Exploration of compact and rigorous simulation-based methods to reduce stochastic failure risk

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Outline of this talk

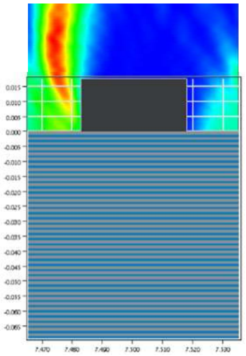
- Review current continuous simulation methods
- Review current stochastic rigorous simulation methods
- Assumptions for stochastic compact failure simulations
- Continuous process window vs. stochastic process window error budgeting
- Examples of compact stochastic model flows for reducing stochastic failure risk

All rigorous simulations are done with Synopsys Sentaurus Lithography (S-Litho™)
All compact simulations are done with Synopsys ProGen™

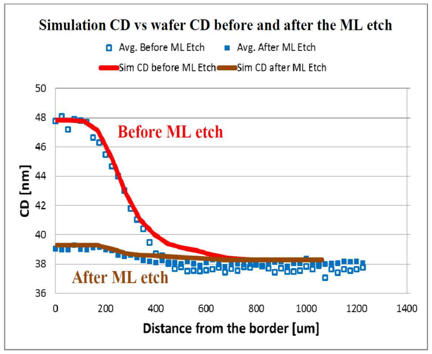
Continuous simulation to reduce lithography failure risk

Most continuous simulation is ultimately to reduce failure risk –> hotspots, CD/EPE control

3D mask/shadow



Die-Die flare impact



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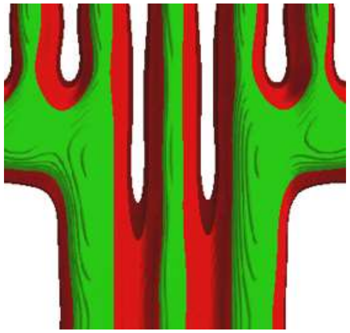
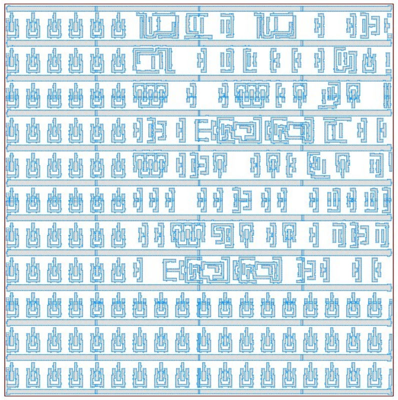
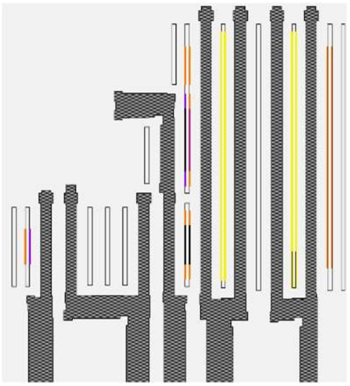
3D resist profiles



OPC/ILT

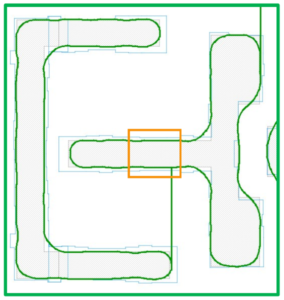


AF print detection

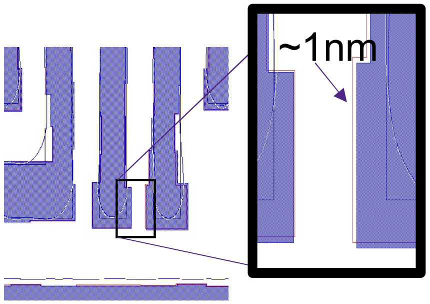


Courtesy J. Word

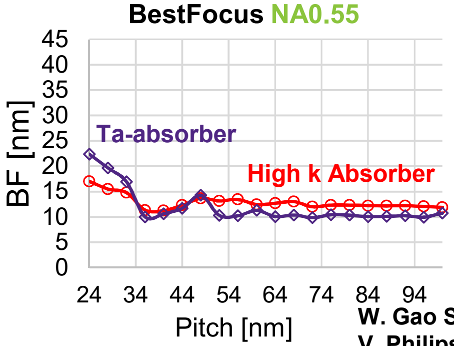
Find hot-spots



Hot-spot fix



Look-ahead studies



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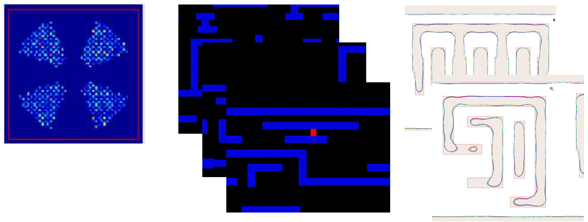
V. Philipsen JM3 2017

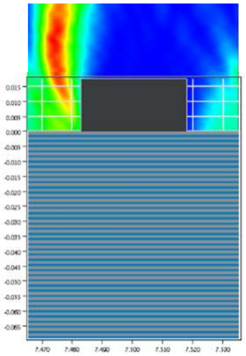
SMO, Design Rules, DTCO



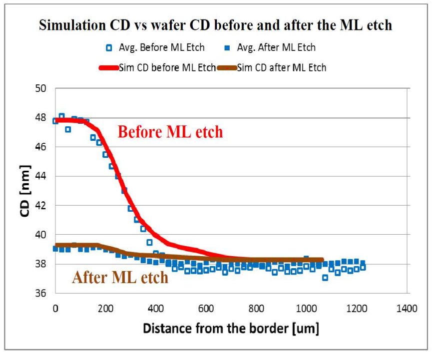
Continuous simulation covers (some) stochastic litho failures

AF printing is an example of easy to observe stochastic litho failure behavior in DUV

3D mask/shadow



Die-Die flare impact



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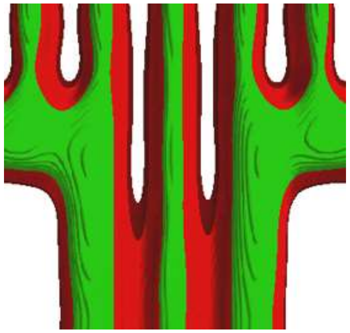
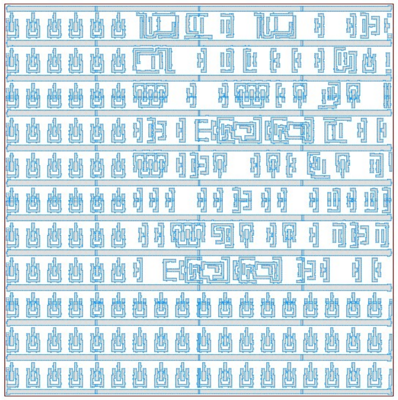
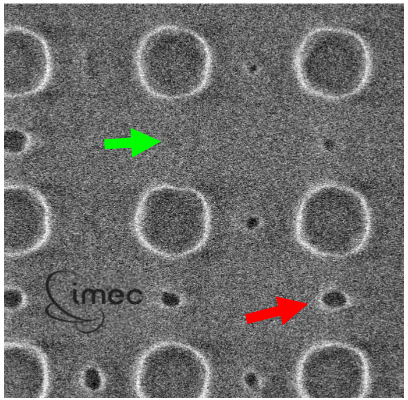
3D resist profiles



OPC/ILT

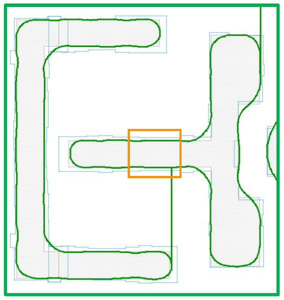


AF print detection

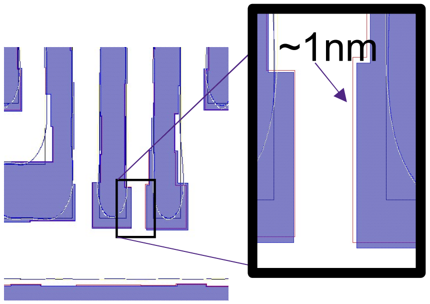


K. Lucas et. al., SPIE 2019

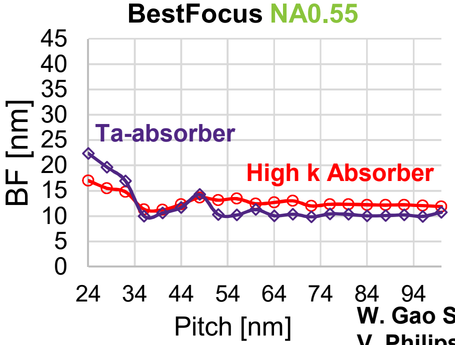
Find hot-spots



Hot-spot fix



Look-ahead studies



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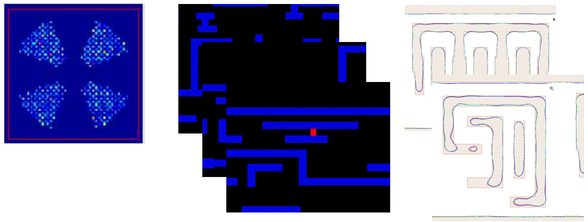
SMO, Design Rules, DTCO

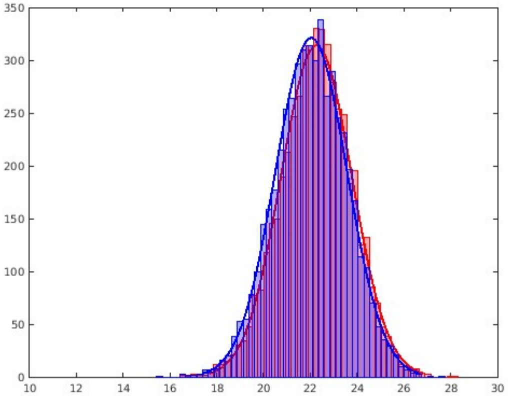


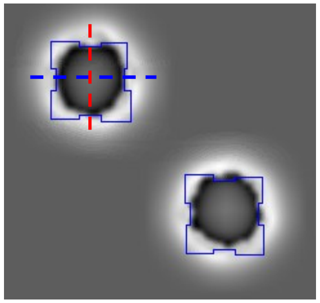
Examples: Rigorous Stochastic Litho Simulation

- mask assessment
- litho process assessment
- manufacturing integration

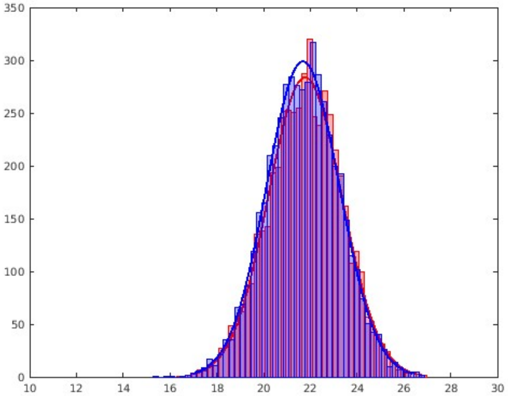
Stochastic EUV image CD distribution comparisons

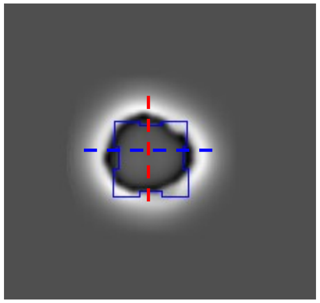
NA0.33 DPT-1
H&V LCDU (3σ) = 4.54nm



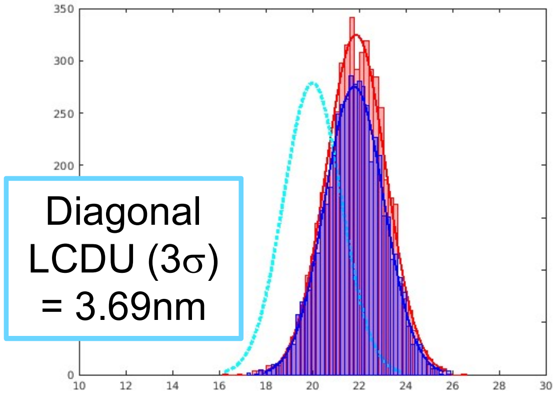


NA0.33 DPT-2
H&V LCDU (3σ) = 4.70nm

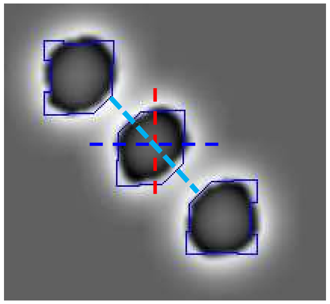




NA0.55 SP
H&V LCDU (3σ) = 3.85nm



Diagonal LCDU (3σ) = 3.69nm



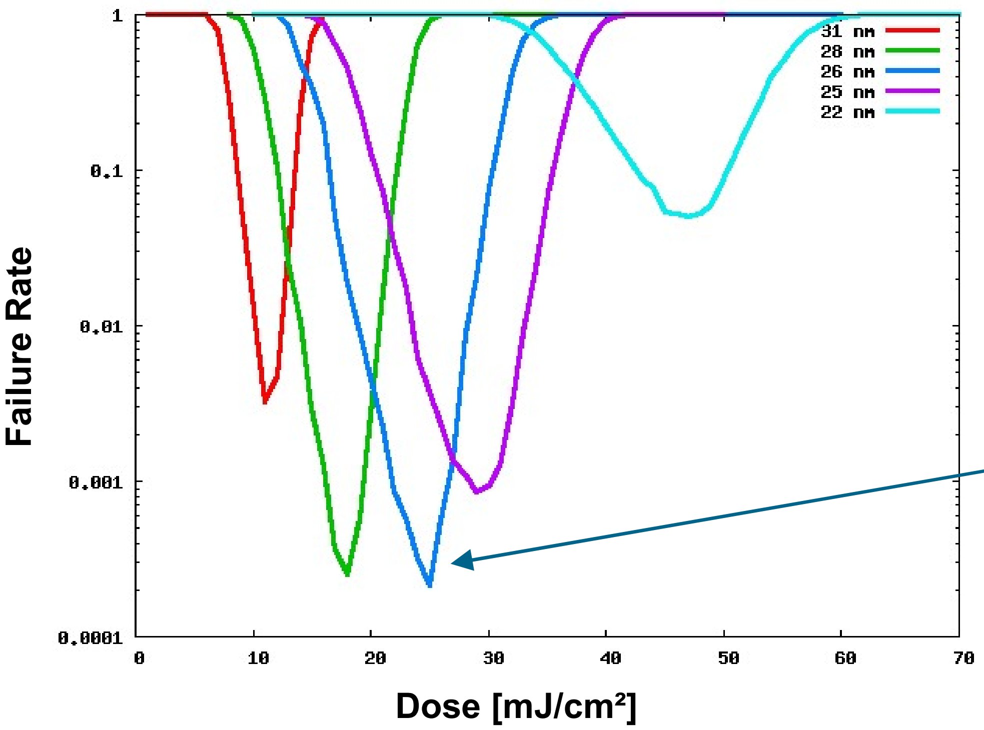
W. Gao et. al. SPIE Vol. 10583, 2018

LCDU NA0.55 SP < LCDU NA0.33 DP

with high-k mask absorber

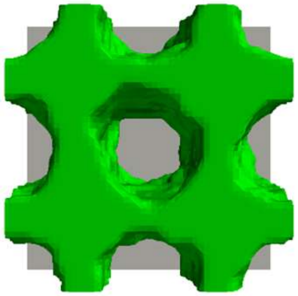
Stochastic failure rate analysis to assess litho options

E.g., Mask Bias Optimization To Minimize Defect Probability



Variation:
Nominal feature size on mask

Test case: Contact hole array

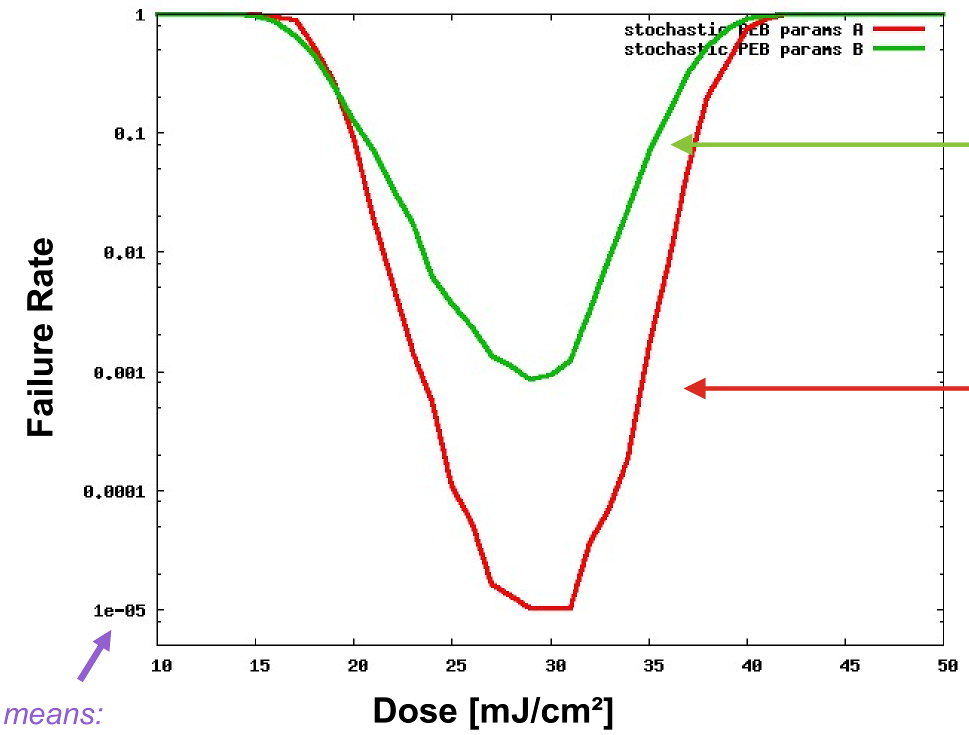


Task
Determine mask feature size with best failure rate behavior

Stochastic simulations support the optimization of layout parameters in order to reduce defect probability

Stochastic failure rate sensitivity analysis of resist properties

Defect Probability Reduction By Resist Parameters Tuning



10^{-5} means: One event in 100,000 simulations

Calibrated rigorous EUV model:

Default stochastic PEB parameters

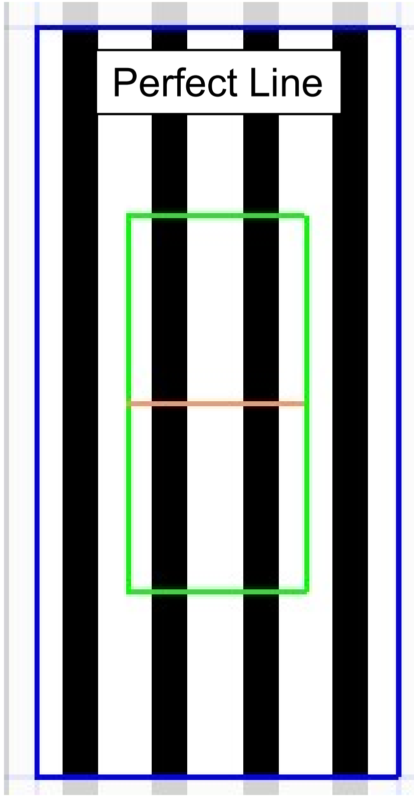
Simulation experiment:

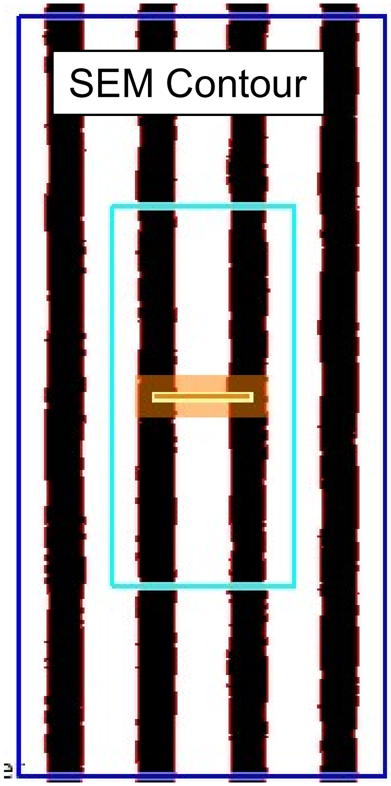
Increase acid and base concentrations by 2x improve failure rate behavior

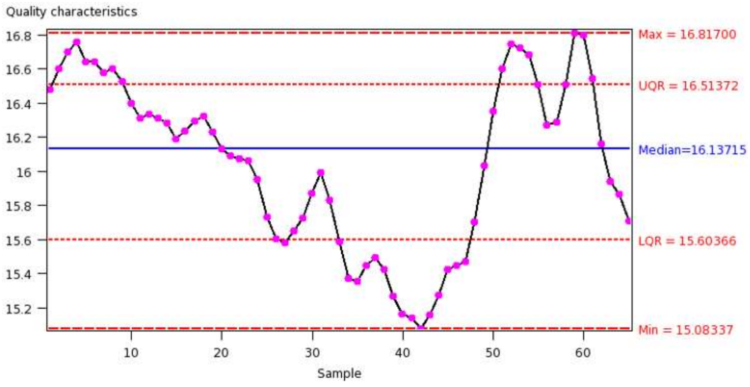
Stochastic simulations can support the optimization of material parameters in order to reduce defect probability

Impact of Mask LWR on Wafer LWR

Example given for Pitch 36nm







Experiment Name=P36V18, a=0, b=0

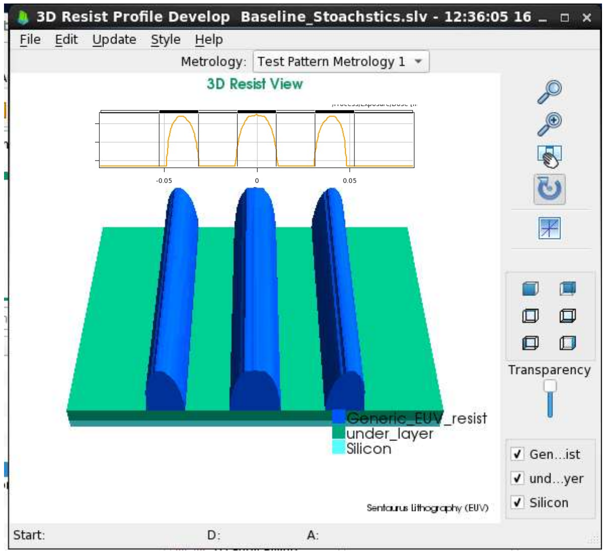
Mean = 16.05182, Standard Deviation = 0.50015, Standard Error = 0.06204, Range = 1.73363

Mask LER extracted from SEM image of mask

Mask LWR ~ 1.5 nm

Stochastic modeling for EUV CAR LWR estimation

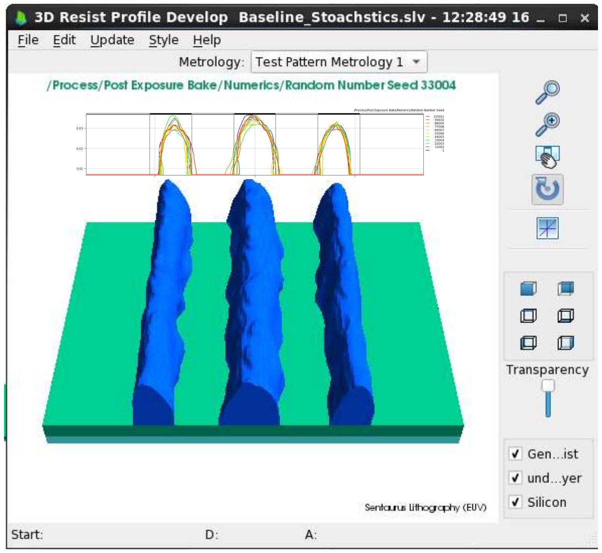
Simulation of species (PAG, Acid, Base) concentrations at interfaces and inside bulk film



3D Resist Profile Develop Baseline_Stoachstics.slv - 12:36:05 16

Metrology: Test Pattern Metrology 1

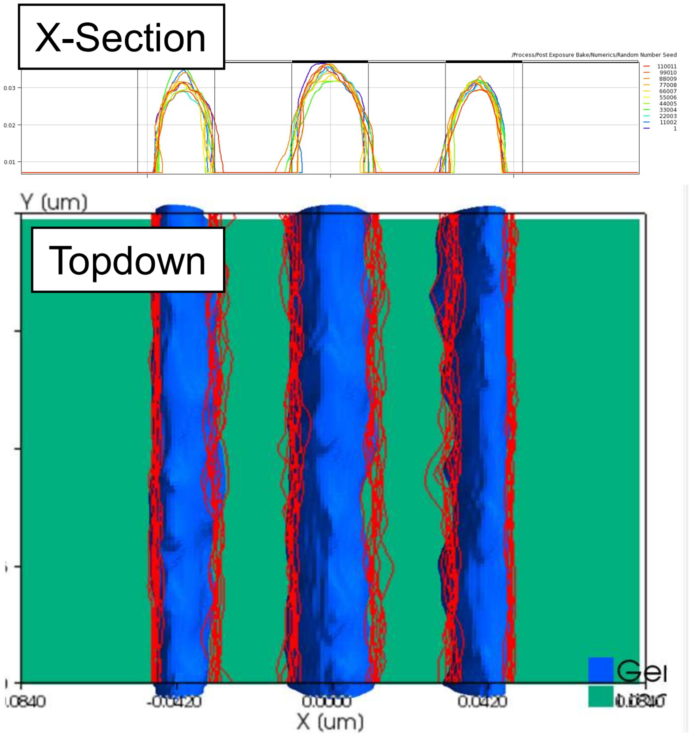
3D Resist View



3D Resist Profile Develop Baseline_Stoachstics.slv - 12:28:49 16

Metrology: Test Pattern Metrology 1

/Process/Post Exposure Bake/Numerics/Random Number Seed 33004



<u>Continuous Model</u>

- Profile shape
- Dose2Size

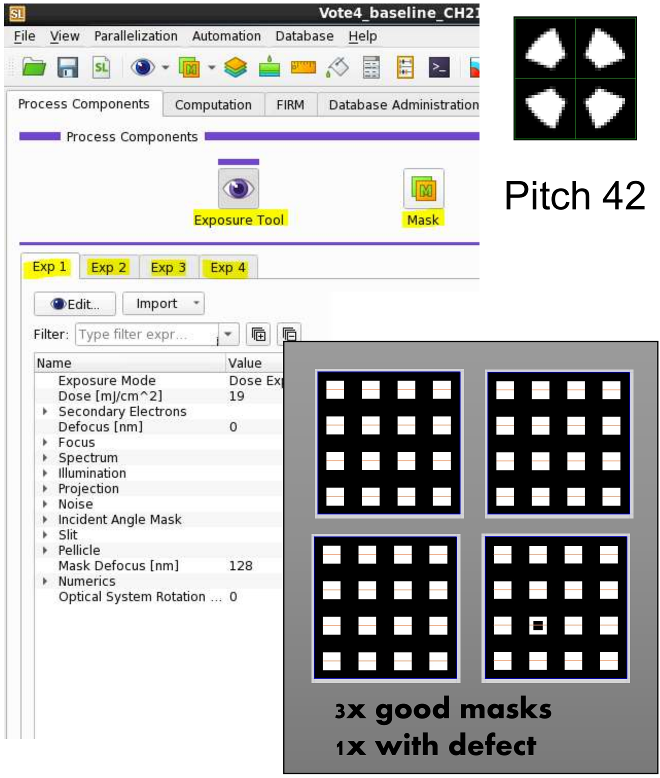
<u>Stochastic Model additional:</u>

- LER, LCDU
- Defectivity

A stochastic model needs many results to provide useful statistics.
Here: Contour band overlay

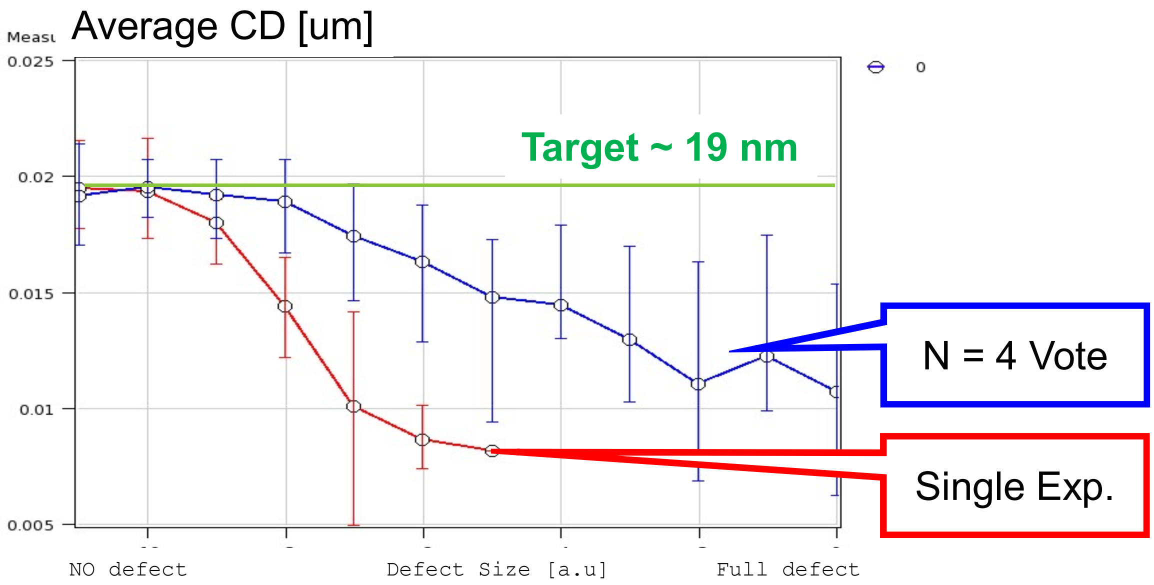
Contact Hole CD vs Defect Size (vote taking lithography)

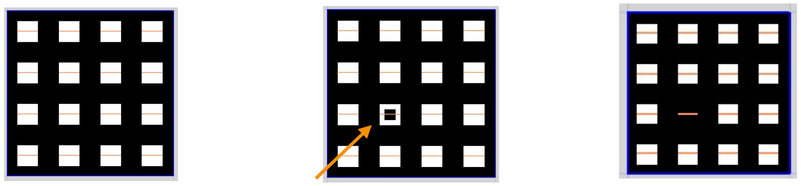
Stochastic simulations assuming perfect overlay



Name	Value
Exposure Mode	Dose Ex
Dose [mJ/cm^2]	19
Secondary Electrons	
Defocus [nm]	0
Focus	
Spectrum	
Illumination	
Projection	
Noise	
Incident Angle Mask	
Slit	
Pellicle	
Mask Defocus [nm]	128
Numerics	
Optical System Rotation ...	0

Pitch 42 nm





No defect

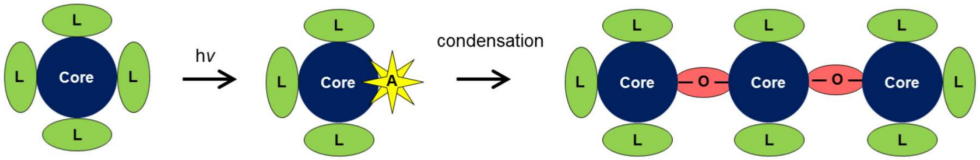
Small defect

Full defect

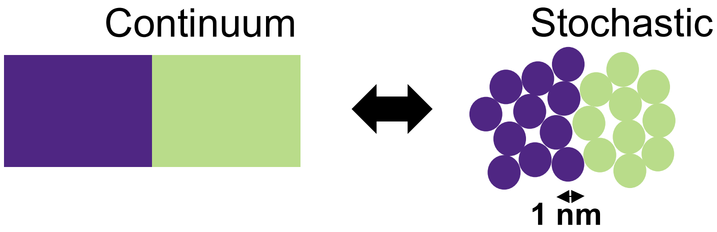
Modeling Metal-Oxide Nanoparticle stochastic resists

Stochastic simulation for photo-bridging of spin coated resist films

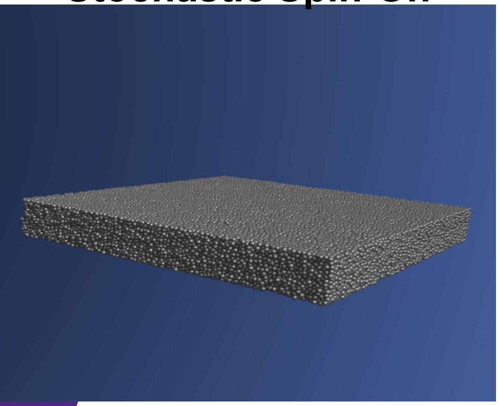
Fundamentally different mechanisms than CAR resists:
- Clustering



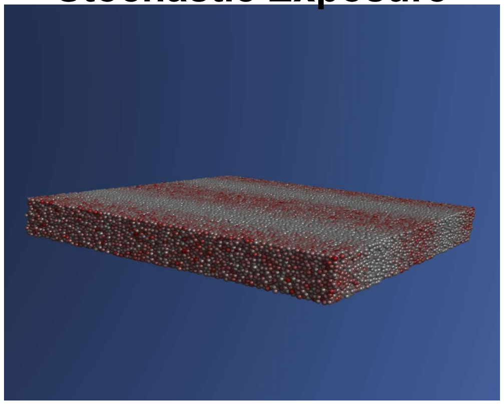
Stochastic MOx model takes into account packing effects and reaction of MOx nanoparticles



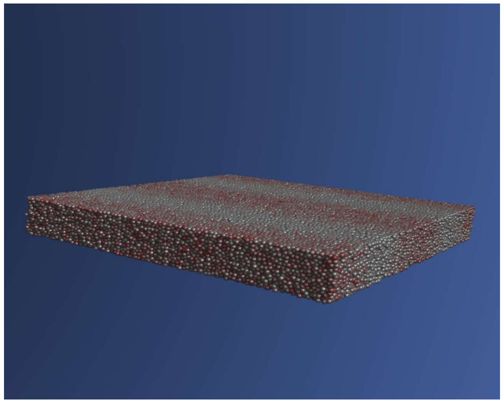
Stochastic Spin-On



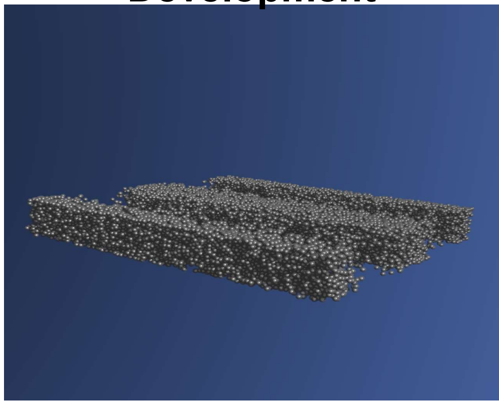
Stochastic Exposure



Stochastic PEB



Development



Stochastic vs. Continuous Process Window (PW)

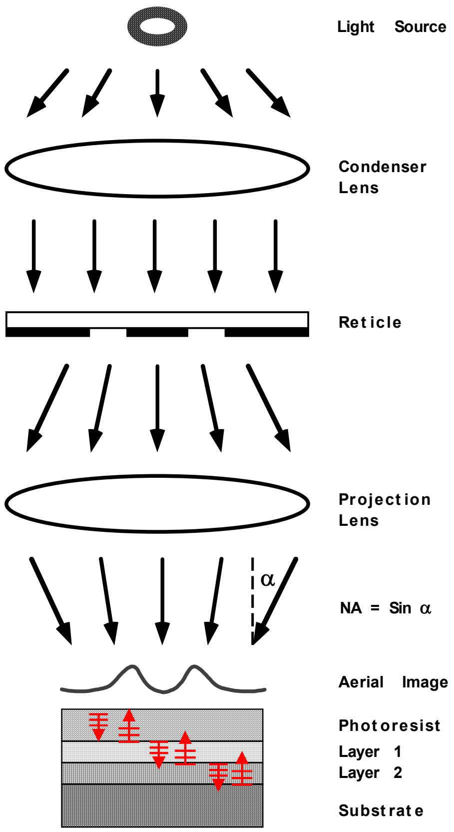
<u>Assumptions for compact stochastic model usage:</u>

1. Will be used for large area analysis and mask synthesis -> fast
2. Will use models at discreet PW conditions
3. Will not be used for Monte-Carlo analysis on large areas

Continuous Model Process Window – 2 main error areas

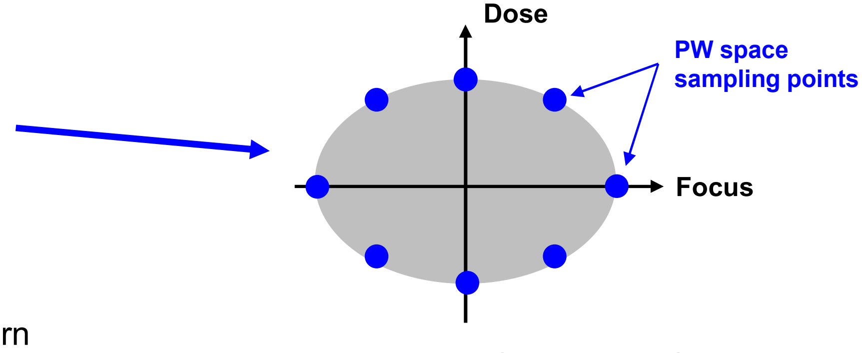
- **Dose** errors (signal intensity, process response to signal)
  - **~Dose effects:** dose, apodization, polarization, flare, source map, mask CD, mask reflectance, resist photospeed, resist/ARC/underlayer thickness, bake temp, developer sensitivity, etch, implant, CD metrology
  - **Systematic:** X-mask, X-slit, X-scan, X-source, X-wafer, X-lot, tool-tool, module-module, total # EUV pulses, resist batch-batch, pattern pitch/density…
  - **Stochastic**: X-mask, X-scan, X-wafer, field-field, wafer-wafer, lot-lot, day-day, CD measurement…
- **Focus** errors (phase, path length offsets) in spatial light orders
  - **~Focus effects:** aberrations, focus offset, resist/ARC/underlayer thickness, mask phase, mask sidewall-angle…
  - **Systematic:** X-mask, X-slit, X-scan, X-source, X-wafer, X-lot, tool-tool, module-module, total # EUV pulses, pattern pitch…
  - **Stochastic:** X-mask, X-scan, X-wafer, field-field, wafer-wafer, lot-lot, day-day…
- Determine **PW budget** for dose and focus independently
  - Linearly combine systematic errors, sum of squares for stochastic errors
  - Define +/- max focus & dose deviations from nominal = PW limits for simulation

Simplified litho system



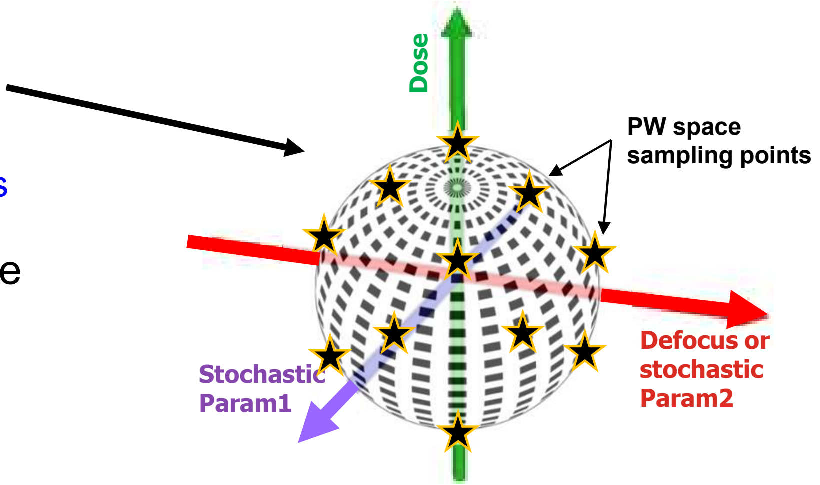
Compact stochastic simulation PW definition

- Traditional 'continuous' PW is only dose & focus space.
  - CD, EPE, PV-band or pinch/bridge simulated at discrete dose & focus sampling points along 2D PW space boundary
  - If no failures seen, PW is '**good**'
  - If any failures seen, PW is '**bad**' -> call hot-spot fix recipe
    - Hot-spot fix uses continuous PW simulations to analyze & repair pattern



2-D DUV PW space of only Dose & Focus

- **Q:** How to extend methodology to EUV stochastic variations?
- **A:** Need to add new parameters for key stochastic EUV effects
  - Dose, focus **and** key parameters which best explain stochastic failures in EUV resist (e.g., ILS, acid concentration, base diffusion)
  - Rigorous stochastic simulation guides choice of parameters & limits



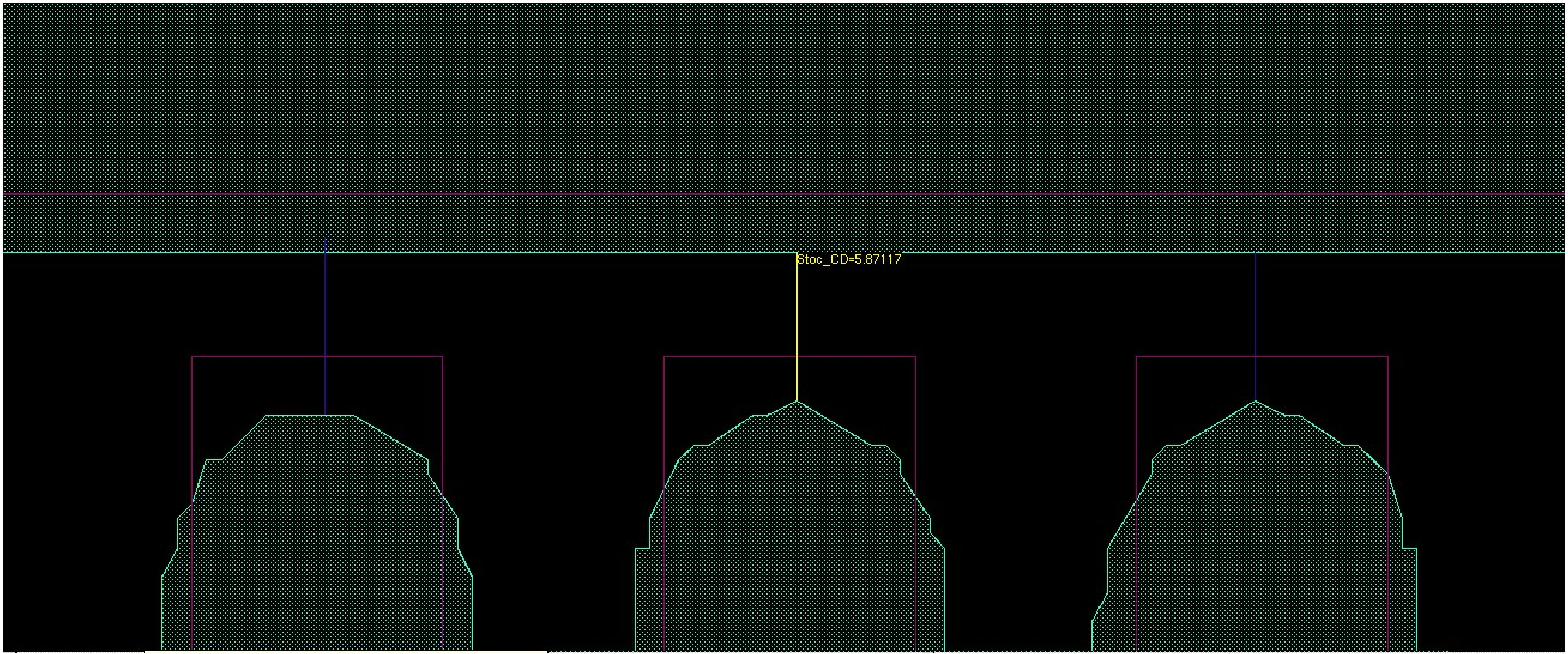
3-D EUV PW space with stochastic parameter(s)

- A discrete set of models can still represent the boundaries of the fab's expected EUV stochastic N-dimensional PW space
  - If no failures seen, PW is '**good**'
  - If any failures seen, PW is '**bad**' -> call hot-spot fix recipe
    - Hot-spot fix uses stochastic PW simulations to analyze & repair pattern

Stochastic Compact PW Model Examples

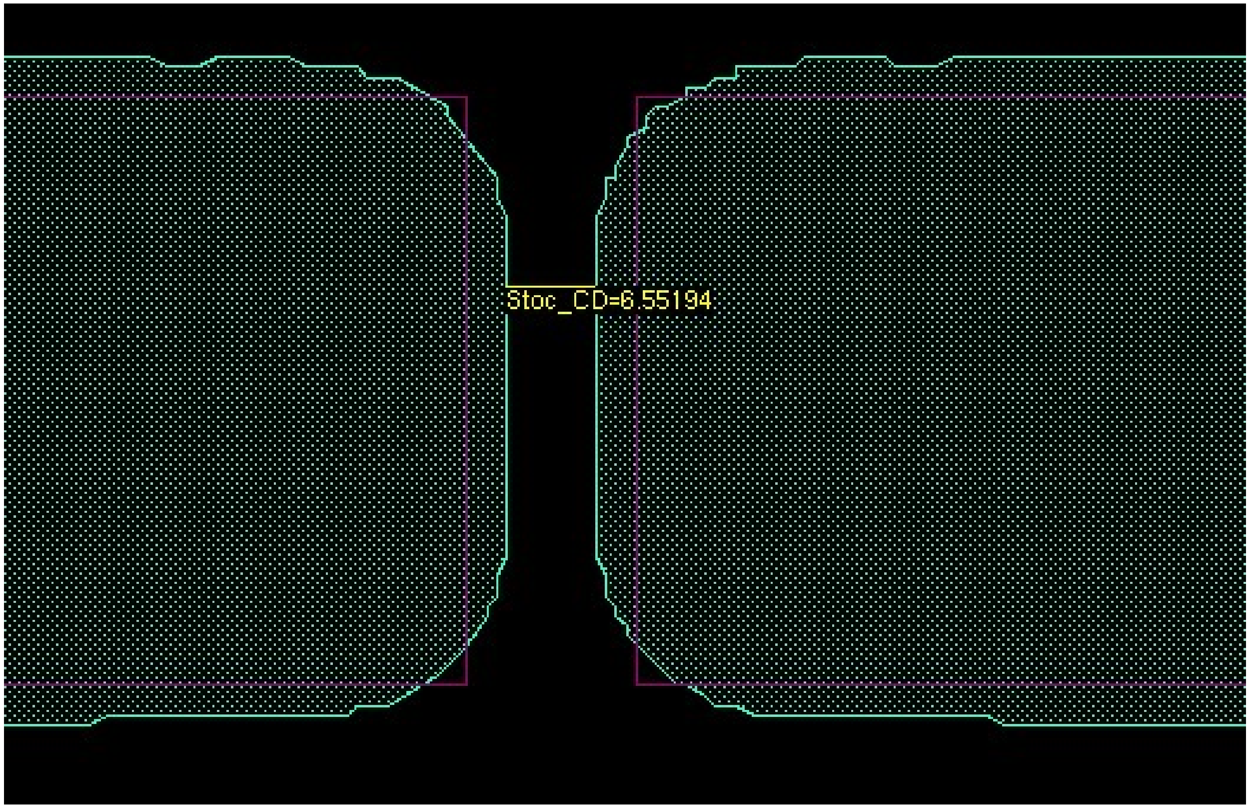
Initial industry approach – using Image-Log Slope (ILS) to approximate stochastic failure sensitivity in EUV OPC verification

Stochastic ILS model: LineEnd to Pad bridging risk detection



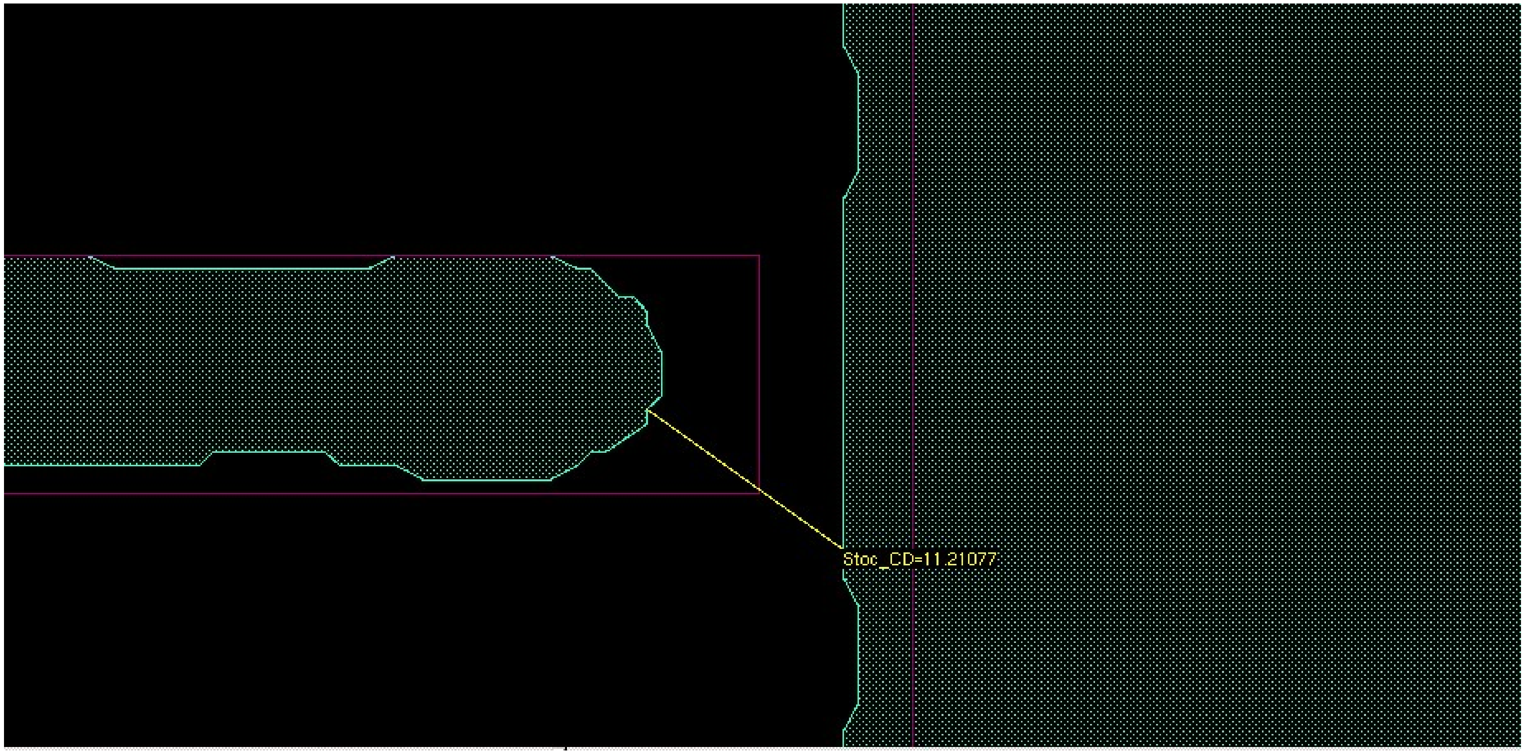
Continuous Model Worst CD	ILS Tail	ILS Head	Stochastic model Worst CD	Stochastic model CD offset
10.0nm	0.048 1/nm	0.030 1/nm	5.9nm	-4.1nm

Stochastic ILS model: Pad to Pad bridging risk detection



Continuous Model Worst CD	ILS Tail	ILS Head	Stochastic model Worst CD	Stochastic model CD offset
9.0nm	0.051 1/nm	0.051 1/nm	6.6nm	-2.4nm

Stochastic ILS model: Non-perpendicular bridge detection

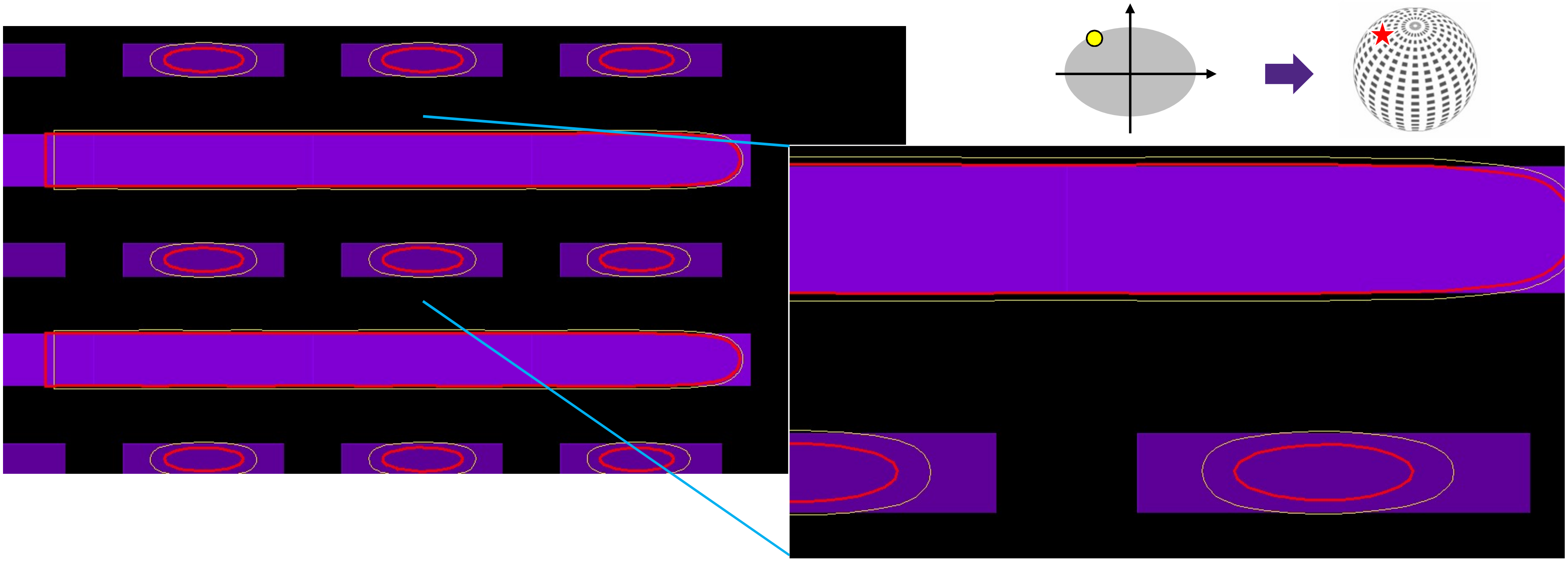


Continuous Model Worst CD	ILS Tail	ILS Head	Stochastic model Worst CD	Stochastic model CD offset
17.2nm	0.021 1/nm	0.031 1/nm	11.2nm	-6.0nm

Improved Compact Stochastic PW Model Examples

Using PW model with optical and resist stochastic parameters to more accurately detect stochastic failure sensitivity in EUV OPC verification

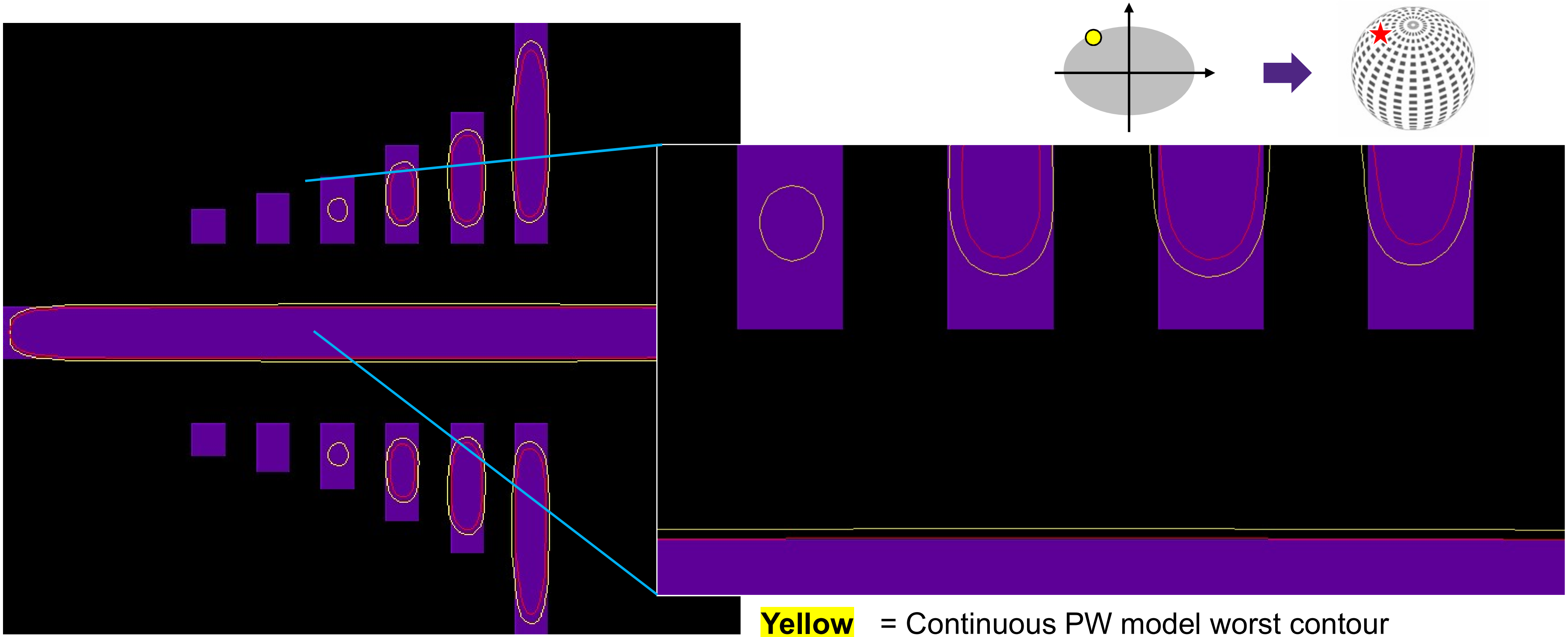
Example: Stochastic Optics + Resist model
- for sensitive pattern pinching risk detection and repair



Yellow = Continuous PW model worst contour

Red = Stochastic (Optics + Resist) model worst contour

Example #2: Stochastic Optics + Resist model
- for sensitive pattern pinching risk detection and repair



Yellow = Continuous PW model worst contour

Red = Stochastic (Optics + Resist) model worst contour

Summary & Conclusions

- Reviewed a broad range of current continuous & stochastic simulation methods
- Compared continuous vs. stochastic process window (PW) error inputs
- Discussed a straight-forward extension of current PW budget methodologies to EUV compact stochastic PW modeling
  - **With help from rigorous stochastic simulation analysis**
- Provided examples of simulation flows for reducing stochastic failure risk by PW compact modeling analysis and mask synthesis
  - **Standard ILS-based CD EUV failure risk increase**
  - **More accurate Optics + Resist stochastic EUV PW contour failure analysis**

- Acknowledgements:
  - Aram Kazarian, Weimin Gao