Rigorous Modeling and Optimization of Multilayer Defect Repair

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Lithography Simulation

Fraunhofer IISB

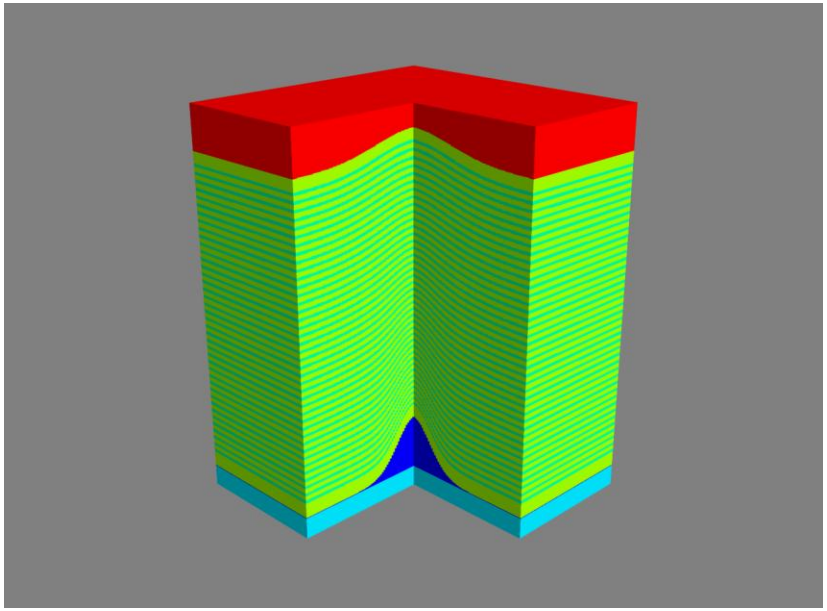
Outline

- Introduction
  Multilayer defect geometries, effects, and modeling methods
- Defect printing simulations
  Modeling parameters, Impact of defect parameters, comparison with experiment
- Repair optimization
  General strategy, speedup by pre-optimization using defect integrals
- Repair simulation results
- Conclusions and outlook

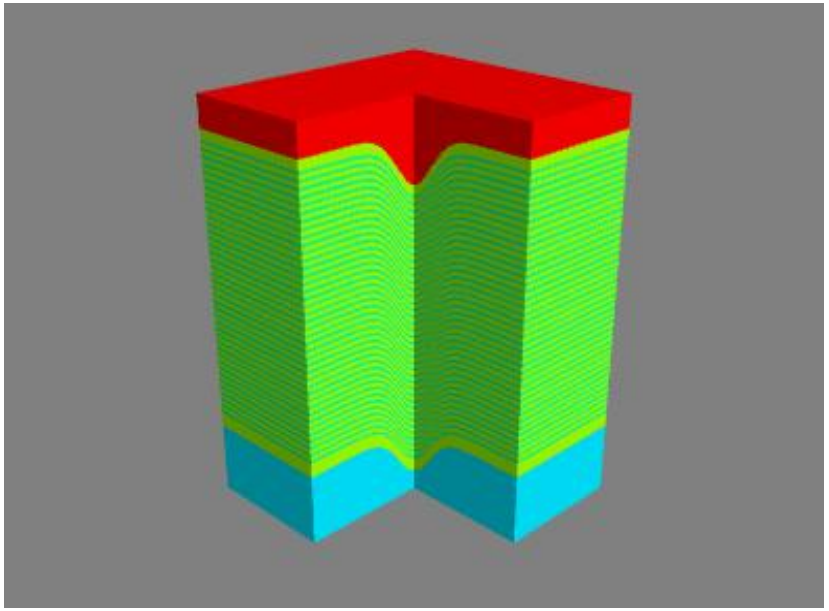
EUV-Mask Multilayer Defects: Geometry

Typical defects

bump defect



pit defect



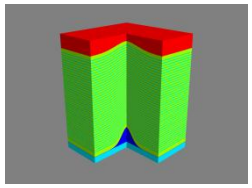
(2D) Gaussian deformation
at top/bottom

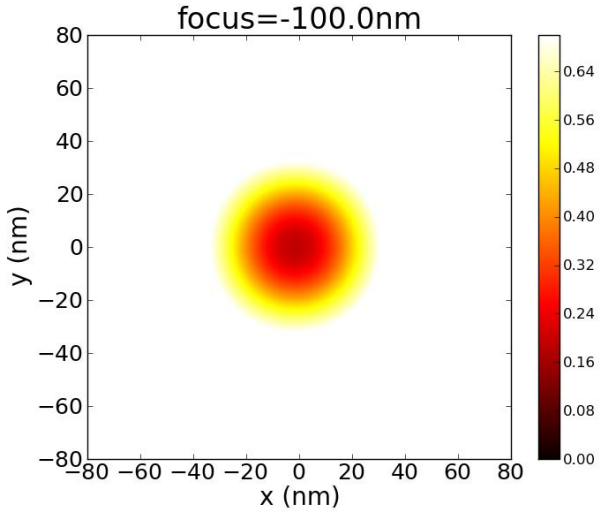
$h_{top/bot}$ – defect height
$w_{top/bot}$ – defect size (FWHM)

EUV-Mask Multilayer Defects: Effects

Aerial images of blank defects versus focus

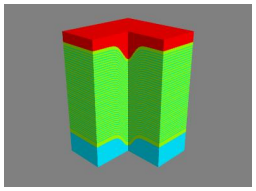
bump defect

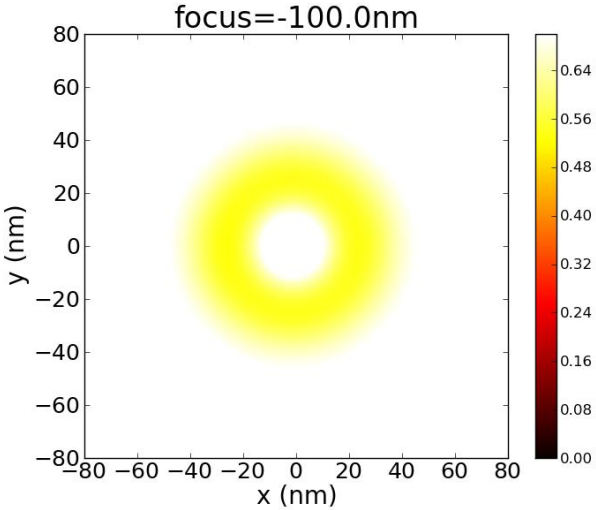




h_{top}=2nm
w_{top}=90nm
h_{bot} =50nm
w_{top}=50nm

pit defect





h_{top}=-2nm
w_{top}=90nm
h_{bot} =-2nm
w_{top}=90nm

- defects cause intensity loss in defect area
- defects are mixed amplitude/phase objects!
- asymmetric printing through focus
- bumps and pits print most severe in opposite focus directions

presented by A. Erdmann at SPIE AL 2012

EUV-Mask Multilayer Defects: Modeling Methods

Rigorous electromagnetic field modeling by:

- Finite-difference time-domain (FDTD) algorithms: Nguyen, Pistor, Evanschitzky
- Waveguide method, Rigorous coupled wave analysis: Schiavone, Evanschitzky, Shao

→ accurate, but time consuming: 1 or 2 days per geometry

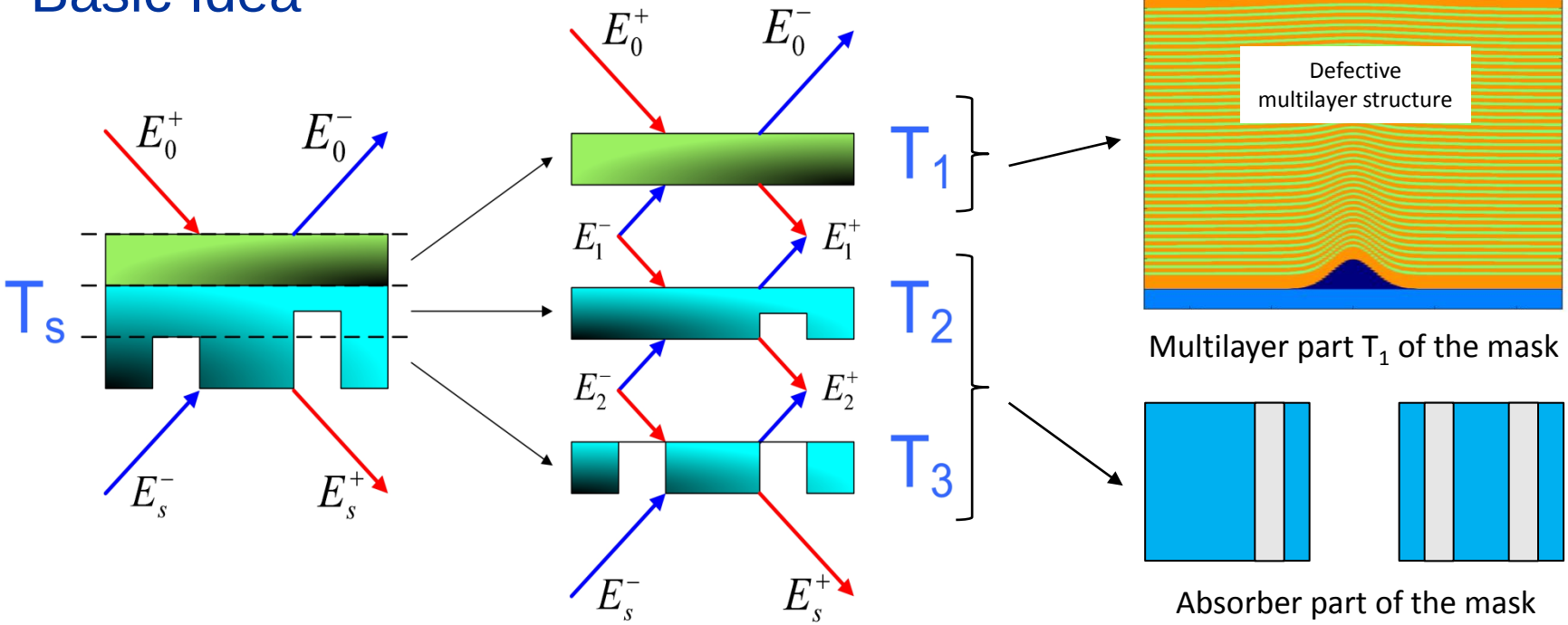
Approximate models:

- Single surface approximation: Gullikson
- Local application of Fresnel: Ito, Evanschitzky
- Ray tracing: Lam; RADICAL: Clifford, Peng

→ fast, but limited range of validity

EUV-Mask Multilayer Defects: Data Base Approach

Basic Idea



Multilayer part T_1 of the mask

Absorber part of the mask with two layers T_2 and T_3

Original mask to be simulated

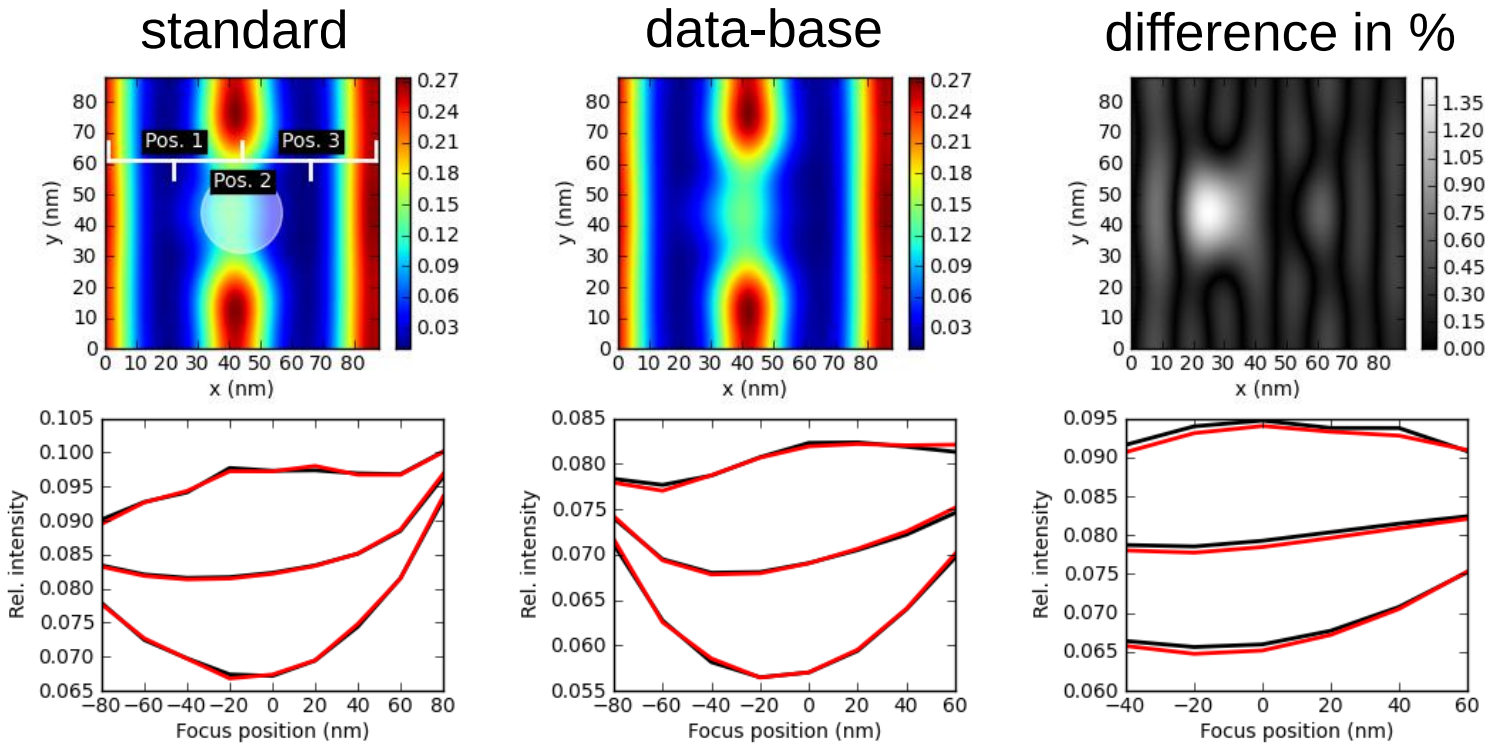
Split-up of the mask into independent parts

Here: T1 = defective ML
T2 = absorber layer
1
T3 = absorber layer
2

Fully rigorous computation of the **transfer matrices** of all parts with Waveguide

EUV-Mask Multilayer Defects: Data Base Approach

Speed and accuracy



→ simulation time: standard- / data-base-simulation: 9500 s / 20 s

presented by P. Evanschitzky at BACUS 2012

Defects Printing Simulations

Parameter settings

Mask:
- standard EUV multilayer mask with Ru-capping and Ta-based absorber
- Gaussian shaped top and bottom bump defects
- 30 nm dense contacts (wafer scale, biased)
- rigorous mask diffraction simulation using the Waveguide of Dr.LiTHO

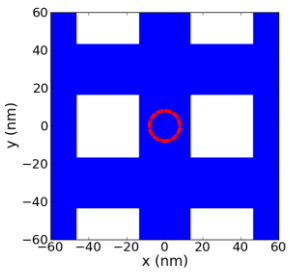
Optics (ASML NXE3100 @ IMEC):
- NA=0.25, λ=13.5nm, σ=0.8, incl. flare
- vectorial simulation of aerial and bulk images using Dr.Image

Resist (SEVR140):
- 50nm thick on Si-wafer
- physical resist model of Dr.LiTHO calibrated to experimental data from IMEC

Visualization/analysis(/repair) of defects:
- based on the MeRiT(R) HR platform from Carl Zeiss SMS, with integrated AFM

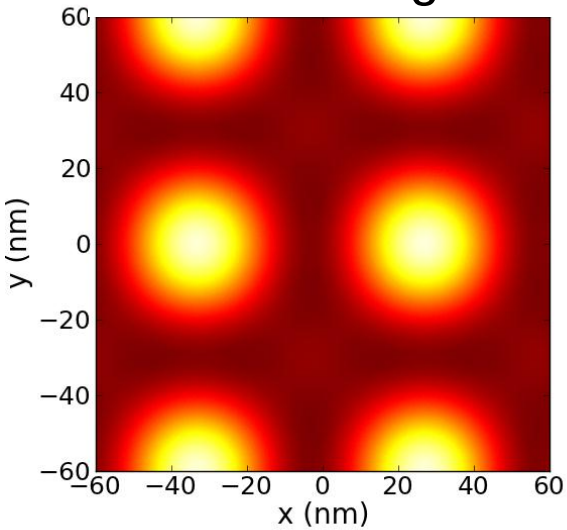
Defects Printing Simulations

Impact of position

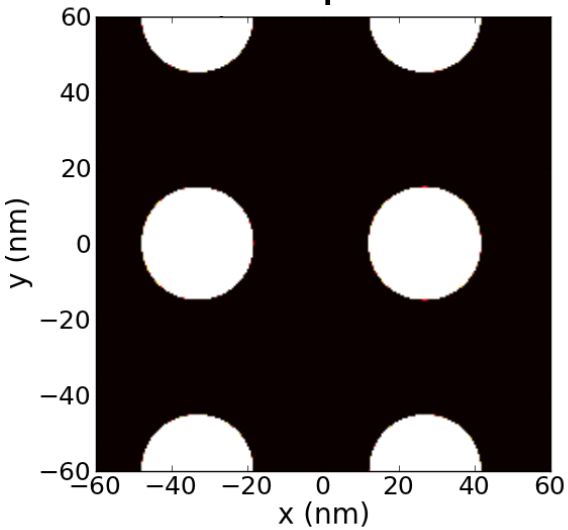


w_{top}=50nm, h_{top}=5nm
h_{bot}=w_{bot}=30nm

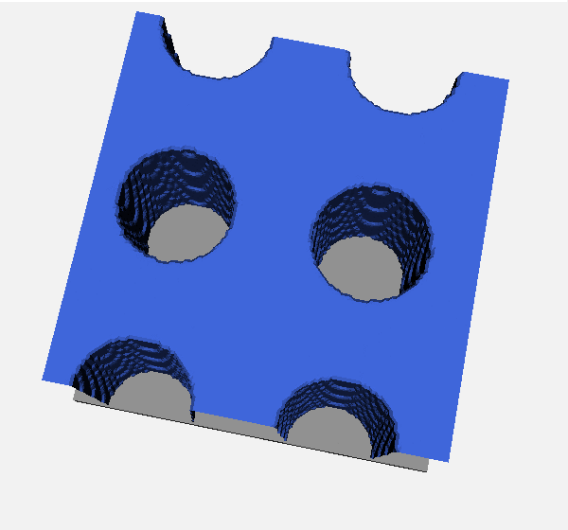
aerial image



footprint



resist profile



→ strong impact of position of defect inside layout

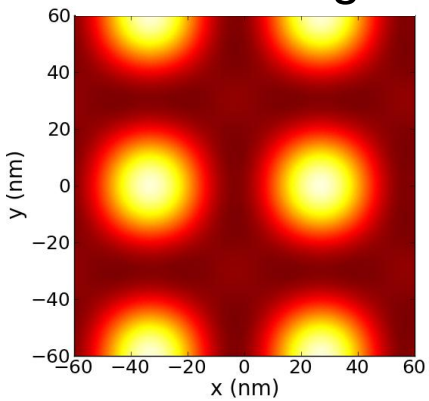
Defects Printing Simulations

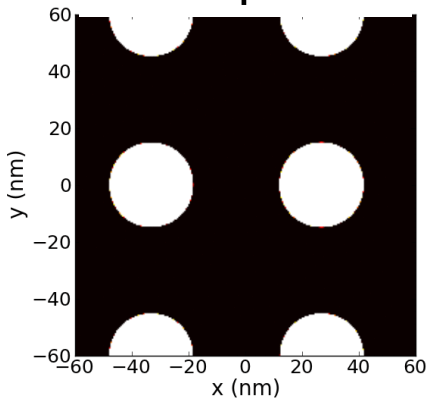
Impact of position and height

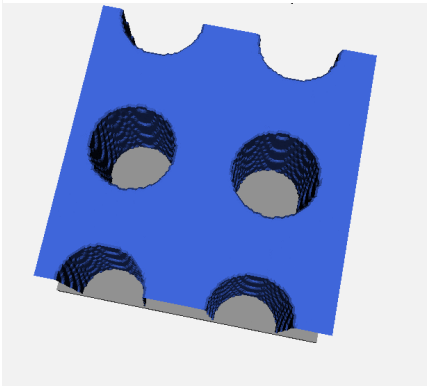
w_{top}=50nm, h_{bot}=w_{bot}=30nm

aerial image | footprint | resist profile

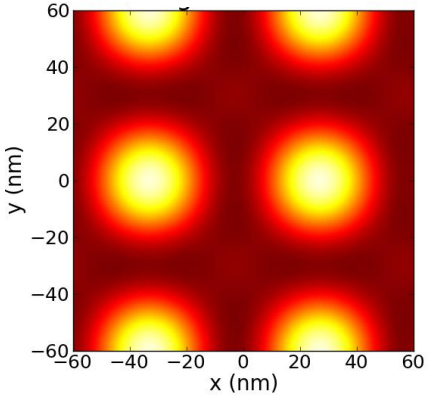
h_{top}=5nm

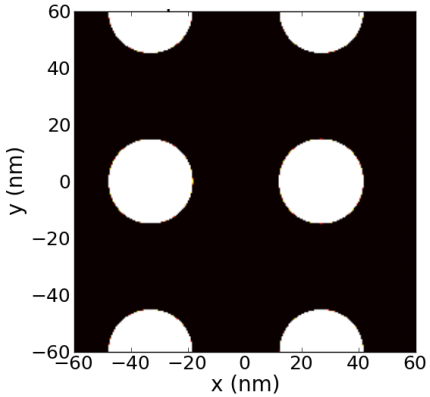


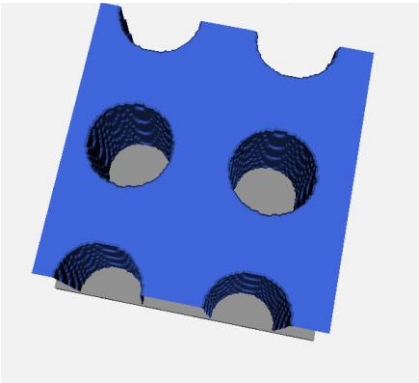


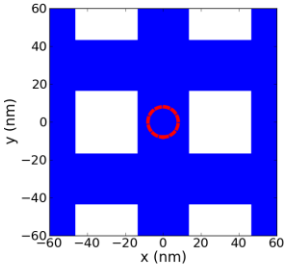


h_{top}=3nm





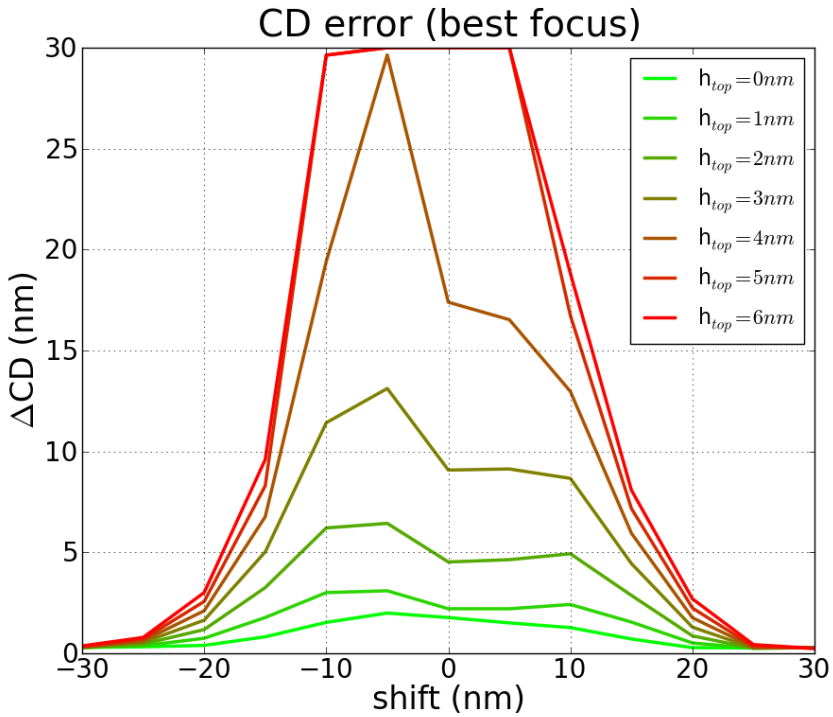




Defects Printing Simulations

Impact of position and height

w_{top}=50nm,
h_{bot}=w_{bot}=30nm

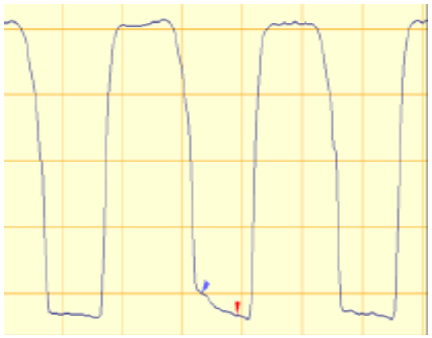


- Defect impact increases with height
- Slight asymmetry of curves results from non-telecentricity
- Similar observations for other defect parameters

Defects Printing Simulations & Experiment

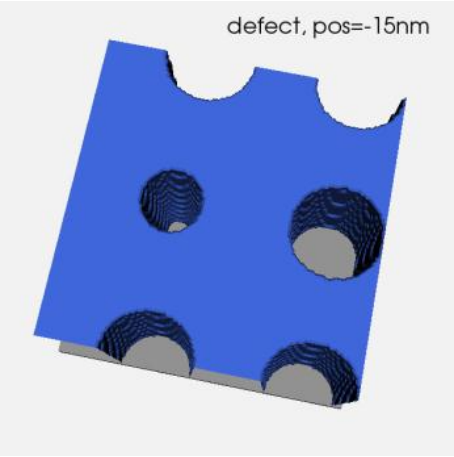
Defect at absorber edge

Mask AFM:
h_{top}=6.72nm

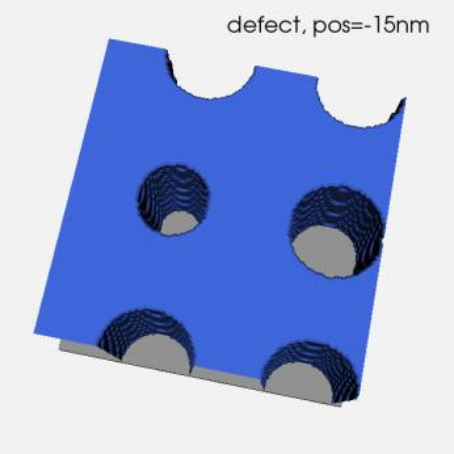


Simulation

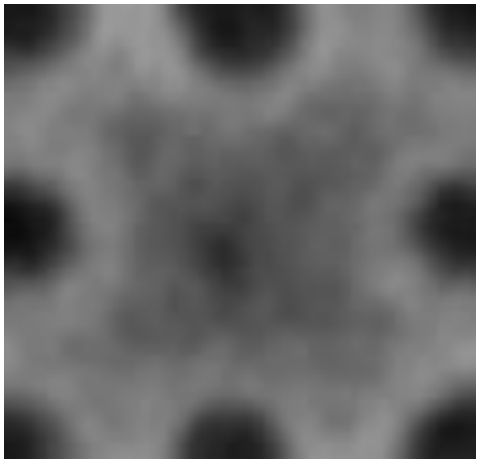
h_{top}=6nm,
w_{top}=50nm,
h_{bot}=w_{bot}=50nm



h_{top}=6nm,
w_{top}=50nm,
h_{bot}=w_{bot}=30nm



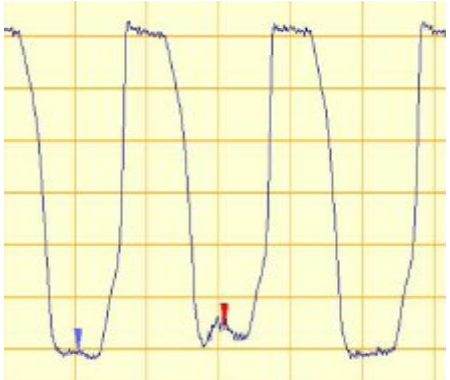
Wafer SEM



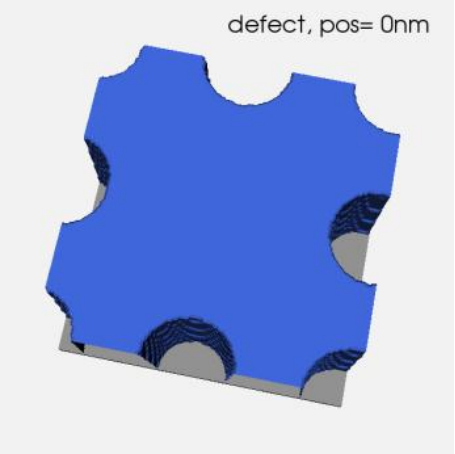
Defects Printing Simulations & Experiment

Defect close to center of contact

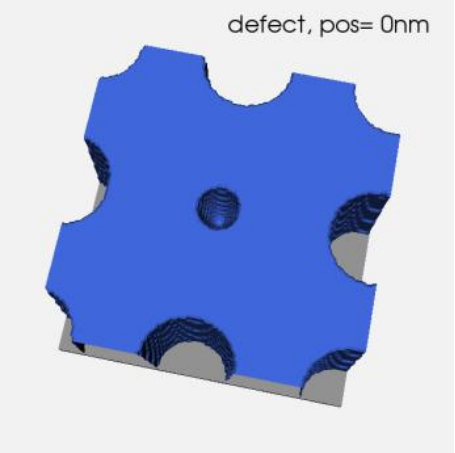
Mask AFM:
h_{top}=4.65



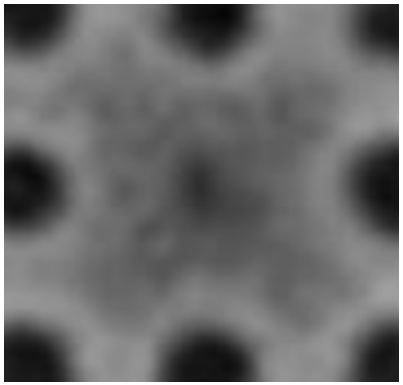
h_{top}=4nm,
w_{top}=50nm,
h_{bot}=w_{bot}=50nm



h_{top}=4nm,
w_{top}=50nm,
h_{bot}=w_{bot}=30nm



Wafer SEM

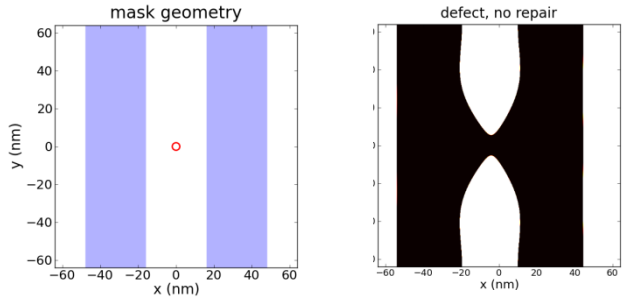


Repair Optimization

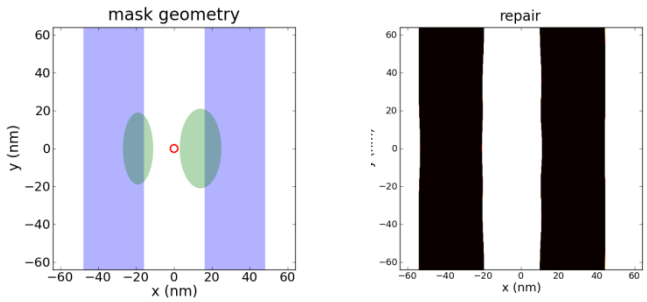
General Procedure

- Place squares/rectangles or circles/ellipses of air (or other material) in the absorber layout to compensate defect induced intensity losses
- Evaluate printing performance in terms of aerial images, footprints, CD-differences, and process windows
- Optimize parameters and positions of repair shapes

without repair



with repair



Repair Optimization: Speedup

Previously used repair strategy:

- Correct simulation of mask with repair shapes and defect
- Optimization of repair shape by a combination of a genetic algorithm with a local optimizer (simplex)
- About 20-300 EMF/image simulations with defect required
- CPU times for repair optimization
  - Without database: 1-12 months
  - With database: 1-20 hours

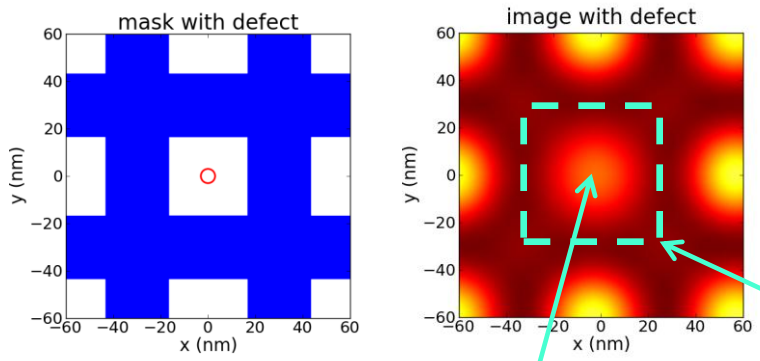
General strategy to reduce CPU-time:

- Apply fast approximate method for a guess of repair optimization
- Apply few EMF simulations in a final local optimization step
- Reduces Optimization of repair to 10-30 minutes

Repair Optimization: Defect Integrals

Image characterization by image integrals

w_{top}=90nm, h_{top}=3nm
h_{bot}=w_{bot}=30nm



I_t = 1312.4 nm^2
I_{lr} = 19.7 nm^2
I_{ud} = 0.0 nm^2

reference position:
x_{ref}, y_{ref}

evaluation area:
x_{min}, x_{max}, y_{min}, y_{max}

total intensity (CD)

$$I_t = \int_{x_{min}}^{x_{max}} \int_{y_{min}}^{y_{max}} I(x,y)\,dxdy$$

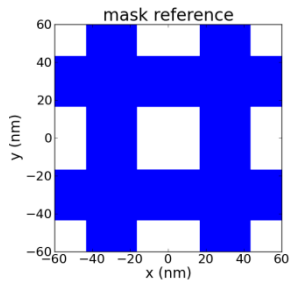
symmetries (placement)

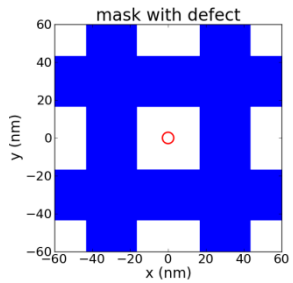
$$I_{lr} = \int_{x_{ref}}^{x_{max}} \int_{y_{min}}^{y_{max}} I(x,y)\,dxdy - \int_{x_{min}}^{x_{ref}} \int_{y_{min}}^{y_{max}} I(x,y)\,dxdy$$

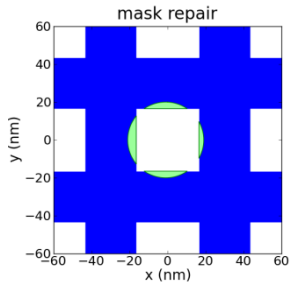
$$I_{ud} = \int_{x_{min}}^{x_{max}} \int_{y_{ref}}^{y_{max}} I(x,y)\,dxdy - \int_{x_{min}}^{x_{max}} \int_{y_{min}}^{y_{ref}} I(x,y)\,dxdy$$

Repair Optimization: Defect Integrals

Compensation of Defect-induced Intensity Loss by Integrated Intensity of Defect Image inside Repair-Cut Area





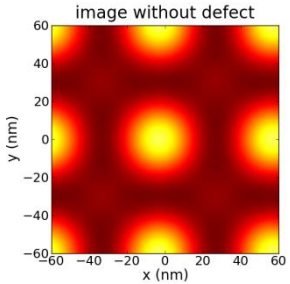


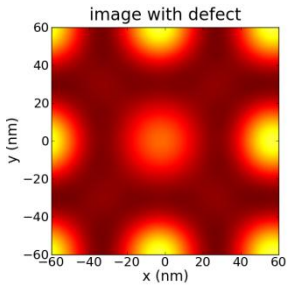
w_{top}=90nm, h_{top}=3nm
h_{bot}=w_{bot}=30nm

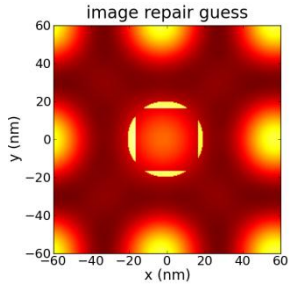
$image_{mask,defect}$ + fac * $image_{blank,defect}$ (inside cut area)

fac = max($image_{mask,nodefect}$)

to be minimized as function repair shape







I_t = 1393.5 nm^2
I_{lr} = 0.0 nm^2
I_{ud} = 0.0 nm^2

I_t = 1312.4 nm^2
I_{lr} = 19.7 nm^2
I_{ud} = 0.0 nm^2

I_t = 1347.5 nm^2
I_{lr} = 12.7 nm^2
I_{ud} = 0.0 nm^2

Repair Optimization: Defect Integrals

w_{top}=90nm, h_{top}=3nm
h_{bot}=w_{bot}=30nm

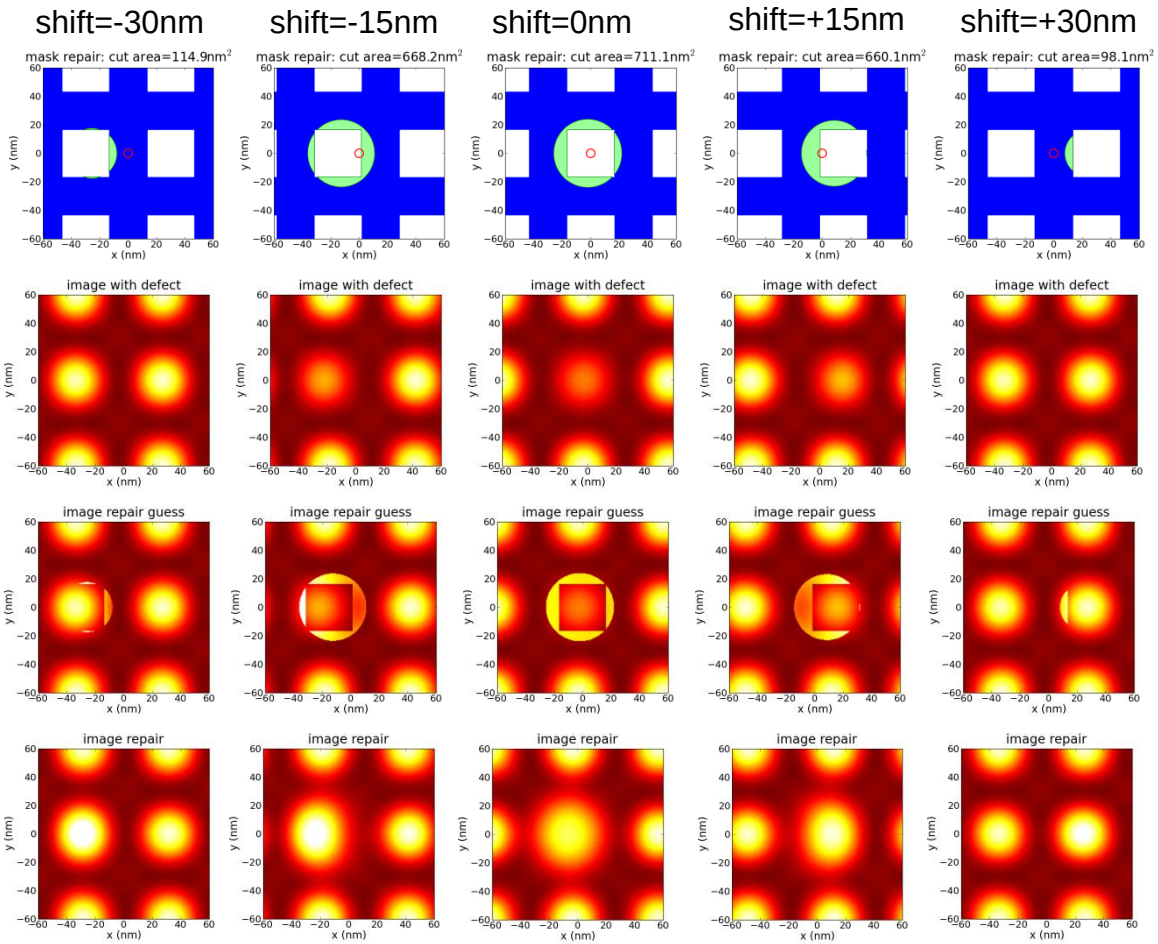
Repair results

mask layout incl. defect & repair

image without repair

repair estimation

image with repair



Repair Simulation Results

Impact of position and height

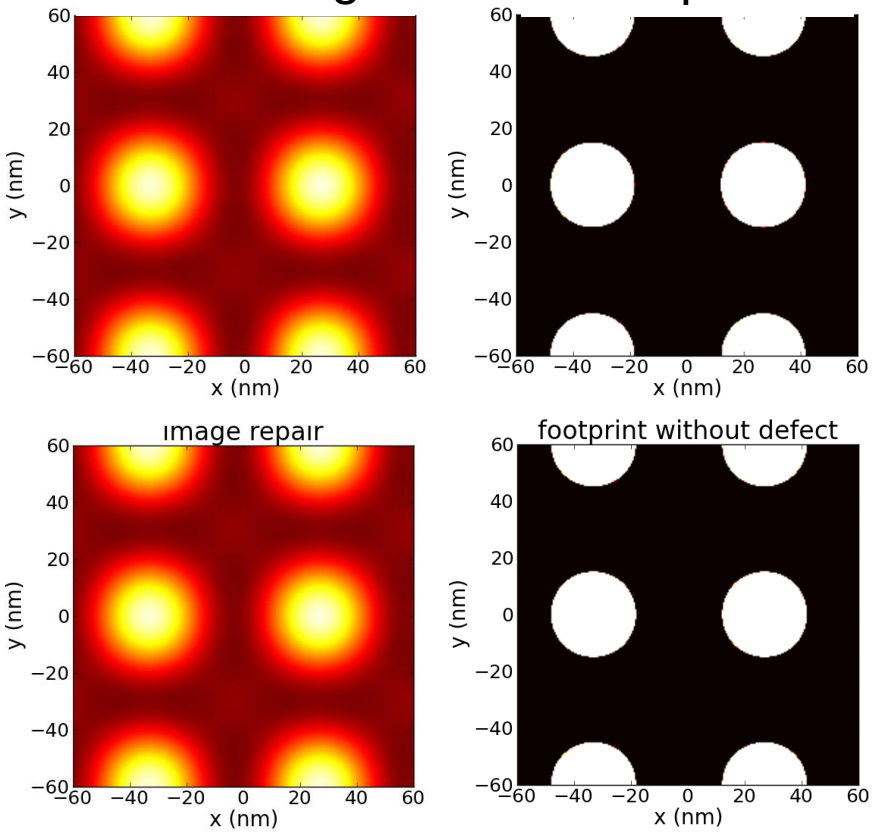
h_{top}=5nm

w_{top}=50nm
h_{bot}=w_{bot}=30nm

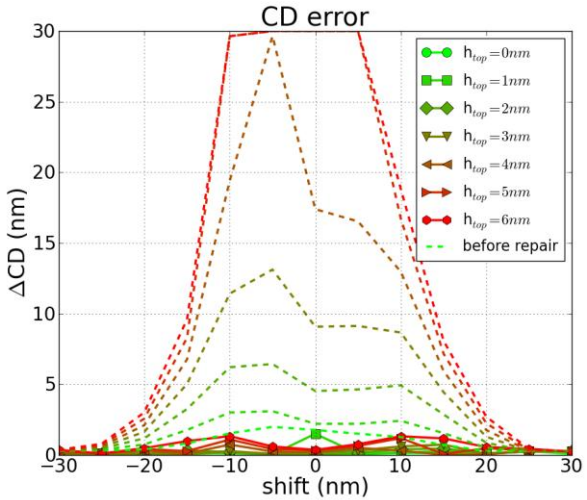
aerial image | footprint

before repair

after repair



performance versus height



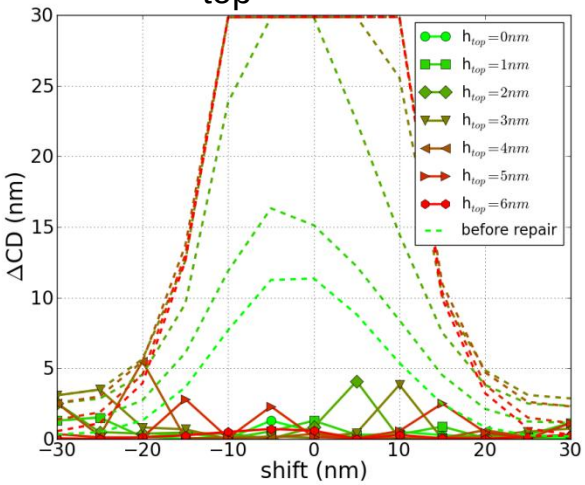
→ all defects up to a height of 6nm can be compensated

Repair Simulation Results

Impact of top size

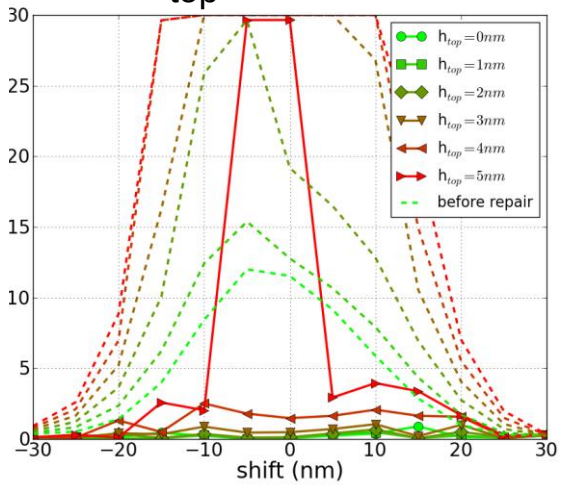
$h_{bot}=w_{bot}=50nm$

$w_{top}=50nm$



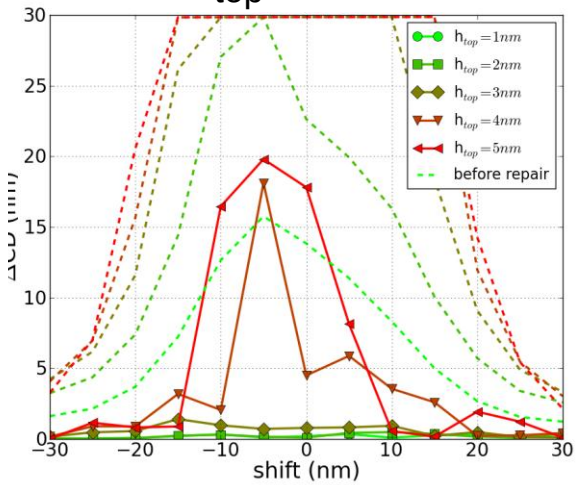
all repairable

$w_{top}=70nm$



max(h_{top}) = 4nm

$w_{top}=90nm$



max(h_{top}) = 3nm

→ qualitatively similar CD variation due to defects of different size

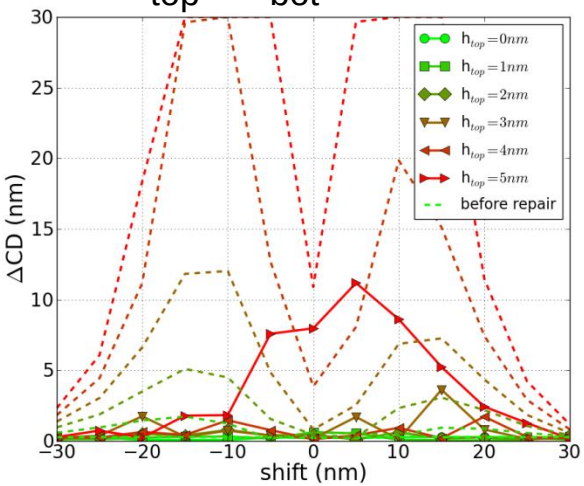
→ larger defects are more difficult to repair

Repair Simulation Results

Impact of bottom size

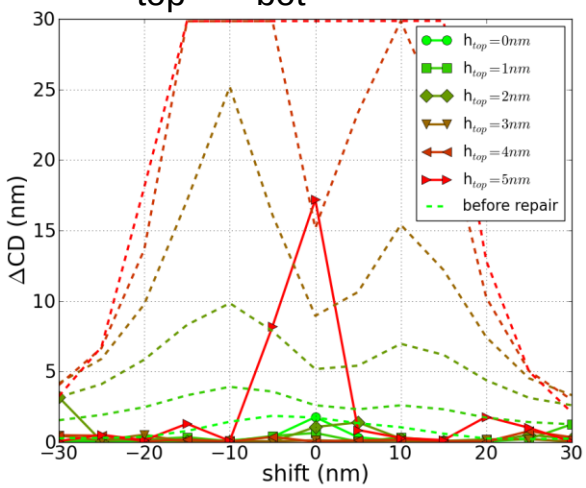
w_{top}=90nm

w_{top}=w_{bot}=10nm



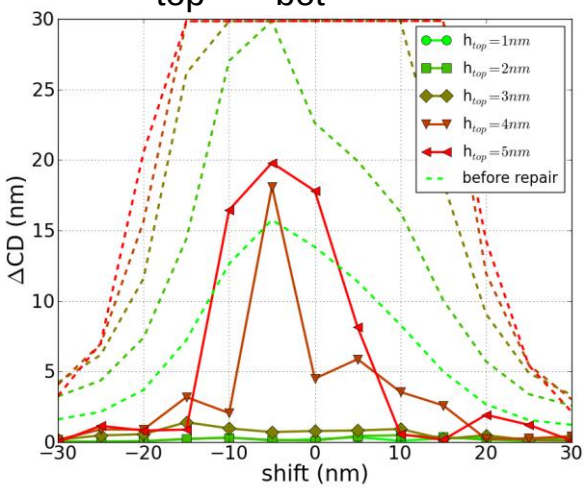
max(h_{top}) = 4nm

w_{top}=w_{bot}=30nm



max(h_{top}) = 4nm

w_{top}=w_{bot}=50nm



max(h_{top}) = 3nm

→ smaller bottom defects may print more critical closer to the edge

→ bottom size impacts max. height of repairable defects

Repair Simulation Results

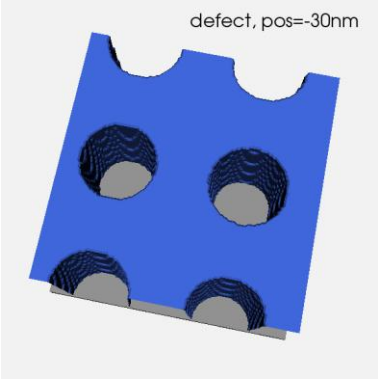
Verification inside resist

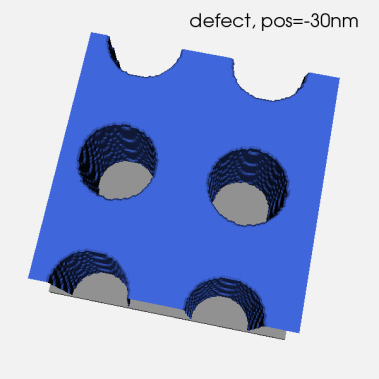
w_{top}=70nm, h_{top}=4nm
w_{top}=w_{bot}=50nm

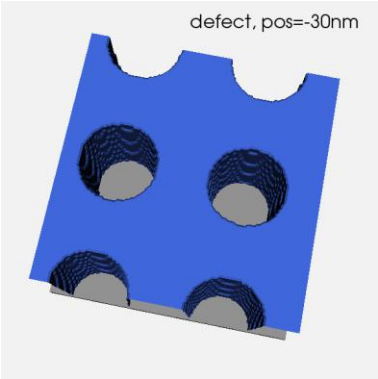
w_{top}=50nm, h_{top}=5nm
w_{top}=w_{bot}=30nm

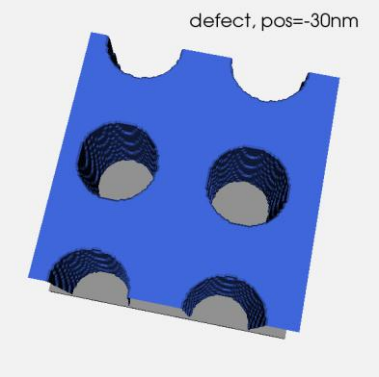
before repair

after repair









- Certain defect configurations show imperfect repair inside photoresist
- Limitations on reparable sizes due to resist?
- Possible reasons:
  - defocus inside resist in combination with absorbtion
  - Diffusion and other resist effects

Conclusions and Outlook

- The proposed method enables the fully rigorous optimization of repair shapes in 10-30 minutes

- Defect printing (and required compensation repair) depend on top and bottom shape (defect propagation) of the defect and on the position in the layout.

- Fully rigorous simulations confirm the feasibility of compensation repair, there are limits regarding the size of repairable defects

see next talk of D. Van den Heuvel:
"Study of Multilayer defects on sub-32nm hp EUV reticles"

- Future work:
  - Explore impact of photoresist effects on repair
  - Develop methods to access information on the bottom shape
  - Explore methods to compensate the phase impact of defects

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