Simulation photolithographischer Prozesse: Grundlagen, Anwendungspotential und Herausforderungen

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Inhalt:

1. Lithographiesimulation am Fraunhofer-Institut IISB
Kompetenzen und Projekte

2. Grundlagen
- optische Projektionstechniken in der Chipherstellung
- Modellierung des Abbildungssystem und der Photolackprozessierung
- Bewertung von Lithographieprozessen

3. Anwendungen
- Wirkungsweise und Optimierung von Phase-Shift Masken
- Optimierung von Masken und Beleuchtungsproblemen
- Belichtungen über nichtebenen Wafern

4. Ausgewählte Herausforderungen

Competencies of the Lithography Group

Modeling of Optical Systems

- projection imaging incl. aberrations, spatial coherence, polarization effects in high NA systems
- rigorous diffraction modeling (FDTD, waveguide method): optical and EUV-masks, defects
- interaction of light & photoresist/wafer

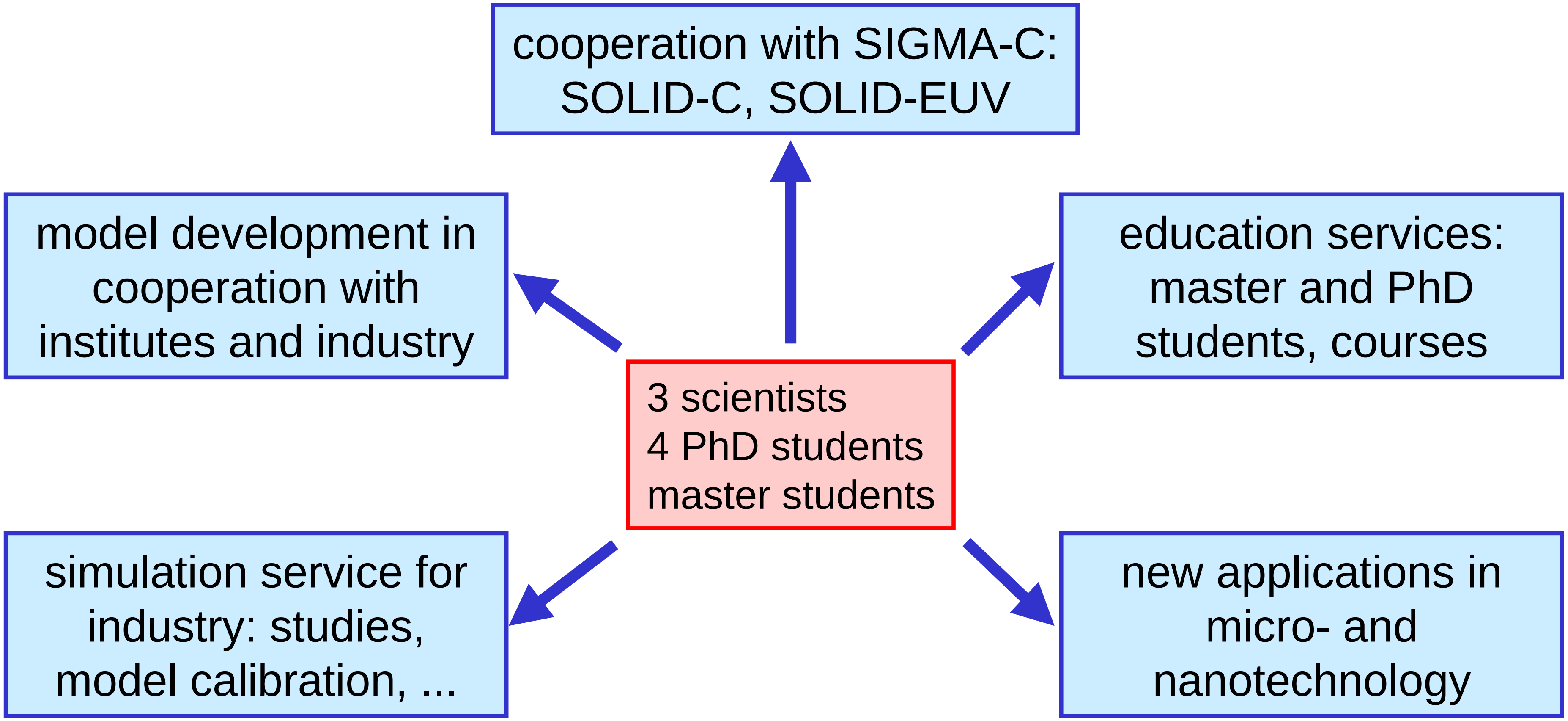
Modeling of Photoresists

- bake : semi-empirical models for kinetic/diffusion processes during baking
- chemical development: flexible rate and surface propagation models
- very efficient models for approximate characterization of photoresist during processing

Full System Simulation

- calibration of model parameters (esp. resist) with experimental data
- process evaluation (process windows, defect-printability, MEEF, ...), correlation of parameters
- optimization of mask and source geometries with genetic algorithms

Projects of the Lithography Group



3 scientists
4 PhD students
master students

cooperation with SIGMA-C:
SOLID-C, SOLID-EUV

education services:
master and PhD students, courses

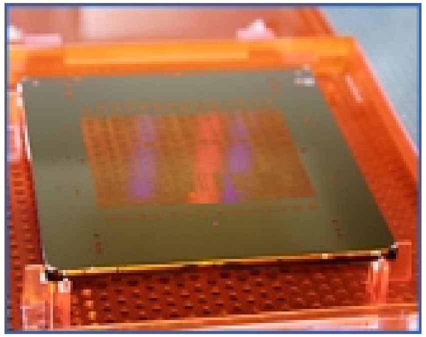
new applications in micro- and nanotechnology

simulation service for industry: studies, model calibration, ...

model development in cooperation with institutes and industry

Optical Projection Techniques - Chip Fabrication

feature sizes: 100 nm
magnification: 1/4

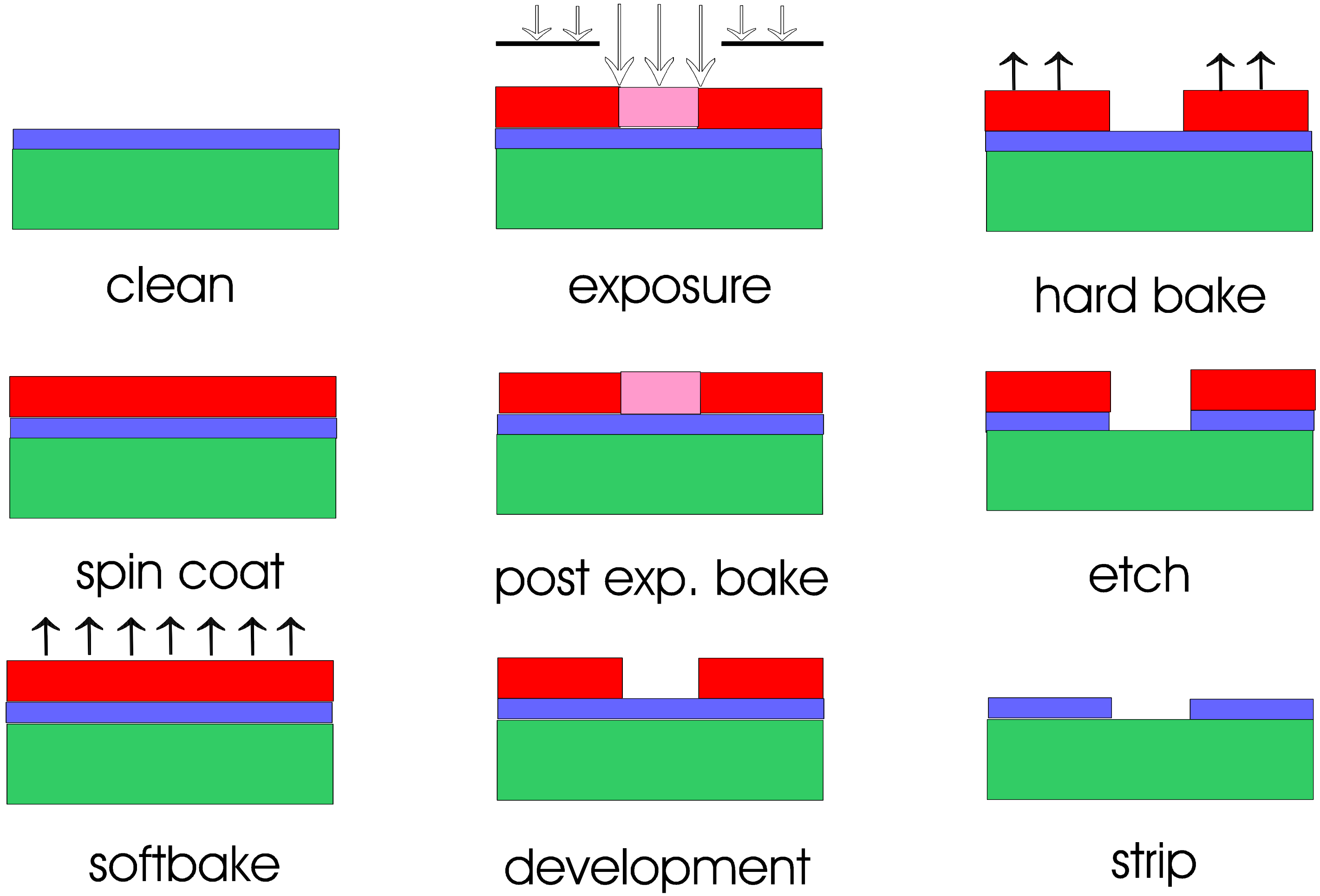


chromium mask

ASML projection scanner from 2001

microprocessor chip

Lithographic Process: Overview



clean

spin coat

softbake

exposure

post exp. bake

development

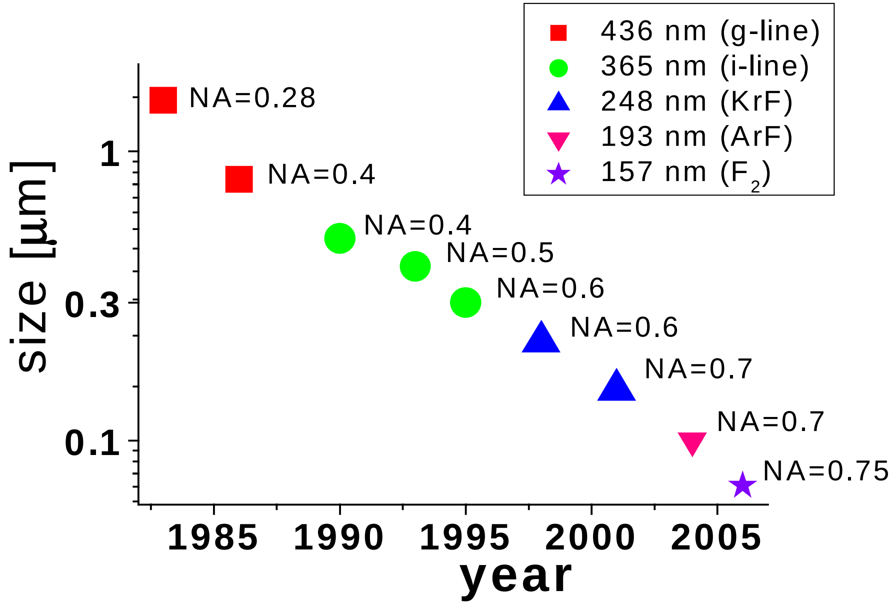
hard bake

etch

strip

Performance of Lithographic Processes

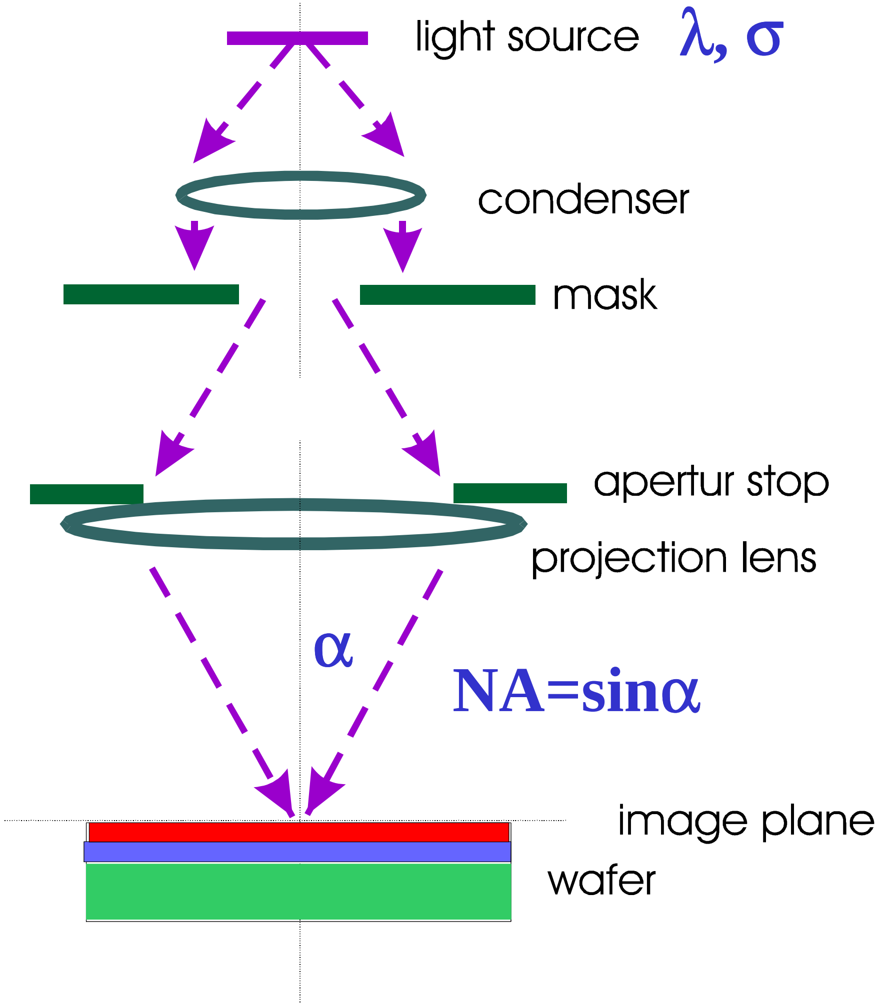
International Technology Roadmap for Semiconductors (ITRS), 2001



prices for lithographic exposure equipment (stepper/scanners)

g-line:	< 1 Mio $
i-line:	1-3 Mio $
KrF:	4-8 Mio $
ArF:	8-18 Mio $
F2:	ca. 30 Mio $
EUV:	50-60 Mio $

Basics: Aerial Image Formation in Optical Projection Systems



assumptions:

- infinitesimal thin mask with complex transmission
- projection lens and condenser lens are characterized by complex transfer functions

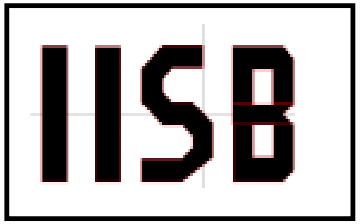
method:

- Fourier-Optics
  including methods to cope with partial coherence, apodization, wave aberrations, polarization, ...

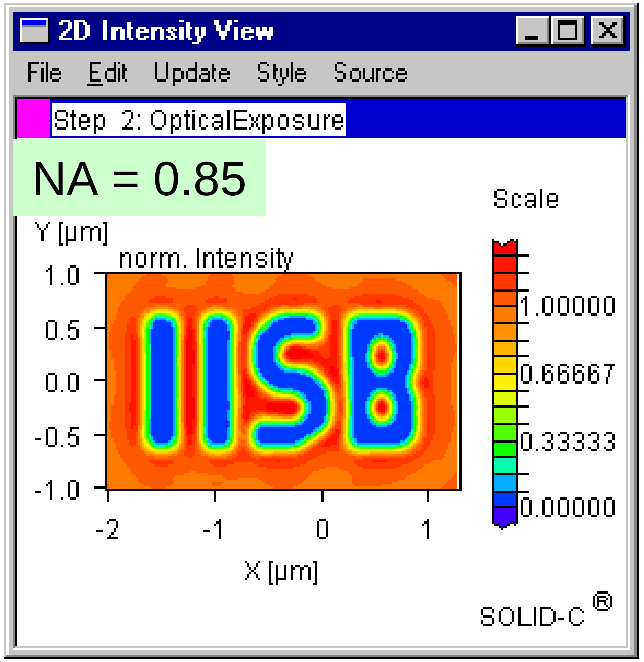
Basics: Aerial Image Formation in Optical Projection Systems

mask layout

(smallest feature
size: 250nm)



aerial image



Step 2: OpticalExposure

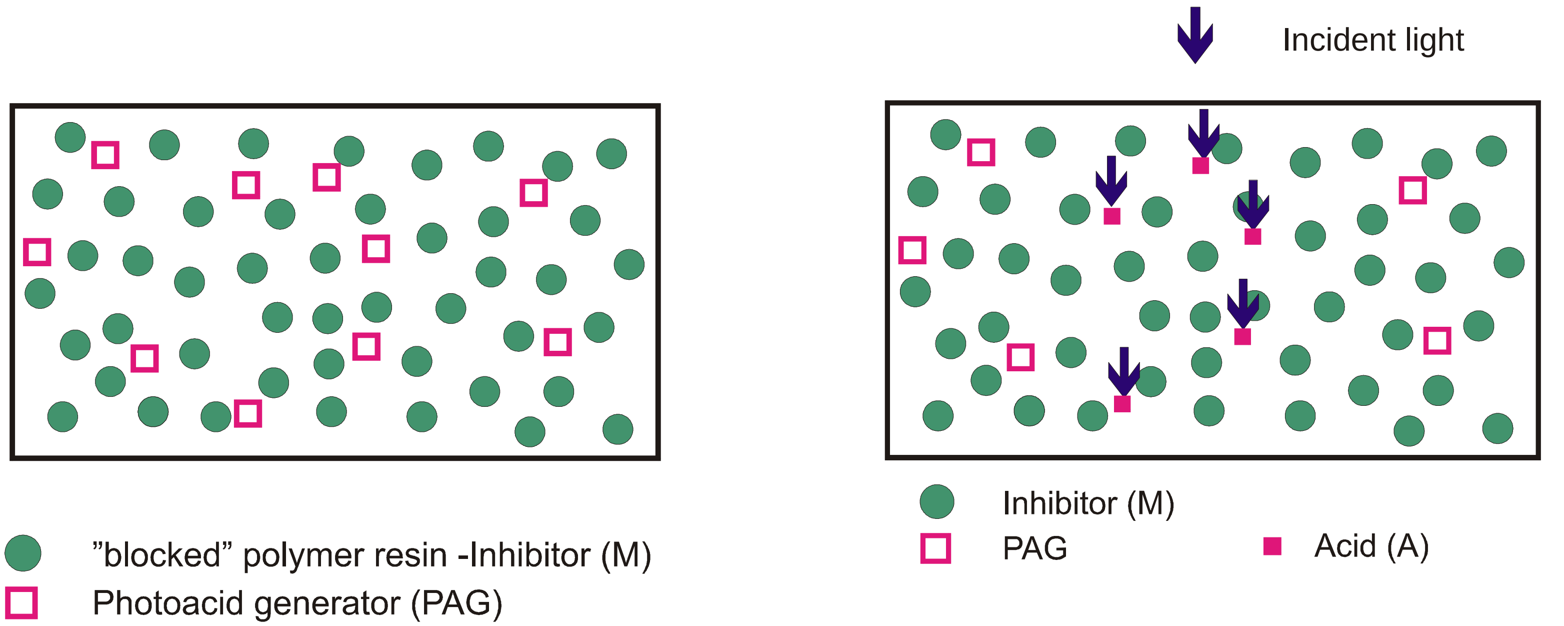
NA = 0.85

imaging with an optical stepper/scanner

(λ=248nm, NA, σ, wave aberrations,...)

Basics: Photoresist Processing

Dill-model for lithographic exposures



Dill equations:

$$\frac{\partial [PAG]}{\partial t} = -C_{dill} \cdot I \cdot [PAG]$$

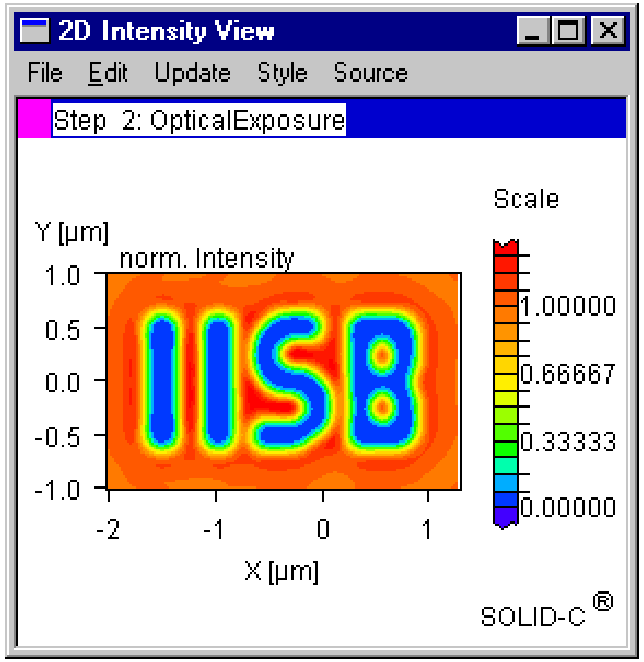
$$\alpha = A_{dill} \cdot [PAG] + B_{dill}$$

$$[A] = 1 - [PAG]$$

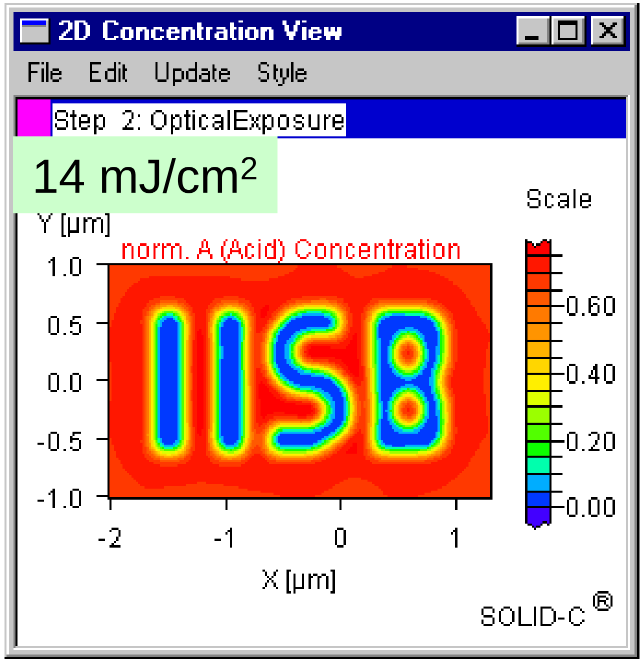
Basics: Photoresist Processing

Dill-model for lithographic exposures (cont.)

aerial image



acid conc.

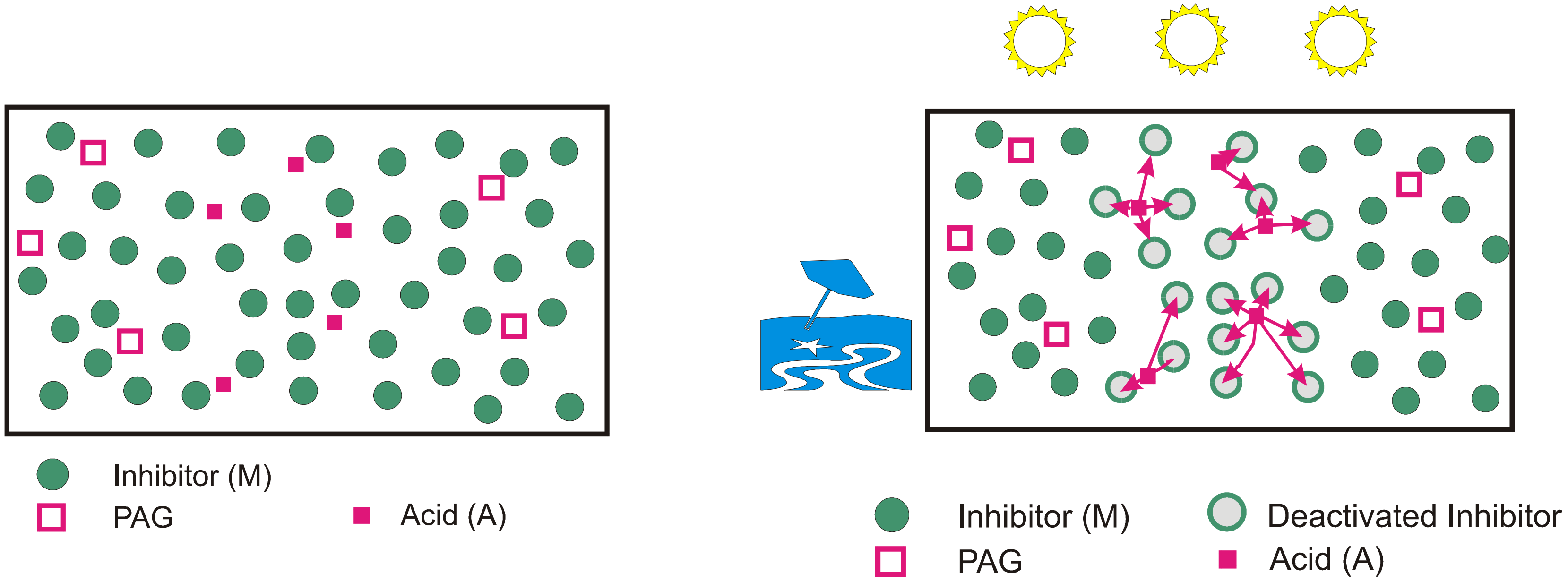


generation of photoacid in exposed areas

(dose, Dill A,B,C)

Basics: Photoresist Processing

post exposure bake (PEB)



catalytic decomposition of inhibitor:

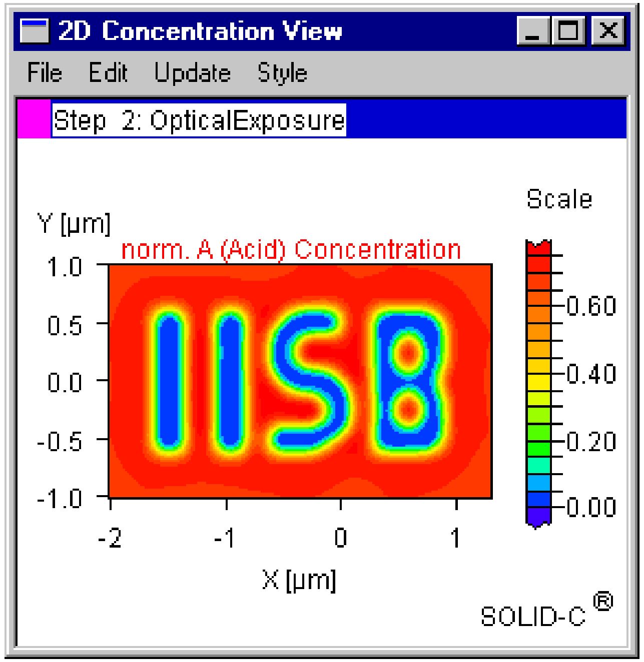
$$\frac{\partial[\mathrm{M}]}{\partial t} = -K_{amp}[\mathrm{M}]\cdot[\mathrm{A}]^{n}$$

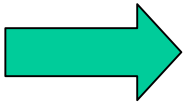
Basics: Photoresist Processing

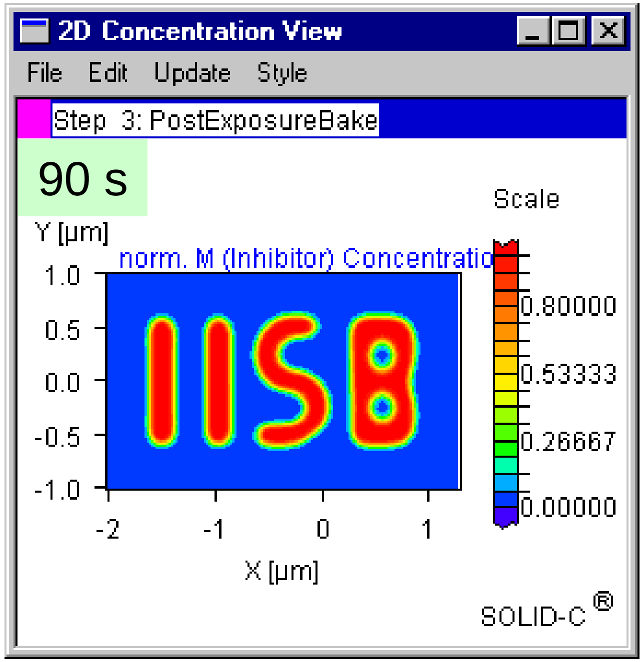
PEB (cont.)

acid conc.

inhib. conc.





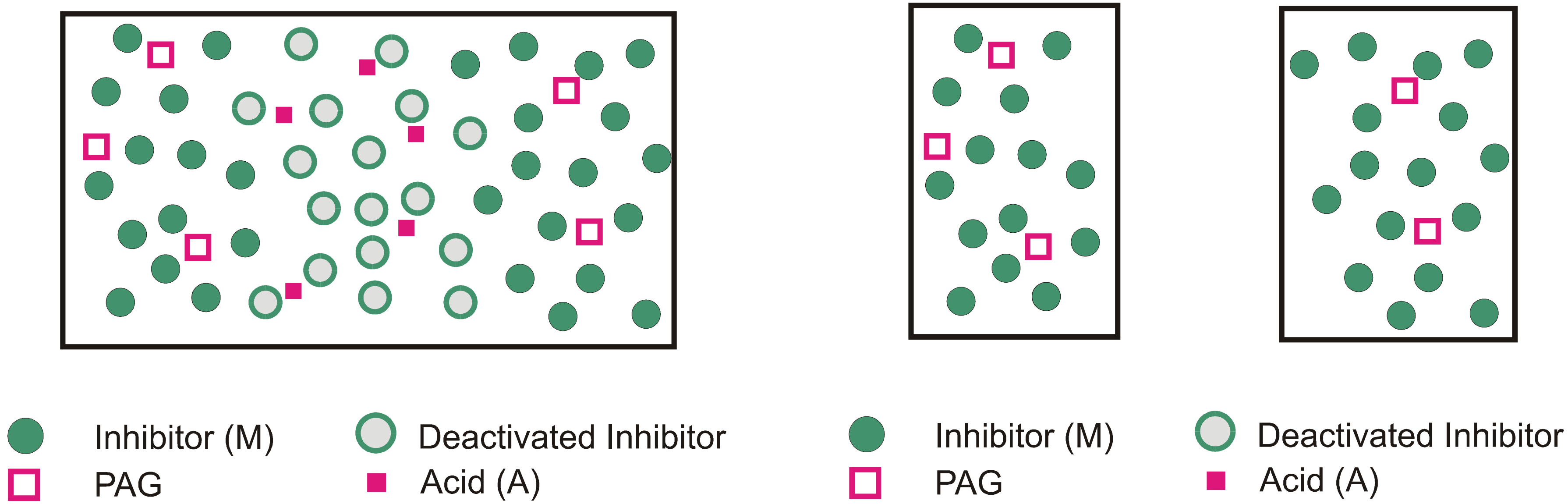


acid catalyzed deprotection of dissolution inhibitors

(PEB time, temperature, diffusion- and kinetik-parameters of photoresist)

Basics: Photoresist Processing

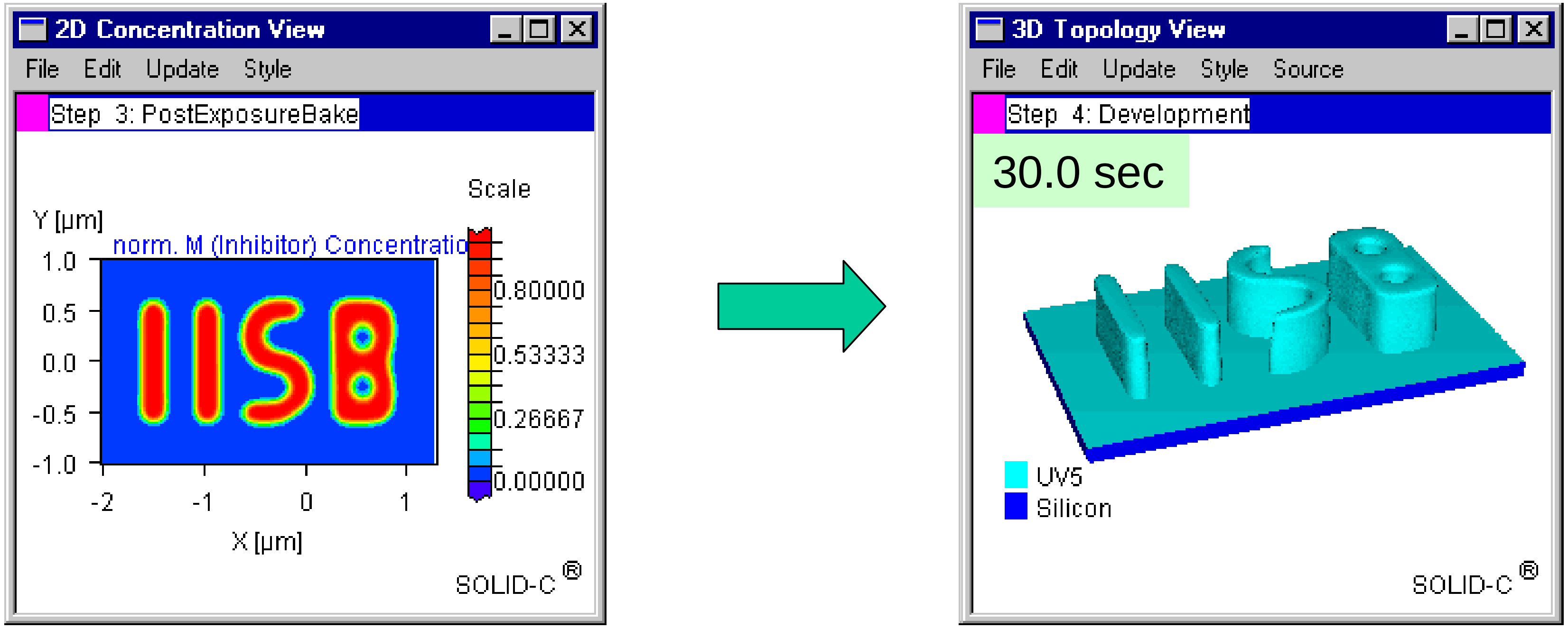
chemical development



dissolution of resist components with reduced inhibitor concentration

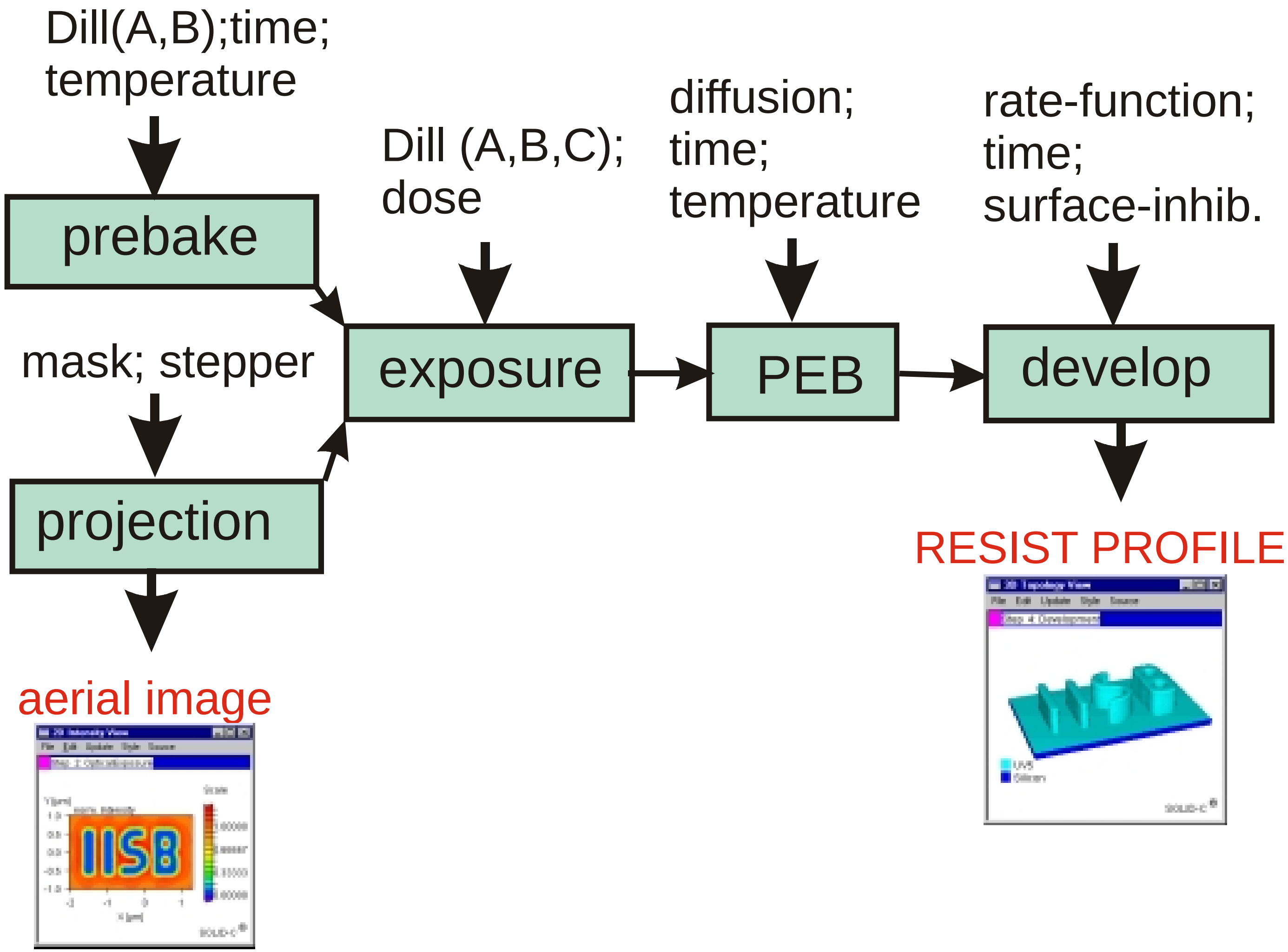
Basics: Photoresist Processing

chemical development

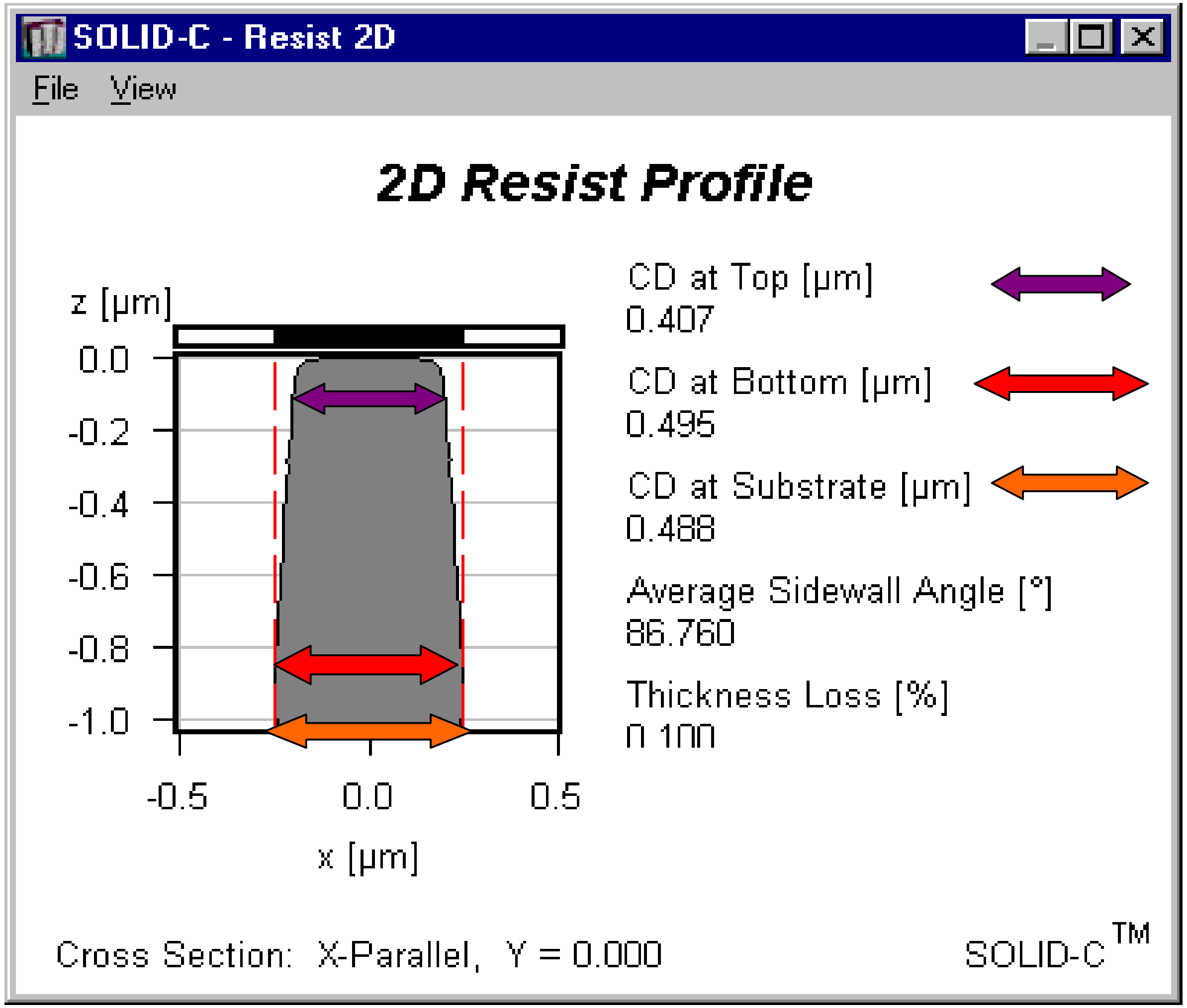


chemical development of the photoresist in areas with reduced concentration of inhibitor
(time, temperature, development parameters of the photoresist)

Basics: General Simulation Flow



Process Evaluation: Resist Profile



2D Resist Profile

CD at Top [µm]
0.407

CD at Bottom [µm]
0.495

CD at Substrate [µm]
0.488

Average Sidewall Angle [°]
86.760

Thickness Loss [%]
0.100

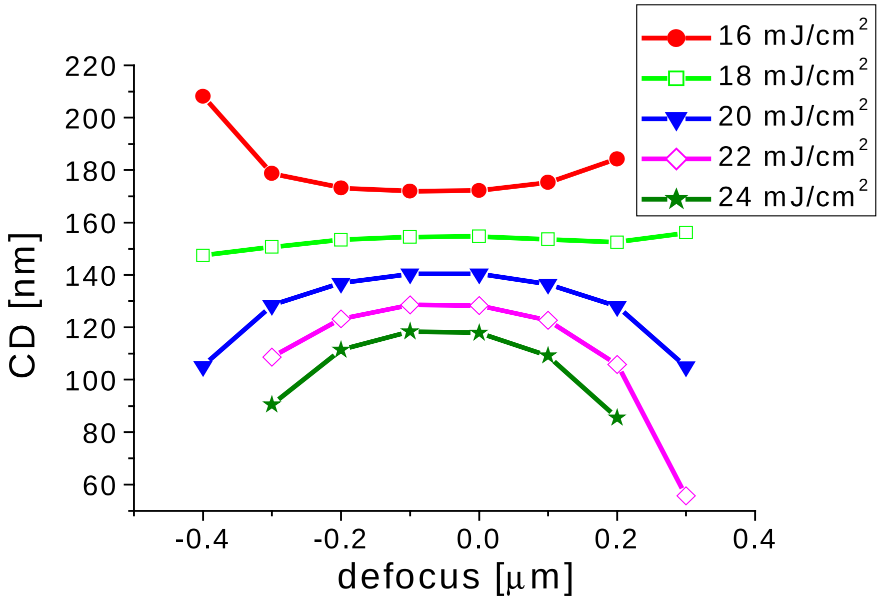
Cross Section: X-Parallel, Y = 0.000

SOLID-C™

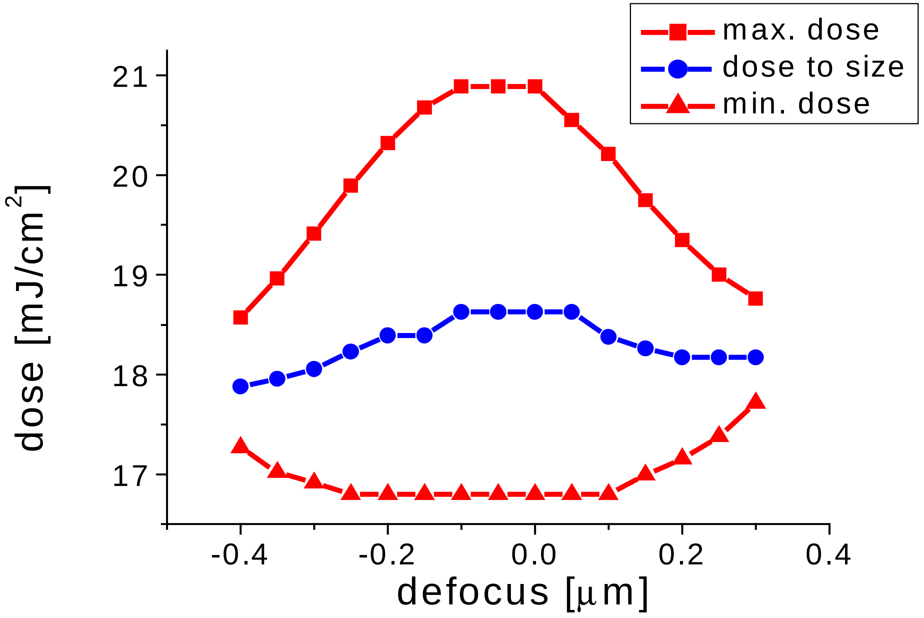
Process Evaluation: Process Window

imaging of 150nm wide dense lines at λ=193nm,
NA=0.75, fixed illumination σ_{in}/σ_{out}= 0.5/0.7

Bossung-curves



process window



Phase Shift Masks (PSM)

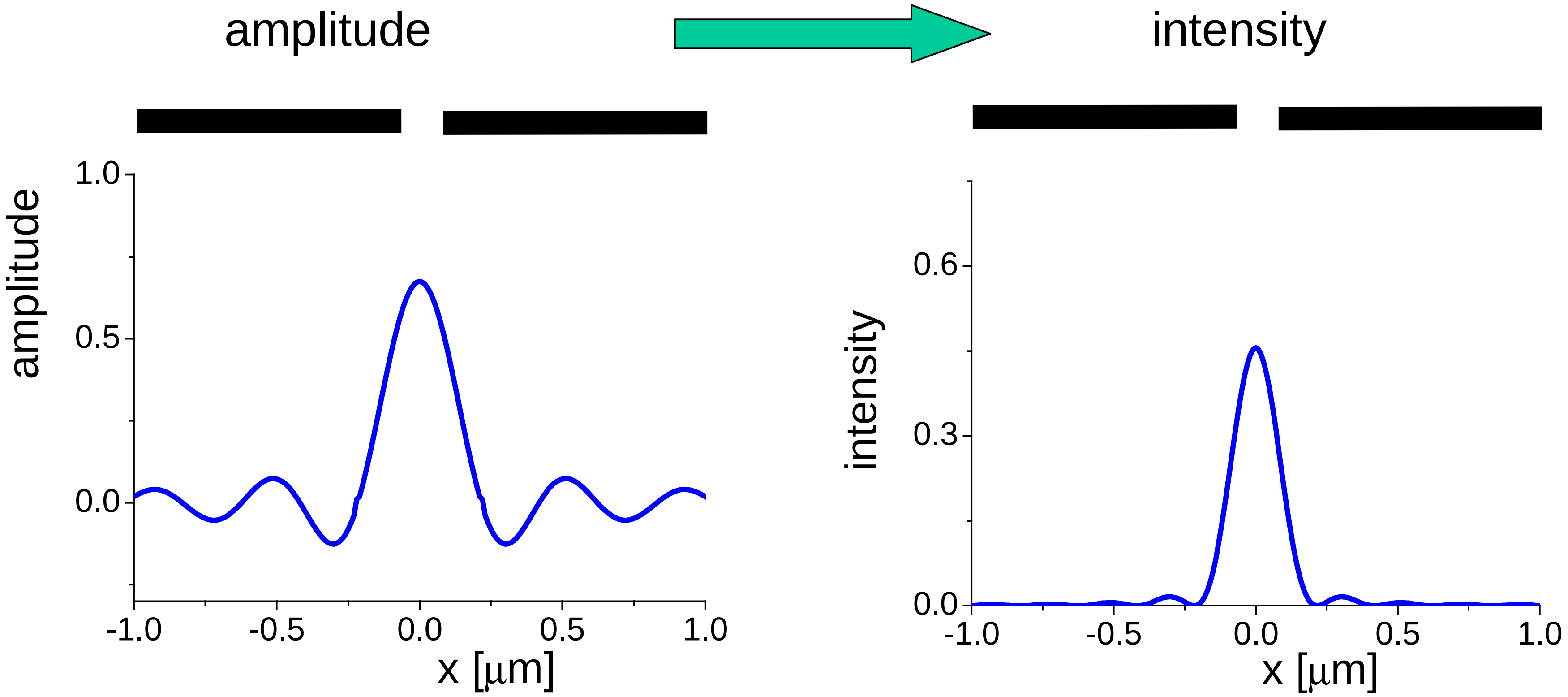
Why is a PSM better than a binary mask (BIM) ?

image of a slit

$$I = a \cdot a^*$$

amplitude

intensity

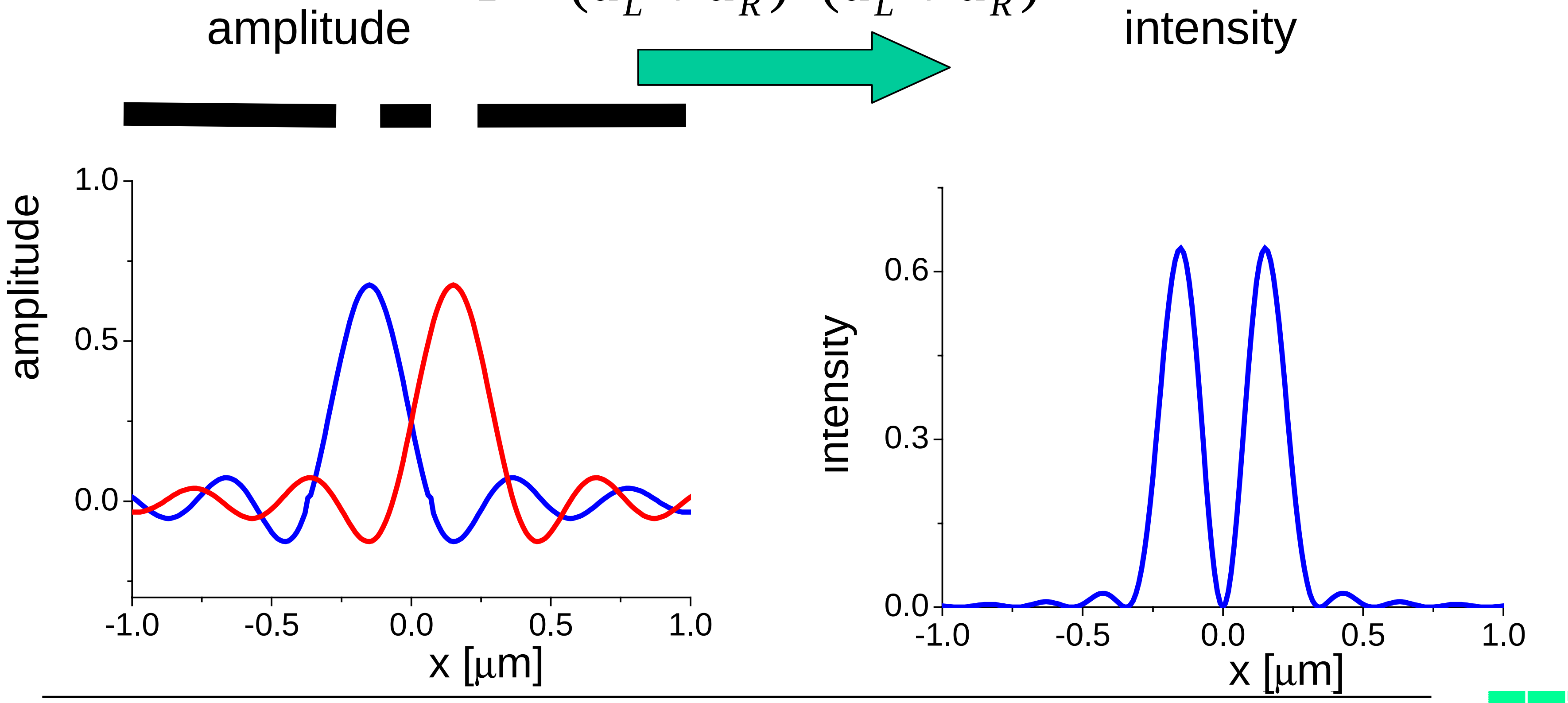


Phase Shift Masks (PSM)

Why is a PSM better than a binary mask (BIM) ?

image of a pair of slits

$$I = (a_L + a_R)\cdot(a_L + a_R)^*$$

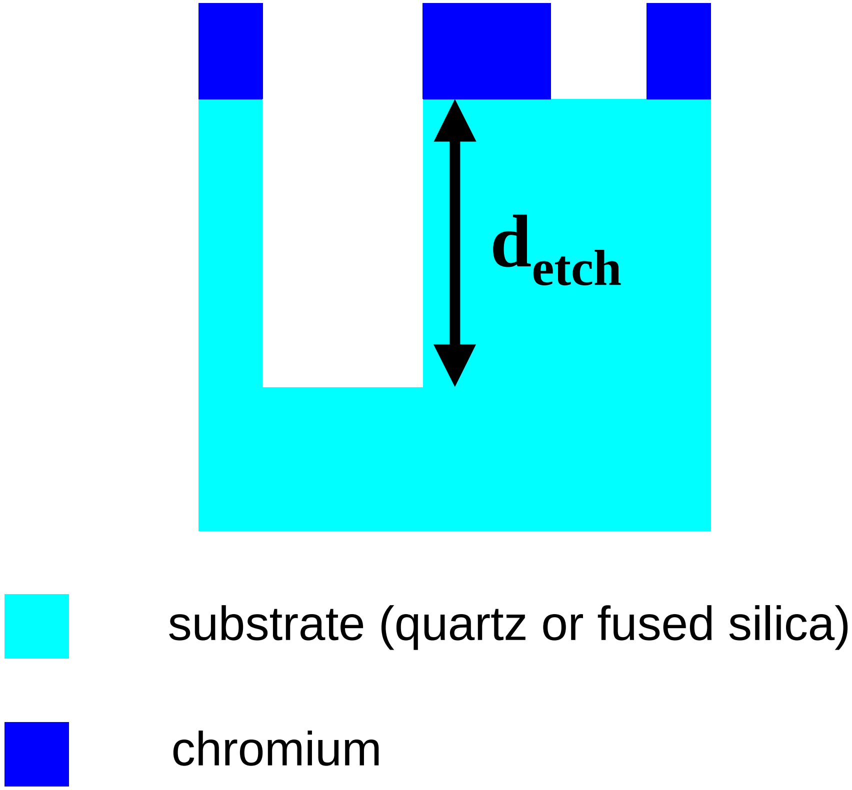


PSM: How To Realize it in Practice ?

180° phase shift requires optical path difference of $\lambda/2$:

$$n_{substrate} \cdot d_{etch} - n_{air} \cdot d_{etch} = \lambda/2$$

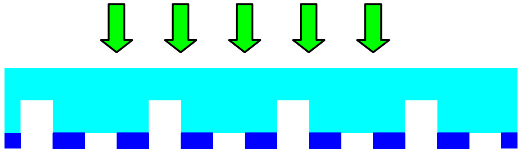
$$\Rightarrow \boxed{d_{etch} = \frac{\lambda}{2[n_{substrate} - n_{air}]}}$$



PSM: Practical Performance

mask topography

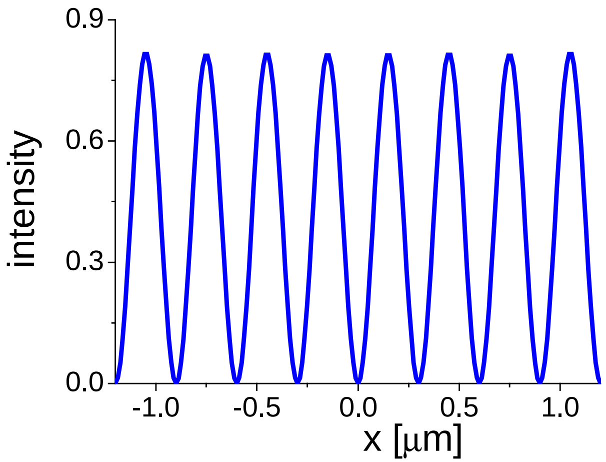
incident light



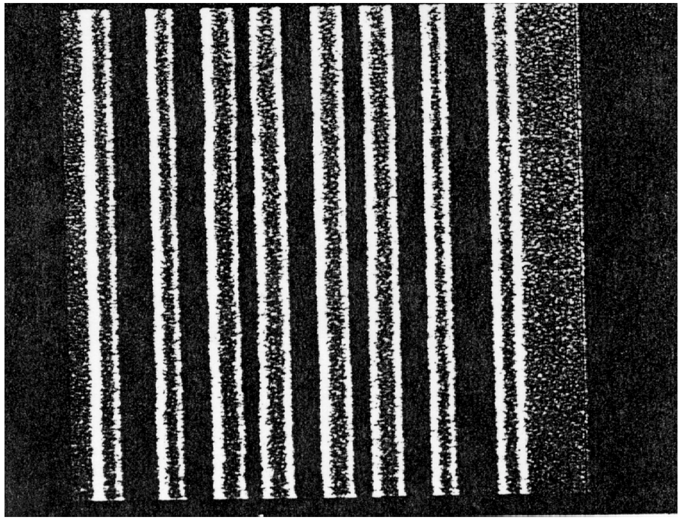
🟦 substrate (glass)

🟦 absorber (chromium)

simulated aerial image



SEM-photograph of patterned resist



➡ What is wrong ?

Basics: Aerial Image Formation in Optical Projection Systems

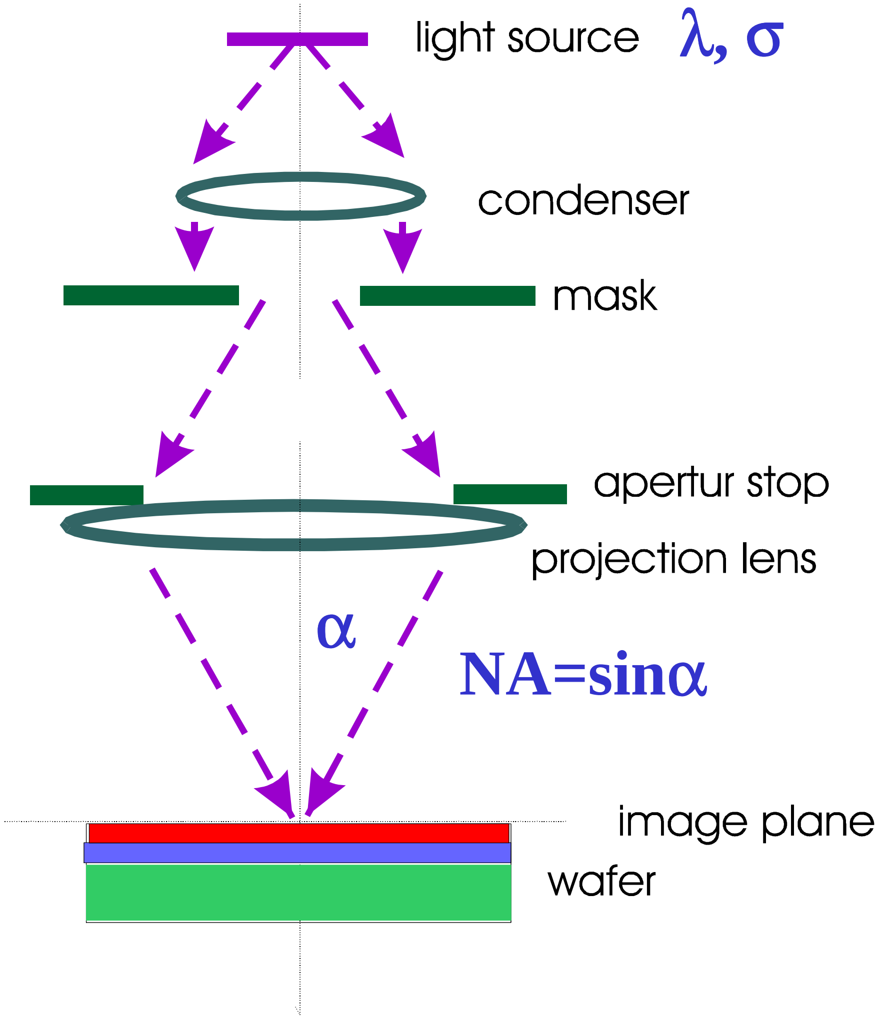
assumptions:

- ~~infinitesimal thin mask with complex transmission~~
- projection lens and condenser lens are characterized by complex transfer functions

method:

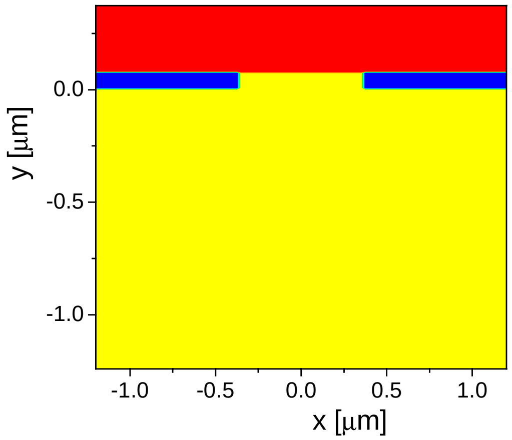
- Fourier-Optics
  including methods to cope with partial coherence, apodization, wave aberrations, polarization, ...

\+ application of rigorous diffraction theory



PSM and Topography Effects: Advanced Simulation Approach

mask topography

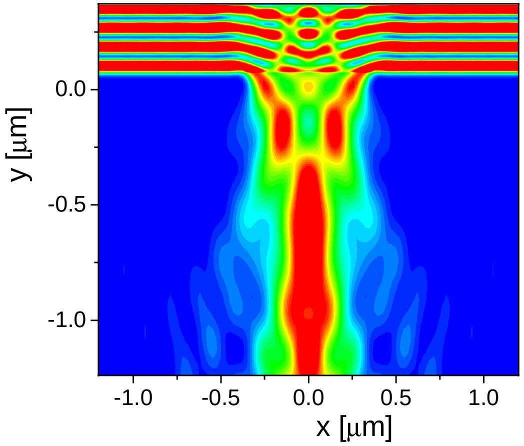


compute the EM-field by a rigorous field solver

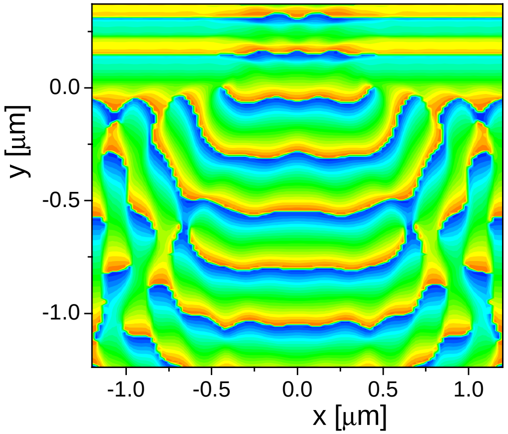
FDTD

finite-difference
time-domain
algorithms

intensity



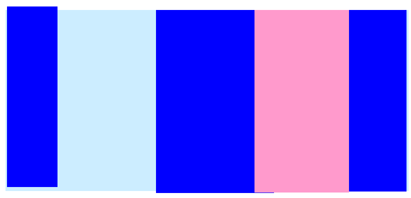
phase



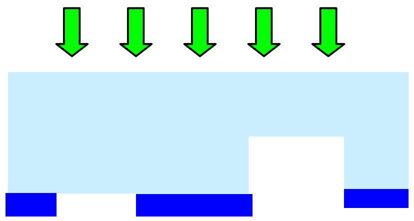
PSM and Topography Effects:
Infinitely Thin Mask Assumption (Kirchhoff Approach)

geometry

top view



cut

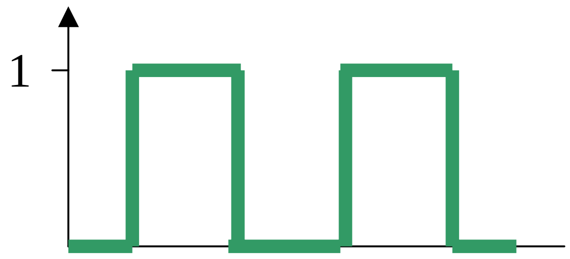


□ glass

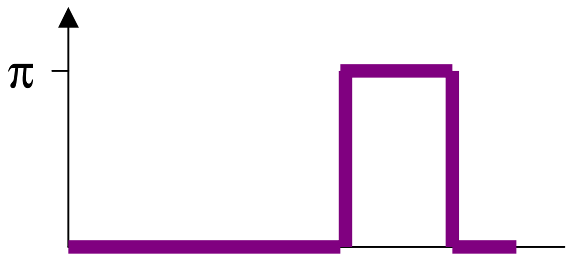
■ chromium

transmission

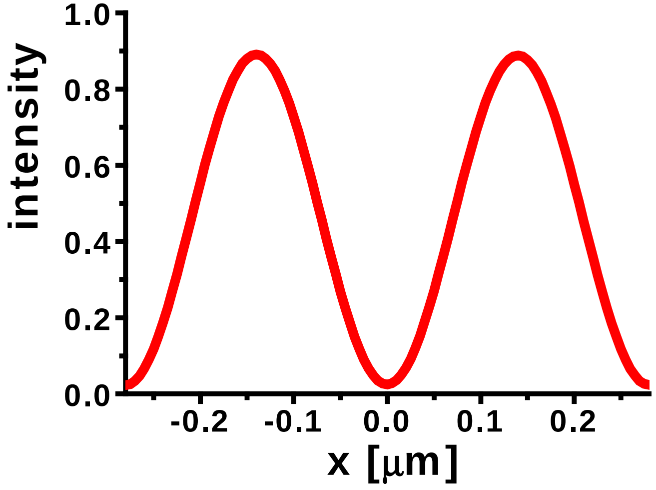
amplitude



phase

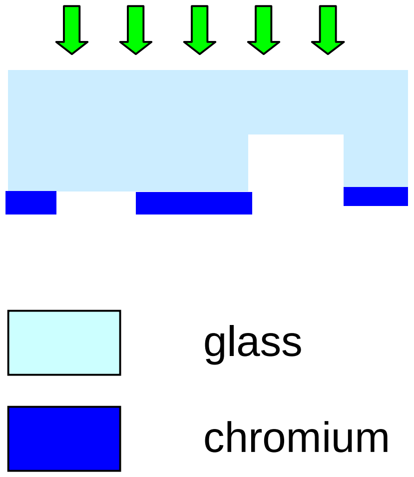


aerial image

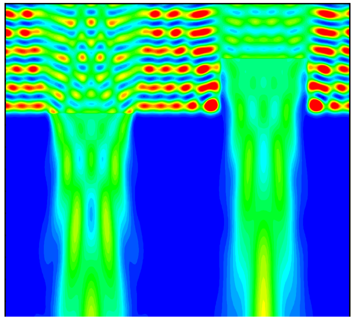


PSM and Topography Effects: Advanced Simulation Approach

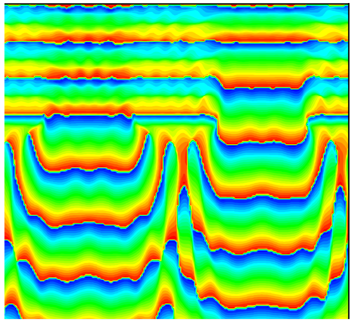
geometry



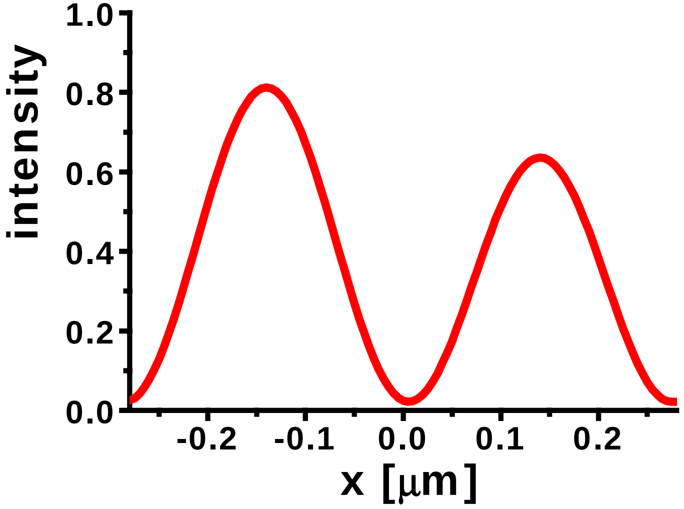
intensity



phase

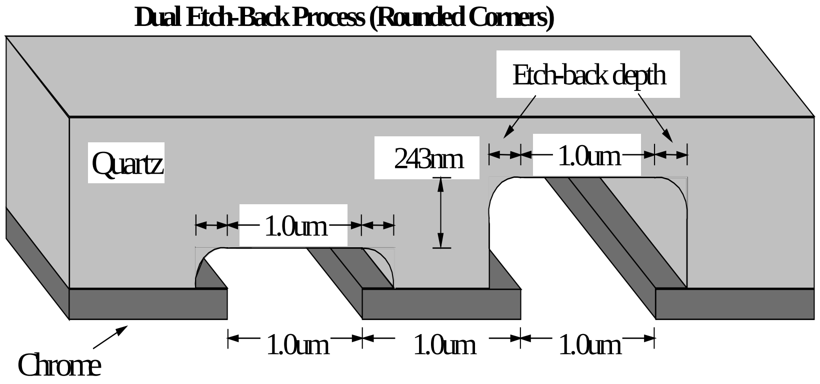


aerial image

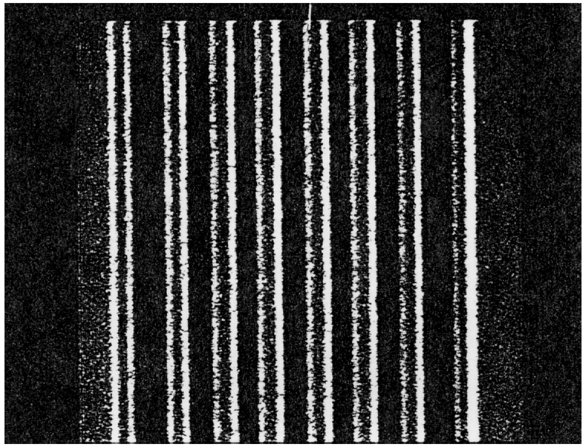


PSM and Topography Effects: Consequences

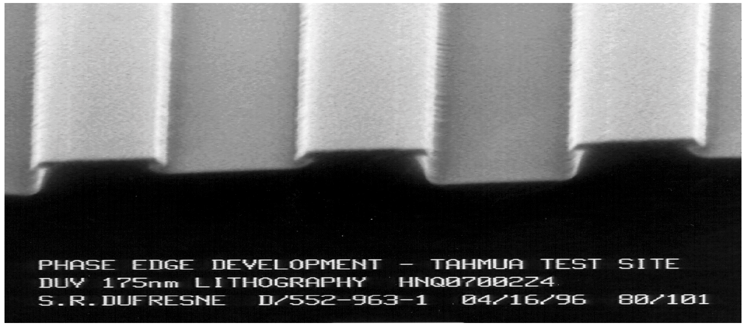
optimized geometry of the mask



SEM-photograph of patterned resist



SEM-photograph of patterned mask



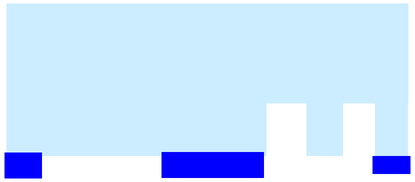
from: A. Erdmann, R. Gordon:
„Mask Topography Effects in
Resolution Enhancement Techniques“

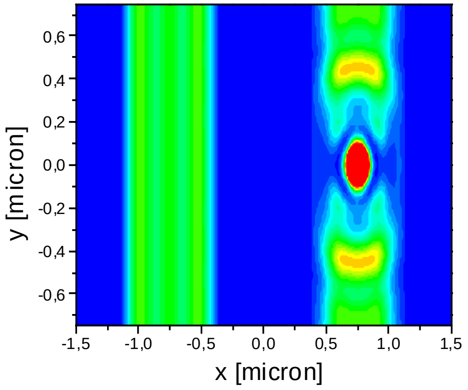
PSM Topography Effects: Defects

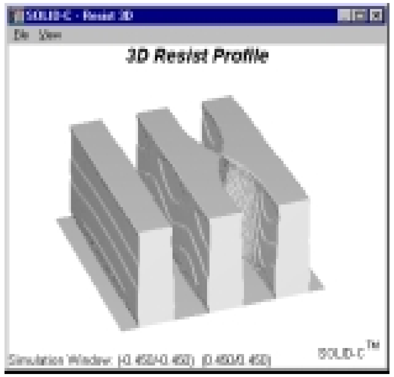
near field

resist profile

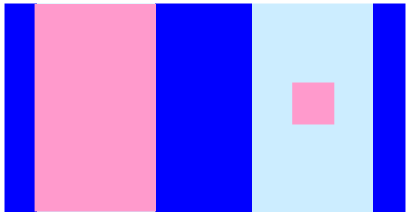
bump defect (cut)



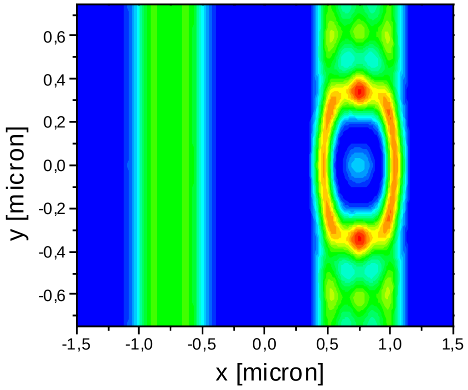


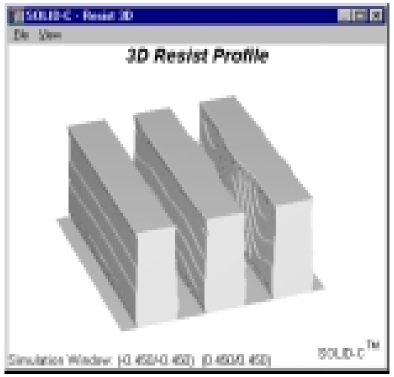


mask (top view)



etch defect (cut)



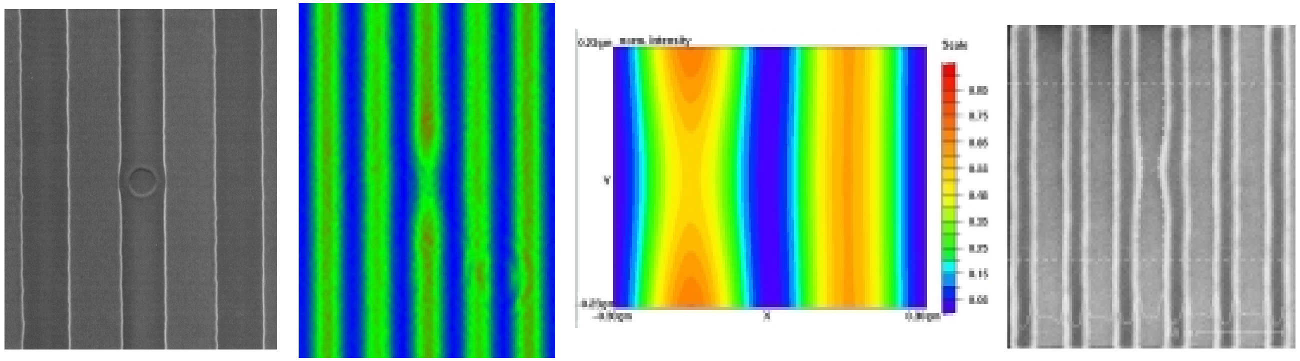


PSM with Defects: Experiment and Simulation

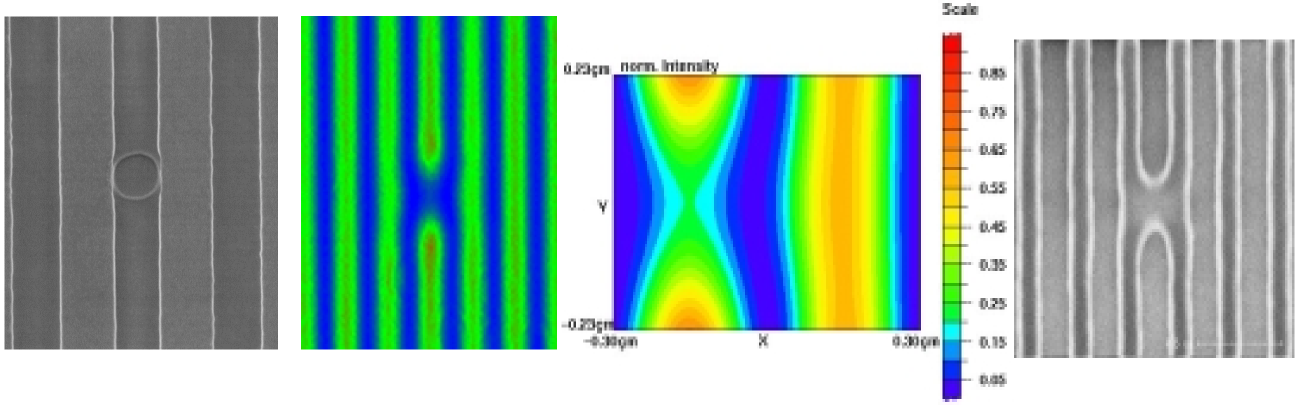
Infineon technologies

cooperation with
Infineon:
Ch. Friedrich,
A. Semmler

hole 700 nm (5x) real 340 nm, best focus


mask SEM AIMS Simulation wafer SEM

hole 800 nm (5x) real 575 nm, best focus

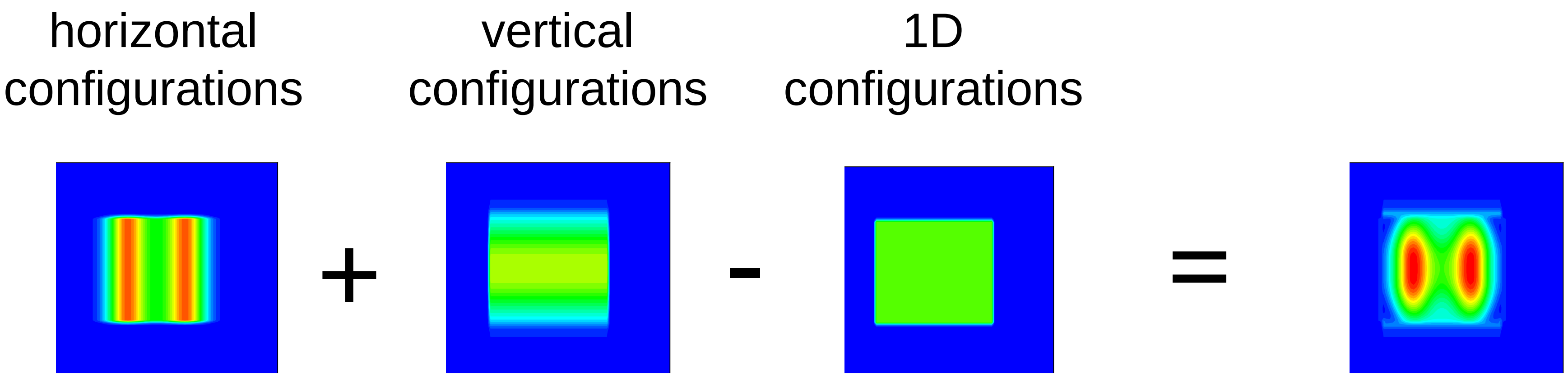

mask SEM AIMS Simulation wafer SEM

Field Decomposition (QUASI 3D) for More Efficient Mask Topography Simulations

→ first proposed by Kostas Adam (Uni Berkeley) at SPIE 2001

simplification of the problem:

- edges of features on the mask occur only along few directions
- optical projection system covers only few diffraction orders



horizontal configurations

vertical configurations

1D configurations

Field Decomposition (QUASI 3D) for More Efficient Mask Topography Simulations

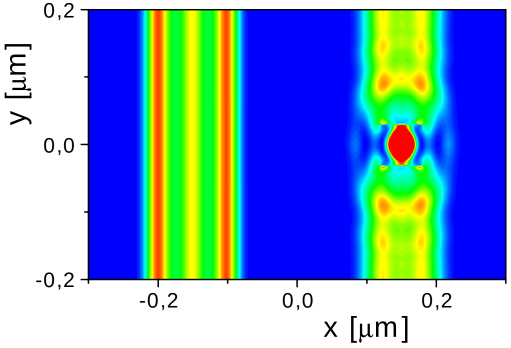
example: alternating PSM with defect

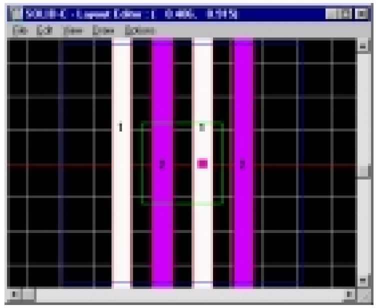
FDTD Full 3D:
103 min, 910 MB

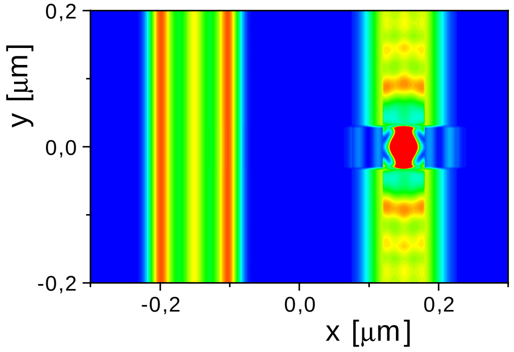
Kirchhoff:

FDTD Quasi 3D:
54 s, 1.9 MB

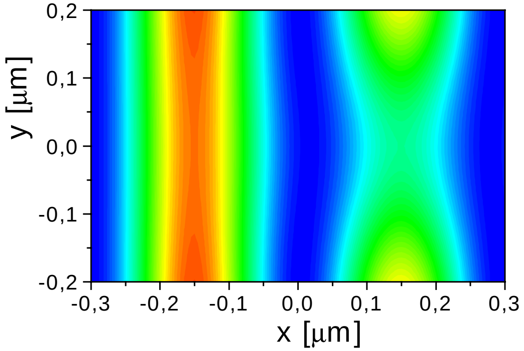
mask transmission

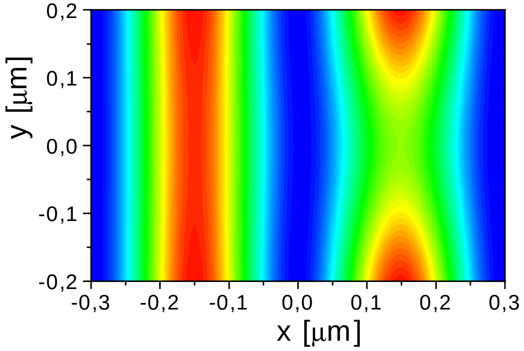


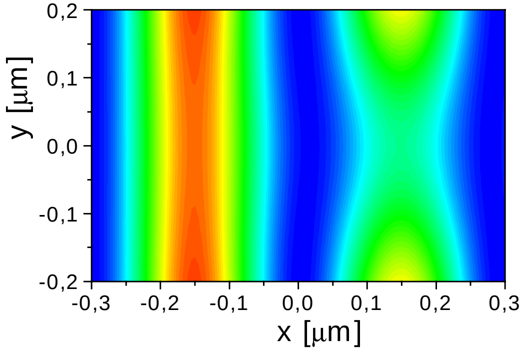




aerial images

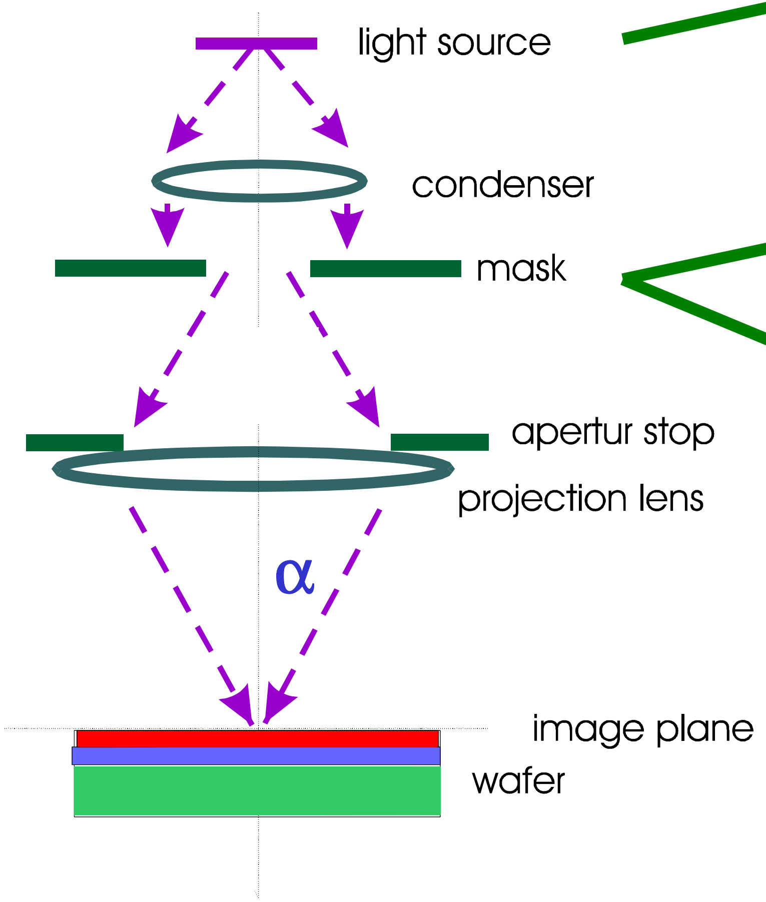






Optical Resolution Enhancement Techniques (RET)

lithographic imaging system



OAI:
- annular
- multipoles
- user defined

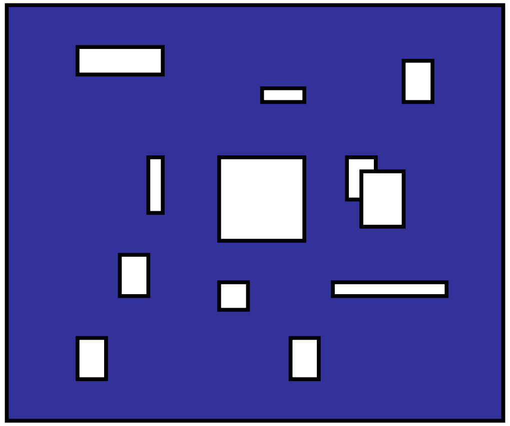
OPC:
- assists
- seriefs

PSM:
- attenuated
- alternating
- chromless

Which mask and illumination provide the best performance ?

Mutual Optimization of Mask & Source: Variables

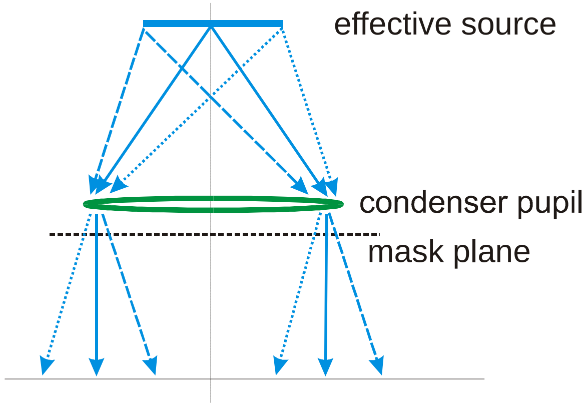
mask



list of rectangles

variables:
position, size and
number of rectangles

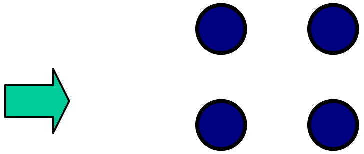
source/illumination



illumination of the mask by a spectrum of plane waves with different tilt (τ_x,τ_y)

illumination directions

variables:
in this work we focus
on multipole
illumination

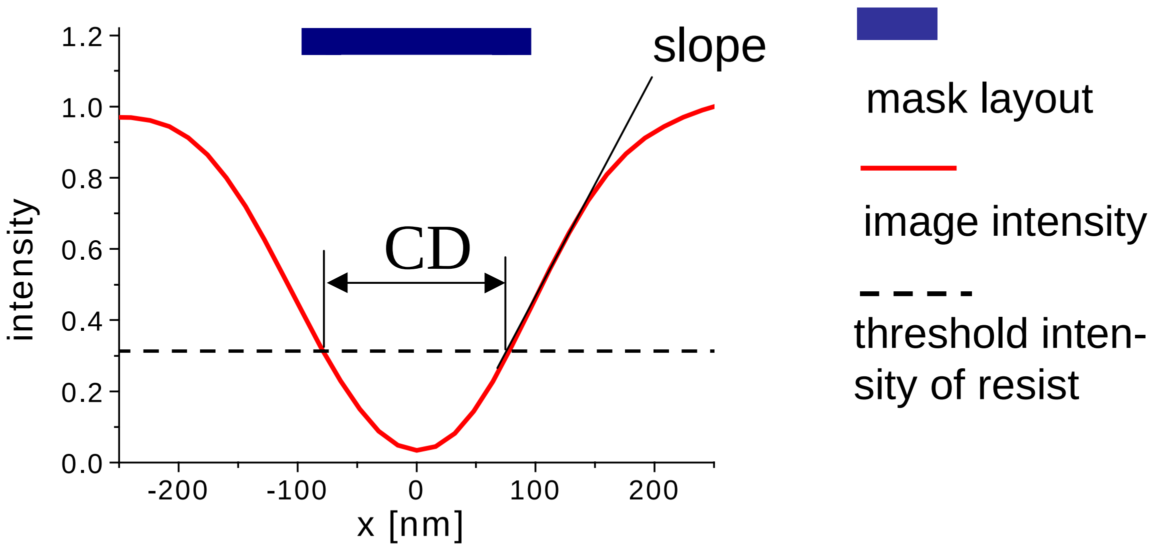


offset, radius,
orientation, number

Mutual Optimization of Mask & Source: Merit Function

- the resist is assumed to be a threshold detector

evaluation of the main feature:

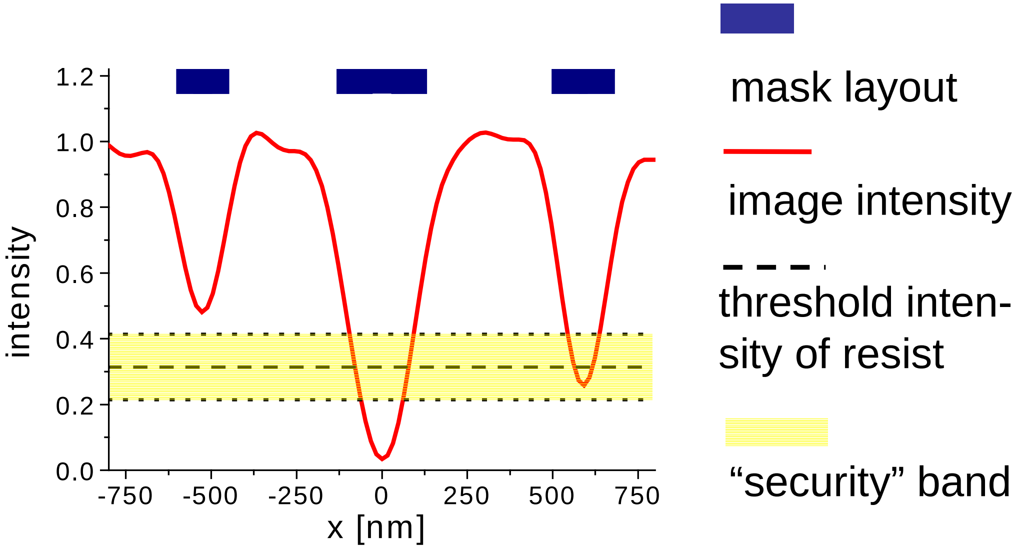


- critical dimension criterion (ΔCD):
  compare the size the printed feature compared to target size

- slope criterion (SC):
  increase the slope of the intensity at the edges of the features to be printed

Mutual Optimization of Mask & Source: Merit Function (cont.)

global image evaluation:

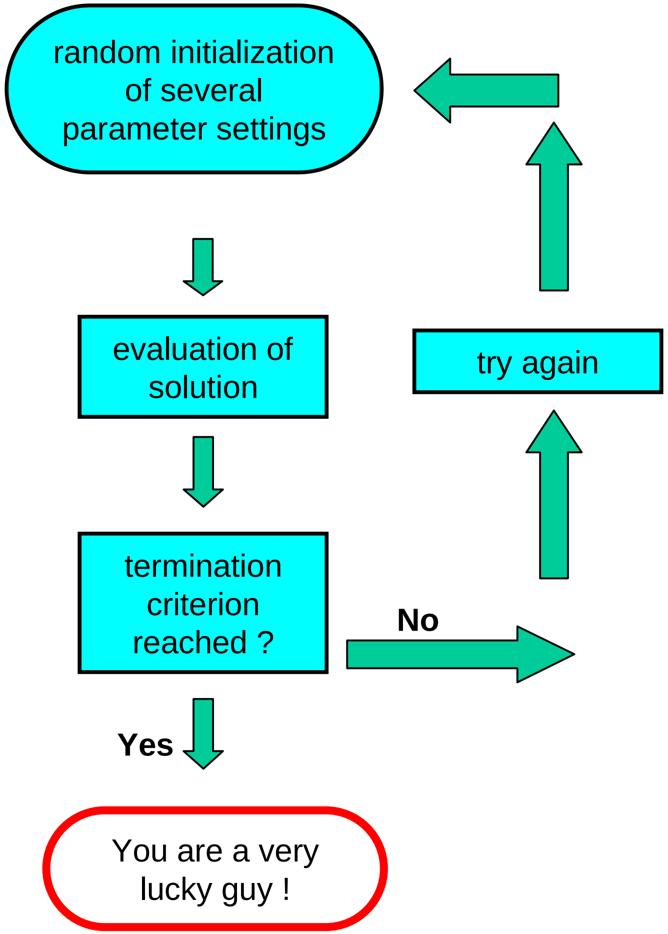


- band criterion (BC):
  punish image sidelobes which cross the security band

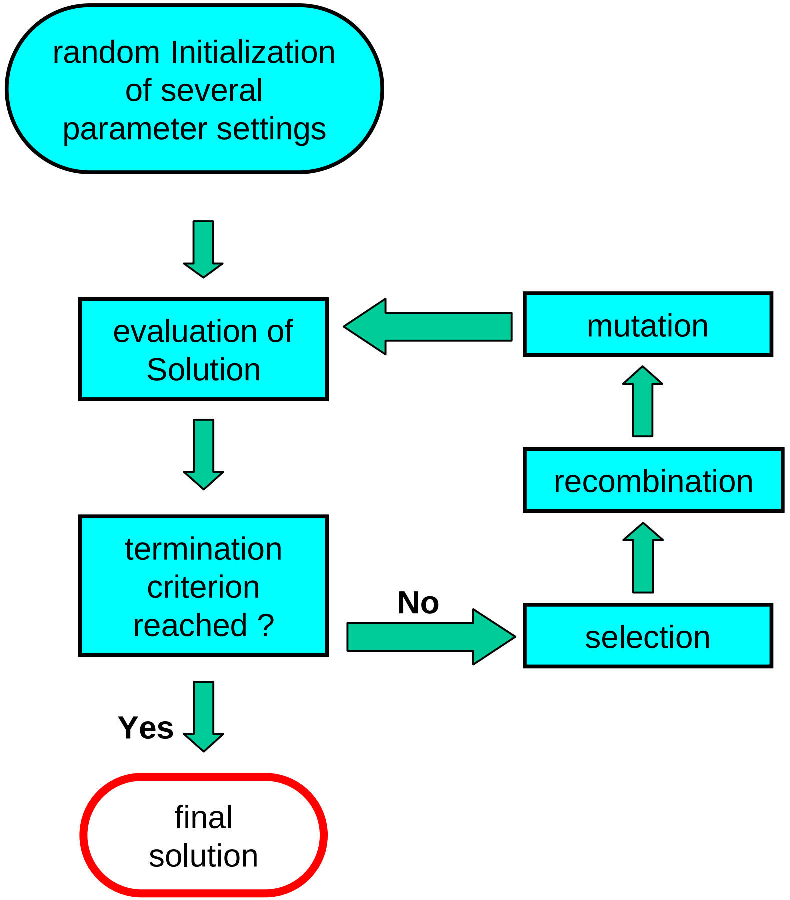
- manufacturability criterion (MC):
  count the number of transitions between different neighbored pixels
  exclude/punish bad rectangles (overlapping, too small areas and distances, ...)

Optimization Procedure: Genetic Algorithm

random walk



genetic algorithm

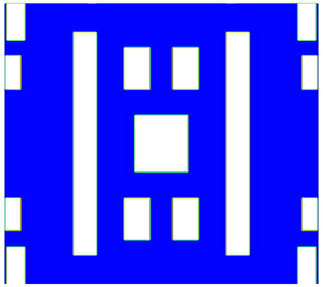


Optimization Procedure: A First Demonstration

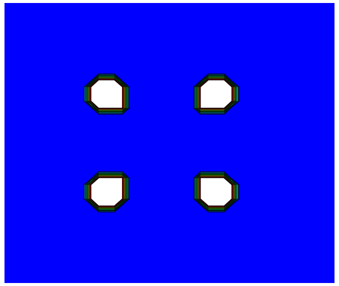
How to create a 140nm×170nm contact hole with a large depth of focus?

mask: high transmission attenuated PSM; optics: λ=193nm, NA=0.7, multipole illum.

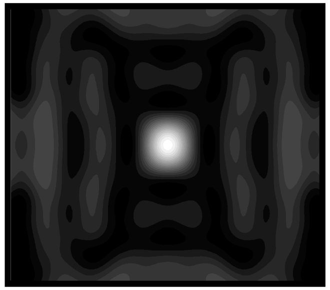
mask



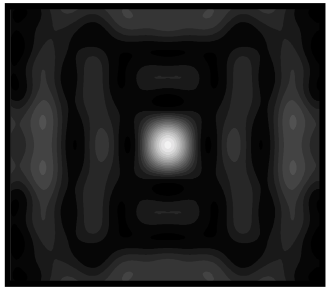
illumination



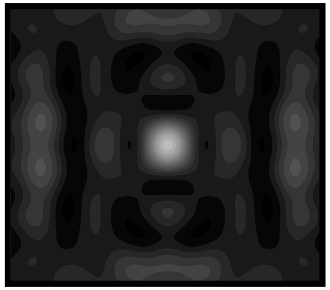
defocus=0nm



defocus=200nm



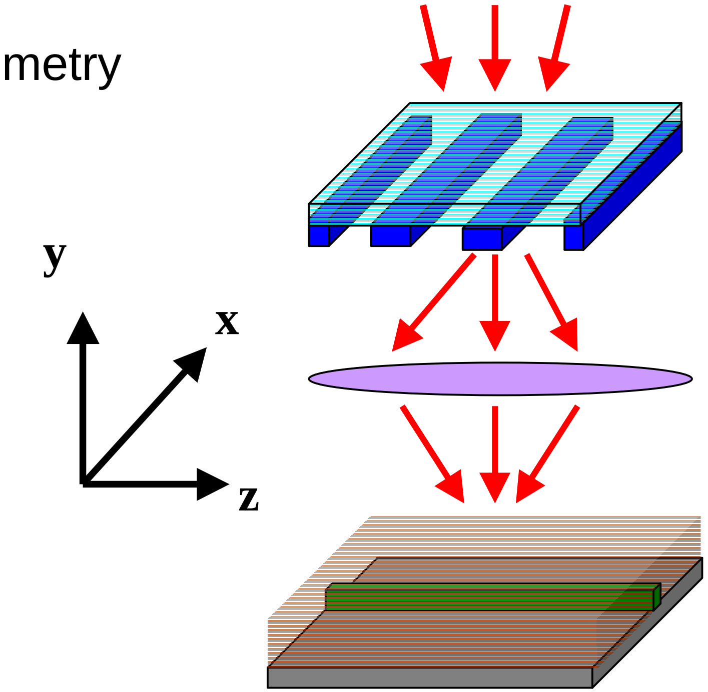
defocus=400nm



Lithographic Exposures over Nonplanar Wafers

simulation settings for a typical problem

geometry



exposure conditions:
NA=0.68, KrF, 4x, σ=0.45, defocus=-300 nm

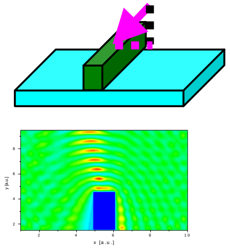
mask: 250 nm lines/spaces (1:1)

wafer: resist: air (500nm)
poly Si-line (w=100 nm, h=175 nm)
SiO_2 - substrate

Lithographic Exposures over Nonplanar Wafers

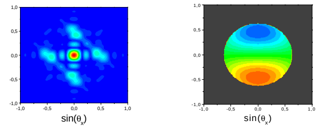
general scheme proposed at SPIE Microlithography 2003

compute EM fields within photoresist for all plane waves emerging from exit pupil (f_x, f_y)



$$E(r,f_x,f_y)$$

compute the diffraction spectrum of the mask $s(f_x, f_y)$, shift it according to the actual source point (q_x,q_y) and multiply the result with the pupil function $P(f_x, f_y)$



$$b(f_x,f_y,q_x,q_y)=s(f_x-q_x,f_y-q_y)\cdot P(f_x,f_y)$$

superpose weighted fields

$$E_{tot}(r,q_x,q_y)=\underset{\text{pupil}}{\quad} E(r,f_x,f_y)\cdot b(f_x,f_y,q_x,q_y)df_x df_y$$

$$I(r,q_x,q_y)=n\cdot E(r,q_x,q_y)\cdot E^*(r,q_x,q_y)$$

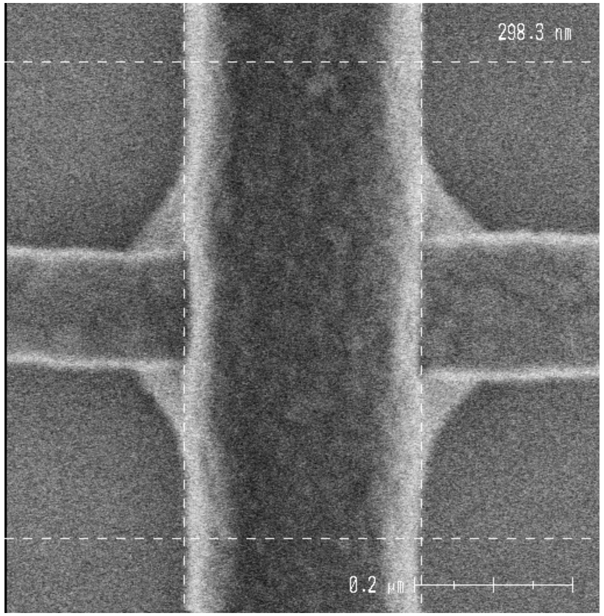
integrate over source

$$I_{tot}=\underset{\text{source}}{\quad} I(r,q_x,q_y)\cdot dq_x\cdot dq_y$$

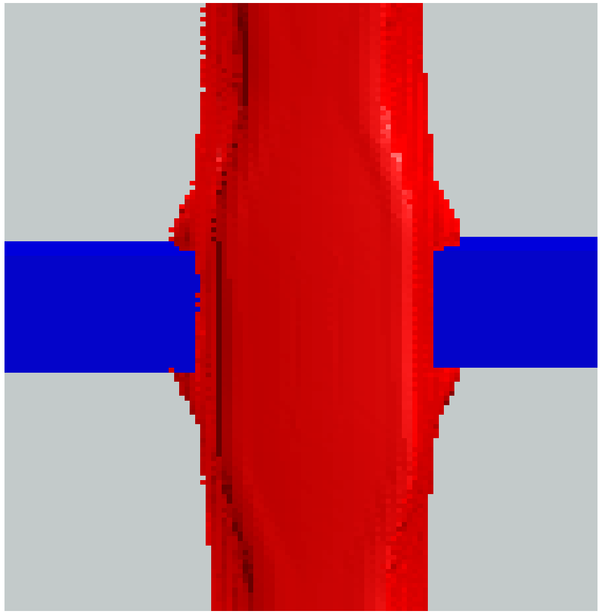
Lithographic Exposures over Nonplanar Wafers

comparison with experiment

top-down wafer SEM
(from T. Sato, Toshiba)



top-view of simulated
resist profile



exposure conditions:
NA=0.6, KrF, 4x, σ=0.45,
defocus=-200 nm

mask: 250 nm lines,
pitch=1000nm

wafer: resist (500nm)
poly Si-line (w=140 nm, h=175 nm), 2.5nm SiO_2 on Si-substrate

→ Both experiment and simulation show a pronounced footing effect in the vicinity of the shadowed region at the bottom of the poly-Si line

Lithographic Exposures over Nonplanar Wafers: RENFT

problem:

FULL: rigorous simulations of exposures over non-planar wafers are extremely time and memory consuming

⇩

limited use for practical applications
extension of present approaches to 3D geometries
is not possible (memory consumption)

proposed solution:

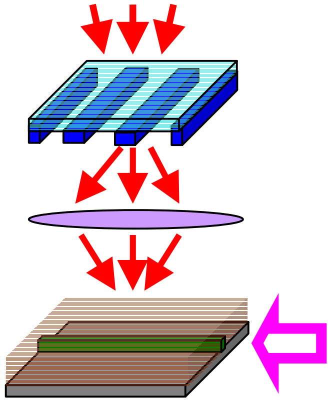
decomposition of a full simulation into

- RENT: real exposure no topography (without topography, application of standard analytical methods)
- FET: flood exposure over topographic wafer (no mask, rigorous simulation - but simplified conditions)
- RENFT = f(RENT,FET)

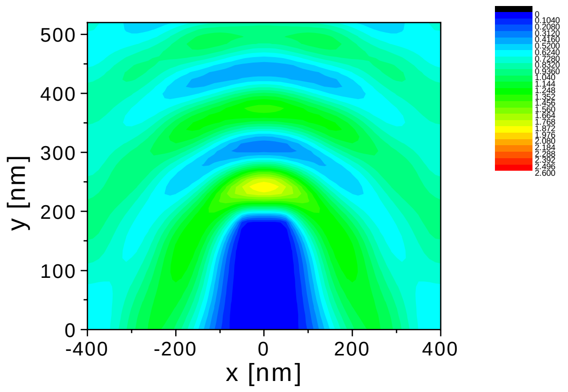
Lithographic Exposures over Nonplanar Wafers: RENFT

RENFT-concept: side view

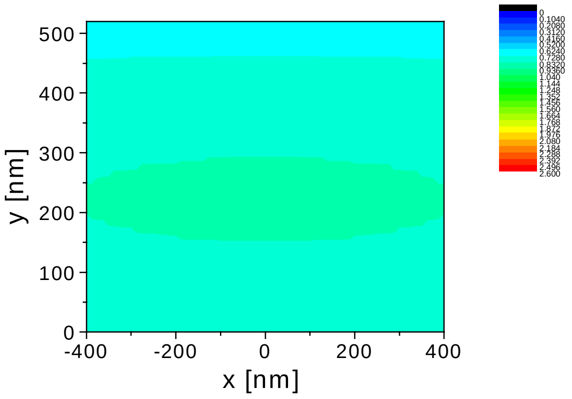
geometry



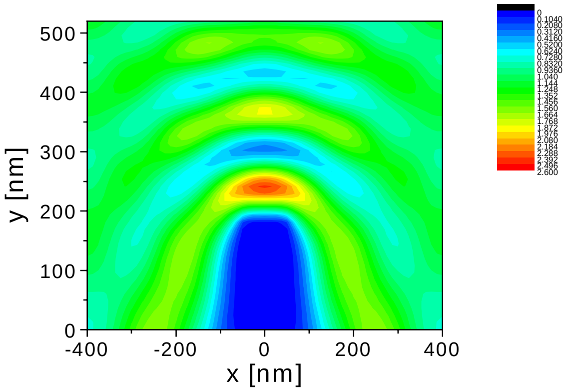
FULL



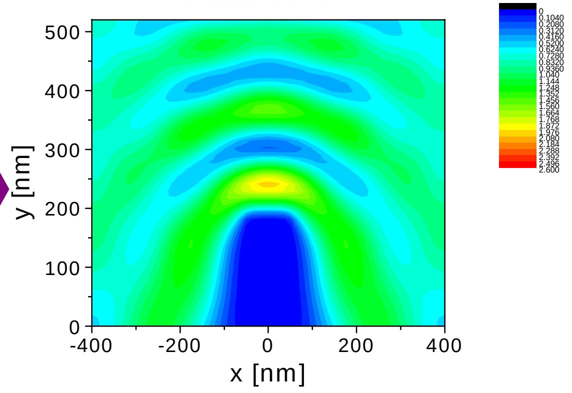
RENT



FET



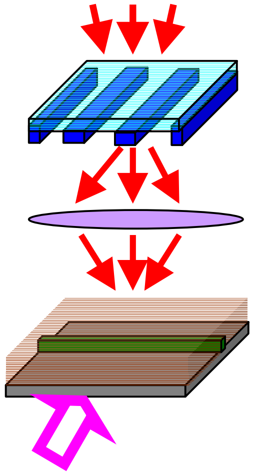
RENFT



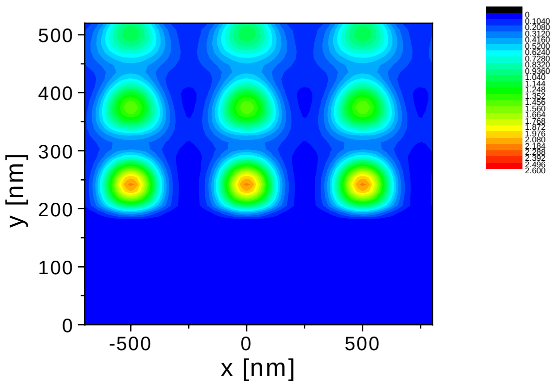
Lithographic Exposures over Nonplanar Wafers: RENFT

RENFT-concept: front view

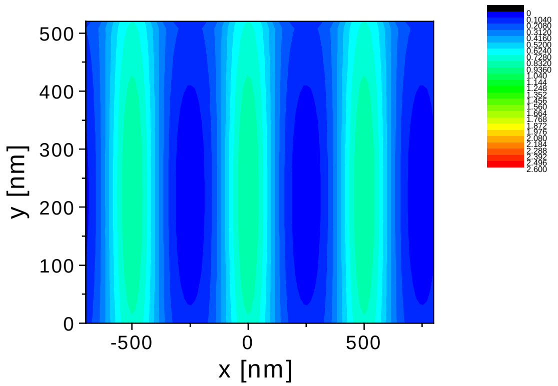
geometry



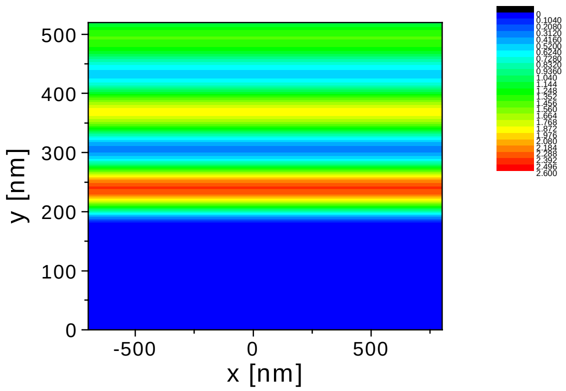
FULL



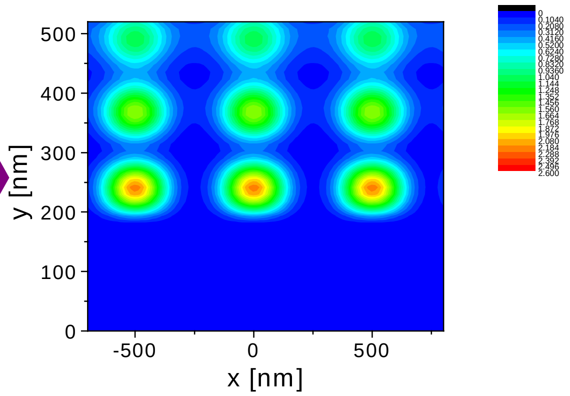
RENT



FET



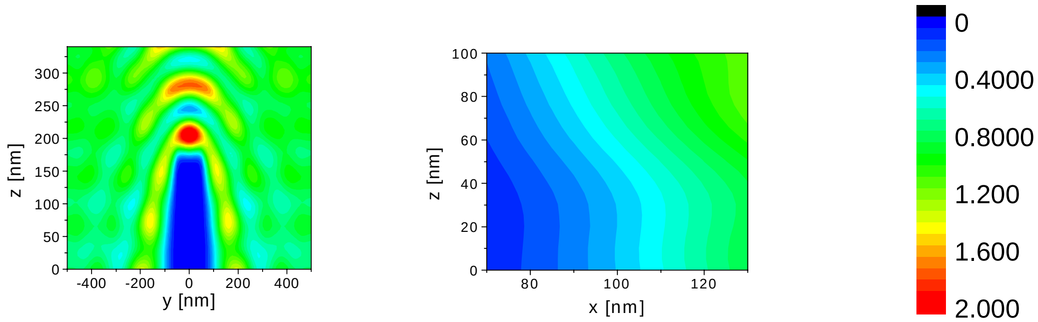
RENFT



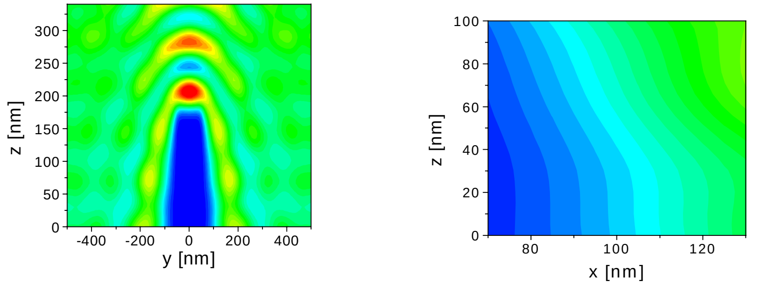
Lithographic Exposures over Nonplanar Wafers: RENFT

quantitative evaluation

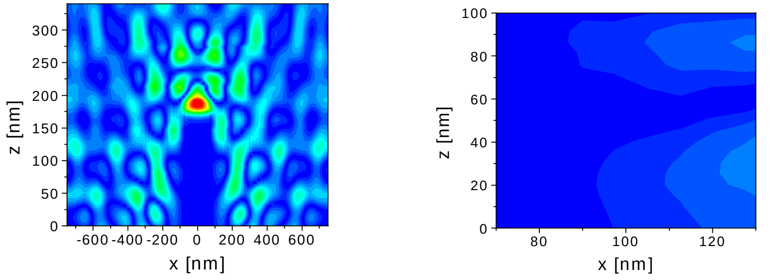
TASPAL
old
result



RENFT
result



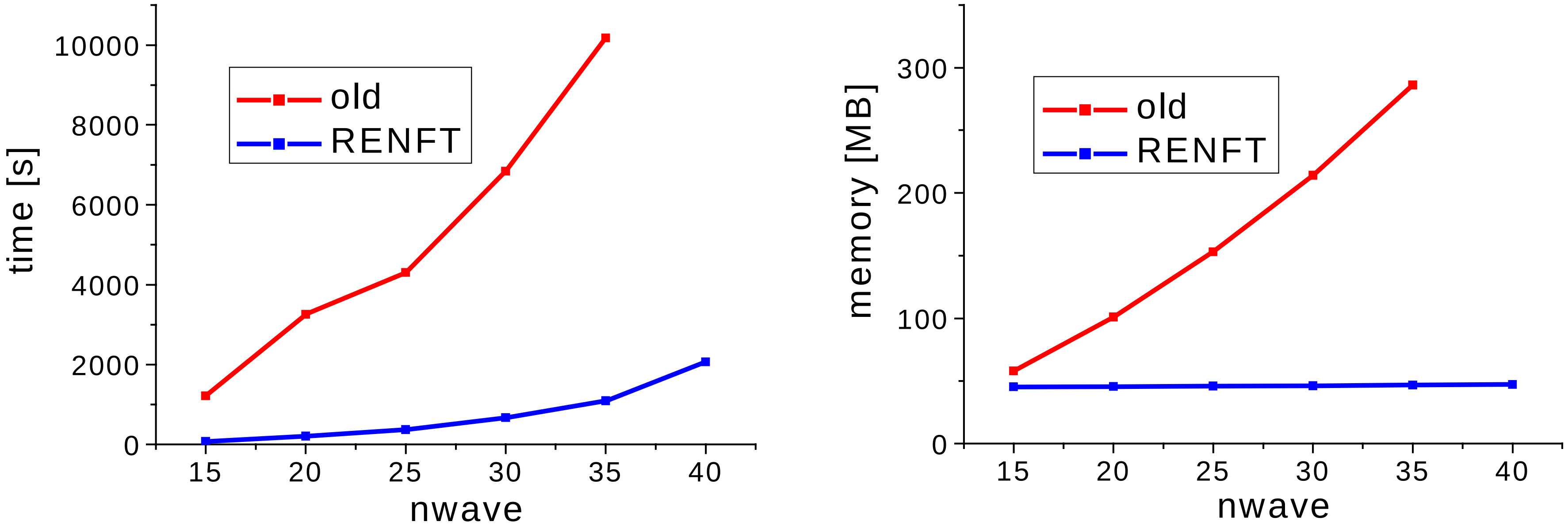
difference
×10



- RENFT predicts footing behavior (including σ-tendencies)
- further investigation are necessary to explore the limits of the RENFT approach

Lithographic Exposures over Nonplanar Wafers: RENFT

performance: timing/memory for σ=0.5



Selected Future Requirements: Aerial Image Formation

- effective and predictive modeling statistical effects: flare resulting from rough interfaces, depolarization effects, speckle phenomena

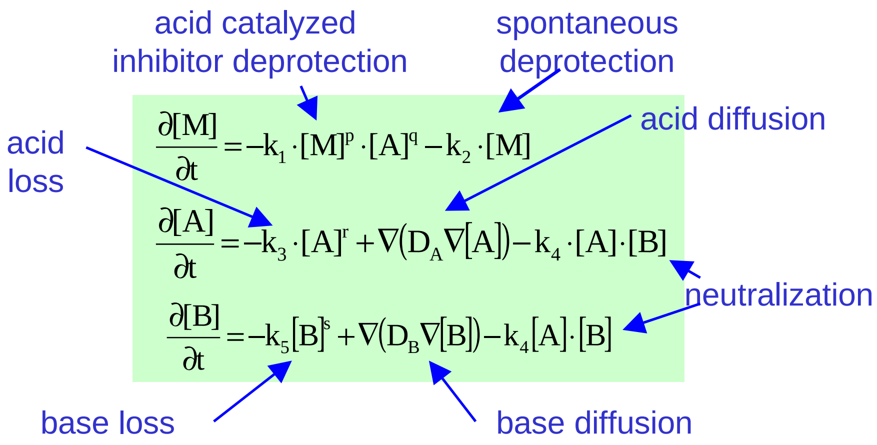
- faster and more efficient imaging algorithms for OPC and PSM

Selected Future Requirements: Mask and Wafer Topography

- comparison between alternative methods (FDTD, RCWA, waveguide method, wavelet based approaches), further benchmarking and experimental validation
- partial coherent exposures over nonplanar wafers: exploration of the limits of RENFT, alternative modeling approaches
- exploration of the limits of field decomposition, non-Manhatten-geometries, defects, larger areas

Selected Future Requirements: Resist Modeling

- efficient methods for solving 3D coupled diffusion/kinetic equations



acid catalyzed inhibitor deprotection

spontaneous deprotection

acid diffusion

acid loss

$$\frac{\partial[M]}{\partial t} = -k_1 \cdot [M]^p \cdot [A]^q - k_2 \cdot [M]$$

$$\frac{\partial[A]}{\partial t} = -k_3 \cdot [A]^r + \nabla\left(D_A \nabla[A]\right) - k_4 \cdot [A] \cdot [B]$$

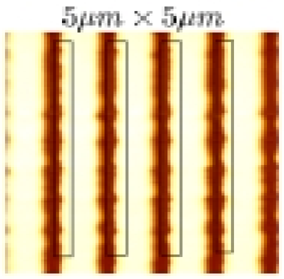
$$\frac{\partial[B]}{\partial t} = -k_5 [B]^s + \nabla\left(D_B \nabla[B]\right) - k_4 [A] \cdot [B]$$

neutralization

base loss

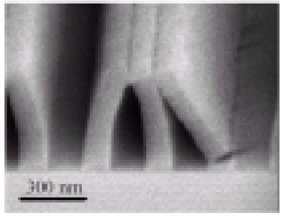
base diffusion

- finite molecular size effects: impact of resist material on line edge roughness



J. Shin et al.
(Univ. Wisconsin)

- mechanical resist properties: pattern collapse for large aspect ratios



H. Cao et al.
(Univ. Wisconsin)

Selected Future Requirements: General

- combination of simulation and experiment
- application of advanced data analysis and optimization tools to cope with the large amount of simulated and measured data
- improved software architecture: flexibility, combination with other tools ...
- application of simulation tools in education
- modeling of alternative micro- and nanopatterning techniques: direct laser- or e-beam write, proximity printing, nanoimprint, ...

Acknowledgements

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