Challenges and Simulation Solutions for Advanced Lithography for Nanometer Interconnect Patterning

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Lithography Simulation

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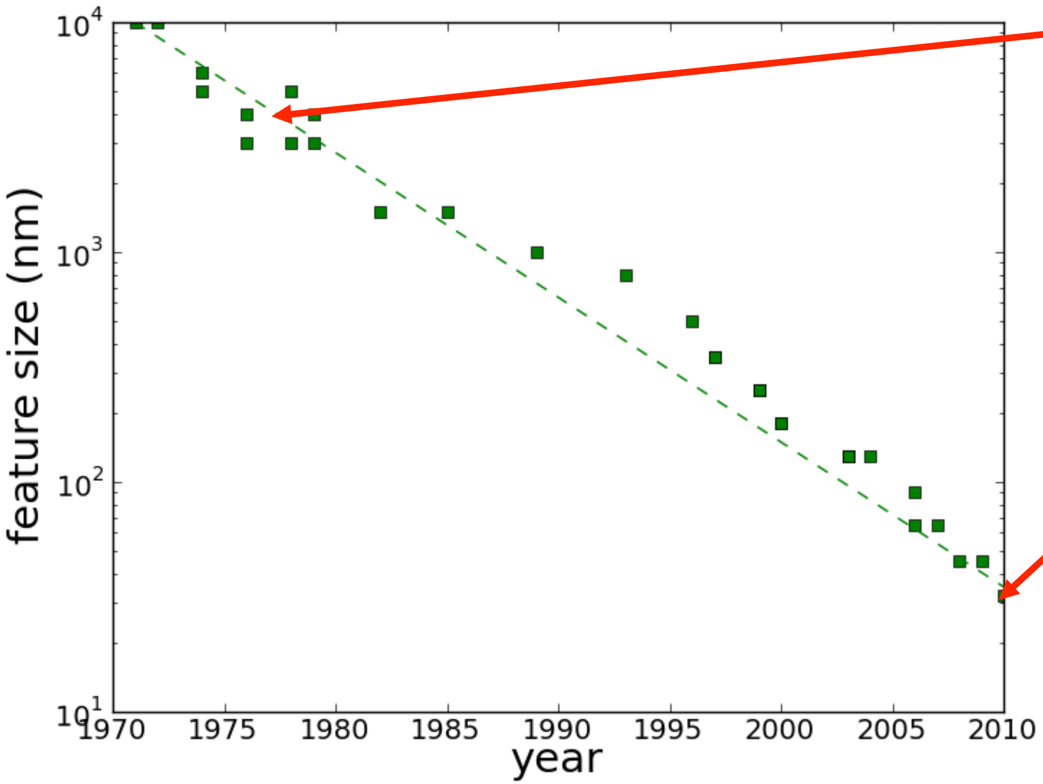
Outline

- Motivation
- Optical projection lithography
- Resolution enhancements, simulation consequences and solutions
    - Image simulation
    - Rigorous mask simulation
    - Optimization
    - Double patterning
- Resist simulation
- Conclusion

Motivation

Feature size compared to illumination wavelength λ



First optical projection stepper:
λ = 436 nm

Feature size ~ 2 μm

Feature size / λ ~ 4.6

Optical projection scanner:
λ = 193 nm

Feature size ~ 36 nm (resolution limit)

Feature size / λ ~ 0.2

EUV:
λ = 13.5 nm

Feature size e.g. 10 nm

Feature size / λ ~ 0.7

Continuously shrinking feature sizes require systems operating near the physical limits and highly accurate simulations covering all important effects

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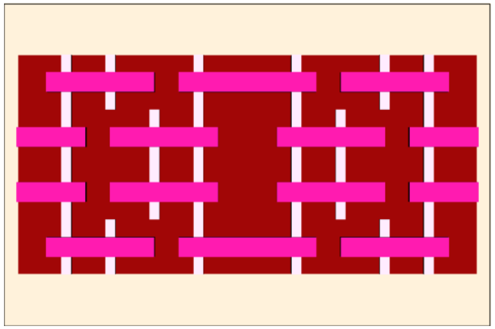
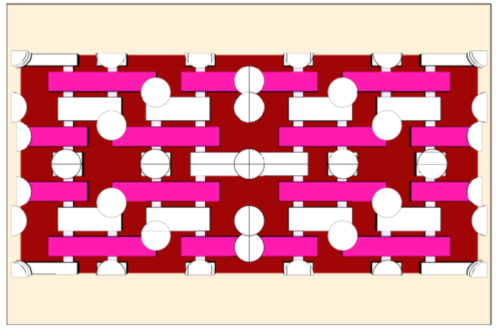
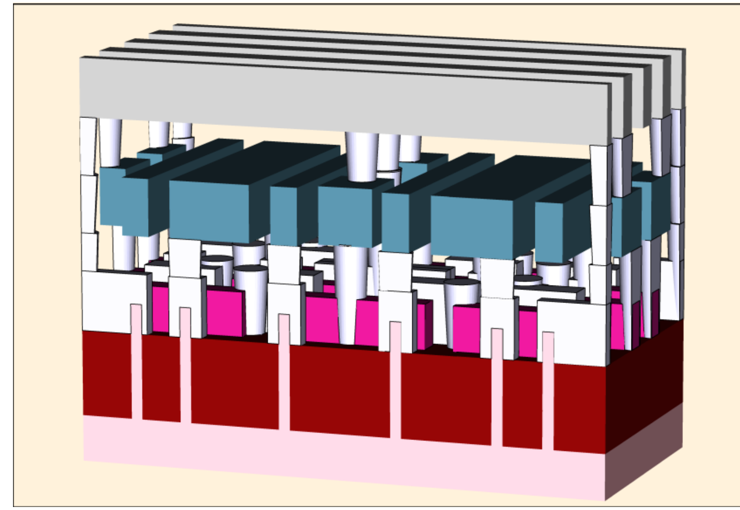
Motivation



6T SRAM cell (4 cells required for lithography simulations due to symmetry reasons)

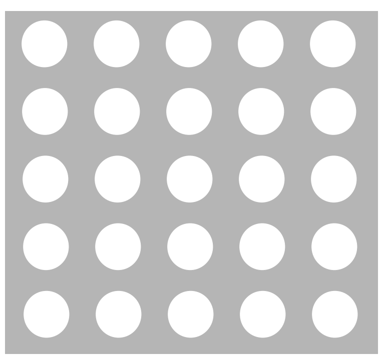


6T SRAM cell with corresponding interconnects



3D view of the SRAM cell

What does it mean for the lithography ? →



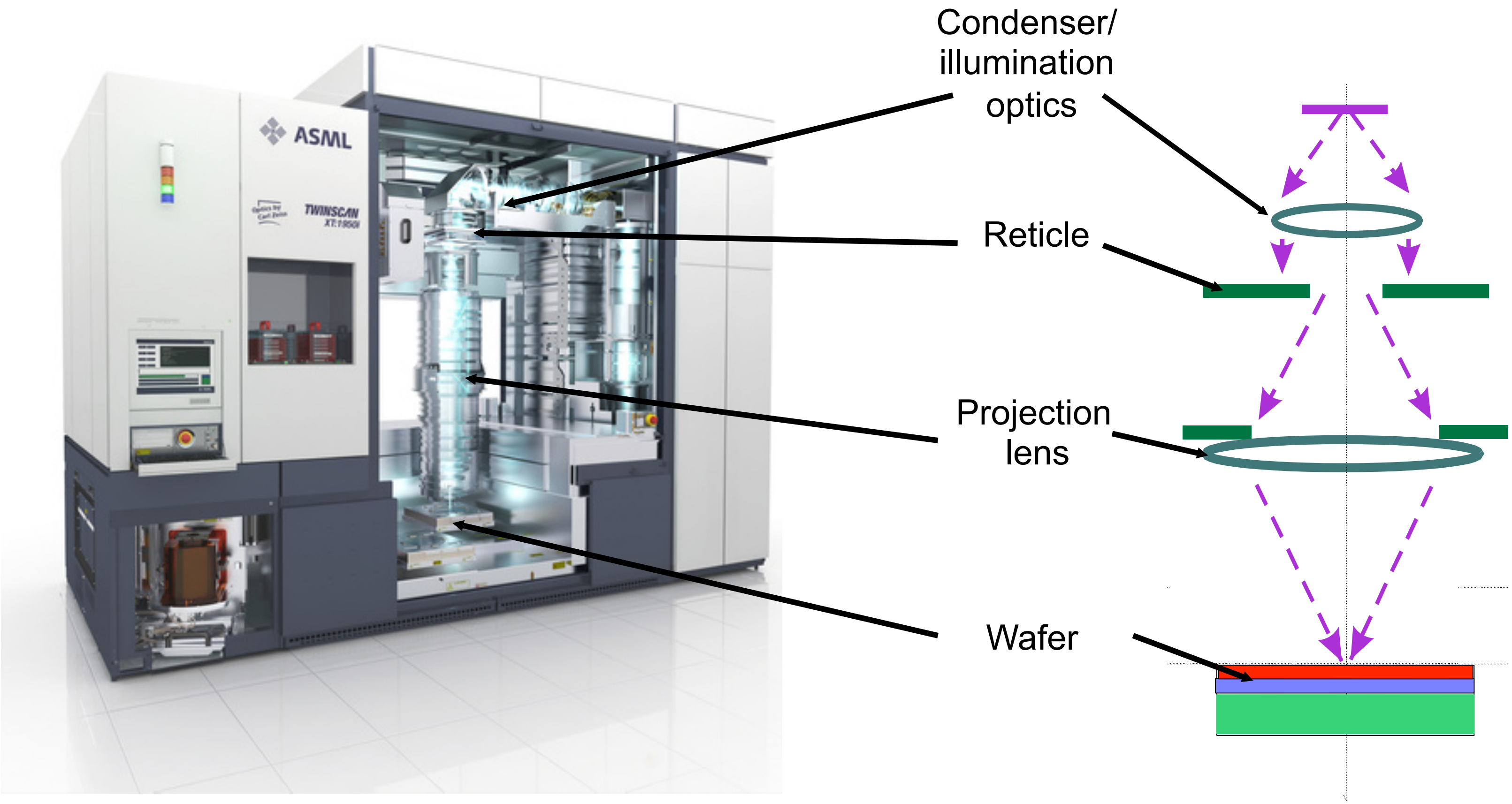
→

- The task for the lithography is (among many other steps) to generate contact holes with specific periods (e.g. in the shown example in the range of 50 nm)
- Very challenging technology operating near the resolution limit
- Very accurate and sufficiently fast simulations of the whole lithography process required

Optical projection lithography

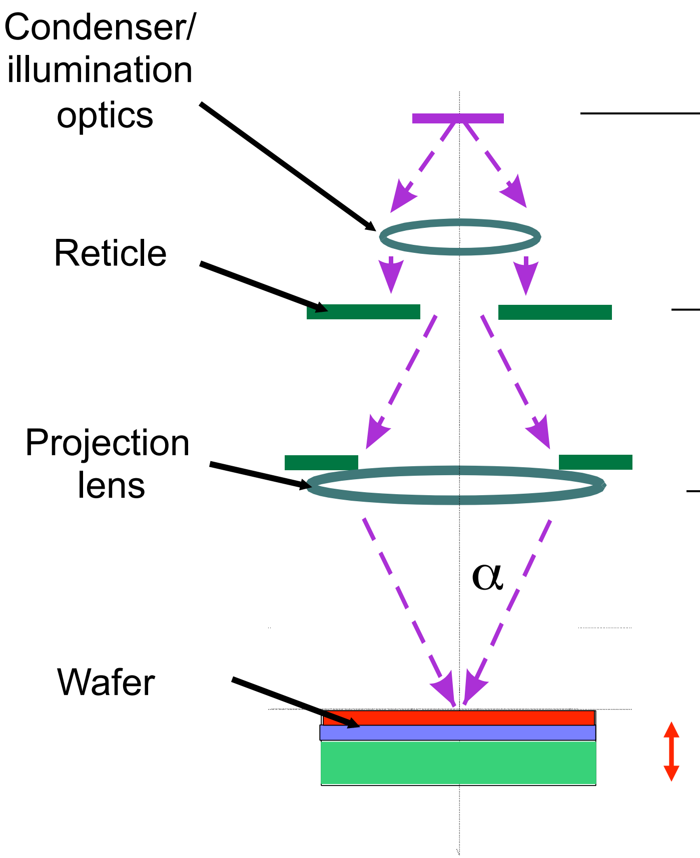
High NA projection scanner

Simulation scheme



Optical projection lithography

Important parameters



Wavelength, direction, coherence, and polarization of the light source

3D Layout of the mask including materials

- Demagnification (usually 4:1)
- Numerical aperture (NA)
- Pupil function

$$NA = n_{imm} \cdot \sin\alpha$$

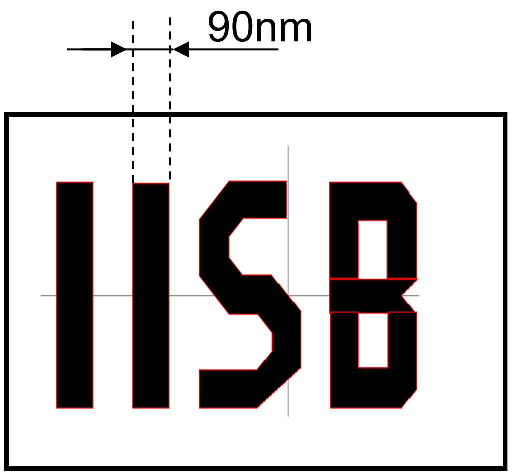
n_{imm} = material refractive index between lense and resist

Defocus

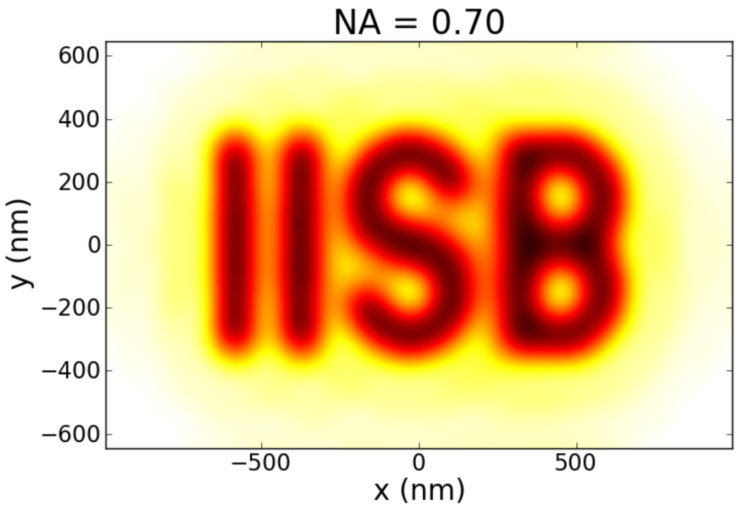
Source: Lecture A. Erdmann, Fraunhofer IISB

Optical projection lithography: Image formation

Mask layout



Aerial image



Imaging with a stepper/scanner

(λ=193nm)

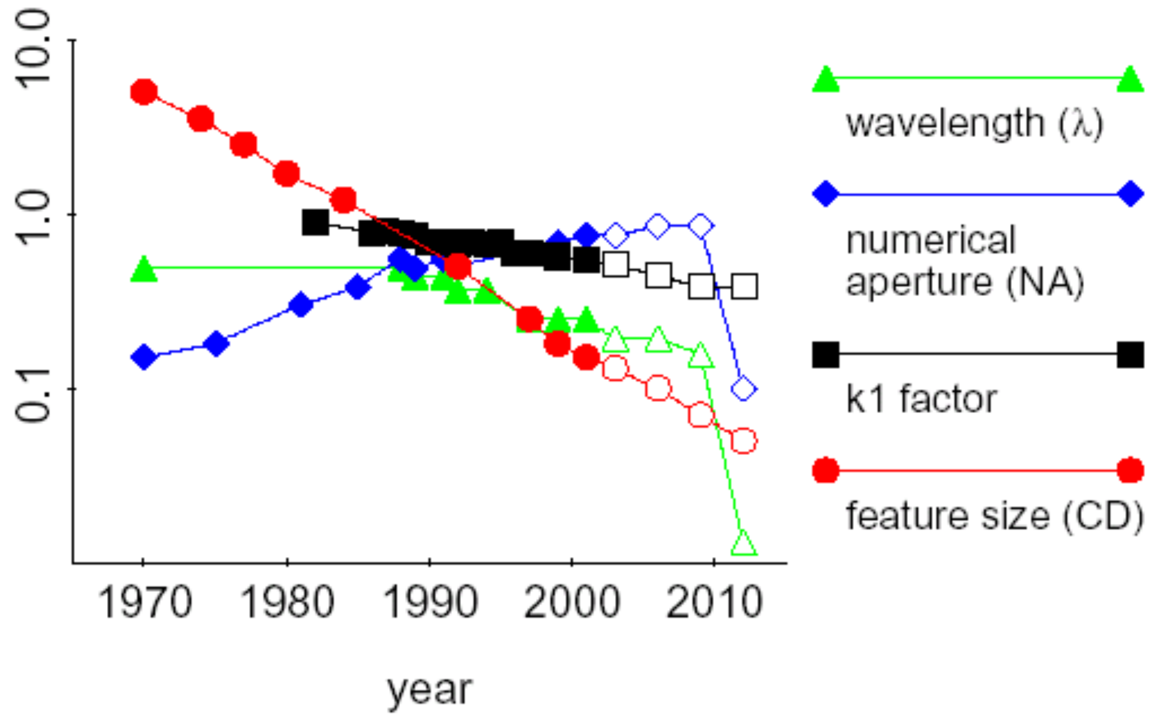
Lithography Simulation

Source: Lecture A. Erdmann, Fraunhofer IISB

Optical projection lithography: Resolution limit

Progress in lithography as predicted by the 1st Rayleigh criterion

$$CD = k_1 \cdot \frac{\lambda}{NA}$$



From: A. Wong: “Wave Optical Considerations in Photolithography”, SPIE Annual Meeting, San Diego, August 2003.

- Theoretical limit for dense features: $k_1 = 0.25$
- No theoretical limit for isolated features

Optical projection lithography: Resolution limit

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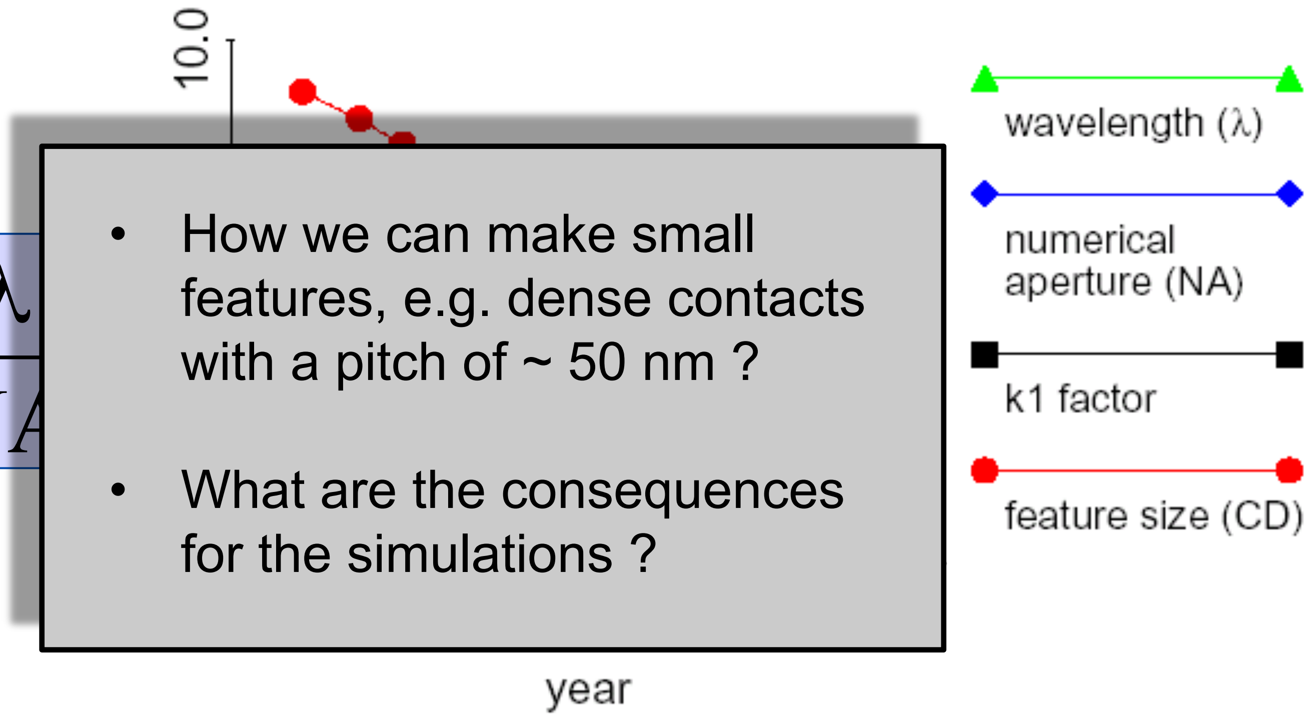
$$CD = k_1 \cdot \frac{\lambda}{NA}$$



- How we can make small features, e.g. dense contacts with a pitch of ~ 50 nm ?
- What are the consequences for the simulations ?

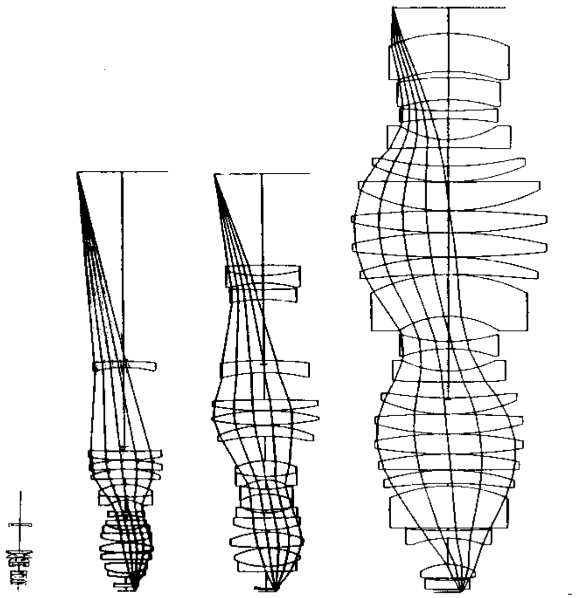
From: A. Wong: “Wave Optical Considerations in Photolithography”, SPIE Annual Meeting, San Diego, August 2003.

- Theoretical limit for dense features: $k_1 = 0.25$
- No theoretical limit for isolated features

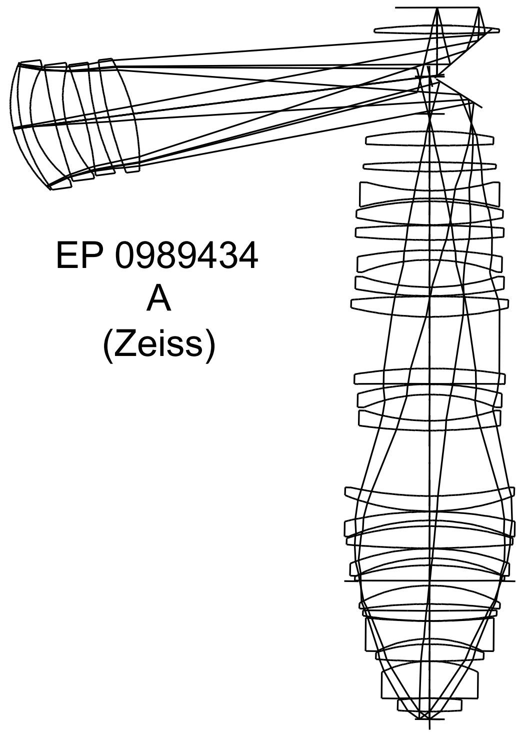
Optical projection lithography: Resolution enhancement

Increase numerical aperture + reduce wavelength
Lithography lenses 1965-2000

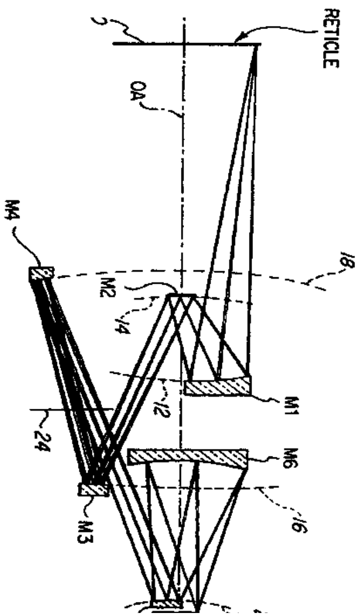
$$CD = k_1 \cdot \frac{\lambda}{NA}$$



EP 0989434
A
(Zeiss)



EP0779528
(SVGL)

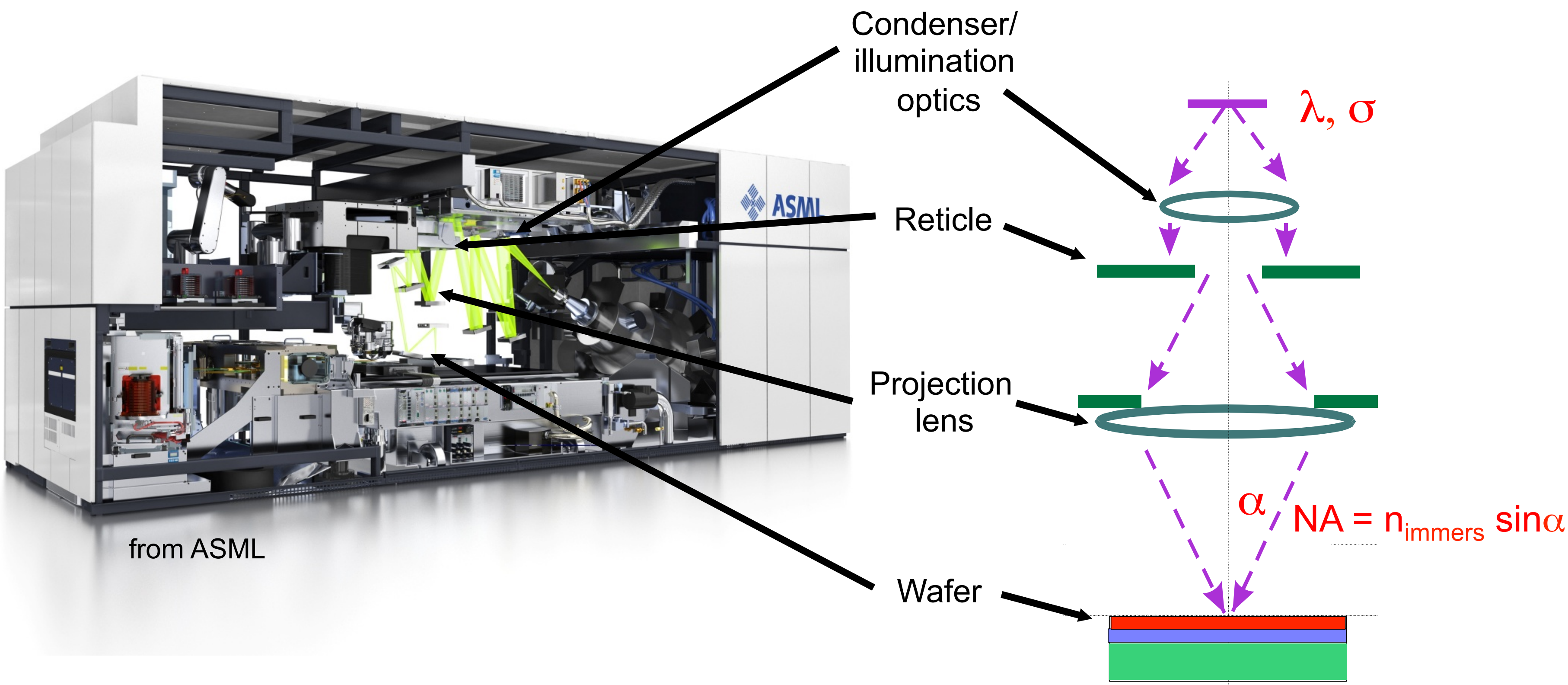


436 nm 1965 | 436 nm 1985 | 365 nm 1989 | 248 nm 1993 | 157 nm 1998 | 13 nm 1999

Source: W. Ullrich, Zeiss SMT AG

Short insight: EUV lithography

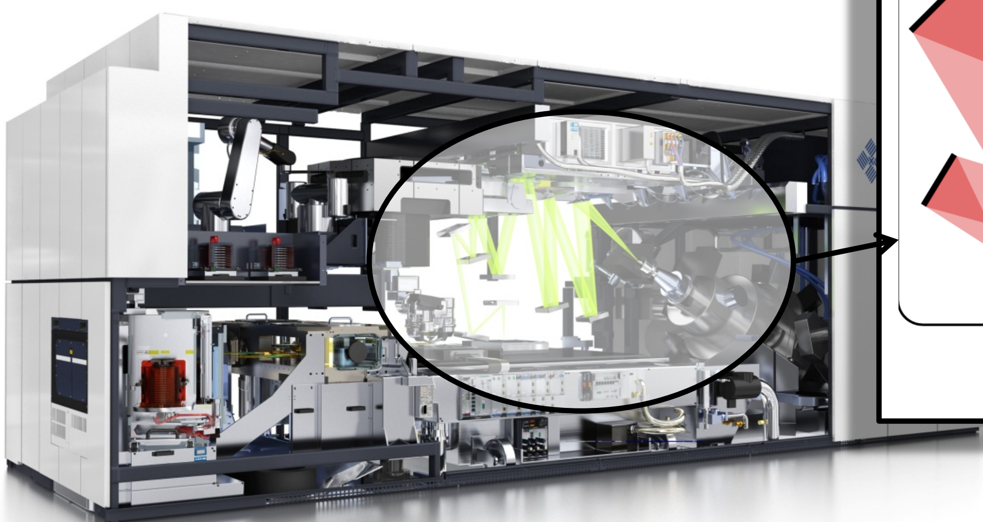
EUV projection system | Simulation scheme



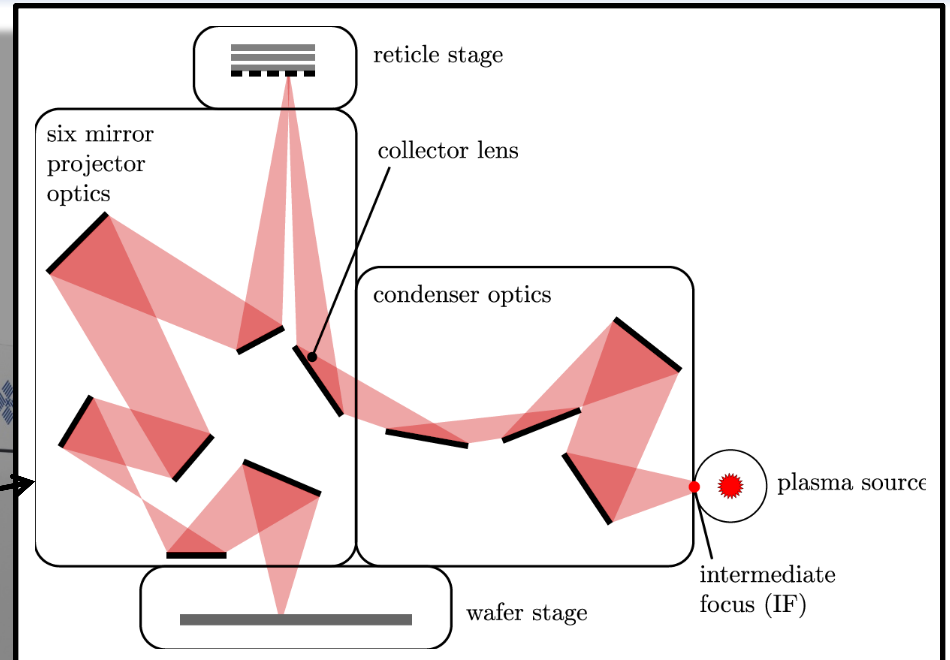
- EUV systems can be described with the same models used for optical systems
- EUV simulations very challenging due to EUV specific features

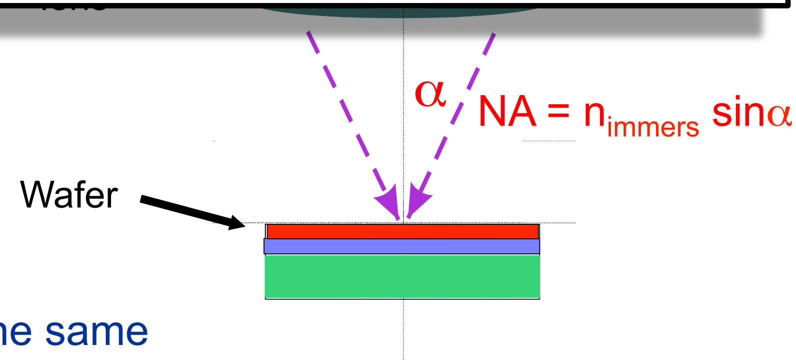
Short insight: EUV lithography

EUV projection system



from ASML





- EUV systems can be described with the same models used for optical systems
- EUV simulations very challenging due to EUV specific features

Lithography Simulation

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Optical projection lithography: Resolution enhancement

Increase numerical aperture by immersion

$$CD = k_1 \cdot \frac{\lambda}{NA}$$

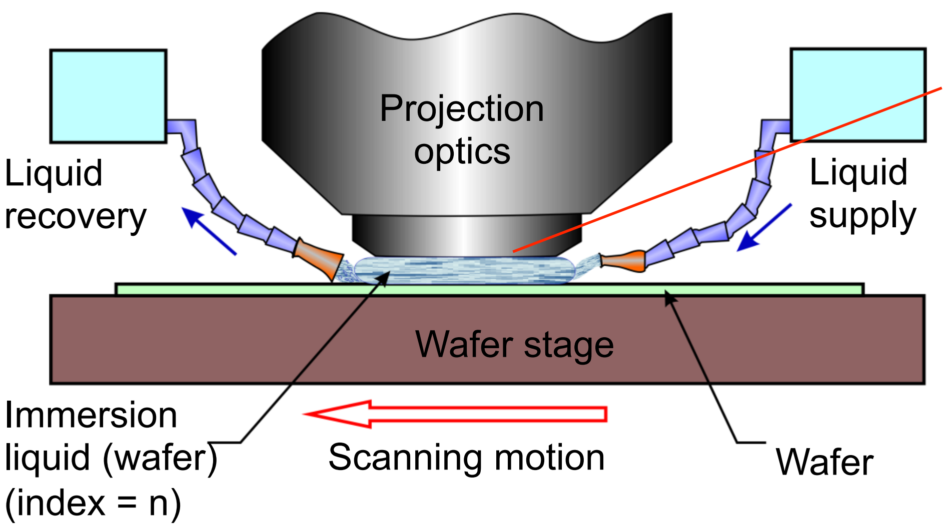
Basic Idea:

$$\Delta x = k_1 \cdot \frac{\lambda}{NA} = k_1 \cdot \frac{\lambda}{n \cdot \sin(\theta)}$$

n - image side refractive index

⇨ Use an immersion fluid (n > 1) instead of air/N_2

Practical realization:



Immersion fluid

- Low absorption
- Good match of refractive index with respect to optics and resist
- Chemically compatible with photoresist

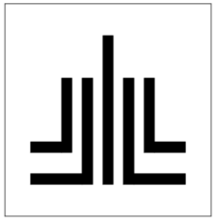
Source: Lecture A. Erdmann, Fraunhofer IISB

Optical projection lithography: Resolution enhancement

Reduce k_1 by off-axis illumination

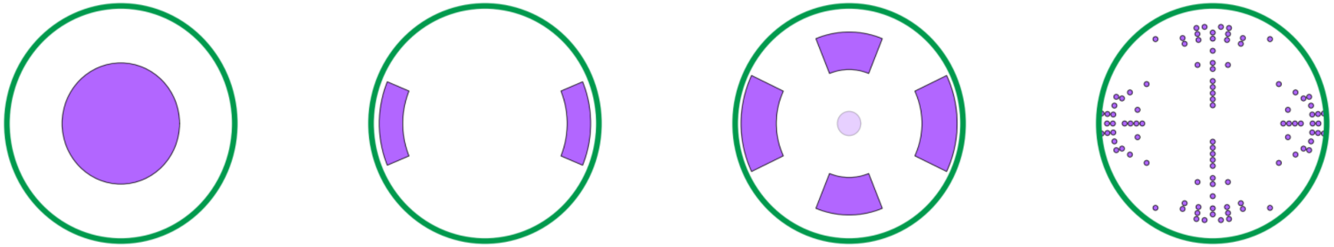
$$CD = k_1 \cdot \frac{\lambda}{NA}$$

Mask layout

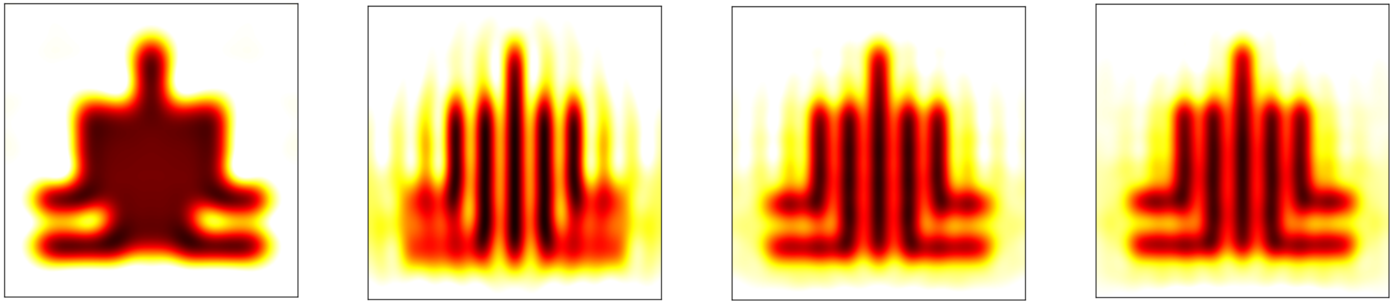


- Linewidth: 45nm, smallest pitch: 90nm
- NA = 1.35, λ=193nm

Illumination shape (direction)



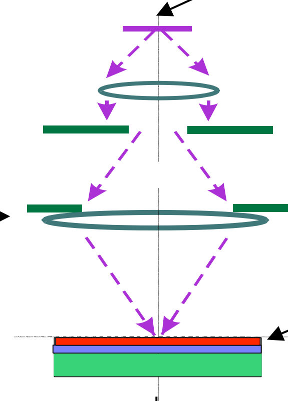
Image

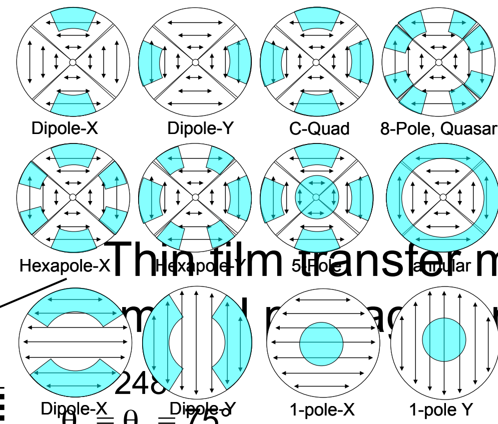


Consequences for lithography simulations

- Fully vectorial imaging model required to cover all relevant effects
- Optimized computation scheme required for short simulation times
- Our solution: Abbe based imaging model with extensions

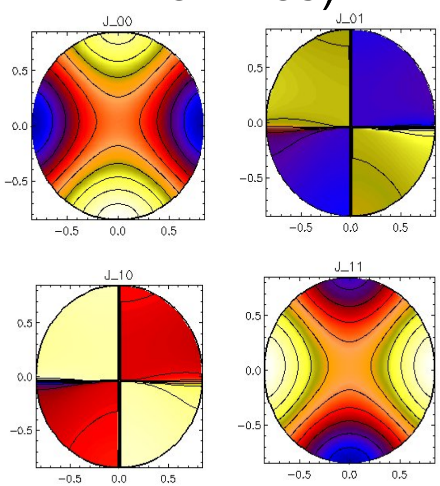
Advanced polarized illumination schemes





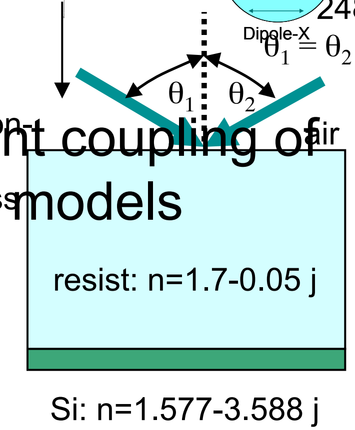
Polarized illumination schemes, from Jaspers et al. SPIE ML 2006

Jones pupil representation of the projection lens (including Zernikes)

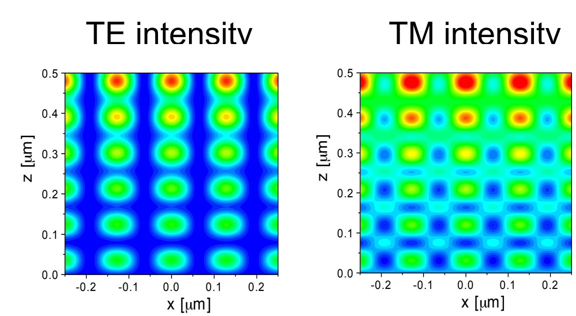


Jones pupil of a non-optimzed lens, pictures from Zeiss

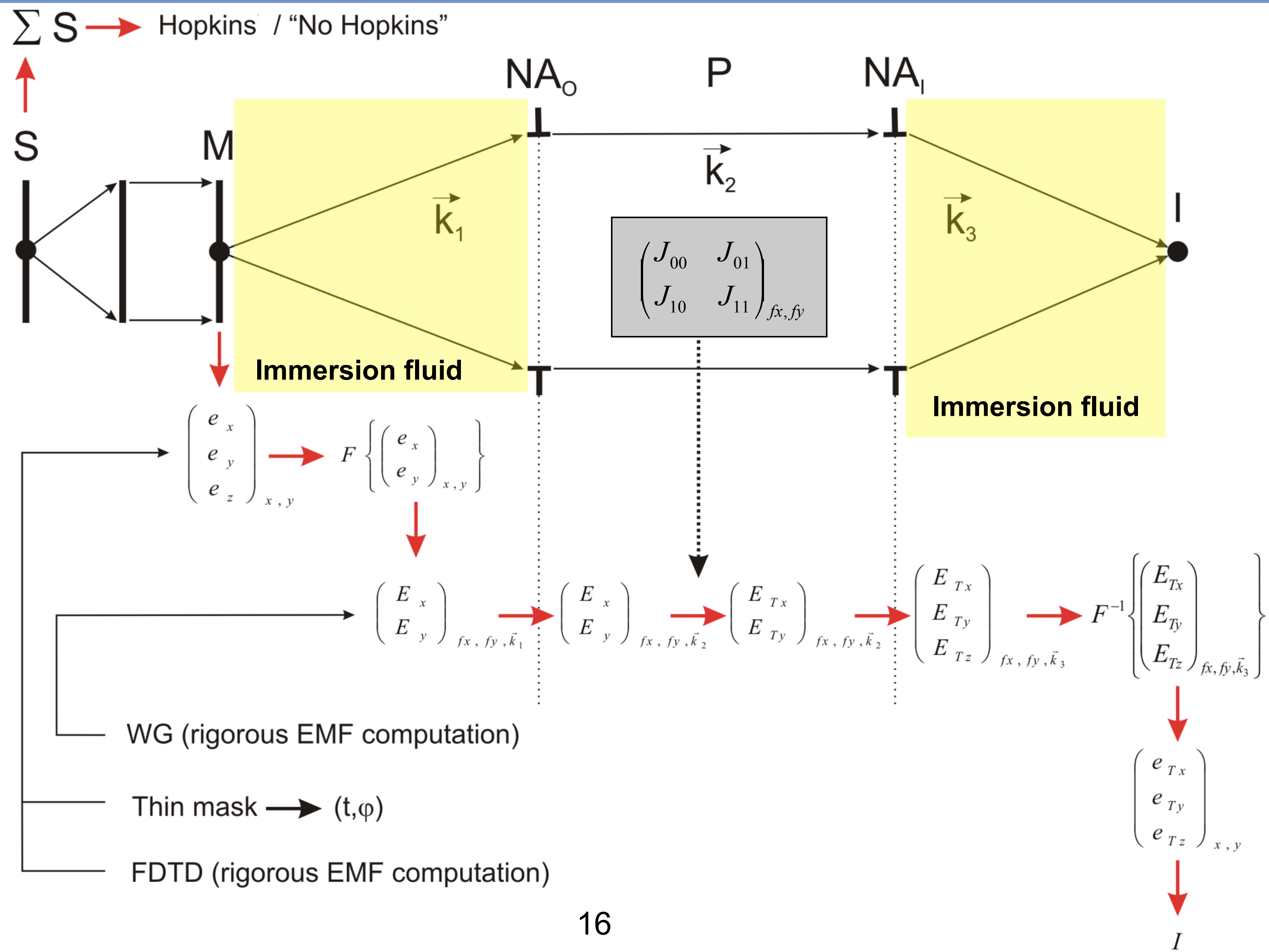
Thin film transfer matrices ... n in stack



Consistent coupling of all models

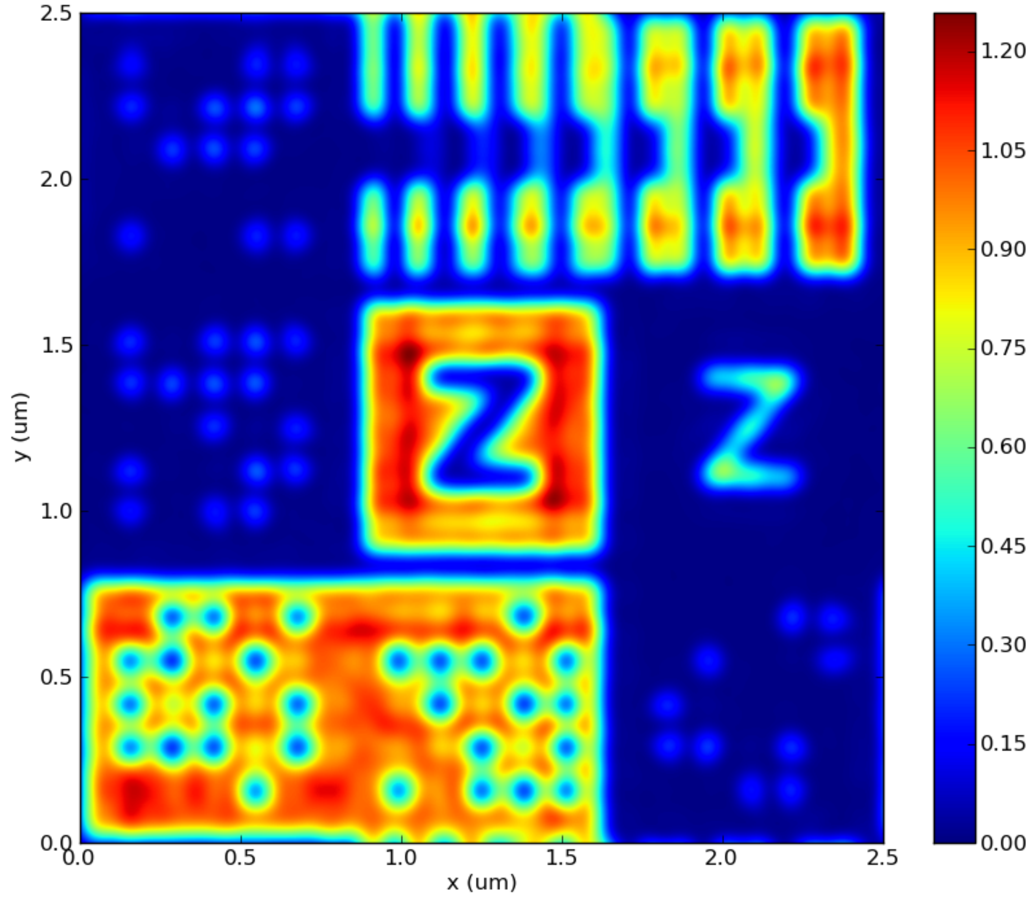


Short insight: Detailed image simulation scheme



Simulation example: Aerial image

Aerial image of a 10 µm x 10 µm mask area (mask scale) with different test structures



- 193 nm immersion system, NA 1.35, Cquad illumination, 4x reduction
- Image resolution 1 nm
- All „high accuracy“ imaging models described before are used
- **Simulation time 9 s on one 2.8 GHz CPU**

Lithography Simulation

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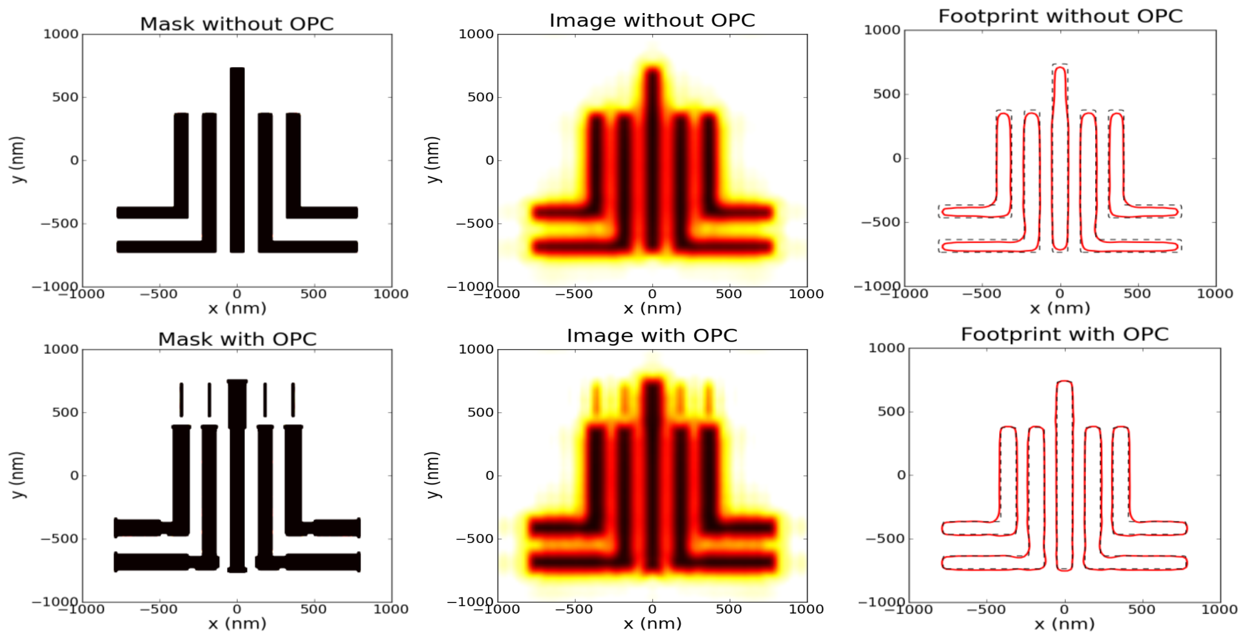
Optical projection lithography: Resolution enhancement

Reduce k_1 by optical proximity correction (OPC)

$$CD = k_1 \cdot \frac{\lambda}{NA}$$

Modify the design of the mask to make the resulting aerial image / resist profile more similar to the target

OPC

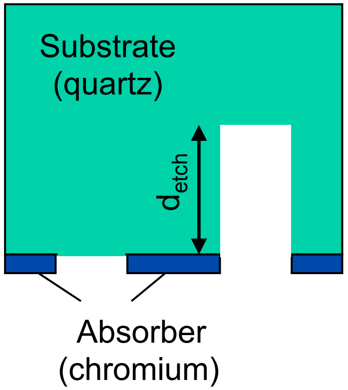


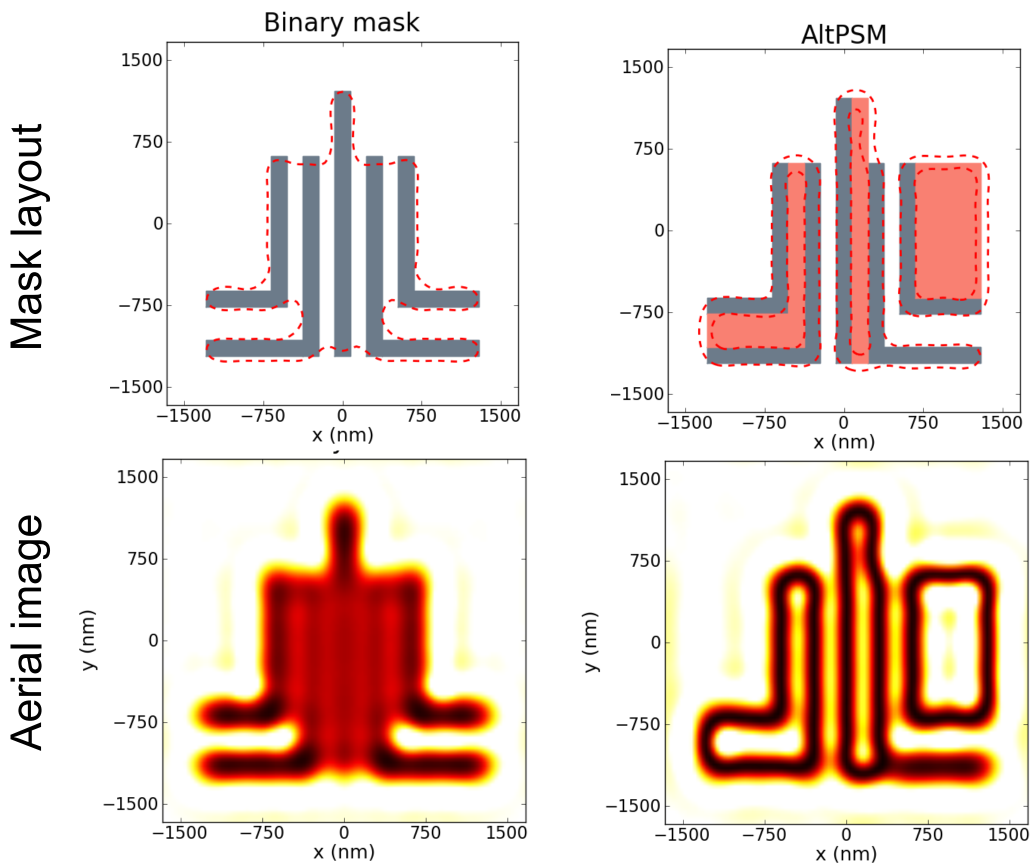
- Model based: Use a simplified simulation model (inverse problem)
- Rule based: Experience of photolithography experts

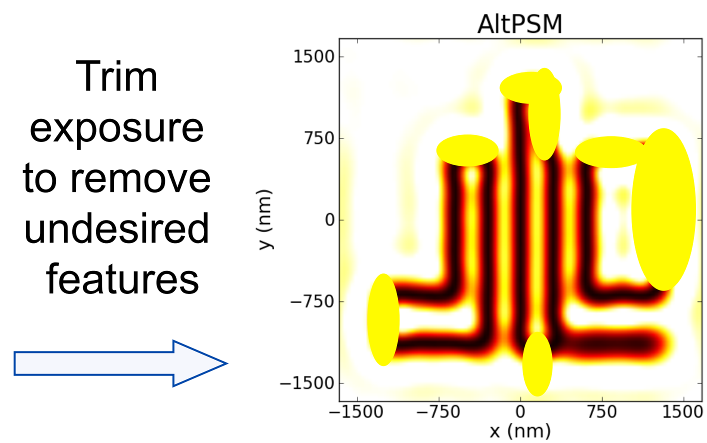
Optical projection lithography: Resolution enhancement

$$CD = k_1 \cdot \frac{\lambda}{NA}$$

Reduce k_1 by phase shift masks
Exemplarily alternating phase shift mask







Mask feature size: 150nm,
NA=0.5, λ=193nm, σ=0.3

Source: Lecture A. Erdmann, Fraunhofer IISB

Consequences for lithography simulations

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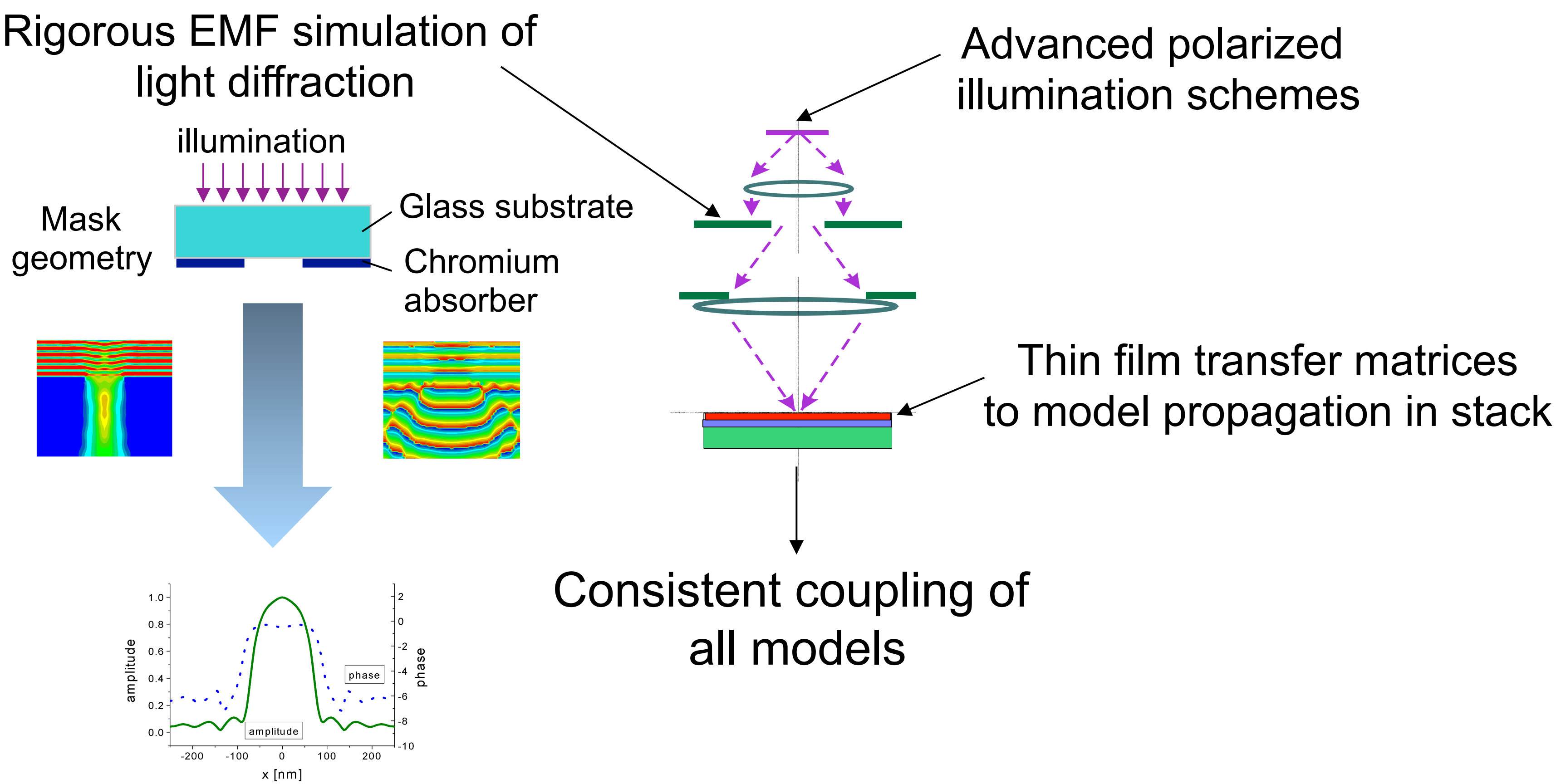
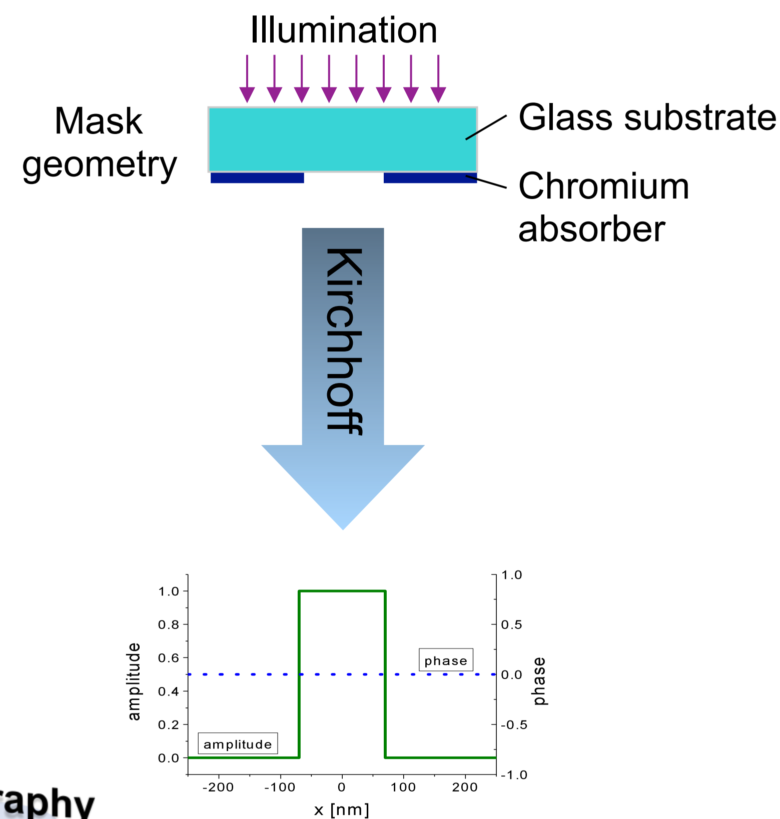
- Our solution: Abbe based imaging model with extensions

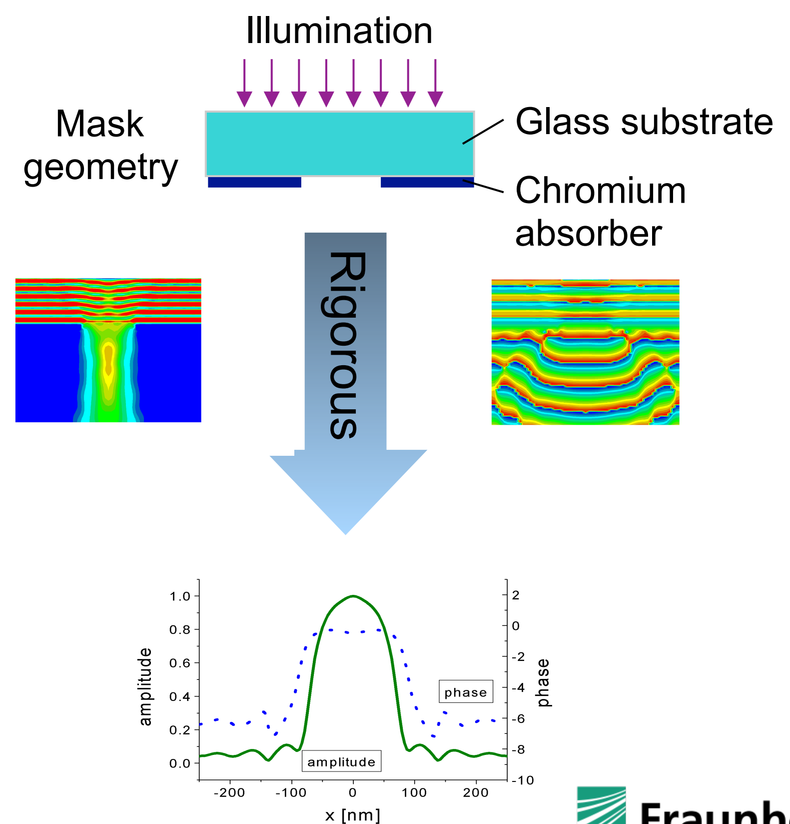


Rigorous mask simulation

- Small feature sizes
- Thick absorber structures
- Advanced material stacks and mask types
- Advanced illumination schemes

→ Rigorous electromagnetic field simulation of light diffraction required for accurate results
→ The Maxwell equations have to be solved (very challenging)
→ Our solution: Rigorous Coupled Wave Analysis (RCWA) and Finite Difference Time Domain (FDTD)





Lithography Simulation

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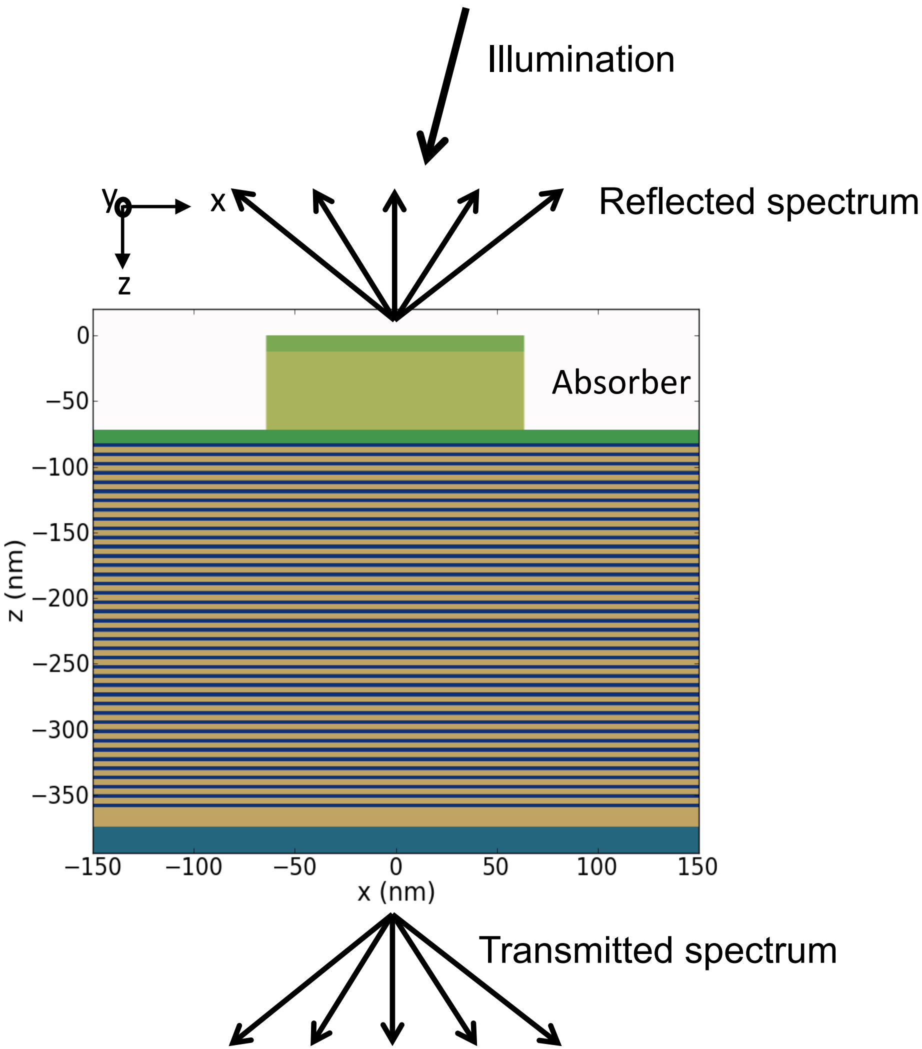
Rigorous mask simulation

Exemplarily: Mask diffraction simulation based on RCWA
→ Solving of the Maxwell equations in the frequency domain



1. Slicing of the mask
2. Description of the fields and of the material distributions with Fourier series
3. Computation of the electromagnetic spectrum inside each slice by defining and solving the eigenvalue problem resulting from the Maxwell equations
4. Coupling of the spectra of all slices according to the boundary conditions between the slices
5. Computation of the resulting reflected, transmitted and internal spectra

Computation time $T \sim n \times M^3$ (in general very critical)

n = number of inhomogeneous layers (typically ~1)

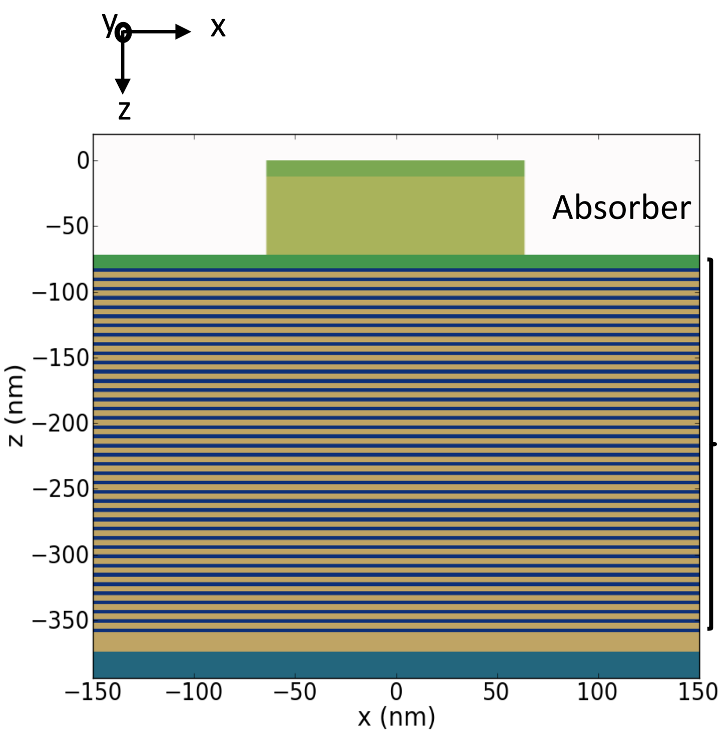
$M = (k*2*b_x/\lambda + 1) \times (k*2*b_y/\lambda + 1)$ for 3D

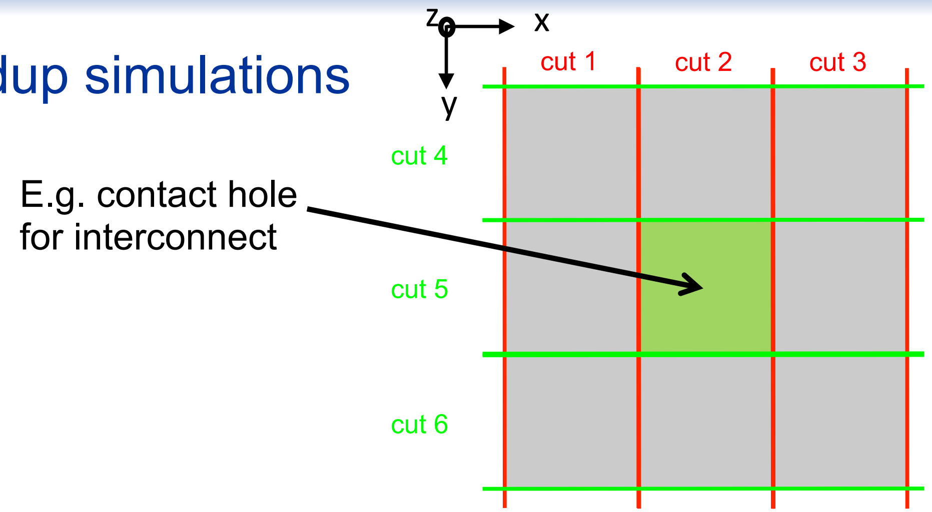
$b_{x/y}$ = mask size in x/y-direction

k ~ 0.5 for EUV, ~3 for 193 nm

Rigorous mask simulation

Decomposition technique to speedup simulations

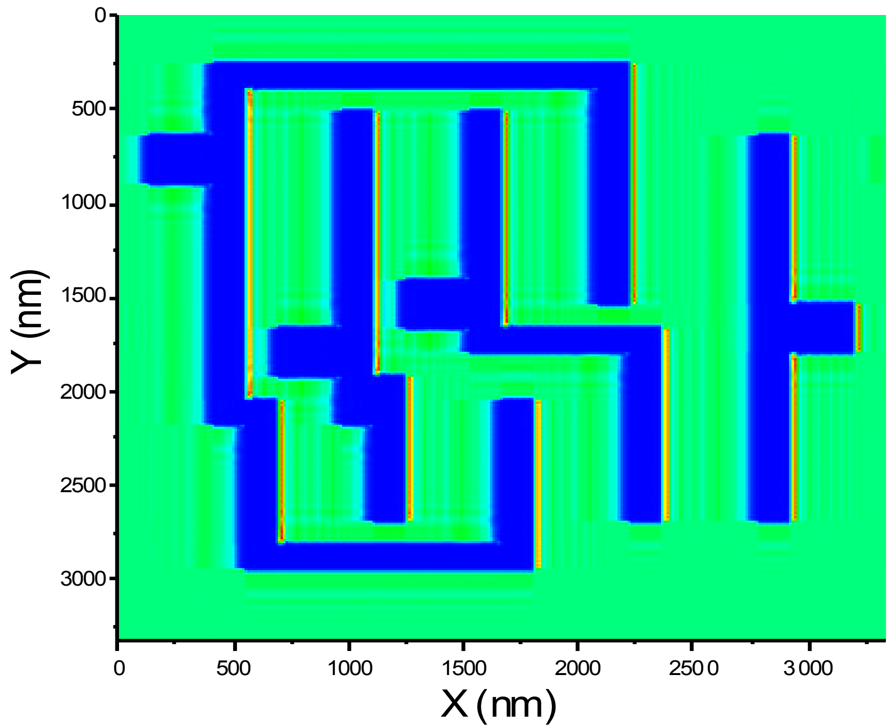




- Split-up of the mask in 2D cuts (here exemplarily cut 1 – cut 6)
- Independent rigorous 2D/1D computation of the cuts/cut overlap areas (parallelization possible)
- Composition of the individual cut/cut overlap area results (for RCWA in the frequency domain for better performance)
- Introduction of an error → in case of standard masks acceptable, to be tested case by case for advanced mask concepts

Simulation example: Rigorous mask simulation

Decomposition technique - Speedup



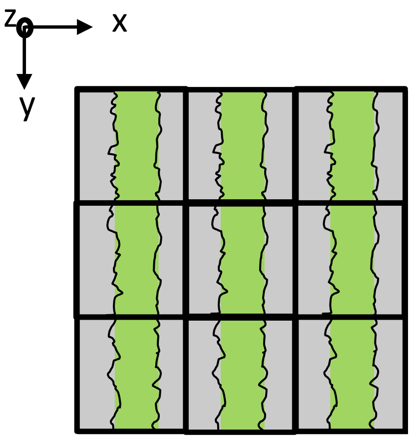
Near field intensity resulting from a rigorous EUV mask simulation
Mask size: 250λ×250λ×50λ

Simulation times

- Full 3D (no decomposition): 400 days (estimation)
- 3D with decomposition: 250 s
- 3D with parallelized decomposition: 10 s (27 CPU)

Rigorous mask simulation

Field stitching to speedup simulations



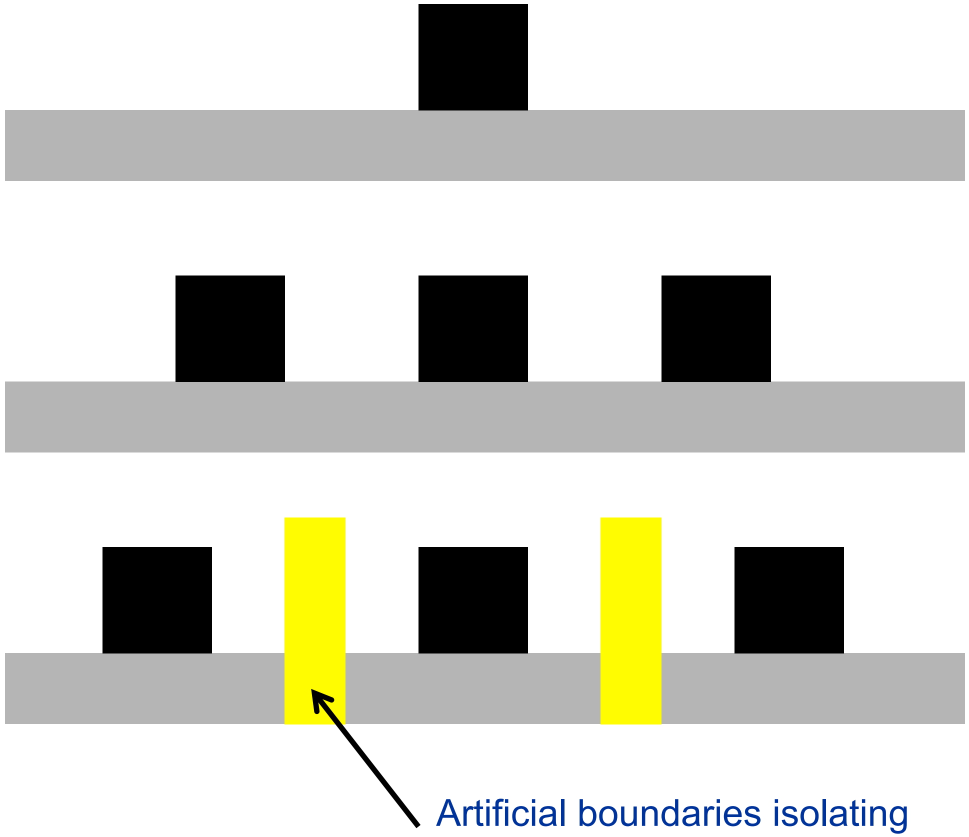
Dense lines/spaces with overlaid roughness → Larger simulation area required

Subdivision of the simulation area in subcells, here exemplarily 3 x 3 subcells

- Subdivision of the area to be simulated into subcells
- Independent 3D simulations of the subcells
- Composition of the subcells by stitching the fields in an appropriate manner
- Very efficient for RCWA based models: Significant speedup due to time scaling behavior, e.g. ~ 20 x faster for 3 x 3 subcells

Rigorous mask simulation

Isolated boundaries to speedup simulations



Isolated feature with large pitch → desired result, relatively slow (see formula for computation time T on slide 22)

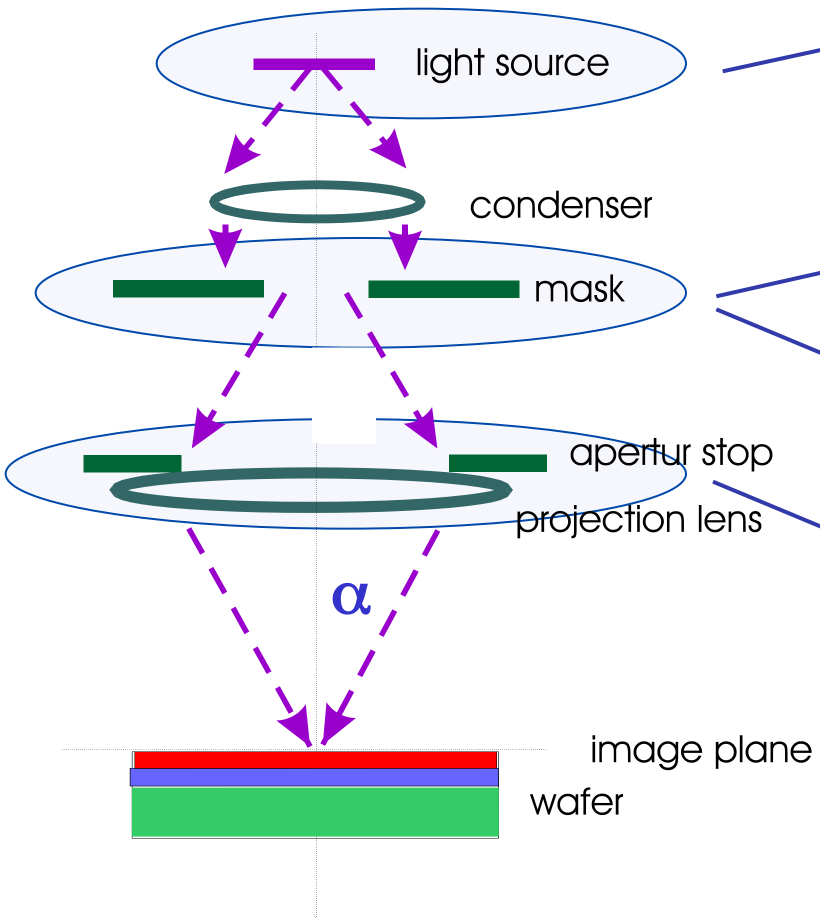
Dense features with small pitch → different result compared to isolated feature, fast

Dense feature with small pitch + additional boundaries → nearly same result compared to isolated feature, relatively fast

Artificial boundaries isolating neighboring cells → dense features behave like isolated features

Optical projection lithography: Resolution enhancement

Reduce k1 by source and mask optimization



OAI:
- Annular
- Multipoles
- Free form

OPC:
- Assists
- Seriefs
- Pixelated

PSM:
- Attenuated
- Alternating
- Chromless

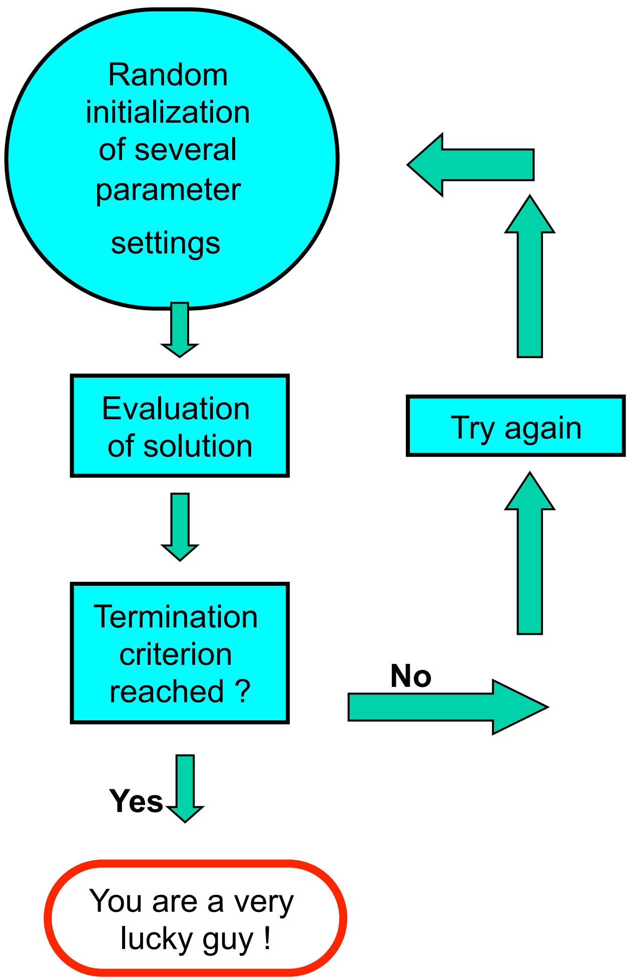
Pupil filter/manipulation etc. FlexWave (ASML) or TAO (Nikon)

Which source, mask (and pupil) provide the best performance ?

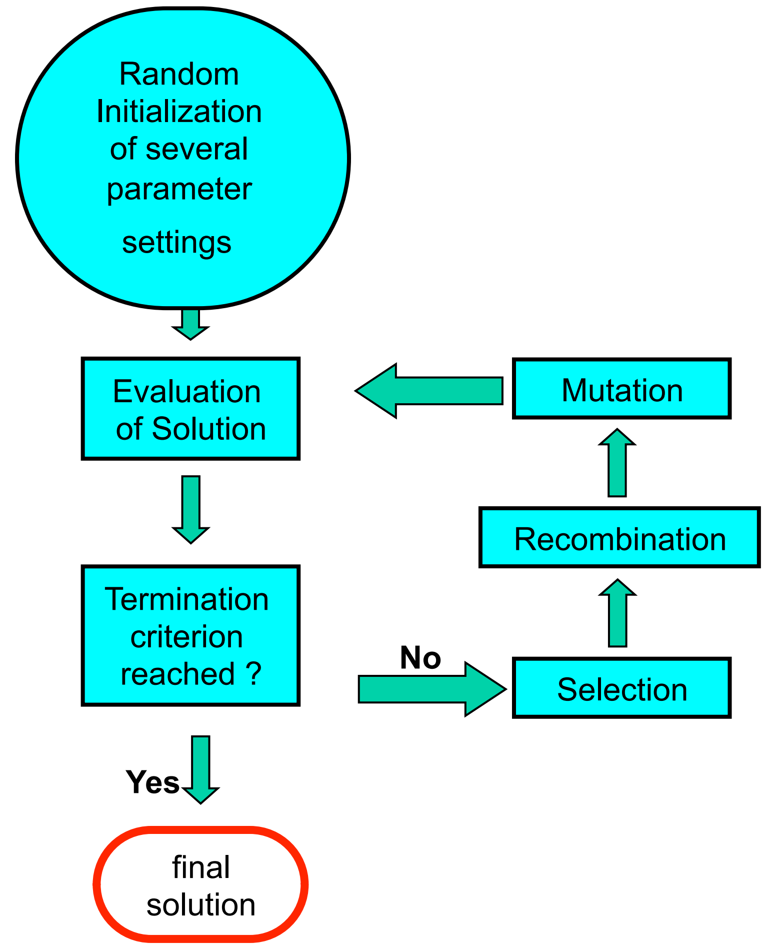
$$CD = k_1 \cdot \frac{\lambda}{NA}$$

Source and mask optimization

Random Walk



Genetic Algorithm



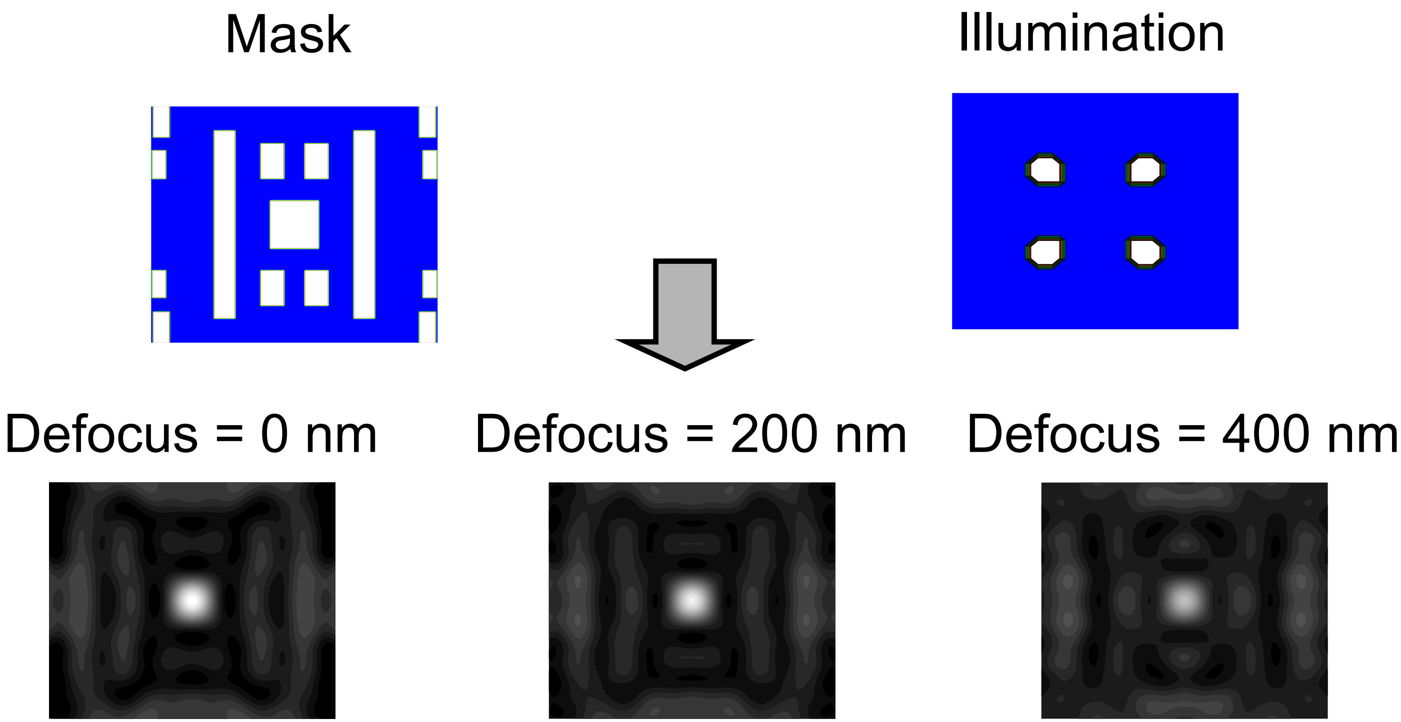
Source: Lecture A. Erdmann, Fraunhofer IISB

Our solution is the combination of a genetic optimization algorithm with the very accurate and fast image and mask simulation shown before

Simulation example: Source and mask optimization

Example: Mask and Source Optimization using a genetic algorithm: How to create a 140 nm × 170 nm contact hole with a large depth of focus ?

Mask: High transmission attenuated PSM; Optics: λ = 193n m, NA = 0.7, multipole illumination



Typically thousands of individual simulations required during an optimization
→ Parallelization required for acceptable simulation times

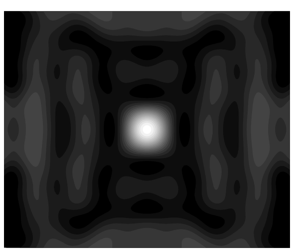
Simulation example: Source and mask optimization

Example: Mask and Source Optimization using a genetic algorithm: How to create a 140 nm × 170 nm contact hole with a large depth of focus ?

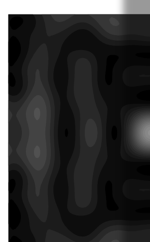
Mask: High transmission attenuated PSM; C
illumination

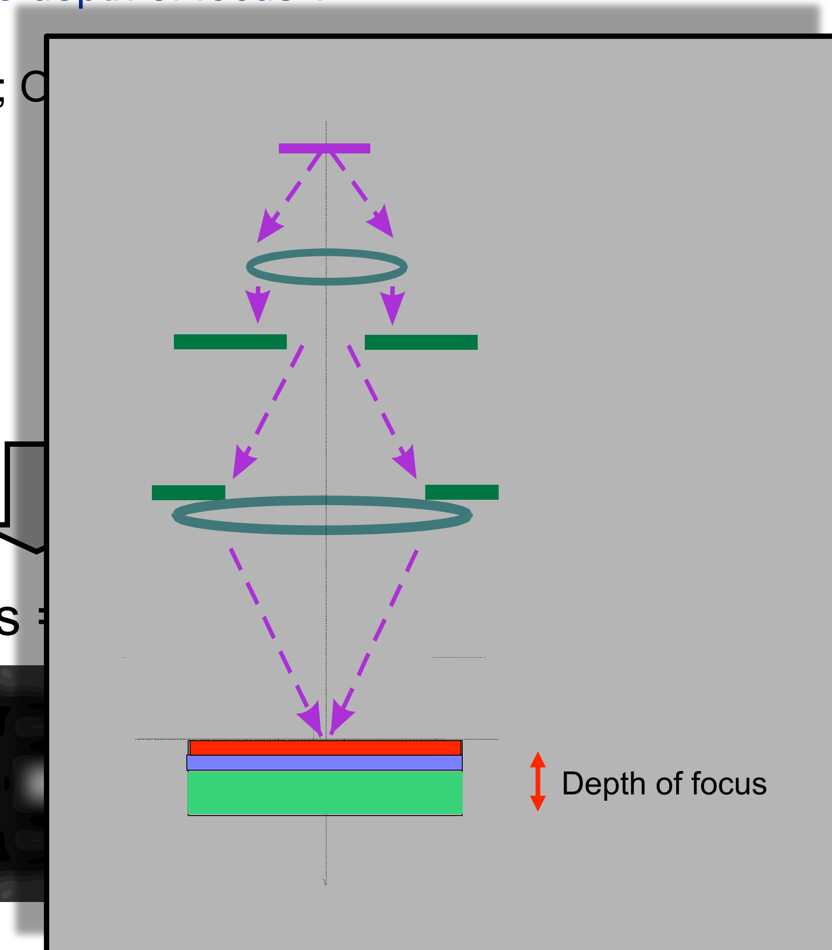
Mask

Defocus = 0 nm



Defocus =





Typically thousands of individual simulations required during an optimization
→ Parallelization required for acceptable simulation times

Beyond the resolution limit

$$CD = k_1 \cdot \frac{\lambda}{NA}$$

Theoretical limit for dense features:

$k_1 = 0.25$

Example from the beginning:

- 25 nm contact (50 nm period)
- λ = 193 nm
- NA = 1.35

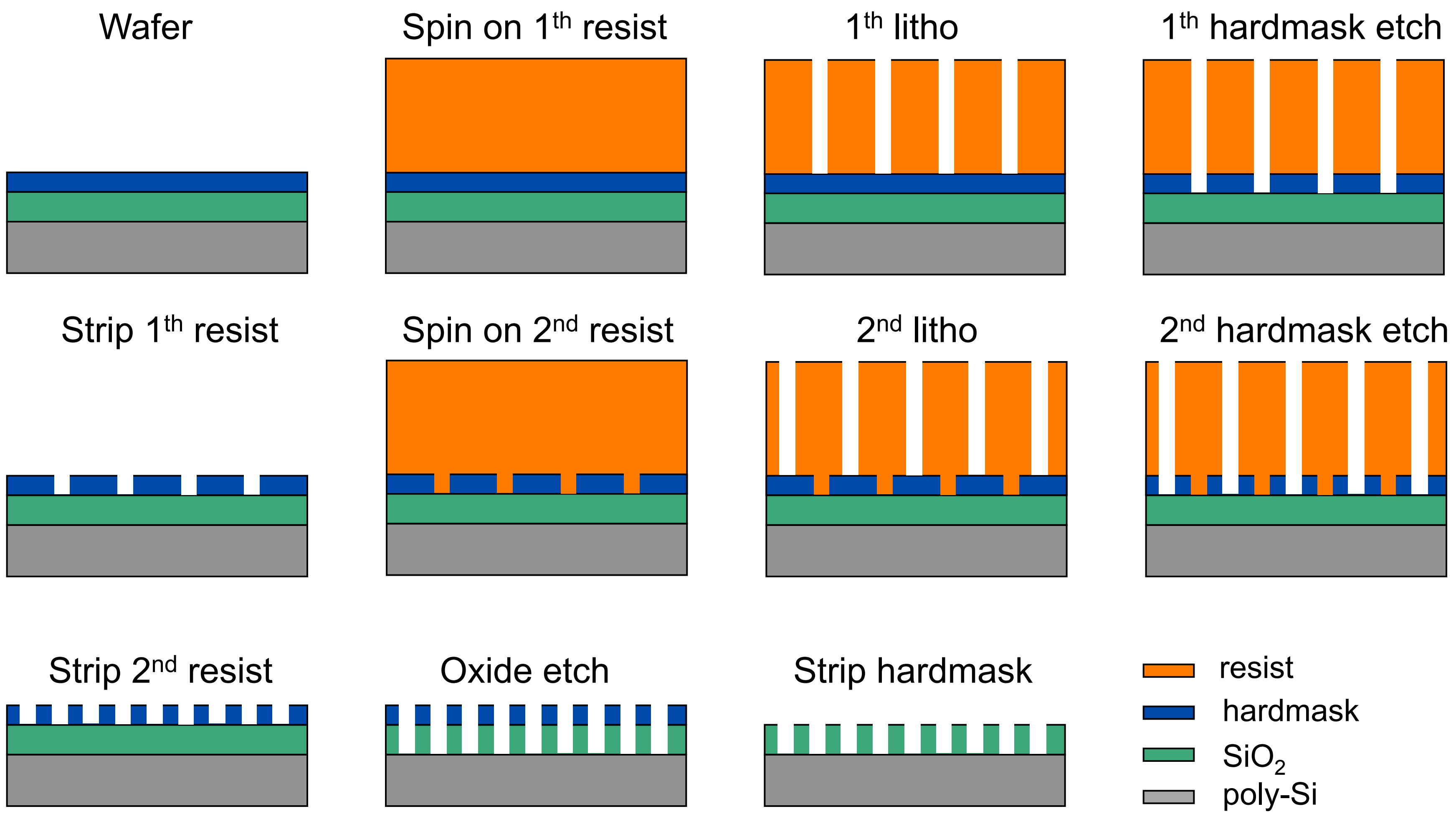
→ $k_1 \sim 0.175$

→ Double exposure / double patterning required

→ Period doubling → $k_1 \sim 0.35$

Double patterning

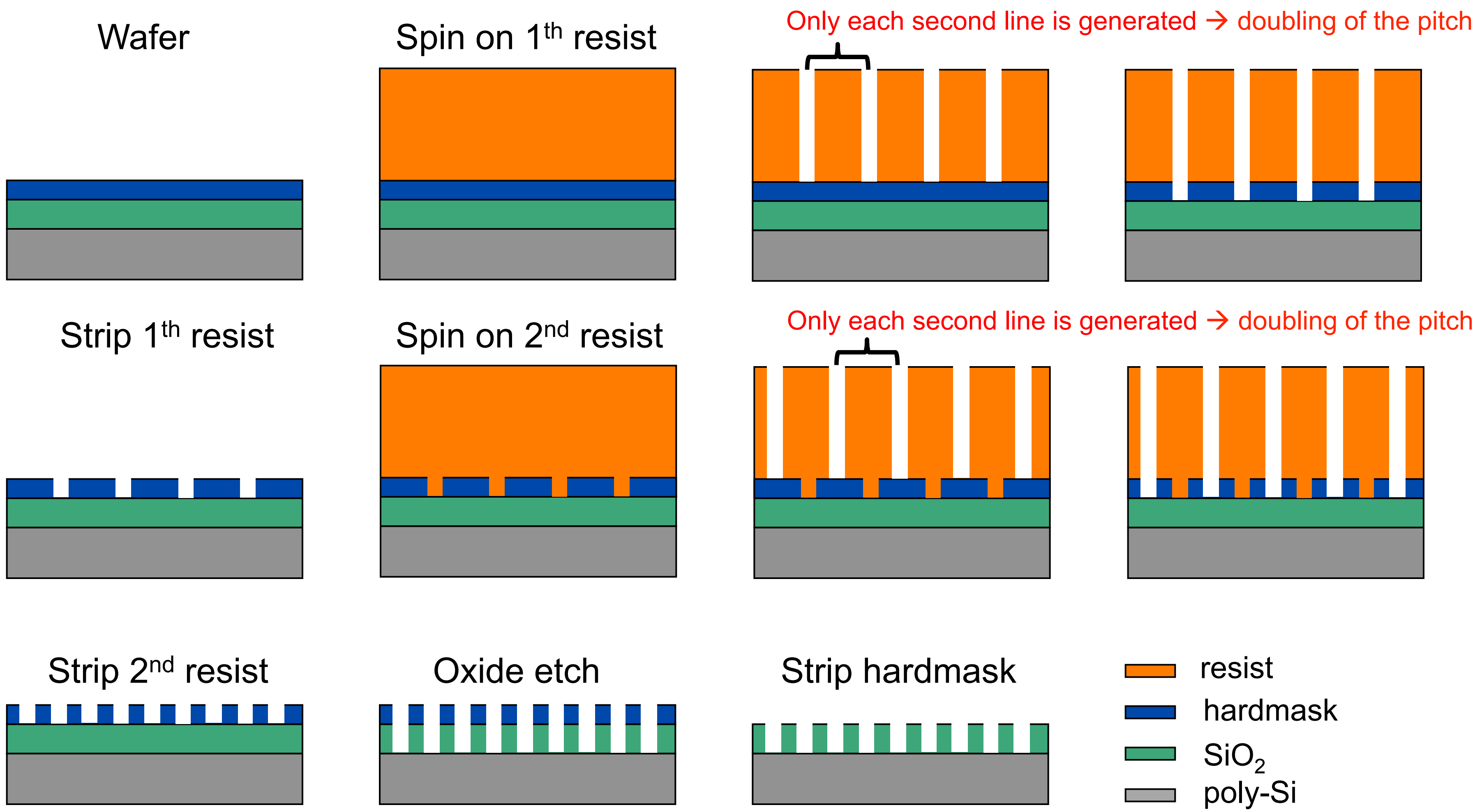
Exemplarily: Double patterning Litho-Etch-Litho-Etch (LELE)



Source: Lecture A. Erdmann, Fraunhofer IISB

Double patterning

Exemplarily: Double patterning Litho-Etch-Litho-Etch (LELE)

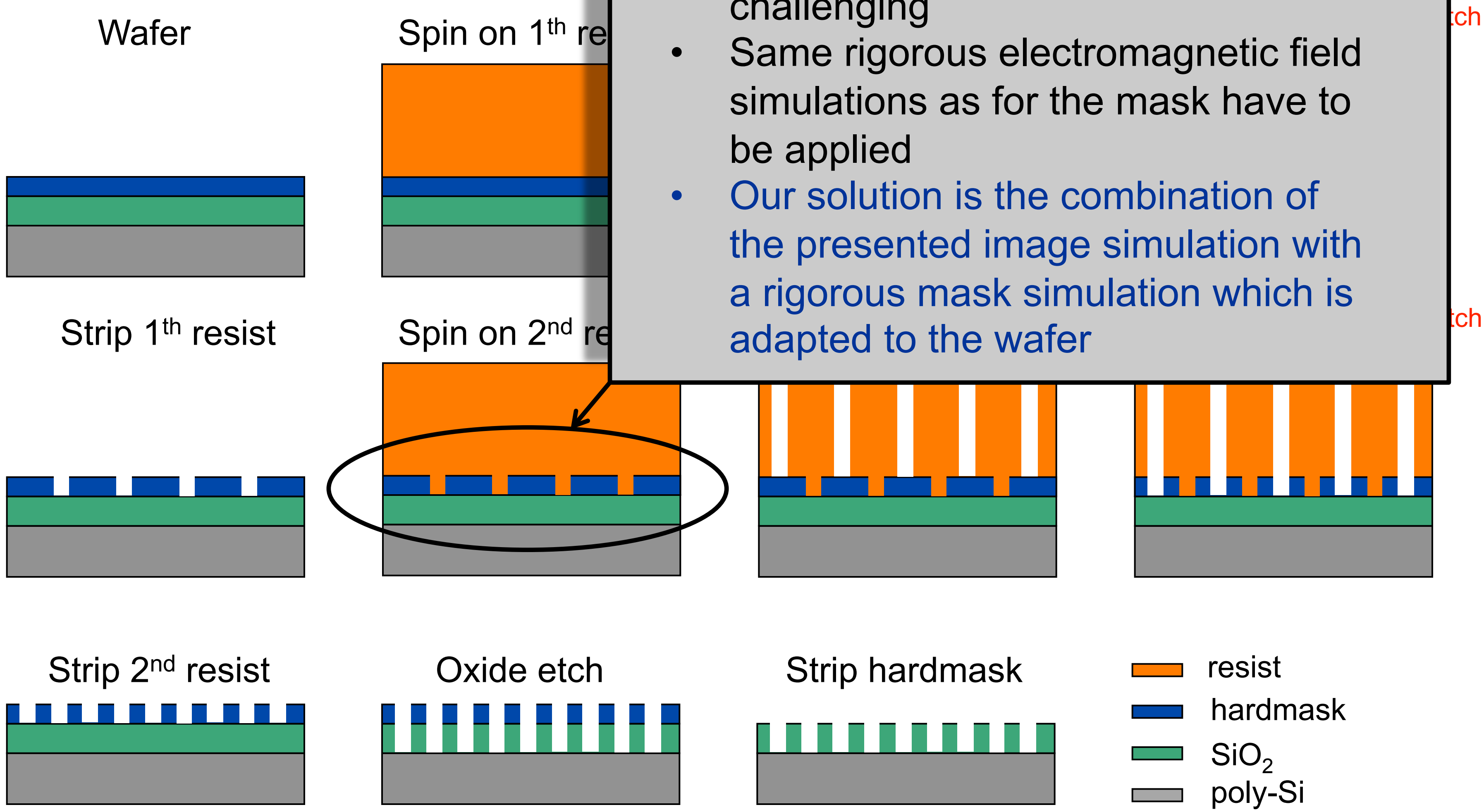


Source: Lecture A. Erdmann, Fraunhofer IISB

Double patterning

Exemplarily: Double patterning

- Structures inside the resist impact the lithography step
- Simulation of light propagation in a resist with structures is very challenging
- Same rigorous electromagnetic field simulations as for the mask have to be applied
- Our solution is the combination of the presented image simulation with a rigorous mask simulation which is adapted to the wafer



Source: Lecture A. Erdmann, Fraunhofer IISB

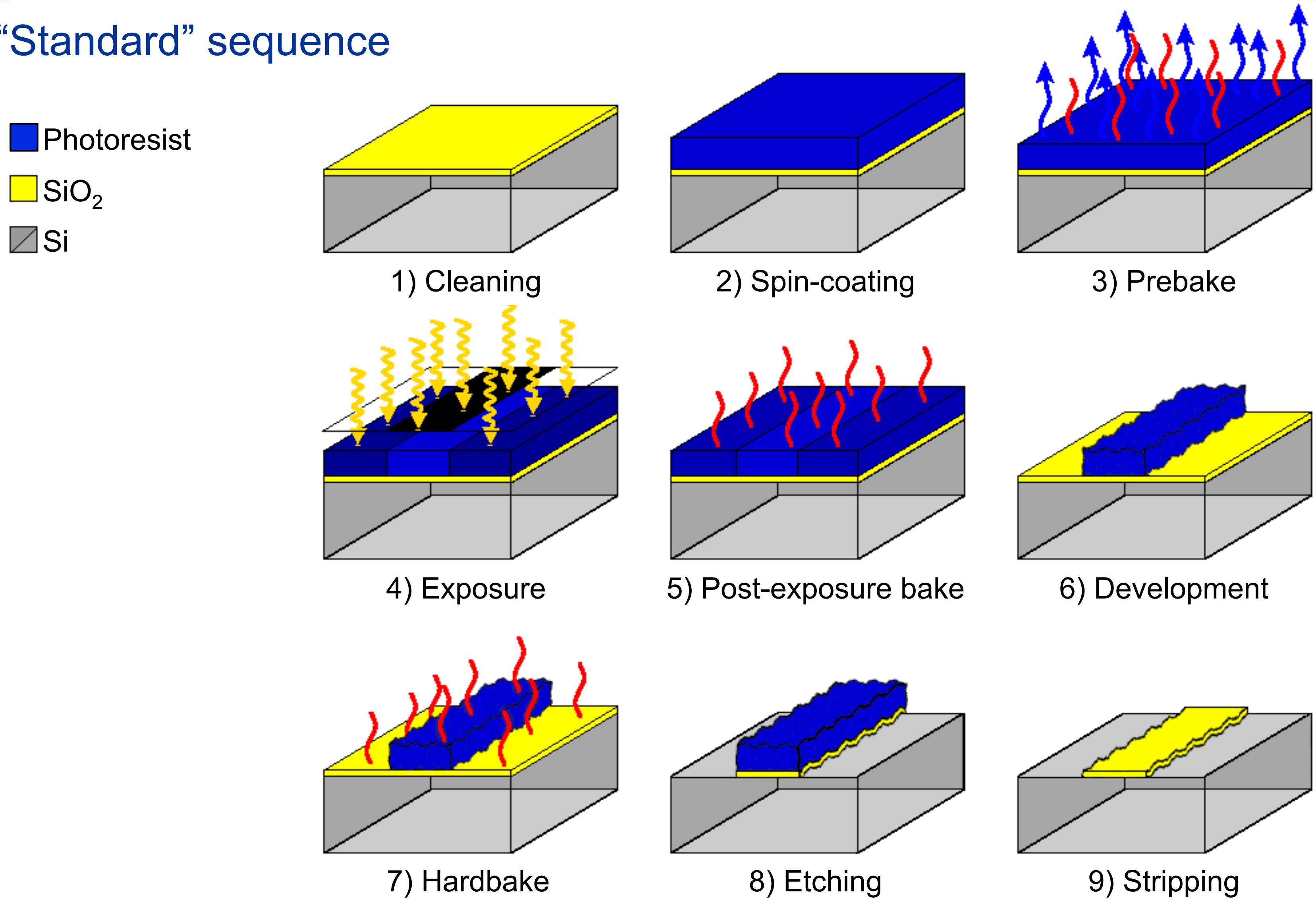
Resist processing and simulation

Some general remarks

- Many investigations can be performed based on aerial images / bulk images
- If specific resist properties have to be taken into account an additional resist simulation after the bulk image simulation has to be performed
- In contrast to the optical models the resist models have to be calibrated with real measurement data → Very challenging task
- Due to the complexity the of resist calibration and simulation only the basic sequence is shown in the following
- Resist simulations are based on: Dill-model (exposure), coupled kinetic/ diffusion equations (post exposure bake), development rate model/level set/cell removal algorithm (development)

Resist processing and simulation

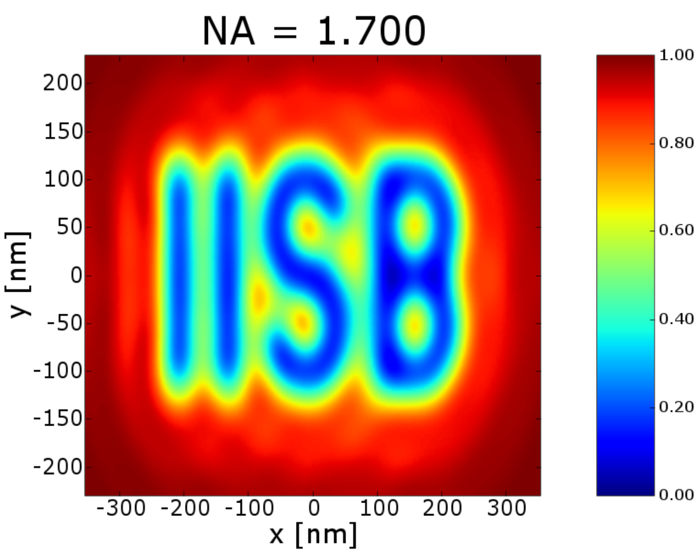
"Standard" sequence



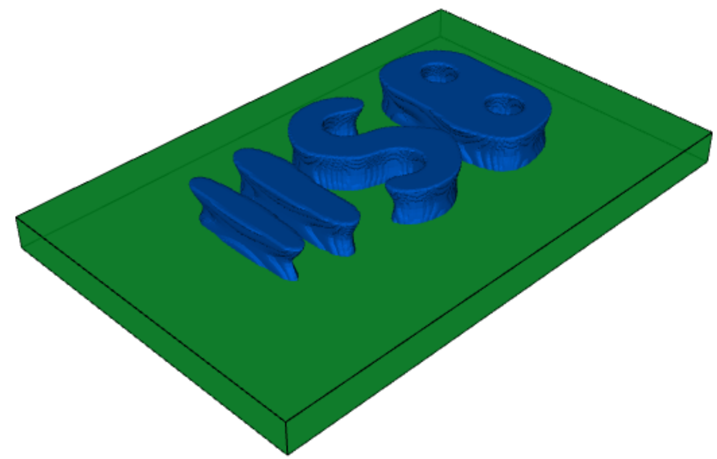
Source: Lecture A. Erdmann, Fraunhofer IISB

Resist processing and simulation

Aerial image



Resist profile



Simulation of exposure, PEB, development

Source: Lecture A. Erdmann, Fraunhofer IISB

Conclusion

- State-of-the-art lithography technology requires highly accurate and fast simulations
- To cover important effects simulations must comprise vectorial image simulations, rigorous electromagnetic mask field simulations, resist simulations and optimizations combining all models
- The most challenging simulation parts are the rigorous mask simulation and inverse problems
- Continuous enhancements of the simulation models required to keep the required accuracy and short simulation times

All simulations were performed with Dr.LiTHO: www.drlitho.com