Forum *Romanians in Micro- and Nanoelectronics,* *6 November 2018, Romanian Academy, Bucharest, Romania*

Moore's Law and Optical Lithography Drive Semiconductor Industry Progress

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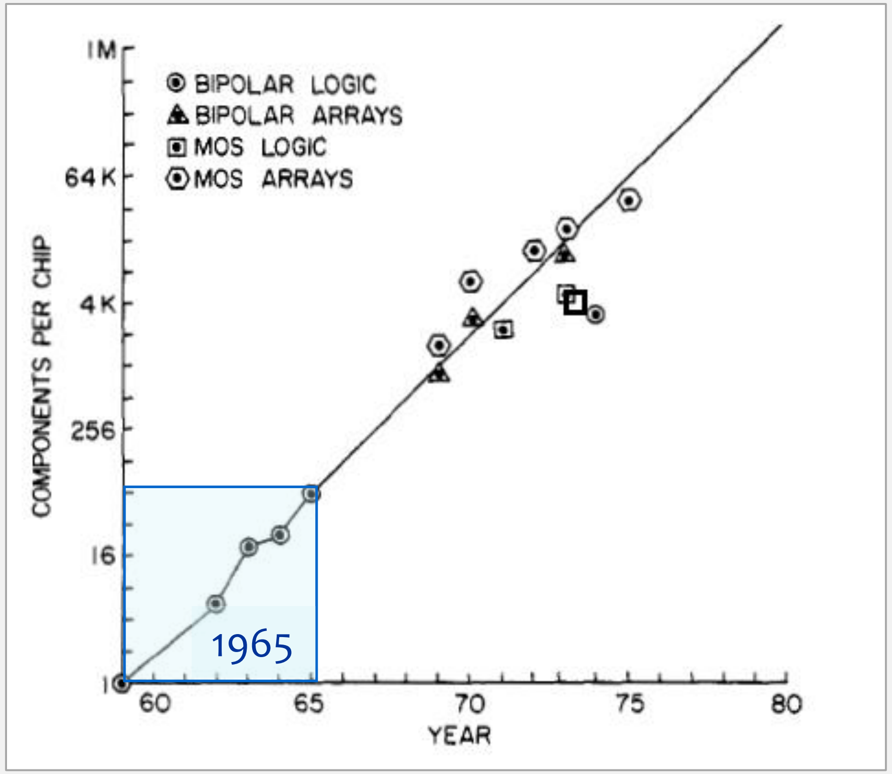
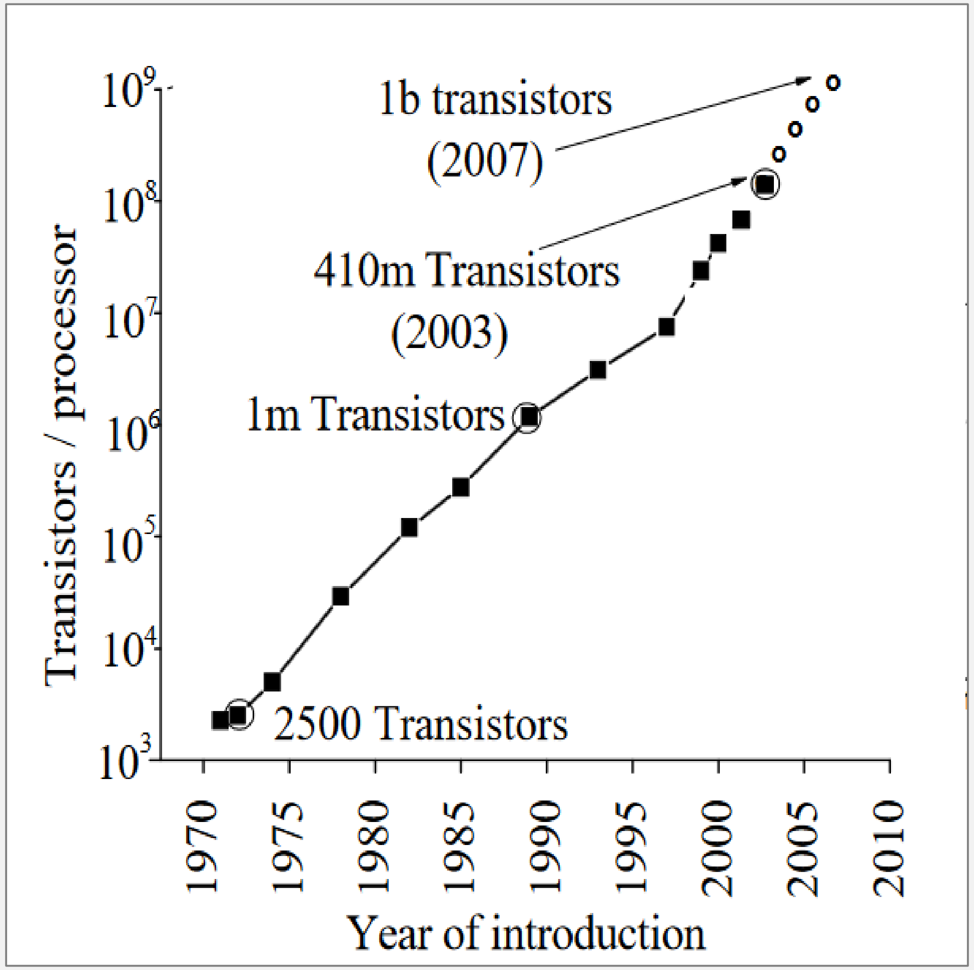
ASML

Moore's Law:
"The number of transistors on a chip doubles every two years"

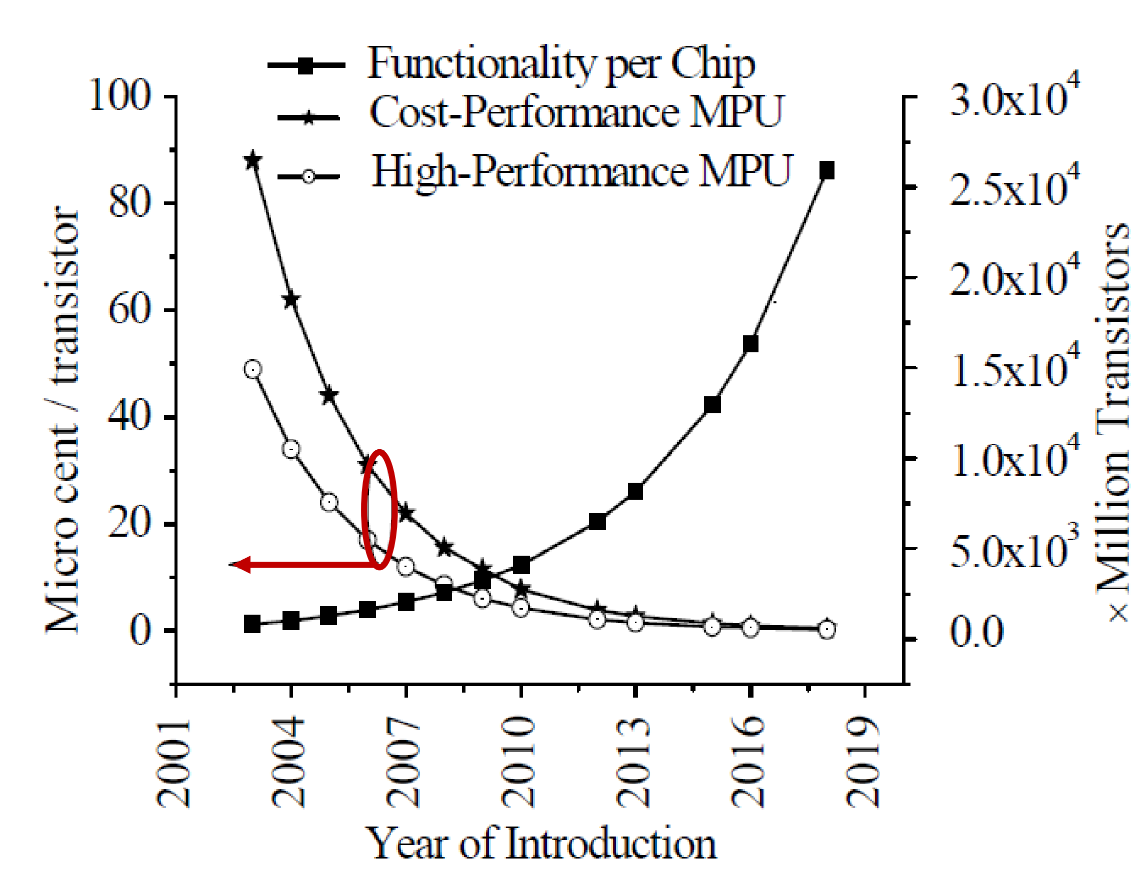


Approximate component count for complex integrated circuits Vs year of production (Moore,1975)



Visualization of Moore's Law in 1995,

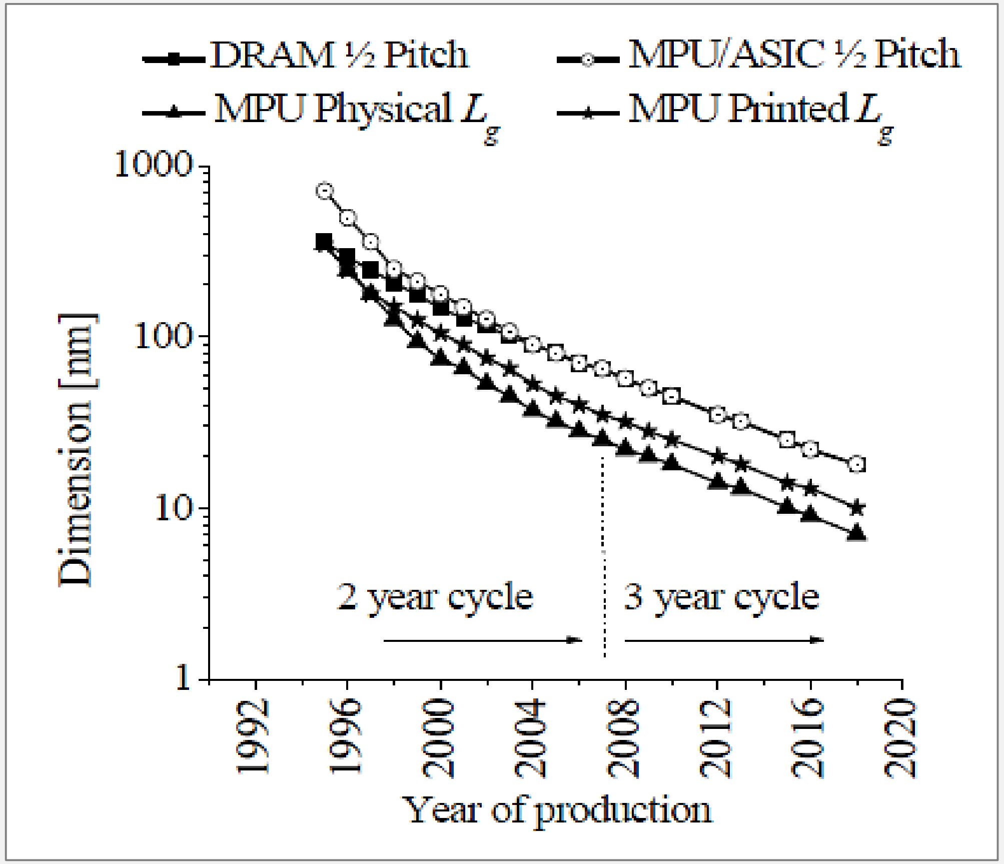
"By making things smaller, everything gets better: device speed goes up, power goes down, system reliability improves, the cost of doing things electronically drops due to technology progress; *60% of the progress had come from chip size increase and finer structures*"



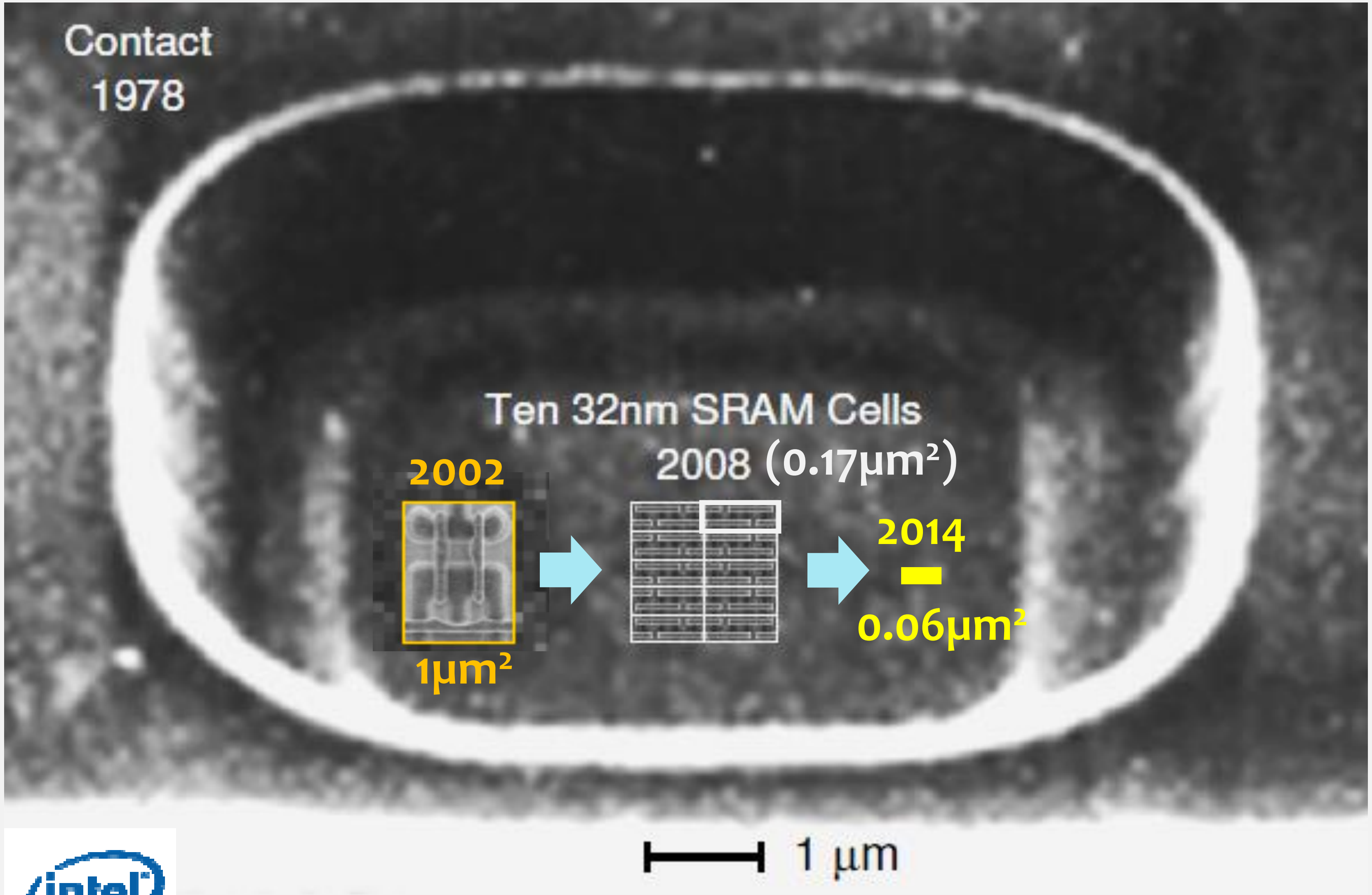
Functionality, as the number of logic transistors in a microprocessor and cost per function (ITRS2007)

A compact formulation of Moore's Law

$N_{transistors/chip} = CD^{-2} * A^{2} * P_E$



36 years of dimensional scaling, SRAM cell area from 1978 to 2014,

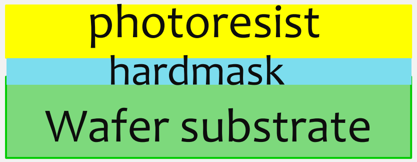


M. Bohr, Intel Sr Fellow, “The New Era of Scaling”, IDF 2014

Optical (Photo)Lithography ‘101’

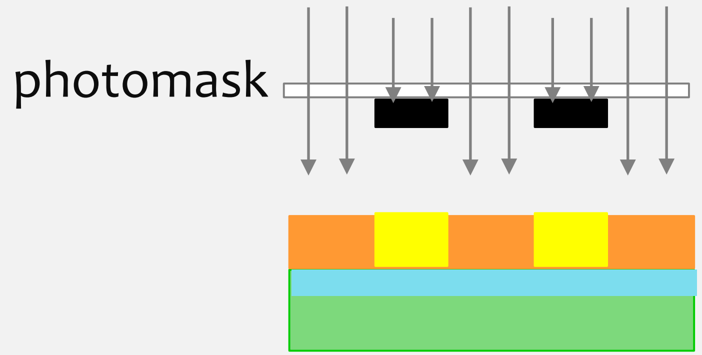
Photolithography process

(1) Resist coating



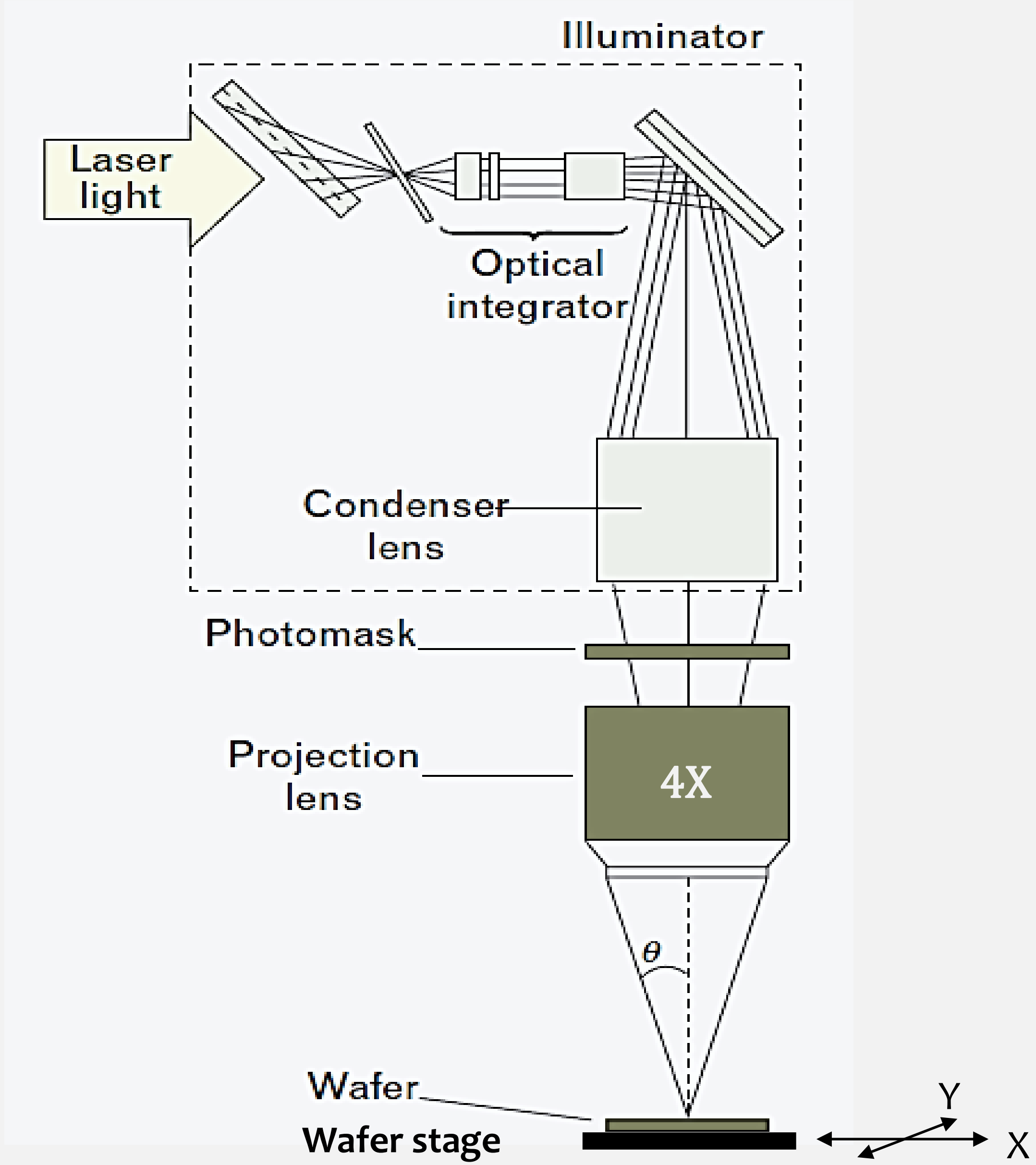
(2) Alignment & Exposure

Exposure light

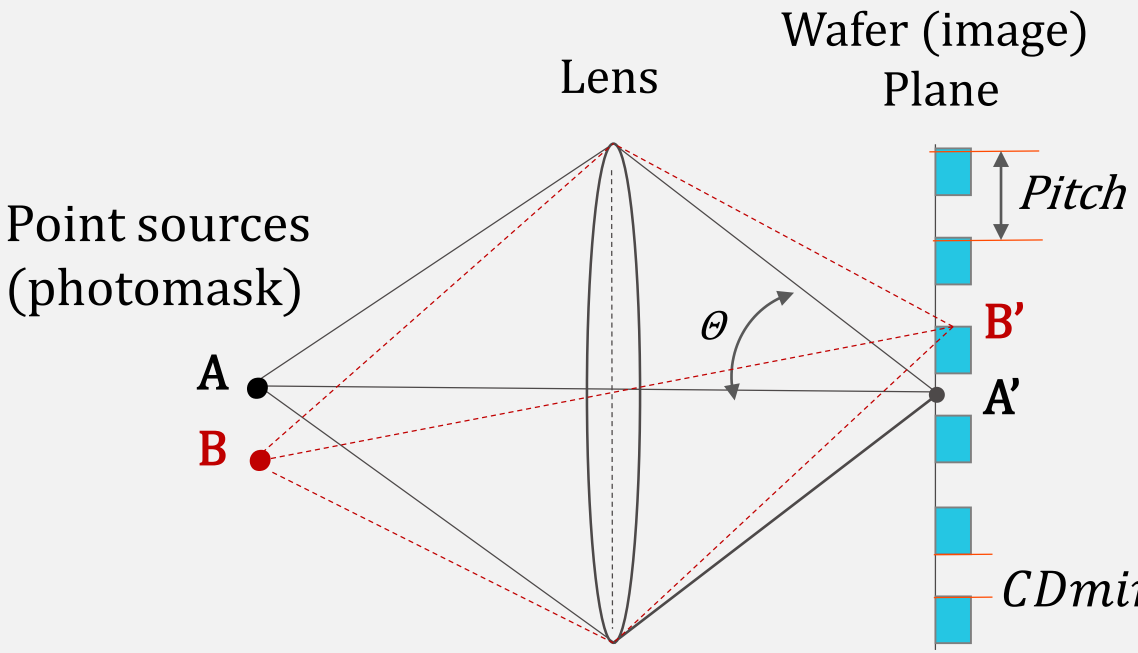


(3) Resist development

Photolithography exposure tool

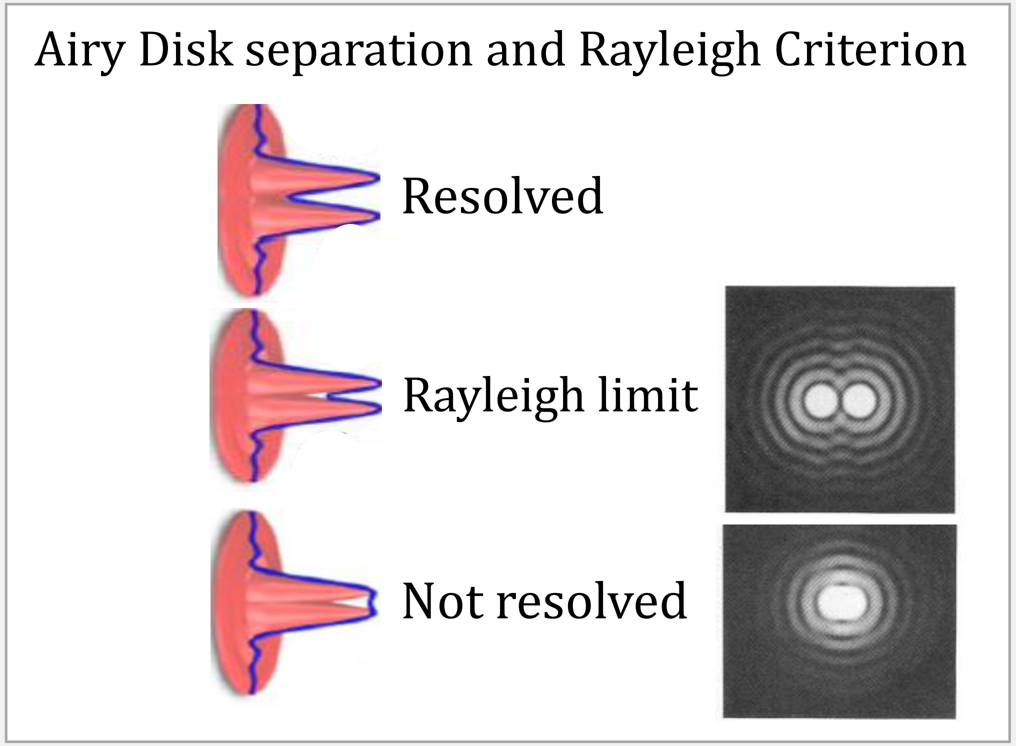


Fraunhofer/far-field diffraction and lithography image formation

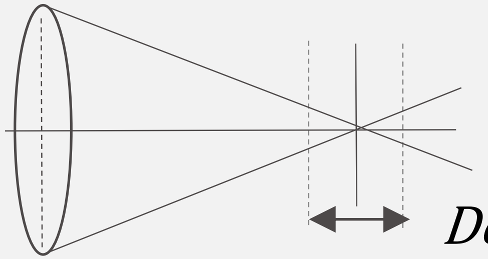


$$CDmin = \frac{1}{2} Pitch$$

Lens NA= n*sinΘ

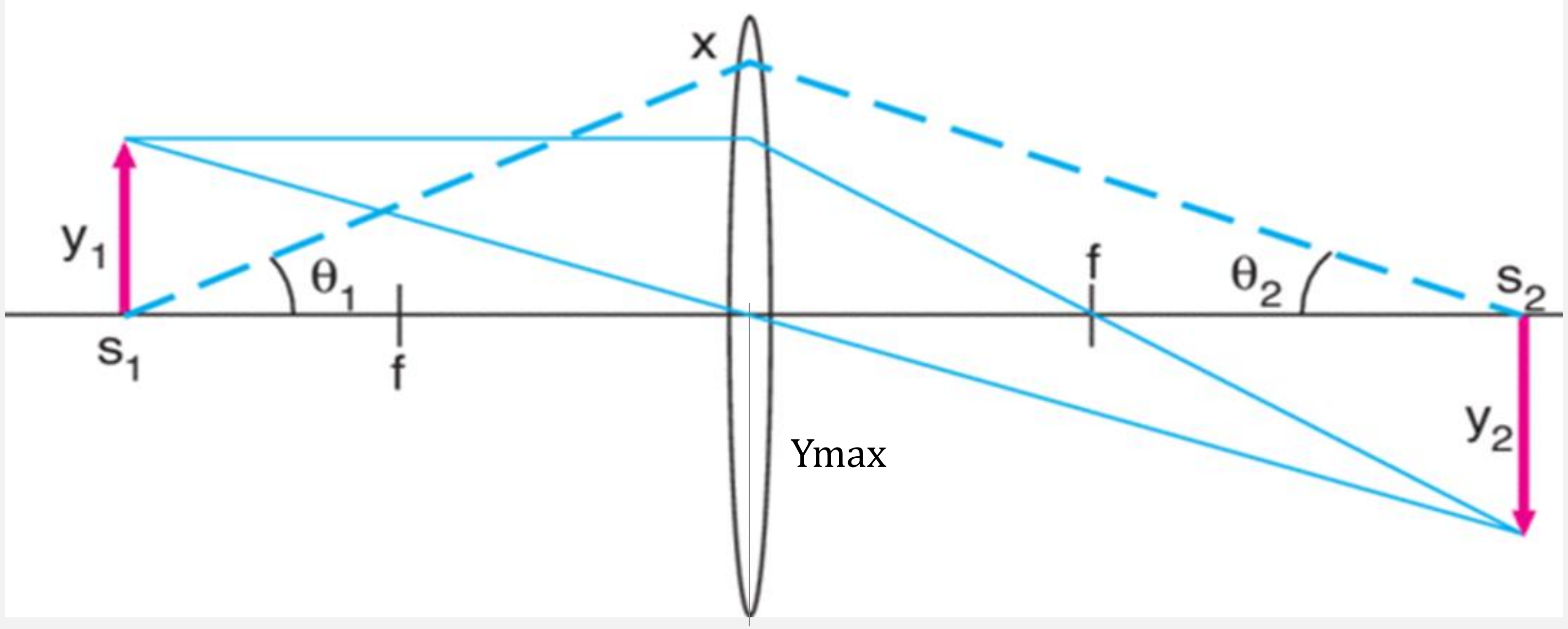


Resolution in Fraunhofer diffraction is defined by Rayleigh criterion: $Resolution = CDmin = k1 \frac{\lambda}{NA}$



$$Depth\ of\ Focus = k2\ \frac{\lambda}{NA^2}$$

Total Transmitted Information through the lens



Lagrange invariant
$H = n_2\, y_2 \theta_2 = n_1\, y_1 \theta_1$.

Total Transmitted Information of a lens (geometrical optics):

$TTI_{geometric} = H^2 = (NA * Y_{imax})^2$; Y_{imax} is maximum image radius

Extended Lagrange invariant is defined to describe the increase in complexity to design and manufacture advanced lithography lenses:

$TTI_{Tool} = H^2_{extended} = S *[(NA * Y_{imax})/ (\lambda * k_1)]^2$; S, is a scanning factor

The functions of Optical Lithography concerning Moore's Law

1. Resolution
2. Area
3. Cost
4. Overlay and CDU

The functions of Optical Lithography concerning Moore's Law

1. $\text{Resolution} = k1\frac{\lambda}{NA}$

   - λ → Exposure wavelength
   - NA → Lens
   - $k1$ → Process

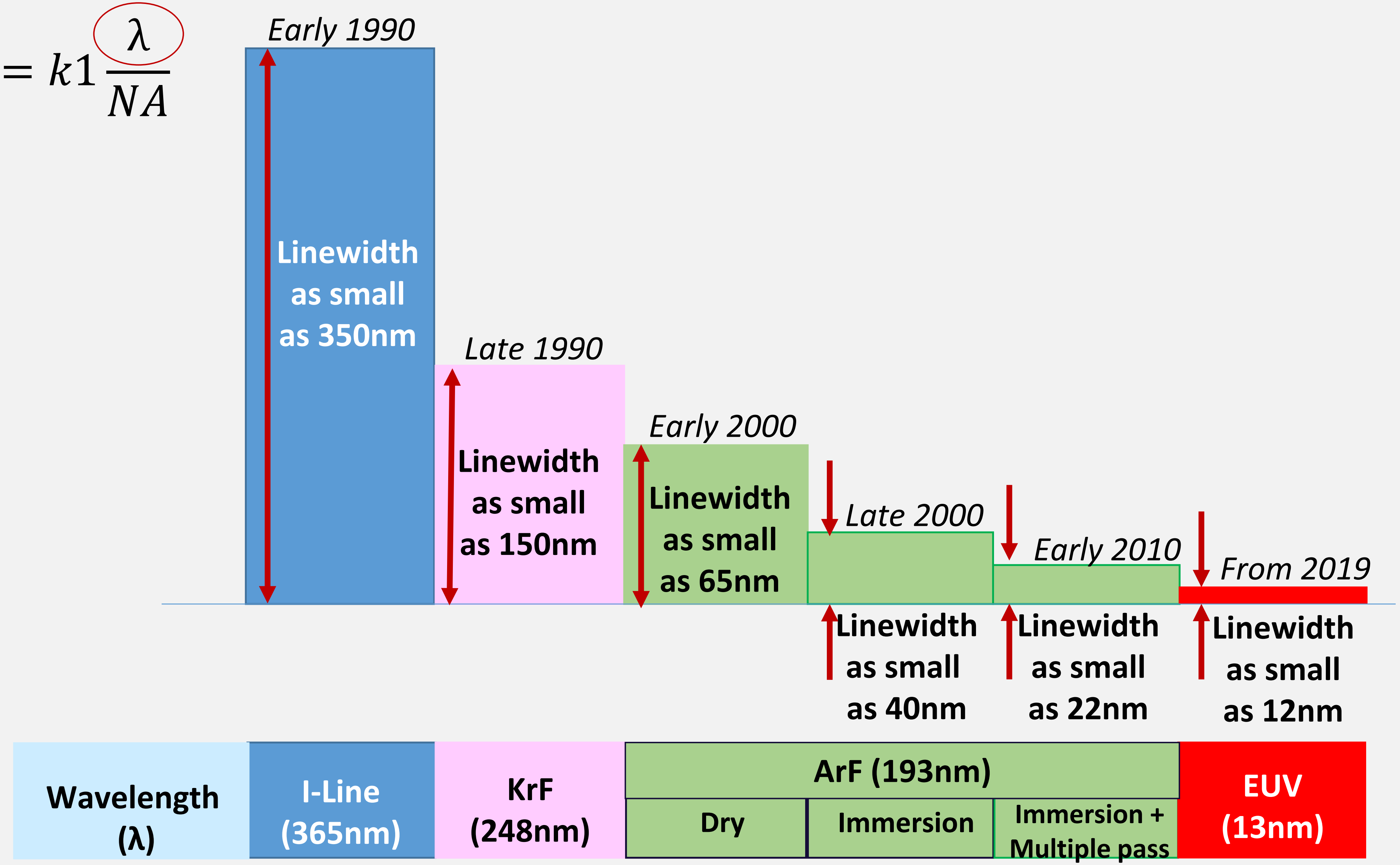
2. Area

3. Cost

4. Overlay and CDU

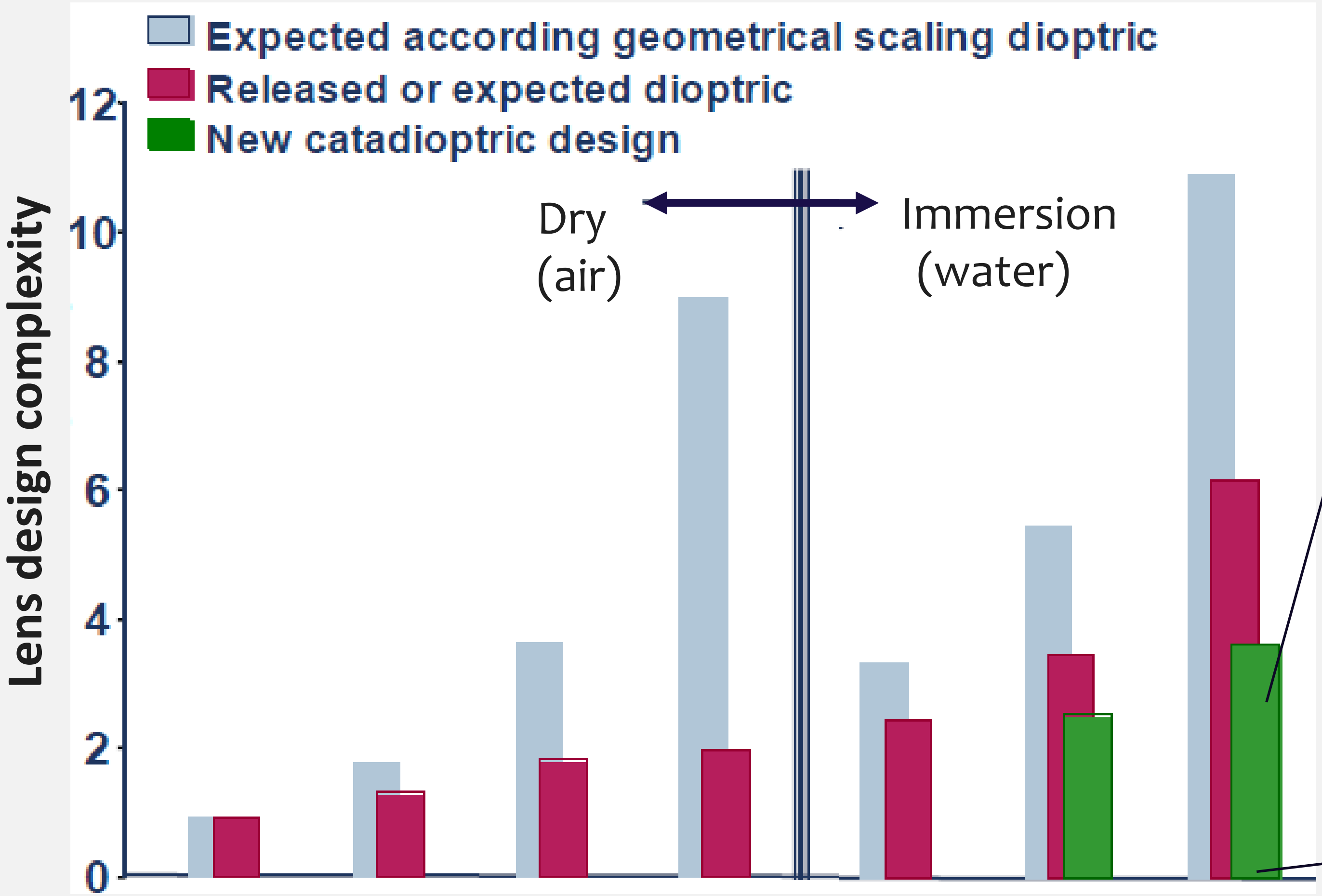
Evolution of lithography exposure wavelength

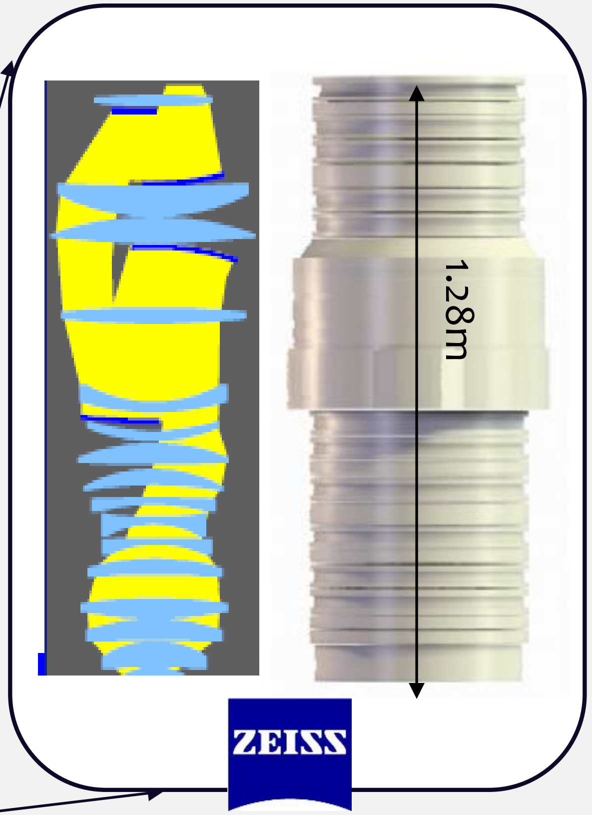
$$R = k1\frac{\lambda}{NA}$$



Evolution of NA and increased # of image transferred pixels

$R = k1\frac{\lambda}{NA}$; Pixel count within image field, $N = A_{image} / (CD_{min})^2$





NA	0.63	0.75	0.85	0.93	1	1.10i	1.20i	1.35i
# of pixels x 10^{10}	4.9	8.3	13	20		33	41	59

Wet imaging enables NA > 1 increase

$$R = k1\frac{\lambda}{NA}$$

In Microscopy (Ernst Abbe, 1879,)
Homogeneous immersion system admits of a useful increase of aperture closely approaching the ultimate resolution limit which is imposed by the optical qualities of the materials available

2003, wet optical lithography, imaging in a fluid with index n → **Water immersion at 193nm λ, n_{water}=1.44,**

$\lambda_{imm} = \lambda_0/n$ → Exposure wavelength: $\lambda_{imm} = 134$nm

$NA_{imm} = n*NA_{air}$ → $NA_{imm} = 1.35$

$Res_{imm} = Res_{air}/n$ → Resolution: $Res_{imm} = Res_{air}/1.44$ → 80nm Pitch

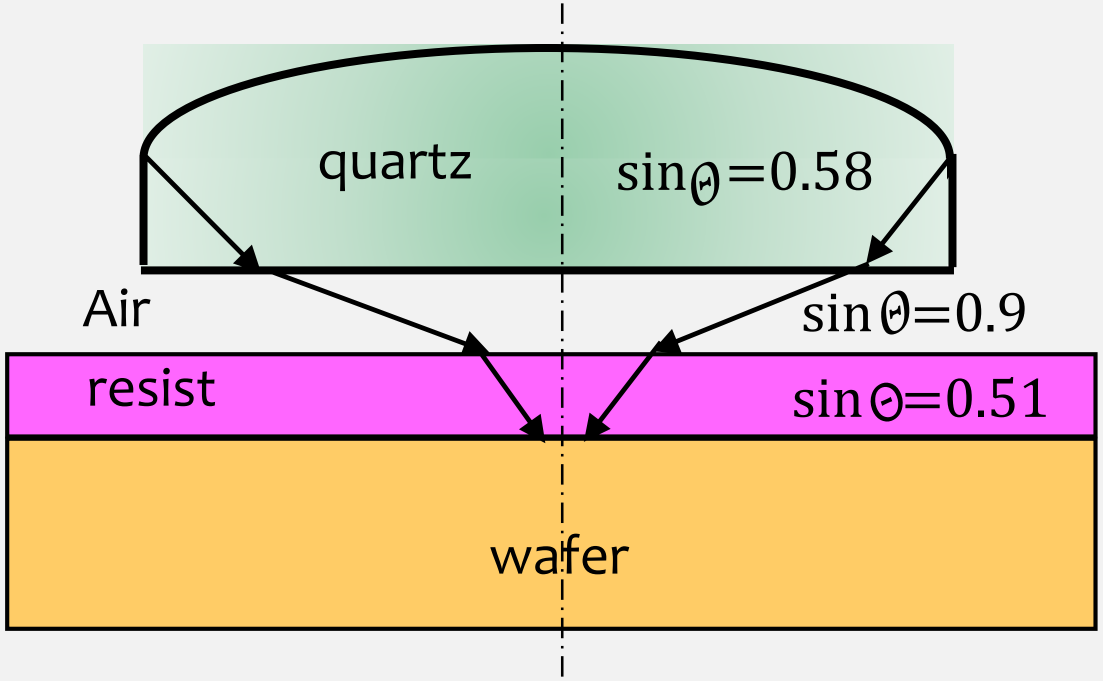
$DOF = k_2\, n\lambda/NA^2$ → Depth of Focus: $DOF_{imm} = 1.44*DOF_{air}$

Principle of water imaging

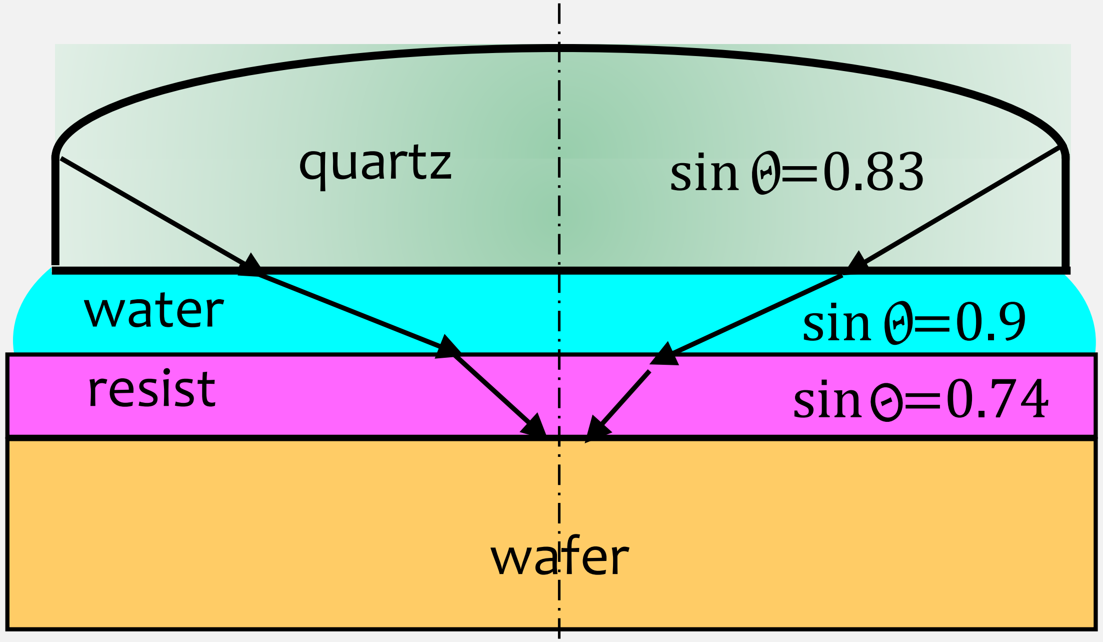
$$R = k1\frac{\lambda}{NA}$$

Snell's Law: $= n_q \sin \Theta_q = n_f \sin \Theta_f = n_r \sin \Theta_r$

Dry optics



Immersion optics

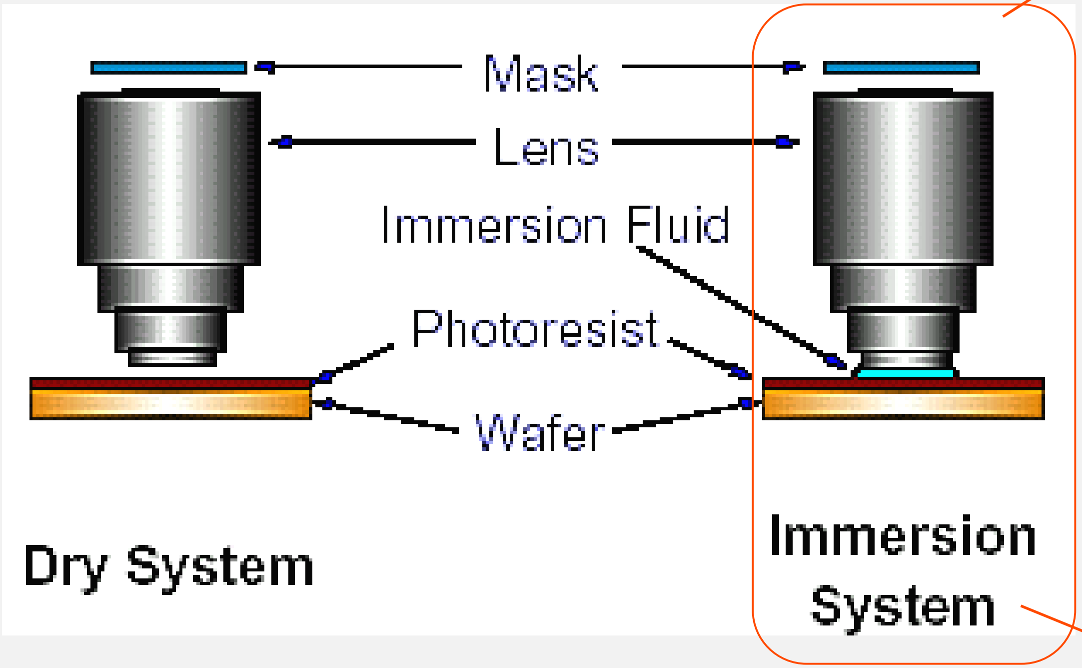


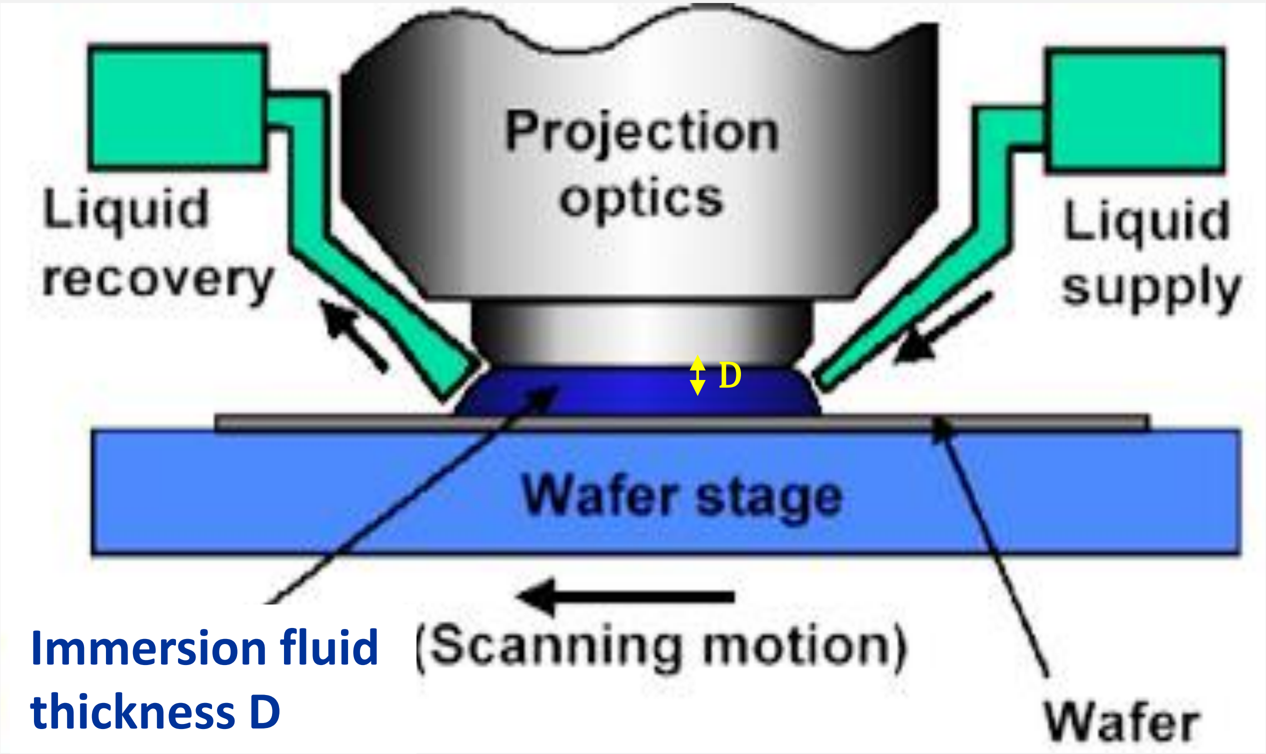
Preserving the physical angle in coupling medium increases resolution ➔ NA>1

n_{quartz} =1.56; n_{water} =1.44; n_{resist} =1.75

Immersion lithography exposure system

$$R = k1\frac{\lambda}{NA}$$





Water absorption at 193nm is 0.035/cm → D < 2mm

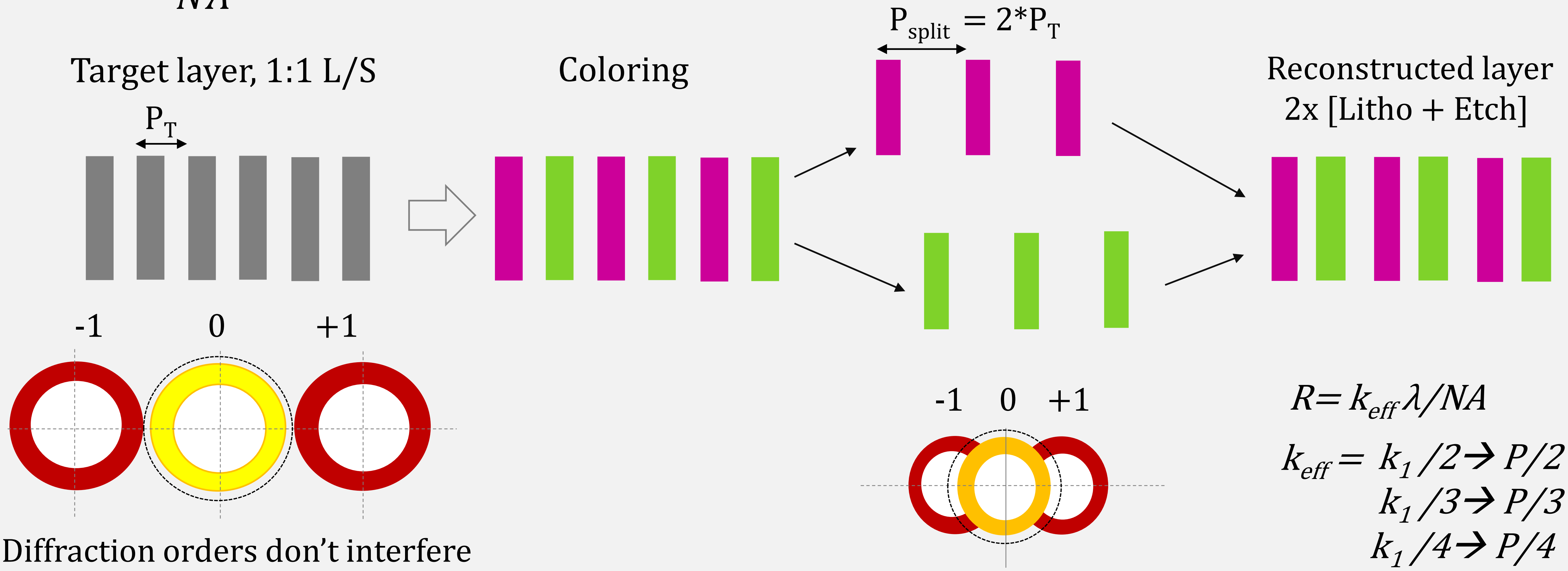
Shear forces on the lens in laminar flow conditions:

$$[A * \mu * V_{scan} * D^{-1} < F_{shear}$$

MultiPass lithography reduces k_1

double patterning or pitch division/2 by LE^2 process

$$R = k1\frac{\lambda}{NA}$$



$R = k_{eff}\lambda/NA$

$k_{eff} = k_1/2 \rightarrow P/2$

$k_1/3 \rightarrow P/3$

$k_1/4 \rightarrow P/4$

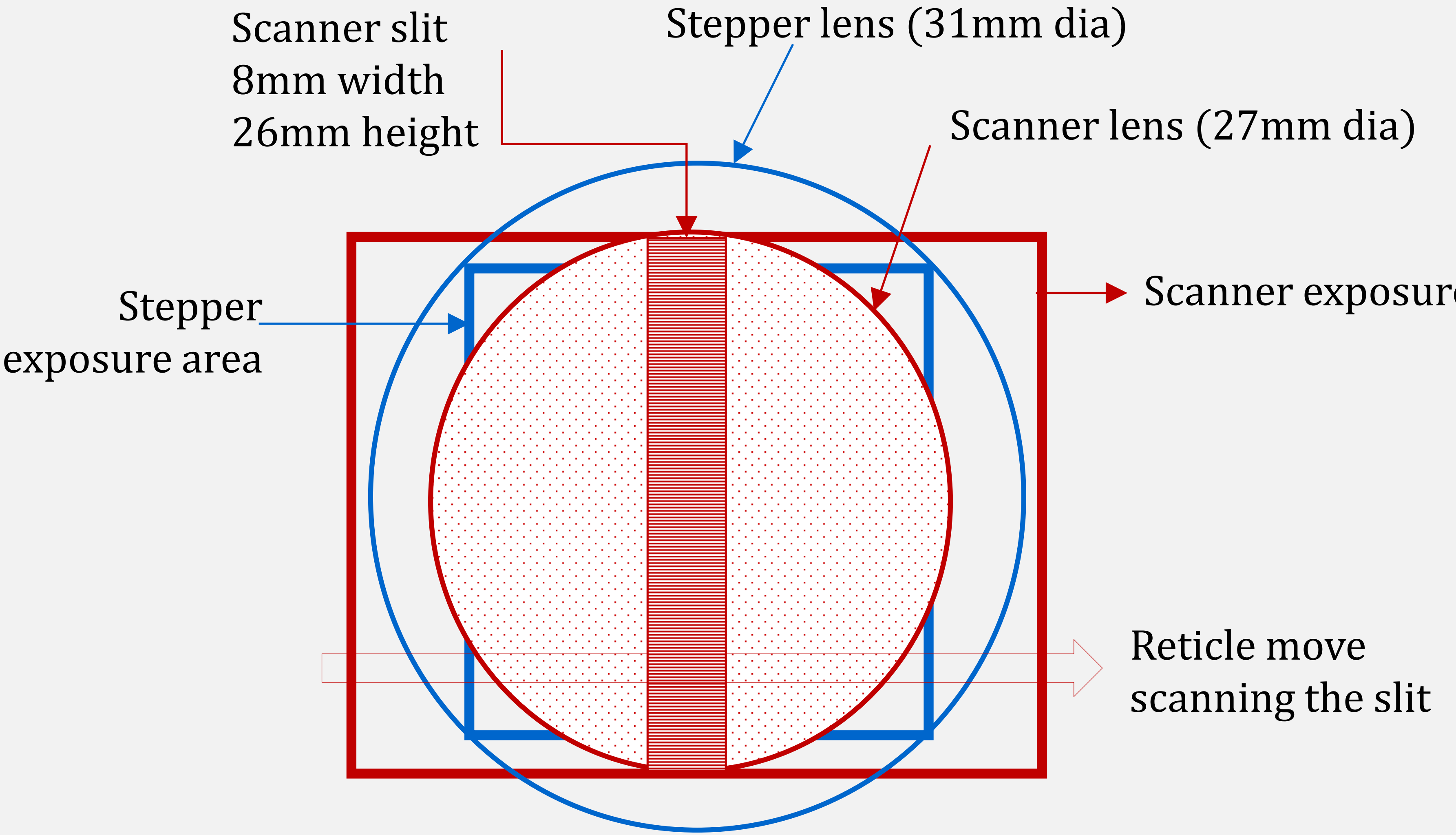
Diffraction orders don’t interfere
No image

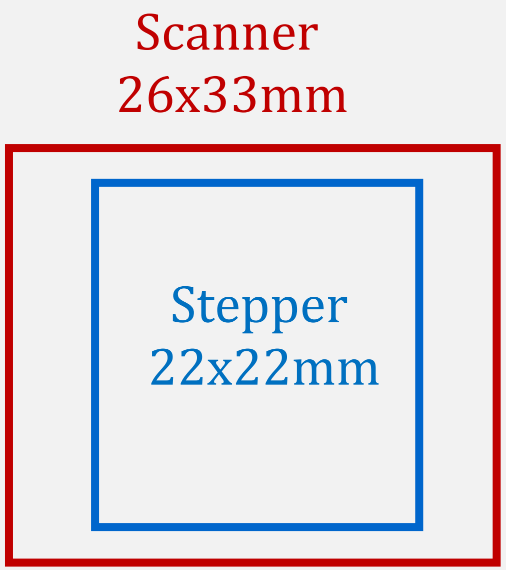
0 , +/- 1 orders interfere
layers A and B images are generated

The functions of Optical Lithography concerning Moore's Law

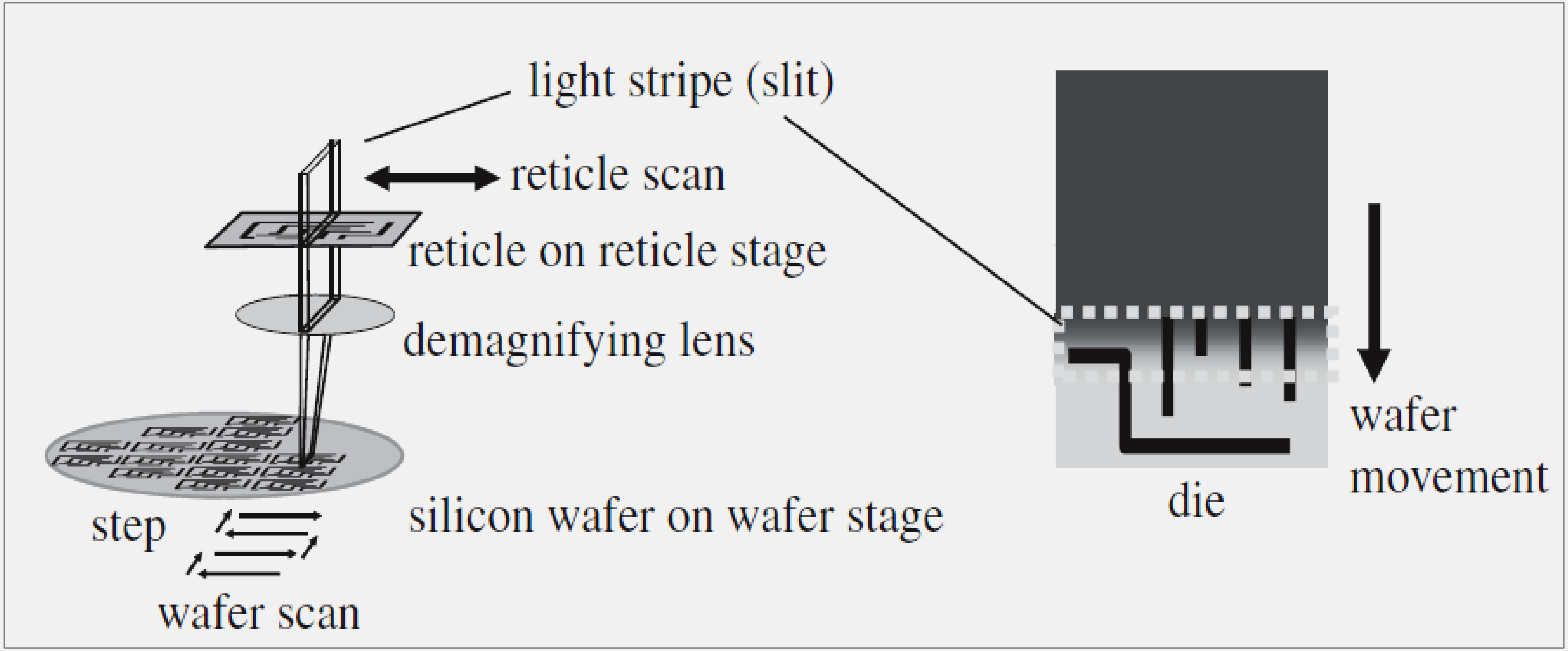
1. Resolution
2. **Area increase, by increasing exposure field size in scanner systems**
3. Cost
4. Overlay and CDU

Increase in image field size on scanner Vs stepper





Operation principle of a scanner exposure system



The principle:

Wafer stage moves in sync and opposite directions with the reticle stage.

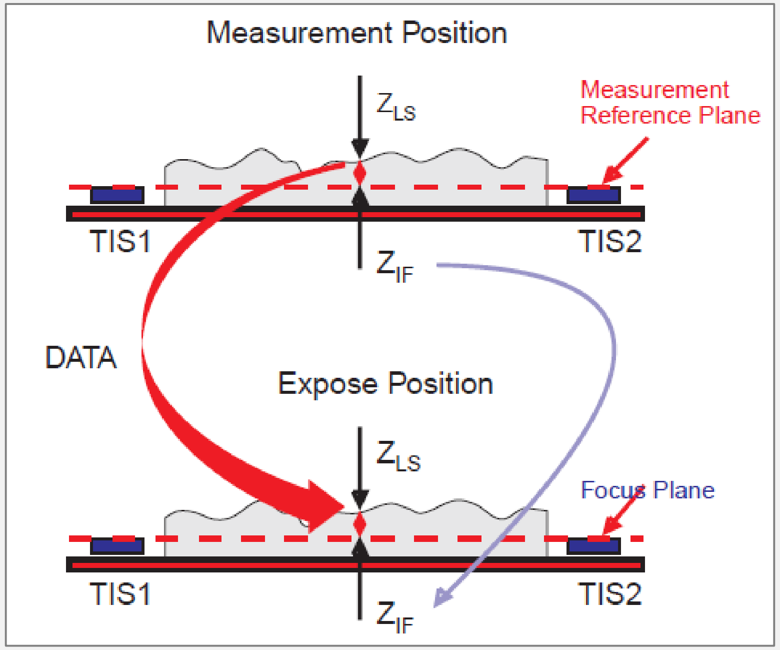
Due to lens 4X demagnification, the reticle stage moves 4X faster than the wafer stage.

The functions of Optical Lithography concerning Moore's Law

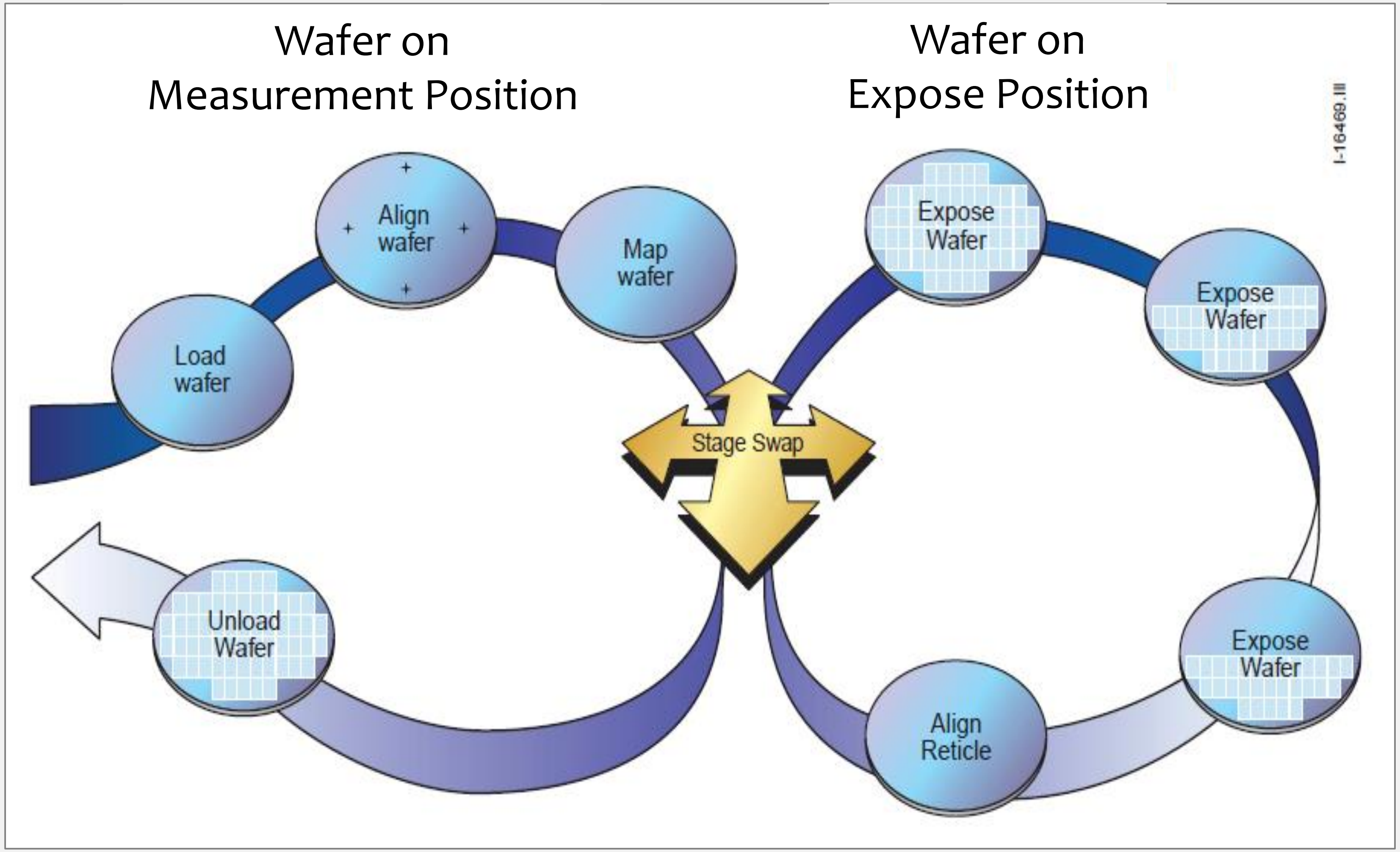
1. Resolution
2. Area, by increasing exposure field size in scanner systems
3. **Cost reduction by increasing the throughput on dual stage scanner systems**
4. Overlay and CDU

TWINSCAN®, the Dual Stage scanner

Focus and leveling principle



Life of a wafer inside Twinscan

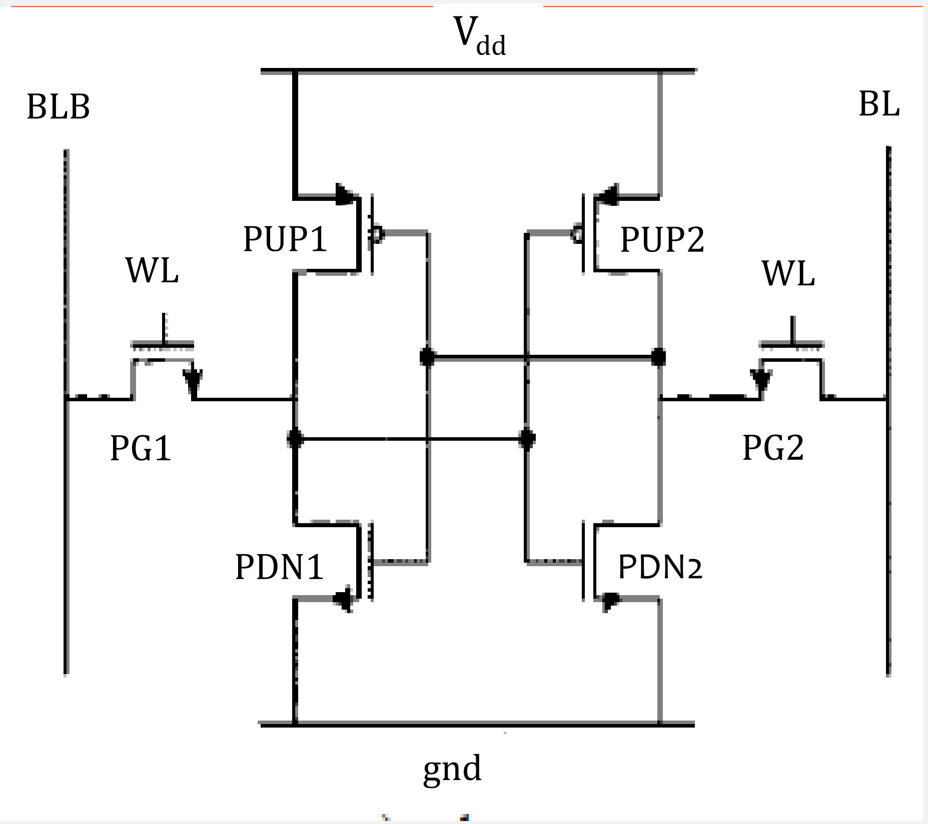


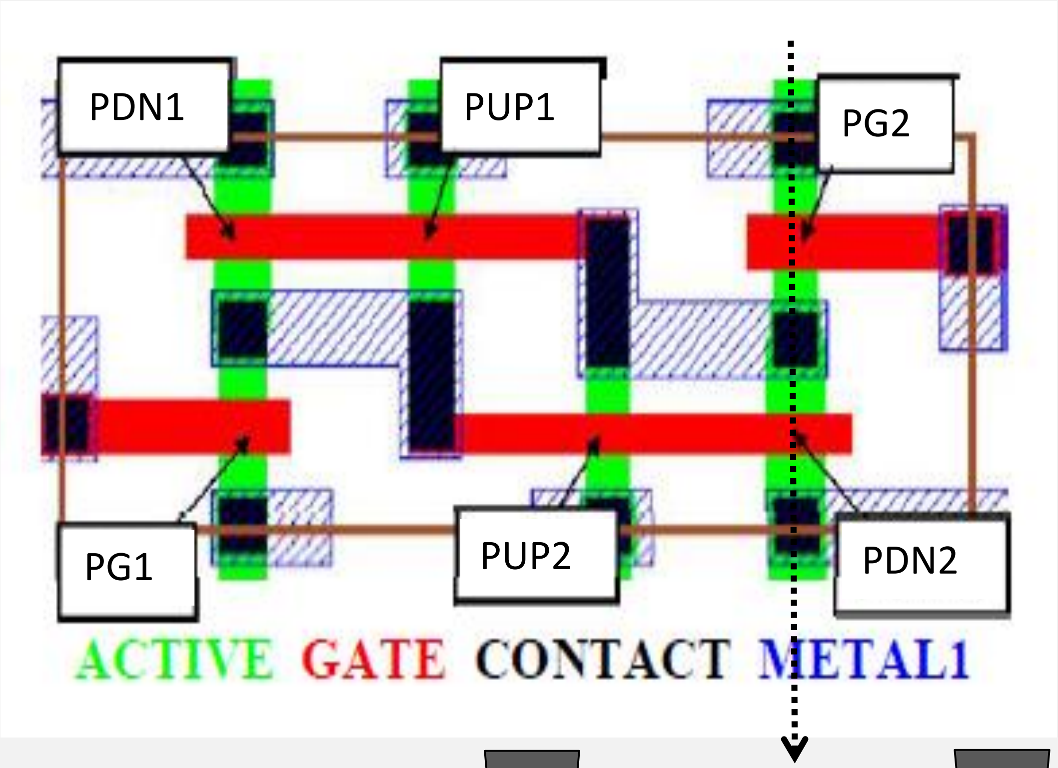
TWINSCAN® productivity is 275 wafers exposed in one hour, or 13sec/wafer

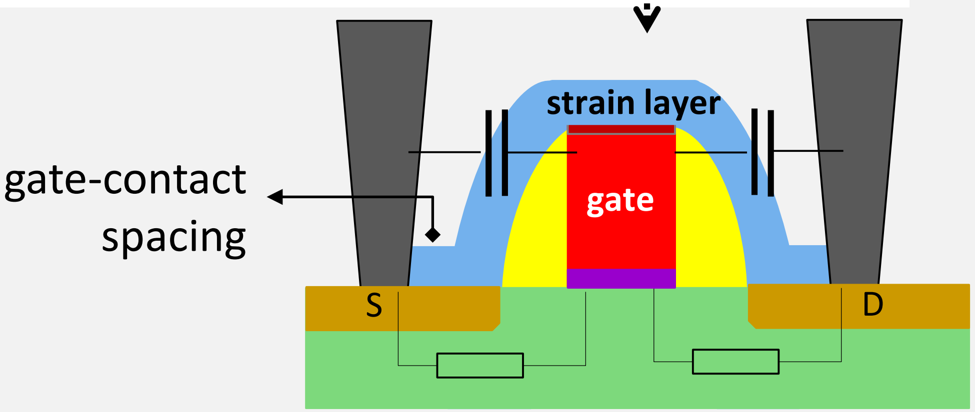
The functions of Optical Lithography concerning Moore's Law

1. Resolution
2. Area, by increasing exposure field size in scanner systems
3. Cost, by increase in throughput on dual stage scanner
4. **Overlay and CDU direct impact on device electrical performance**

6-T SRAM cell design, electrical and layout





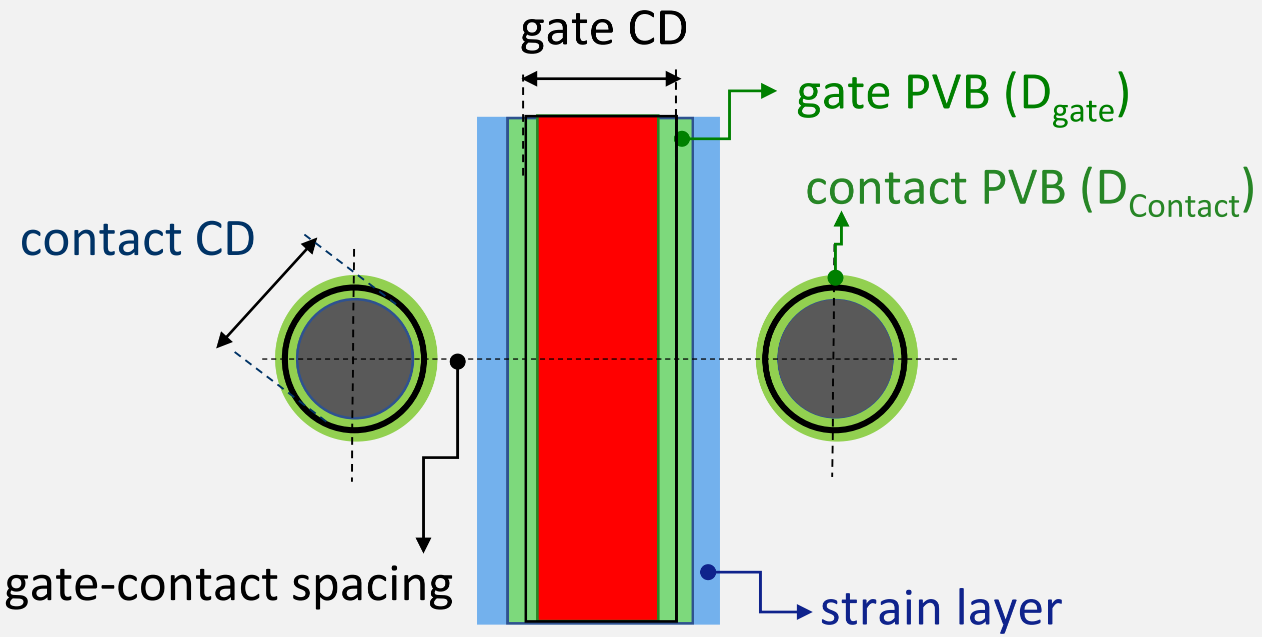


Impact of CD and Overlay errors on SRAM functionality

Short failures when: $D(CDU_{CH}) + D(CDU_{gate}) + |D(overlay)| >$ spacing gate-contact

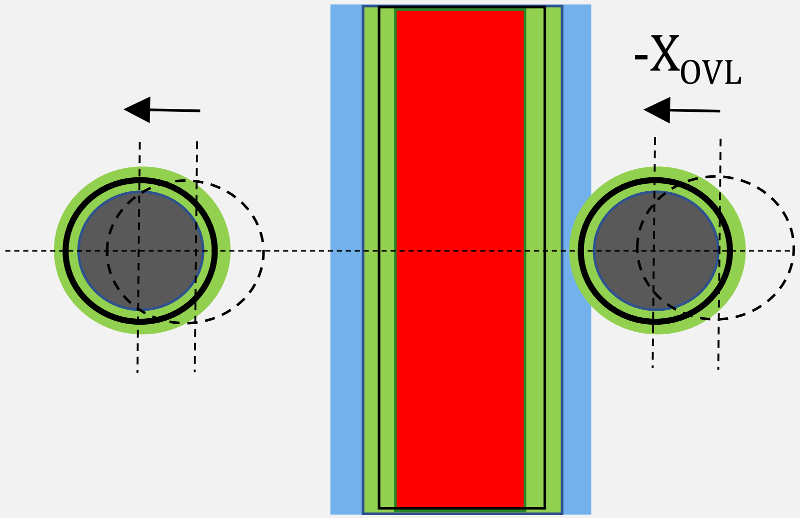
(D is Edge Displacement)

Gate CD error



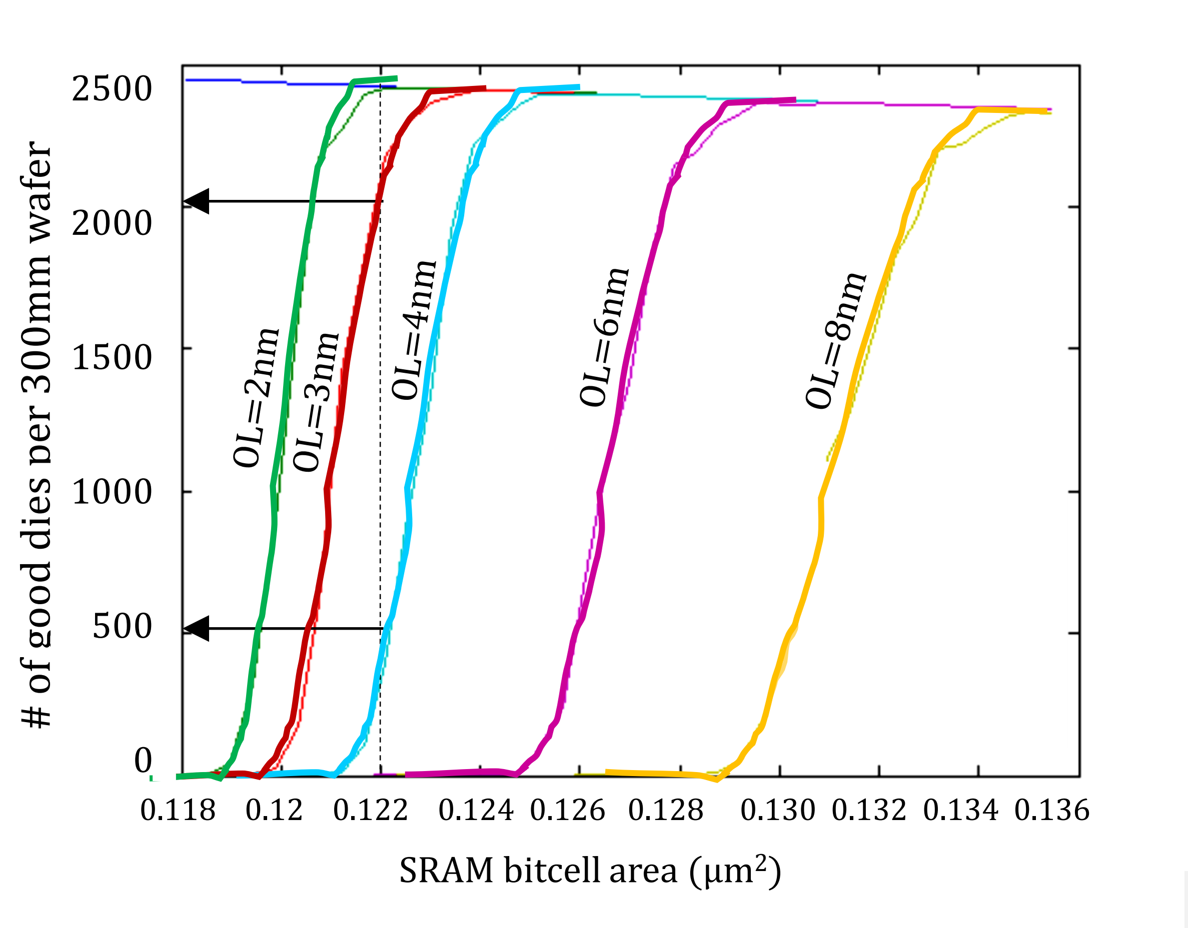
V_T variability induced by gate and contact CD errors

Contact to gate overlay error



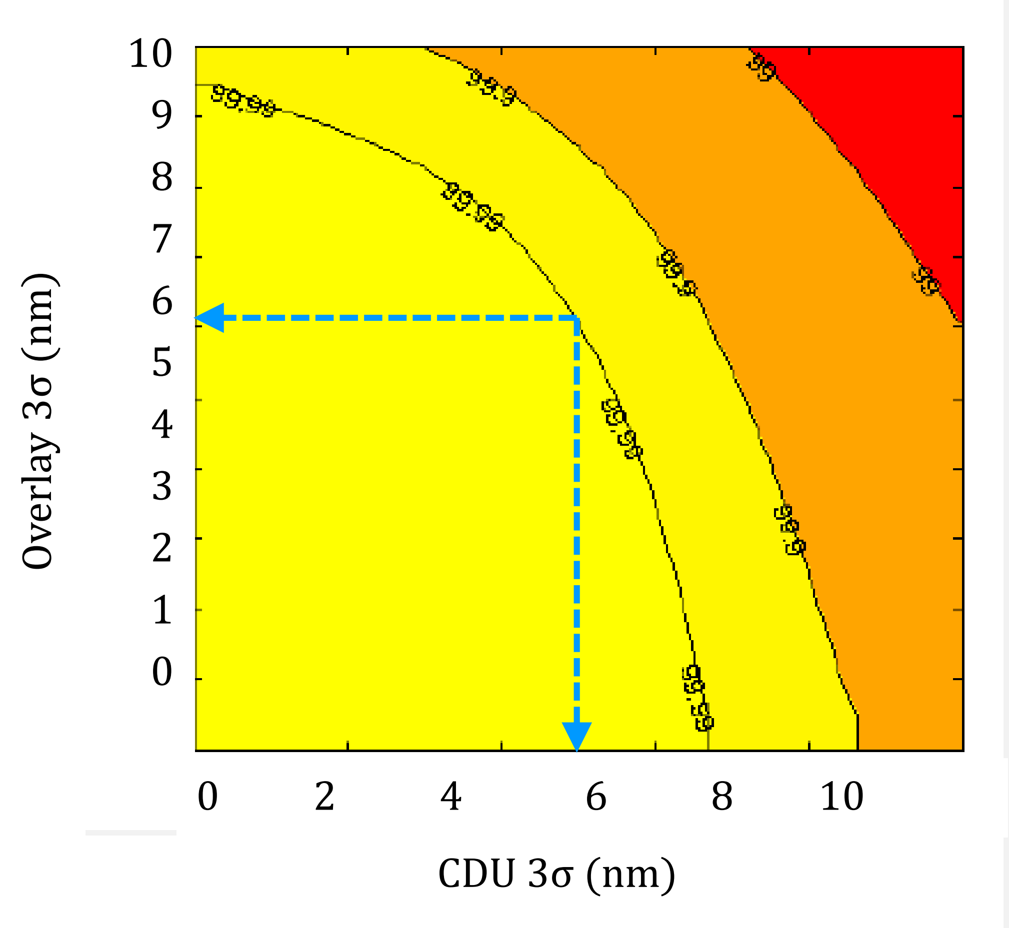
Device mobility degradation from reduced local strain caused by contact overlay error

Impact of Overlay and CDU errors on SRAM yield



The number of good 64 Mbit SRAM dies/wafer.

1nm better overlay = 4X more good dies/wafer



Functional yield (%) of 0.132um^2, 32nm node SRAM cell; 20nm gate-contact spacing

Extreme Ultra Violet, EUV,

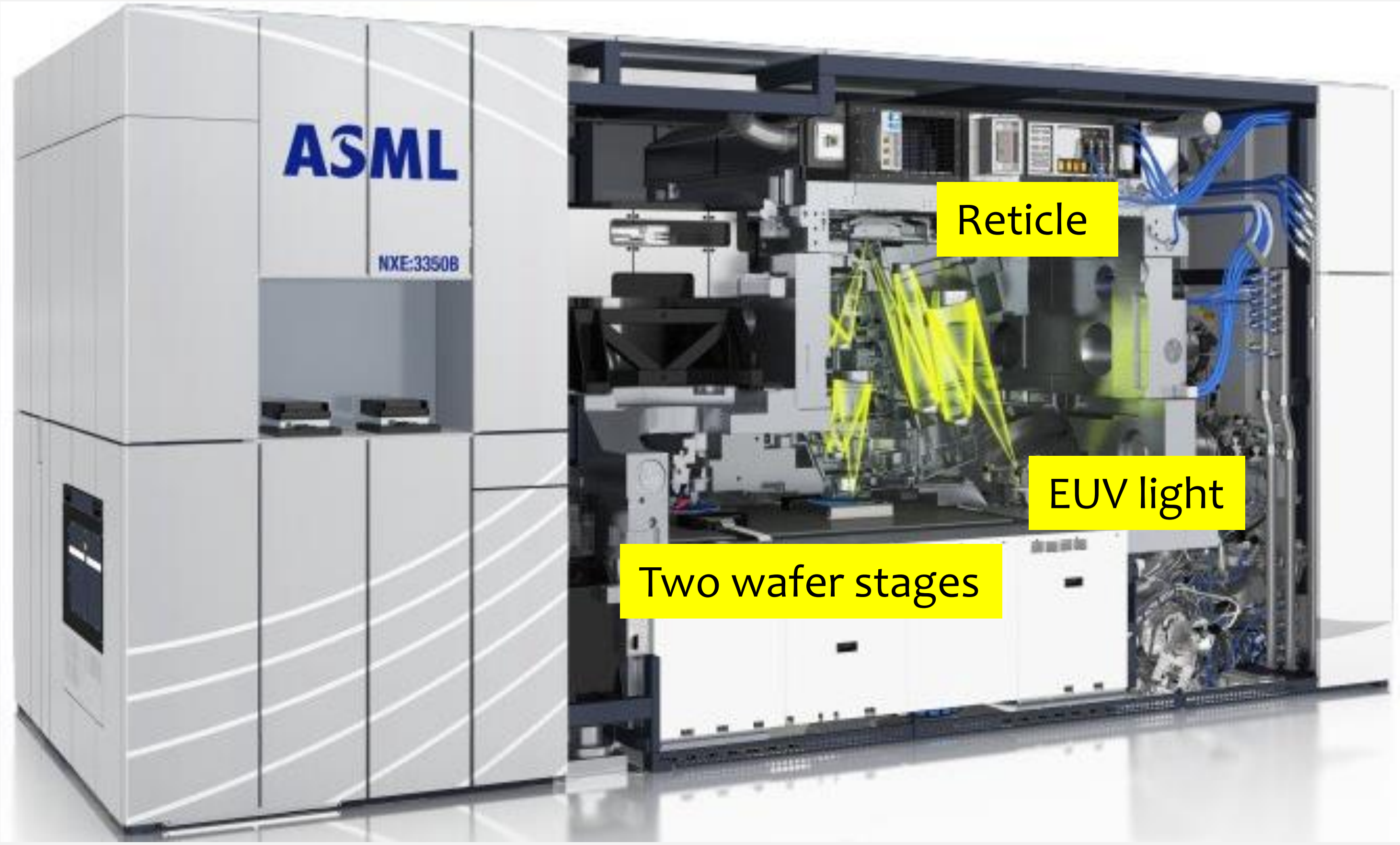
- the lithography of tomorrow -

EUV, Lithography gets extreme

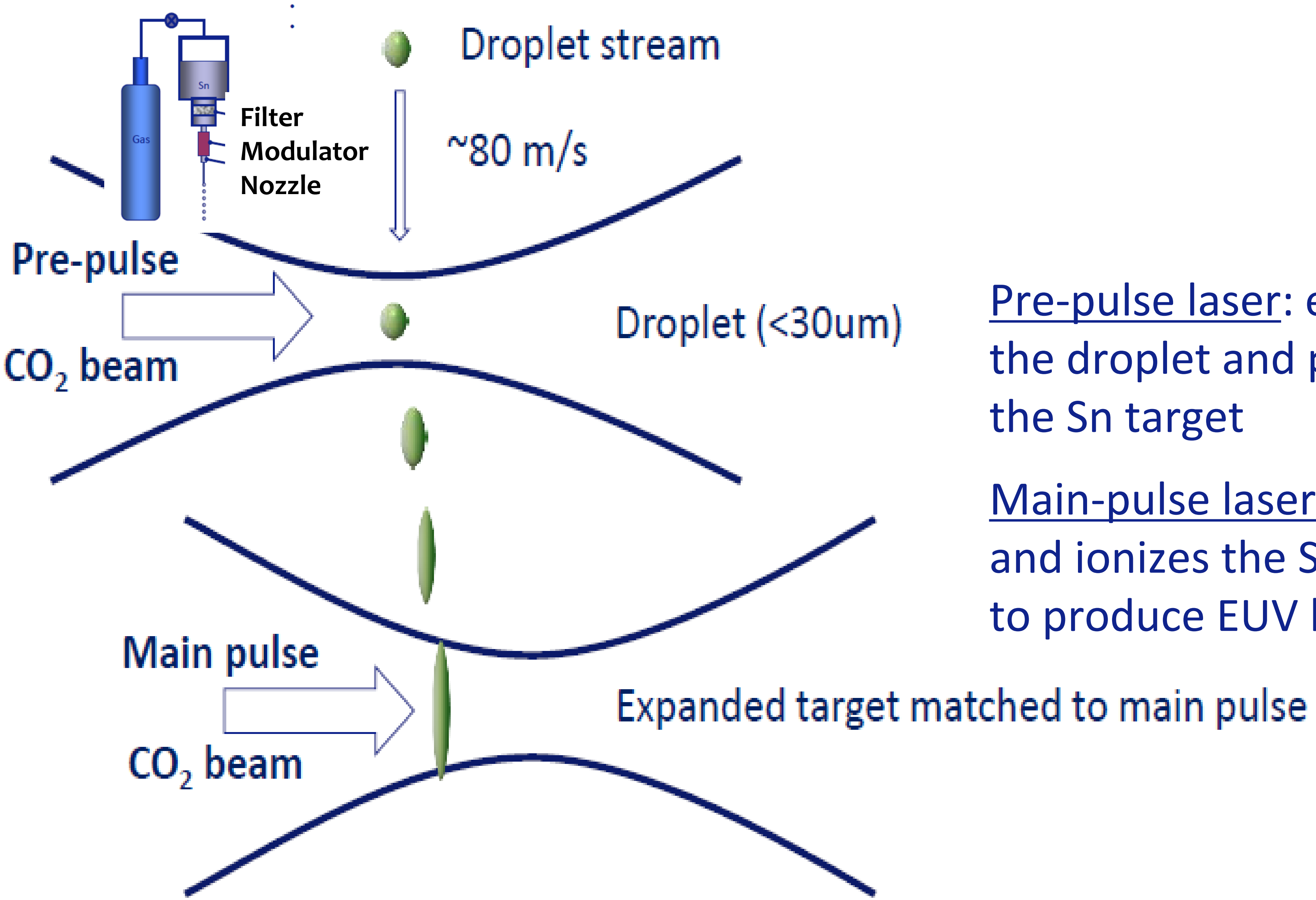
λ 13.5nm
NA 0.33
Field $26x33mm^2$
Resolution (min CD) ≤ 15nm
# of pixels: $11*10^{11}$ (2X193i)

In vacuum
All reflective optics

Key technologies:
- EUV Source
- Multilayer mirror lenses
- Laser



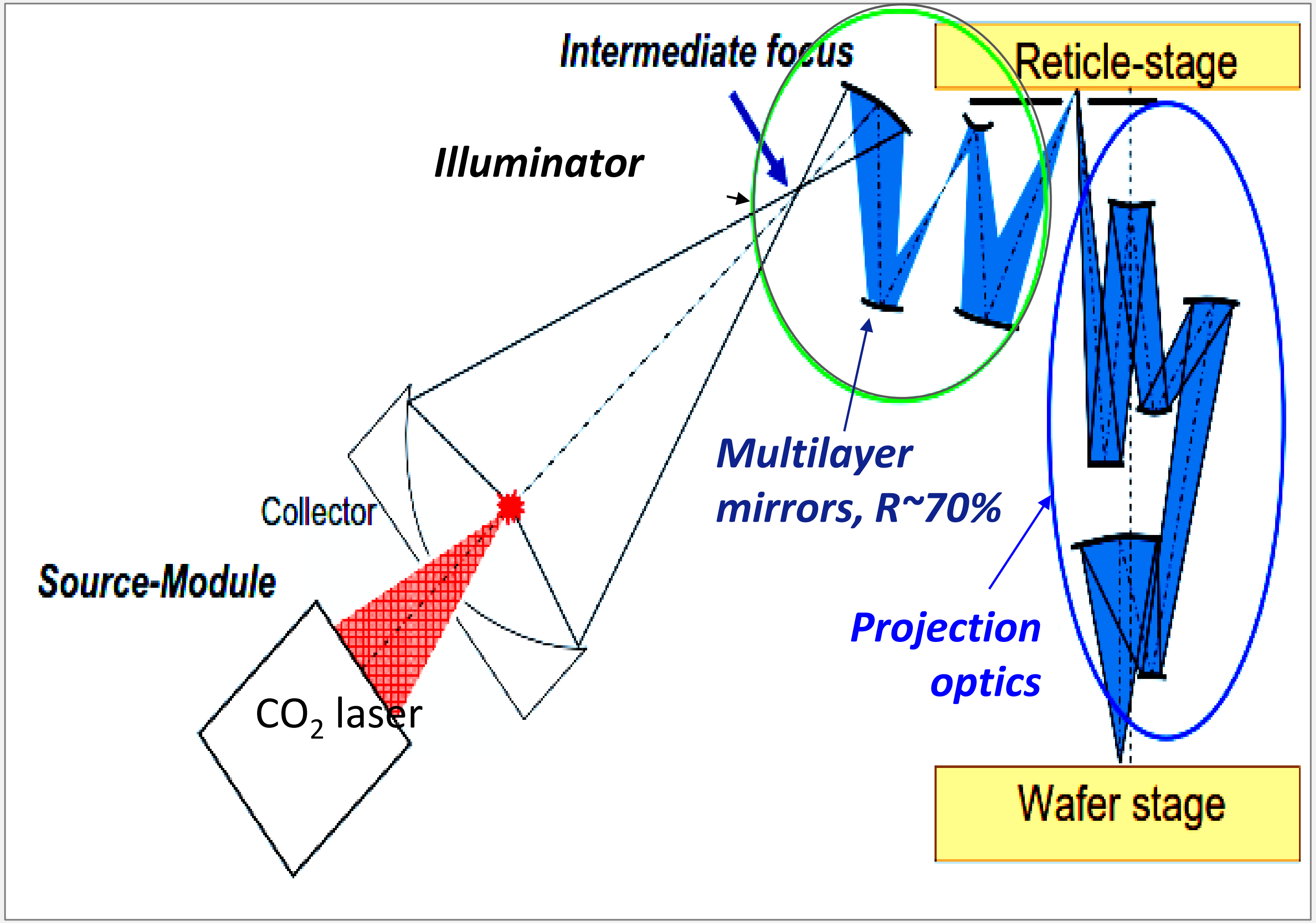
EUV source architecture



Pre-pulse laser: expands the droplet and prepares the Sn target

Main-pulse laser: heats and ionizes the Sn target to produce EUV light

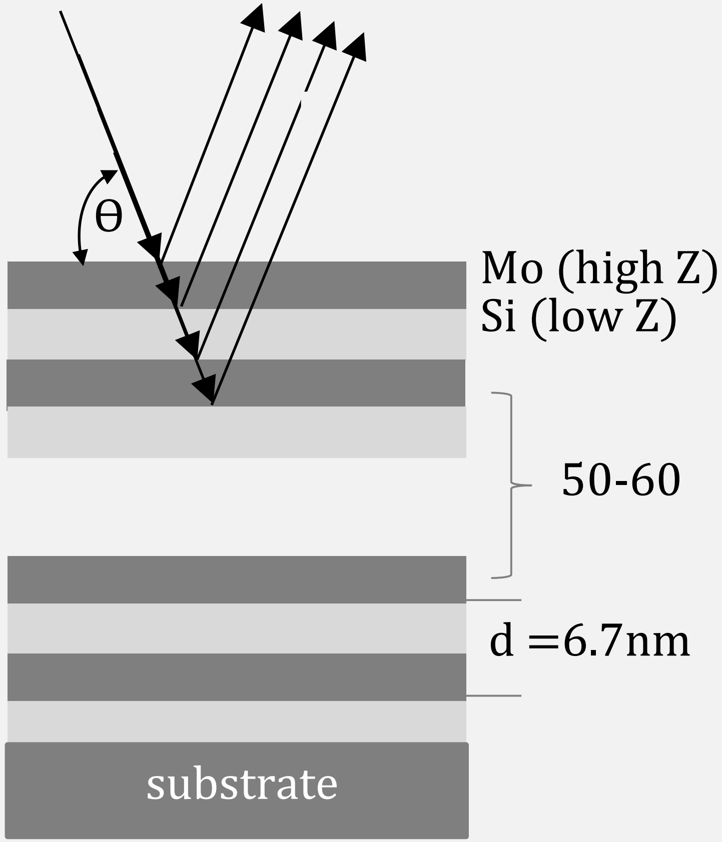
Multilayer mirror lenses for EUV optics



Multilayer mirrors

Reflection by Bragg interference,

$m\lambda=2d \sin\Theta$



In place of conclusions, *“The future isn’t what is used to be”*

(Y. Borodovsky, Intel Fellow, 2018)

- On Moore’s Law future:

  “Once lateral scaling had run out, scaling will go vertical” (*P. Gorgini, Intel Fellow)*

- On Optical (Photo)Lithography future:

  The effective pixel-rate of optical lithography is and has been the highest of any lithography technology.

  193immersion scanner exposing 275wafer/hour, has a pixel exposure rate of $3x10^{15}$ pixels/sec or about $3x10^{17}$ bits/sec.

  It is currently inconceivable that this exposure rate could be exceeded by any other means