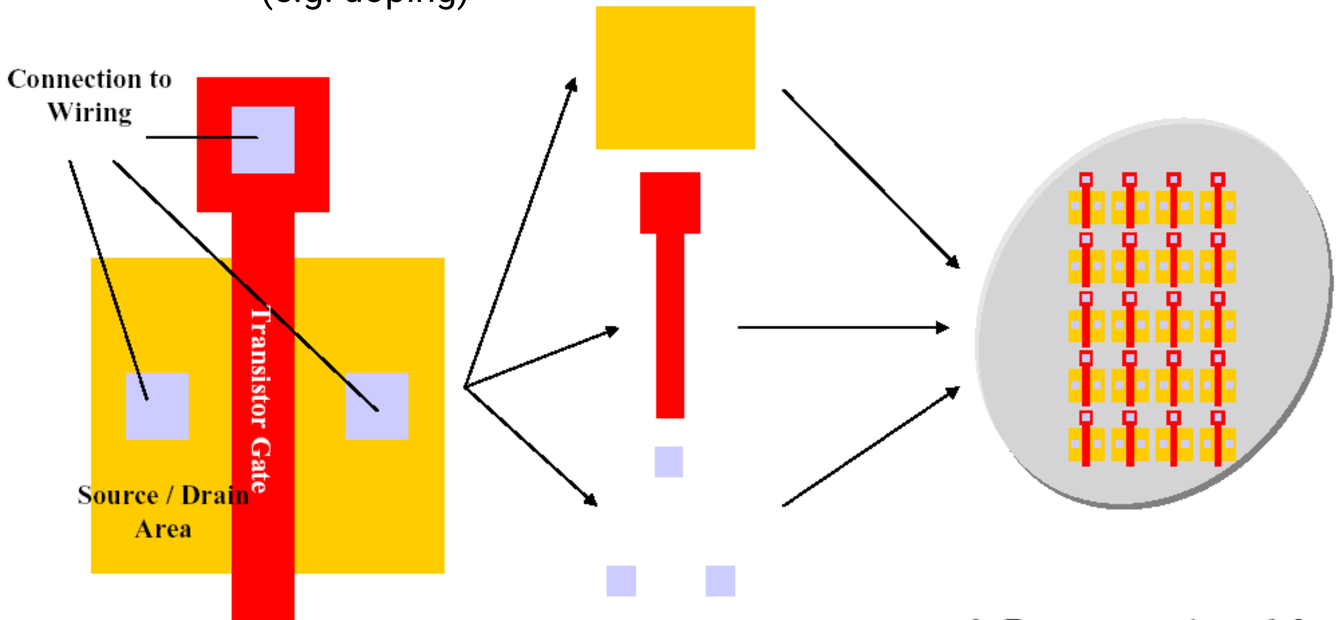
Status: 16.5.2018

3.6 Lithography and Mask Process

3.6.1 Introduction

Purpose of Lithography:

- Pattern transfer from mask to wafer to form functional components
- Preliminary step for selective wafer treatment (e.g. doping)



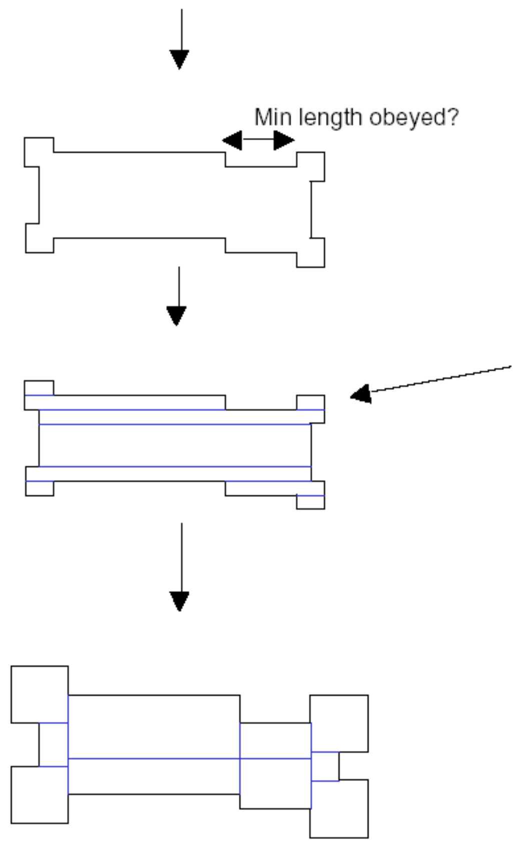
1. Circuit Idea

2. Separation into different Features and Tranfer of the Pattern onto the Wafer by Lithography

3. Reconstruction of the original Circuit by Implantation, Etch, etc.

Design Data Flow

Project Phase	Additional Structures	Data Format
Mask Rule Check (MRC)	Frame patterns, Test structures	GDSII
Mask Data-preparation(MDP, „Fracture" 4x scaling)	Mixing in of Frame patterns, Test structures	MDP format (e.g. MEBES)
Mask Process Compensation, Process Bias, Pattern optimization	(automatic) generation of barcode, addition of alignment pattern	MDP format (e.g. VSB11)



↓

Mask Fabrication

↓

Lithographic process

Design Data Flow

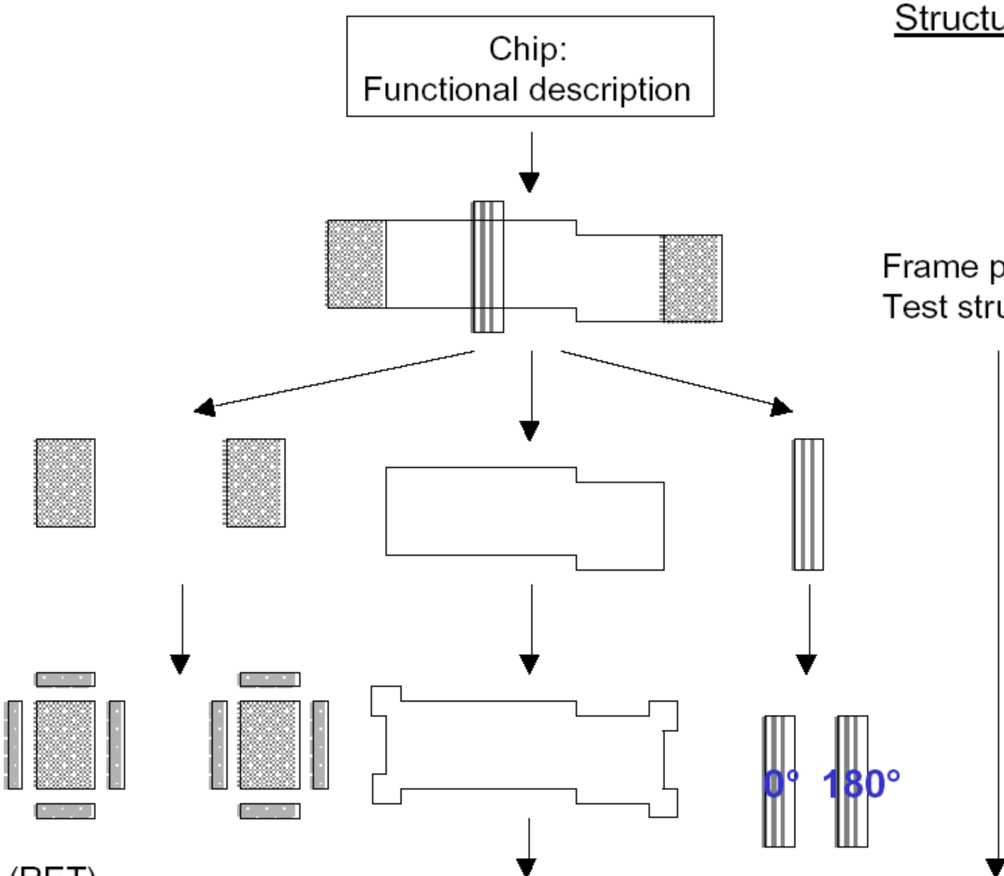
Project Phase

Design

Layout

Layer Extraction

Resolution Enhancement (RET)



Additional Structures

Data Format

VHDL, ...

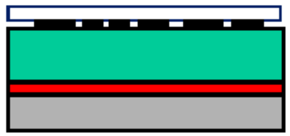
GDSII

GDSII

GDSII

Early Optical Lithography

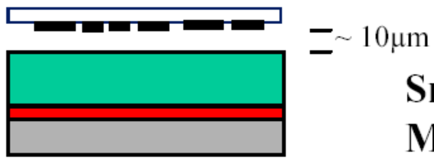
Contact Printing



Mask in direct contact with resist

- Defects on Wafer and Mask
- Mask Lifetime

Proximity Printing



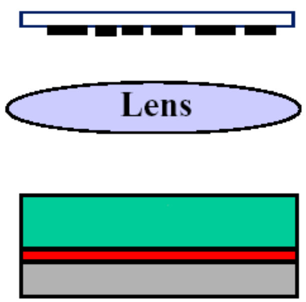
Small Gap between Mask and Resist

g ~ 10 µm

- Defects on Wafer
- Reduced Resolution

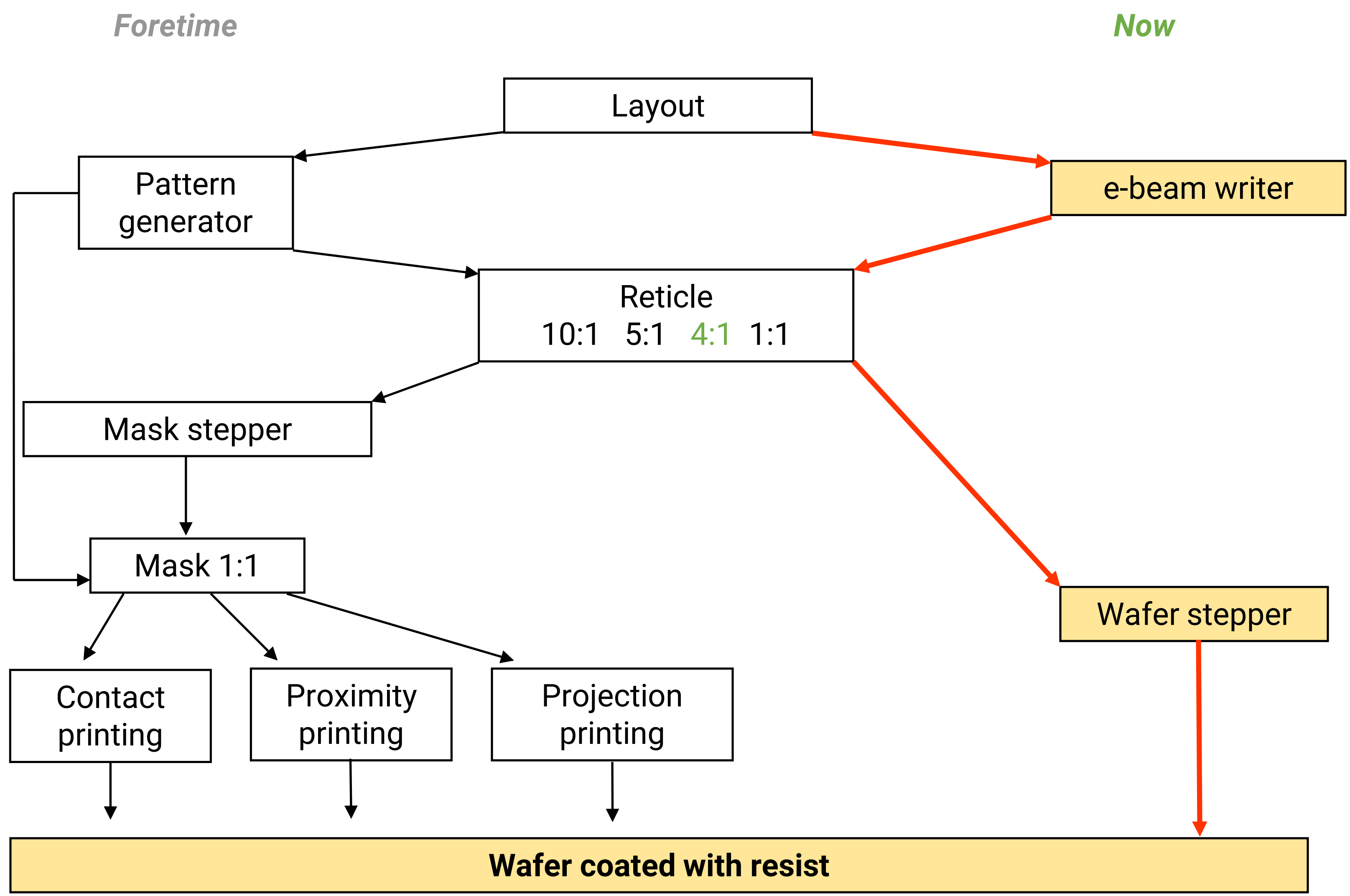
$$CD \cong \sqrt{\lambda g}$$

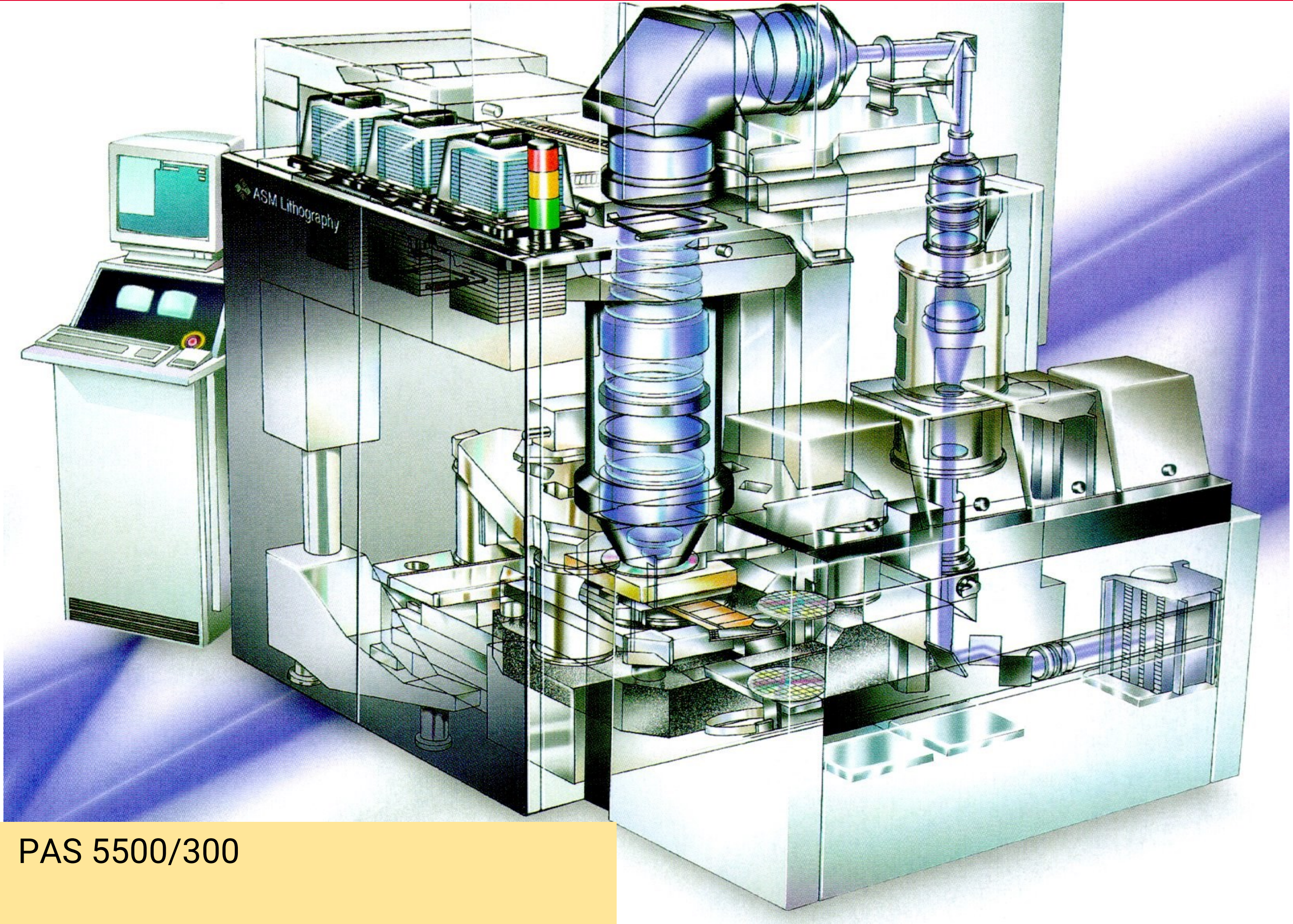
Projection Printing



Mask Pattern projected by Lens on Resist

Lithographic approaches





DUV wafer stepper PAS 5500/300

d_{min} = 0.25 µm

ASML Lithography

Excimer laser, DUV lenses from Zeiss (1996)

3.6.2 Lithographic Process

Overview

Wafer Prime (HMDS) | ARC Coating, ARC Bake

↓

Resist Coating

↓

***S**oft **B**ake, **P**ost **A**pply **B**ake*

↓

Exposure

↓

***P**ost **E**xposure **B**ake*

↓

Develop

↓

***H**ard **B**ake*

↓

(UV Harden)

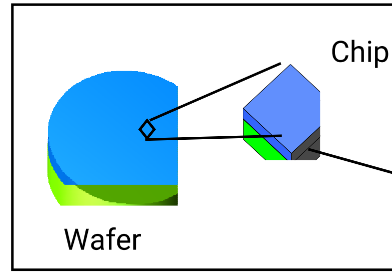
Rework → ARC Coating (**If Specifications are not met**)

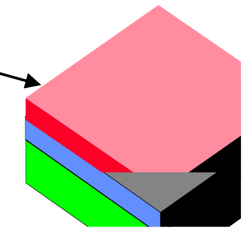
↓

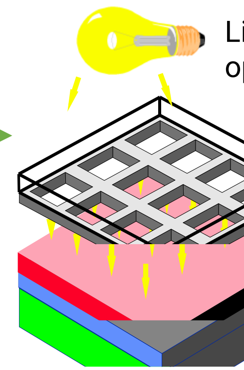
Pattern transfer (etching, implantation)

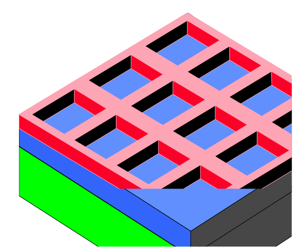
↓

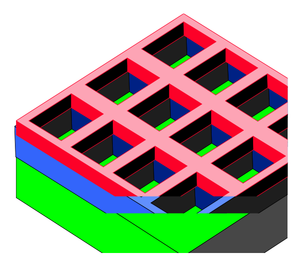
Resist removal (stripping, dry, wet)

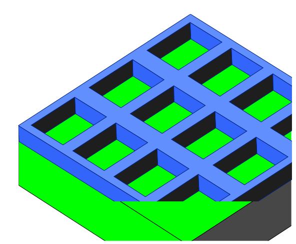












HMDS – Hexamethyldisilazan (Primer)
ARC - Anti-reflective coating

Resist

Type	Positive Optical Resist	Negative Optical Resist
Components		
– Matrix	nonvolac resin	cyclized synthetic rubber resin
– Sensitizer (PAC)	diazoquinones	bisarylzide
– Solvent	n-butyl acetate, xylene, etc.	aromatic solvent
– Developer	*Hydroxides*	*organic solvents*

Mechanism

- Exposure to radiation leads to breakdown of PAC
- Dissolution rate in developer (hydroxide) changes

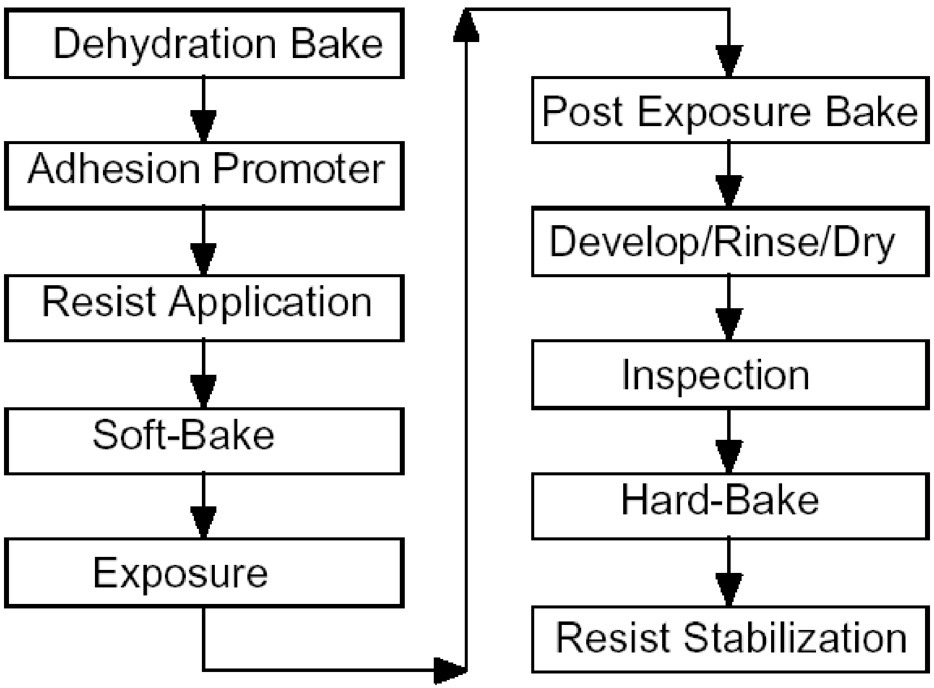
- Negative optical resist becomes insoluble in regions exposed to light
  - Photochemical reaction generates cross-linking to form 3D molecular network
  - New structure insoluble in developer (usually an organic solvent)

Detailed chemistry depends strongly on wavelength

PAC - photo-active compound

Lithographic process example

Dehydration bake: 150-200 °C, drive off water
Adhesion promoter: wafer primed with hexamethyldisilazane (HMDS)
Resist coating: static or dynamic dispense, spin coating on vacuum chuck @ 2-6 Krpm. Thickness (0.1 -10 µm) depends on speed and viscosity
Softbake: drive off solvents (115 °C, 30s)
Exposure: 60 - 120 mJ cm^{-2}
Post-Exposure Bake: remove standing waves by diffusing PAC
Develop: Hydroxide, puddle or spray, with temperature control; rinse & dry bake (115°C) follows
Inspection: of critical dimension (CD) structures
Hard Bake: high temperature bake (115°C - 170°C) to harden resist against further energetic processes



Most of photoresist processing is automated on coater / developer tracks

Source: http://hackman.mit.edu/6152J/SP_2004/lectures/sp_2005_Lecture11.pdf

Resist removal (stripping)

Requirement: Complete removal of resist layers after patterning or implantation without damaging the underlying films

Approaches:

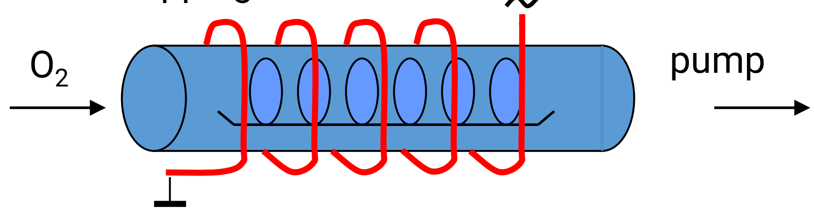
Weakly stressed resist:
Wet removal using
- acetone
- H_2O_2+ H_2SO_4
- hydroxyl amines

heavily stressed resist:
Dry removal (or dry + wet)

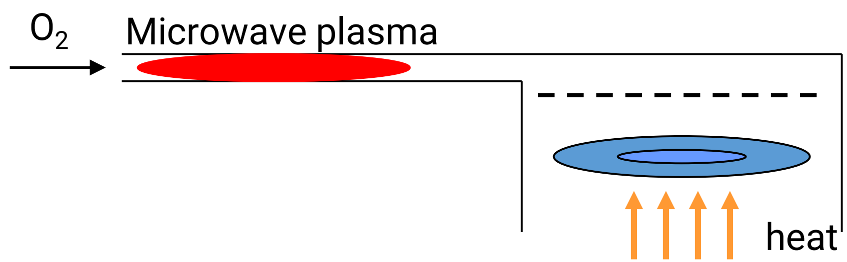
Dry resist removal using oxygen

(generation of CO, CO_2, H_2O)

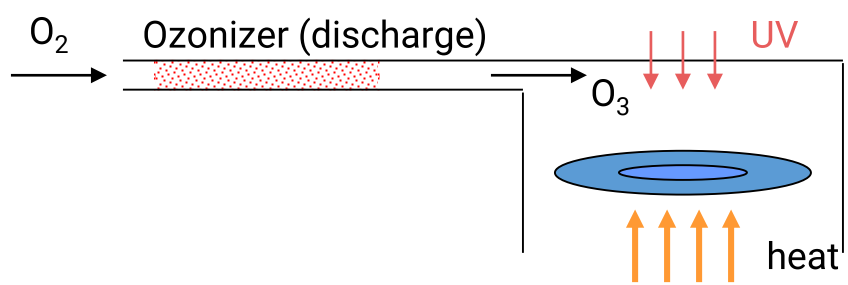
- Plasma stripping in Barrel reactors



- Downstream stripping (less radiative damage)

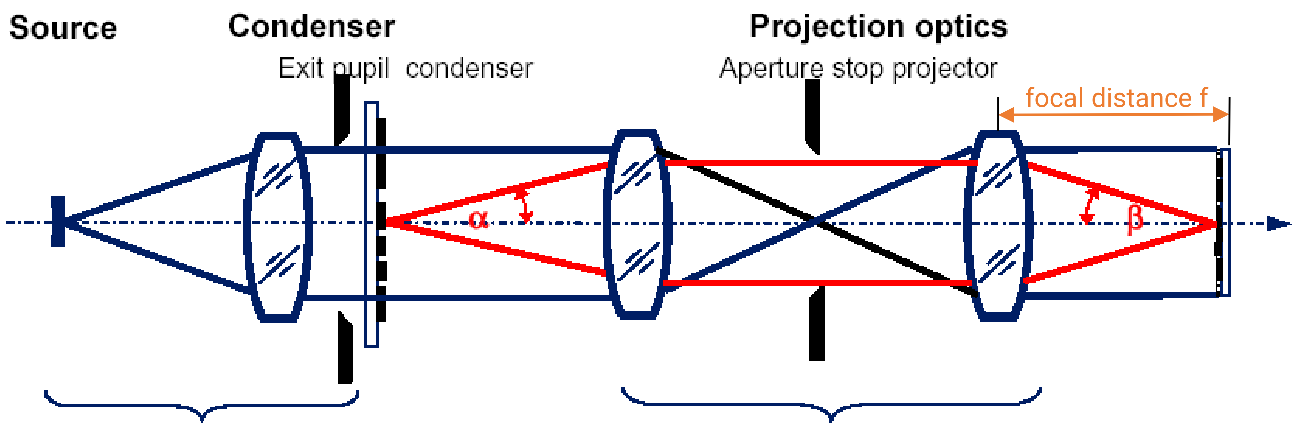


- Plasma-free (ozone and UV) stripping



Exposure

Conceptual Design of Stepper/Scanner Optics



Illumination system
- source
- pupil shaping system
- homogenizer
- elements to eliminate temporal and spatial coherence
- energy sensor

Reticle
- fused Silica plate
- Cr patterns
- PSM materials and patterns
- pellicles

Projection system
- lens system
- TTL alignment optics
- variable aperture stop
- NA = sin β
- β half aperture angle, i.e. maximum acceptance angle that can be focused by the optical system

Wafer
- resists
- underlying thin films

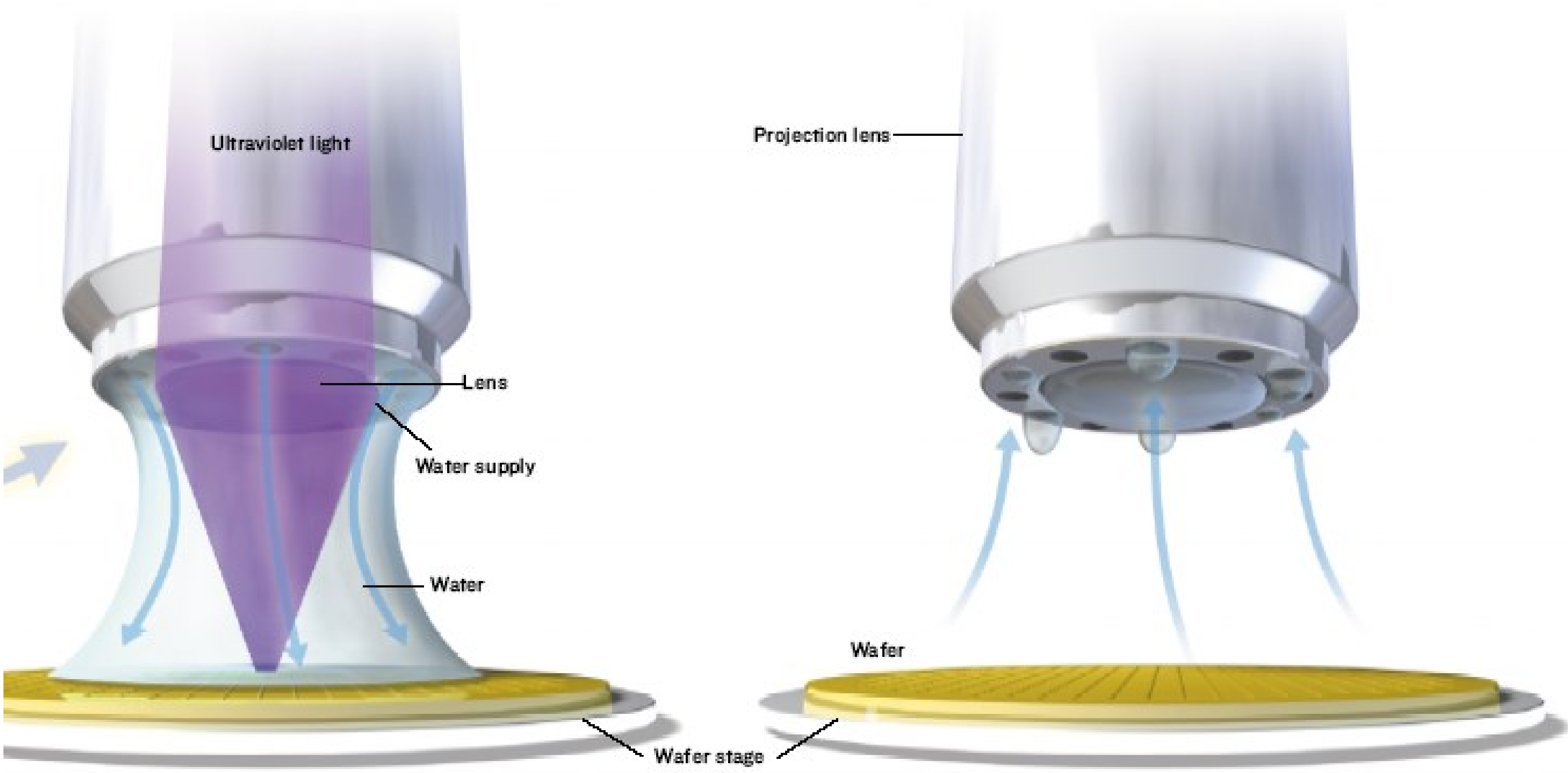
Numerical Aperture NA = n sin β

n - refractive index, n = 1 for air, n = 1.4 for water @ 20 °C and 193 nm

typical values for λ = 193 nm: NA = 0.85 (dry) NA = 1.2 (wet)

typical values for λ = 13.5 nm (EUV): NA = 0.25 ... 0.30

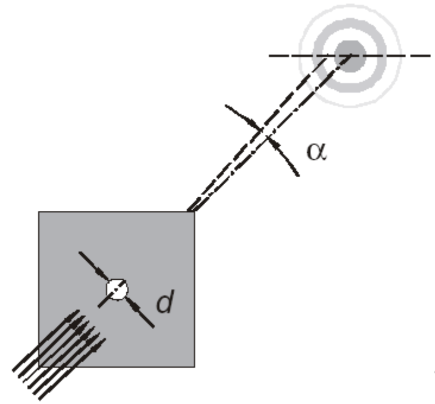
Immersion Lithography

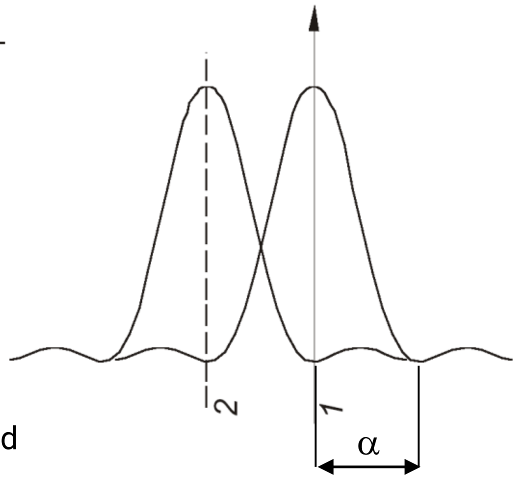


Source: Geppert, L. **Chip making's wet new world** Spectrum, IEEE Volume 41, Issue 5, May 2004 Page(s): 29 - 33

Criteria of imaging performance

Resolution





Fraunhofer diffraction: $\sin \alpha = 1.22\, \lambda / d$

Rayleigh's criterion defines two light points as resolved if the positions of both main maxima of intensity lay outside the range between the respective other main maximum and the related first diffraction minimum.

Equivalent formulation: The peak widths at half-maximum do not overlap.

Resolution limit = Minimum line width:

$$l_{min} = k_1 \cdot \frac{\lambda}{NA}$$

3 ways to reduce l_{min}:
- *reduce λ (→ DUV → EUV → X-ray)*
- *increase NA (immersion litho)*
- *reduce k_1 (RET)*

Rayleigh:	$k_1 = 0.61$	*depending on the optical system,*
without RET:	$k_1 = 0.61 \ldots 0.8$	*resist capability, tool control,*
now: λ = 193 nm NA ≈ 0.85 (dry)	$k_1 \approx 0.4$	*reticle pattern adjustment,*
theoretical limit:	$k_1 = 0.25$	*process control, RET*

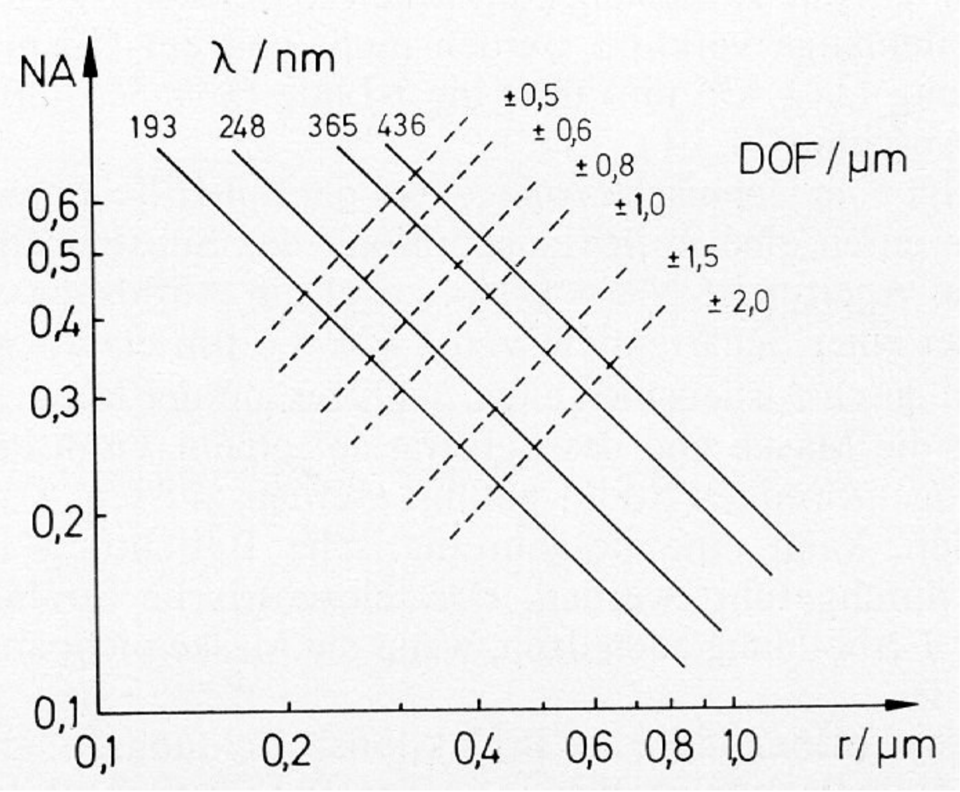
RET = Resolution enhancement Techniques

Depth of focus (DOF)

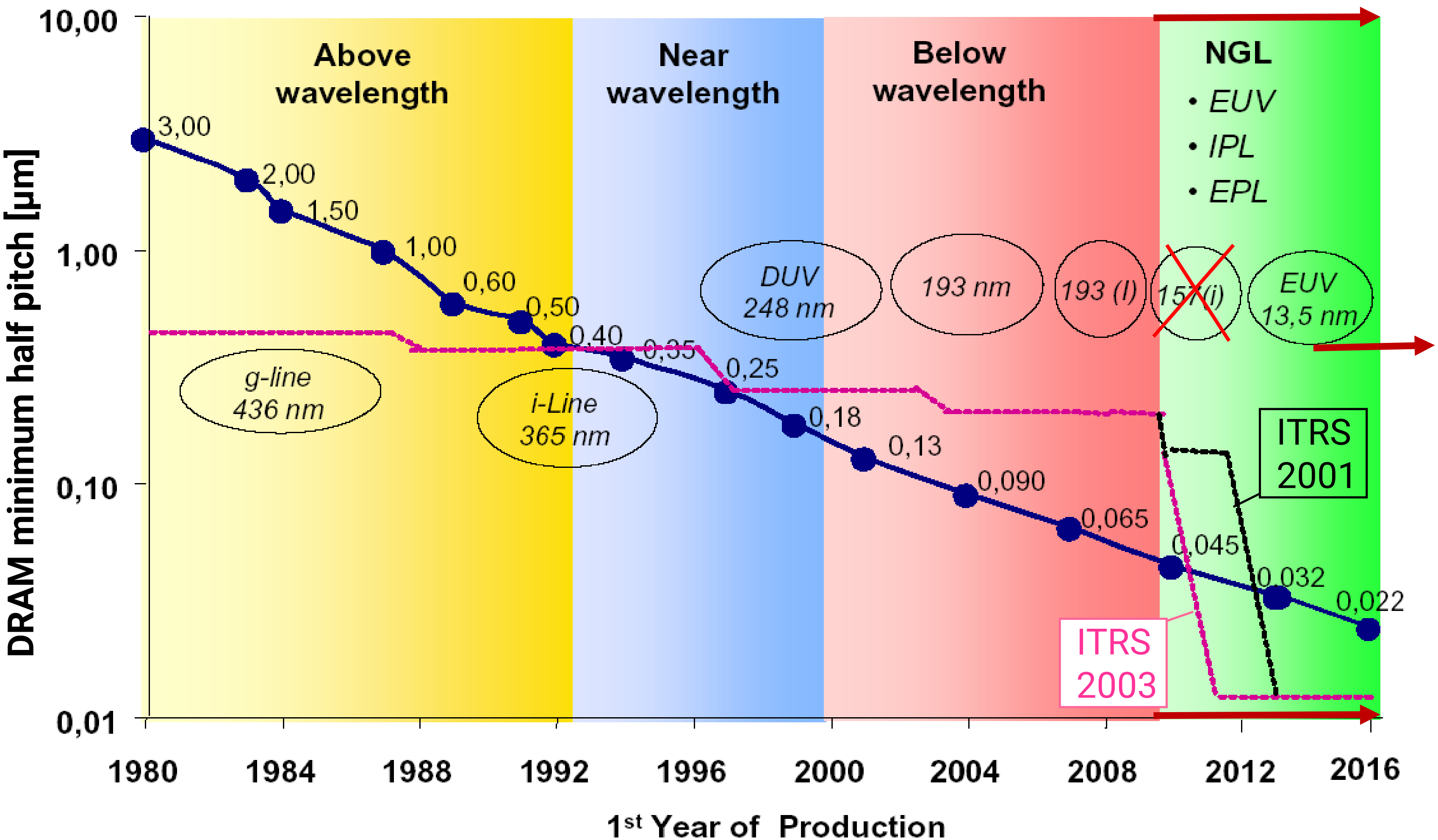
Criterion for depth of focus (DOF) is that two optical path lengths do not differ by more than λ / 4

$$\mathrm{DOF} \approx \pm k_2 \cdot \frac{\lambda}{(\mathrm{NA})^2}$$

now: $k_2 \approx 1.0$
theoretical limit: k_2 = 0.5 (dense L/S pattern)



Technology Nodes and Lithography Wavelength



NGL - next generation lithography
IPL - ion projection lithography
DUV - deep ultraviolet
EPL - electron projection lithography
EUV - extreme ultraviolet

Light sources

- High pressure Hg arc lamp

  g - line (436 nm)

  h - line (405 nm)

  i - line (365 nm)

- DUV laser
  (Excimer laser, excited dimer)

  KrF (248 nm)

  ArF (193 nm)

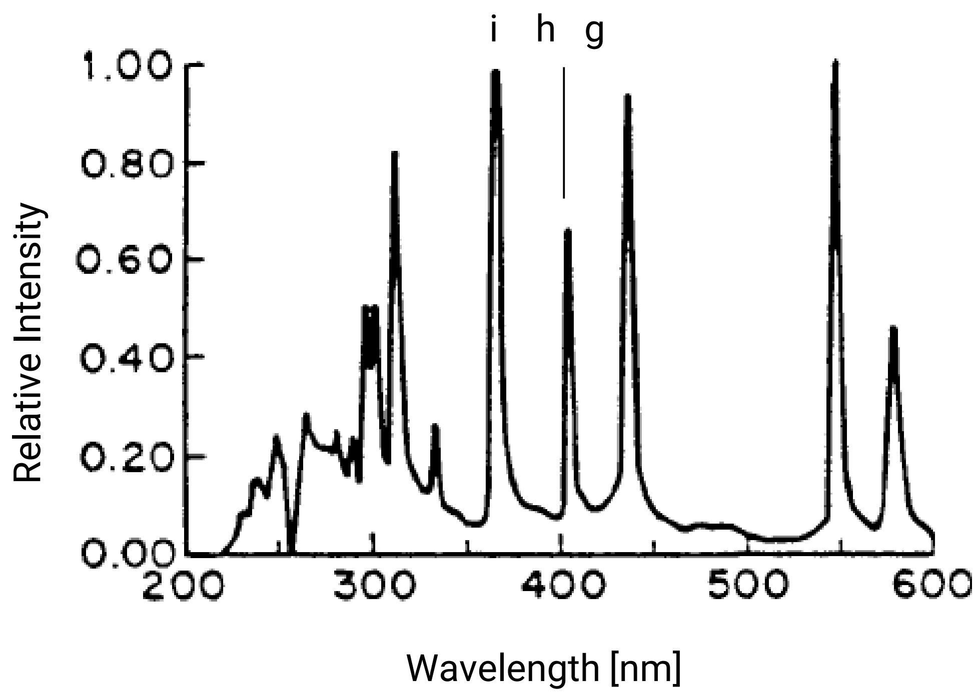
  { F_2 (157 nm), cancelled ! }

- EUV (13.5 nm)

  laser- or discharge-produced plasmas (**Xe**, Sn, In)

  electron-impact ionization (excitation) of atomic inner shells (e.g. L-shell of Si)

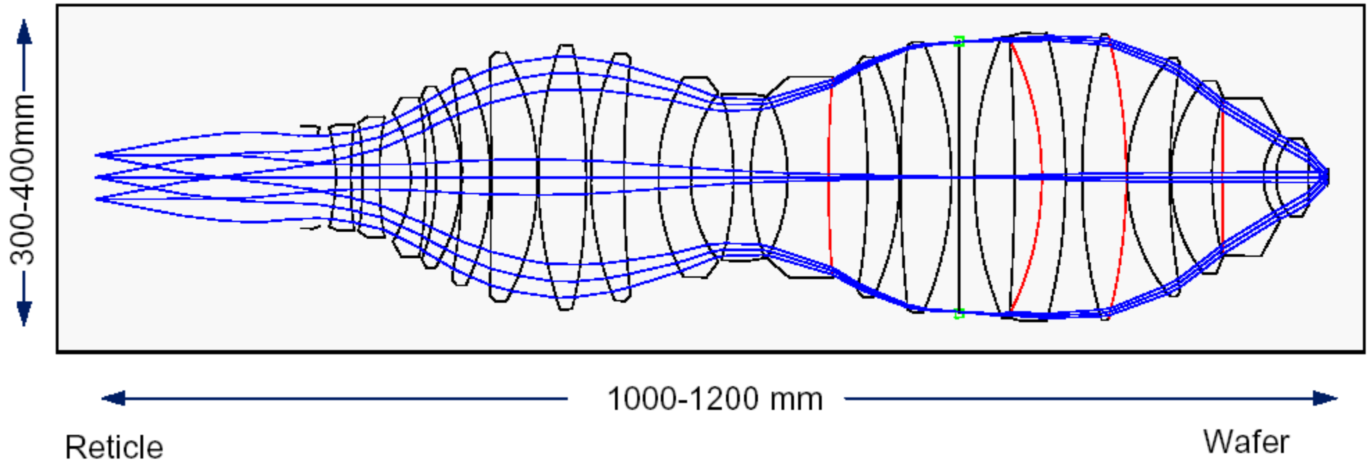
Hg lamp spectrum



Source: L.F.Thompson, C.G.Wilson, M.J.Bowden, Introduction to Microlithography, Am. Chem. Soc. 1983

Optic materials

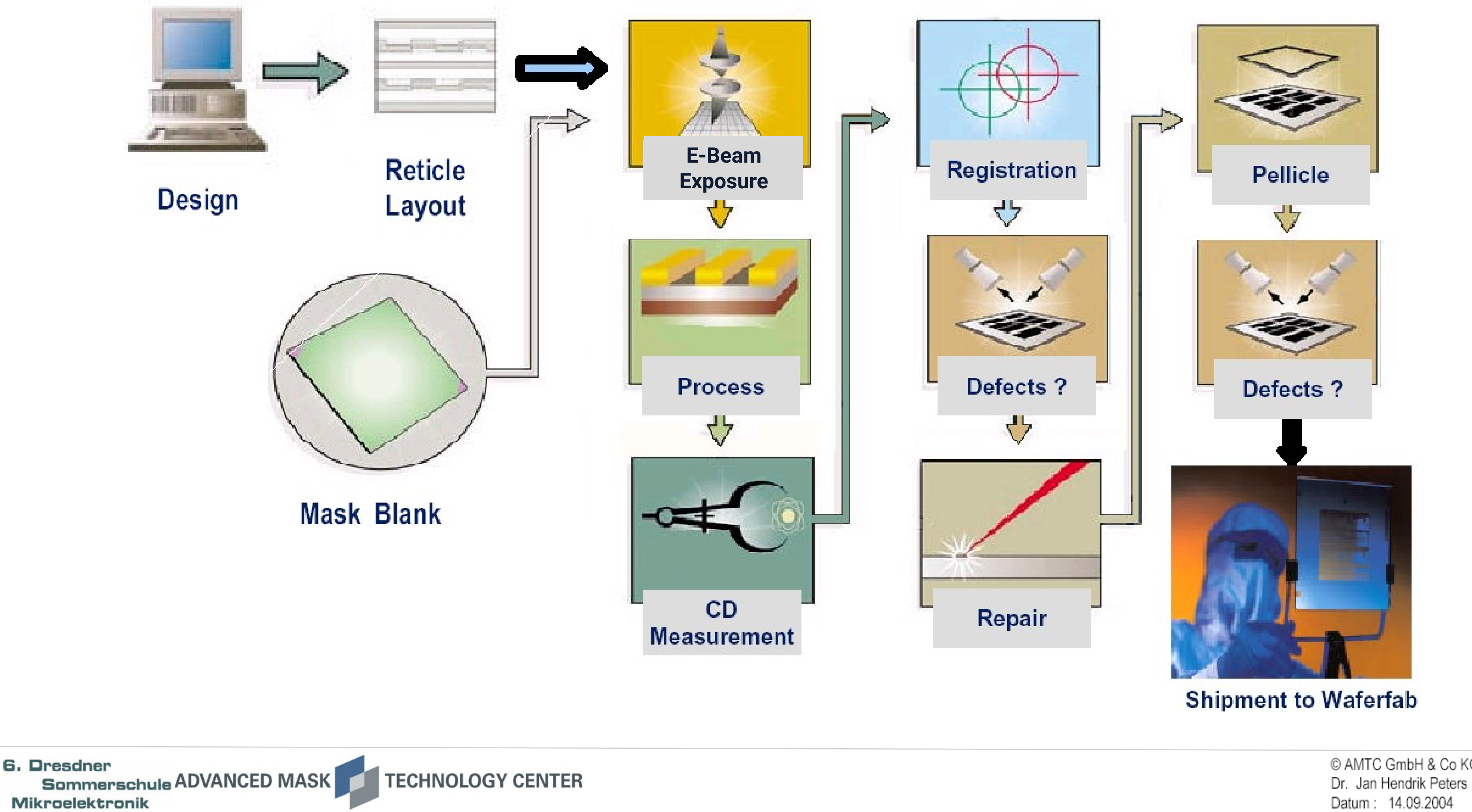
Refractive optics



Light source	Optical system	NA	Resolution (nm)
i - line (365 nm)	special high-purity glass ~30 individual lens elements	0.45 - 0.65	> 280
KrF (248 nm)	fused silica ~30 individual lens elements	0.4 - 0.7	> 150
ArF (193 nm)	quartz glass calcium fluoride (single lenses)	0.65 - 0.93	> 55
	immersion	>1	> 45
EUV (13.5 nm)	reflective optics (mirrors only) vacuum		< 45

3.6.3 Mask Manufacturing Process

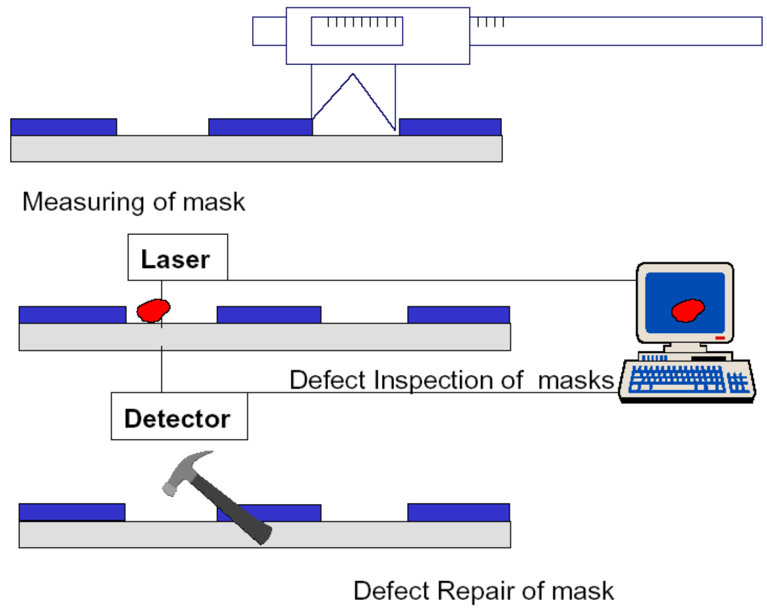
3.6.3.1 Overview



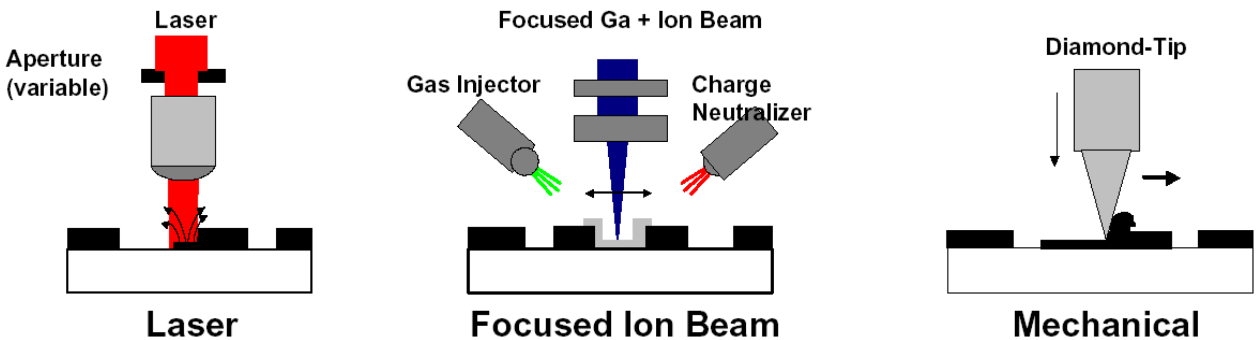
3.6.3.2 Mask Inspection and Repair

Inspection techniques

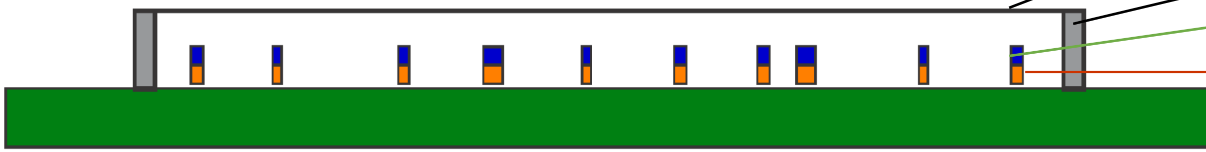
- Die-to-Die
  - Compare identical designs on mask
- Die-to-Database
  - Compare design on mask to design in database
- Check printability of found defect with aerial image tool



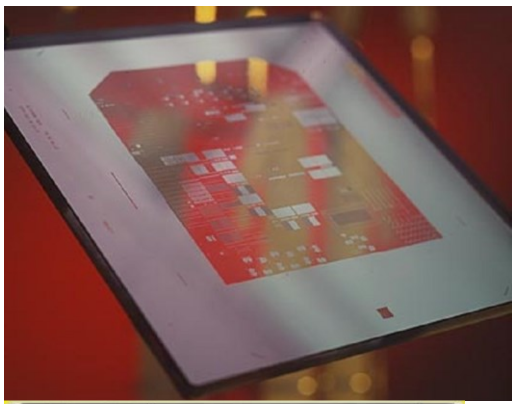
Repair techniques

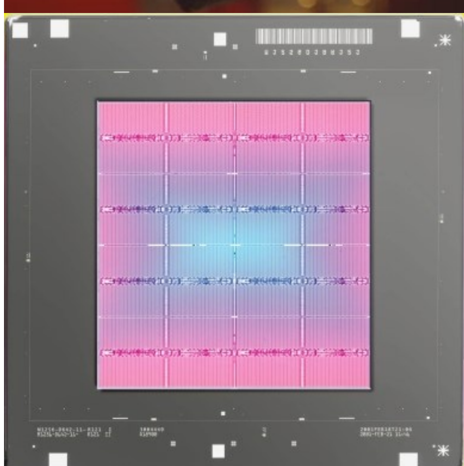


3.6.3.3 Pellicle Mounting

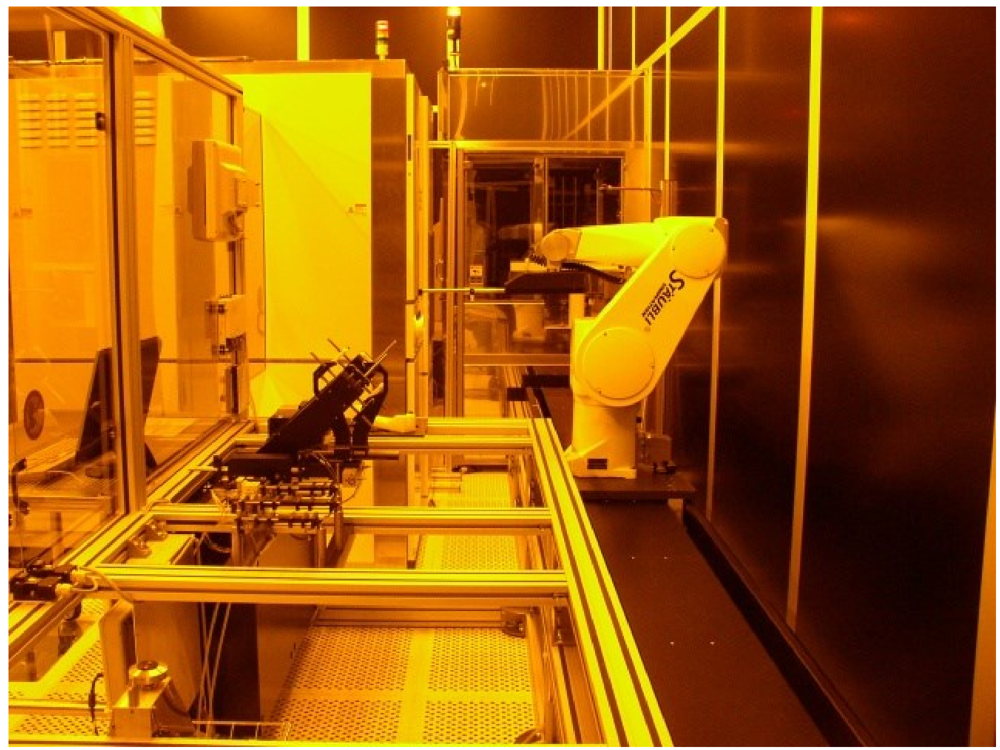


Pellicle (frame, membrane (polymer))
Spacer (Al)
ARC (CrO, 20 nm)
Cr film (80 nm)
Substrate (Quartz, 6.35 mm)





Pellicle mounting line (AMTC)



Source: http://www.amtc-dresden.de/index_gallery.php

3.6.4 Resolution Enhancement Technologies (RET)

Resolution:

$$l_{min} = k_1 \cdot \frac{\lambda}{NA}$$

RET shift k_1 below the Rayleigh limit (k_1 ~ 0.6 … 0.8) down towards 0.25

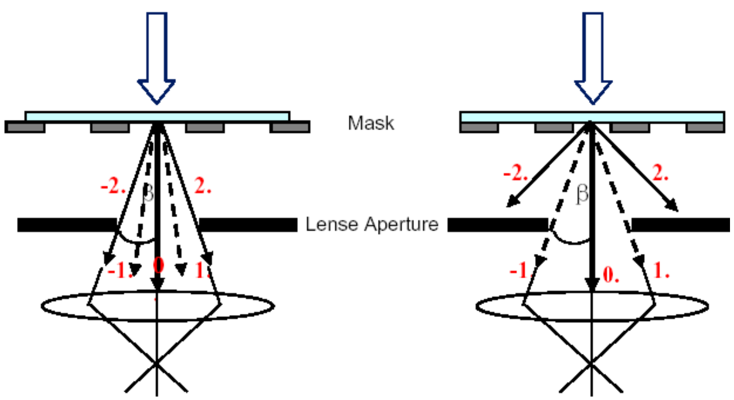
3.6.4.1 Optical Proximity Correction (OPC)

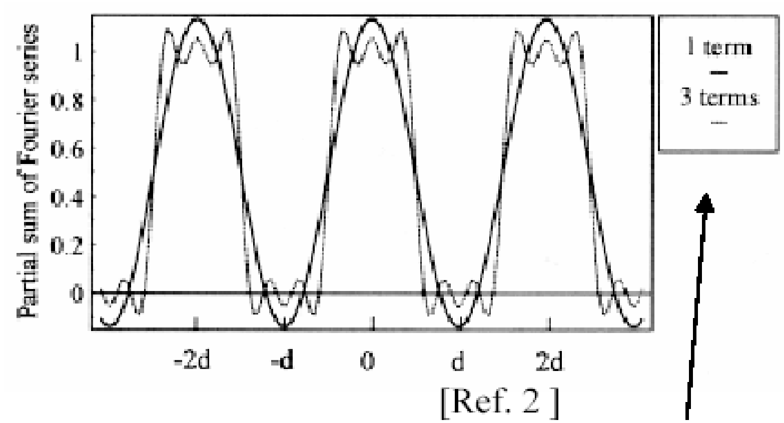
Proximity Effects: Effects that lead to a difference of the designed features to the imaged structures due to the proximity of the structures

Cause: Different diffraction orders contribute to imaging

Result:
- line shortening
- dense/isolated vias

CD difference
process window impact



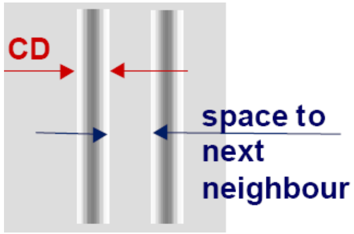


Number of Diffraction Orders determine
Quality of reassembled Image

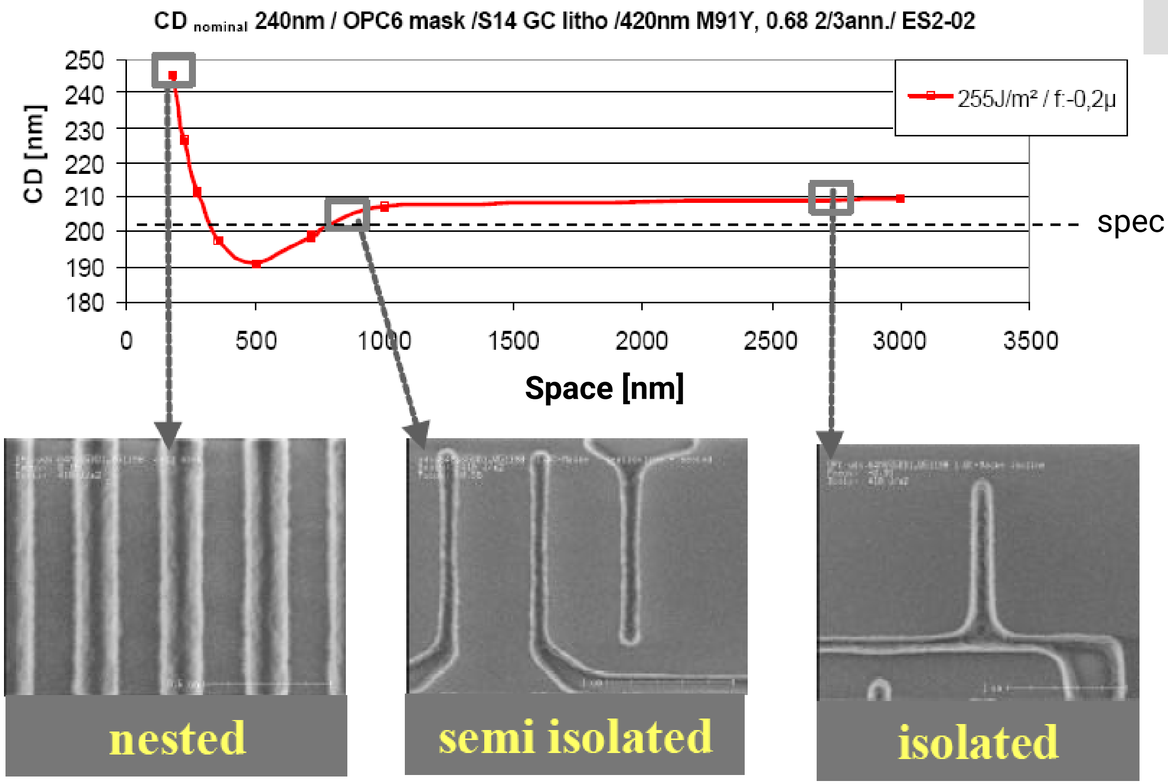
Optical Proximity Correction is a pattern dependent technology bias

Correction of linewidth deviations

depending on proximity to neighbours



OPC Curve



Leads to big CD Variation for nominally same Feature Size
Especially critical in Gate Level

6. Dresdner Sommerschule Mikroelektronik

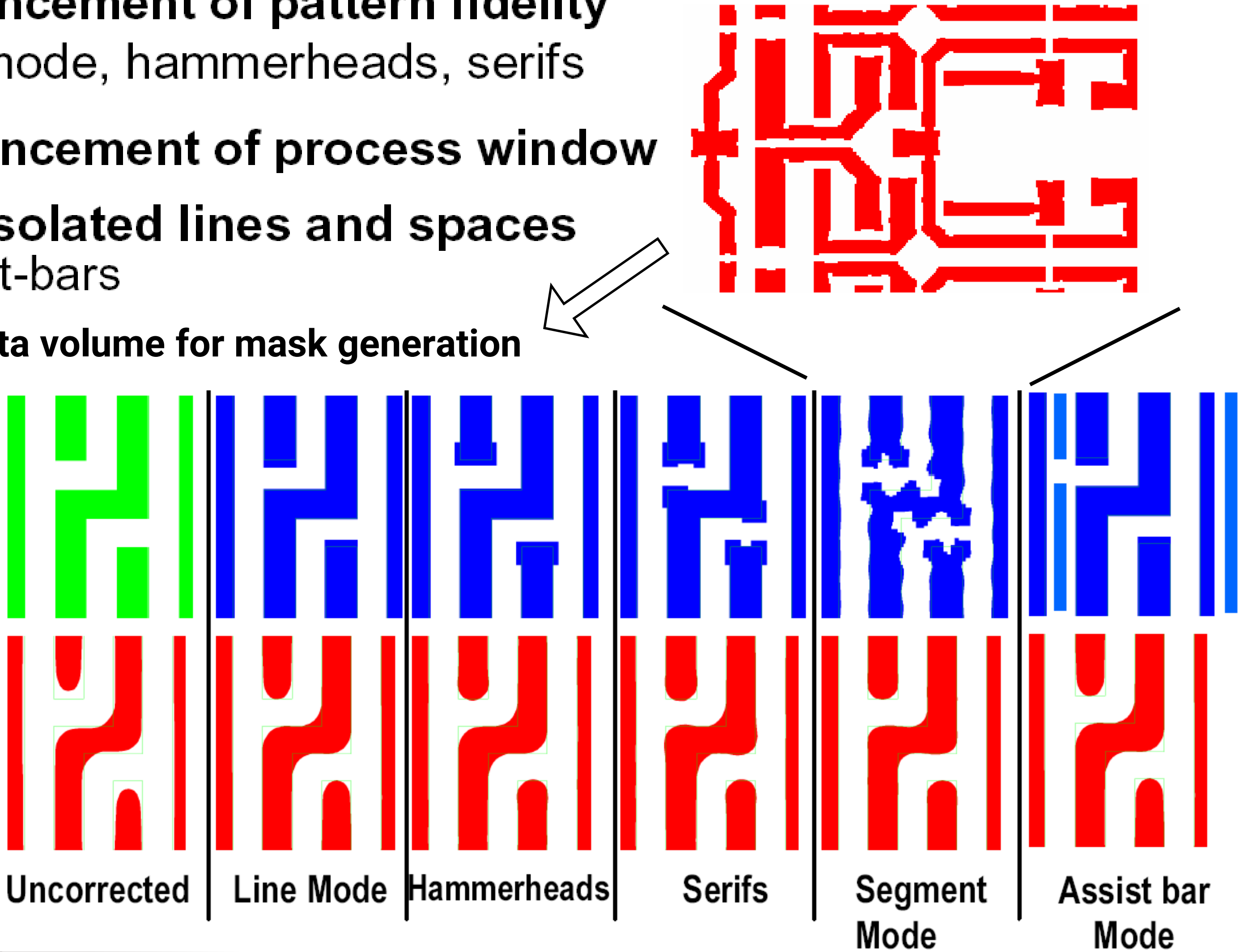
Infineon technologies
92. VDE Symposium September 2002
Never stop thinking
Karl Heinz Küsters
MDC TDT
Memory Products

⇨ **Enhancement of pattern fidelity**
line mode, hammerheads, serifs

⇨ **Enhancement of process window**

for isolated lines and spaces
assist-bars

Big data volume for mask generation

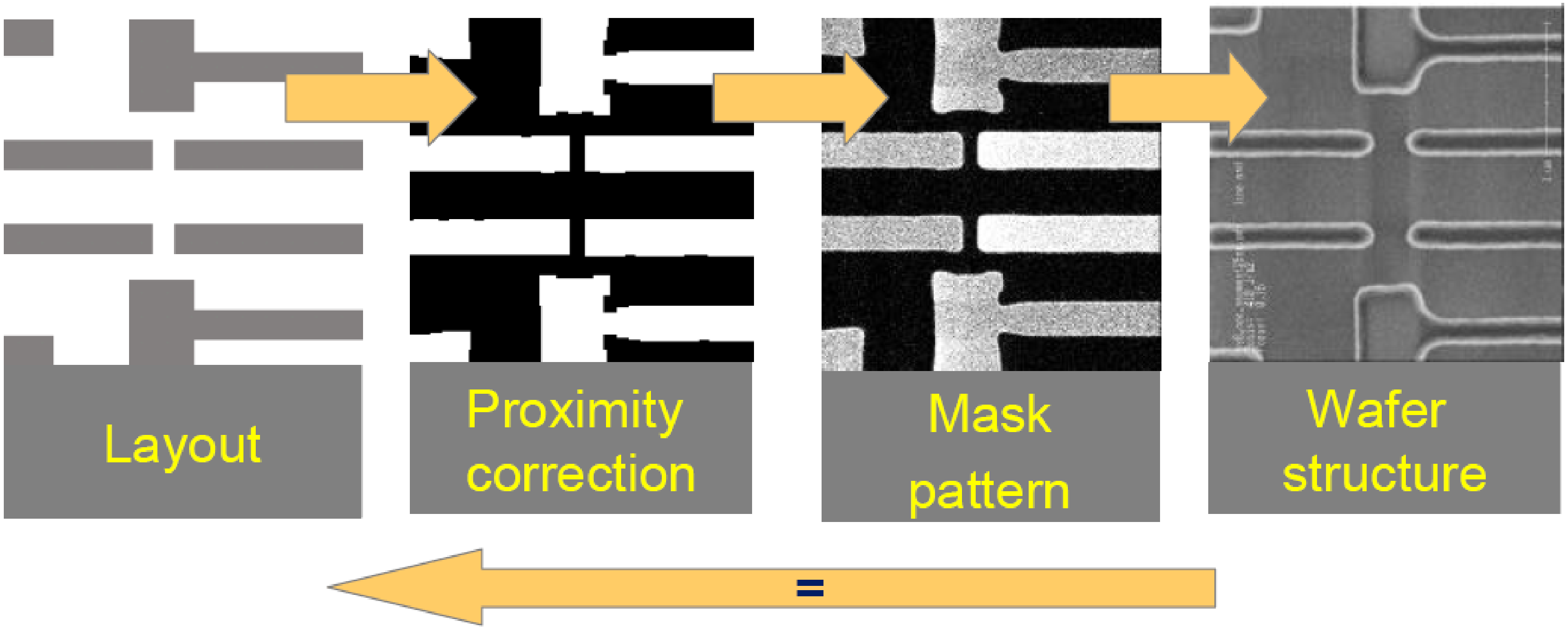


Optical proximity correction: structural adjustments

From Layout to wafer:

Structures on masks changed

to print the same structure on the wafer as in the layout of the circuit



Infineon technologies
92. VDE Symposium September 2002
Karl Heinz Küsters
MDC TDT
Memory Products

Optical proximity correction : assists / scatter bars

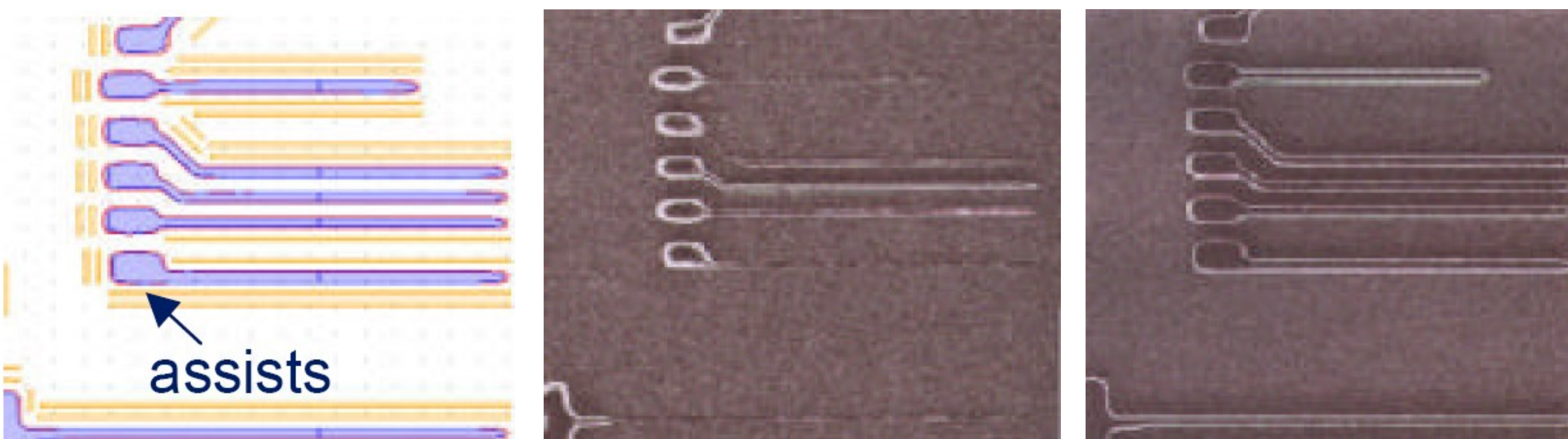
From Layout to wafer:

Assist structures on mask to improve image

Big Challenges for mask production !

Infineon technologies
92. VDE Symposium September 2002

Design | Wafer | Wafer

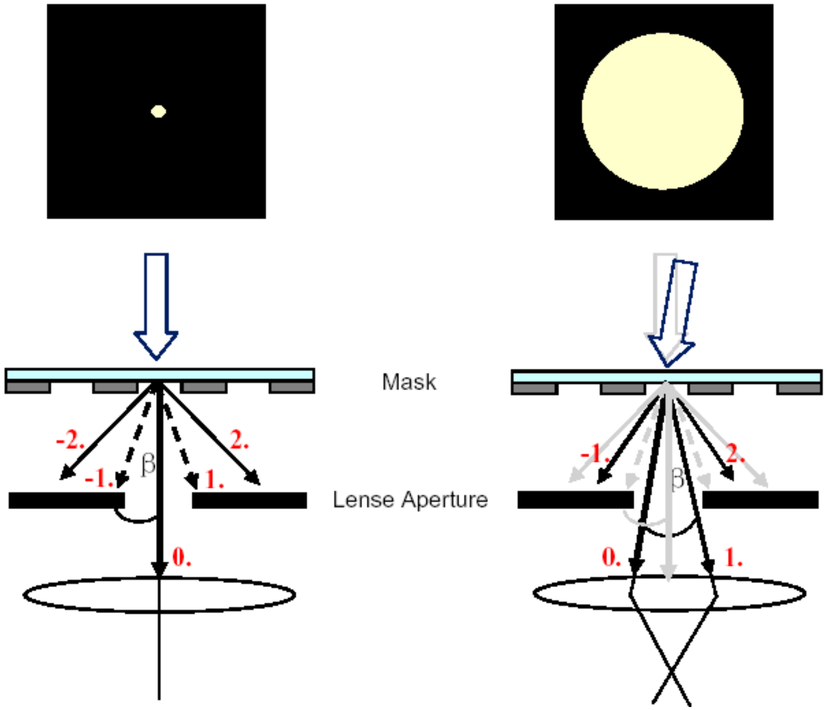


No assists | with assists on mask

Karl Heinz Küsters
MDC TDT
Memory Products

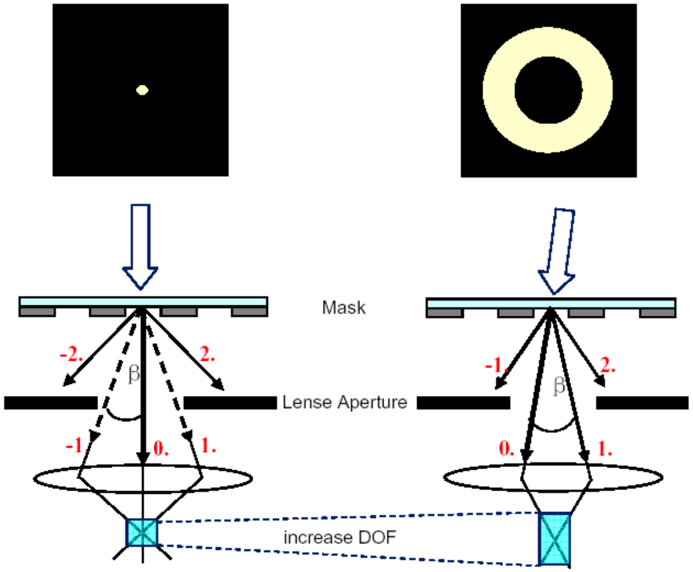
3.6.4.2 Off-Axis Illumination (OAI)

OAI is the use of an aperture to limit the light from an illumination system to only enter a lens system at an angle to the optical axis of the lens system.



By changing the illumination conditions the diffraction orders captured by the lens can be changed.

OAI is used with advanced exposure systems such as steppers and scanners to improve resolution at a given wavelength.



By choosing the appropriate illumination conditions resolution and process window can be optimized.

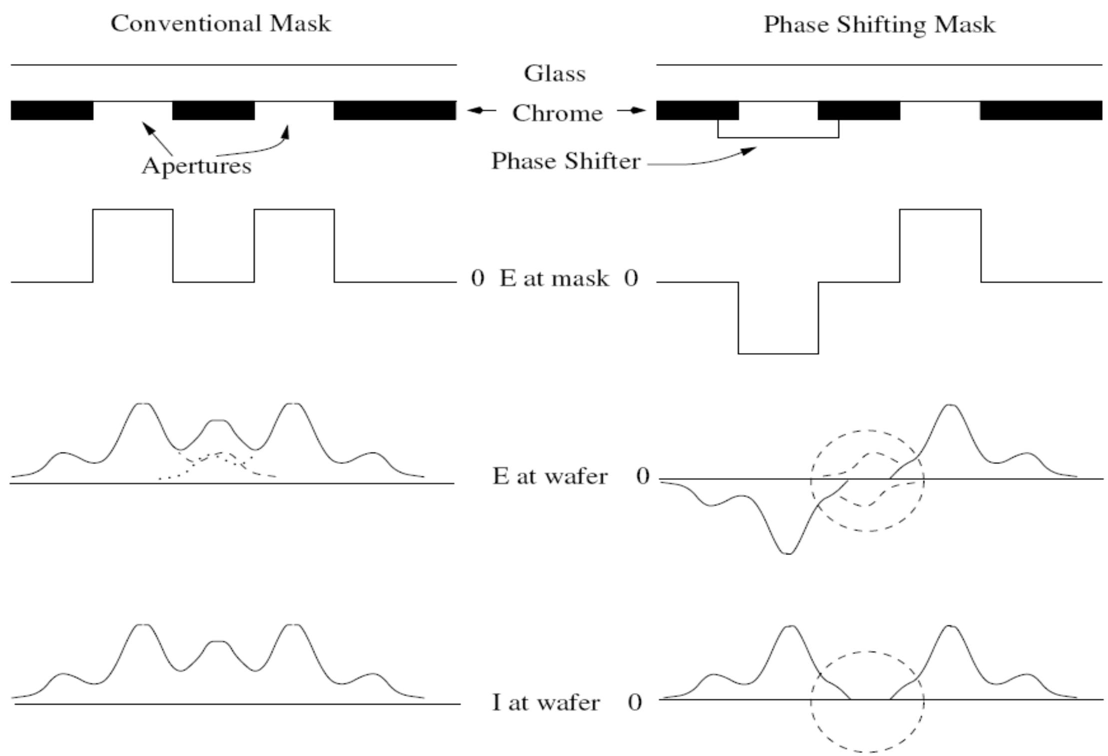
Shape	standard	quadrupole	annular	small sigma
Resolution & DOF	bad	considerably improved	improved	improved if applied with PSM
Pattern dependence	weak	strong	medium	

3.6.4.3 Phase Shift Masks (PSM)

Purpose: Enhanced contrast --> enhanced resolution
--> improvement of process window

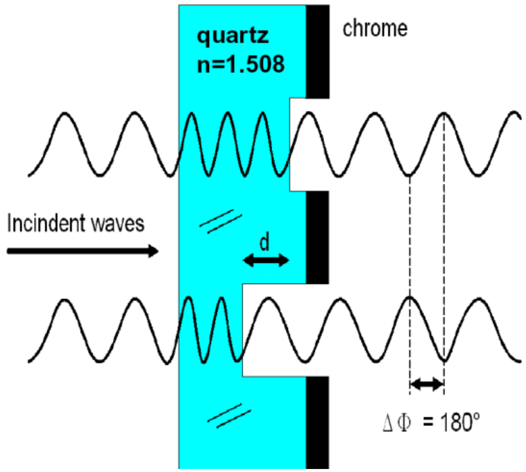
Basic principle: Introduction of a phase difference of 180° on specific parts of the mask structure

- The Phase Shifter reverses the sign of the electric field.
- The light diffracted into the nominally dark region will interfere destructively.
- So PSM can help in resolving the features which may be violating the minimum spacing design rule by assigning opposite phases to the conflicting features.



Kahng et. al., 1999 DAC

Principle of Alternating Phase Shift Masks (AltPSM)



Required etch depth for 180° phase shift:

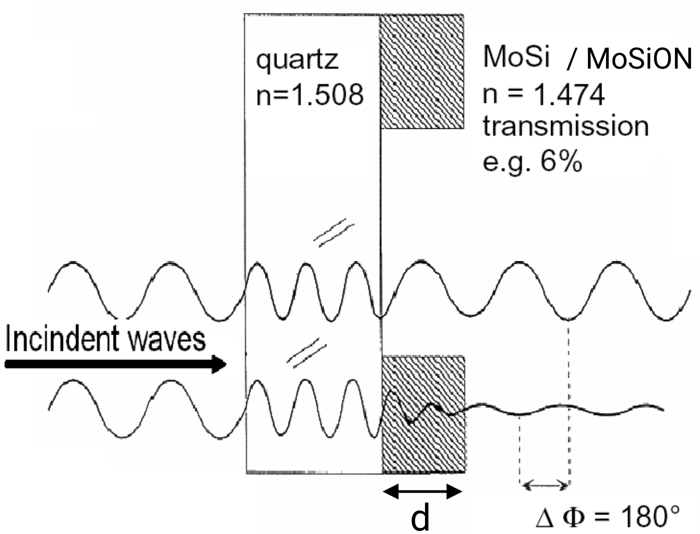
$$d = \frac{\lambda}{2\ (n-1)}$$

Other names for an alternating PSM:
- *strong PSM*
- *Levenson type PSM*

Benefit: Better resolution, enlargement of process latitude & DOF in lithography;

Application: Poly, AA, DT, metal levels

Principle of Halftone Phase Shift Masks (HTPSM)



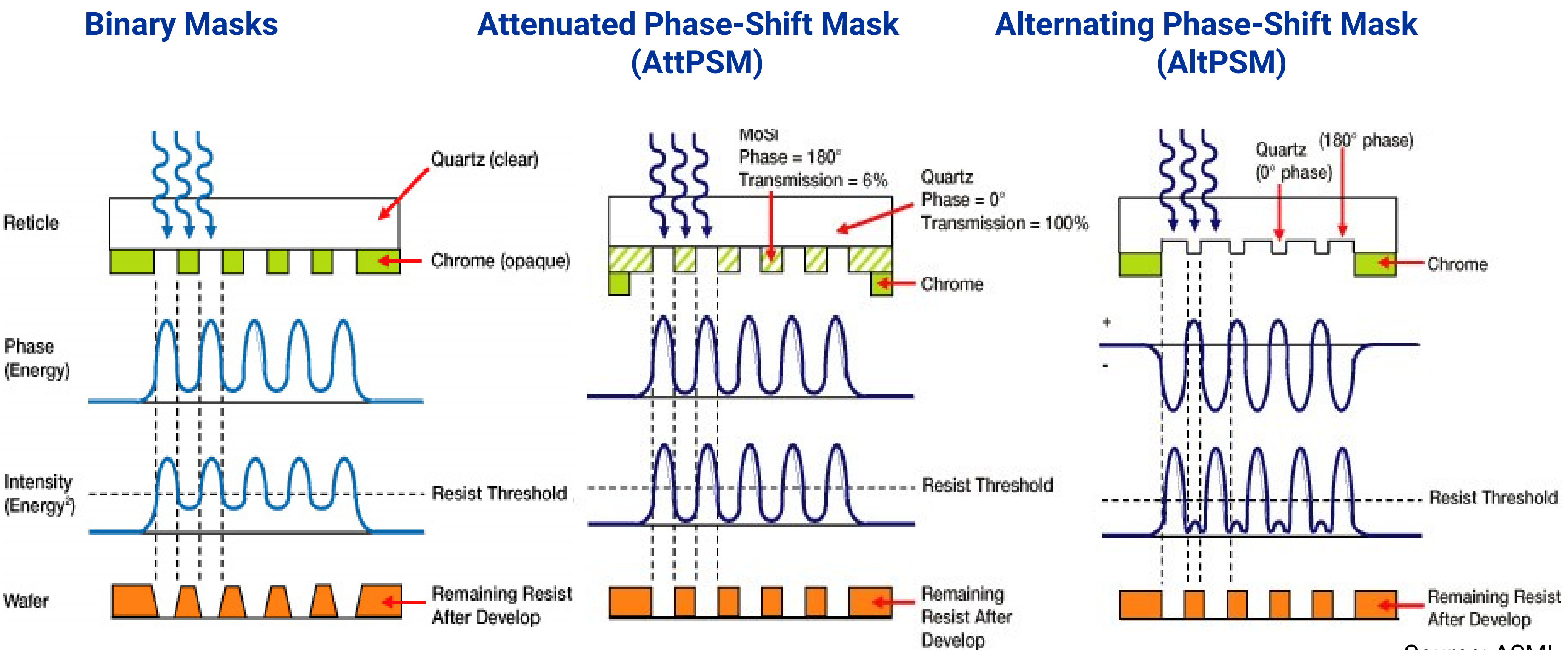
Required thickness for 180° phase shift:

$$d = \frac{\lambda}{2\ (n-1)}$$

Benefit: Enlargement of process latitude in lithography; small improvement of resolution.
Application: Levels with contact-holes or similar structures.

Other names for an halftone PSM:
- attenuated PSM (AttPSM)
- embedded PSM
- weak PSM
- special: chromeless PSM (CPL)

PSM Types



Source: ASML

Special application:

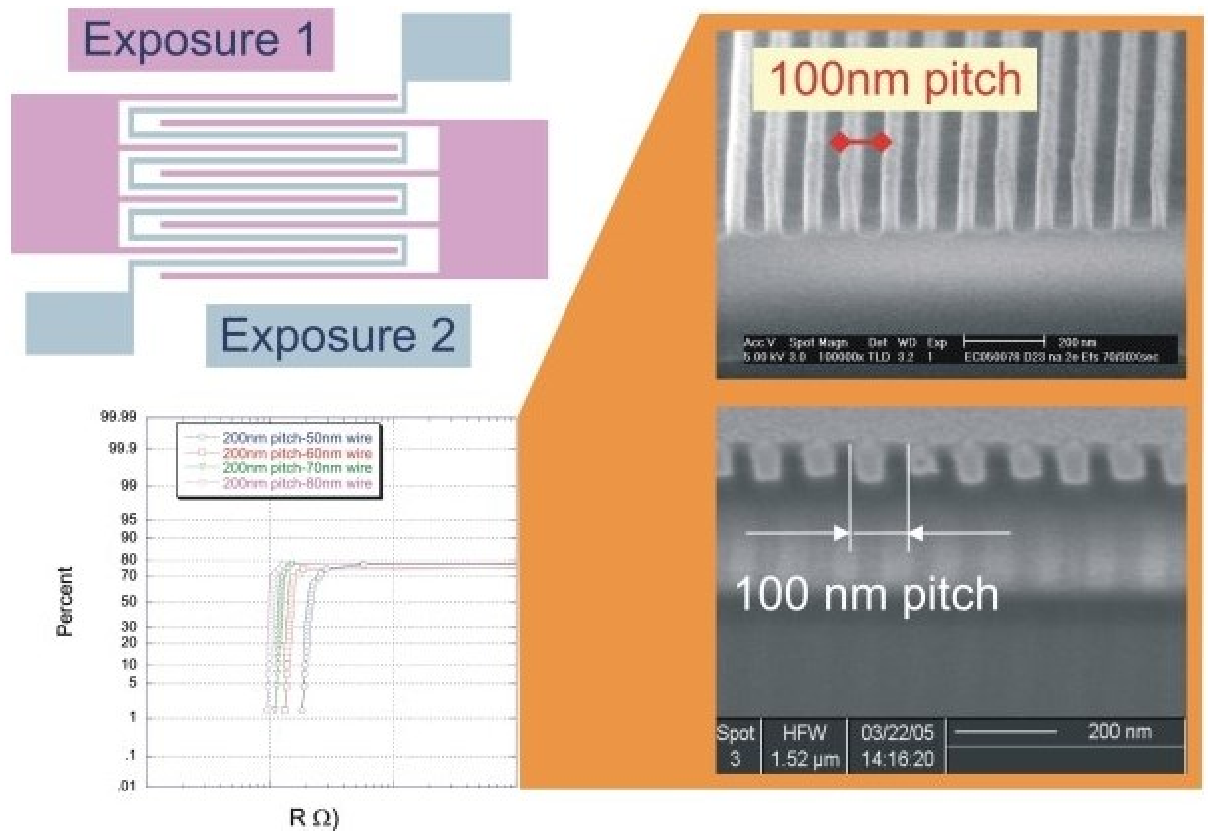
Chromeless Phase Lithography (CPL)

- complex mask manufacturing process
- need for a second "Trim" reticle --> 2 Exposures

3.6.4.4 Double Exposure (DE)

Basic ideas: - Double patterning
- Reduction of k_1 below the theoretical limit of 0.25 for a single print (pitch 100 nm, NA = 0.75, λ = 193 nm --> k_1 = 0.19)
- Separation of critical features aligned in X and in Y direction, resp., for improved OAI

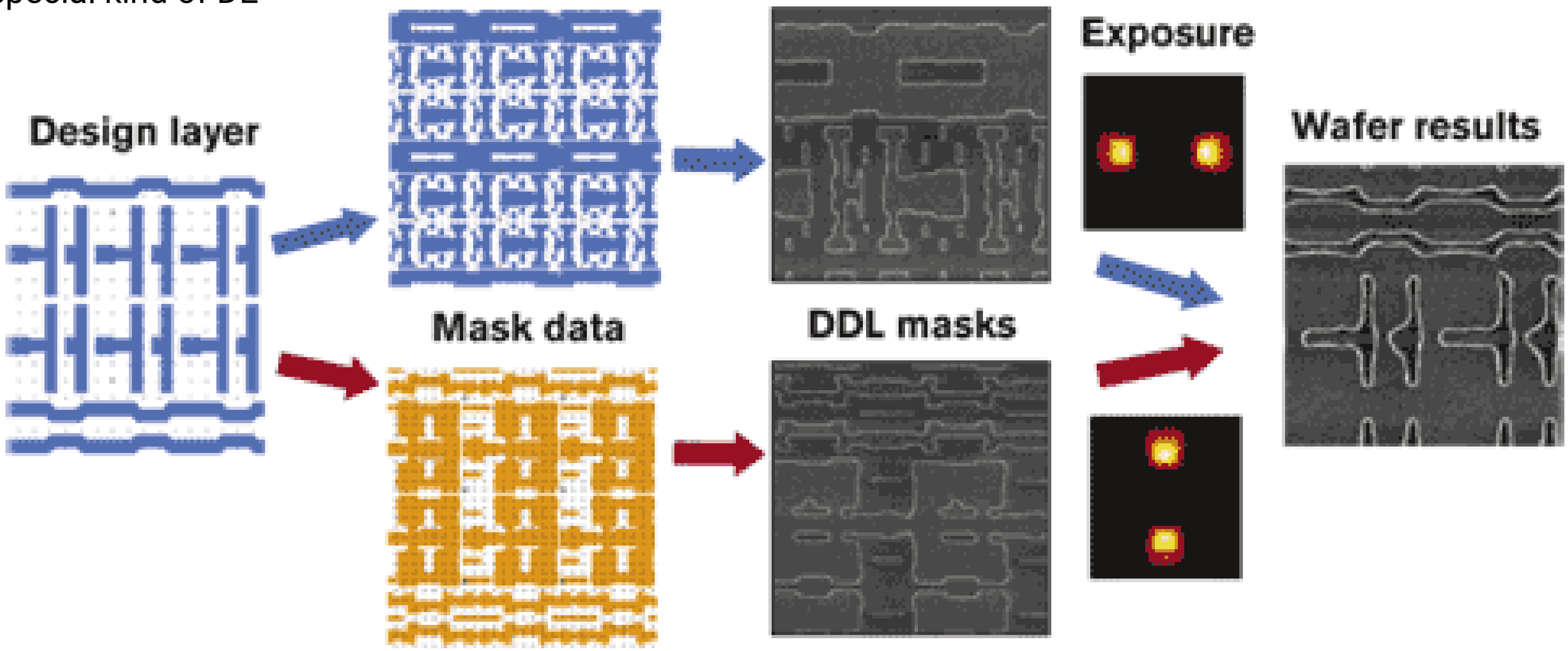
Double patterning approach to obtain 100 nm pitch structures with 193 nm optical lithography. Cross-sections of trenches after the second patterning step and after metallization. Corresponding electrical results are shown left.



Source: http://www.imec.be/wwwinter/mediacenter/en/SR2005/html/142317.html

Double Dipole Lithography (DDL)

- special kind of DE

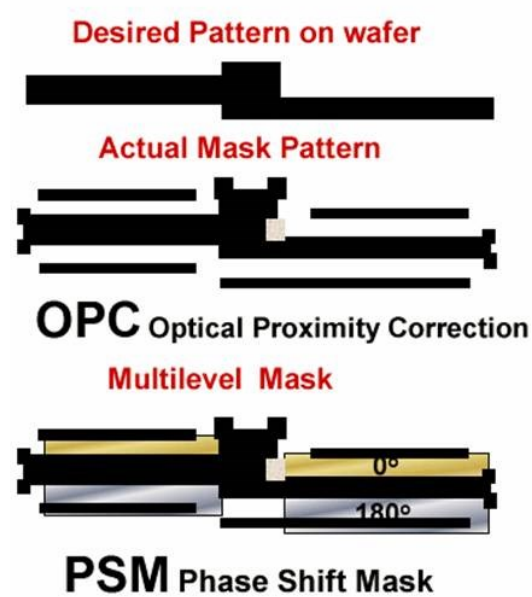


Double dipole lithography (DDL) breaks a mask into two layers, one with critical features aligned in the X axis, and one with critical features aligned in the Y axis.

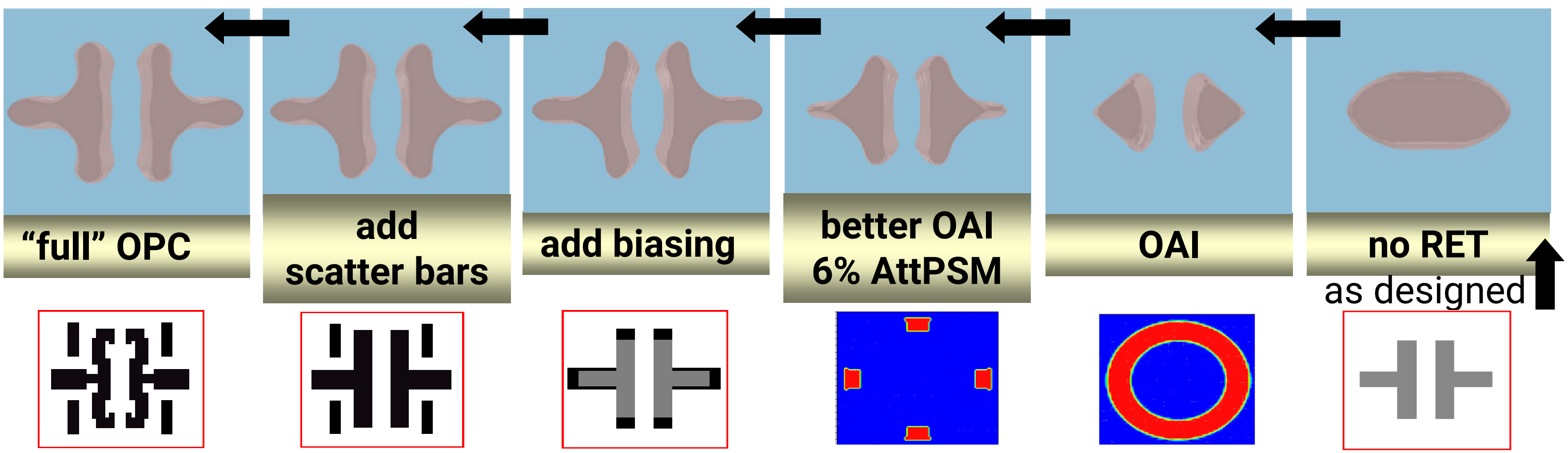
Source: S. Hsu et al., “65 nm Full-Chip Implementation Using Double Dipole Lithography,” *Proc. SPIE*, 2003, Vol. 5040, p. 215.

Combination of RET Solutions

- This is what the designer drew
- Added ‘scattering bars’ and serifs to make the polygon print more exactly
- Added additional phase features to allow printing smaller features at the same wavelength



Accurate and flexible modeling is key!



(Courtesy ASML)