Introducing ProLE™:
The Programmable Lithography Engine

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PETERSEN ADVANCED LITHOGRAPHY INC.

Outline

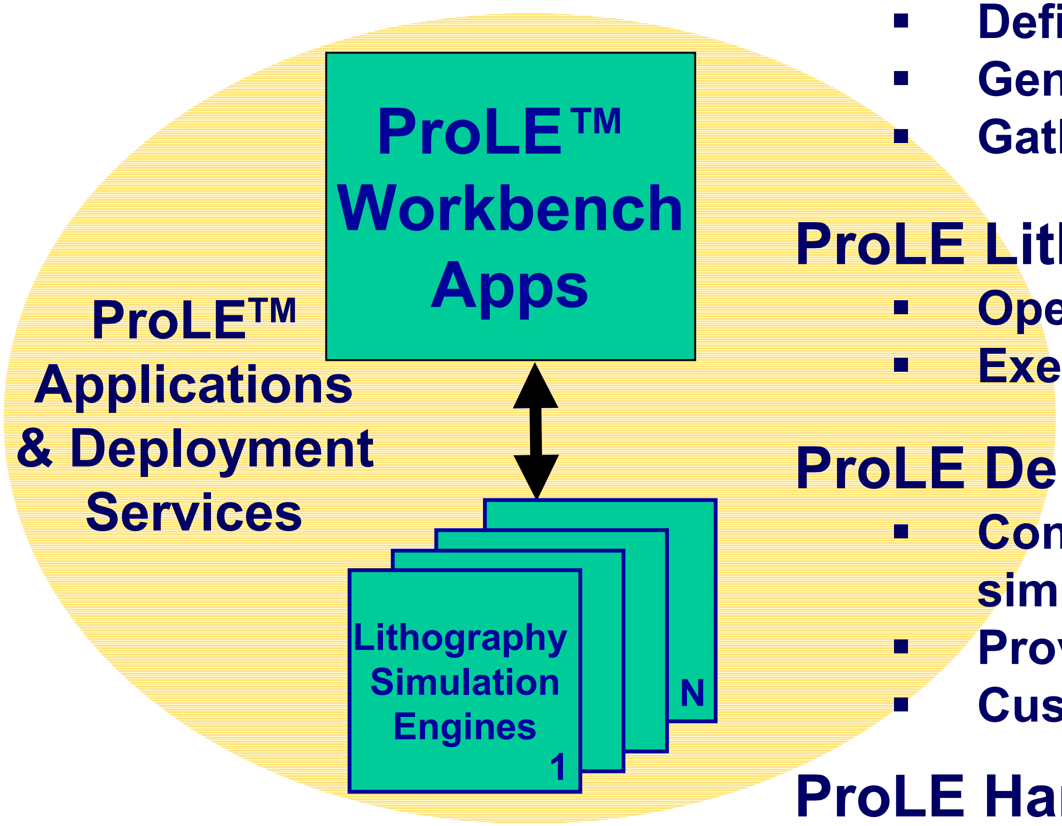
- Introduction – What is ProLE^{TM}?
- ProLE Components
  - ProLE Workbench
  - ProLE Limited Edition (ProLE-LE)
  - ProLE Hardware
  - ProLE Services
- Examples and Use Cases
  - Lithography optimization
  - RET validation, optimization, rule generation
  - EDA – true design for yield

What is ProLE?

- **ProLE is a design-for-yield optimization solution that:**
  - Reduces litho-related systematic design failures
    - Improves price:performance potential
  - Reduces learning cycles before getting to market
    - Fewer patterning related mask/design iterations
    - Reduced wafer costs to achieve yield entitlement
    - Improved engineering effectiveness
  - Provides greater revenue potential thru shorter time to market
    - Improves average selling price (ASP) and market size
    - Provides competitive advantage by early insertion
    - Improves performance and quality

  - **ProLE is a software-service-hardware solution using single and distributive computing capability.**

ProLE™ System Overview



ProLE™ Workbench Apps

ProLE™ Applications & Deployment Services

Lithography Simulation Engines

ProLE Workbench

- Defines simulation work
- Generates, submits and monitors jobs
- Gathers and analyzes results

ProLE Litho Simulation "Engines"

- Operate independently, in-parallel
- Execute jobs automatically

ProLE Deployment Services

- Configure, calibrate & maintain litho simulation models
- Provide technical consulting
- Customize applications

ProLE Hardware

- ProLE server and workstations
- Engine blade-computers in "grid"
- Infrastructure HW & SW

What is the ProLE™ Workbench?

- SERIOUS Lithography Simulation Capabilities
  - Front-load simulation setup
  - Perform Monte Carlo Simulations
  - Investigate Higher Order Aberrations
  - Eliminate unnecessary simulation conditions
  - Distribute PROLITH Simulations across a Network Grid (Cluster Computer)
- Tasks that are orders of magnitude too complex otherwise become manageable with the ProLE Workbench

The ProLE™ Workbench Software

- Drive & distribute complex PROLITH* simulation jobs
  - Easily generate matrix-diagonals of PROLITH inputs
  - Advanced aberration package including the ability to do aberrations of 136 Zernike terms (allows study of localized flare).
  - Automate the output of results for Excel or ProDATA analysis
  - Find dose-to-size and then seamlessly run properly bracketed focus-exposure matrices
  - Quickly sort and categorize focus-exposure simulation results prior to final analysis (optional)
  - Automatically build case tables of batch results
  - Get multiple metrology sample cut data from multiple simulation windows and from multiple mask input files
  - Monte Carlo variation of any PROLITH input

*PROLITH™ and PRODATA™ are from KLA-Tencor Inc.

ProLE™ Workbench

- Workbench embeds ProLE, PROLITH, Data sorter and Automated ProData plus other software utilities.

Open *.pl2

Close PROLITH & Job Builder

Info

Launch ProLE Client

Launch ProData

Display Parameters

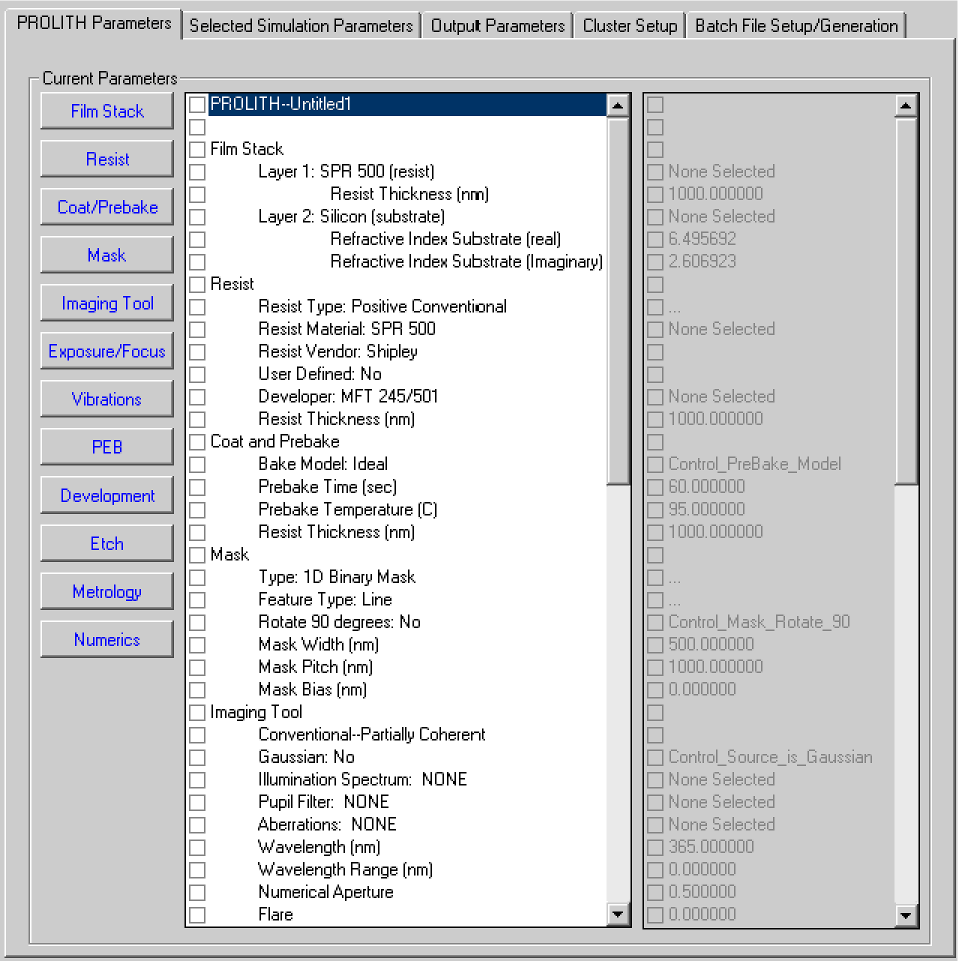
Display Help

PROLITH

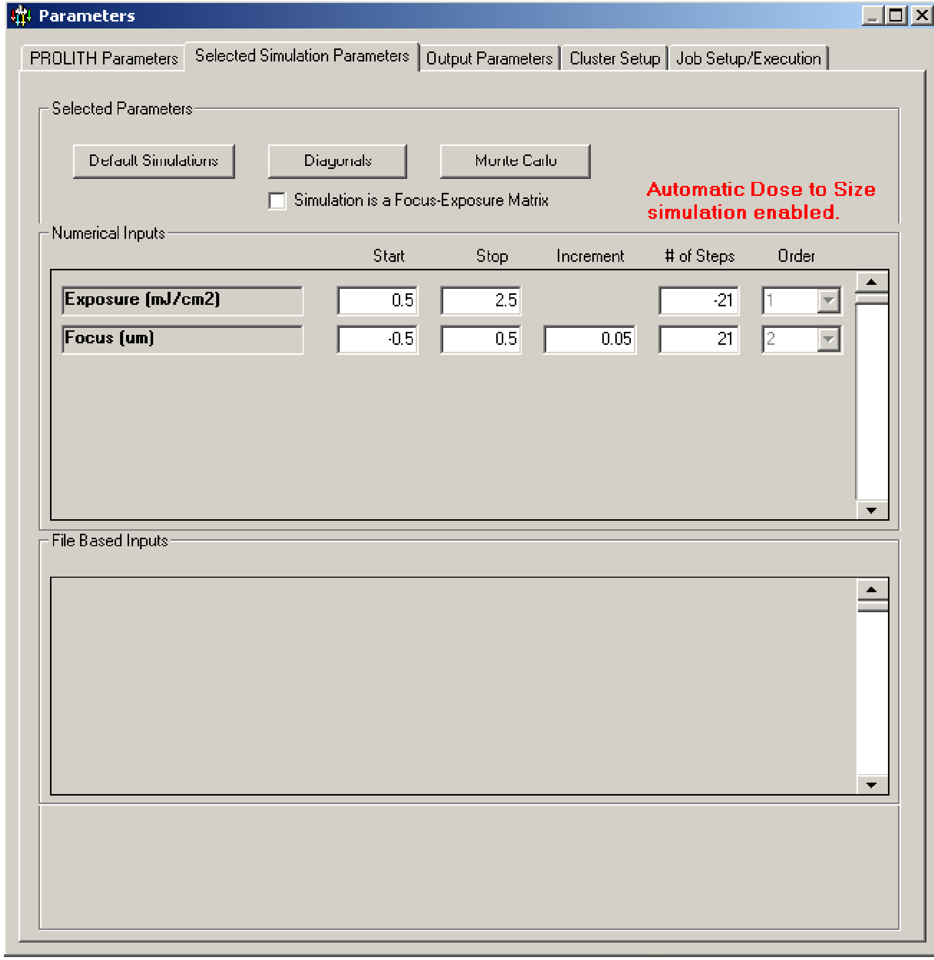
Analyze ProLE Simulation

ProLE™ Workbench

- Select any PROLITH input parameter including File Based inputs



☐ PROLITH--Untitled1	☐
☐	☐
☐ Film Stack	☐
☐ Layer 1: SPR 500 (resist)	☐ None Selected
☐ Resist Thickness (nm)	☐ 1000.000000
☐ Layer 2: Silicon (substrate)	☐ None Selected
☐ Refractive Index Substrate (real)	☐ 6.495692
☐ Refractive Index Substrate (Imaginary)	☐ 2.606923
☐ Resist	☐
☐ Resist Type: Positive Conventional	☐ ...
☐ Resist Material: SPR 500	☐ None Selected
☐ Resist Vendor: Shipley	☐
☐ User Defined: No	☐
☐ Developer: MFT 245/501	☐ None Selected
☐ Resist Thickness (nm)	☐ 1000.000000
☐ Coat and Prebake	☐
☐ Bake Model: Ideal	☐ Control_PreBake_Model
☐ Prebake Time (sec)	☐ 60.000000
☐ Prebake Temperature (C)	☐ 95.000000
☐ Resist Thickness (nm)	☐ 1000.000000
☐ Mask	☐
☐ Type: 1D Binary Mask	☐ ...
☐ Feature Type: Line	☐ ...
☐ Rotate 90 degrees: No	☐ Control_Mask_Rotate_90
☐ Mask Width (nm)	☐ 500.000000
☐ Mask Pitch (nm)	☐ 1000.000000
☐ Mask Bias (nm)	☐ 0.000000
☐ Imaging Tool	☐
☐ Conventional--Partially Coherent	☐
☐ Gaussian: No	☐ Control_Source_is_Gaussian
☐ Illumination Spectrum: NONE	☐ None Selected
☐ Pupil Filter: NONE	☐ None Selected
☐ Aberrations: NONE	☐ None Selected
☐ Wavelength (nm)	☐ 365.000000
☐ Wavelength Range (nm)	☐ 0.000000
☐ Numerical Aperture	☐ 0.500000
☐ Flare	☐ 0.000000



☐ Simulation is a Focus-Exposure Matrix

Automatic Dose to Size simulation enabled.

	Start	Stop	Increment	# of Steps	Order
Exposure (mJ/cm2)	0.5	2.5		-21	1
Focus (um)	-0.5	0.5	0.05	21	2

Select File-based PROLITH Inputs

Select inputs defined by PROLITH database files and ProLE Workbench will generate simulations varying the selected files automatically.

Available File-based Inputs

Aberration Files - .ZRN

Mask Files - .MSK

1D Grayscale Masks -.GRY

Source Shape Files - .SRC

Spectrum Files - .ILL

Vibration Files - .VIB

Resist Files - .RES

Temp.(Bake)Profiles - .TPR

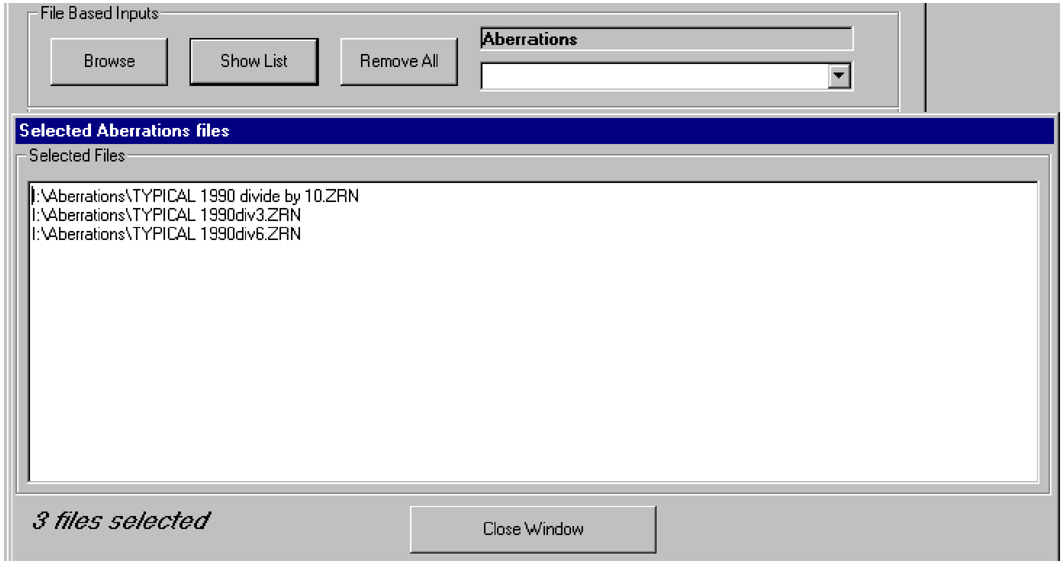
Pupil Filter Files - .FIL

CODE-V Aberrations -.INT

New file type:

High Order Zernikes - .HOZ

User Defined Distribution - .UDD

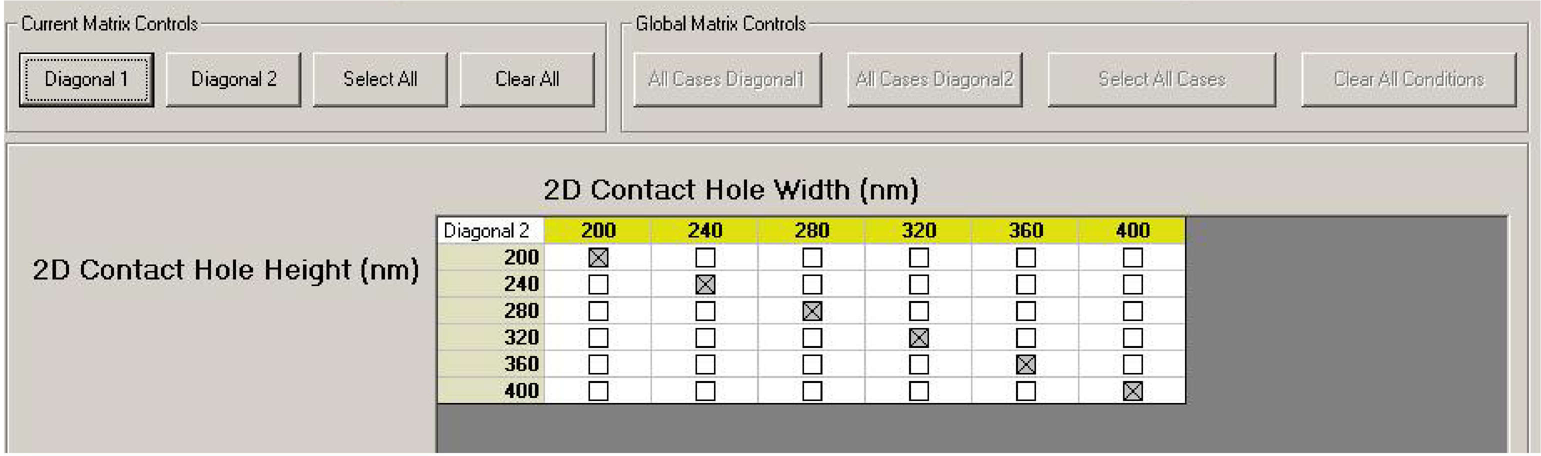


Selected Aberrations files

I:\Aberrations\TYPICAL 1990 divide by 10.ZRN
I:\Aberrations\TYPICAL 1990div3.ZRN
I:\Aberrations\TYPICAL 1990div6.ZRN

3 files selected

Control the PROLITH Simulation Matrix

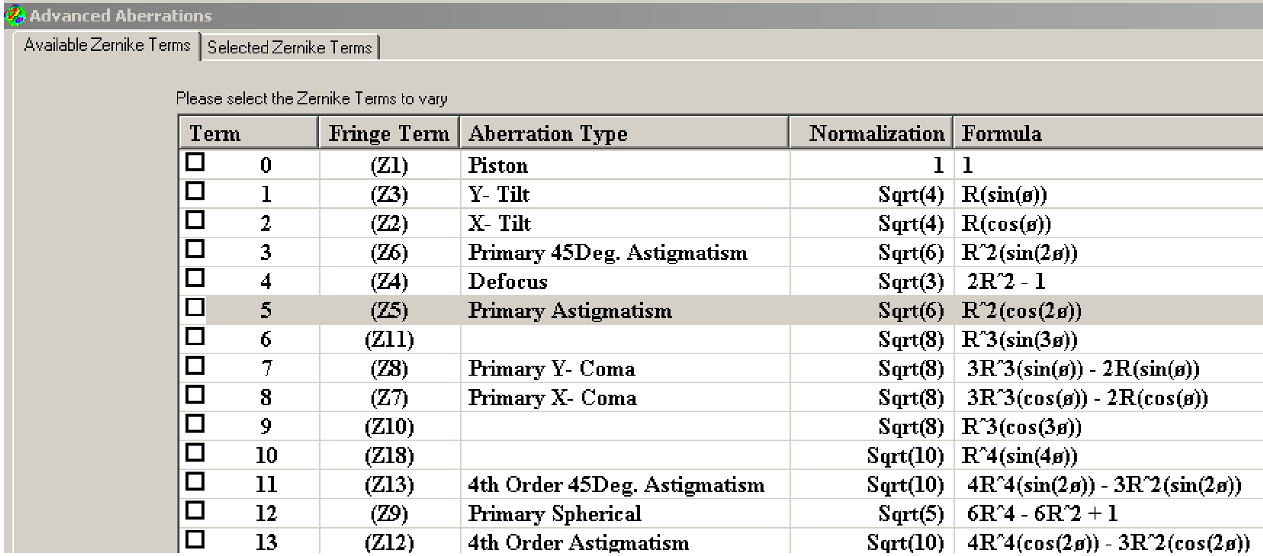


Diagonal 2	200	240	280	320	360	400
200	☒	☐	☐	☐	☐	☐
240	☐	☒	☐	☐	☐	☐
280	☐	☐	☒	☐	☐	☐
320	☐	☐	☐	☒	☐	☐
360	☐	☐	☐	☐	☒	☐
400	☐	☐	☐	☐	☐	☒

- Eliminate unnecessary simulations by taking control of the Simulation Matrix
- Use ProLE to simulate coupled inputs such as Contact Hole Width/Height, Alt. PSM Chrome Widths, and more

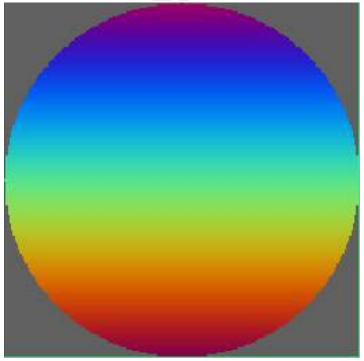
Simulate Higher Order Aberrations with PROLITH

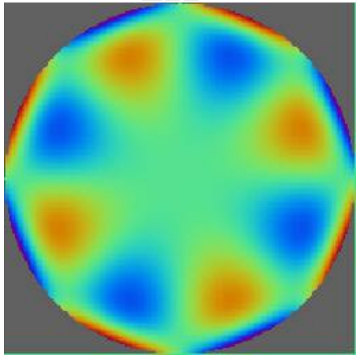
- Investigate Zernike aberrations up to Z136
- Correlate PROLITH aberrations with CODE-V™ Lens information
- Load and combine .ZRN, .INT and the new .HOZ files

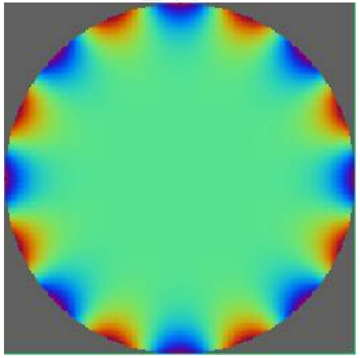


Please select the Zernike Terms to vary

Term	Fringe Term	Aberration Type	Normalization	Formula
☐ 0	(Z1)	Piston	1	1
☐ 1	(Z3)	Y- Tilt	Sqrt(4)	R(sin(ø))
☐ 2	(Z2)	X- Tilt	Sqrt(4)	R(cos(ø))
☐ 3	(Z6)	Primary 45Deg. Astigmatism	Sqrt(6)	R^2(sin(2ø))
☐ 4	(Z4)	Defocus	Sqrt(3)	2R^2 - 1
☐ 5	(Z5)	Primary Astigmatism	Sqrt(6)	R^2(cos(2ø))
☐ 6	(Z11)		Sqrt(8)	R^3(sin(3ø))
☐ 7	(Z8)	Primary Y- Coma	Sqrt(8)	3R^3(sin(ø)) - 2R(sin(ø))
☐ 8	(Z7)	Primary X- Coma	Sqrt(8)	3R^3(cos(ø)) - 2R(cos(ø))
☐ 9	(Z10)		Sqrt(8)	R^3(cos(3ø))
☐ 10	(Z18)		Sqrt(10)	R^4(sin(4ø))
☐ 11	(Z13)	4th Order 45Deg. Astigmatism	Sqrt(10)	4R^4(sin(2ø)) - 3R^2(sin(2ø))
☐ 12	(Z9)	Primary Spherical	Sqrt(5)	6R^4 - 6R^2 + 1
☐ 13	(Z12)	4th Order Astigmatism	Sqrt(10)	4R^4(cos(2ø)) - 3R^2(cos(2ø))


Z1


Z22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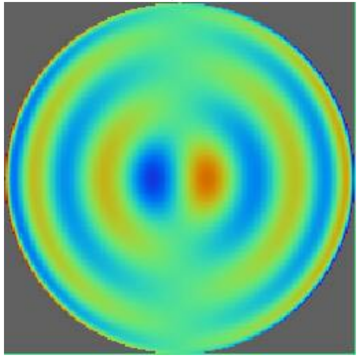
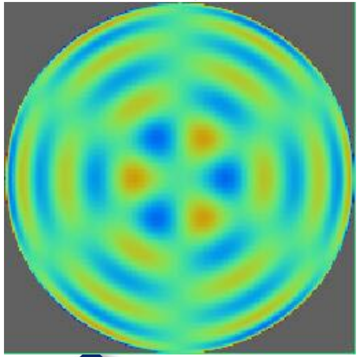
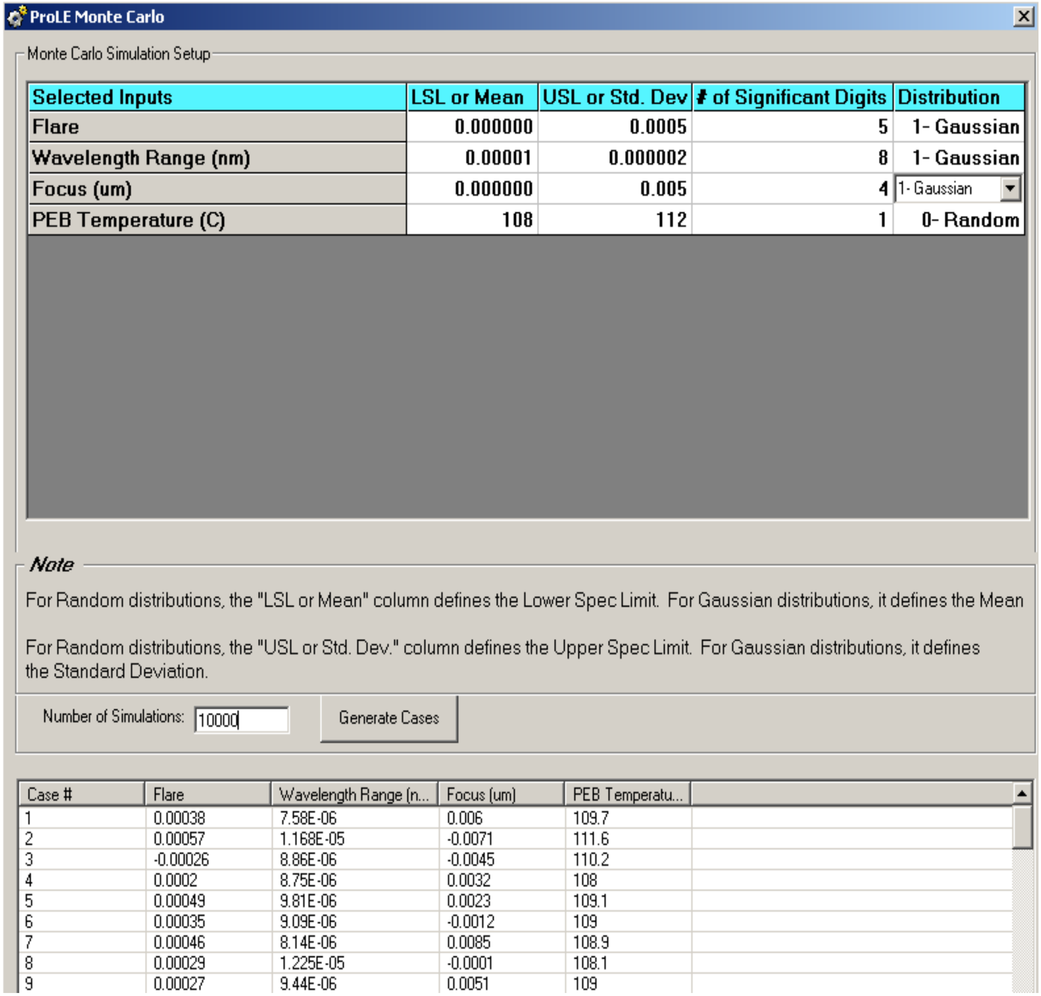

Z72


Z129

Monte Carlo Simulations with PROLITH

- Select up to 20 different numerical inputs
- Create purely random conditions, Gaussian weighted conditions or user defined distributions



Selected Inputs	LSL or Mean	USL or Std. Dev	# of Significant Digits	Distribution
Flare	0.000000	0.0005	5	1- Gaussian
Wavelength Range (nm)	0.00001	0.000002	8	1- Gaussian
Focus (um)	0.000000	0.005	4	1- Gaussian
PEB Temperature (C)	108	112	1	0- Random

Note

For Random distributions, the "LSL or Mean" column defines the Lower Spec Limit. For Gaussian distributions, it defines the Mean

For Random distributions, the "USL or Std. Dev." column defines the Upper Spec Limit. For Gaussian distributions, it defines the Standard Deviation.

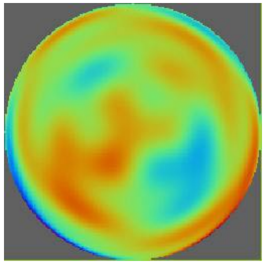
Number of Simulations: 10000

Case #	Flare	Wavelength Range (n...	Focus (um)	PEB Temperatu...
1	0.00038	7.58E-06	0.006	109.7
2	0.00057	1.168E-05	-0.0071	111.6
3	-0.00026	8.86E-06	-0.0045	110.2
4	0.0002	8.75E-06	0.0032	108
5	0.00049	9.81E-06	0.0023	109.1
6	0.00035	9.09E-06	-0.0012	109
7	0.00046	8.14E-06	0.0085	108.9
8	0.00029	1.225E-05	-0.0001	108.1
9	0.00027	9.44E-06	0.0051	109

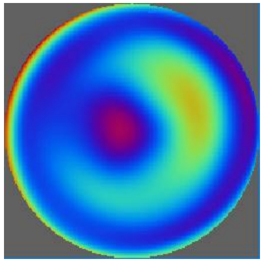
✸ Note: This feature requires the ProLE cluster hardware system to execute

Example: Complex Aberrations

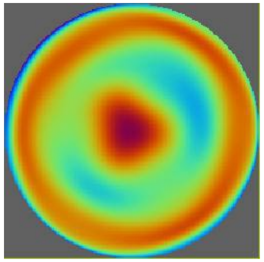
Zernike Terms: Z8 (X- Coma), Z11 (45Deg. Astigmatism),
Z24 (Spherical), Z99 (X- Trifoil)



Conditions: -0.04, 0.07, 0.03, 0.05



Conditions: 0.15, 0.07, -0.13, -0.02



Conditions: -0.03, -0.04, 0.11, 0.03

Note: Above values are in Waves

ProLE™ Limited-Edition: An Introductory Product

- ProLE-LE is the ProLE Workbench for a single computer
  - Does not distribute jobs over multiple processors
  - Does not perform Monte Carlo simulations
  - All other features are available
  - **Huge productivity gain over ProBatch* coding, using same hardware**

*ProBatch is a set of commands for driving PROLITH™, from KLA-Tencor Inc.

The ProLE™ Hardware

- ProLE Engine uses a system of compact "blade" computers
  - 16-1000+ Engine blades: 2.6GHz P4/1GB SDRAM /40GB HD
  - ProLE server(s)
  - Hardware infrastructure
    - NAS
    - Smart switches
    - Racks
    - Cabling
    - UPS and clean power
  - Software infrastructure
    - Deployment
    - Management
    - Monitoring
    - Diagnostic
- ProLE has a special grid-based licensing agreement for PROLITH
  - Favorable pricing based on ProLE license management system
  - Built in redundancy and temporary expansion

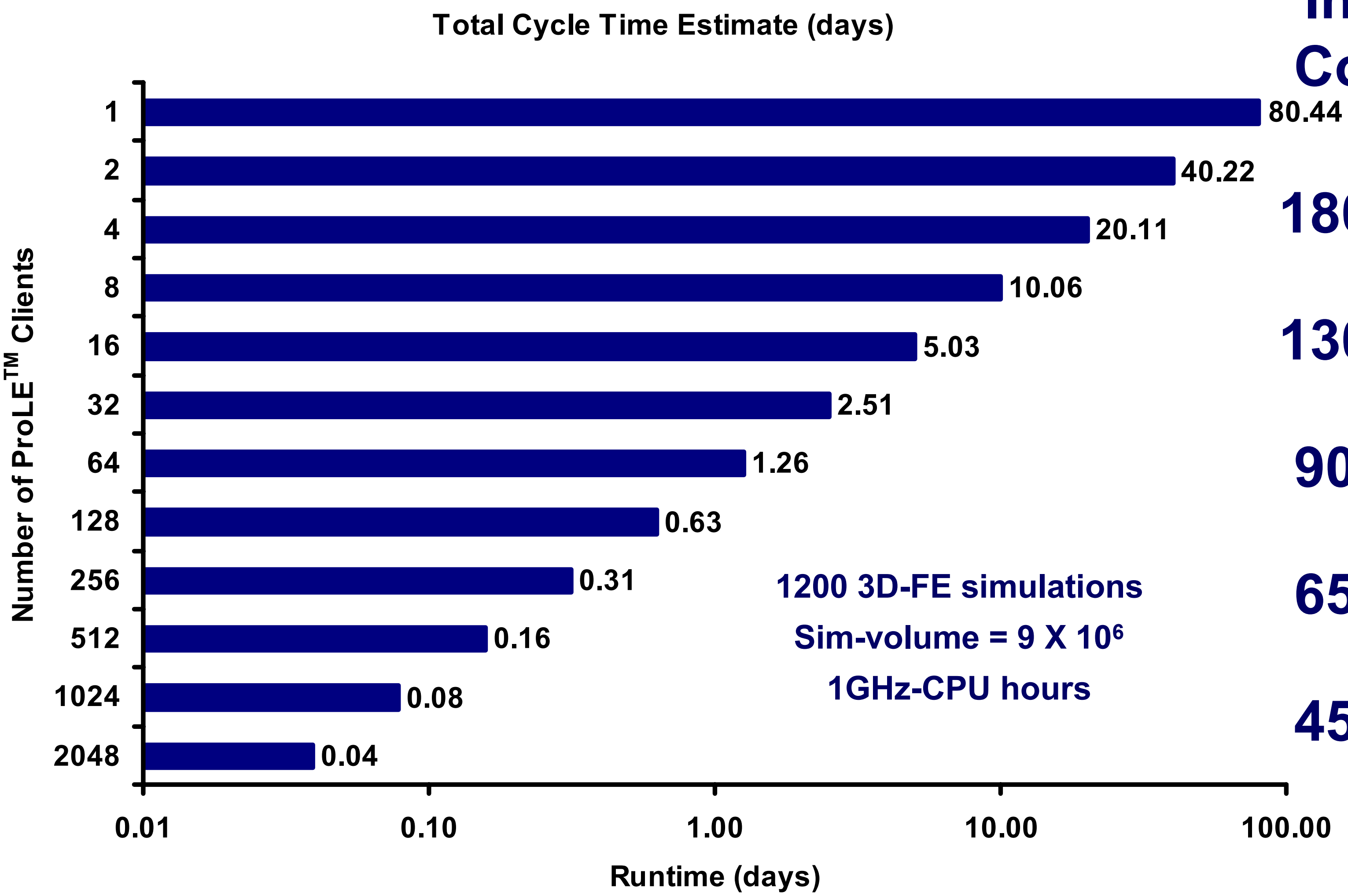
The ProLE™ Hardware

PAL Cluster History

- Phase 0: 5 Engines 2000
- Phase 1: 13 Engines 2001
- Phase 2: 16 Engines 2002
- Phase 3: 128 Engines 2003
- Phase 4: 256 Engines 2004
- Phase 5: 1024 Engines 2005

First 64 Engines of the Phase 3 expansion

The ProLE™ Hardware



1200 3D-FE simulations

Sim-volume = 9 X 10^6

1GHz-CPU hours

Increasing Complexity

180nm Node

130nm Node

90nm Node

65nm Node

45nm Node

ProLE™ Services

- ProLE On-site Solution
  - Distributive computing solution
    - Installed ProLE system at customer site, including calibration
    - Entry level costs comparable to an EDA “design seat”
  - Model calibration and monitoring, updated RET models
  - ProLE training and software tools for customer engineers
- ProLE Litho-Simulation Foundry (Off-site) Solution
  - ProLE cluster resides at PAL service center
  - Secure on demand service
  - Parameter generation, calibration and maintenance by PAL
- ProLE Consulting Service
  - PAL analyzes design using model based OPC software and validated with ProLE at PAL service center
    - Model calibration and monitoring
    - Lowest cost entry point (evaluation level service)

ProLE™ Litho-Simulator Foundry Service

- The ProLE foundry service provides access to a larger cluster, via timesharing
  - This allows access to much higher throughput potential
- ProLE timeshare
  - Customer pays for a system that resides at PAL
  - Several pricing options available
- Access is by terminal service to a secure ProLE Workbench
- PAL calibration services are strongly recommended

ProLE™ Consulting Service

- ProLE off-site consulting services:
  - PAL analyzes design using model based OPC software and customer defined locations validated with ProLE at PAL service center
    - Good for checking legacy OPC software
  - PAL provides optimized critical area designs
    - Bit-cells, NAND gates, leaf cells, etc.
  - Physical chemical analysis of resists
  - Lowest cost entry point (evaluation level service)
- ProLE on-site services:
  - Model parameter determination, calibration and monitoring
  - Litho-process audit

Who Needs ProLE™?

- ProLE provides the power to solve problems of incredible complexity
- ProLE can be used by all lithographic and design-for-yield disciplines to do studies such as:
  - Lithography optimization
  - RET validation, optimization, rule generation
  - EDA – true design-for-yield

Quotes

"PAL's designs of a 180nm embedded SRAM IP yielded 60%. This yield is 3X the competitors; further, ProLE helped pull the product release in three months and eliminated the need for doing additional tapeouts." **Mark Craig, TestChip**

"By using ProLE, PAL helped design accurate CPL test structures quickly. In the past without ProLE, designs involved a lot of brute force optimization that took many hours. With ProLE, we are able to generate accurate results and speed up our learning. Therefore, ASML was able to deliver something to the market much sooner. …" **Robert Socha, ASML**

"During a beta-test of ProLE, I pulled my 100nm contact hole design project in by over 9 months. Also under a JDP with ASML, ProLE produced working chromeless phase-shift lithography patterns for our 65nm technology node process that showed production worthy imaging processes …!" **Will Conley, Motorola**

ProLE™ for Lithographers

- Process Development
  - High-NA and super-high NA (immersion)
  - RET solutions for across pitch across feature type
  - Analysis and diagnosis of illuminator source shapes
  - Full EMF solutions mask design
  - Studying and designing resist formulation
- Process Optimization
  - Process sensitivity using Monte Carlo methods
  - Simulating advanced imaging system abnormalities such as aberration of 136 Zernike polynomial terms, pellicle degradation and mask blank variation
- Metrology Applications
  - Line-edge-roughness for resist formulation and process optimization
  - Two- and three-dimensional structure optimization for scatterometric and alignment target processes

Hot Plate Thermal Cycle Feature Accumulated Error

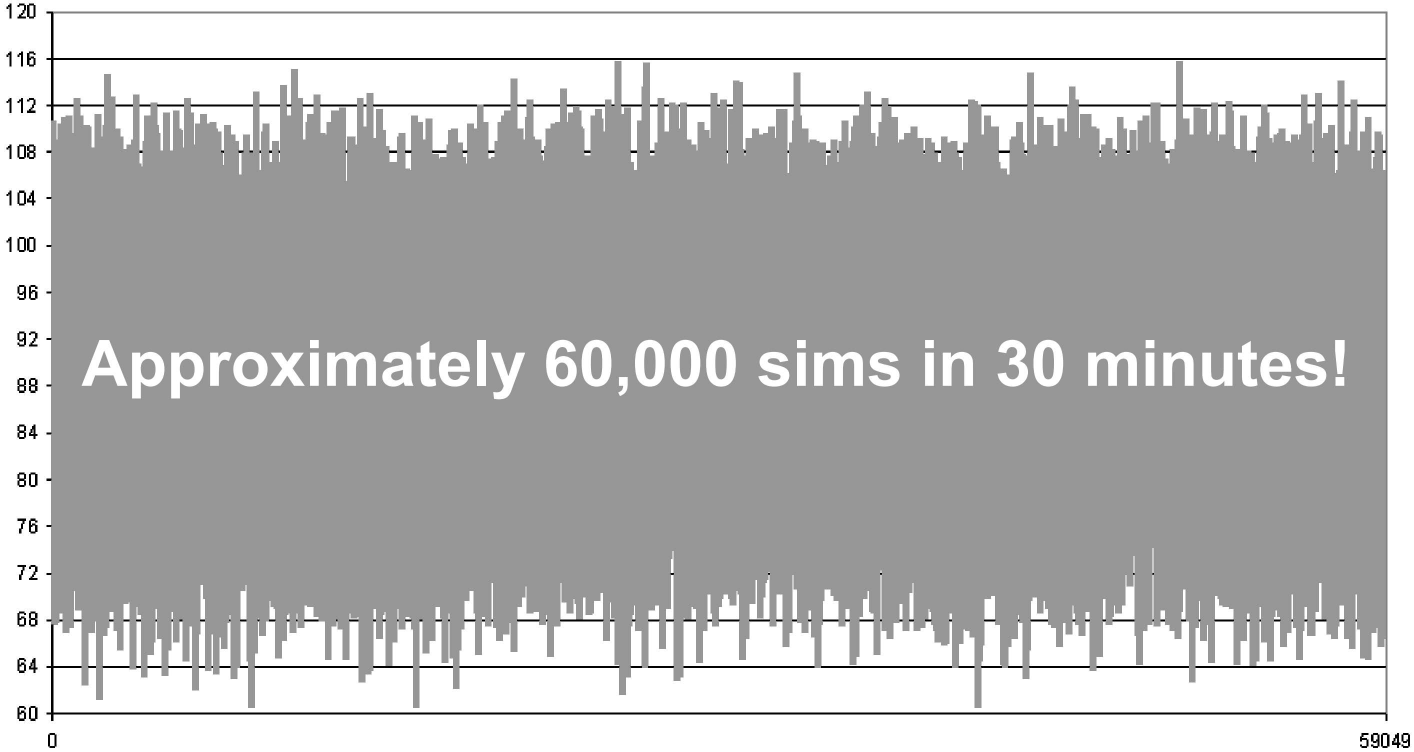
$$\begin{aligned}
\Delta CD^2 = {} & \left(\frac{\partial CD}{\partial Rs}\right)^2 (\Delta Rs)^2 + \left(\frac{\partial CD}{\partial PC}\right)^2 (\Delta PC)^2 + \left(\frac{\partial CD}{\partial TC}\right)^2 (\Delta TC)^2 + \left(\frac{\partial CD}{\partial Ps}\right)^2 (\Delta Ps)^2 + \left(\frac{\partial CD}{\partial Ts}\right)^2 (\Delta Ts)^2 \\
& + \left(\frac{\partial CD}{\partial Rs}\right)\left(\frac{\partial CD}{\partial PC}\right)(\Delta Rs)(\Delta PC) + \left(\frac{\partial CD}{\partial Rs}\right)\left(\frac{\partial CD}{\partial TC}\right)(\Delta Rs)(\Delta TC) + \left(\frac{\partial CD}{\partial RS}\right)\left(\frac{\partial CD}{\partial Ps}\right)(\Delta RS)(\Delta Ps) \\
& + \left(\frac{\partial CD}{\partial RS}\right)\left(\frac{\partial CD}{\partial Ts}\right)(\Delta RS)(\Delta Ts) + \left(\frac{\partial CD}{\partial PC}\right)\left(\frac{\partial CD}{\partial TC}\right)(\Delta PC)(\Delta TC) + \left(\frac{\partial CD}{\partial PC}\right)\left(\frac{\partial CD}{\partial Ps}\right)(\Delta PC)(\Delta Ps) \\
& + \left(\frac{\partial CD}{\partial PC}\right)\left(\frac{\partial CD}{\partial Ts}\right)(\Delta PC)(\Delta Ts) + \left(\frac{\partial CD}{\partial TC}\right)\left(\frac{\partial CD}{\partial Ps}\right)(\Delta TC)(\Delta Ps) + \left(\frac{\partial CD}{\partial TC}\right)\left(\frac{\partial CD}{\partial Ts}\right)(\Delta TC)(\Delta Ts)
\end{aligned}$$

$$\text{where } Rs = \text{RiseTime}; PC = \text{PEBTemp}; TC = \text{TransitionTemp}; Ps = \text{PEBTime}; Ts = \text{Transition time}$$

ProLE Simulation conditions:
248nm Resist
Quasar OAI; 0.80 NA; Binary mask; Results Analyzed in JMP using stepwise regression and scaling and then exported to Excel

Line-Edge-Roughness for 90nm 1:1 Line:Space

RMS=15.8nm



Approximately 60,000 sims in 30 minutes!

Simulated with ProLE by varying develop and thermodynamic properties using a Monte Carlo technique.

Resolution Enhancement

RET design optimization tools:

- Used for sorting and optimizing imaging technologies
  - Weak vs. strong PSM two-beam imaging optimization
- Used for OPC model based rule generation, OPC optimization and validation.
- Use ProLE^2 to do this work efficiently or supercharge it using ProLE distributive computing solution
- Use Monte Carlo techniques and ProLE-IIS to find low level systematic defects

Shortcomings of Today's Optical Proximity Correction Solutions

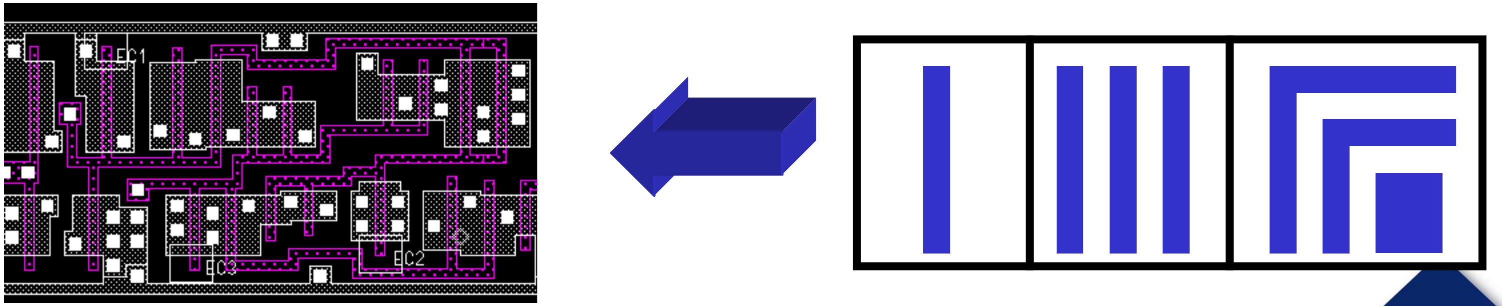
Commercial OPC solutions:

- **Models derived from small test bed (last generation)**
- **Models comprehend fraction of product-like features**

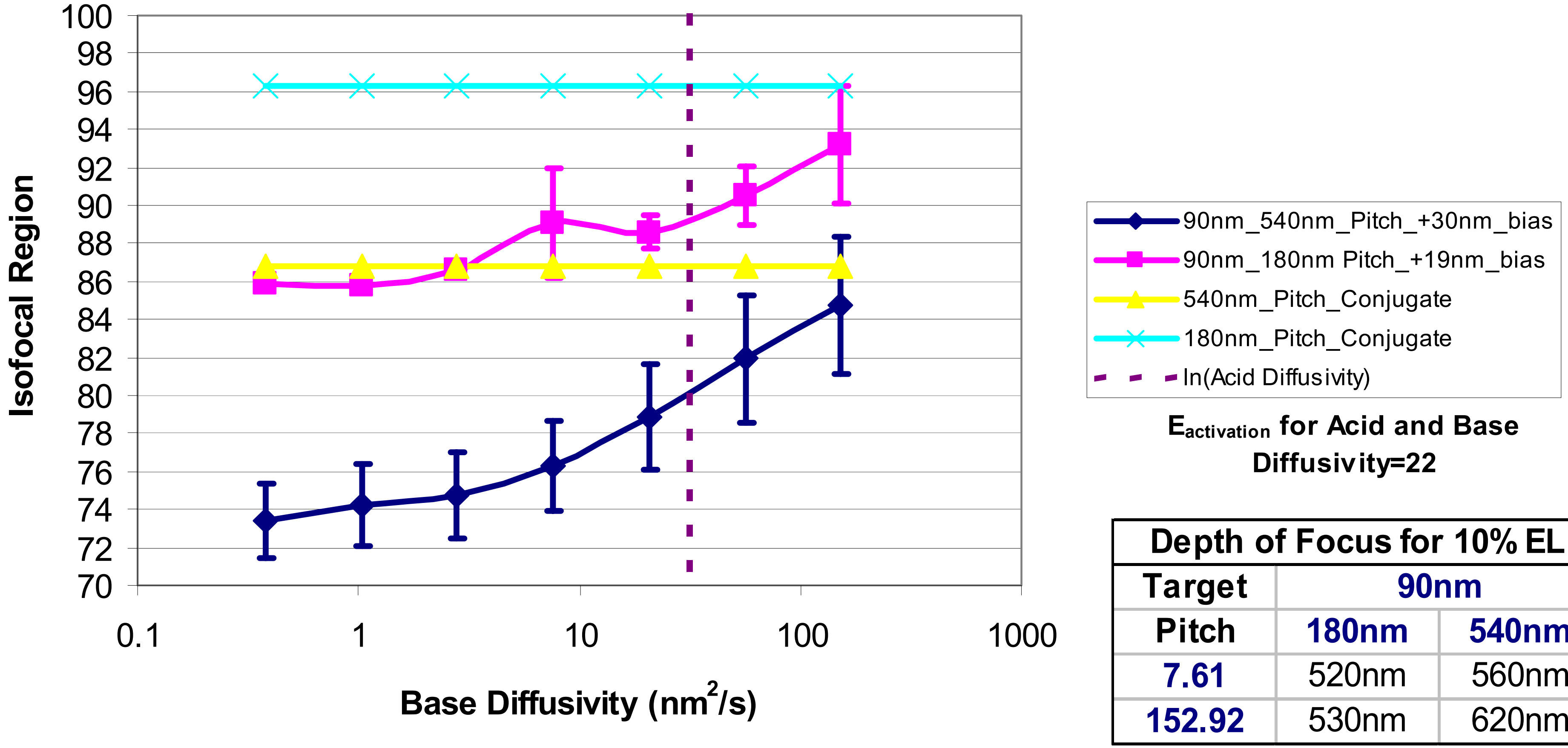
- **Litho tool-specific aberrations, high NA & vector affects ignored**
- **Mask errors & process biases (etch, resist) ignored**
- **Process integration effects ignored (cumulative errors)**

Critical for sub-0.18um DFM considerations

Example feature test bed for commercial OPC/RET:



Isofocal Region Dependence on Base Diffusivity



$E_{activation}$ for Acid and Base Diffusivity=22

Depth of Focus for 10% EL		
Target	**90nm**	
Pitch	**180nm**	**540nm**
7.61	520nm	560nm
152.92	530nm	620nm

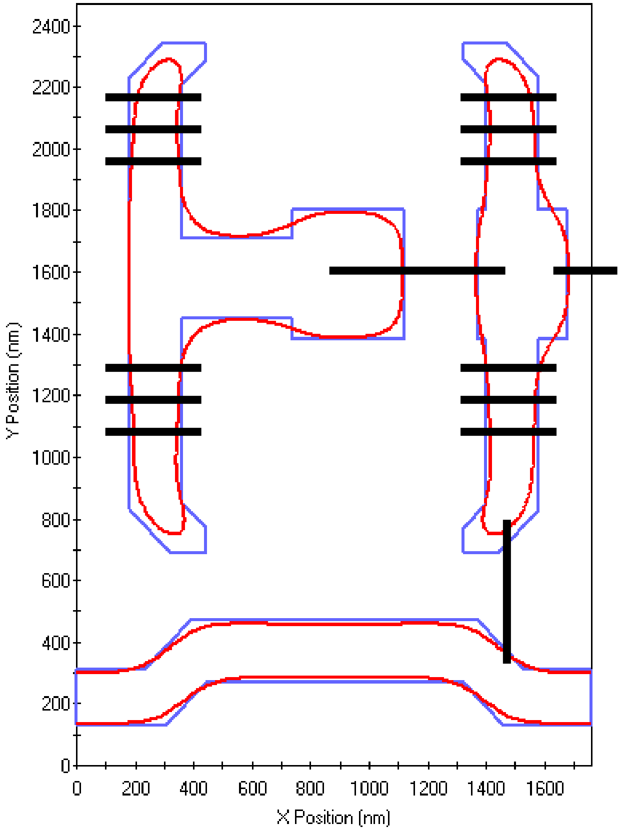
OPC decisions that do not comprehend the resist and etch will lead to costly mistakes!

ProLE RET/EDA Application: Customer Success Story

- Zero Yield experienced in embedded memory IP
  - Customer requirement of optimized FEOL layers (diffusion, poly…)
  - Focus-exposure process window optimization generated by ProLE™
    - Active, Poly, contact and metal_1 optimized to minimize systematic failures per layer and layer-to-layer
  - Manufacturable design created in 3 days using ProLE™
- Results
  - 60% yield on 1st silicon with PAL-based OPC, controls yielded zero with no OPC and 20% with non-PAL OPC
  - 3 month schedule acceleration to volume production
  - Significant process window enhancement (100% increase in DOF)
  - No mask revisions (typical 2 or 3 spins for embedded SRAM IP)

ProLE RET Application: Issues Uncovered with Original Poly Design

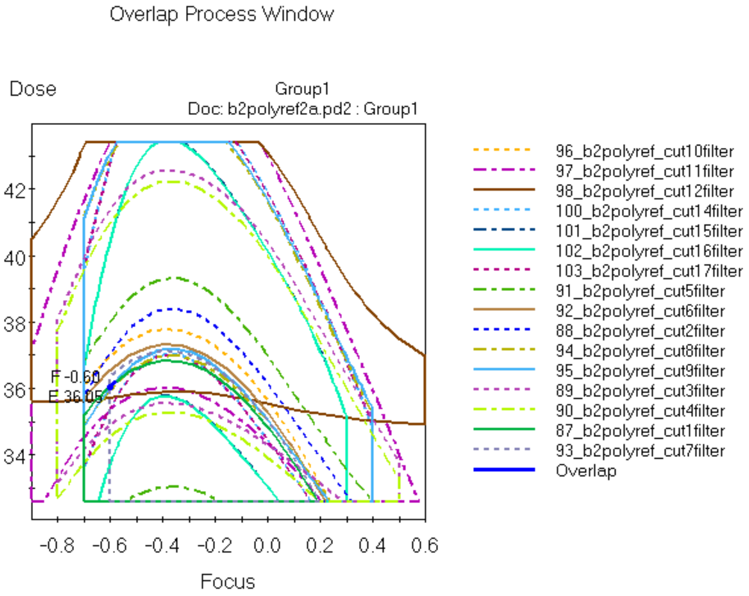
Using ProLE, PAL uncovered problems with original design manufacturability:



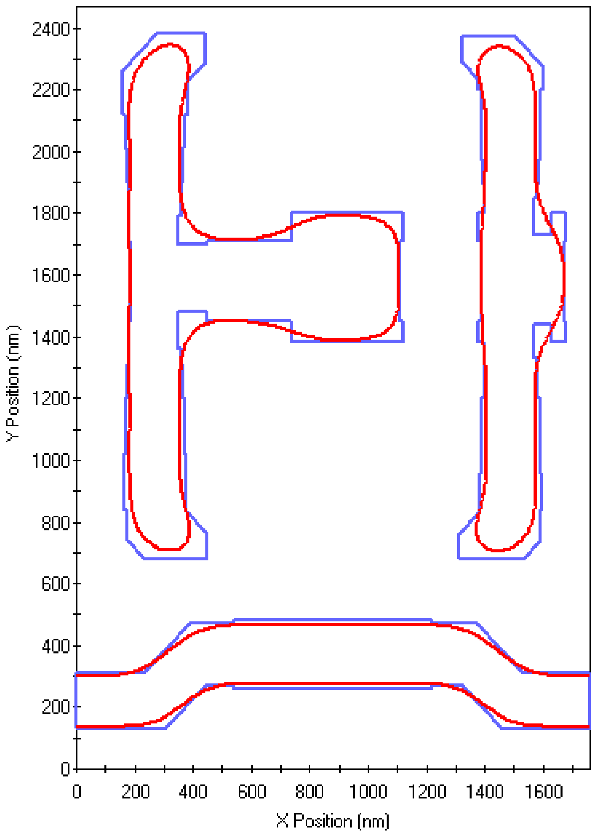
Line CDs

Space CDs

Not Manufacturable! No DOF!

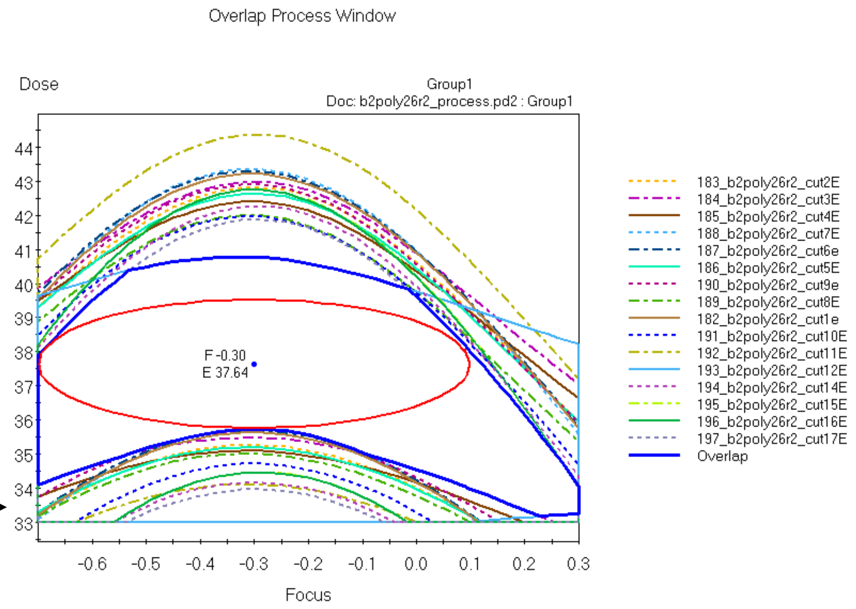


ProLE RET Application: Manufacturable Design Achieved by PAL



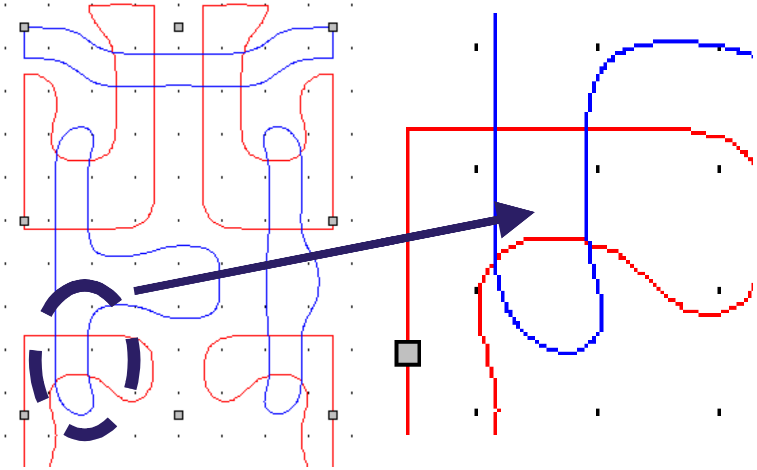
PAL delivered a manufacturable design in 3 days!

Manufacturable
0.8µm DOF!
@ 10% EL!



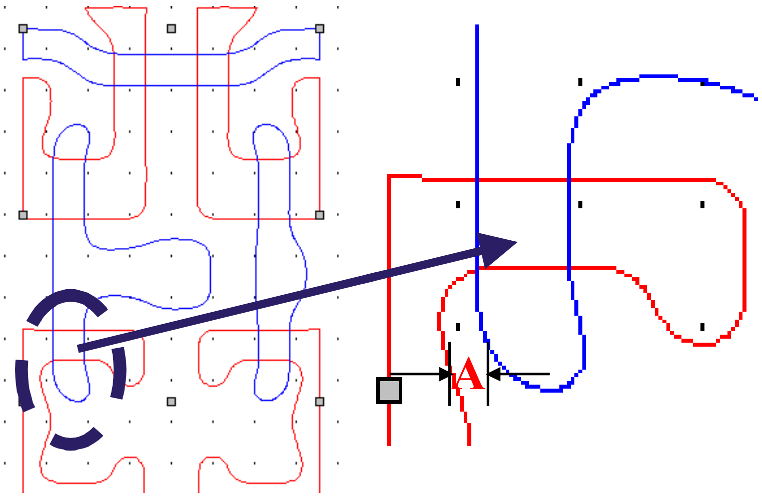
ProLE RET/EDA Application: Critical layer-to-layer imaging strategies to maximize device yield and performance

Uncorrected Active/Corrected Poly
Low Yield and Poor Performance



F/E = -0.2 um / 38 mJ

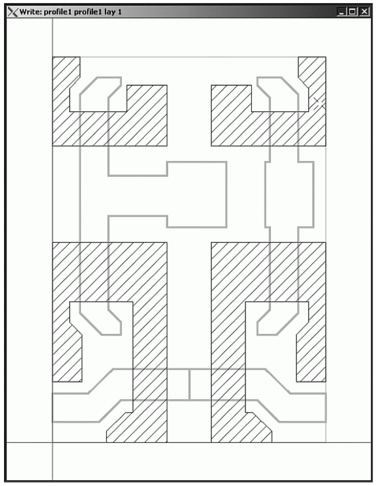
Corrected Active/Corrected Poly
Good Yield and Enhanced Performance



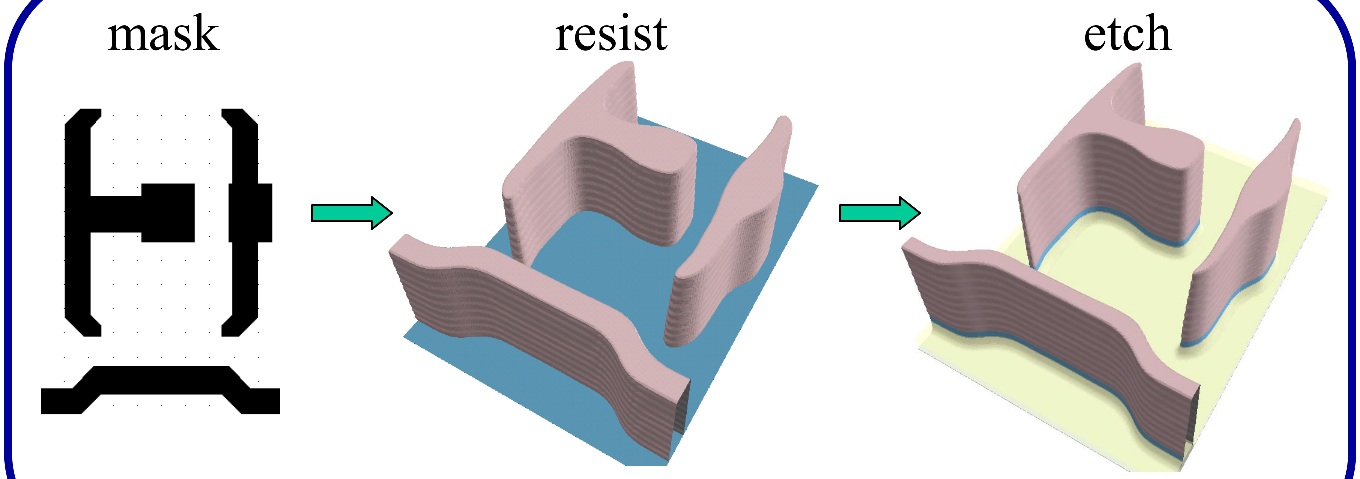
F/E = -0.2 um / 38 mJ

Craig, Mark J., Petersen, John S., Lund, Joshua, Gerold, David J., Chen, Nien-Po, *Design, Process Integration, and Characterization for Microelectronics*, Proc. SPIE Vol. 4692, p. 380-389 (2002).

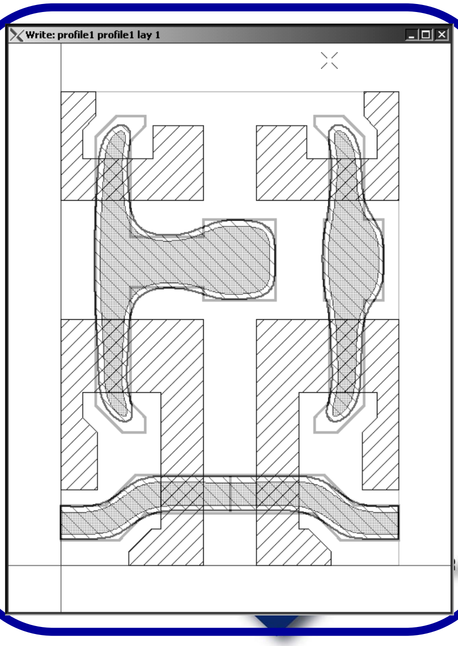
ProLE EDA Application: Mask GDSII ⇒ Process Simulation ⇒ Silicon GDSII out ⇒ Parasitic Extraction or ProDATA



GDSII layout



Process simulation



GDSII layout

- ▨ 14active_mask
- ▦ 33poly_etch
- ▧ 23poly_resist
- ☐ 13poly_mask

Parasitic Extraction Tool or ProDATA

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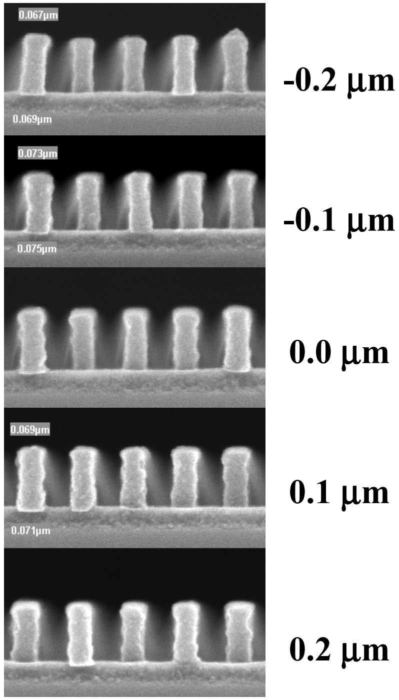
Lithography Drives Yield

- PAL is the lithography expert
- We embed this experience into our products
- Contact us to do the same for your products!
- Thank You.



75 nm 1:1 dense lines imaged with SCAA Mask and 0.75 NA/193 nm/0.15 σ

J. V. Beach, J. S. Petersen, M. J. Maslow, D. J. Gerold, D. McCafferty, "Evaluation of SCAA Mask Technology as a Pathway to the 65 nm Node," SPIE paper 5040-17, 2003.