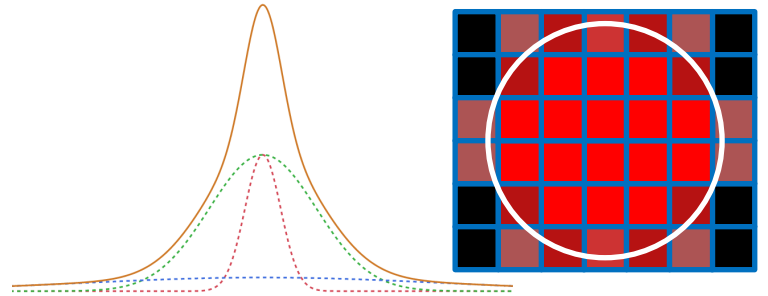
Mask Modeling Must Separate Dose and Shape Effects





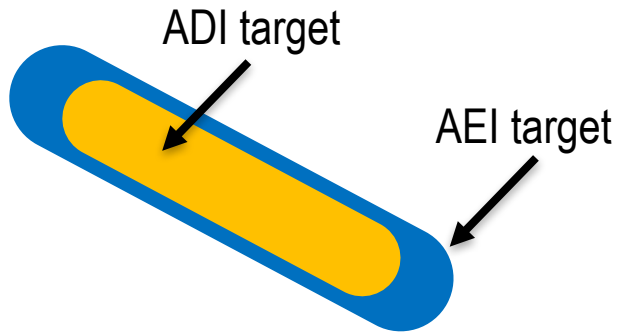


Dose effects



Dose profiles are now complex!

Shape effects



Shape effects are now curvilinear!

Reviewing the Complexities in the EUV Era

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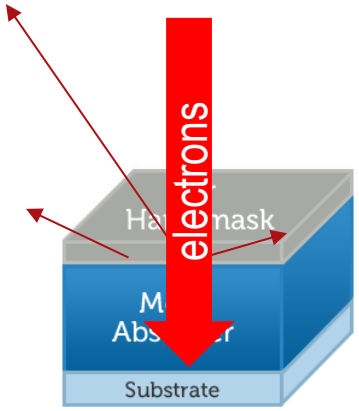
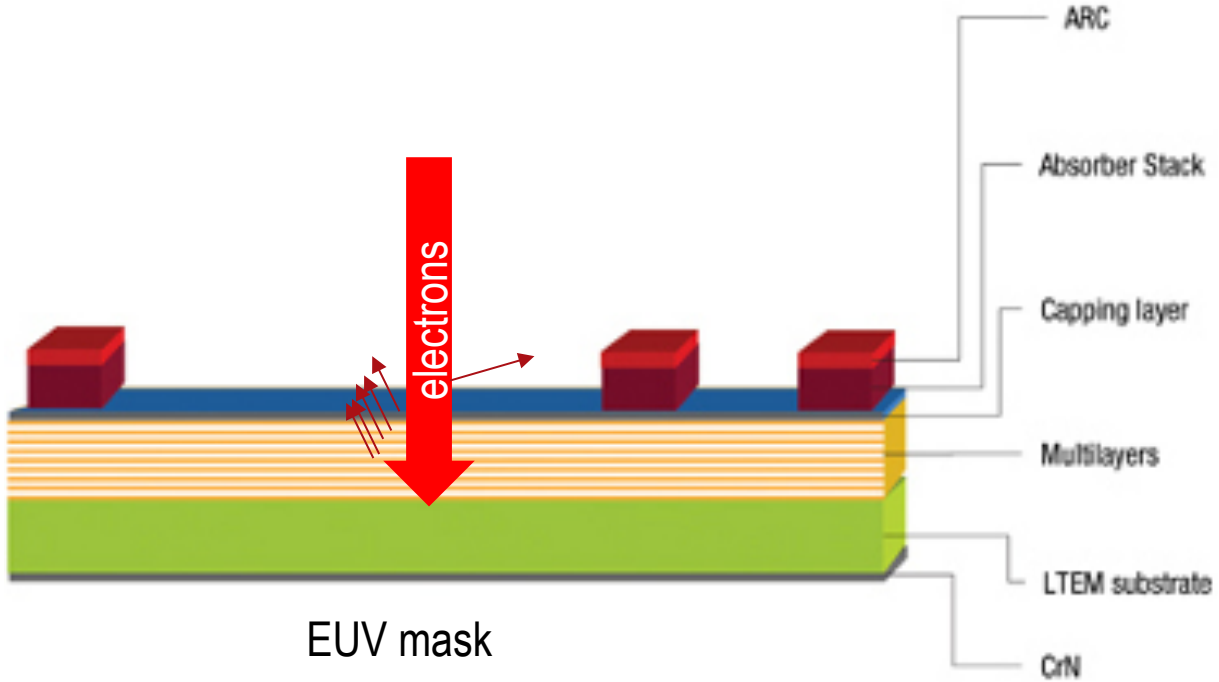
eBeam Scattering is More Complex in EUV



193i OMOG mask



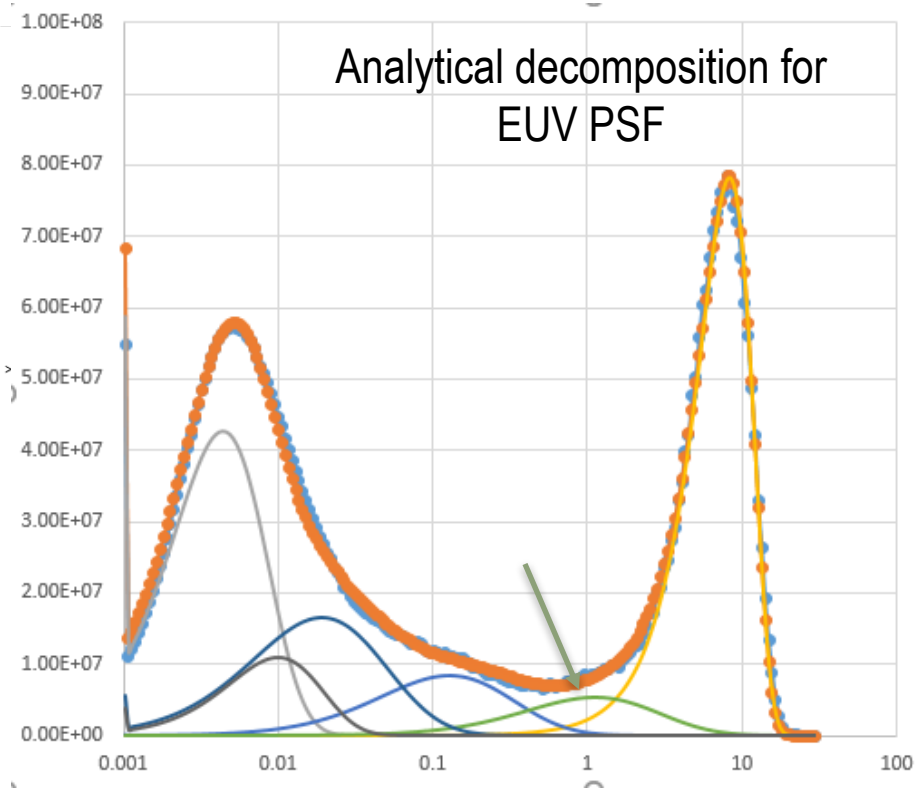
EUV mask

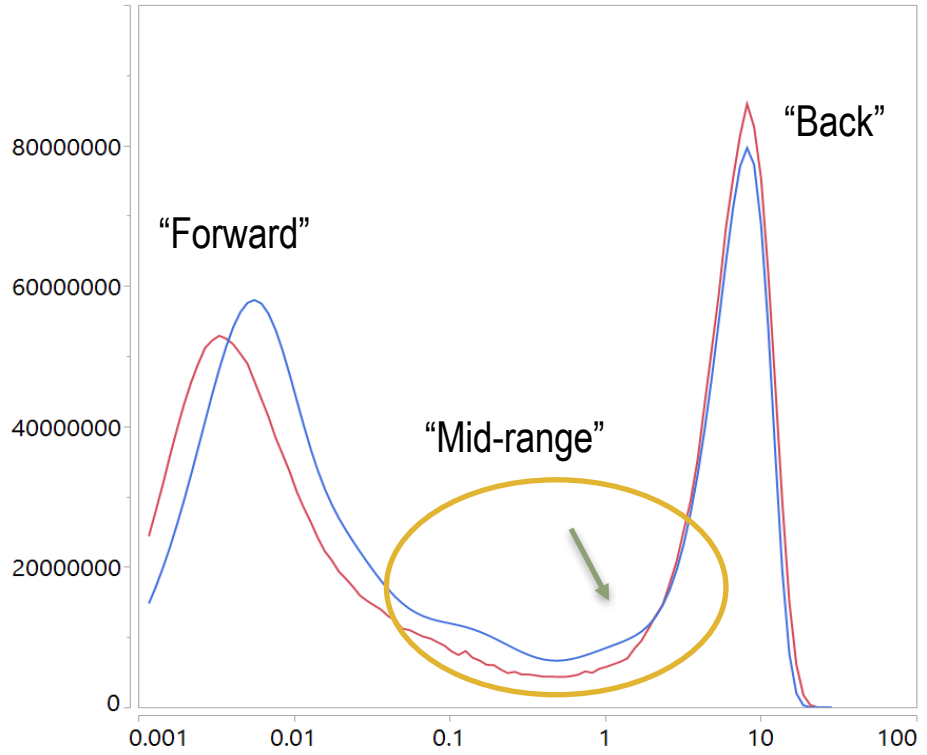
Electrons scatter off of each interface
There are many more interfaces in the EUV mask stack
More interfaces = broader scattering

Source: Toppan

Source: http://semimd.com

EUV has the Well-Known "Mid-range" Effect





EUV
MoSi

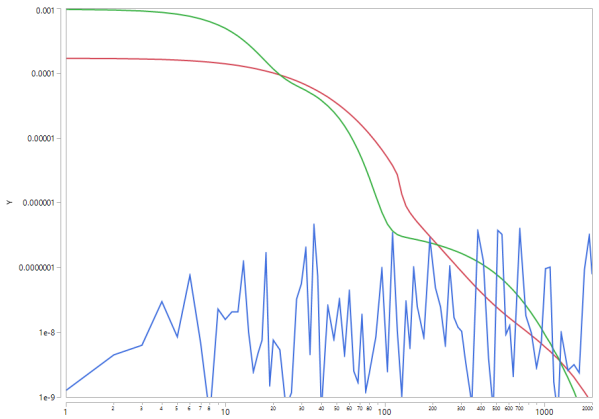
In addition to the standard <n>G model, a ~1um "exponential" kernel needs to be added:
In reality, a sum of Gaussians is no longer accurate enough for EUV modeling
Correction runtime concern: length scale are larger than just "forward scattering"

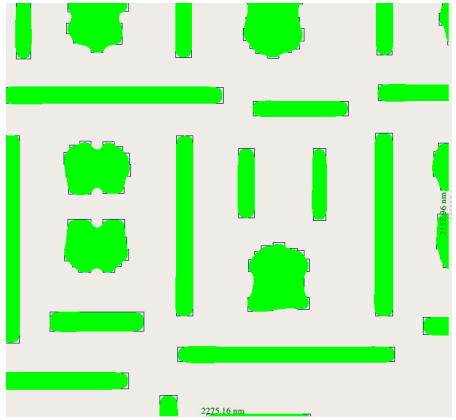
Source: CHARIOT software

PMJ, 2017

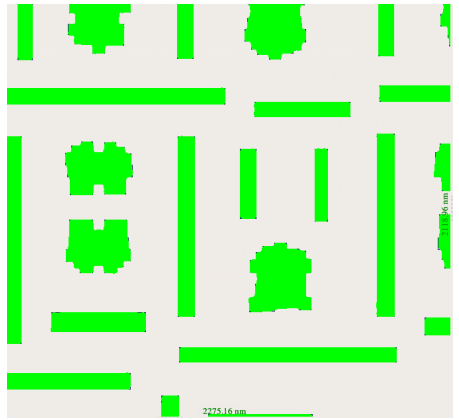
GPU Modeling Enables Arbitrary PSF

- If you compute using GPUs, the PSF can be read into a texture
  - **Runtime is independent of PSF choice (Gaussian, or more complex)**
- Can use the PSF from first principles directly
  - Can use analytical approximations to it (<n>G + 1E)
  - Can even use random numbers

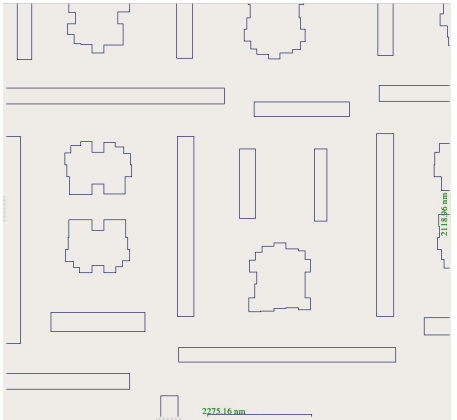




25nm blurred MC-Sim PSF



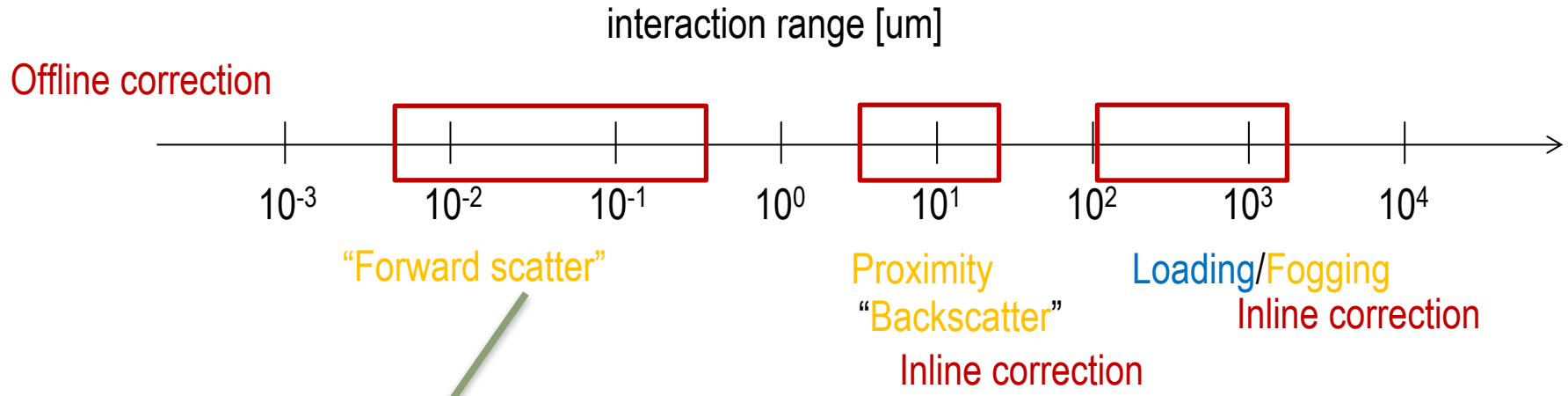
Analytical EUV PSF



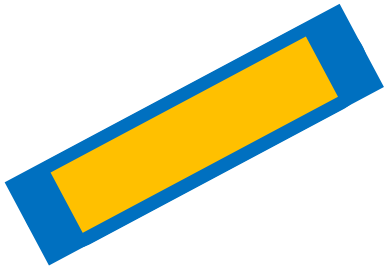
Random PSF

Mask Process Modeling/Correction

VSB era corrections

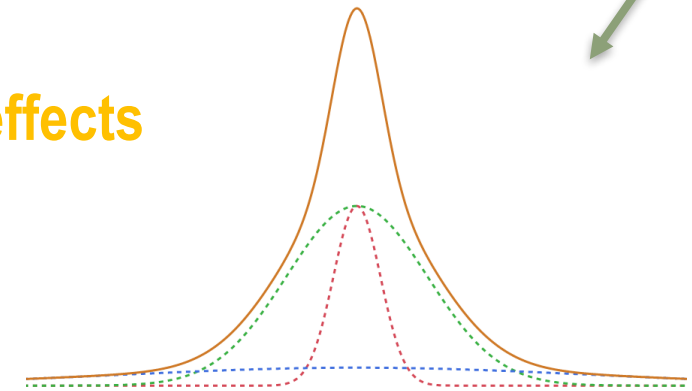


Shape effects



Shape MPC

Dose effects

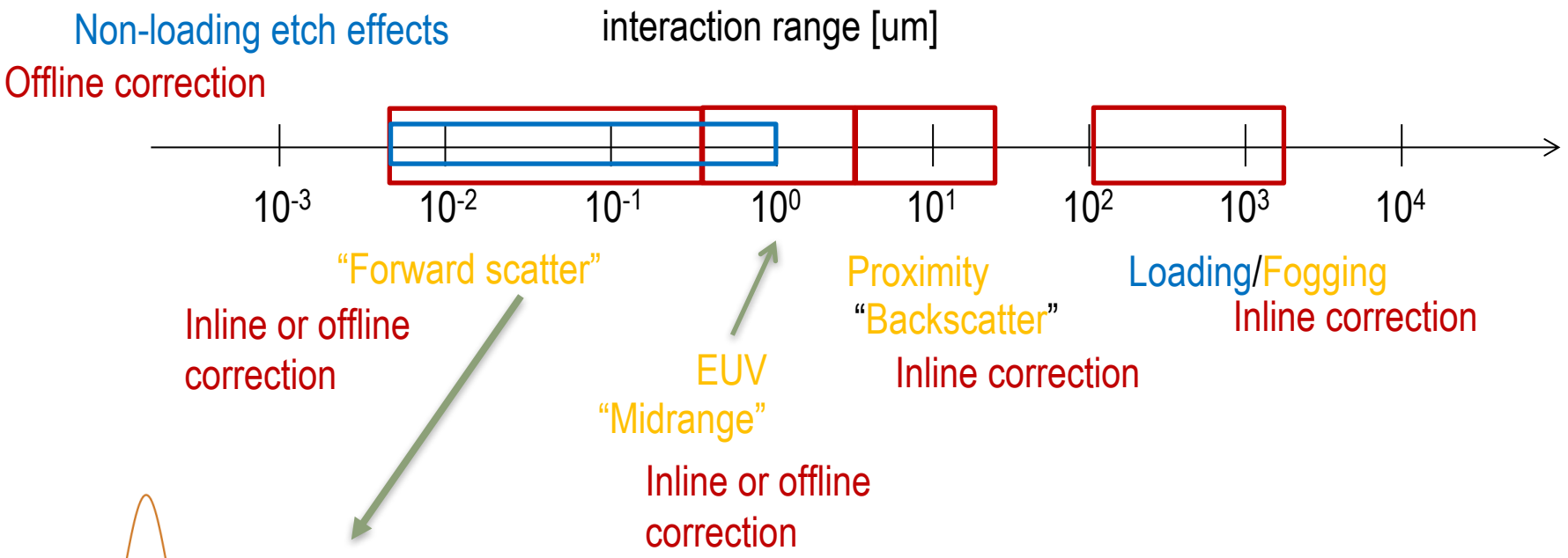


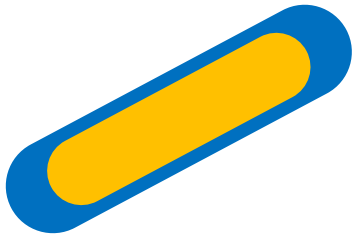
PSF or <n> functions

Short range eBeam/process effects

Mask Process Modeling/Correction

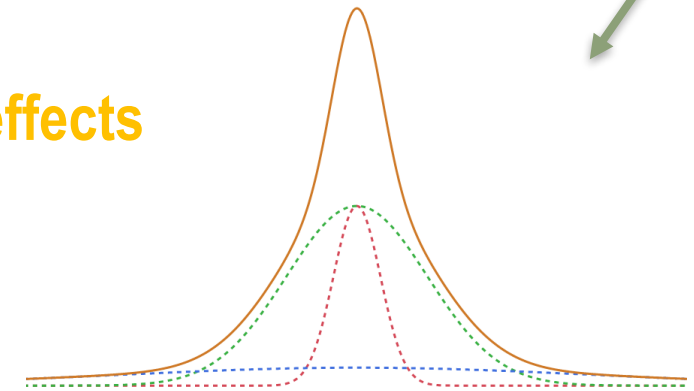
In the Multi-beam Mask Writing Era





Curvilinear etch effects

Dose effects



PSF or <n> functions

Short range eBeam/process effects

Dose "scatter" is still the same:

EUV is a target for MBW, complex PSF is needed

Dose profiles are more complex

Still have "shape-based" etch effects

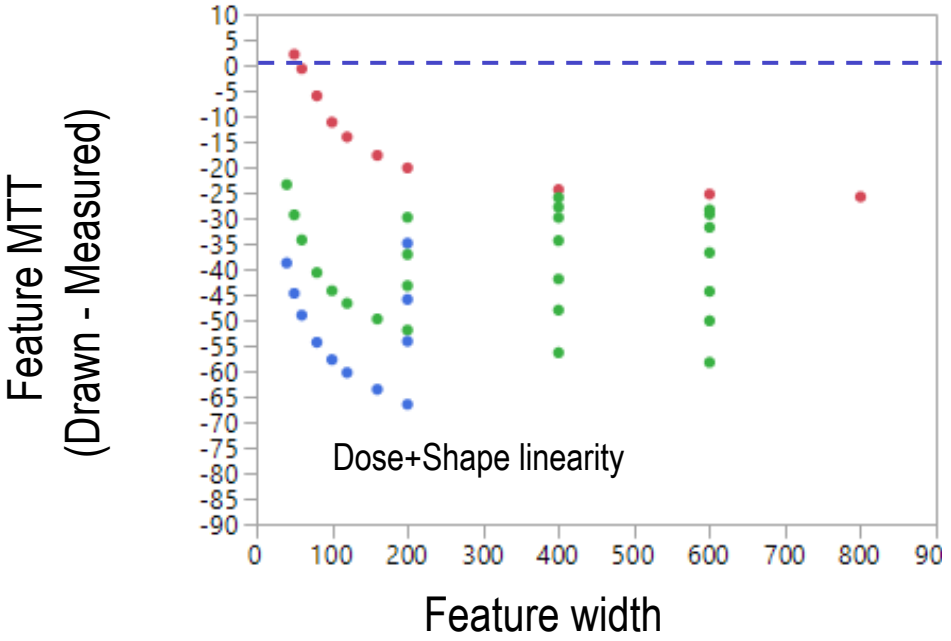
These will need to be curvilinear, not manhattan

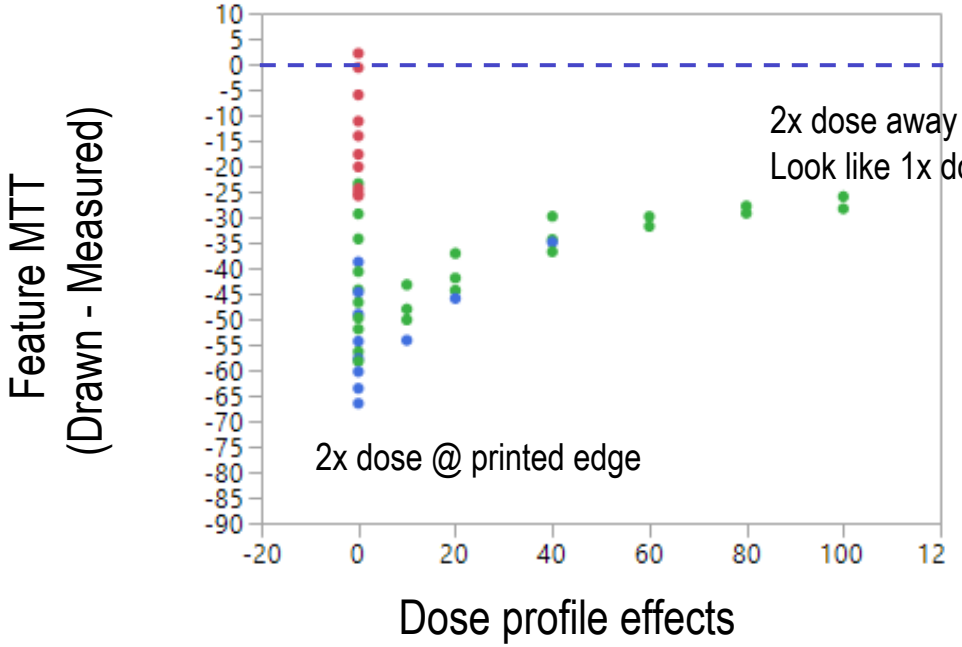
Integrating EUV and Multi-beam Modeling

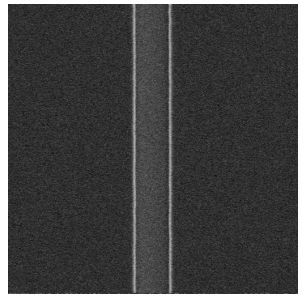
D2S Patented Technology

193i Mask Data Exhibit Both Shape and Dose Effects

Non-zero y-axis values mean: mask print errors if uncorrected







Iso Lines

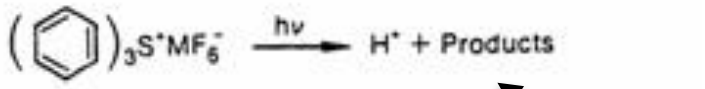
Shape and
Dose effects

<200nm = 193i assist feature

Dose effects

>200nm = 193i main feature

Dose/Shape Separation Requires Complete Physics

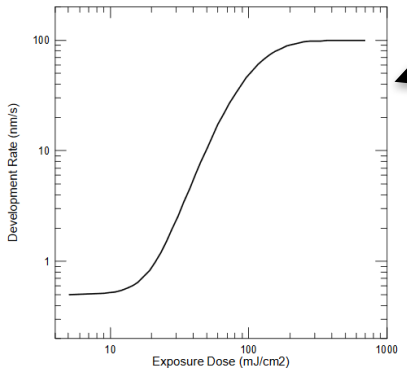


Source = Cliff Henderson

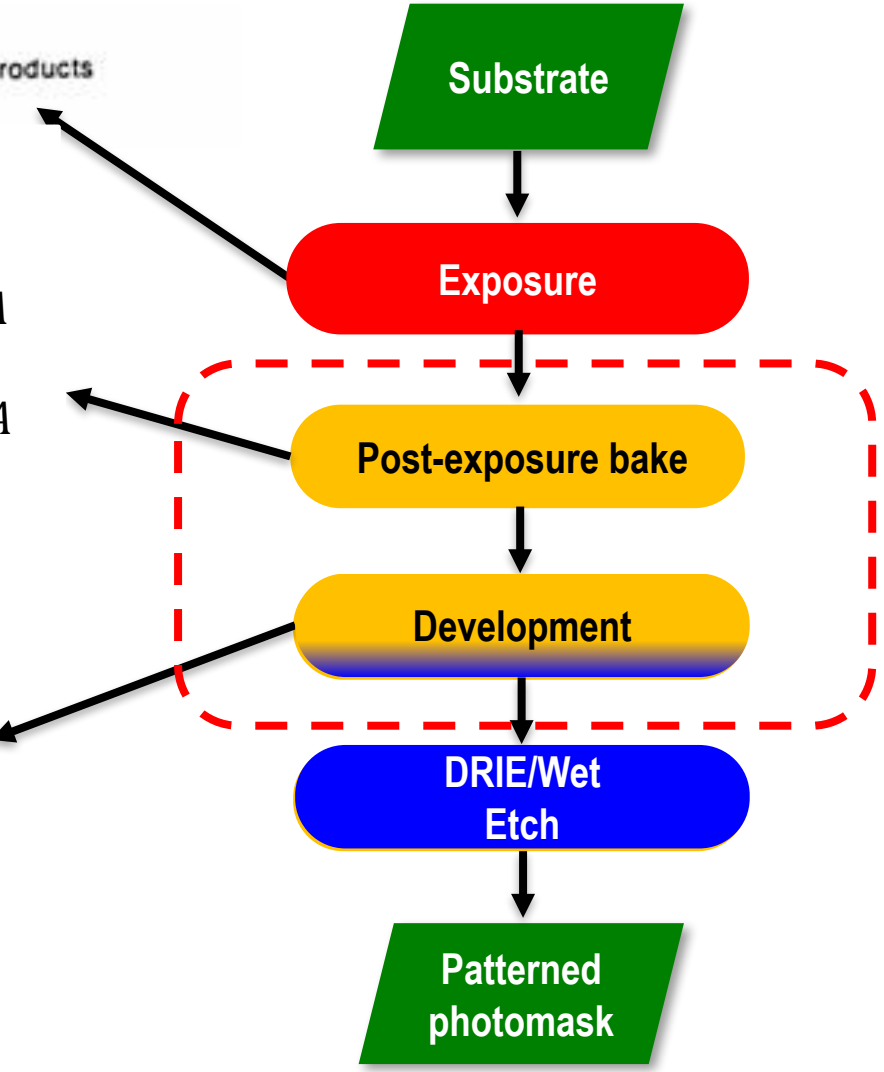
$$\frac{dA}{dt} = D_A \nabla^2 A - k_1 BA$$

$$\frac{dB}{dT} = D_B \nabla^2 B - k_1 BA$$

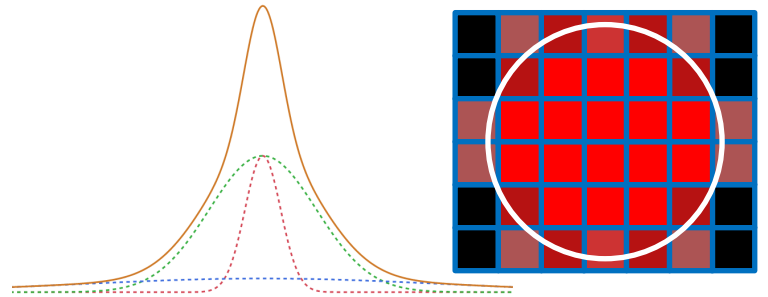
$$\frac{dR}{dt} = -k_4 RA$$

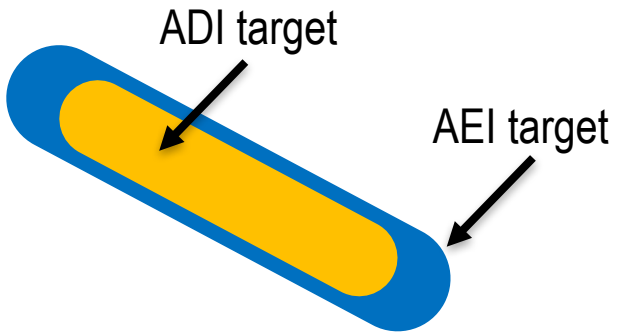


Source = Lithoguru



Dose effects

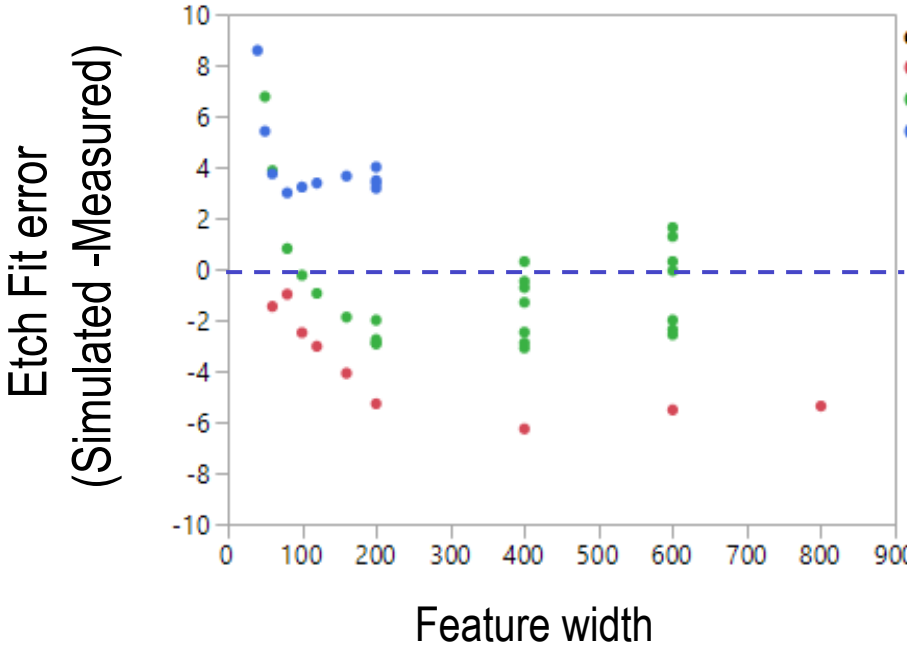




Shape effects

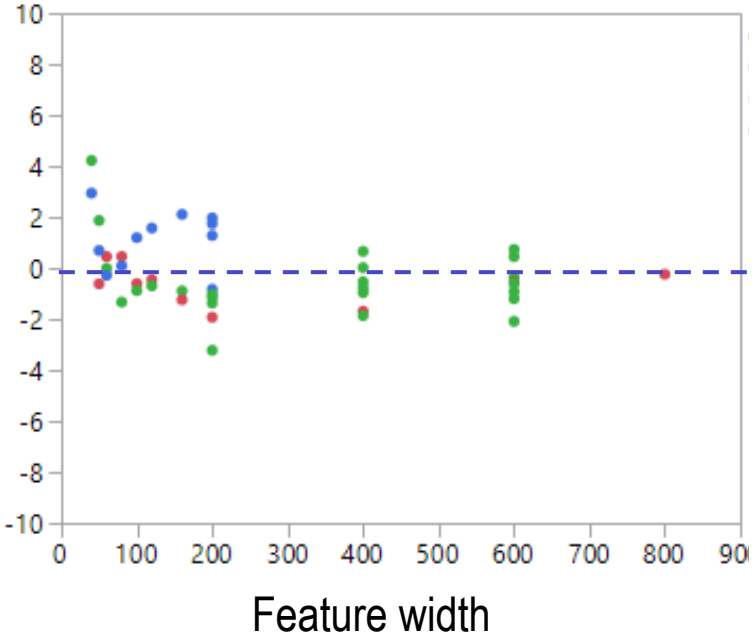
Must Treat Shape and Dose Effects Correctly for 193i

Non-zero y-axis values mean: mask print errors from model



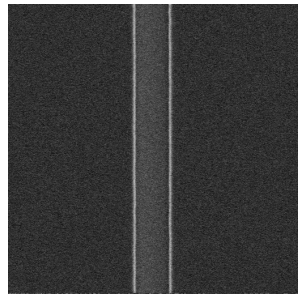
Non-separable "standard" models

Do not meet specification



Separable dose and shape mask models

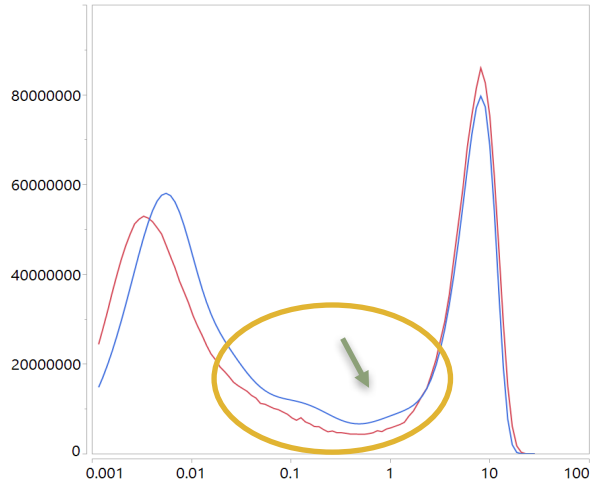
Meet specification!

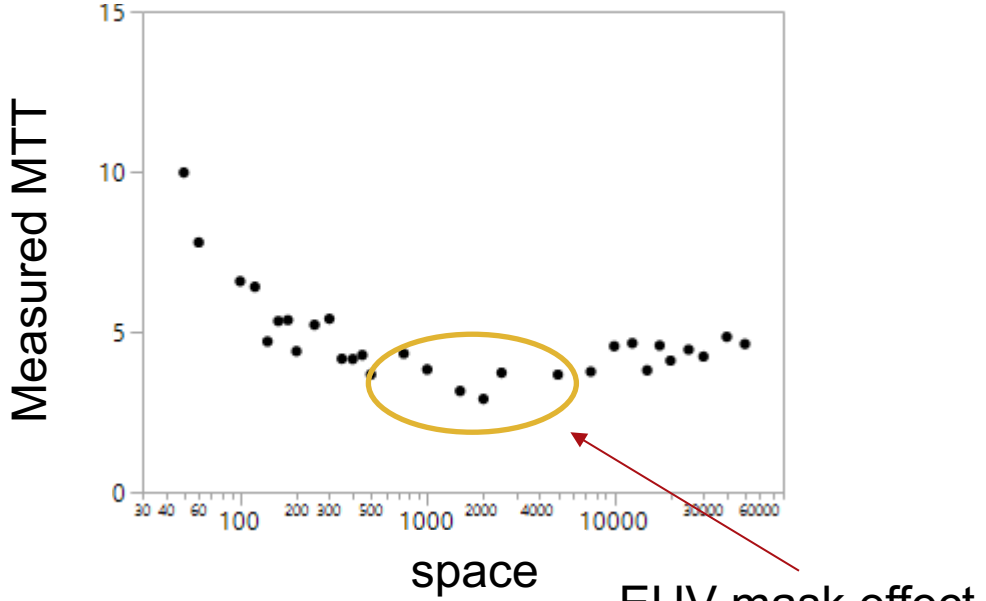


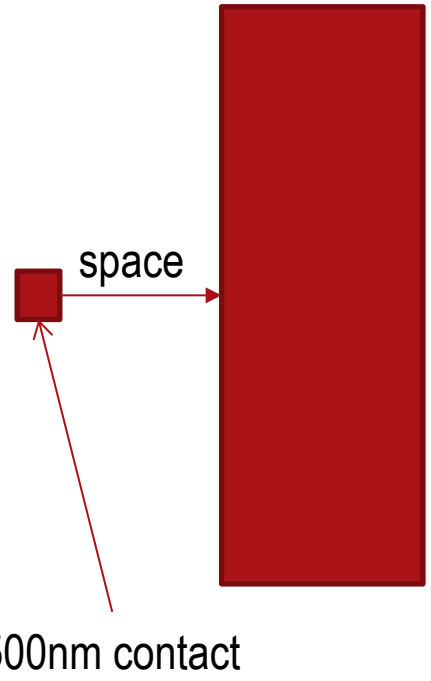
Iso Lines

EUV Mask Data Adds Mid-Range Effects

Non-zero y-axis values mean: mask print errors if uncorrected



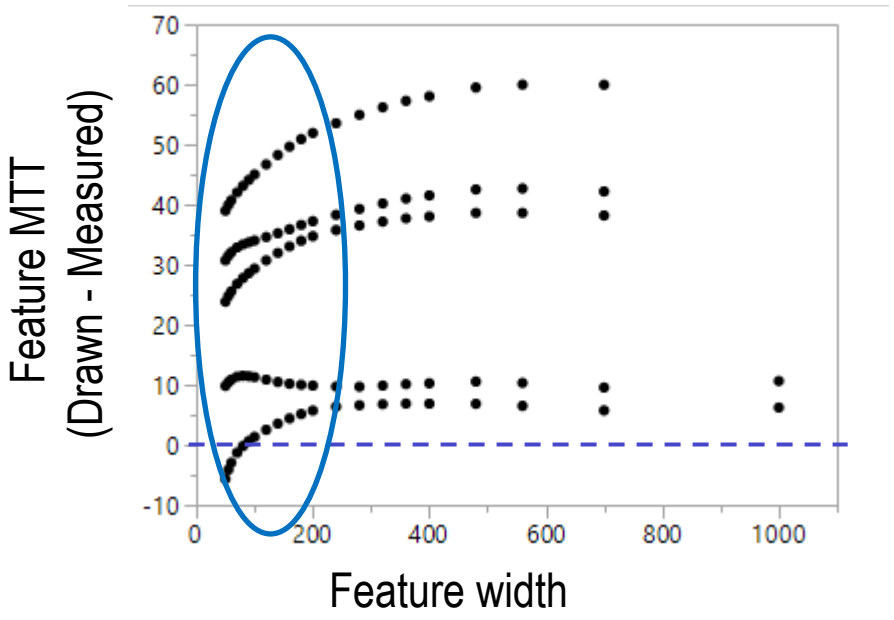




Mid-range correction needed to predict 1um effects!

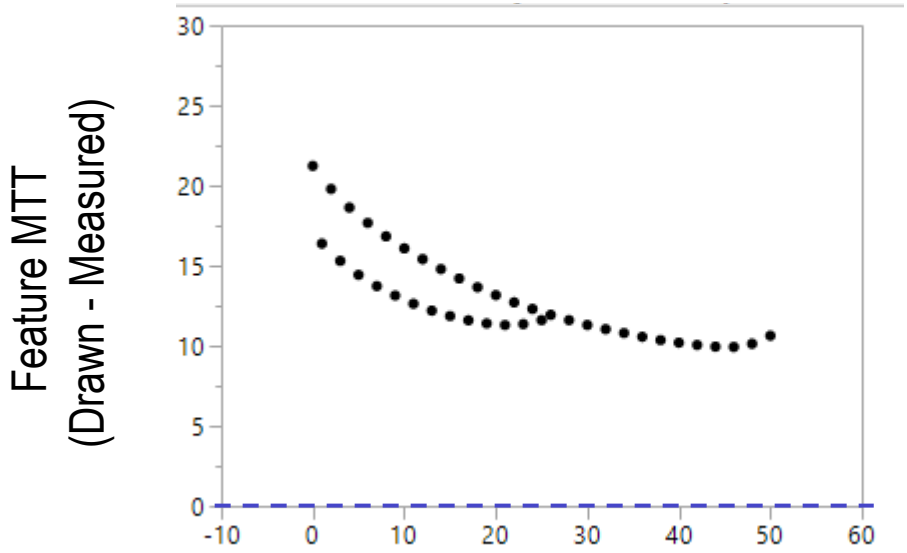
Must Treat Shape and EUV Dose Effects Correctly

Non-zero y-axis values mean: mask print errors if uncorrected



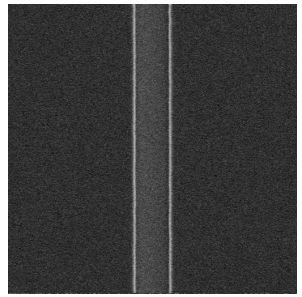
Shape and Dose effects

193i assist feature
EUV main feature



Dose effects

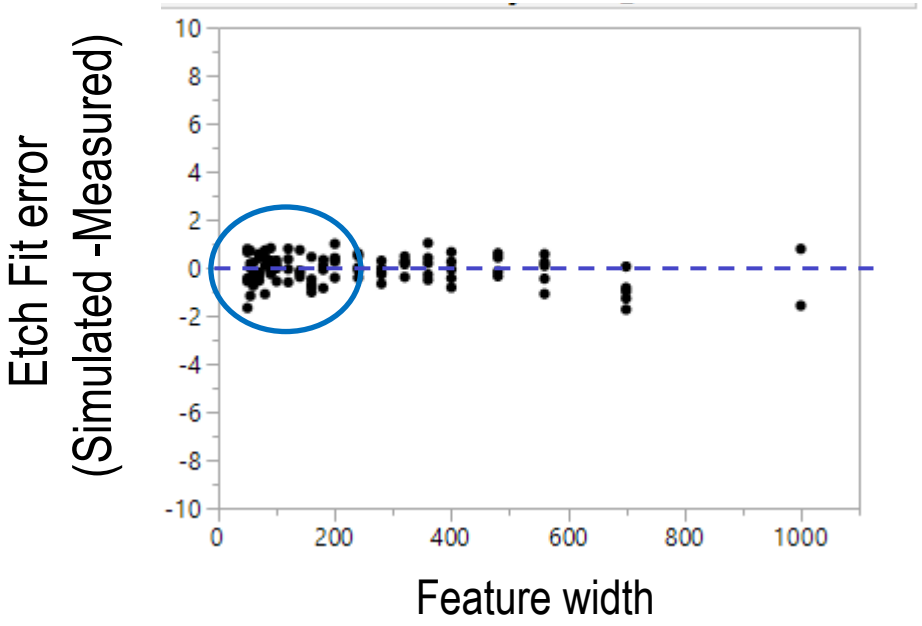
193i main feature
EUV main feature



Iso Lines

Must Treat Shape and EUV Dose Effects Correctly

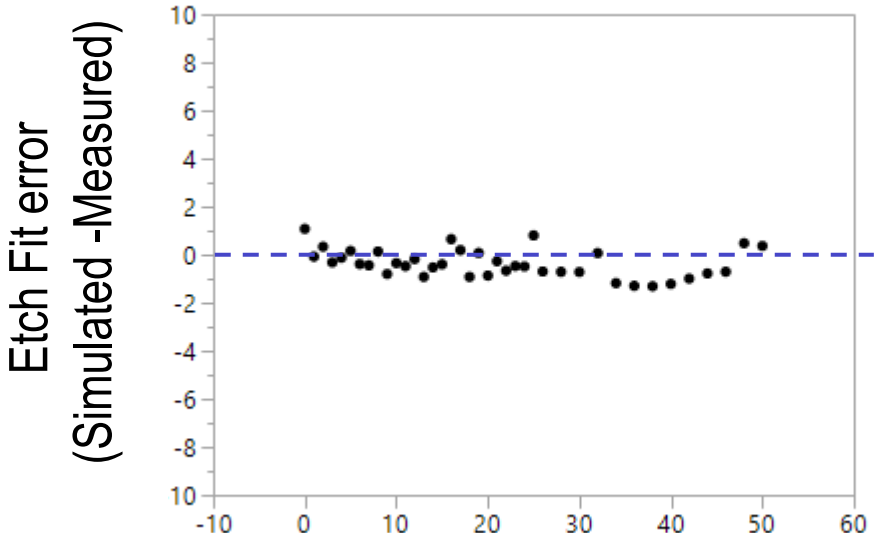
Non-zero y-axis values mean: mask print errors from model



Shape and

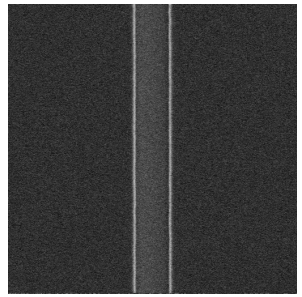
Dose effects

Meet specification!



Dose effects

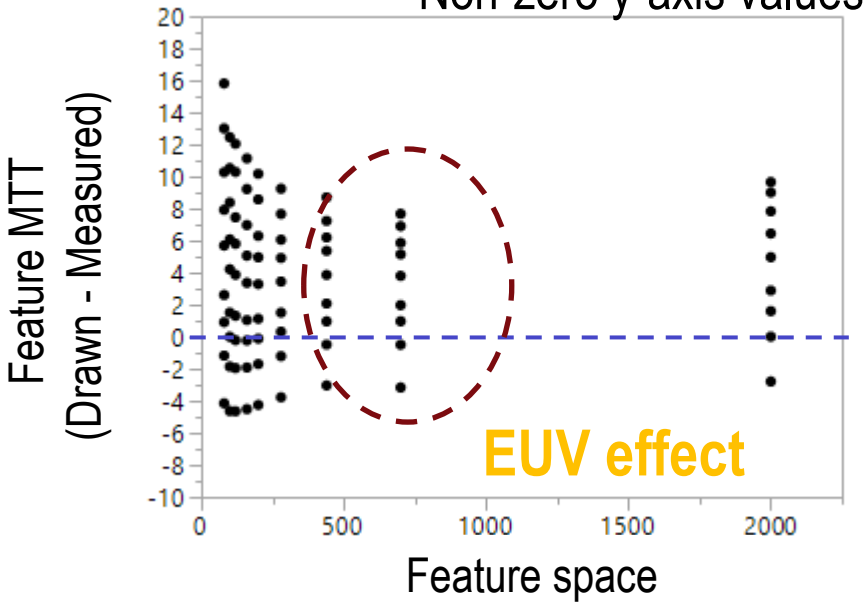
Meet specification!

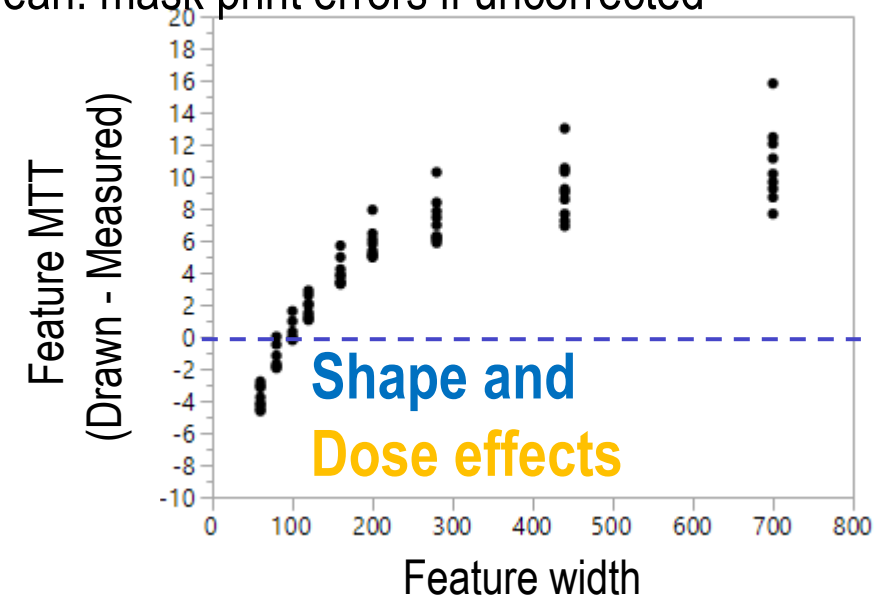


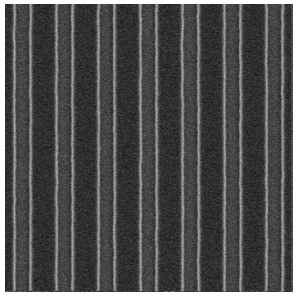
Iso Lines

Must Treat Shape and EUV Dose Effects Correctly

Non-zero y-axis values mean: mask print errors if uncorrected

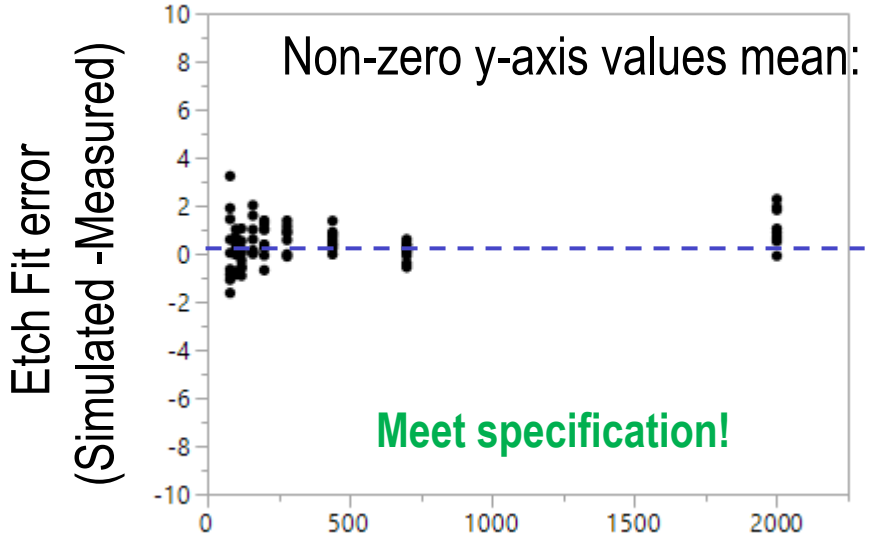




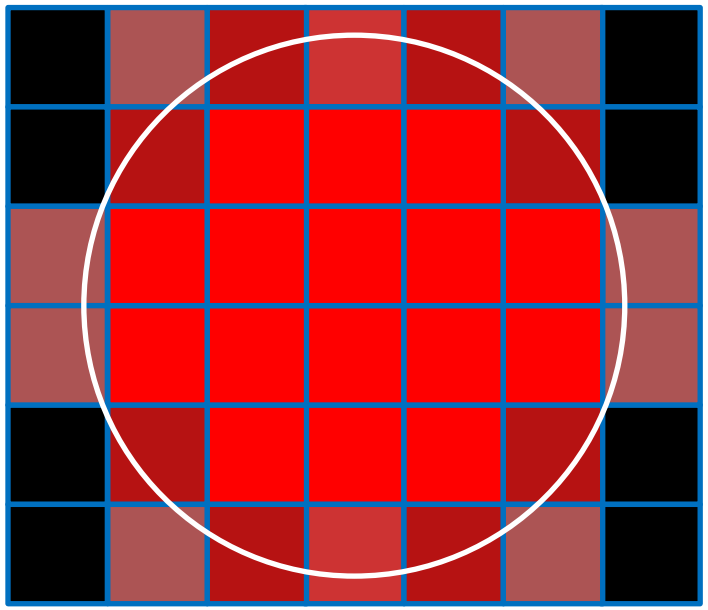


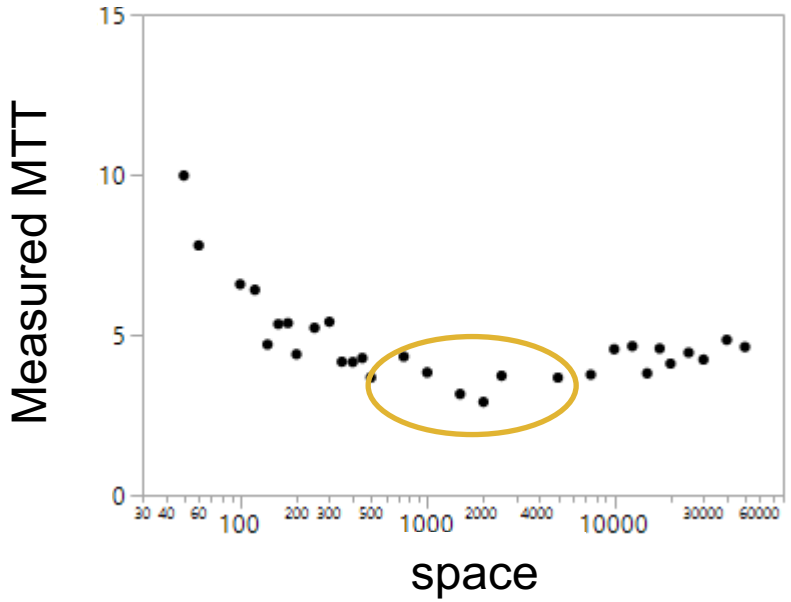
Many Lines

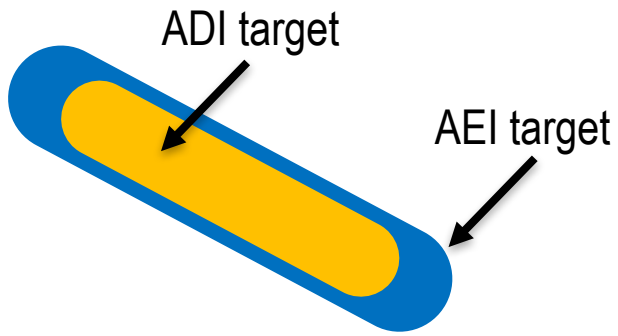
Non-zero y-axis values mean: mask print errors from model



The EUV Multi-beam Era Requires Advanced Modeling







Complex Dose effects combined with Curvilinear Shape effects mean

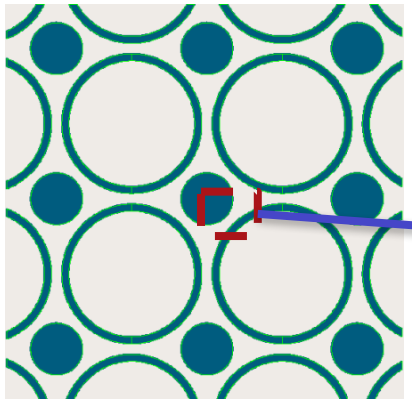
Dose / Shape separable models required for EUV accuracy specifications

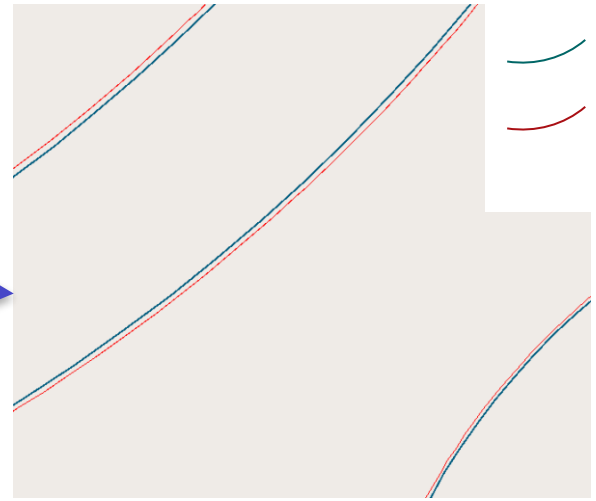
EUV Modeling Enabled by GPUs

Dose / Shape separable models required for EUV accuracy

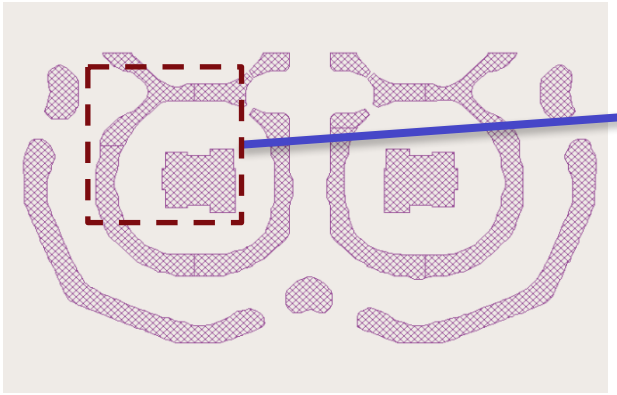
- Uniquely suited for all-angle shape operations

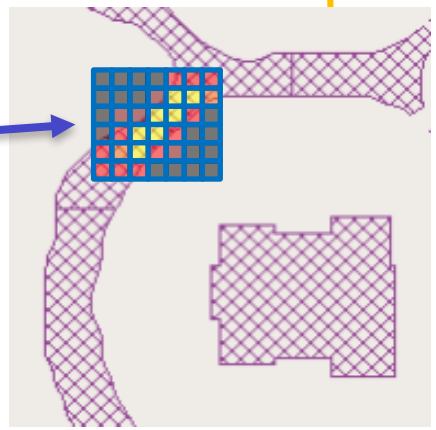
Output of shape correction should be target for dose model!





- Uniquely suited for PSF convolution-like operations





Complex dose profiles can be computed in real-time!


D2S