Nanometer Scale Patterning and Processing

Spring 2016

Lecture 10

Optical Lithography - Resolution Enhancement Techniques (RETs) in Optical Project Lithography

Minimum Linewidth (0.5*p*)

$$W_{min} = k_1 \lambda / \text{NA}$$

Process Window:

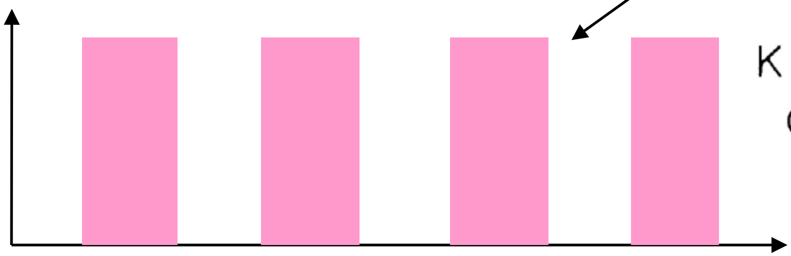
Depth of focus

$$R = 2\lambda / 4(\text{NA})^2$$

$$= \lambda / 2(\text{NA})^2$$

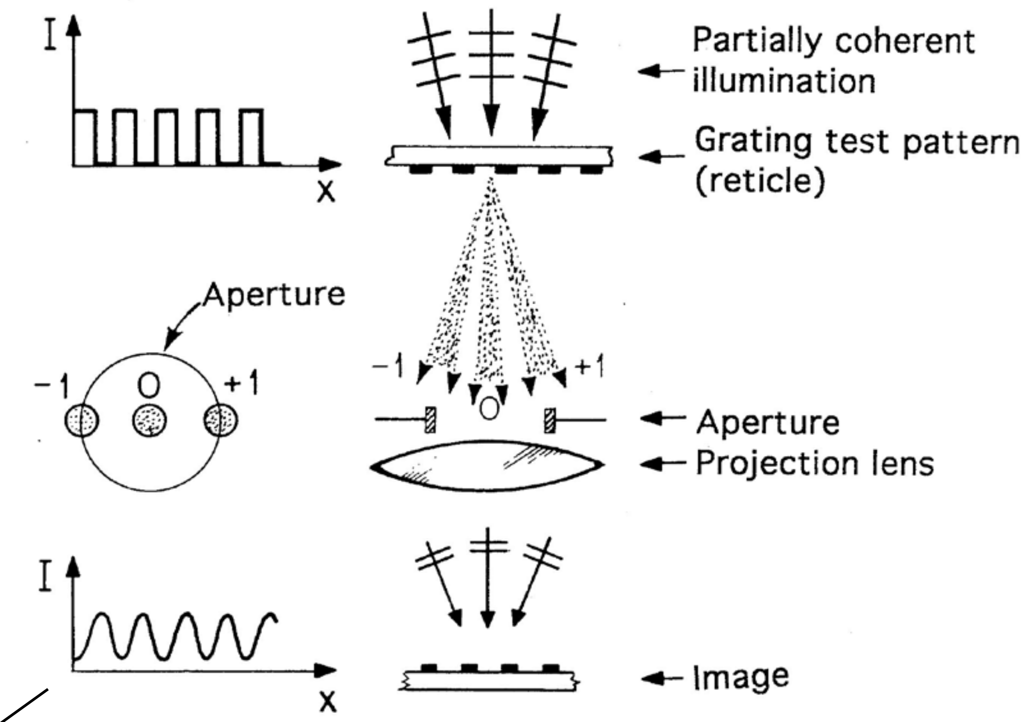
Contrast

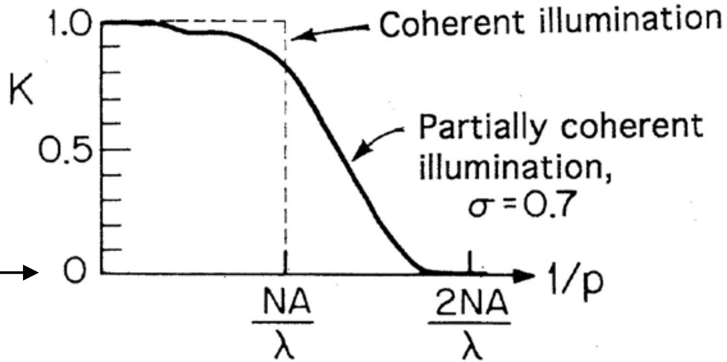
$$K = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}.$$



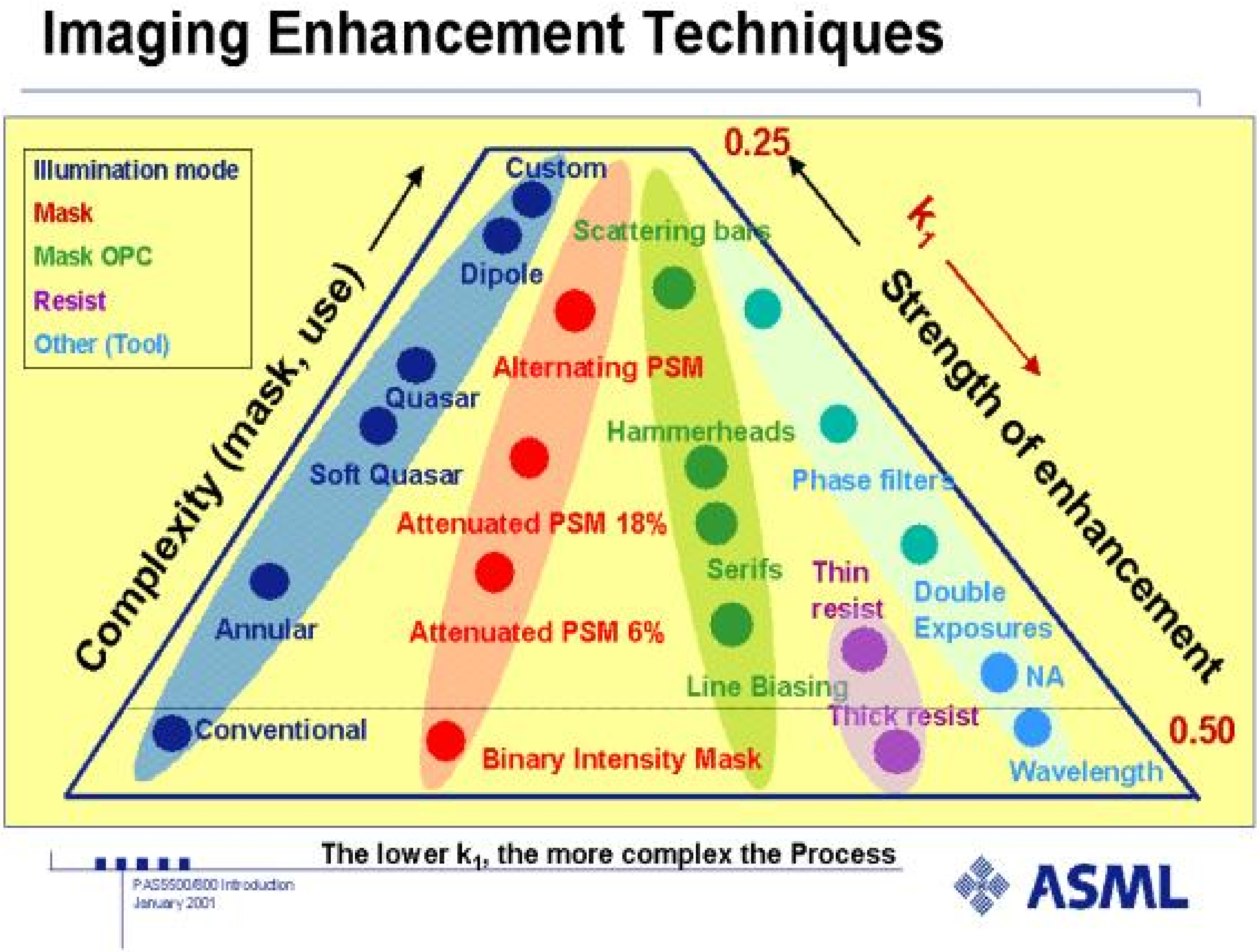
Developed resist profile

Optical Projection Lithography





Meet Lithography Requirements without Drastic Infrastructure Changes



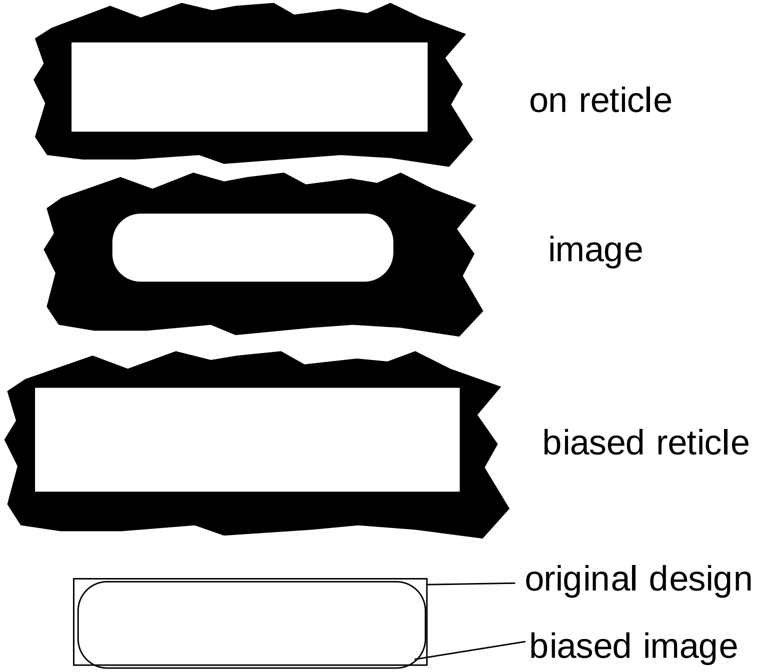
Imaging Enhancement Techniques

The lower k_1, the more complex the Process

PAS5500/800 Introduction
January 2001

Resolution Enhancement Techniques (RETs)

Linewidth biasing

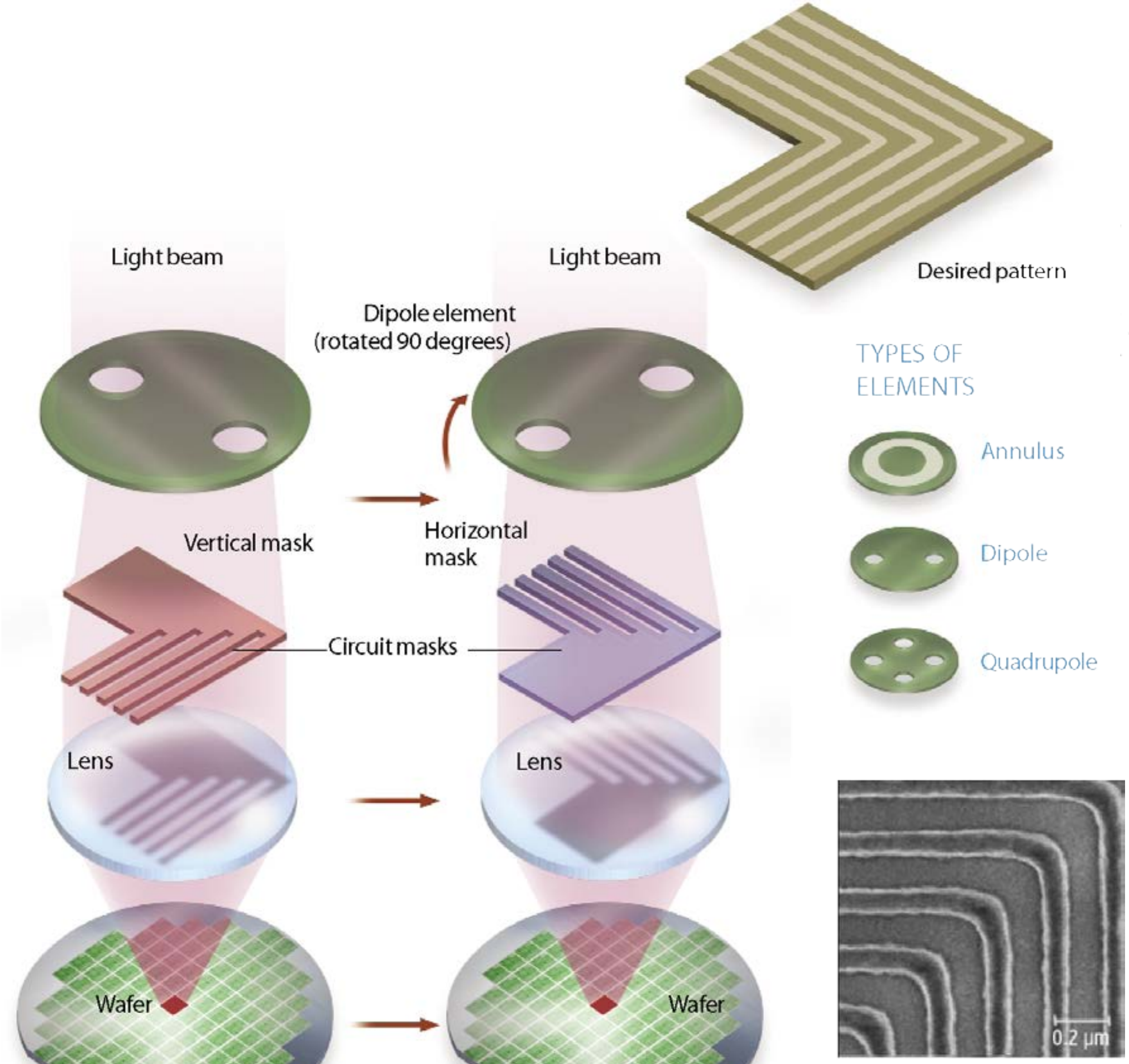


Earliest form of optical proximity compensation,

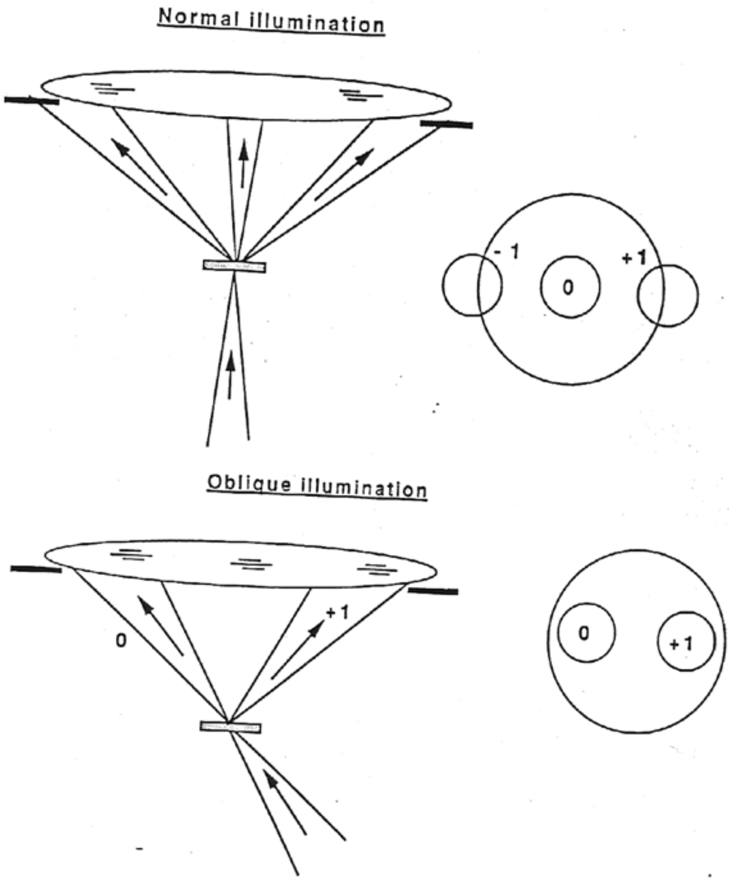
Improves pattern fidelity, but not increasing resolution or contrast

Should use *Imaging Enhancement Techniques* rather than RETs

RET 1: Partially Coherent Illumination

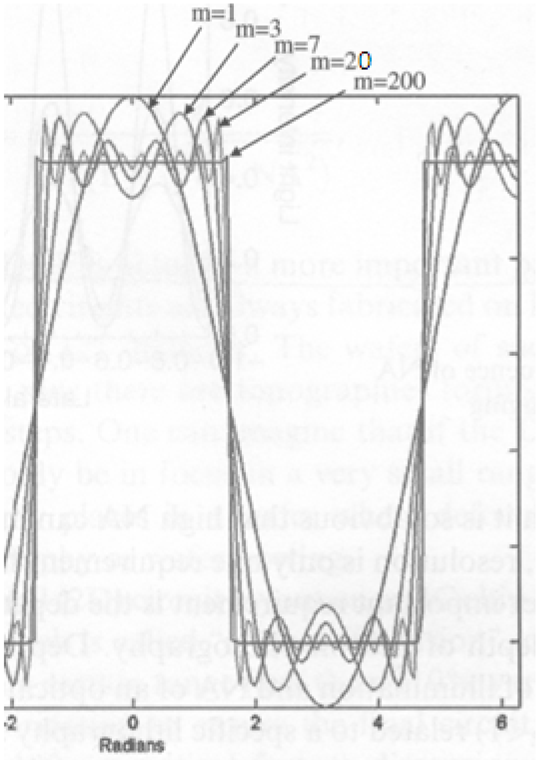


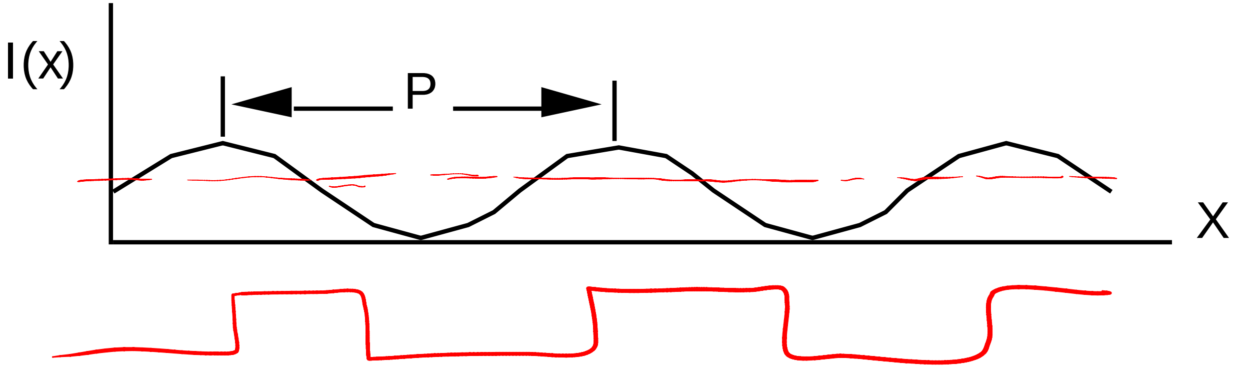
Pattern on wafer after dipole double exposure

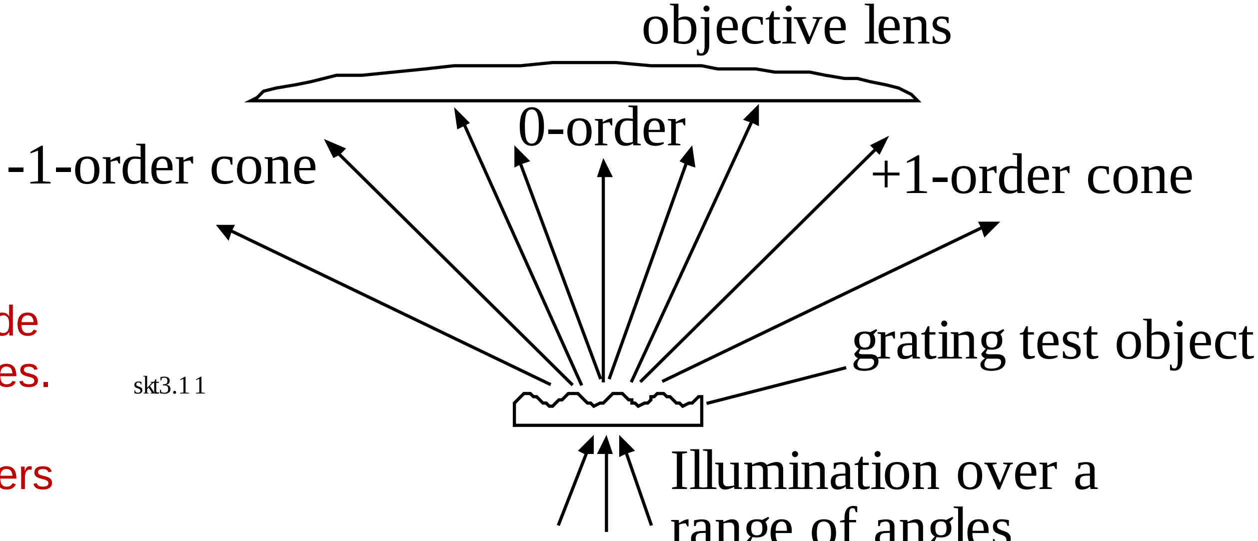


- More order of diffraction
- Reduces contrast
- Pattern dependent
- Best for Manhattan Structures

Image contrast



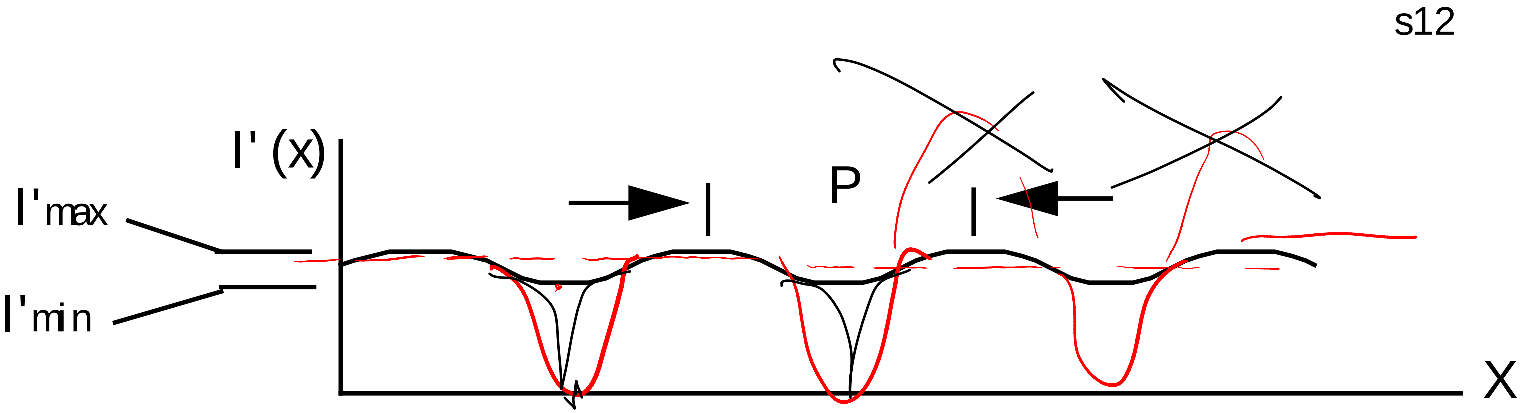


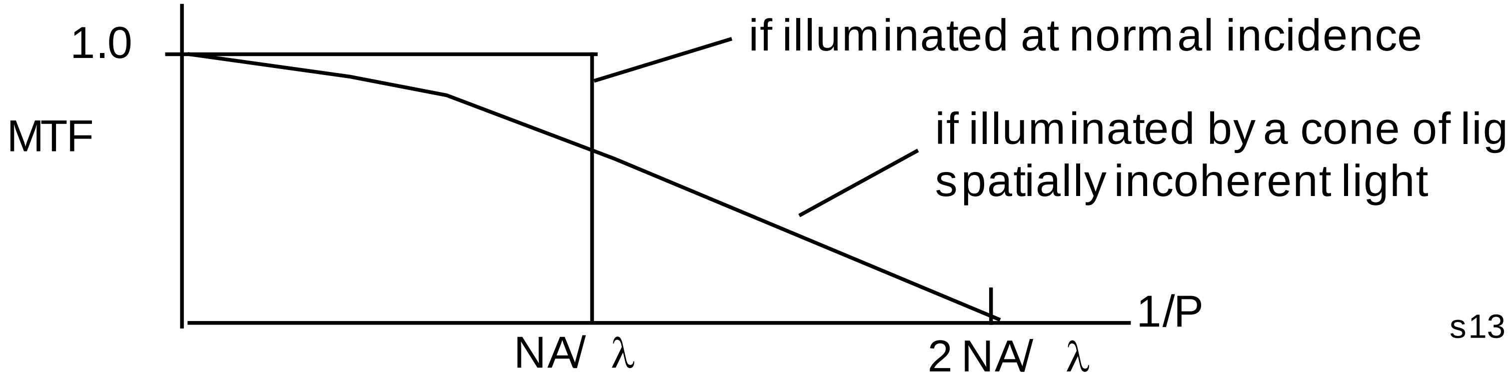


Higher order diffractions provide
Additional details of the features.

But at least two diffraction orders
need to be captured

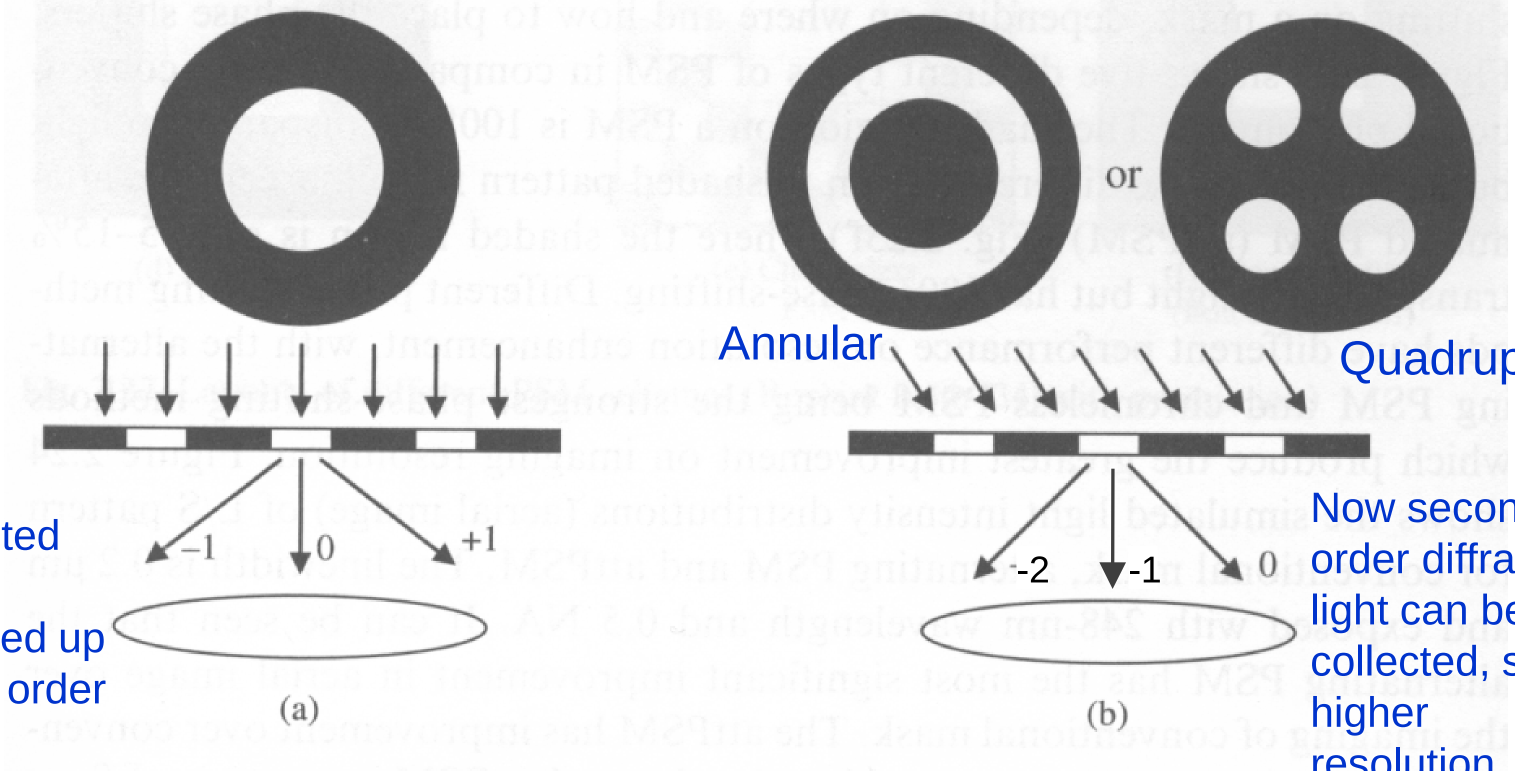
Modulation-Transfer Function (MTF)





$$MTF = \frac{I'(\max) - I'(\min)}{I(\max) - I(\min)}$$

Types of Off Axis Illumination (OAI)



Conventional illumination

Off-axis illumination

Annular

Quadrupole

Diffracted light collected up to first order

Now second order diffracted light can be collected, so higher resolution

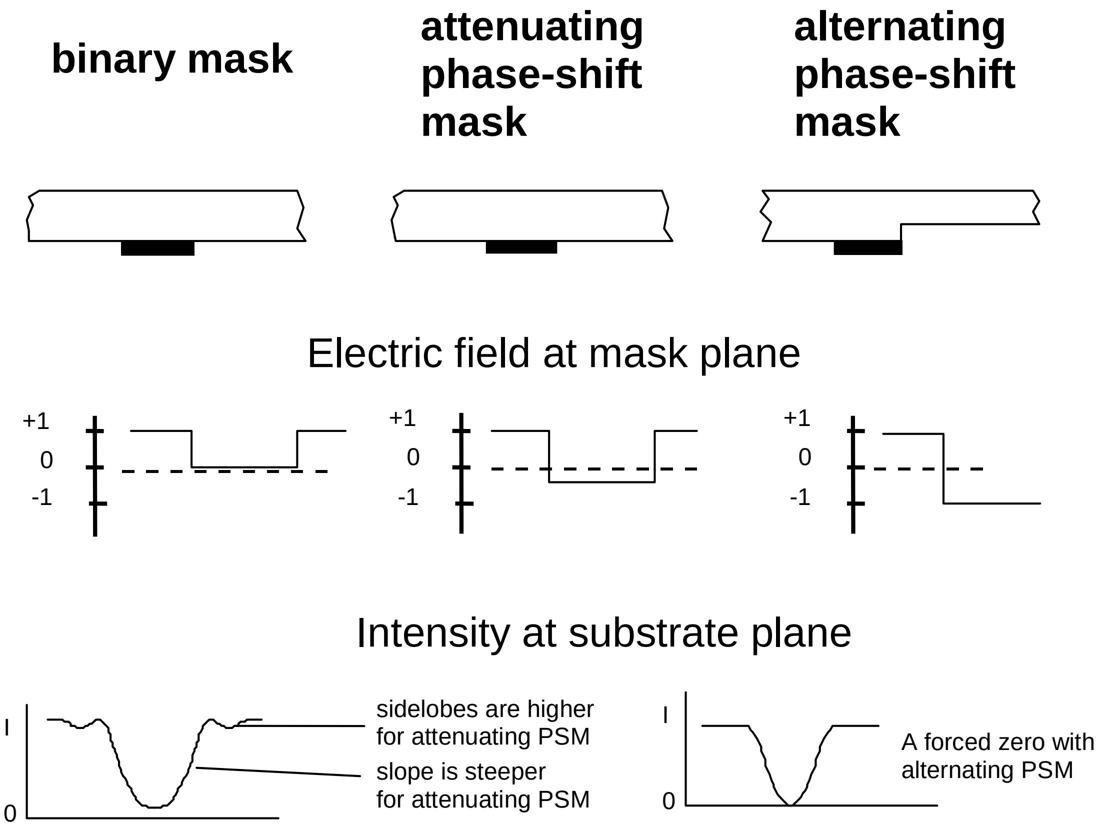
Fig. 2.21 Comparison of conventional and off-axis illumination schemes: (**a**) conventional aperture (**b**) off-axis apertures (annular or quadrupole)

Quadrupole: most effective for line/space pattern (depends on line orientation, best for vertical or horizontal line/space pattern), less for isolated features.

Annular OAI: less resolution enhancement, but orientation independent.

Easiest and cheapest RET, state-of-art OAI apparatus are programmable for each set of masks.

RET 2: Phase-Shifting Masks (PSM)



binary mask

attenuating phase-shift mask

alternating phase-shift mask

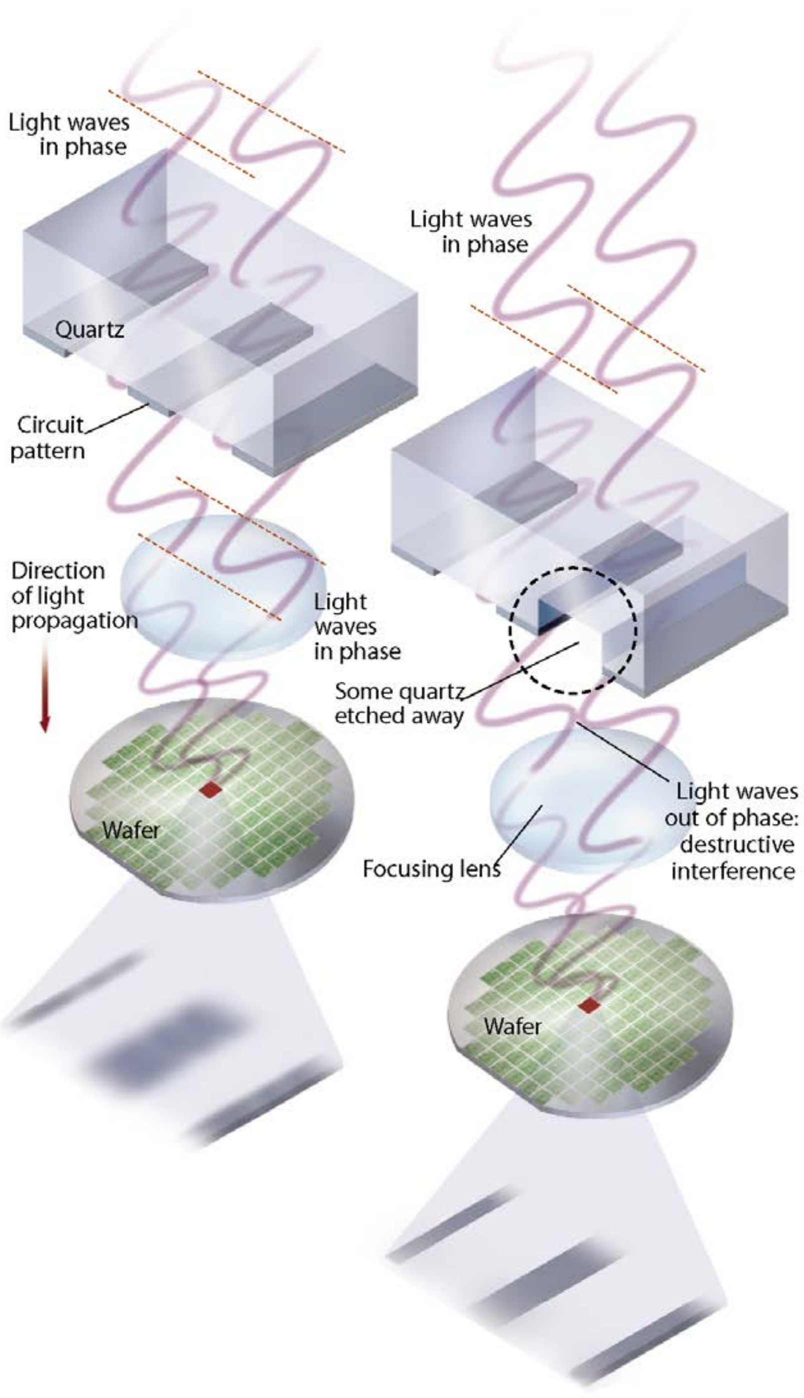
Electric field at mask plane

Intensity at substrate plane

sidelobes are higher for attenuating PSM

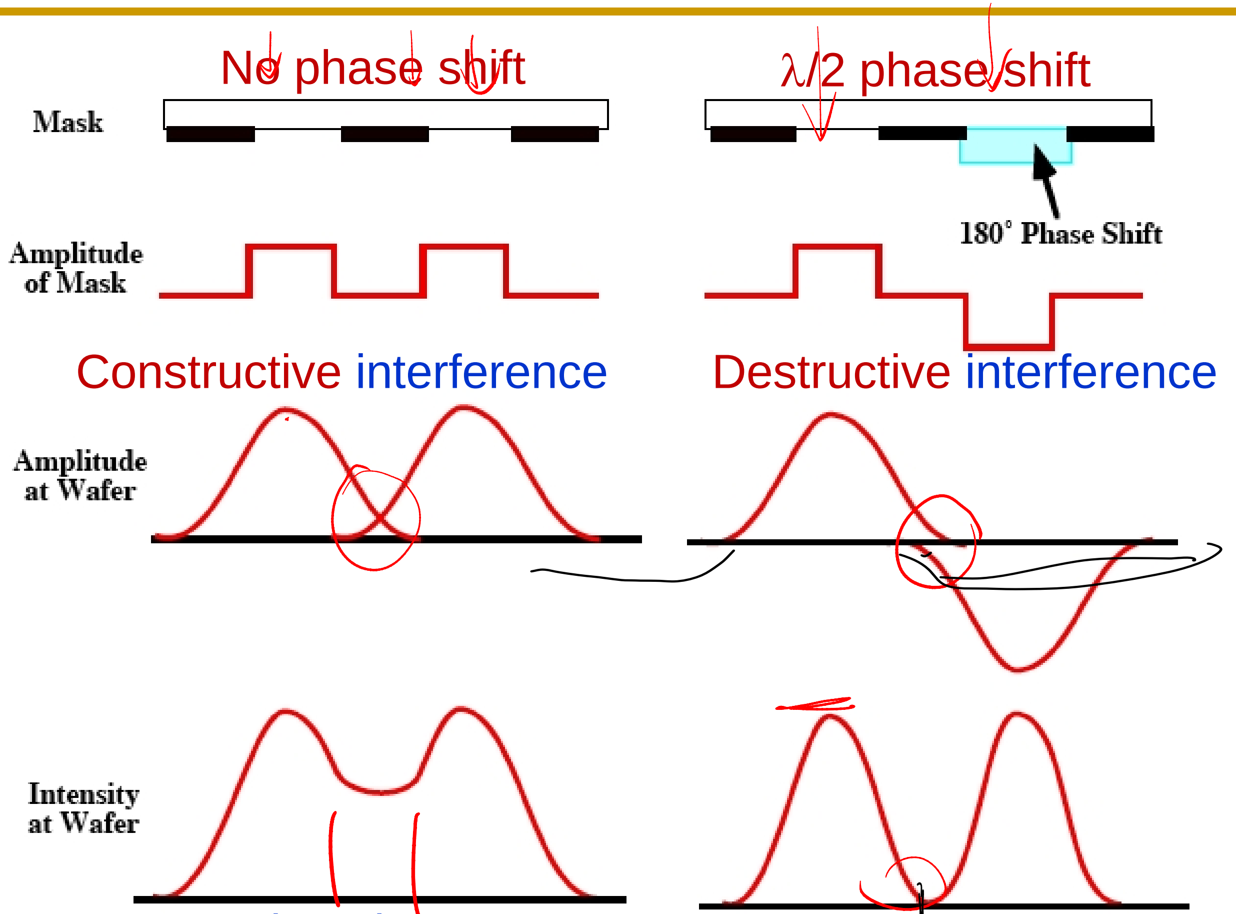
slope is steeper for attenuating PSM

A forced zero with alternating PSM



- Increases the contrast, not resolution
- Extensive calculation and pre-compensation
- Increases mask cost

Alternating Phase Shift Mask



No phase shift

λ/2 phase shift

Constructive interference

Destructive interference

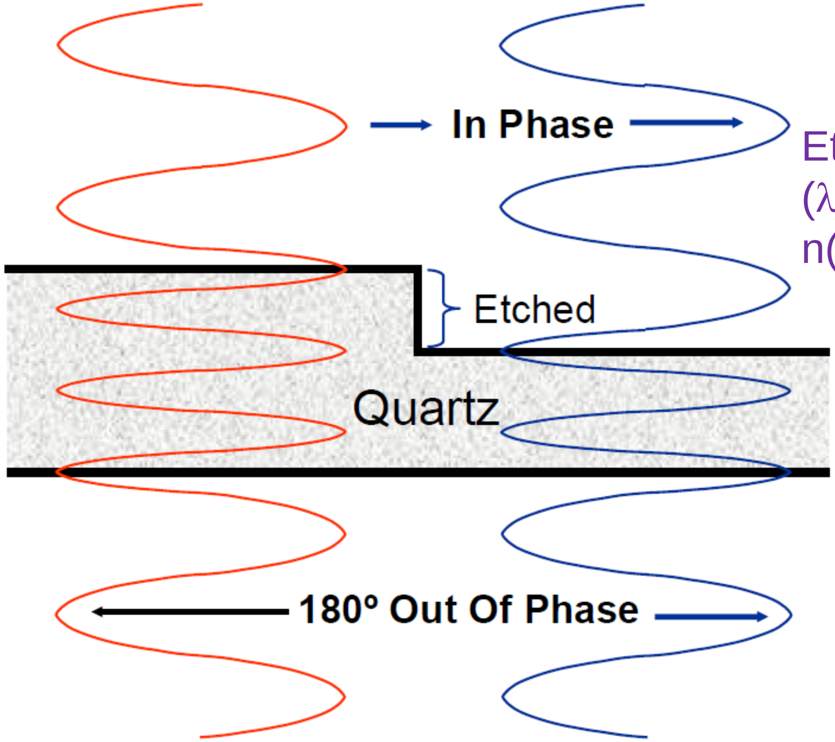
Reduced contrast

Reduced line-width

Improved contrast, higher resolution (HP)

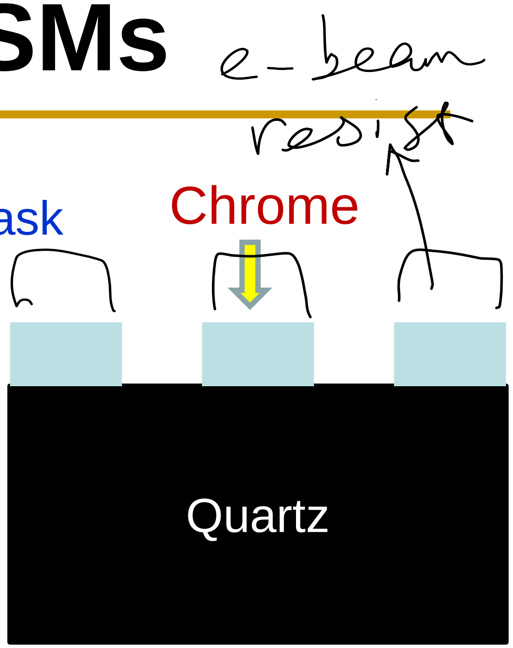
- PSM changes the phase of light by 180° in adjacent patterns, leading to destructive interference rather than constructive interference.
- Improves contrast of aerial image on wafer. Making k_1 smaller.

Fabrication of Alternating PSMs

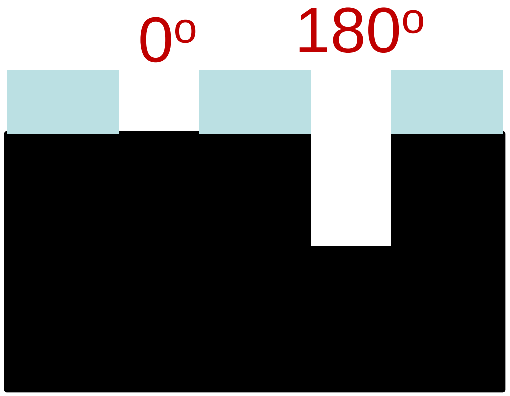


Etch depth:
(λ/2)/(1.56-1)=172nm
n(quartz)=1.56

Standard mask



Phase-
shift mask

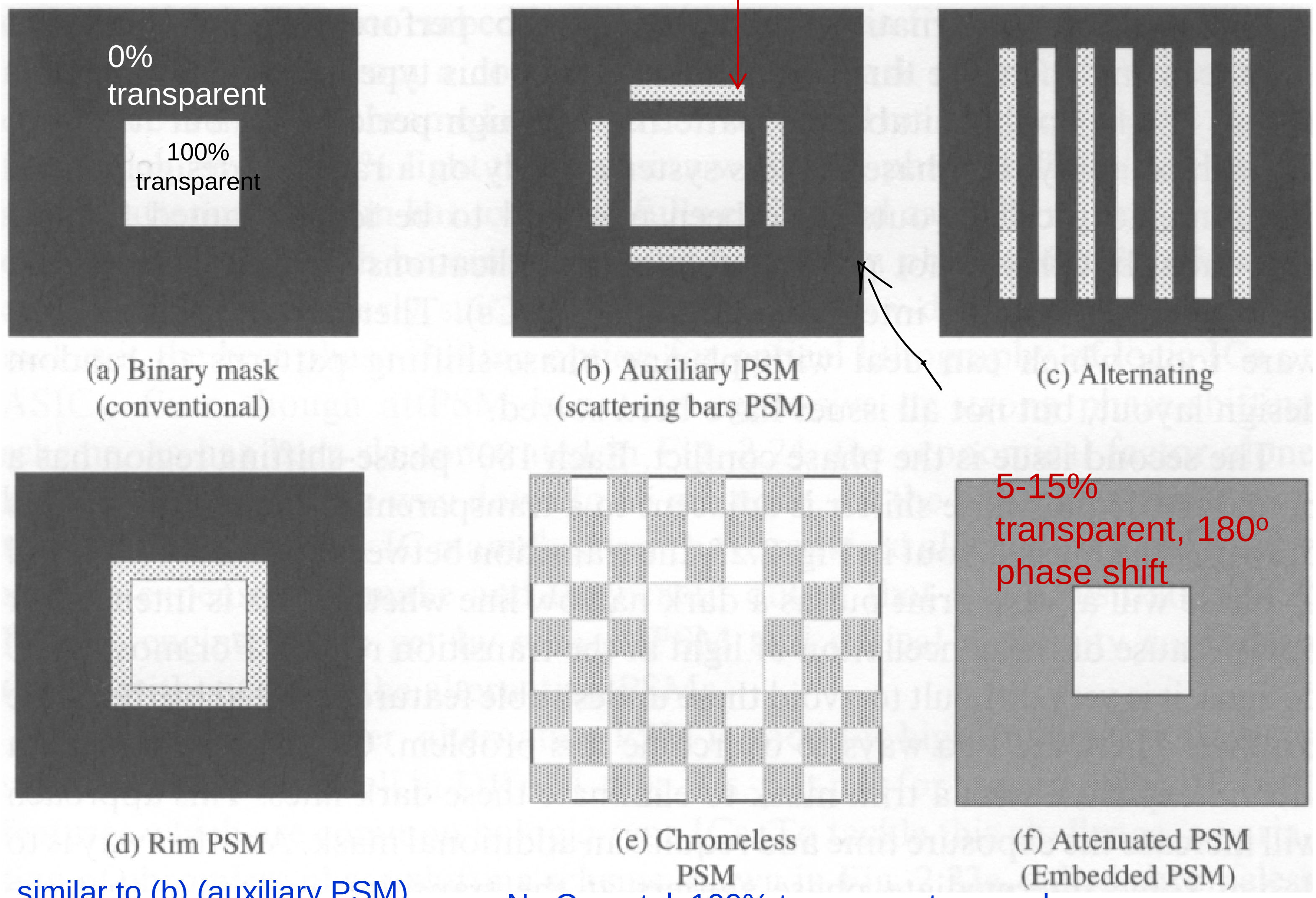


Quartz etched to induce shift in phase

- Need two patterning steps with accurate alignment.
- Fabrication cost 10× that of binary mask.

Different phase-shift mask schemes

Shaded region: 100% transparent, but 180º phase shift



(a) Binary mask (conventional)

(b) Auxiliary PSM (scattering bars PSM)

(c) Alternating

(d) Rim PSM

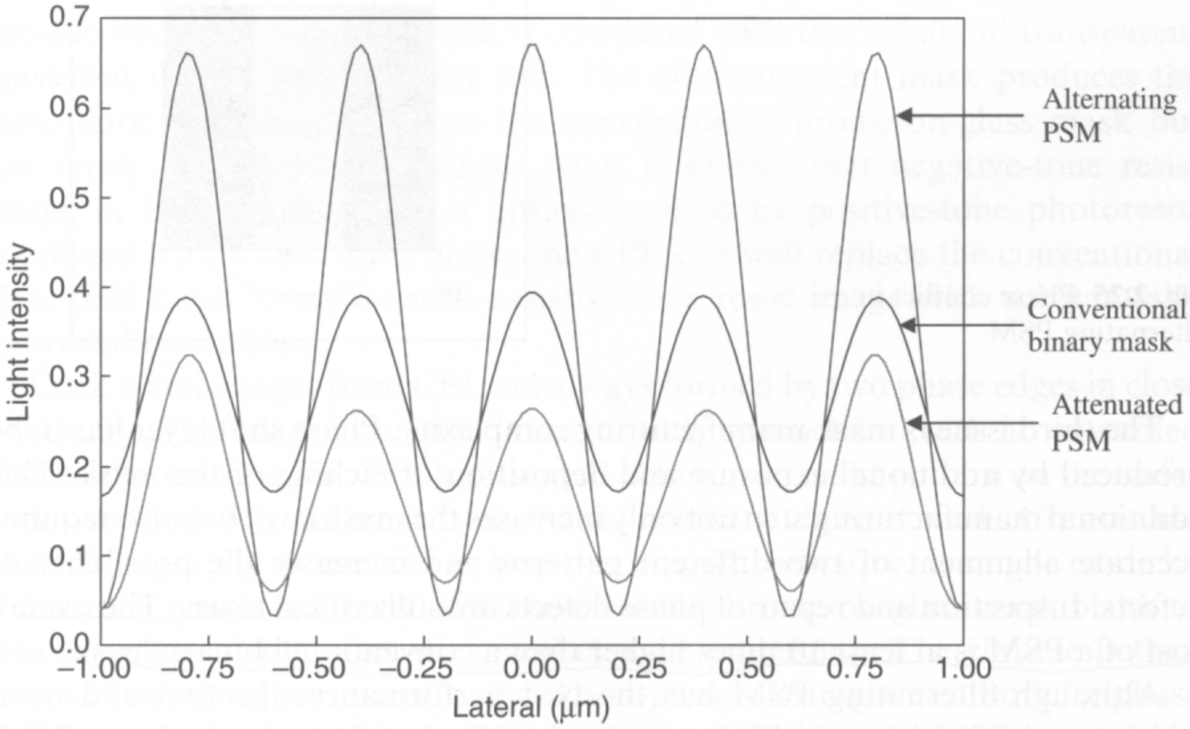
(e) Chromeless PSM

(f) Attenuated PSM (Embedded PSM)

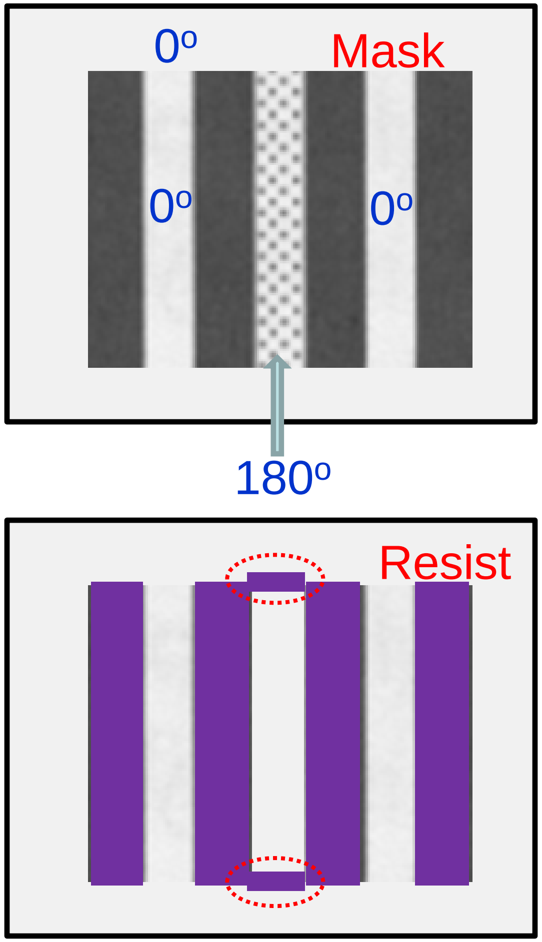
similar to (b) (auxiliary PSM)

No Cr metal: 100% transparent everywhere

Comparison of binary, alternating and attenuated PSM



Phase conflict



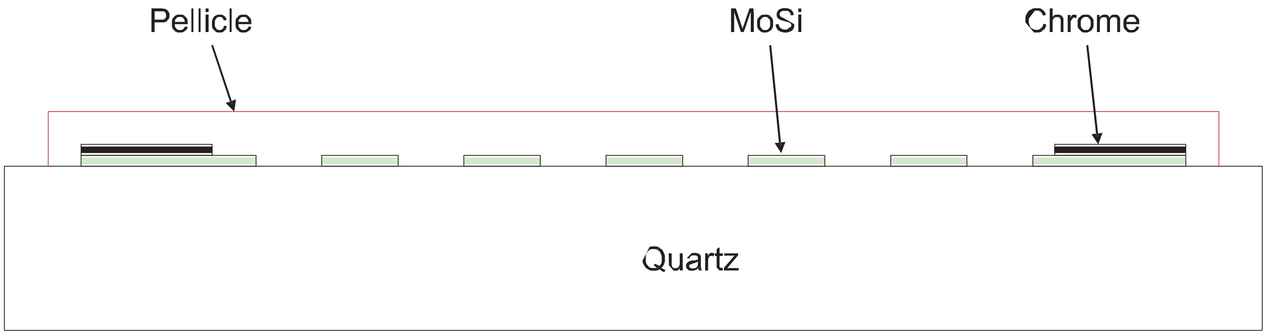
Positive resist after development

Alternating PSM gives highest contrast, but

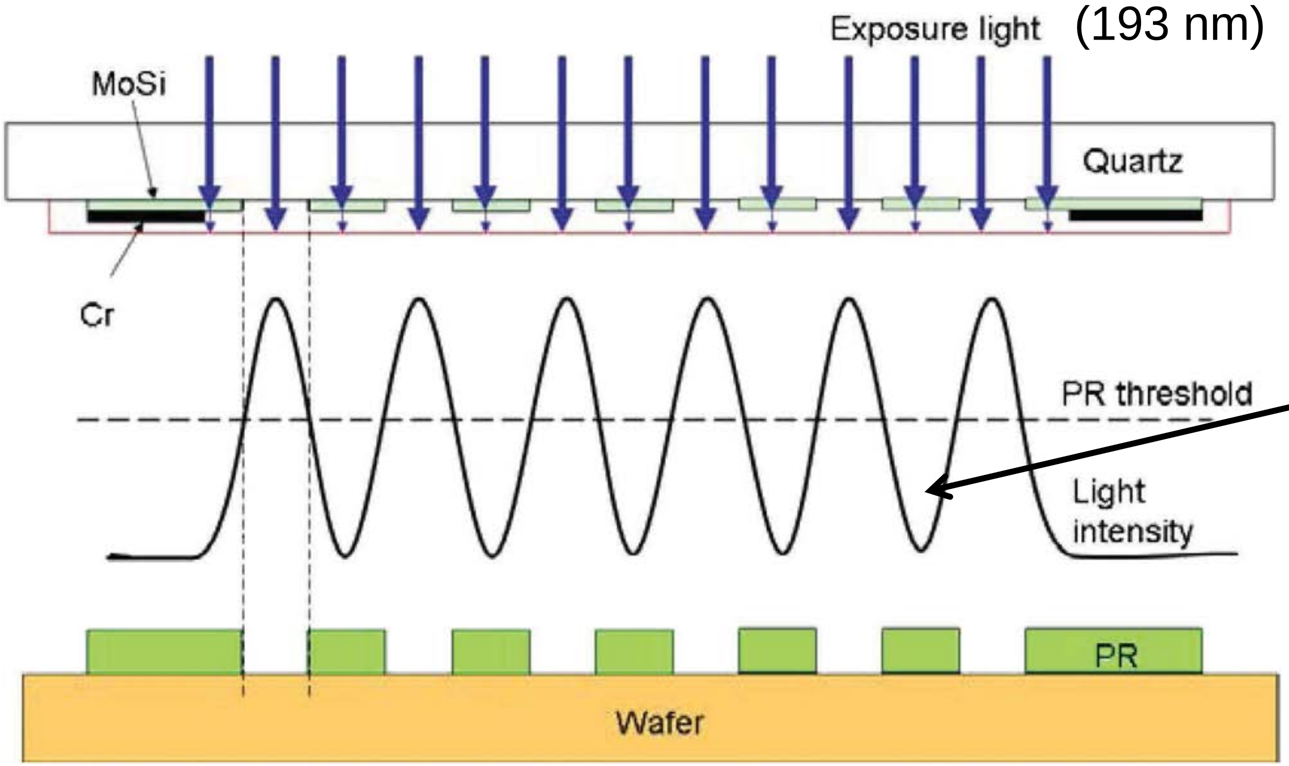
- It is good only for periodic structures (memory cell), not for random patterns (CMOS).
- Phase conflict may happen → undesired dark regions at the boundary of 0º and 180º phase.

In reality, the attenuated PSM is most widely used.

Attenuated Phase Shift Mask (AttPSM)



MoSi: 6-20% transmission, but induces a 180° phase shift for 193 nm light

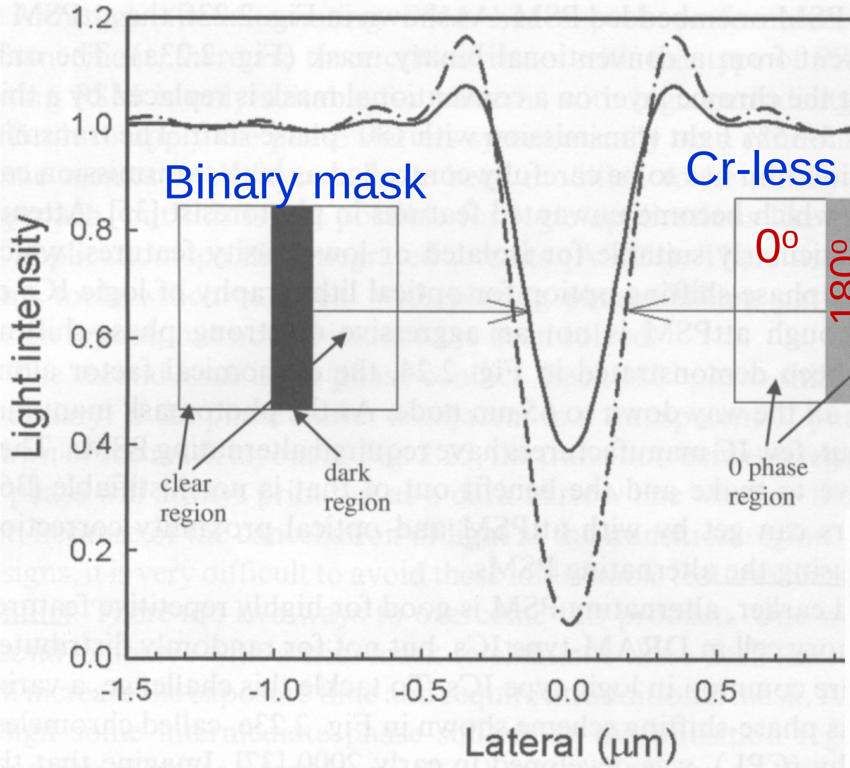


(193 nm)

Transmitted light cancels out the diffracted light from the clear apertures

The dominant technology today

Chromeless phase lithography (CPL)

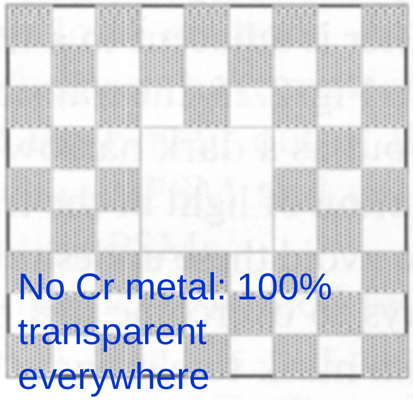


Binary mask

Cr-less phase mask

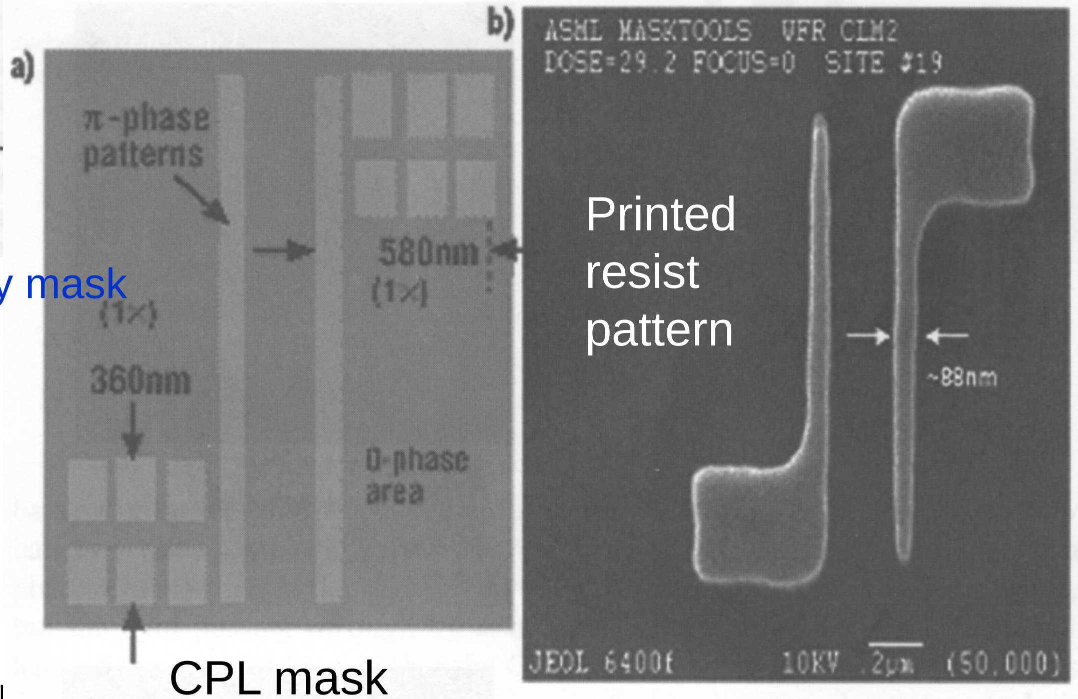
Comparison of CPL with conventional binary mask

CPL has better image contrast, thus higher process window.



No Cr metal: 100% transparent everywhere

(e) Chromeless PSM

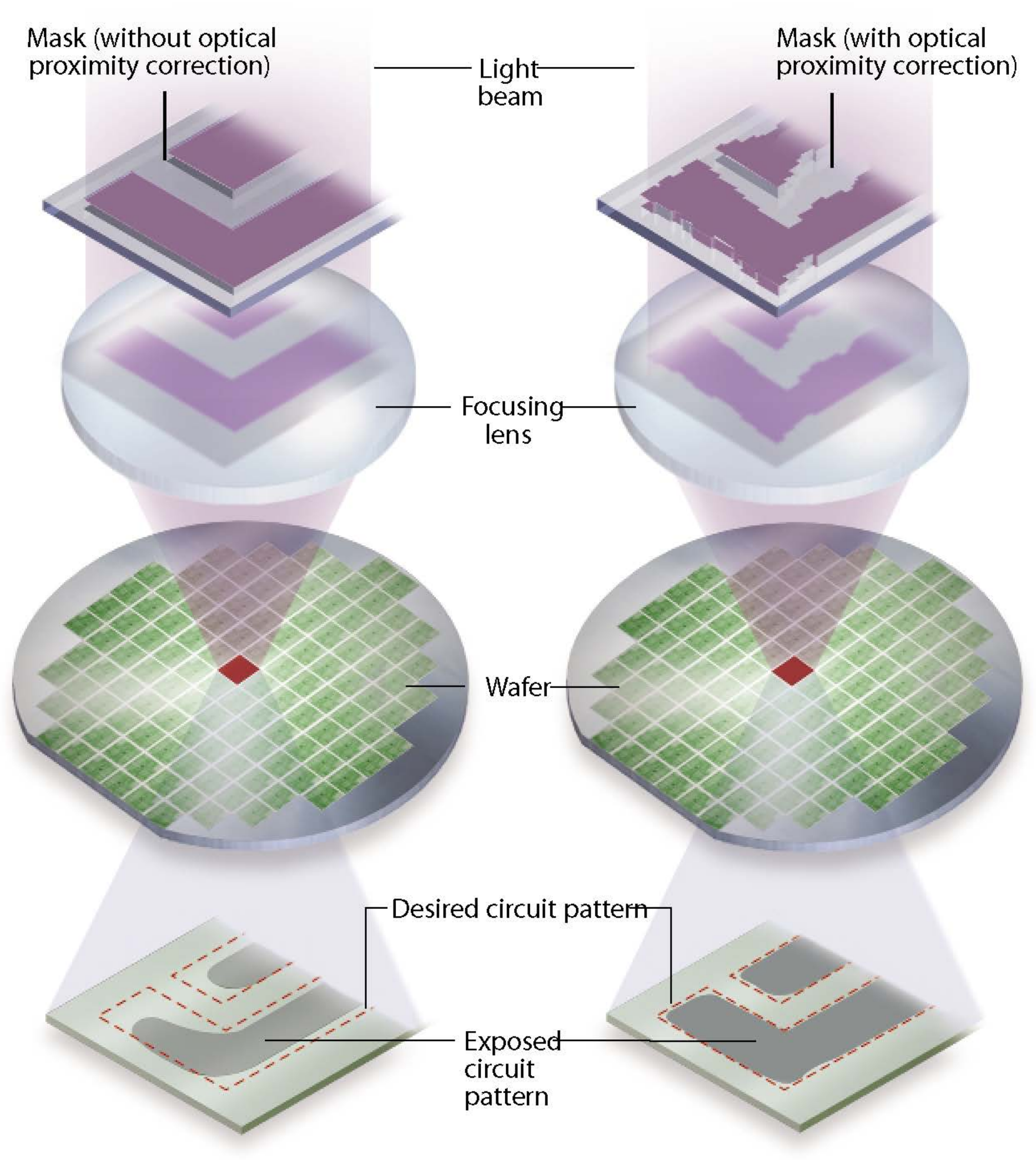


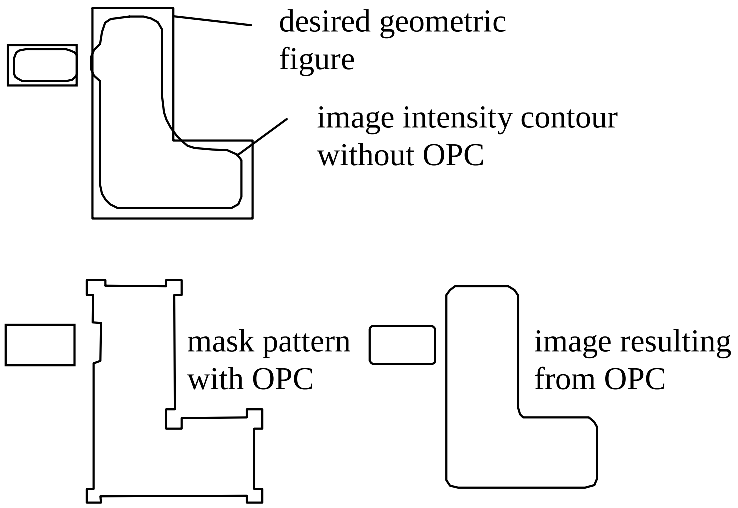
Printed resist pattern

CPL mask

Fig. 2.27 CPL mask and printed resist patterns (Reprint from [38] with permission)

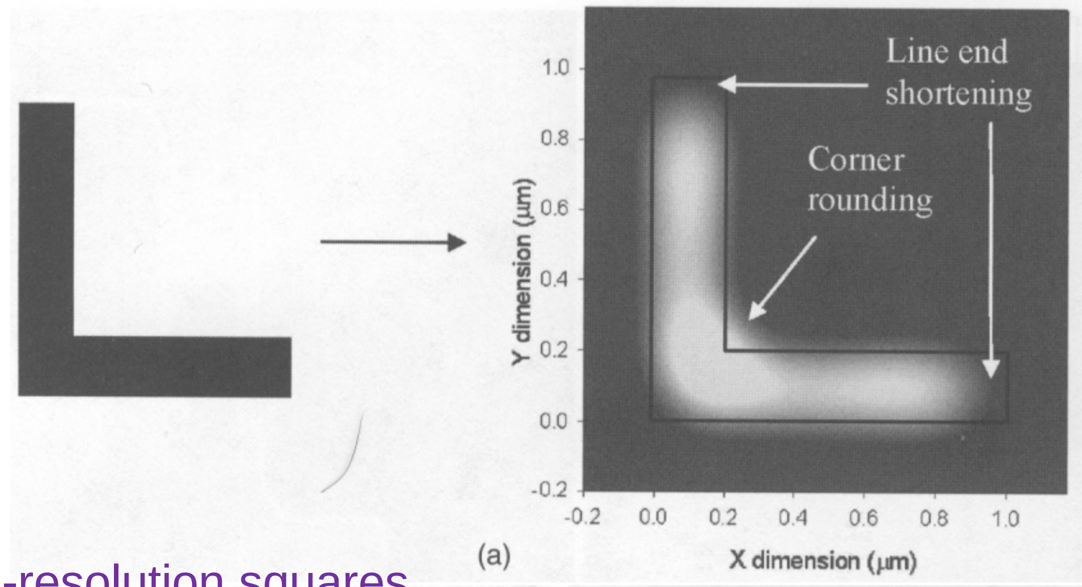
RET 3: Optical Proximity Correction (OPC)





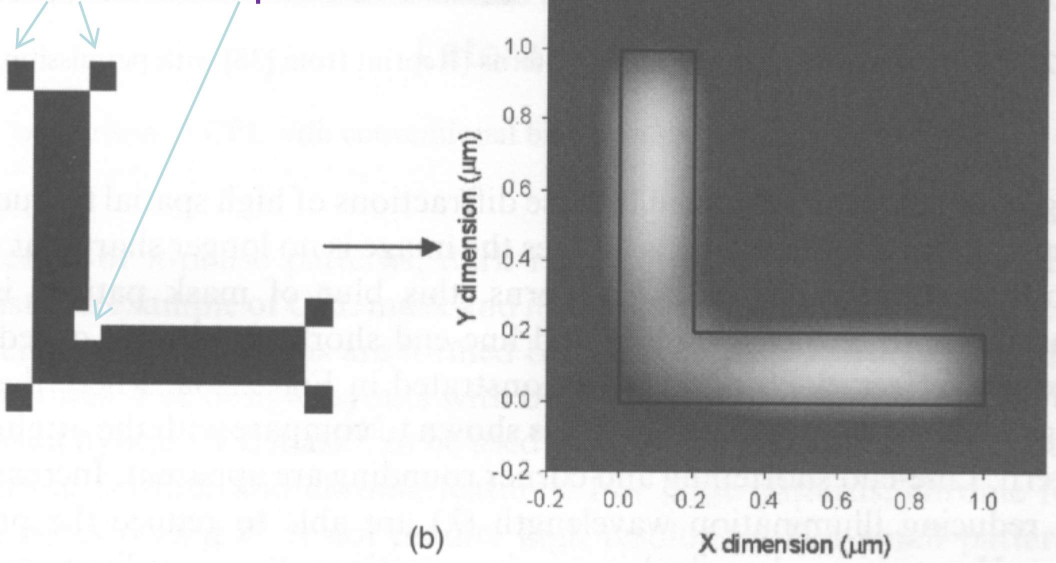
- Improves pattern fidelity
- Requires extremely high computation power (OPC correction is pattern dependent)
- Increases mask cost (defeats the advantages of 4x pattern reduction)

OPC by adding/taking away sub-resolution features



Optical proximity effect result in corner rounding and line-end shortening.

Sub-resolution squares

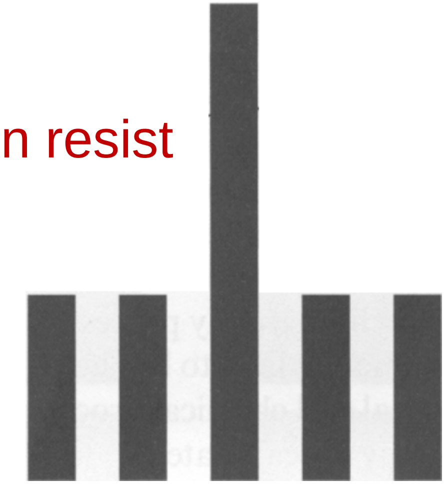


Optical proximity correction: modifies the mask design to restore the desired pattern.

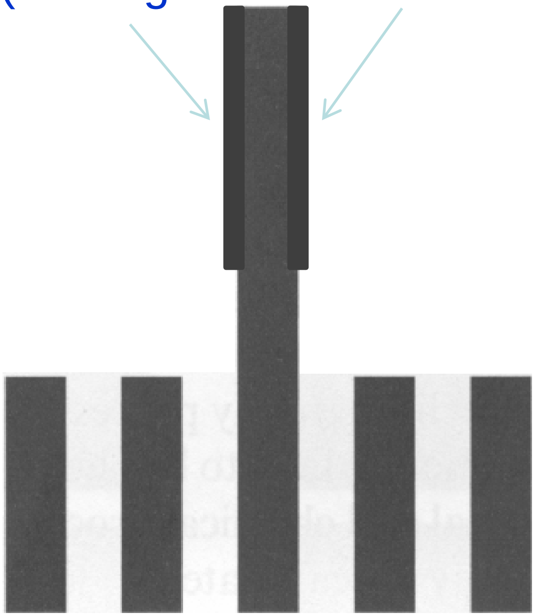
The sub-resolution features won't appear in the resist.

OPC: biasing or adding scattering bars

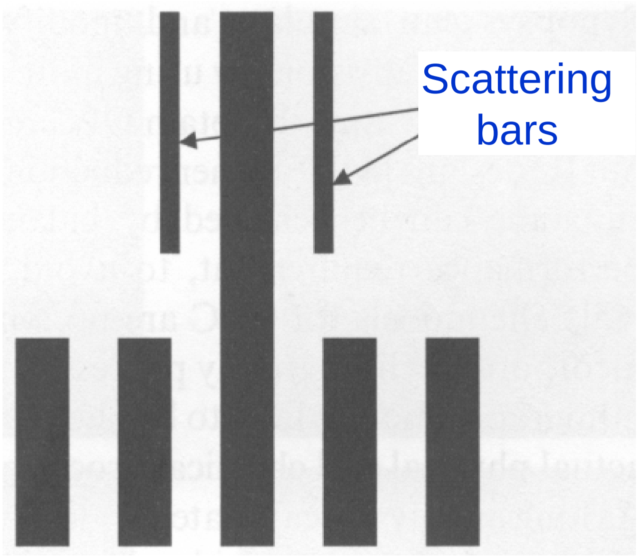
Desired dose in resist



Biasing (making isolated line wider)

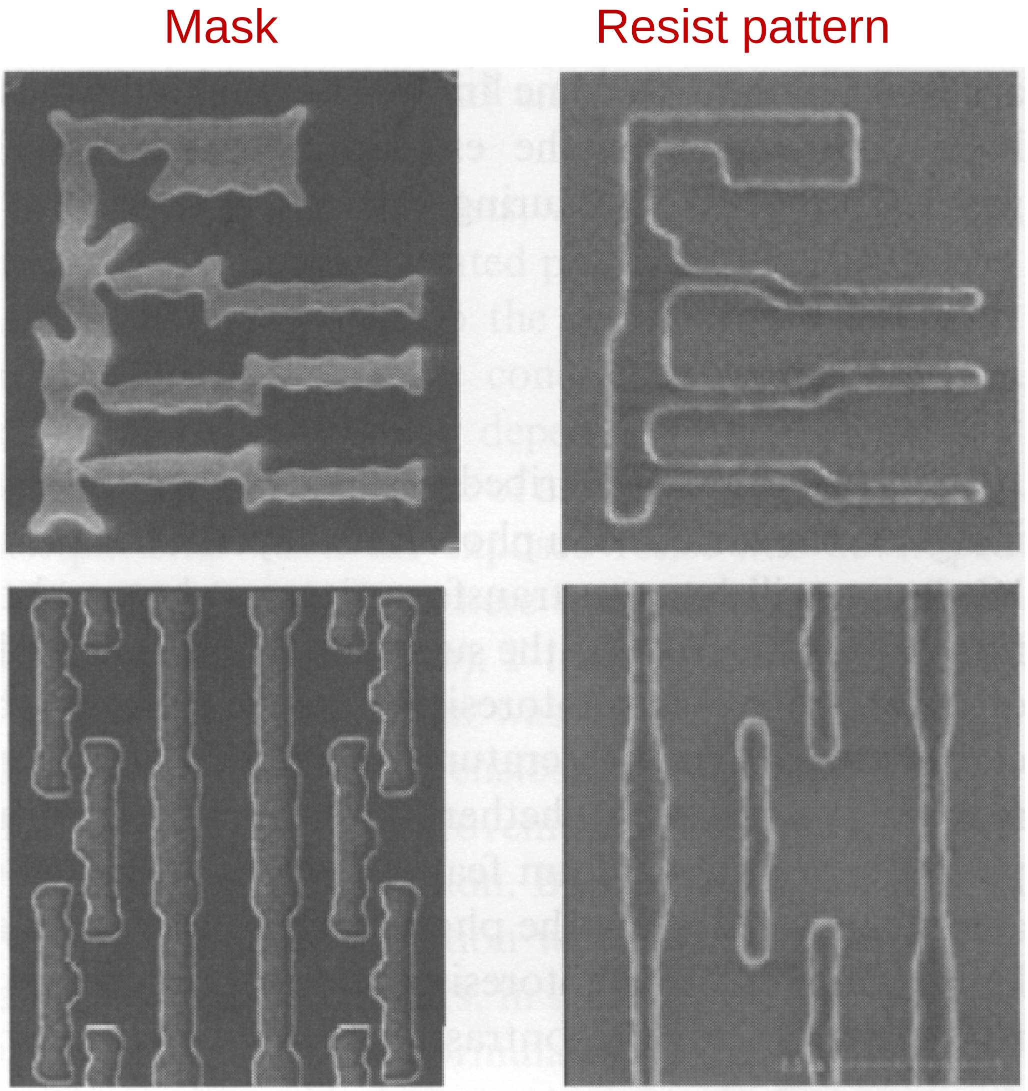


Adding (sub-resolution) scattering bars



Inverse lithography technology (ILT) (ultimate solution for OPC)

- Design the photomask by working out how an ideal image is generated. I.e. working backwards to find the “perfect” mask that can generate the ideal image.
- Very complicated math, data file for such a mask ~1000GB.
- Still limited by the resolution (pixel size) of the lithography used to make the mask.



Top: aggressive ILT mask.
Bottom: non-aggressive OPC mask.

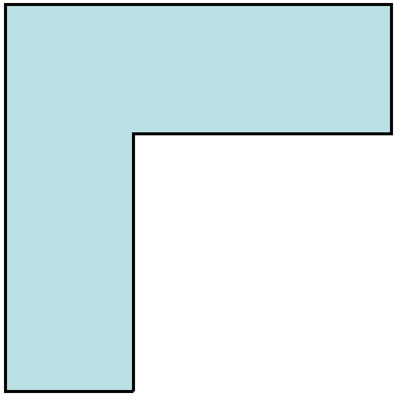
OPC Enables Resolution Enhancement

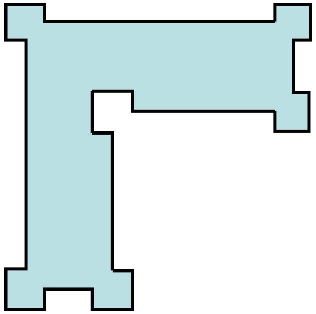
180nm Conventional mask

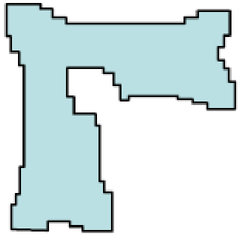
Rule-based OPC

Model-based OPC

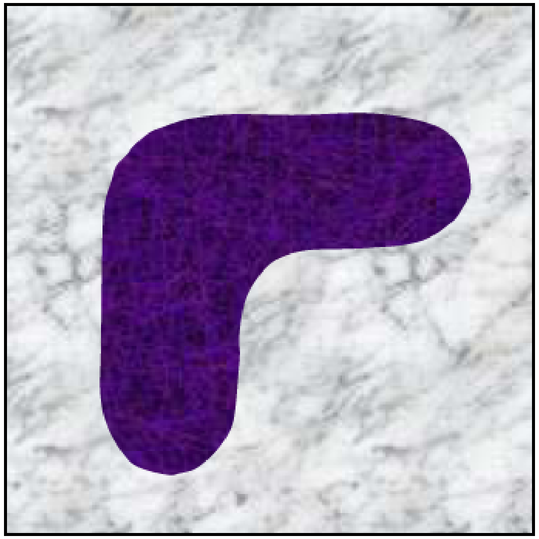
Mask

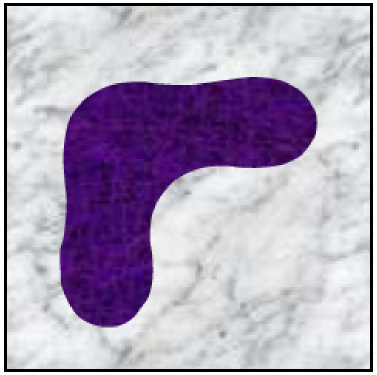


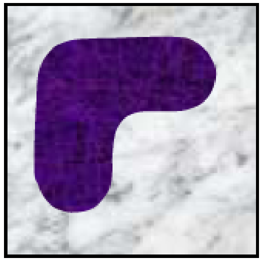




Wafer





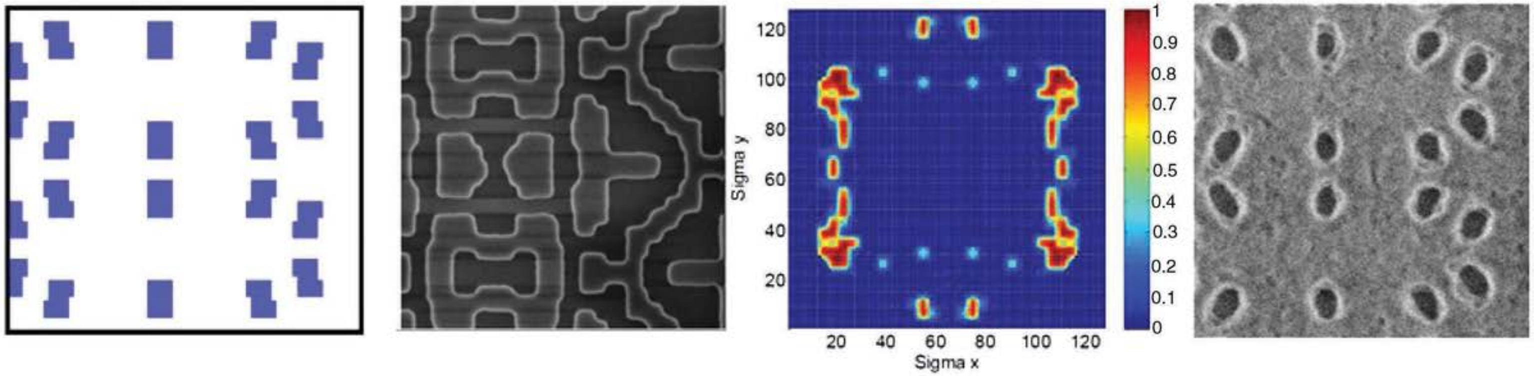


Rule-based OPC improves 130nm

Model-based OPC enables 100nm

Source Mask Optimization (SMO)

- Optimize Simultaneously the aperture features and mask patterns
- Does not require Phase Shift Masks



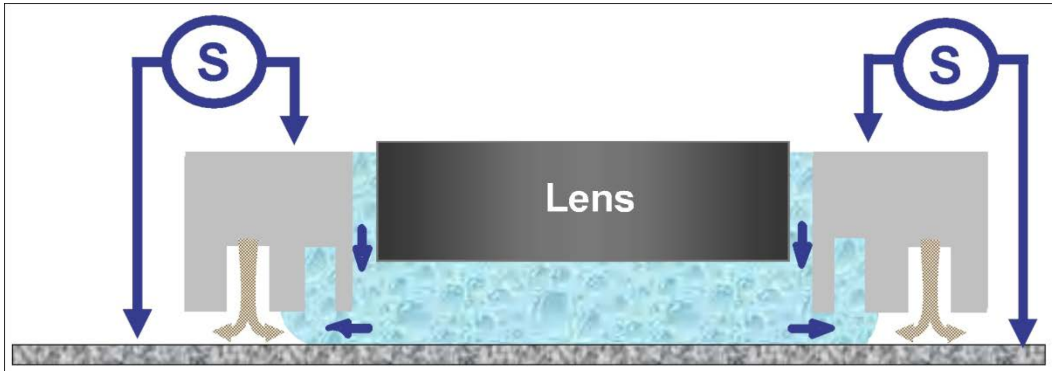
(a) (b) (c) (d)

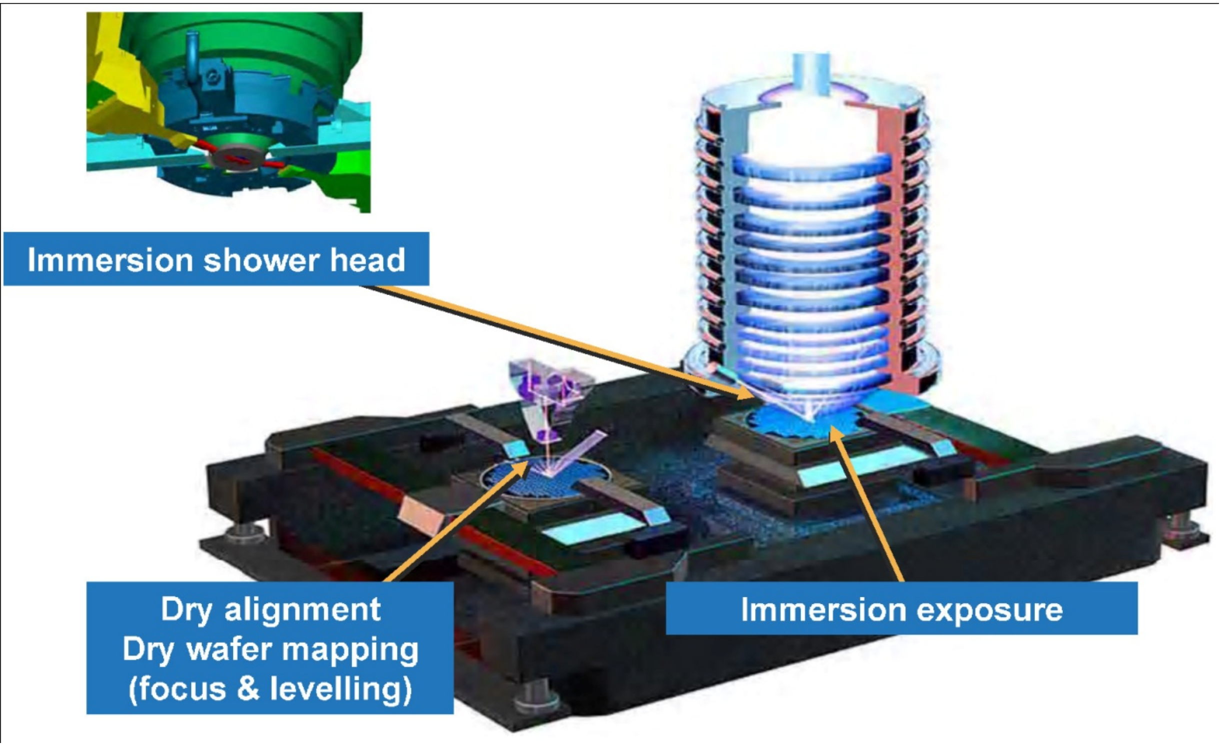
***Xiao* Figure 6.56** Example of SMO of contact photolithography: (a) design layout, (b) mask (binary, no PSM), (c) designed source, and (d) photoresist pattern on the wafer (K. Lai, et al., *Proc. of SPIE*).

OPC vs PPC (process proximity correction)

- Other processes (like etch) also have *proximity* effect.
- Presence or absence of neighbor will affect how a process behaves for a particular feature
  - Lithography ‘neighborhood’ is about 1μm.
  - Etch neighborhood is probably few microns (free radical diffusion length).
  - CMP (chemical mechanical polishing) neighborhood can be few mm.
- Correcting for optical (lithography) and few other processes is called *process proximity correction* (PPC).
- Typically lithography + etch corrections are used for PPC.
- CMP corrections are at a different (larger) scale: dummy features added to make the feature distribution more even across the wafer.

RET 4: Liquid Immersion





- Increases *n*, thus NA
- Currently the liquid is water
- New liquid under development
- Limited by indices of immersion liquid or final lens

Immersion: Increase NA to > 1

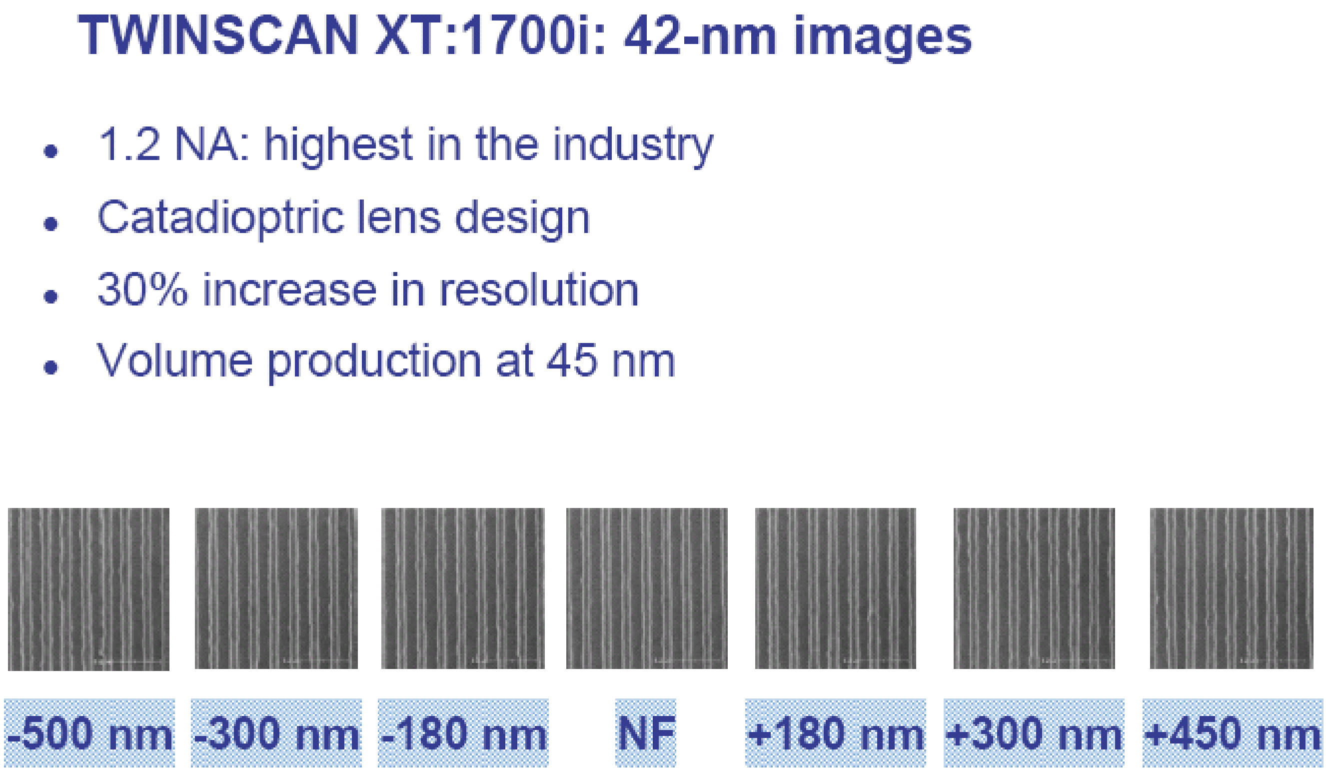
- Very simple idea. Indeed, immersion is NOT new for optical imaging: oil immersion in optical microscope has been used for a century.
- But Immersion lithography is highly complex, and was adopted by semiconductor industry only recently (since 2004).

From research idea

to development

Like chemical mechanical polishing (CMP) used for IC interconnection, immersion lithography has been considered as impractical at the beginning.

Lithography Example



TWINSCAN XT:1700i: 42-nm images

- 1.2 NA: highest in the industry
- Catadioptric lens design
- 30% increase in resolution
- Volume production at 45 nm

-500 nm -300 nm -180 nm NF +180 nm +300 nm +450 nm

42 nm HP, 84 nm pitch
NA = 1.2, σ=0.89/0.98 dipole X-35, polarized
Resist: 120 nm FFEM RK 2101
BARC: 42 nm 1C5D
Top coat: 140 nm TILC019
Tool: XT:1700Fi

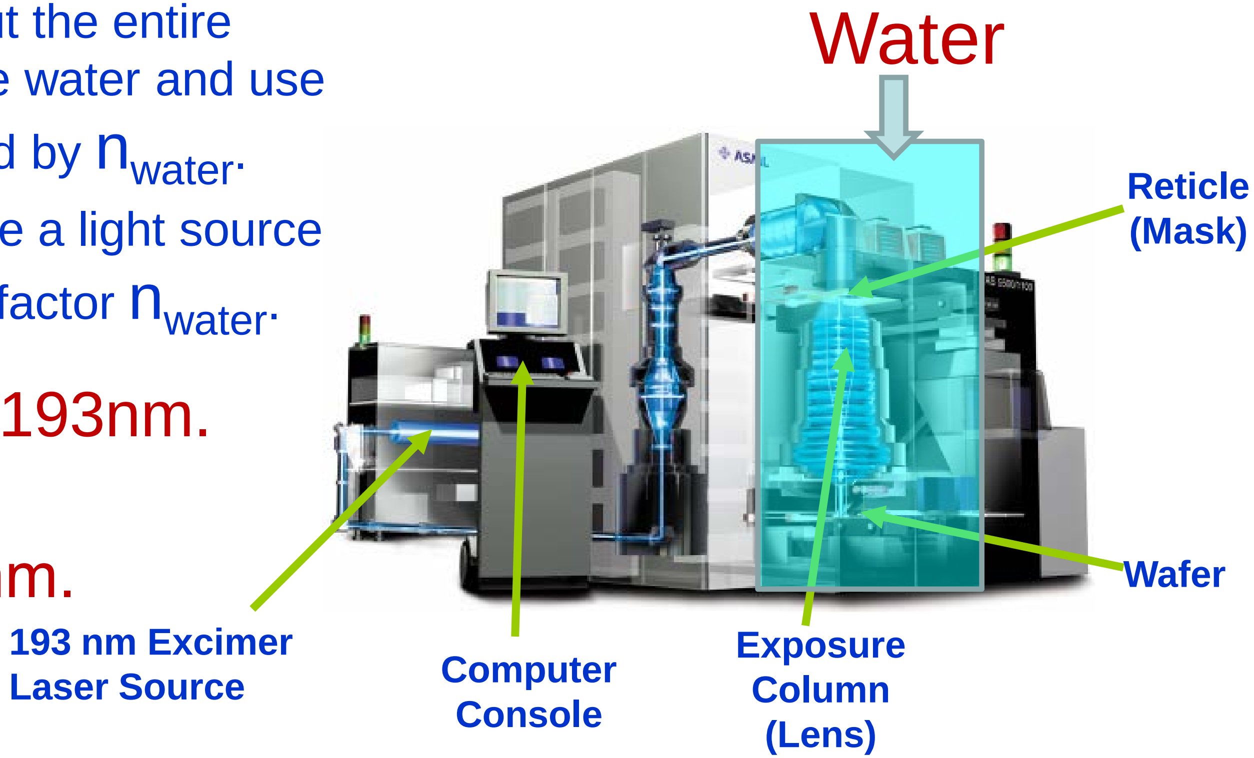
What to be Immersed?

$$R = k_1 \frac{\lambda}{NA} = k_1 \frac{\lambda}{n \sin\theta} = k_1 \frac{\lambda / n}{\sin\theta} = k_1 \frac{\lambda'}{\sin\theta}$$

In principle, one can put the entire exposure system inside water and use lens having n multiplied by n_{water}. This is equivalent to use a light source having λ reduced by a factor n_{water}.

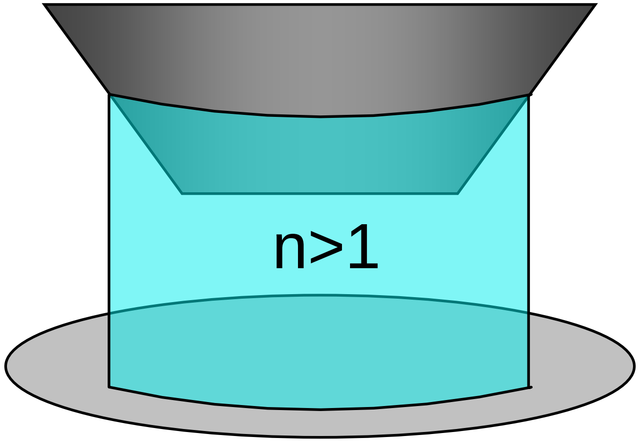
n_{water} =1.44 at 193nm.

So λ: 193→134nm.

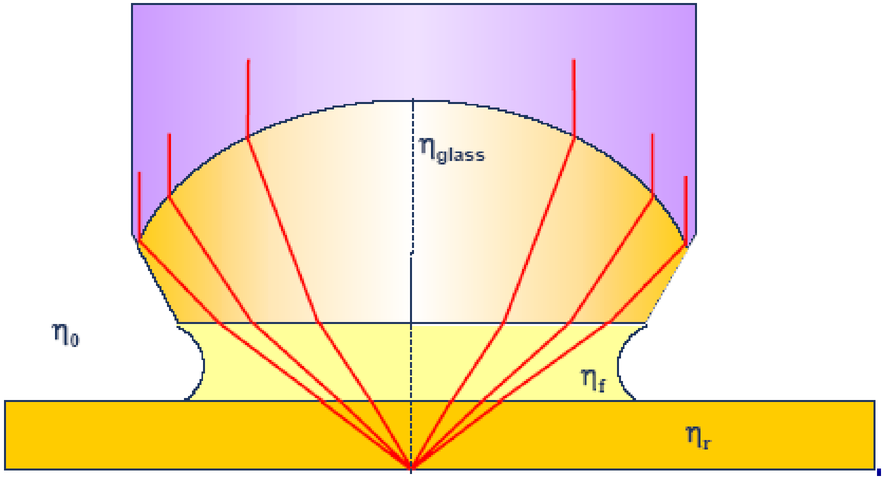


However, total immersion is not practical, and is not necessary.

Immersion between projection lens and wafer



Snell's law : $NA = \eta_0 \sin\theta_0 = \eta_f \sin\theta_f = \eta_r \sin\theta_r$



The medium between the lens and the wafer must:

- Have an index of refraction >1
- Have low optical absorption at 193 nm
- Be compatible with photoresist and the lens material
- Be uniform and non-contaminating

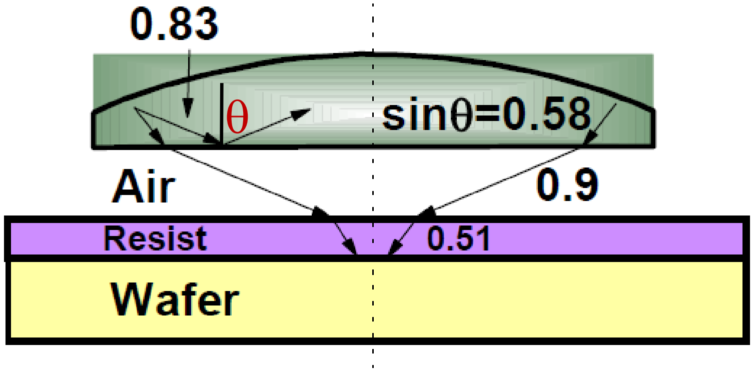
$NA = n \times \sin\alpha \propto n$

Can be >1 for n>1

Surprisingly, ultrapure water meets all of these requirements:
n = 1.44, absorption of <5% at working distances of up to 6mm, compatible with photoresist and lens, non-contaminating in it's ultrapure form.

Mechanism for Resolution Enhancement

Air

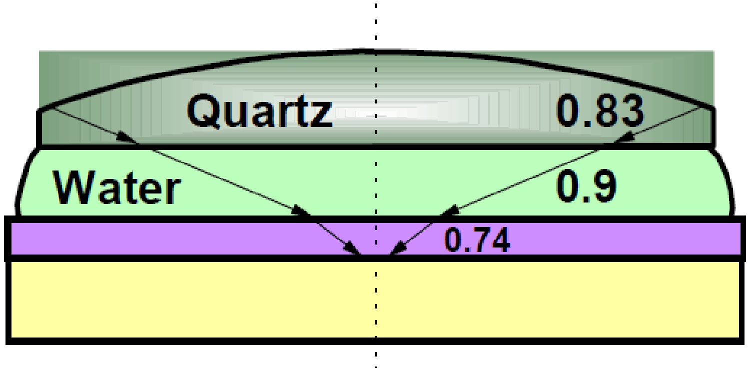


For NA=0.9, inside lens sinθ=0.9/1.56=0.58 (θ=35.5°)

Total internal reflection for sinθ>1/1.56=0.64 (θ=39.8°)

Collect light up to 35.5°;

Water immersion



$n_{quartz}=1.56$

$n_{water}=1.44$

$n_{resist}=1.75$

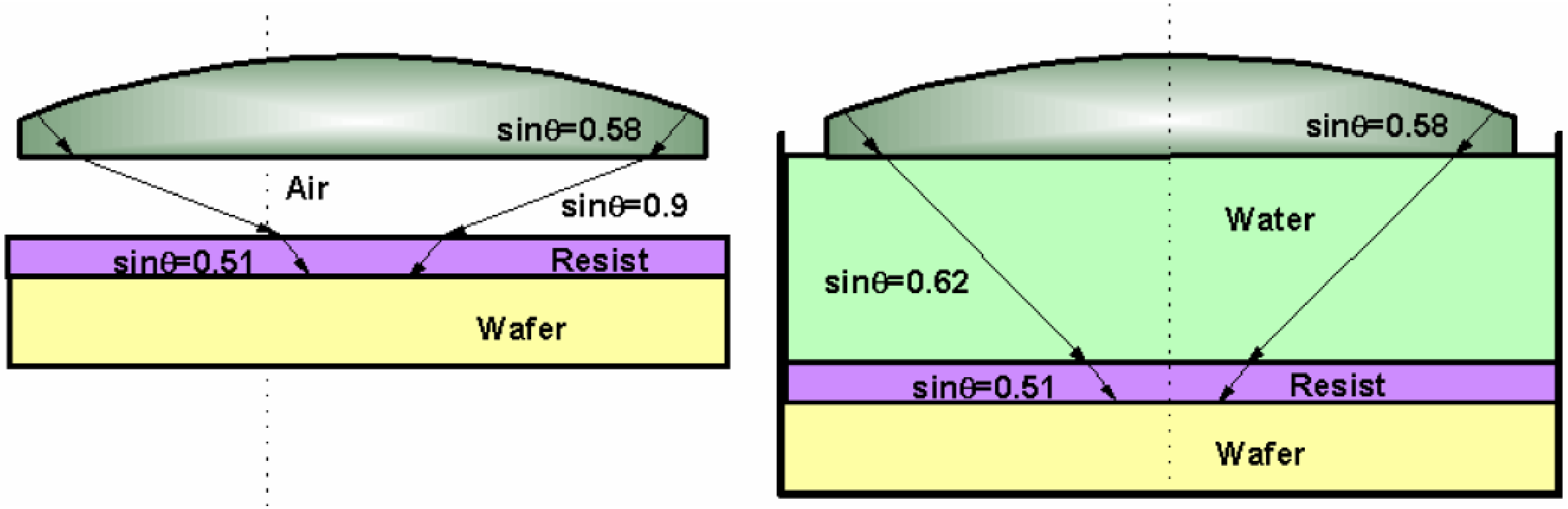
Inside lens sinθ=1.44 × 0.9/1.56=0.83 (θ=56°)

So light, which is internally total-reflected for air, can now be collected to form image in the resist.

Collect light up to 56° (angle inside lens)

NA=0.9 in air; NA=1.3 in water

For the same resolution, immersion also increases depth of focus (DOF)



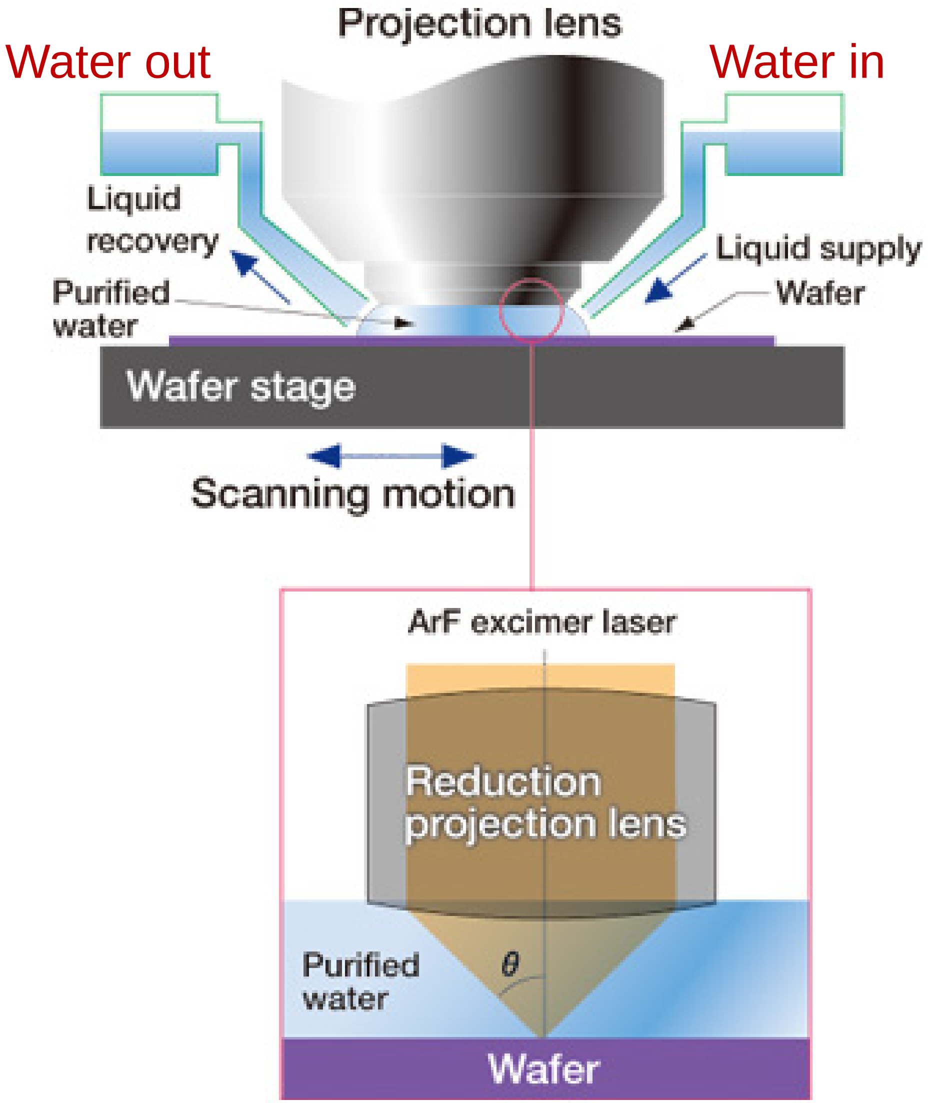
Depth of Focus or Depth of Field (DOF):

$$DOF = k_2 \frac{\lambda}{(NA)^2}$$ For NA ≤ 0.5

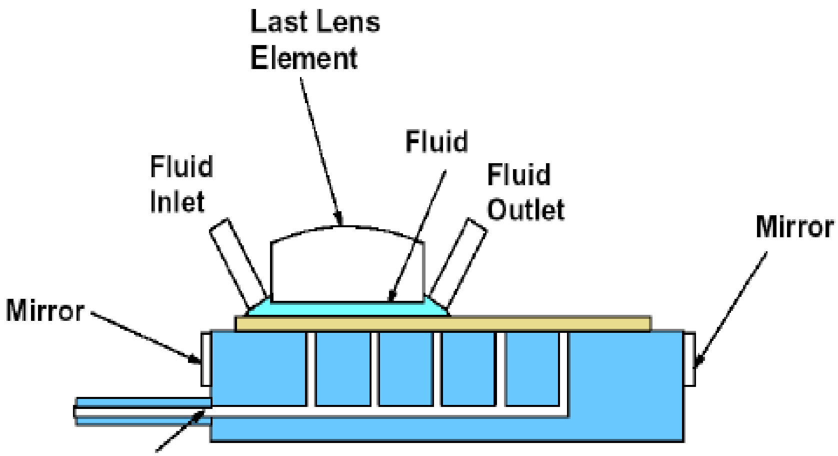
$$DOF = k_3 \frac{\lambda}{2\left(1-\sqrt{1-NA^2}\right)}$$ For NA > 0.5

But when at higher resolution by n×, depth of focus will become an issue.

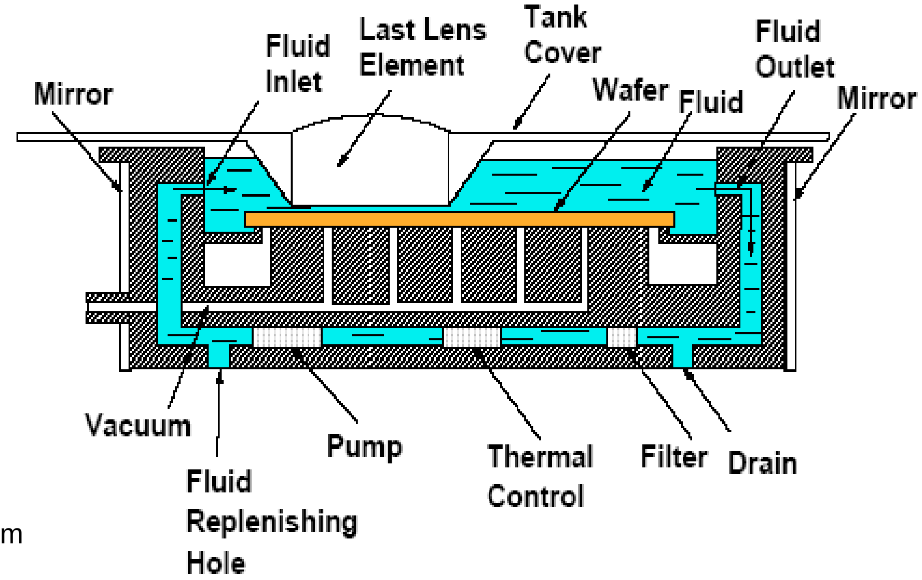
Immersion lithography system: >$50M



http://www.nikon.com/about/technology/rd/core/optics/immersion_e/index.htm



Fluid pumped in through thermal control and filter



ArF Immersion extension with High Index?

Fluid	Water	Available	Available	New
Refractive Index	1.44	1.65	1.65	>1.8
Glass	Current	Current	New Material	New Material
Refractive Index	1.57	1.57	1.9	1.9
Max NA (0.95 * RI*min*)	1.35	1.4	1.55	1.65
Minimum Resolution, $k_1=0.28$	40	39	35	33
Shrink		4%	13%	18%
Estimated Timing	2007	2009	>2010	>>2010

Immersion at higher refractive indices

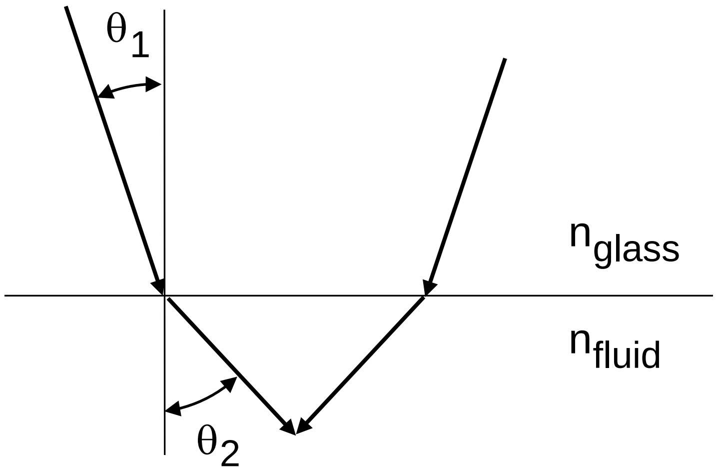
Limitations of water immersion:

- $n\sin\theta \leq 0.93\times\min(n_{glass}, n_{fluid}, n_{resist})$
- Indices of refraction for water immersion.
  - SiO_2: 1.56
  - Water: 1.435
  - Resists ~ 1.70

$$\left.\begin{array}{l}SiO_2: 1.56\\ \text{Water}: 1.435\\ \text{Resists} \sim 1.70\end{array}\right\} 0.93 \times 1.435 = 1.33$$

NA≤1.33 for water

$n_{glass} > n_{fluid}$



High-index fluid needs high-index lens material.

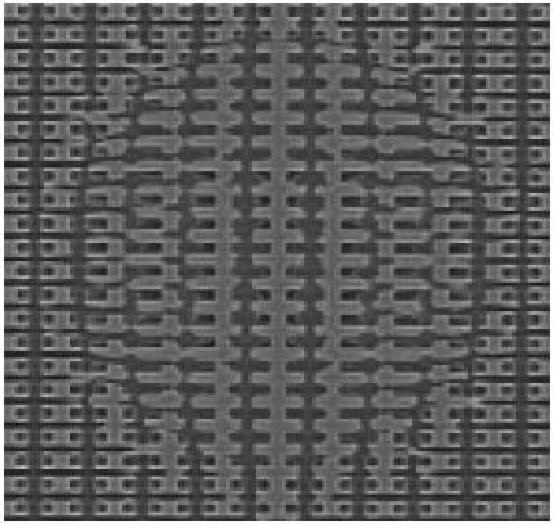
Options for high index immersion lithography

- Glass.
  - $BaLiF_3$: 1.64
  - Lutetium aluminum garnet ($Lu_3Al_5O_{12}$, LuAG): 2.1
  - Pyrope ($Mg_3Al_2Si_3O_{12}$): 2.0
- Fluid: cyclic organics, such as decalene: 1.64 - 1.65

Issues with immersion lithography

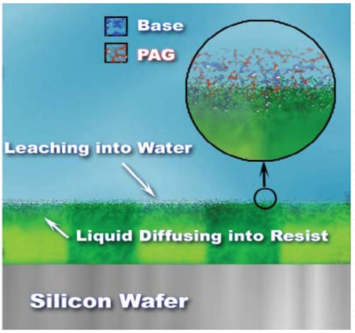
- Mechanical issues and hydrodynamics
  Throughput 100 wafer/hour, order of 50 dies each wafer, so 5000 exposures/hour, or <1sec for each exposure. Therefore, water in, expose, water out, stage move, all within 1sec.
- Bubble formation disturbing the image (defect)
- Stage vibrations transferred to lens
- Heating of immersion liquid upon exposure
- New defect mechanisms at wafer level
- Interaction of photoresist with immersion liquid
- Fluid contamination (defect)
- Polarization effects degrading contrast

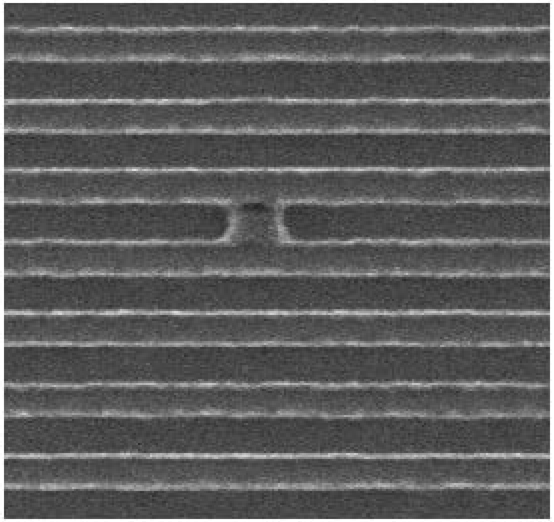
Major challenge: defect in immersion lithography

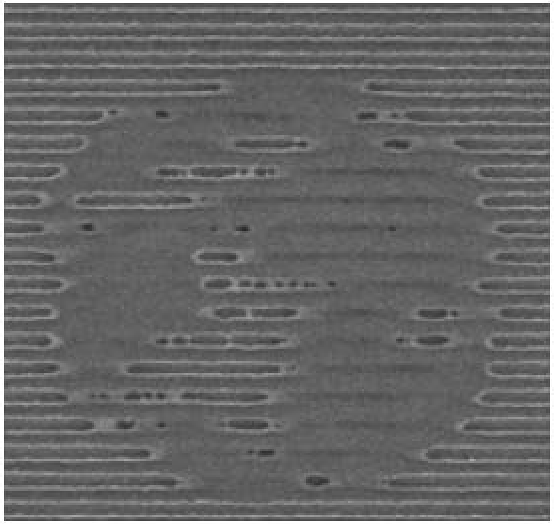


Air bubbles

Resist/TC – water interaction

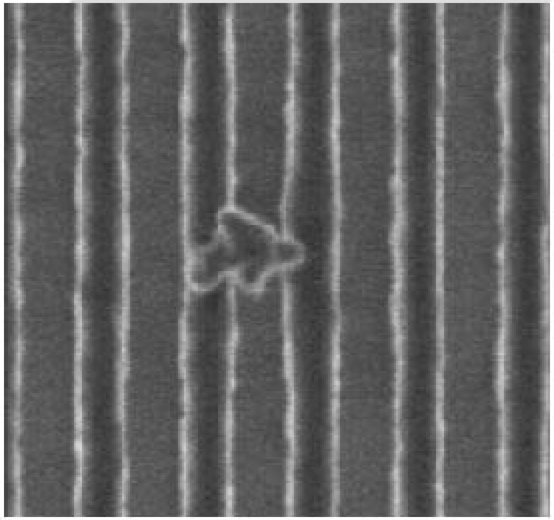




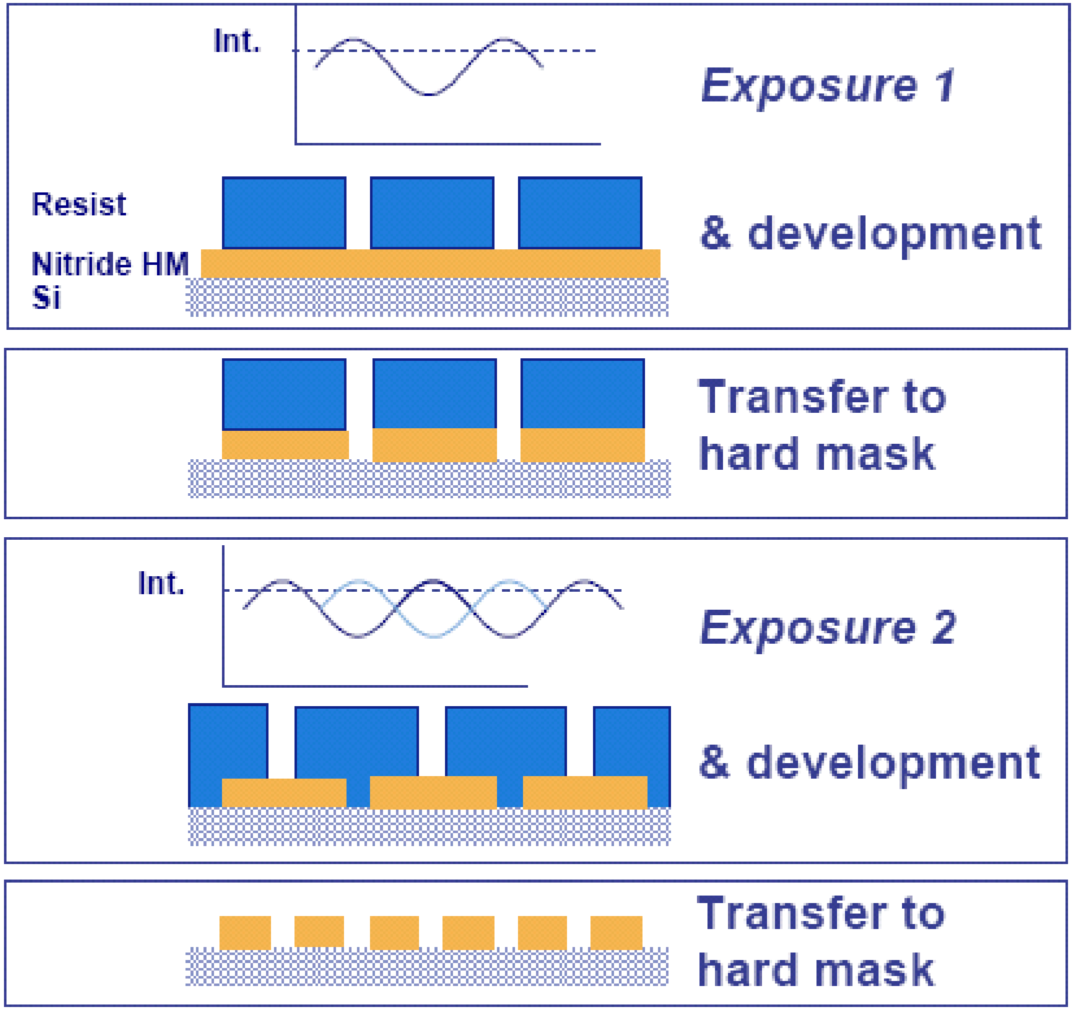


Water marks and drying stains (Try to make super-hydrophilic surface)

Particles from water



RET 5: Double Patterning Technology (DPT)



Exposure 1

& development

Transfer to hard mask

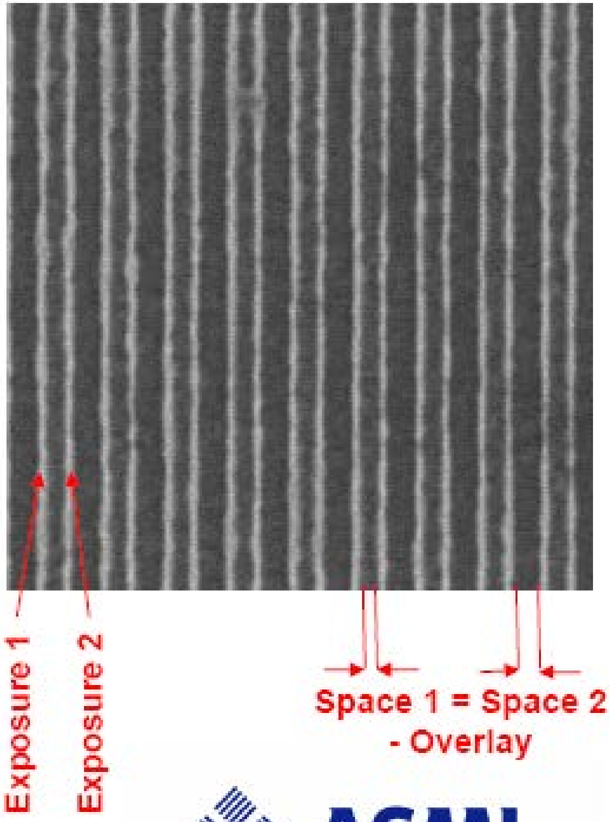
Exposure 2

& development

Transfer to hard mask

80-nm pitch

k_1=0.2, ArF, 0.93 NA



ASML