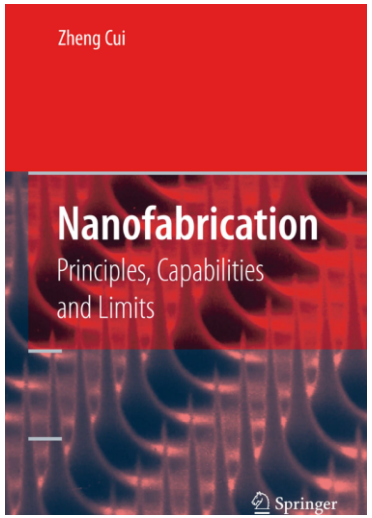
Nanofabrication and Nanocharacterization

Part II PC3242

A/Prof Jeroen van Kan
phyjavk@nus.edu.sg



Books
Micro-Nanofabrication Zheng Cui 2005
Nanofabrication Zheng Cui 2008

Course objectives

Top-Down Nano lithography – Nano fabrication – Nano characterization

- Optical lithography (X-ray?)
- E-beam Lithography
- Focused Ion Beam Lithography
- Proton Beam Writing
- Nano Imprint Lithography
- 3DP
- Etching

↔ Characterization using electrons
↔ Secondary Ion Mass Spectrometry
↔ Ion Beam Analysis (RBS/PIXE/NRA)

Module Assessment

Part I: 30% (Prof Ho)

Part II: 30% (A/P van Kan) Comprising of:

15% 2 Simulation projects (S1 & S2, < 5 pages each)
Simulation 1: Casino + SRIM (7.5%)
Simulation 2: RBS (7.5%) Measure and fit Metal/Si sample we have prepared.

10% Test (22 Oct 2024)

5% In class Quiz (Canvas quizzes)

Final exam: 40% (covers Part I + II)

Tues 12^{00}-14^{00} S12 04-01(7) S16-04-37 (8-13)

Fri 10^{00}-12^{00} S13-M-09 (7-13)

PC3242 Lesson plan Part II

Week 7

- L1+2 S12 04-01 Optics Lithography + Quiz
- L3 + T1 (19) EBL (Electron Beam Lithography) + T1; Casino + Quiz

Week 8

- L 4+5 (34) EBL & SIMS + Quiz
- L6 + T2 (15) SIMS + T2; SRIM Low Energy + Quiz

Week 9

- L 7+8 (32) SIMS, FIB & MeV Ions + Quiz
- L9 + T3 (19) MeV Ions + T3; High Energy (S1 7.5%) + Quiz

Week 10

- Test 22/10/2024 (10%) + Test
- L10 + T4 (19) Etching Lecture + T4 (SRIM) +RBS + Quiz (S1 due)

Week 11

- Lab tour RBS experiment (S2 fit RBS spectra Metal/Si 7.5%)
- NUS wellness day

Week 12

- L11+12 (19) Etching Lecture + Quiz
- T5 + T6 + T5,6 RBS SIMNRA

Week 13

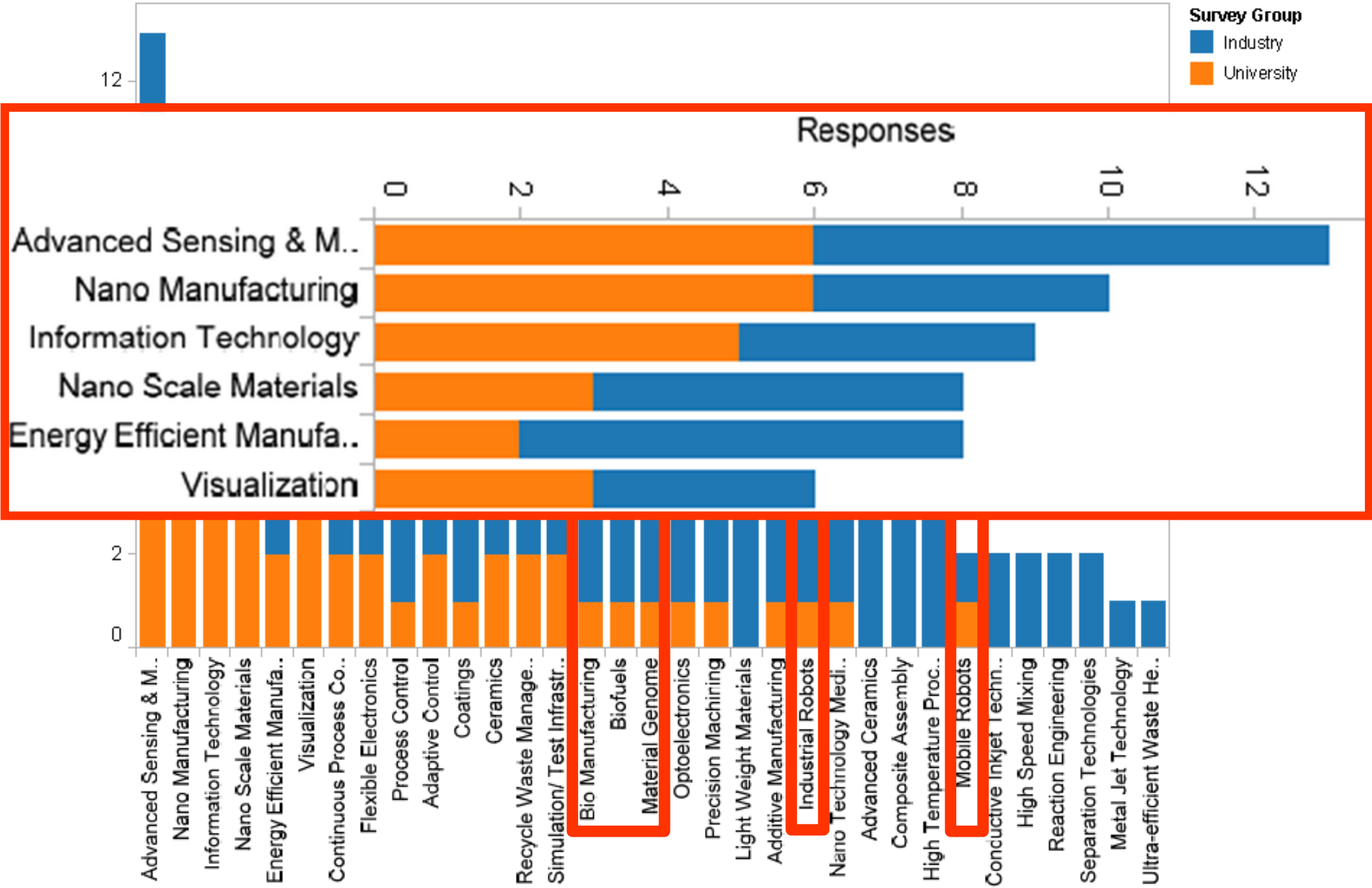
- L13 + 14 (33) NIL + 3DP + Quiz (S2 due 13/11/24)
- Summary (20) Summary, Tut discussion + Discussion: Test & S1 & 2

*CIBA lab tour/RBS experiments on 29/10/2024

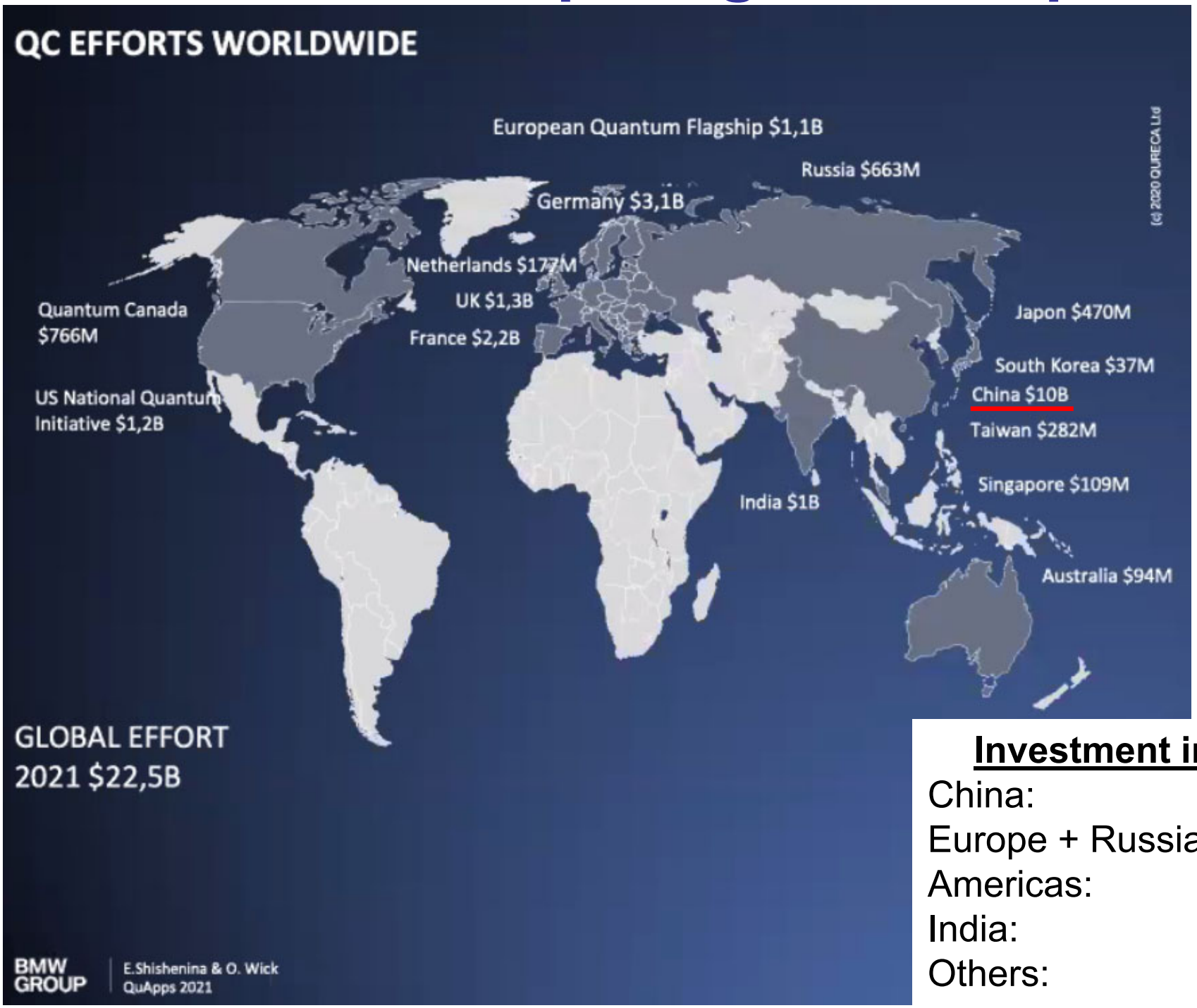
PC 3242 Part II

Topic	Text Book (Zhen Cui '05)	Lectures
Optical lithography	Chapter 2	1, 2 & 3
Electron Beam Lithography	Chapter 3	4 & 5
Focused Ion Beam Technology	Chapter 4	
Low Energetic Ions (keV)		6, 7 & 8
SIMS	Extra material provided	
FIB in Lithography	Chapter 4	
High Energetic Ions (MeV)	Extra material provided	9
RBS	Extra material provided	10
Light ions in lithography	Extra material provided	11
Nano Imprint Lithography	Chapter 7	12
3DP Three Dimensional Printing	Extra material provided	13
Etching	Chapter 6	14

Combined Survey Results: Top Technologies Deemed Most Critical for U.S. Advanced Manufacturing



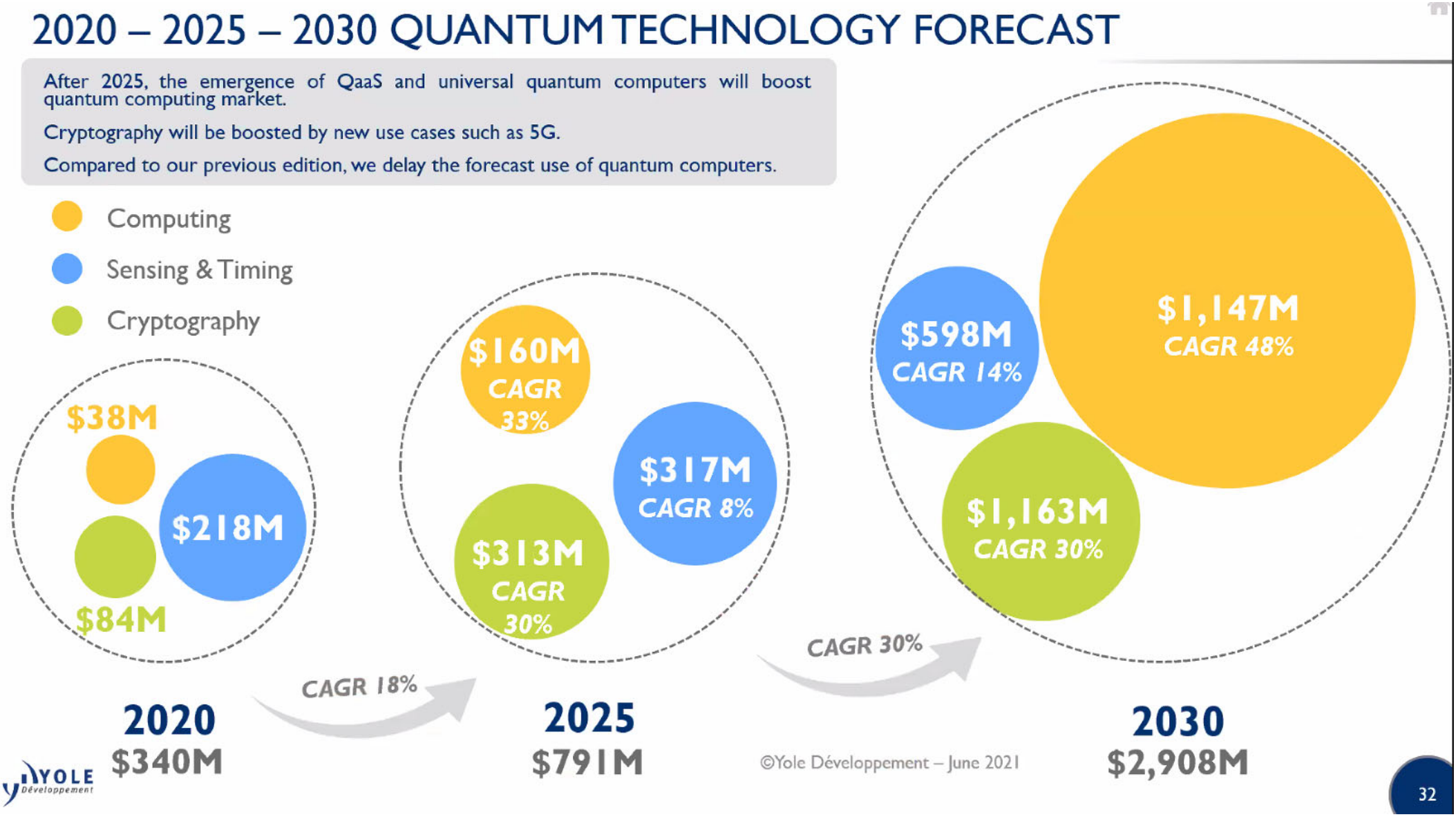
Quantum Computing Landscape



Investment in QC

China:	$10B
Europe + Russia:	$8.5B
Americas:	$2B
India:	$1B
Others:	$1B

Quantum Technology Outlook



Nanotechnology in future cars

Self driving cars (Quantum computers)

Windscreens stay clean through nano coating

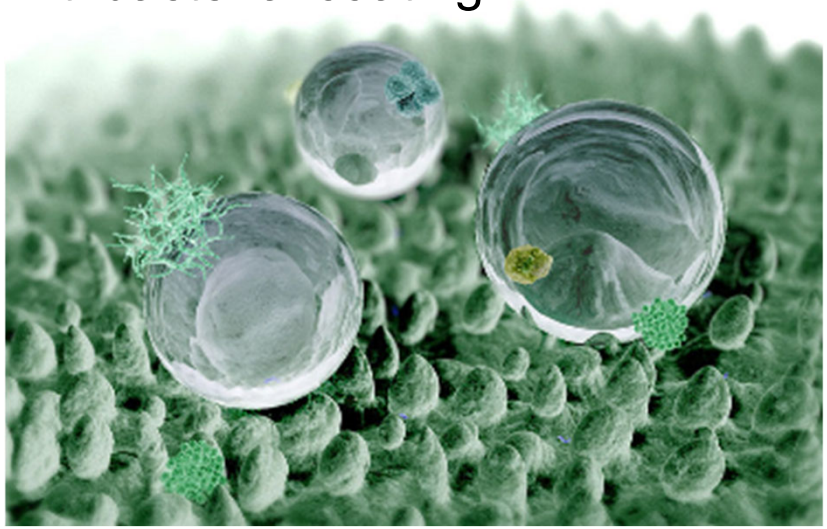
Self cleaning paint (Hydrophobic surface) Lotus effect also called “easy clean “

Using nanotechnology the paint on a vehicle could even be designed as a solar cell (already available)

Nanotechnology used in LED lighting of cars; it is faster and more energy efficient (already implemented)

https://www.youtube.com/watch?v=sYPzB1g5_5E

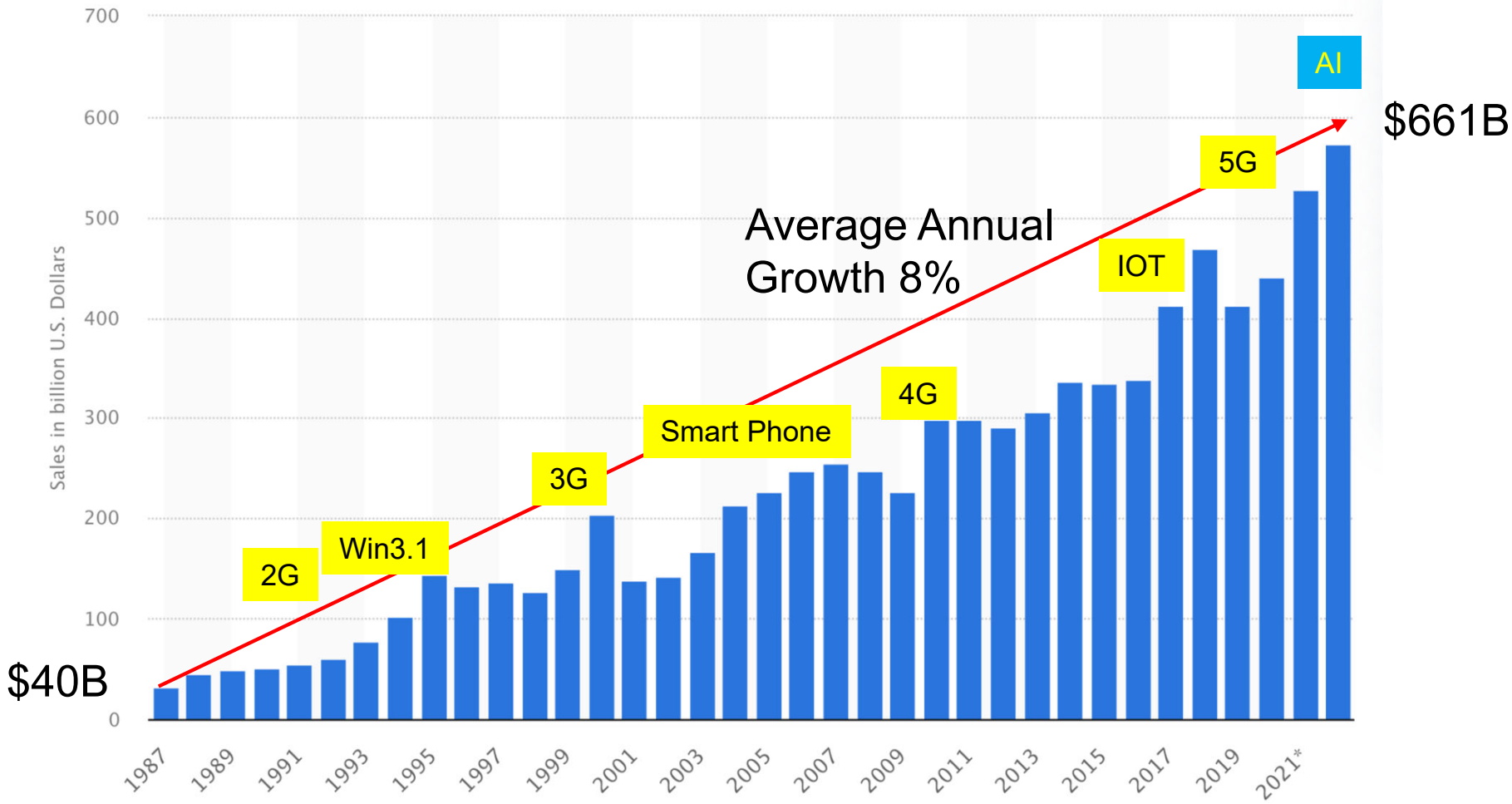
Self cleaning through Nano imprinting; Anti bacterial coating



Lotus or cleaning effect

Semiconductors industry (2023): US $611B
A Key Industry for the World Economy

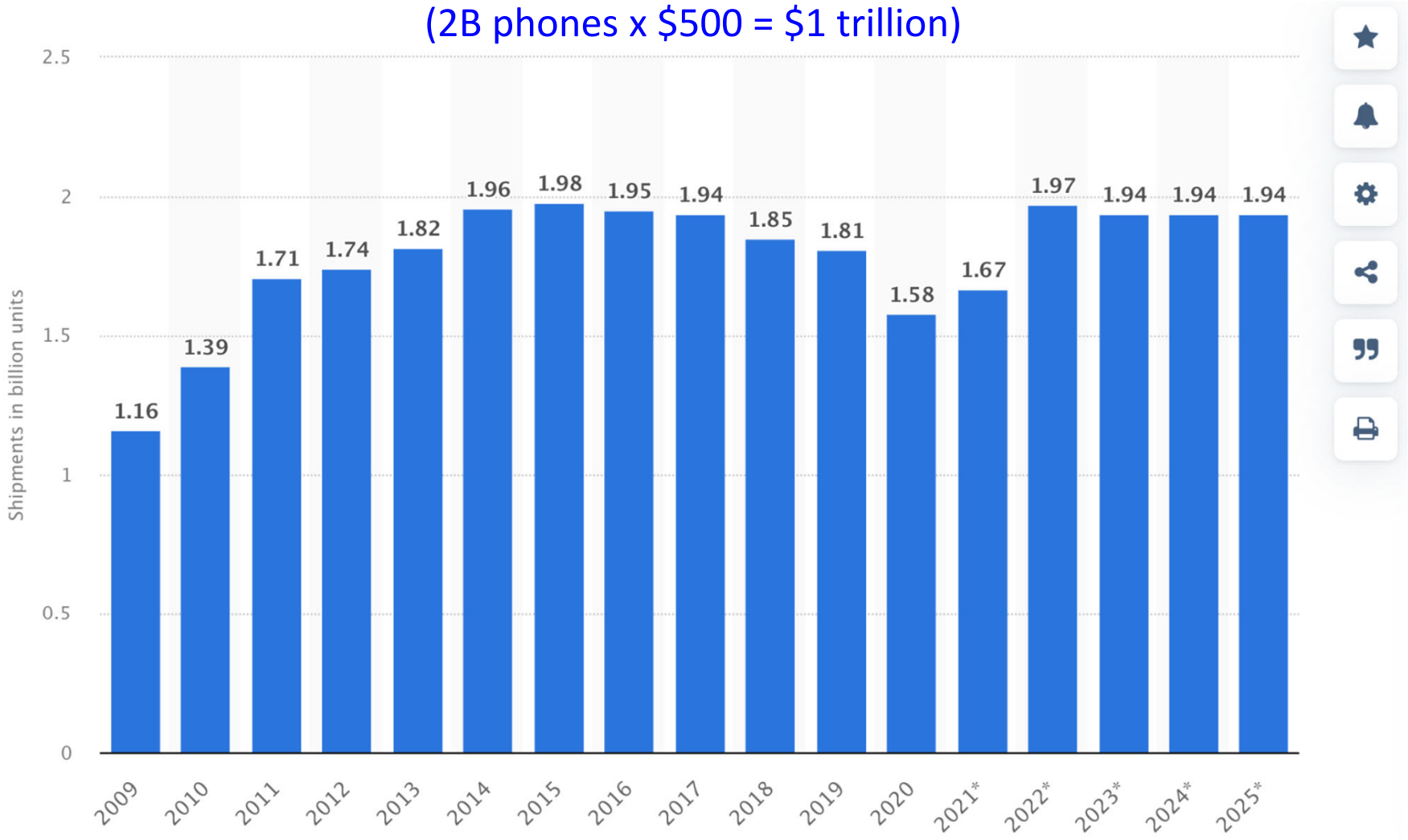
Each $ of Semiconductor produces ~5x of end products



https://www.semiconductors.org/global-semiconductor-sales-increase-3-9-month-to-month-in-october-annual-sales-projected-to-increase-13-1-in-2024/

Unit shipments of mobile phones worldwide from 2009 to 2025

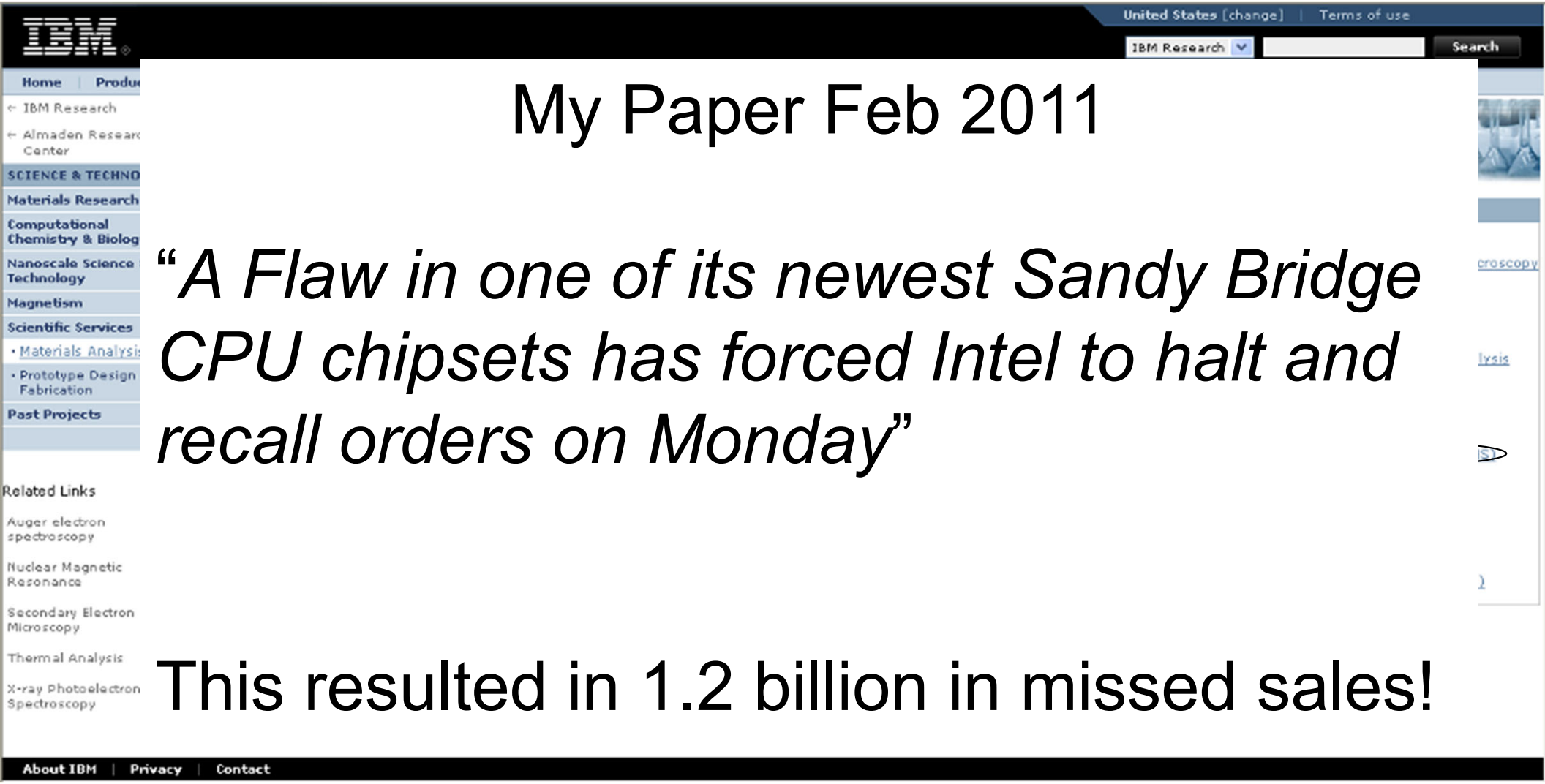
(2B phones x $500 = $1 trillion)



https://www.statista.com/statistics/272696/mobile-phone-shipments-worldwide-by-quarter/

http://www.almaden.ibm.com/st/scientific_services/materials_analysis/ib_surface/

Their website has been revamped, this is the link to the new website:
http://researcher.watson.ibm.com/researcher/view_group.php?id=3558



My Paper Feb 2011

"A Flaw in one of its newest Sandy Bridge CPU chipsets has forced Intel to halt and recall orders on Monday"

This resulted in 1.2 billion in missed sales!

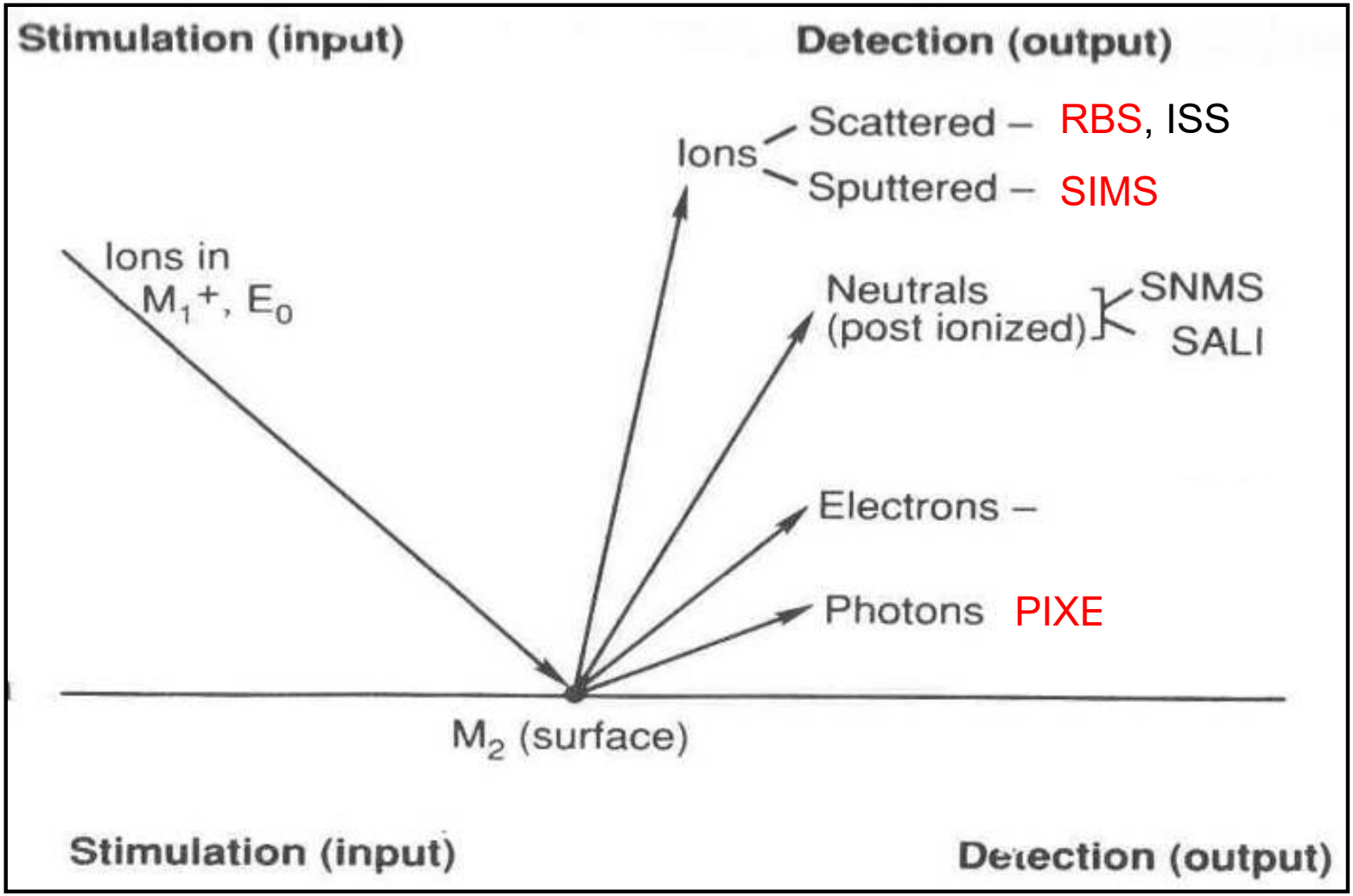
Surface Techniques

- Most physics techniques can be classified as **scattering experiments**: a particle is incident on the sample, and another particle (not necessarily the same) is detected after the interaction with the sample.

- Surface Physics is no exception: we can think of an incident *Probe* X and a *Response* Y. If we understand the nature/physics of the scattering, then we can interpret the experiment and deduce the corresponding characteristics of the sample.

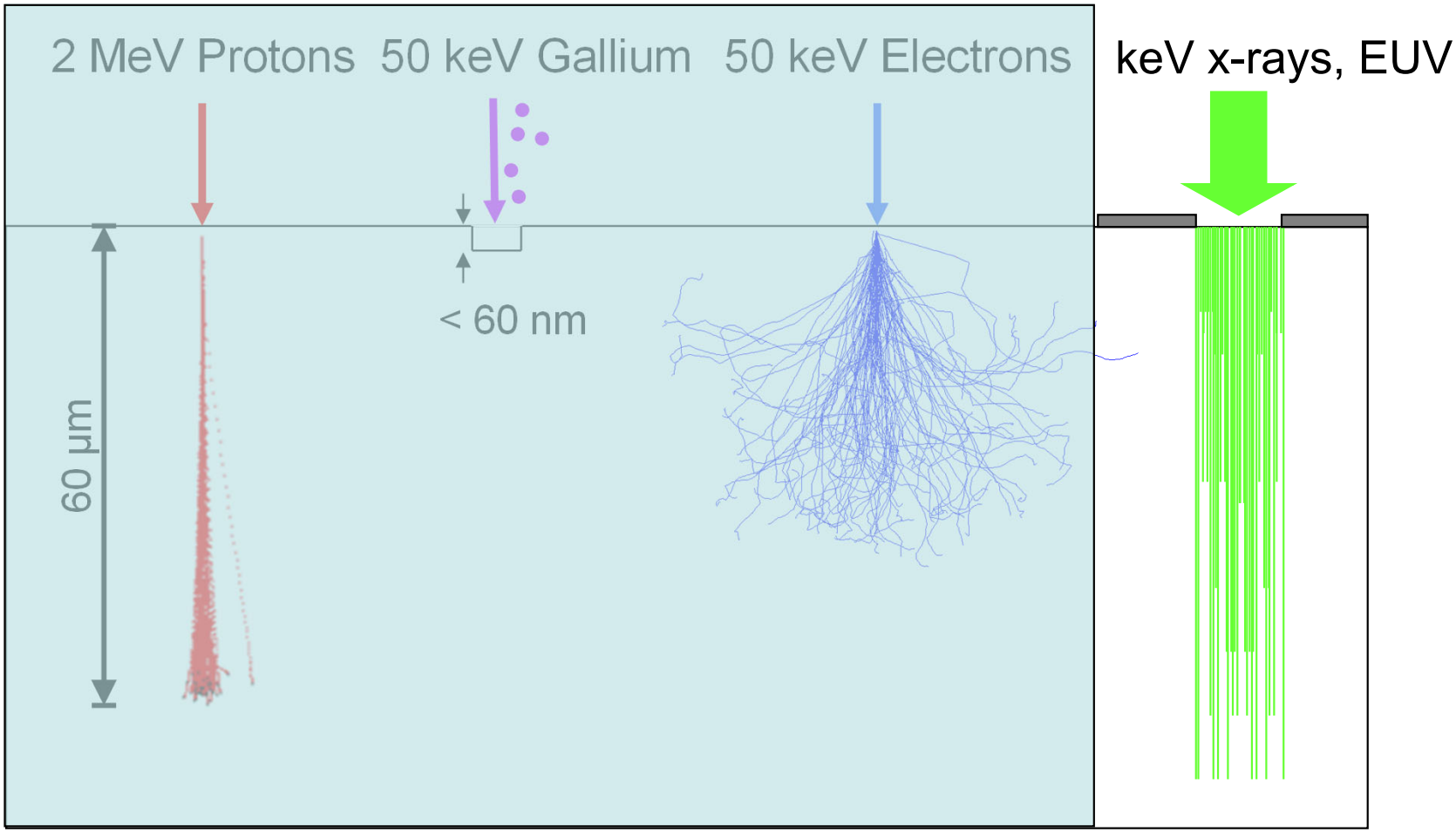
Probe		**Response**
X		**Y**
Electrons (E_0,k_0, ..spin s)		Electrons (E,k, ..spin s)
Radiation (ω_0,k_0, ..polarisation) →	**Sample** →	Radiation (ω,k, ..polarisation)
Atoms (E_0,k_0,Z)		Atoms (E,k, Z')
Ions (E_0,k_0, $\pm$Z)		Ions (E,k, $\pm$Z')

Primary Particle Probes



SNMS: Sputtered Neutral Mass Spectrometry
SALI: Surface analysis by Laser Ionization
ISS: Ion Scattering Spectroscopy or LEIS: Low Energy Ion Scattering Spectroscopy
RBS: Rutherford Backscattering Spectrometry
SIMS: Secondary Ion Mass Spectrometry
PIXE: Particle Induced X-ray Emission

Particle/wave interaction with material



2 MeV protons: Well defined path + Dose homogeneity

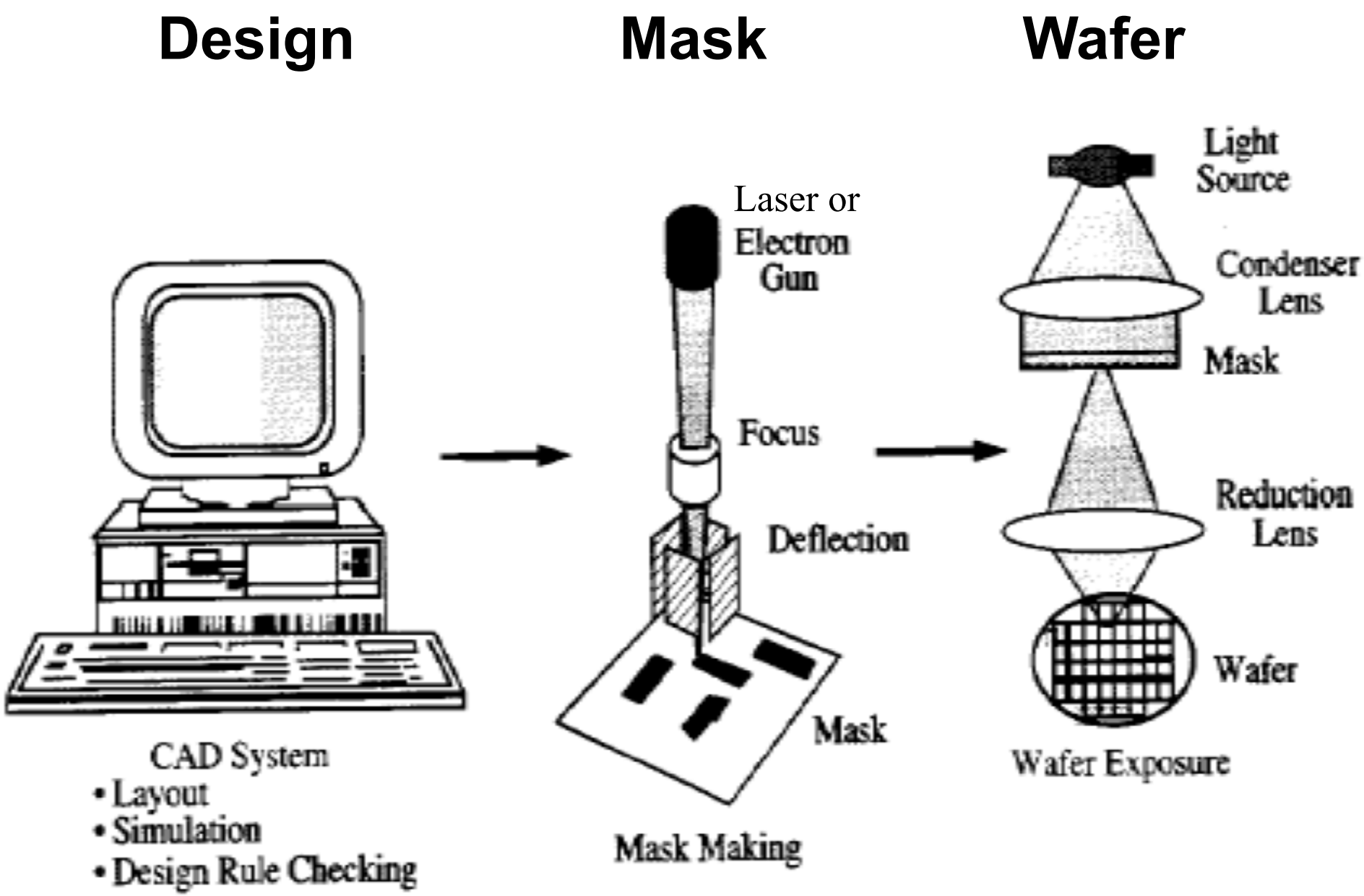
(Focused ion beam FIB): Surface atoms removed by sputtering

50 keV electrons: beam broadening below the surface

X-Rays need mask, well defined path: dose exp decay with depth

- **Nanolithography** using particles or waves can be planned if we understand the physics of the interactions.
  E.g. like in Optical lithography, Electron Beam Writing, FIB and Proton Beam Writing.

Optical Lithography

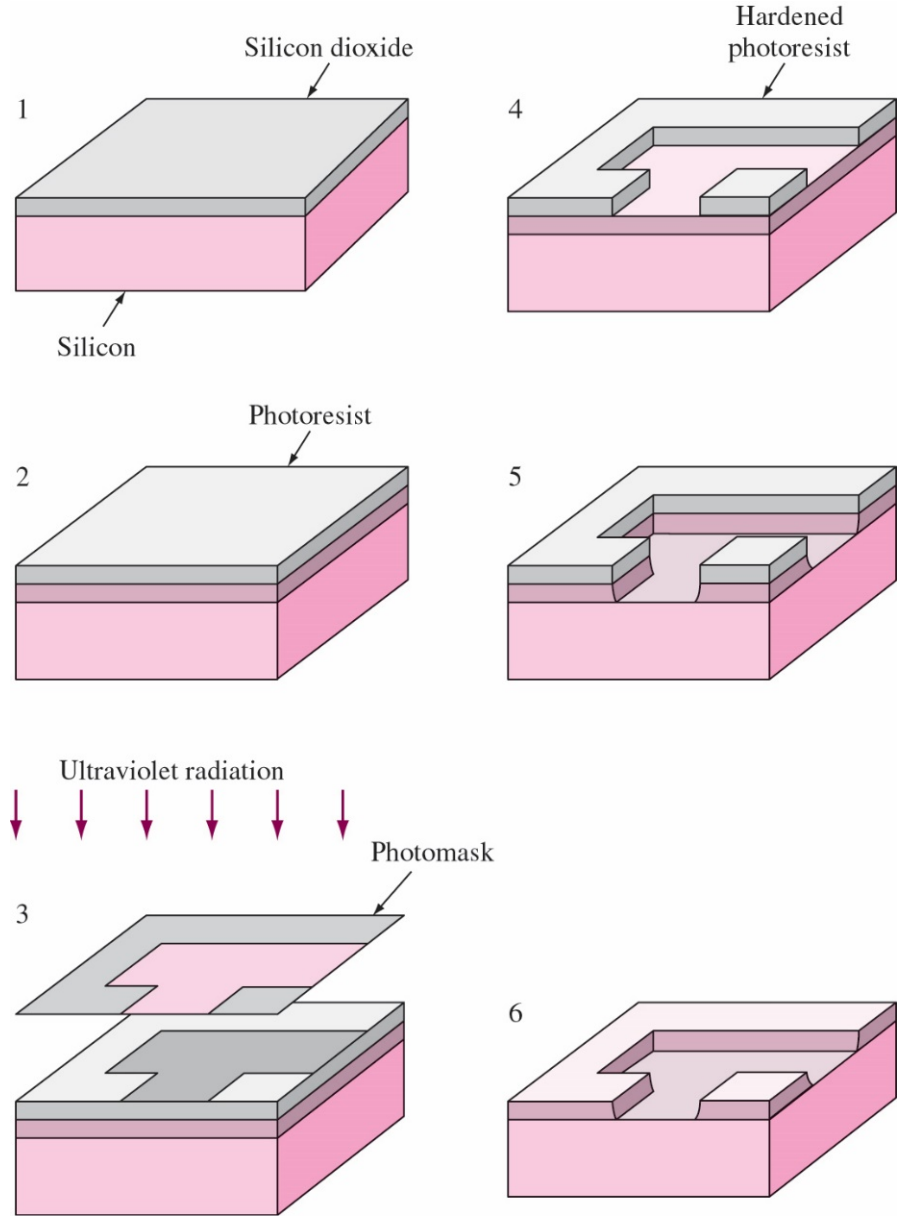


Optical Lithography

Fabrication of Integrated Circuits Chips

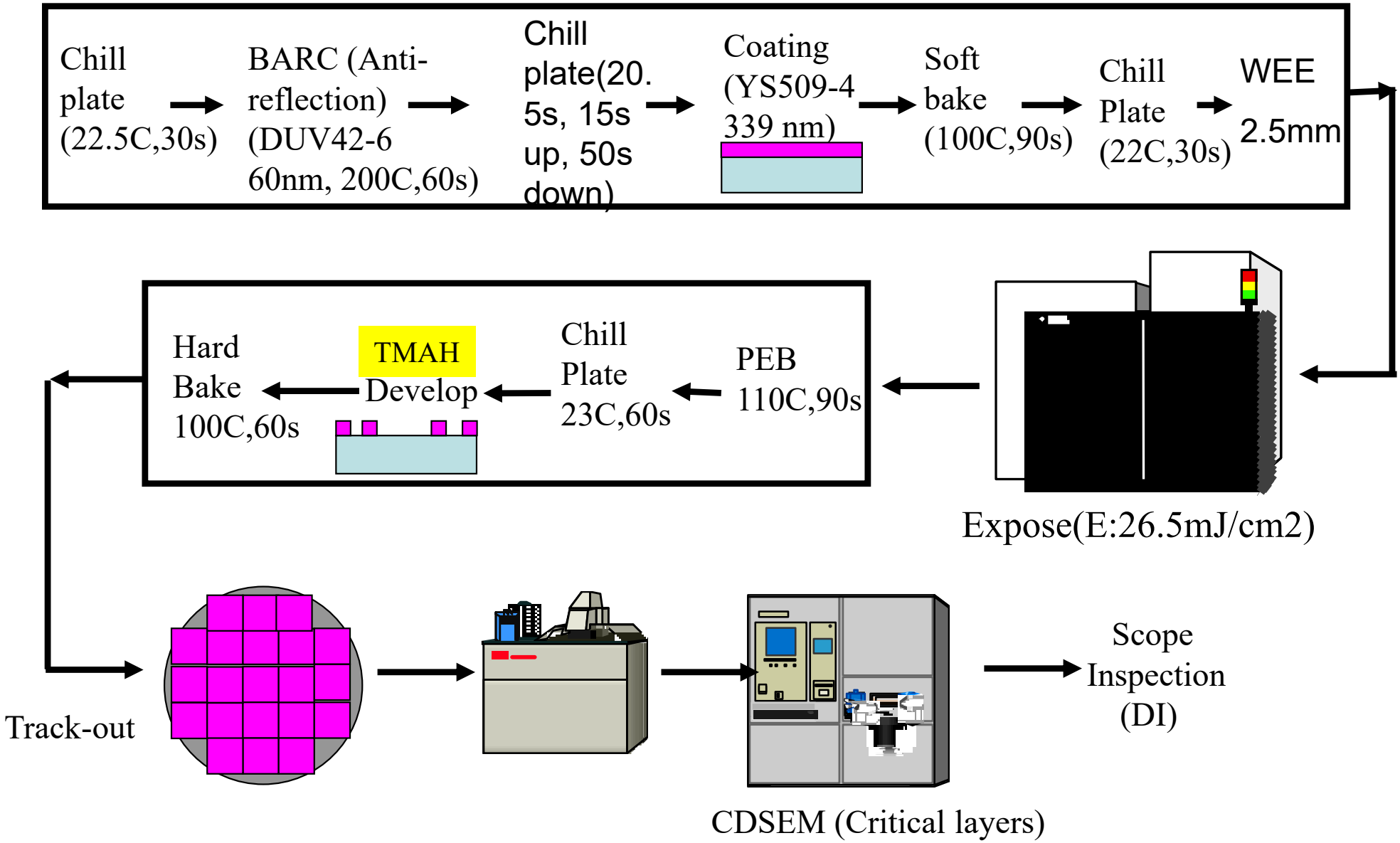
Photolithography: The process by which microscopic pattern is transferred from a photomask to the silicon wafer surface.

- ✓ Wafer is coated with photoresist.
- ✓ Then exposed to ultra-violet light through photomask (or reticle).
- ✓ Pattern of photoresist is left where mask is transparent.
- ✓ Wafer is immersed in hydrofluoric acid.
- ✓ Photoresist pattern is removed by chemicals.



Optical Lithography

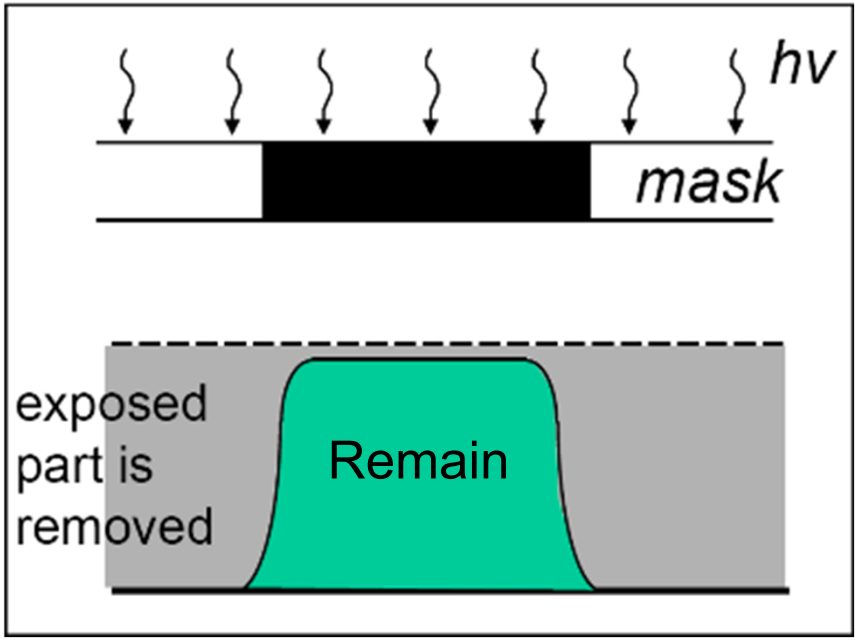
Process Flow of Photolithography

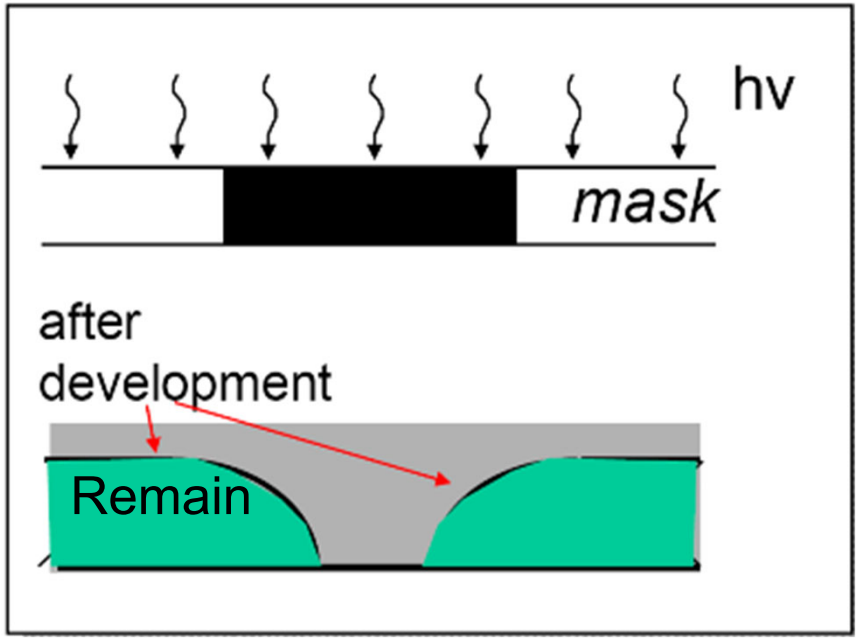


Optical Lithography
(Resist Exposure)

Positive-tone ← → ***Negative-tone***

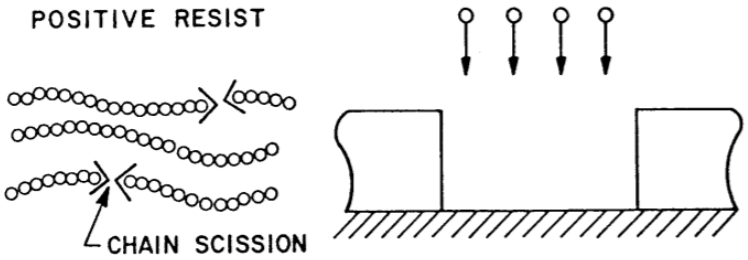
photoresist

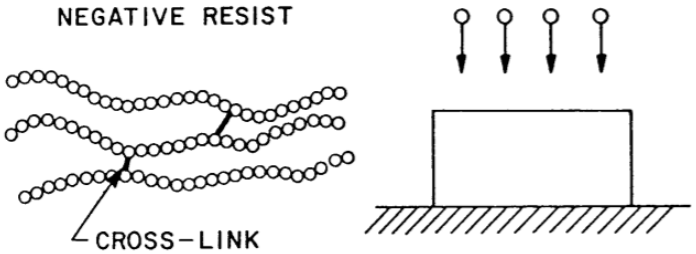




hv =>"chain scission" =>
soluble in developer solution.

hv => cross-linking =>
insoluble in developer solution.



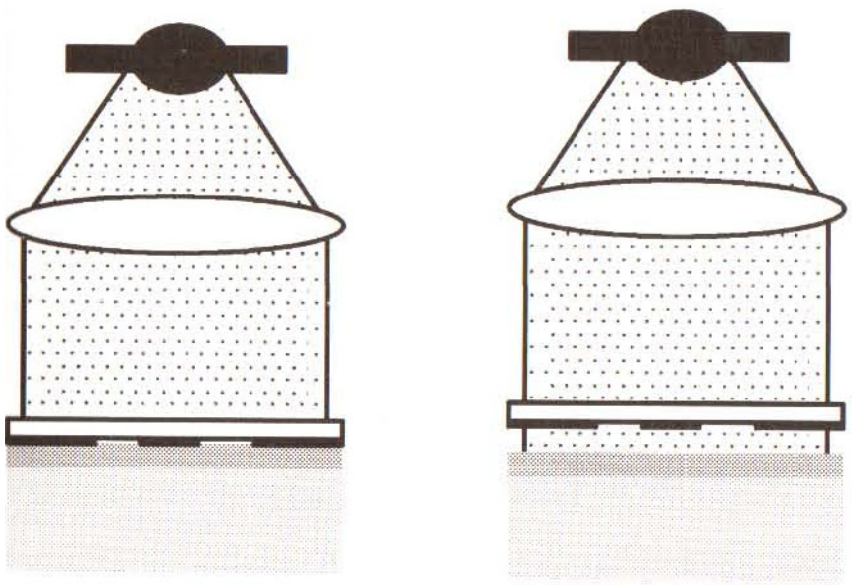


Optical Lithography

(Exposure Modes)

There are 2 basic ways to do optical lithography

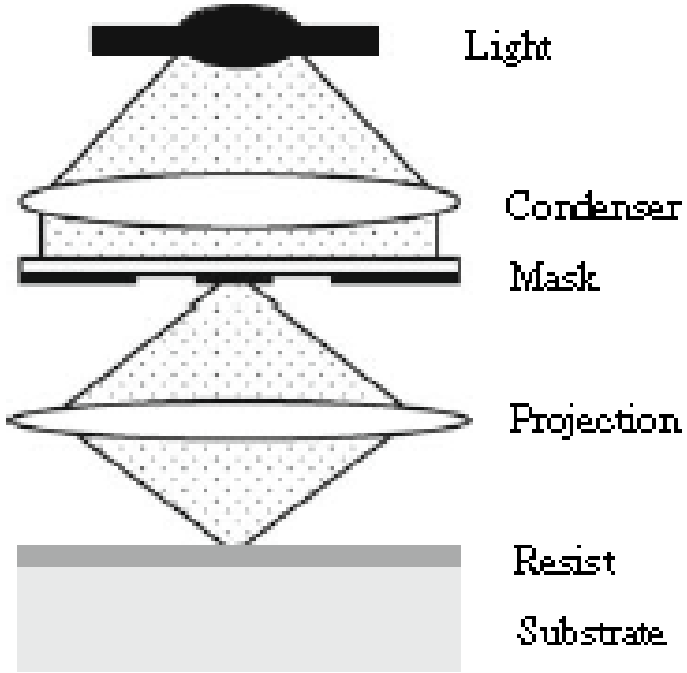
Mask aligning



Either contact or proximity

Mask Aligner

Projection



Projection 5:1 or 10:1 reduction

Stepper

A system in which the wafer is aligned with respect to a photo mask is called a mask aligner

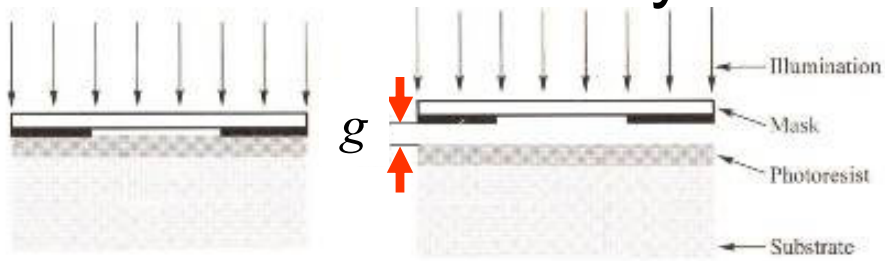
Optical Lithography
(Contact Printing)

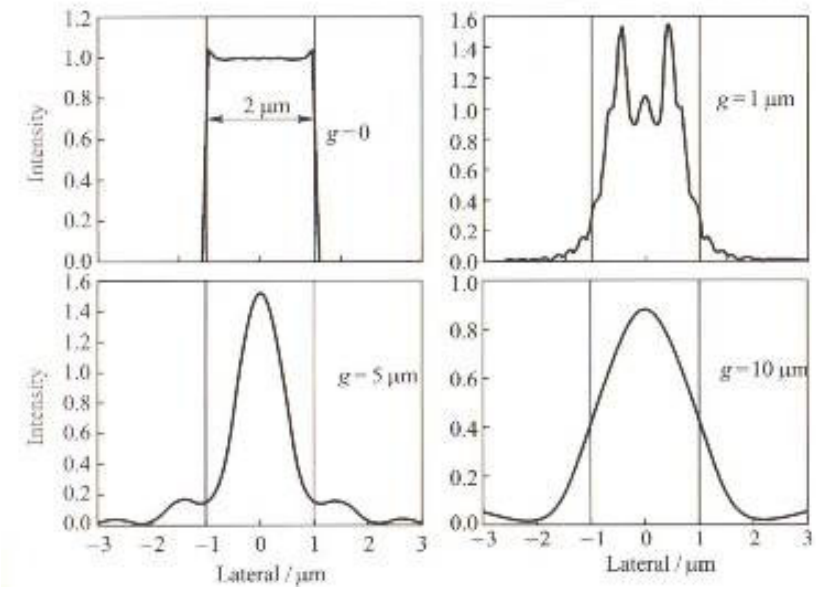
Mask Aligner

Contact / Proximity printing

In early days in IC fabrication mask aligners were used (Early 1980s).

Contact / Proximity





Simulated energy deposition profile

The minimum line-width l_m

$$l_m = k\sqrt{\lambda g}$$

Here we have the following parameters:

- λ the wavelength of the light
- g (or z), proximity (mask and wafer)
- k resist processing condition parameter

Optical Lithography
(Contact Printing vs Projection Printing)

<u>In Contact printing a MASK</u> will **<u>deteriorate FAST</u>** due to:

1) Resist adhesion to the mask (regular cleaning required)
2) Scratches in the Cr mask

<u>This leads to low mask life time.</u>

→ **<u>Introduction of Projection Printing in IC Industry</u>**

<u>Projection Printing</u>

First 1:1 printing was employed but soon higher resolution masks were needed

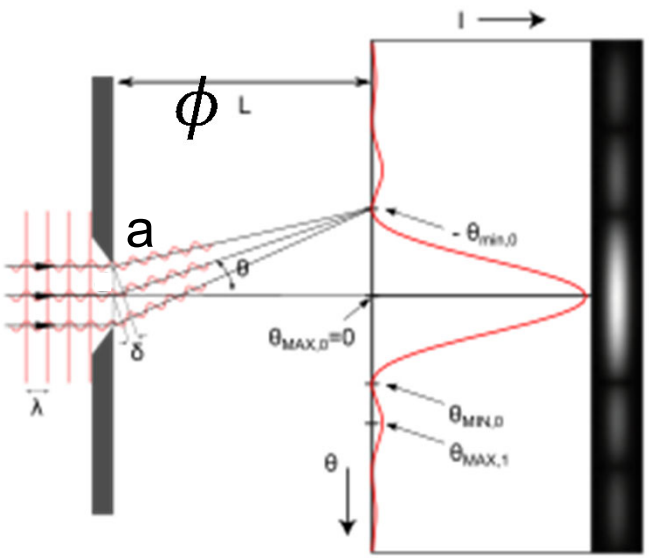
➔Introduction of 5:1 projection optics
➔Now commonly used are up to 10:1 projection systems

<u>Limits in proximity gaps</u>

- Si wafer *<u>flatness</u>* (bowing) becoming more pronounced for large wafers
- Internal stress due to thermal processing and deposition

Optical Lithography
(Projection Printing)

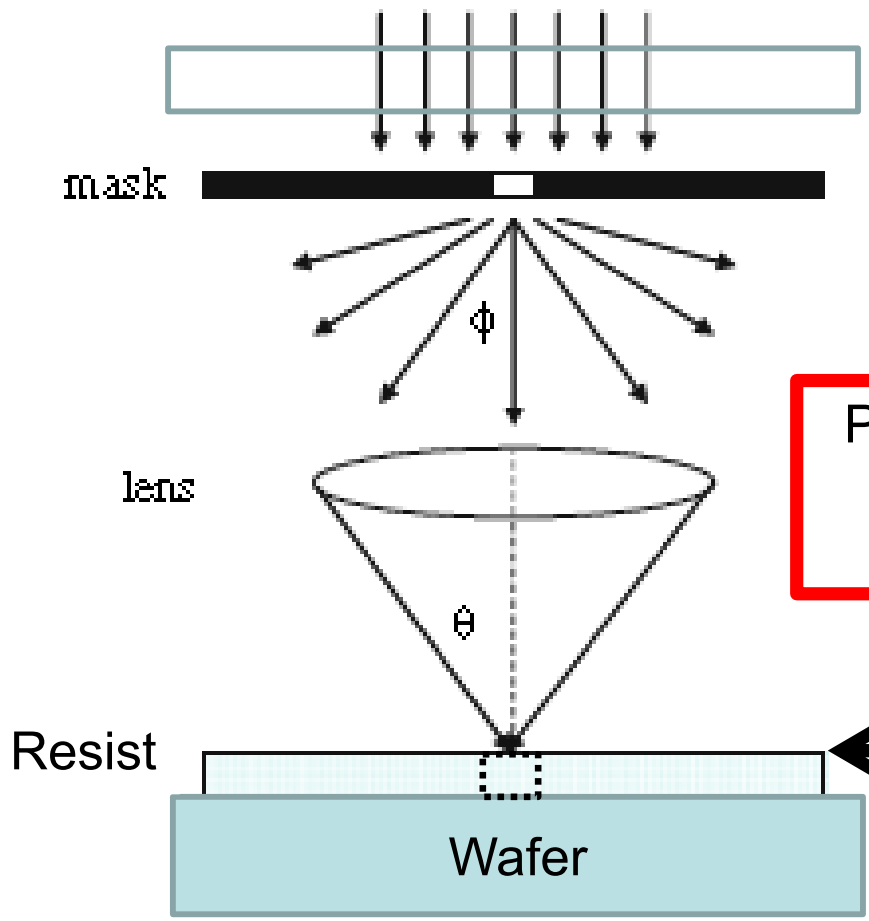
Single Slit Diffraction



$$\sin\theta_m = m\frac{\lambda}{a}$$

$$m = 1,2,3,\ldots$$

Angles at which minimum occur



Illumination (λ)

Mask

Diffracted Light

Projection Lens has to be big enough to capture $m = 1$!

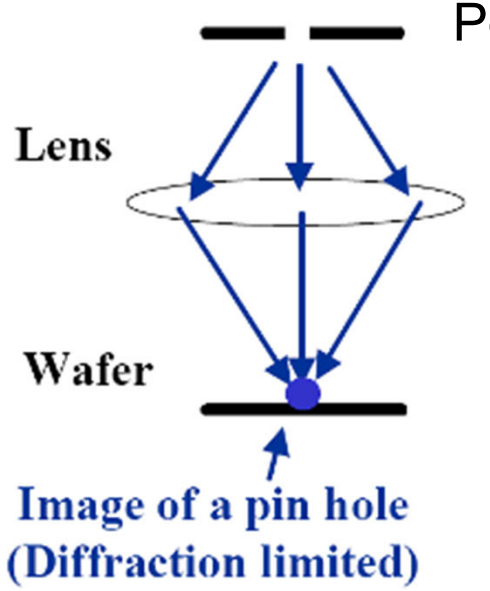
Focal plane

Period = $\frac{\lambda}{\sin\theta_1 - \sin\theta_2} = \frac{\lambda}{2\sin\theta}$

Optical Lithography

(Resolution in Projection Printing)

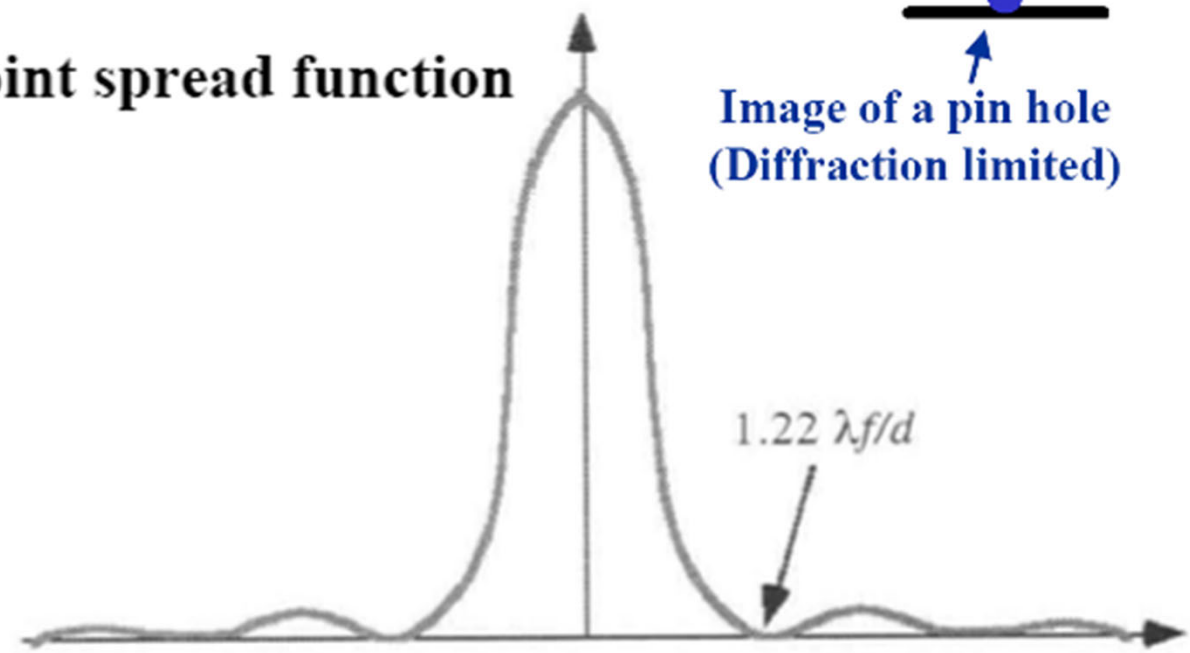
Point source (coherent illumination)

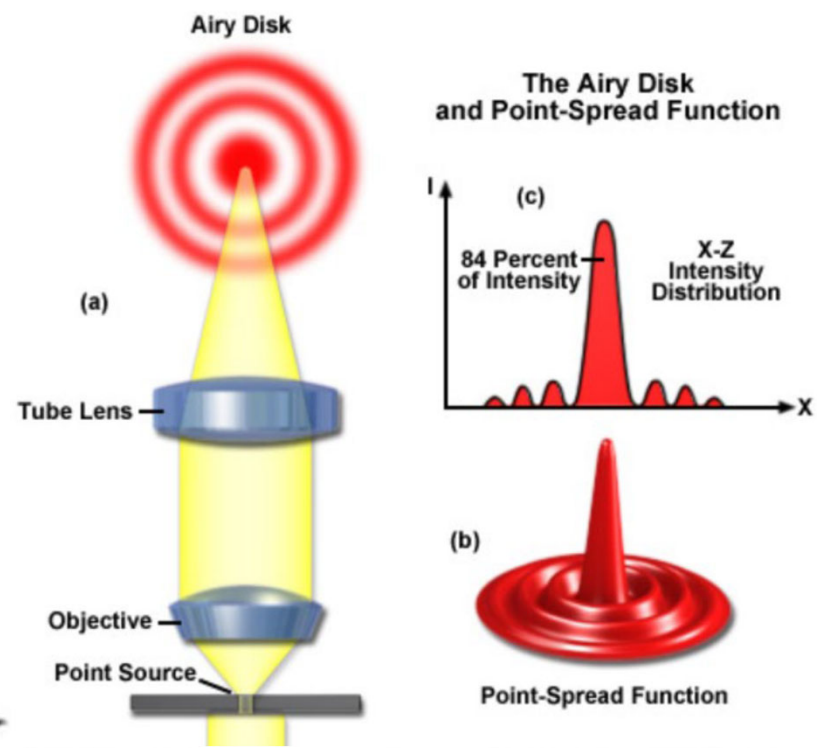


$$NA = \frac{d}{2f} = \sin\theta$$

f = focal distance
d = lens diameter

Point spread function

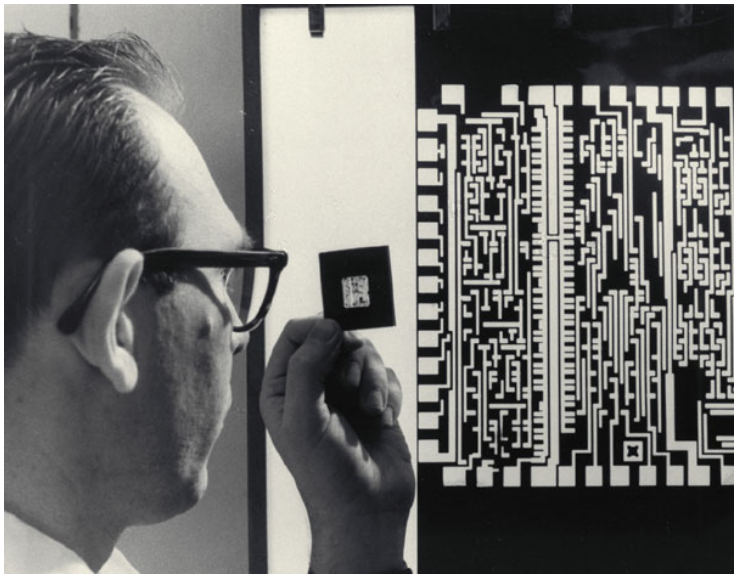


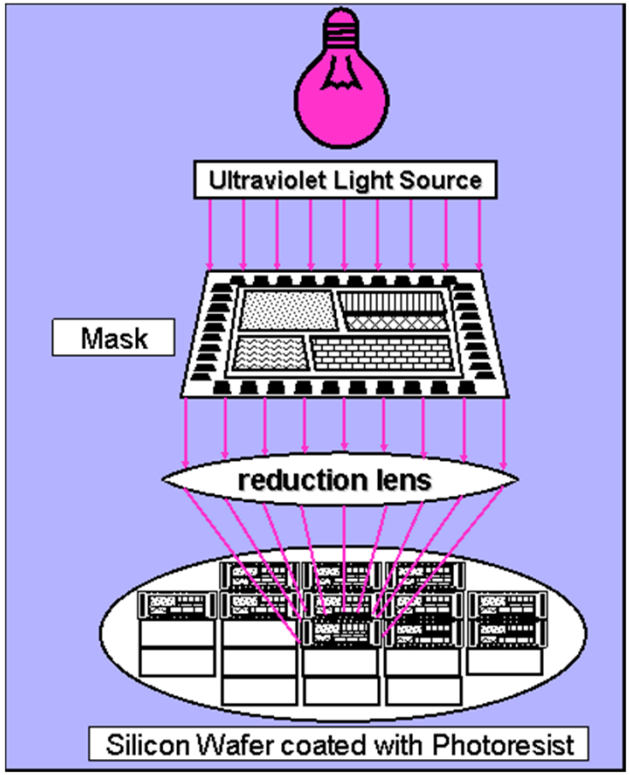


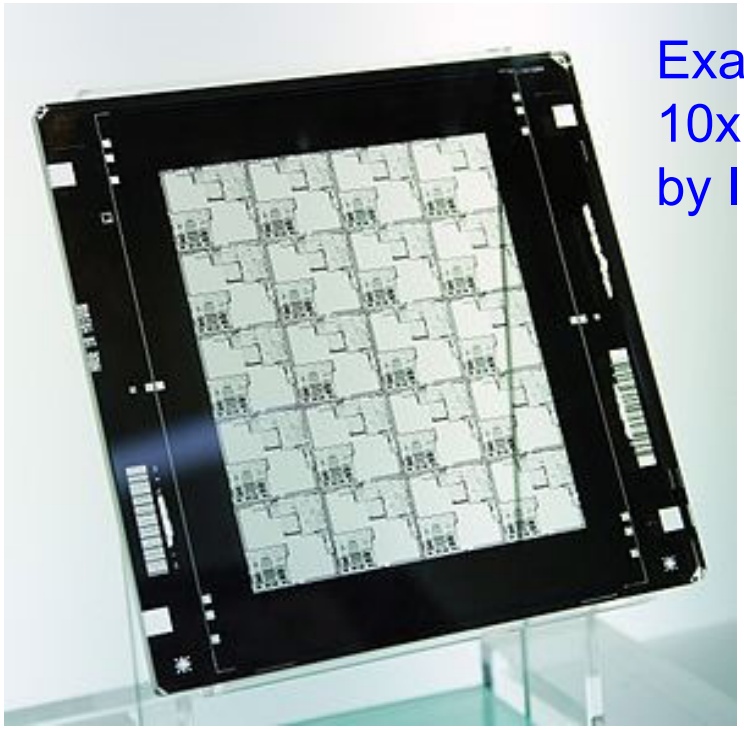
$$Null\ position = 1.22\lambda\left(\frac{f}{d}\right) = 0.61\ \frac{\lambda}{NA}$$

Minimum visible separation

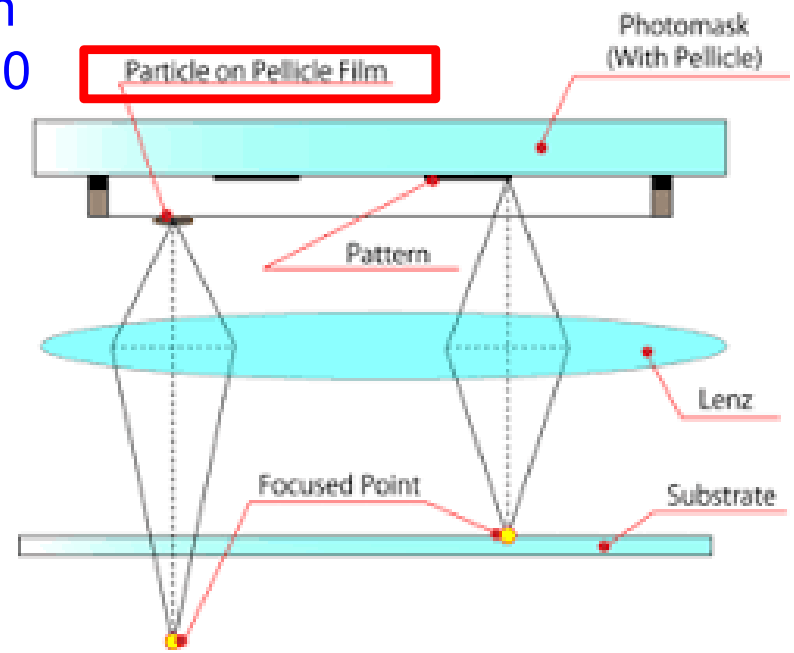
Projection Lithography – Photo Mask (or Reticle)







Example:
10x Reduction
by IBM in 1980



Optical Lithography

(Resolution in Projection Printing)

The **Resolution** is now determined by:

$$R = l_m = k_1 \frac{\lambda}{NA}$$

$$NA = n \sin\theta$$

Here NA is the numerical aperture and n the refractive index and k_1 >0.5 for n = 1

Manufacturing Lithography Technology by ASML – Immersion Scanner Cost from USD 70 Million

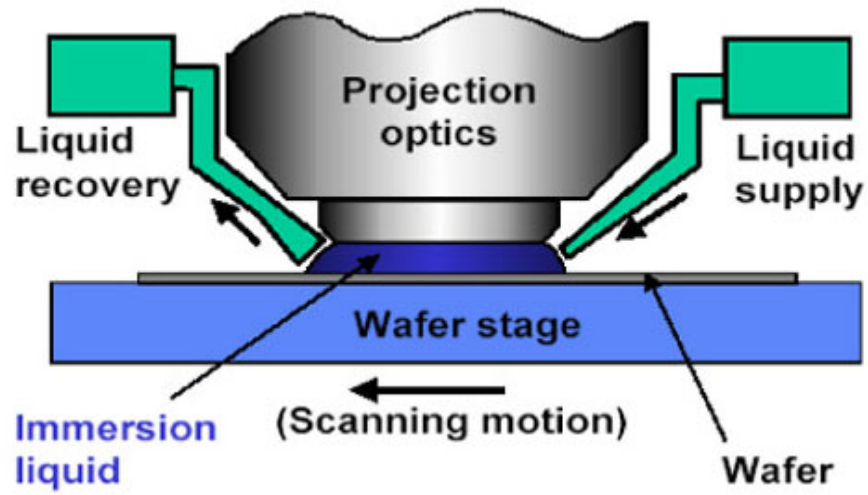
RESOLUTION

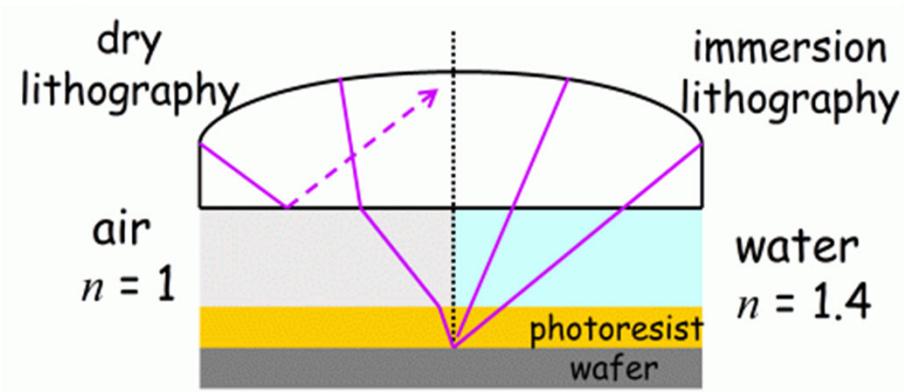
Rayleigh Resolution $R = K_1 \frac{\lambda}{NA}$

Traditional $K_1 = 0.8$

Advanced $K_1 = 0.5 - 0.7$

193nm ArF and 1.35 NA (numerical aperture)



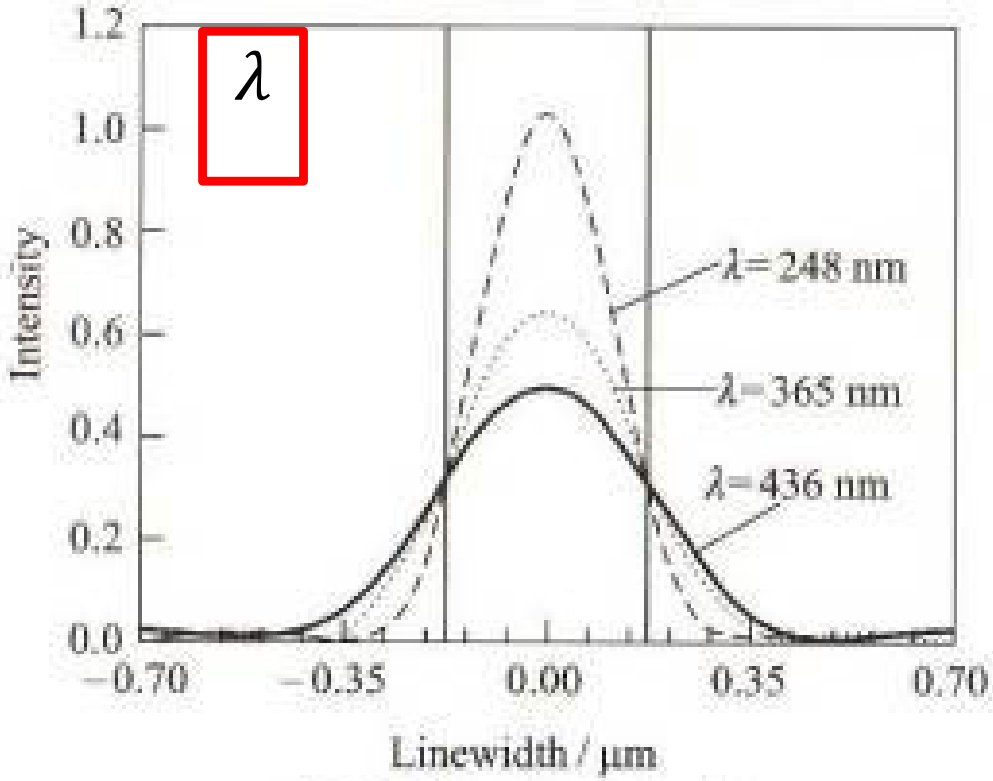


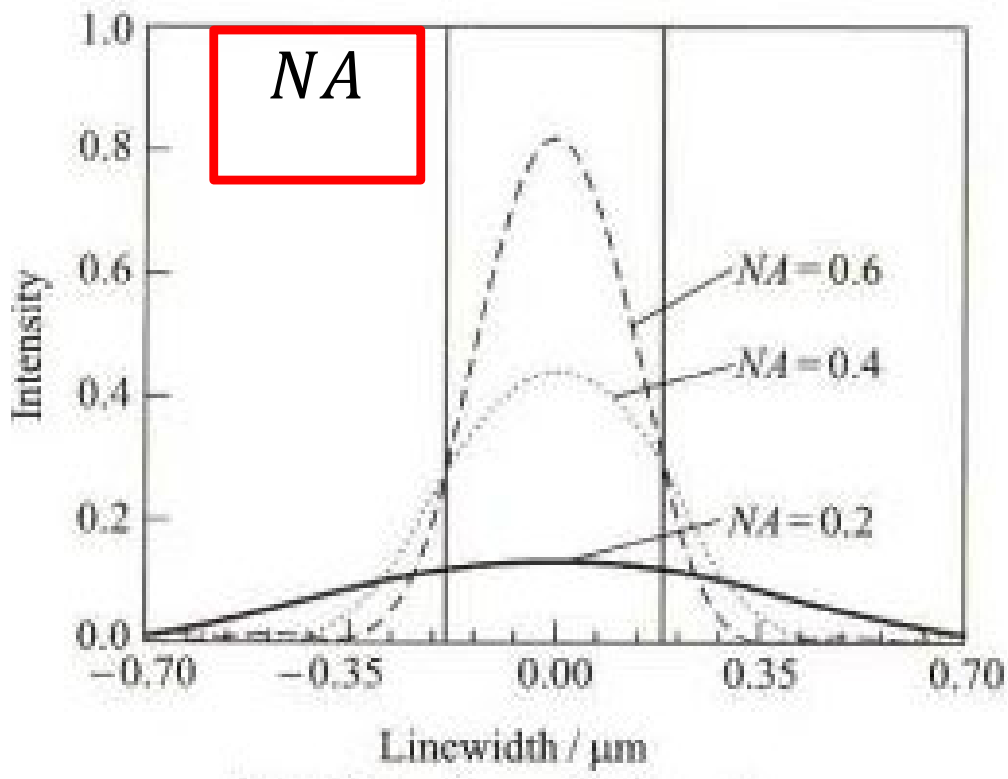
http://www.eetimes.com/document.asp?doc_id=1171720

Why water helps?
Can you do better?

Optical Lithography

(Resolution in Projection Printing)

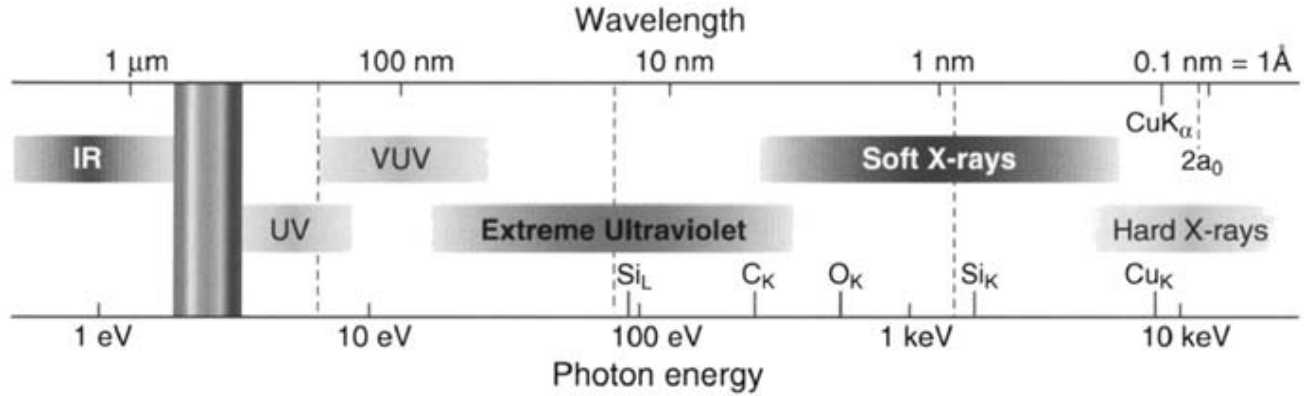




Simulations for a 0.35 μm line at the wafer surface

Optical Lithography (Photon Sources)

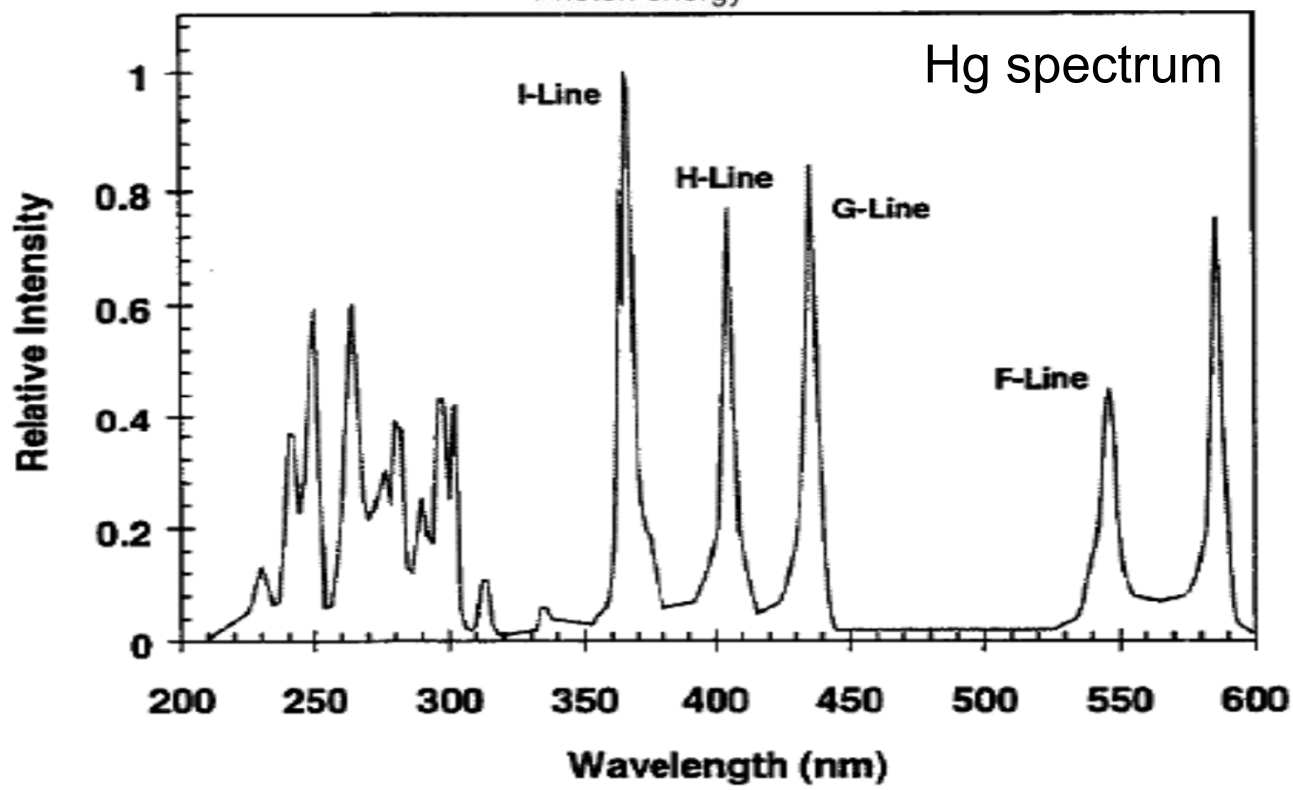
Photon Sources



- **Hg Arc lamps:**
G-line 436, H-line 405,
I-line 365 nm

- **Excimer lasers:**
KrF 248nm & ArF 193nm

- Laser pulsed plasma
(13nm, EUV)

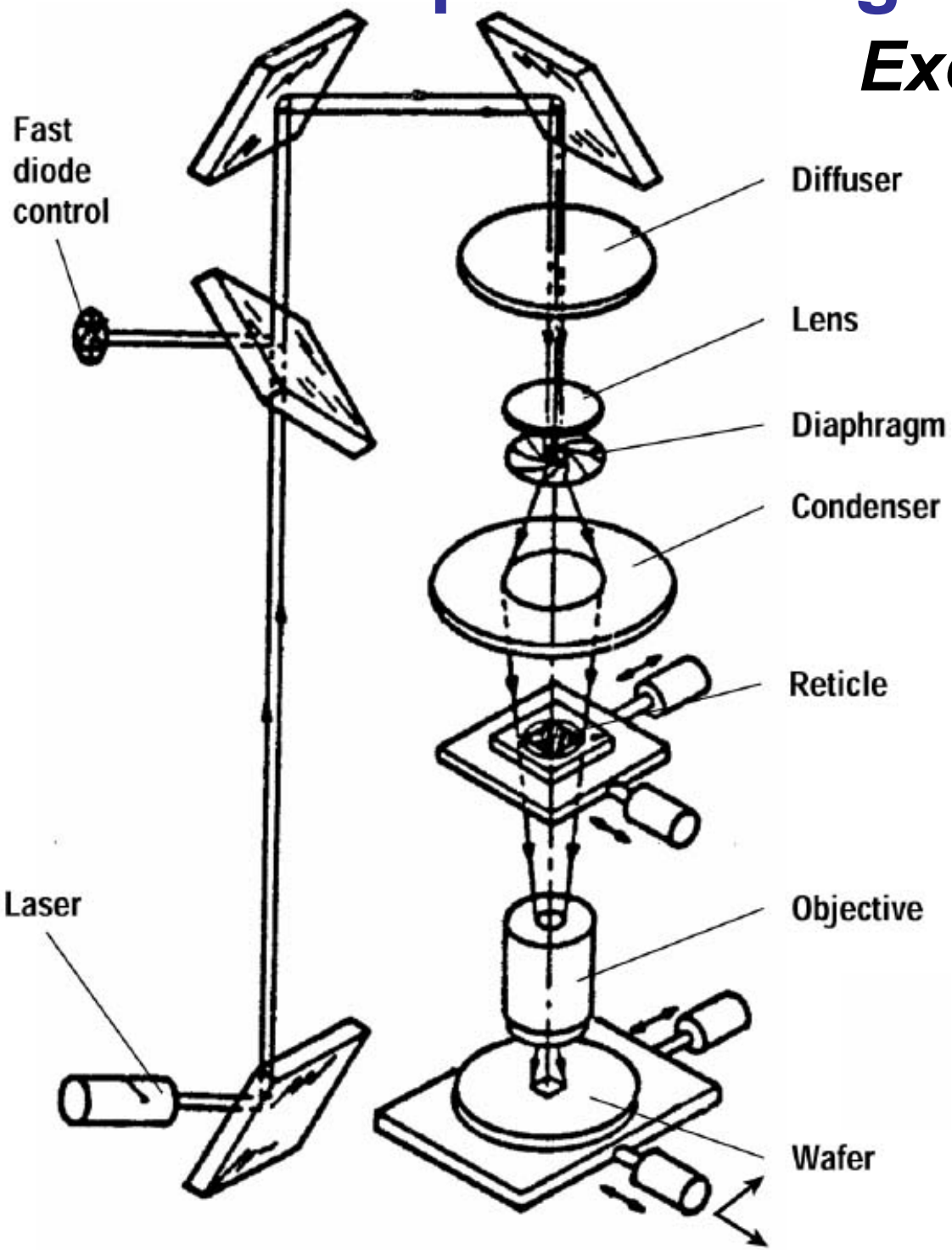


Source Monitoring

- Filters can be used to limit exposure wavelengths
- Intensity uniformity has to be better than several % over the collection area
- Needs spectral exposure meter for routine calibration due to aging

Optical Lithography

Excimer Laser Stepper



KrF (248nm)
ArF (193nm)

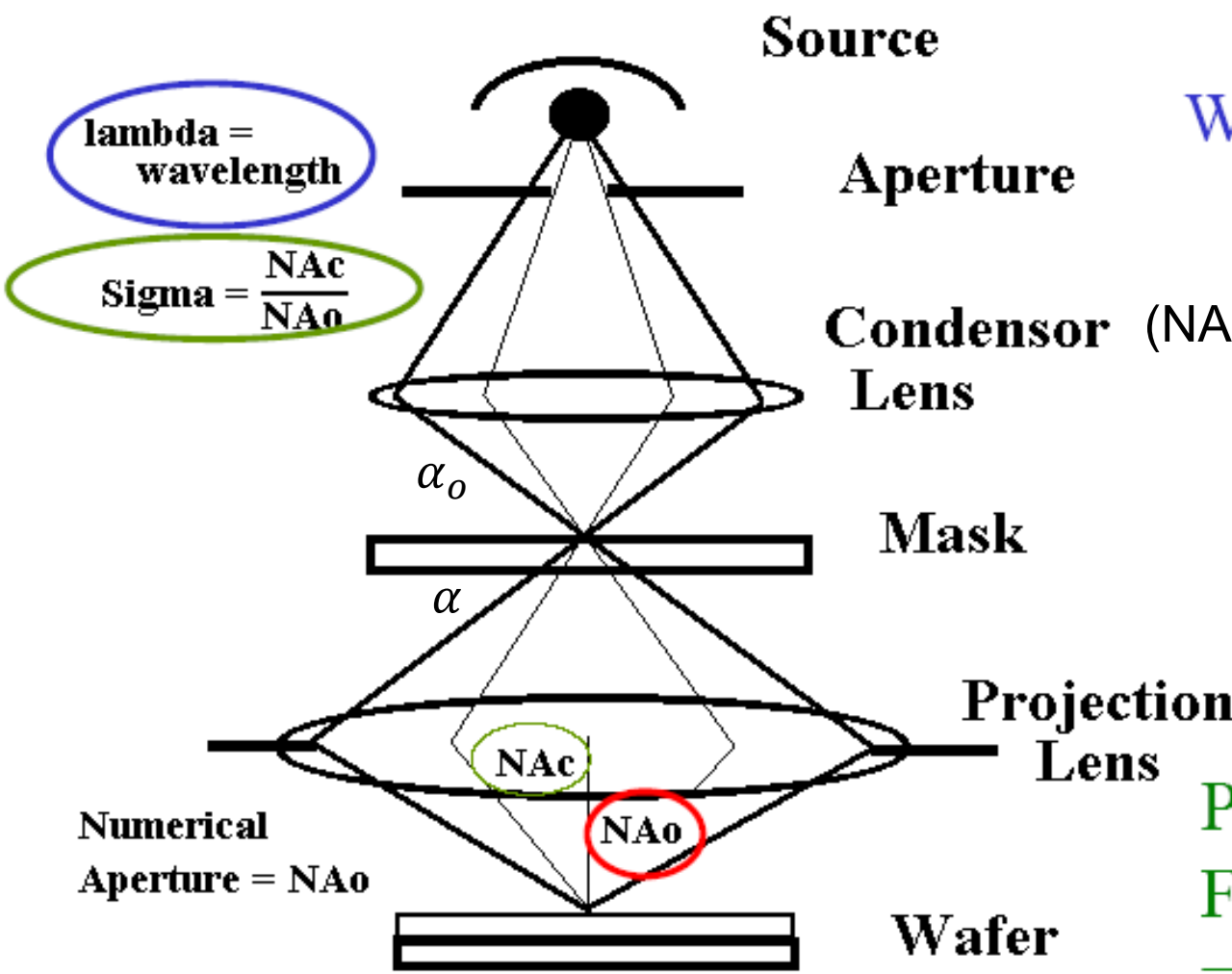
Light is in pulses of 20 ns duration at a repetition rate of a few kHz. About 50 pulses per field.

Limited exposure area in one pulse
➔
Step + scan became necessary because of introduction of lasers

Wafer stage + laser interferometry;
Overlay 10s nm
➔ Now Reaching 2 nm

Optical Lithography
Optical Projection Printing Parameters

#0 Key Parameters: λ, NA, σ



Wavelength $\lambda = 248$ nm

Condensor Lens (NA_c)

Numerical Aperture
$NA = \sin(\theta) = 0.5$

Projection Lens (NA_o)

Partial Coherence Factor $\sigma = (NAc/NAo) = 0.3$

Note σ is not used in the 2008 book

$\sigma = 0$ Fully coherent beam

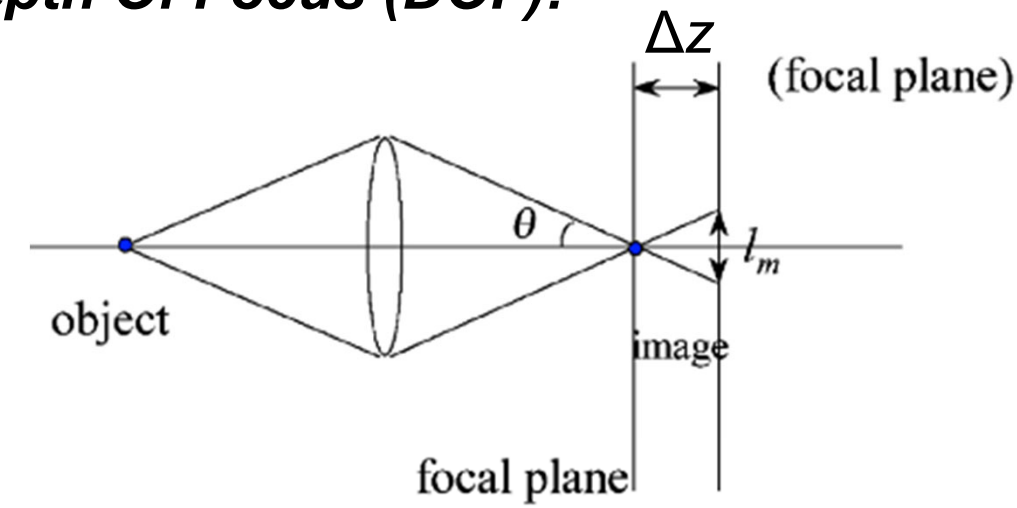
$$\sigma = \frac{n_0 \sin \alpha_0}{n \sin \alpha}$$

(see eq 2.6 Cui 2005)
$0 < \sigma < 1$

Optical Lithography (DOF)

An other important aspect is the ***Depth Of Focus (DOF):***

In other words how well we can focus the light on the sample will determine the quality of the image



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

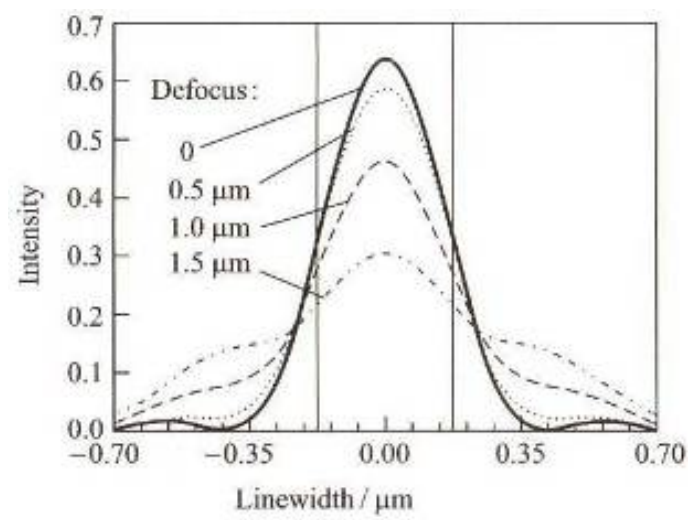
$$\Delta z = k_2 \frac{\lambda}{(NA)^2}$$

$$0.5 < k_2 < 1$$

$$\approx \frac{\pm l_m/2}{\tan\theta} \approx \frac{\pm l_m/2}{\sin\theta} = \pm \frac{\lambda}{2(NA)^2}$$

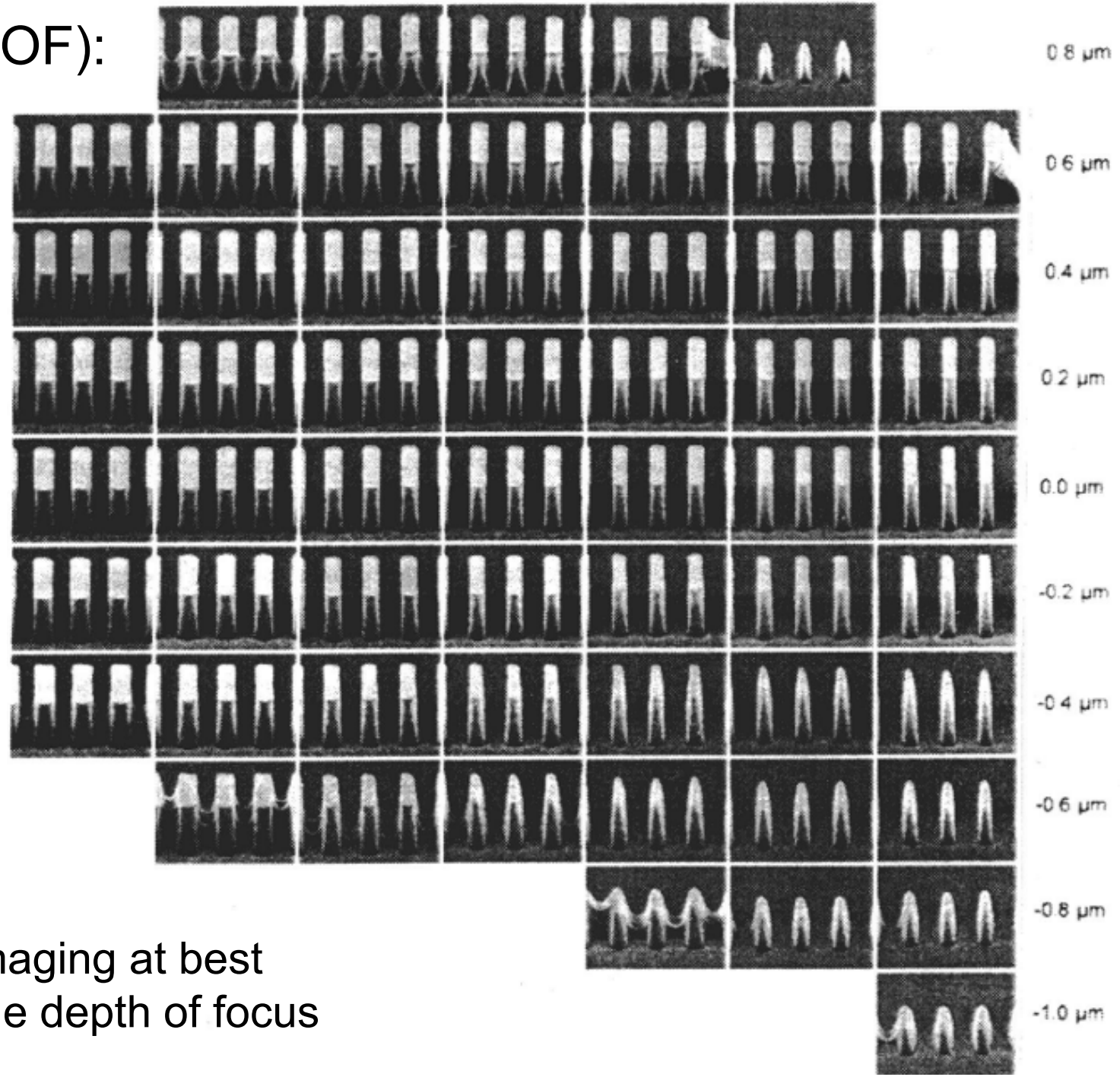
for small θ

As we saw before the bow of a (large) wafer can be a cause of big concern!



Optical Lithography (DOF)

Depth Of Focus (DOF):



Resist profiles for imaging at best focus and outside the depth of focus

Optical Lithography

Common features of photoresist

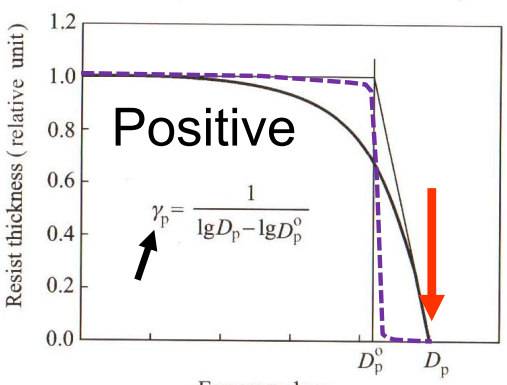
Sensitivity

Amount of energy required (speed of a photo resist)

Contrast (γ)

Contrast of resist determines the sidewall slope of resist

$$\gamma_p = \frac{1}{\lg D_p - \lg D_p^o}$$



D_p^o threshold dose D_p sensitivity γ_p contrast

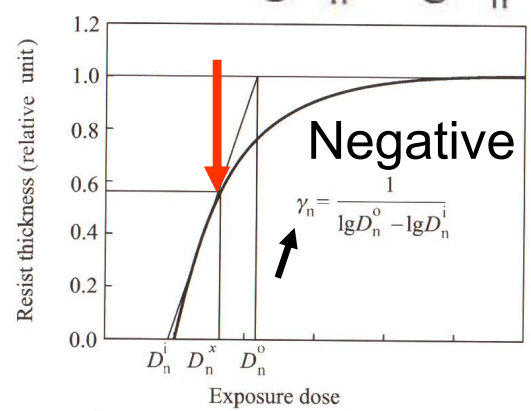
(a) Sensitivity and contrast for positive photoresists

High contrast resist

➔ vertical side walls

- - - -

$$\gamma_n = \frac{1}{\lg D_n^o - \lg D_n^i}$$



D_n^o threshold dose D_n^x sensitivity γ_n contrast

(b) Sensitivity and contrast for negative photoresists

Etching selectivity

High etch selectivity is desired if the resist is used as an etch mask

Optical Lithography

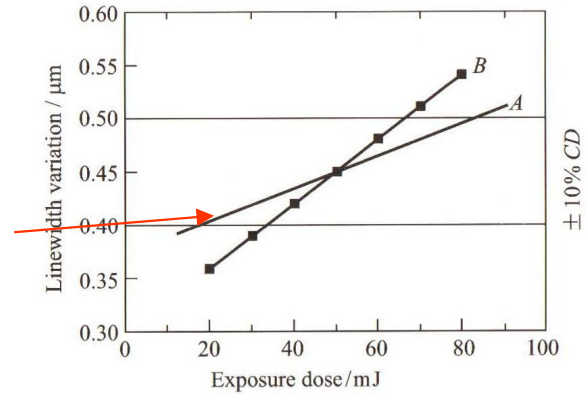
Common features of photoresist

Resolution

- Optical exposure system
- Molecular weight of the resist
- Development conditions ➔ Pre- post- bake temperature

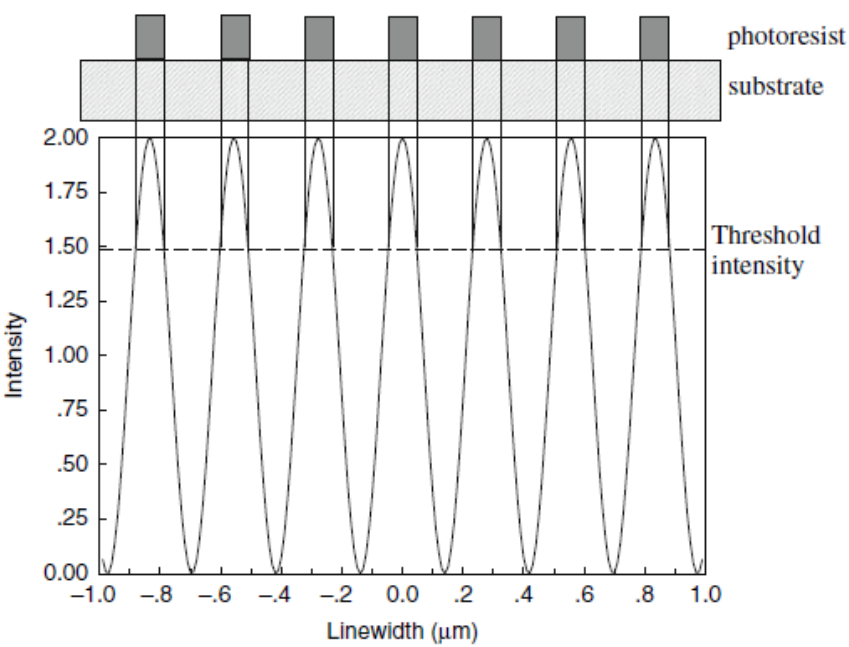
Exposure latitude

If the CD changes only little with exposure dose variation the resist has **large** "exposure latitude"

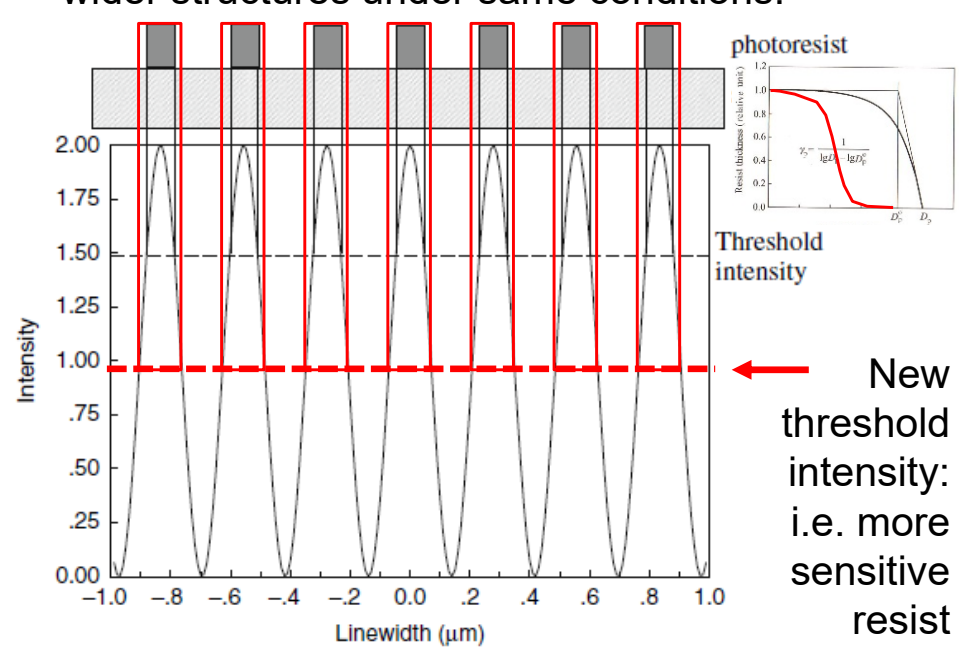


Intensity profile in resist

By choosing sensitivity of a resist & exposure time we can control the structure size



Taking a more sensitive resist we get wider structures under same conditions:



New threshold intensity: i.e. more sensitive resist

Optical Lithography (Issues)

When 248 nm was put in place excimer lasers were introduced:

248 nm (KrF gas) + 193 nm (ArF gas)

⇒ Quartz is no longer usable, it absorbs too much, therefore CaF crystals lenses were introduced

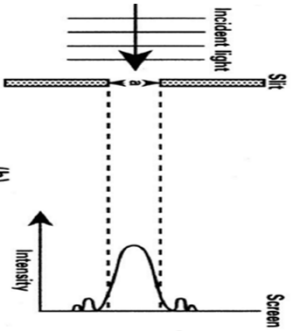
➔ Optical aberrations had to be corrected by introducing more optical elements

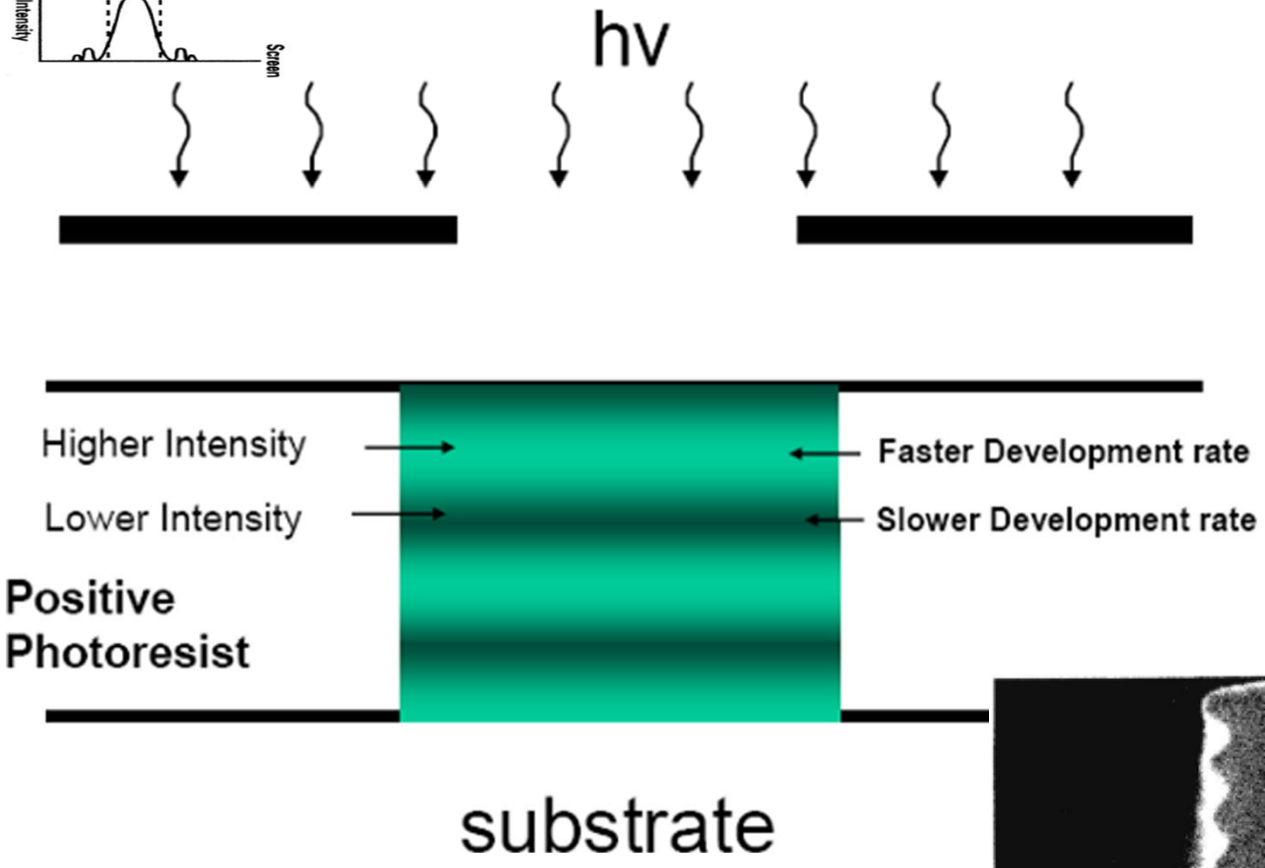
➔ Complex lens system (20-30 lenses in a DUV system)

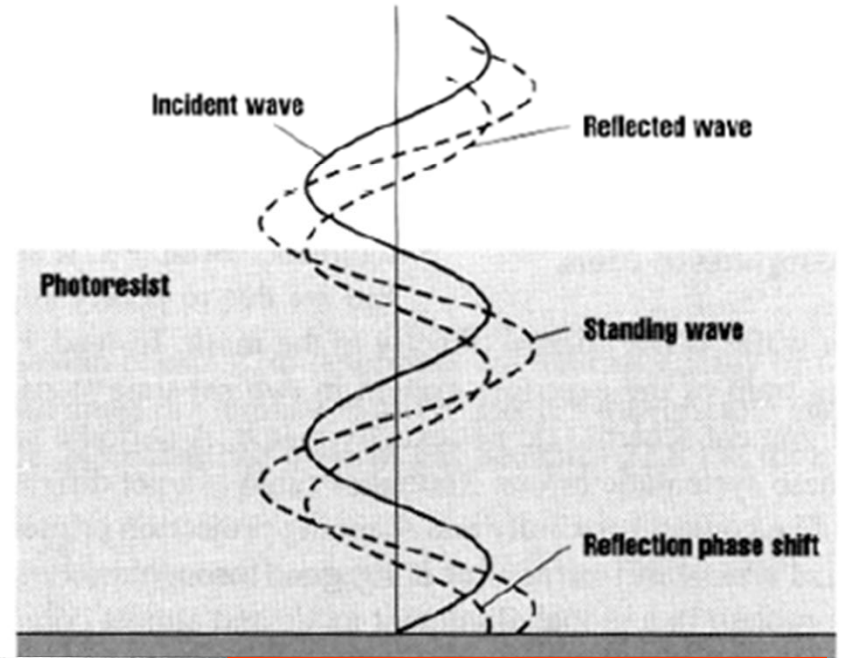
	1980s	Late 1990s :
R	0.65 um	0.25 um
λ	i-line	DUV used for Pentium III + IV
$$	a few 100k / machine	a few Million $ / machine
Exposure field	20x20 mm^2	26x33 mm^2

Optical Lithography

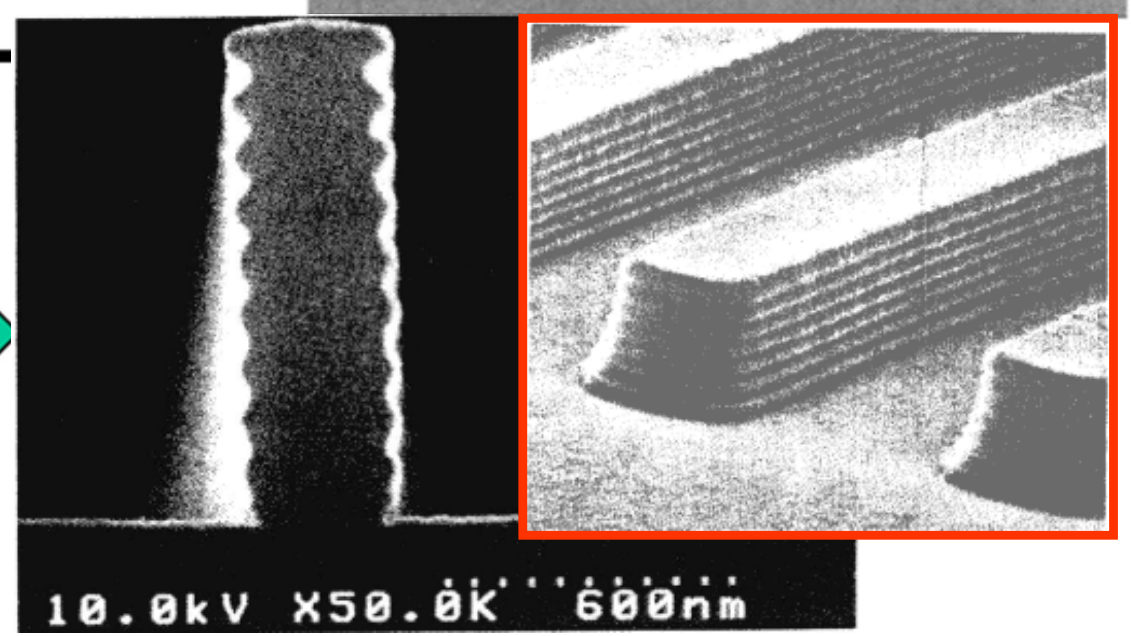
Standing Waves





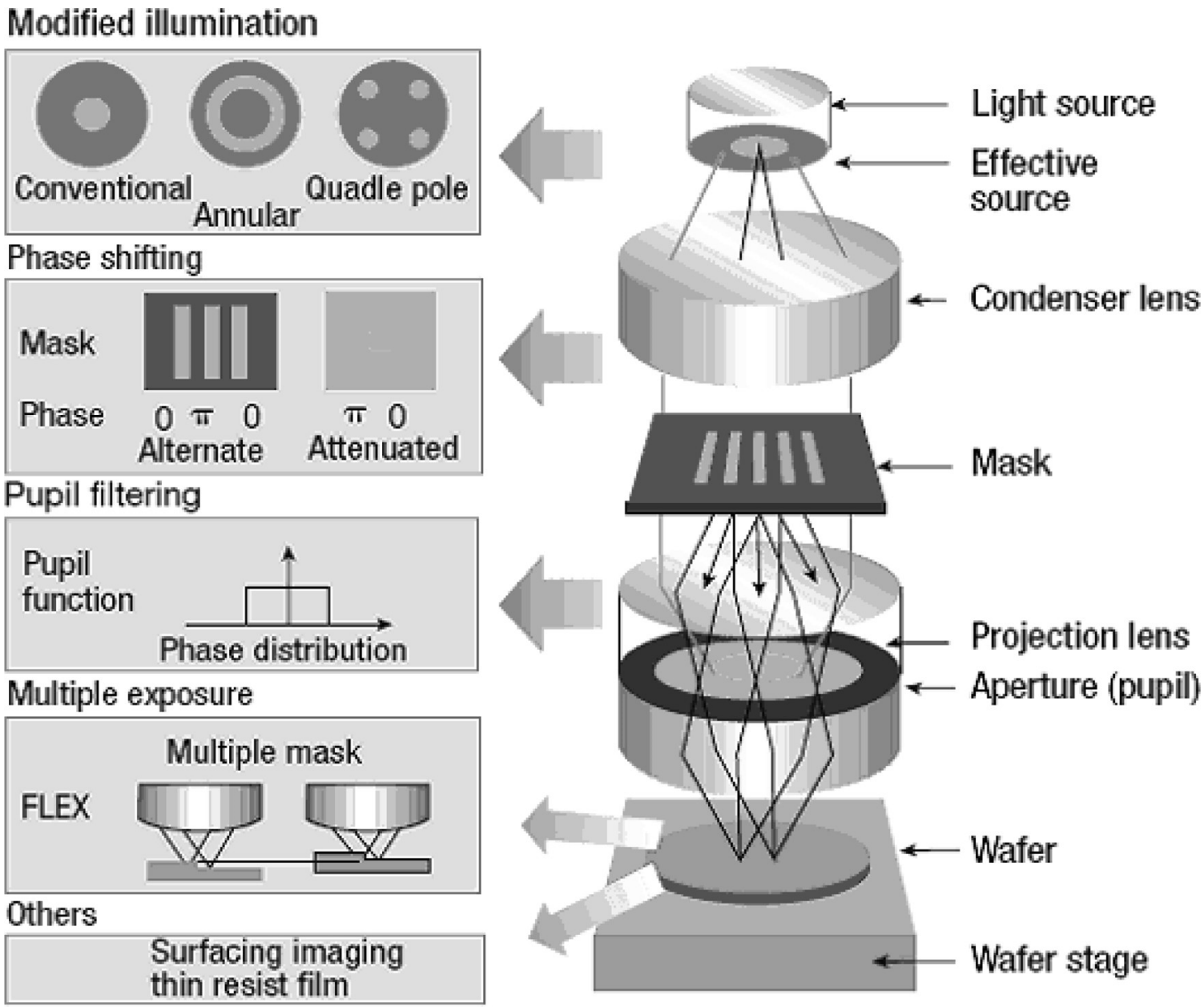


After development



Optical Lithography

Resolution Enhancement Technologies (RET)



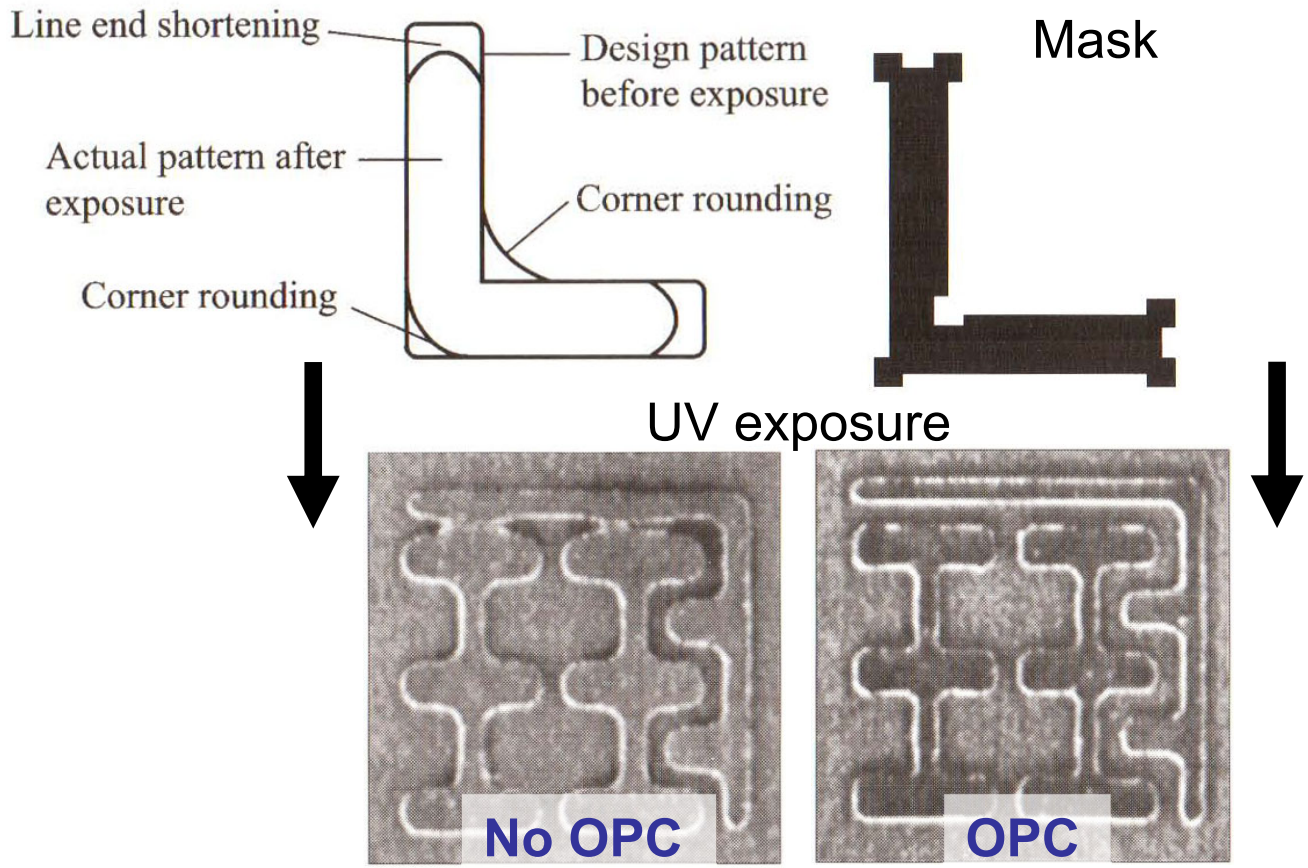
Chem. Rev. 2010, 110, 1, 321–360, January 13, 2010

RET

Optical Lithography

Optical proximity correction OPC

Looking closely at individual patterns we get loss of image sharpness like image rounding and line shortening. This is called *optical proximity effect*.



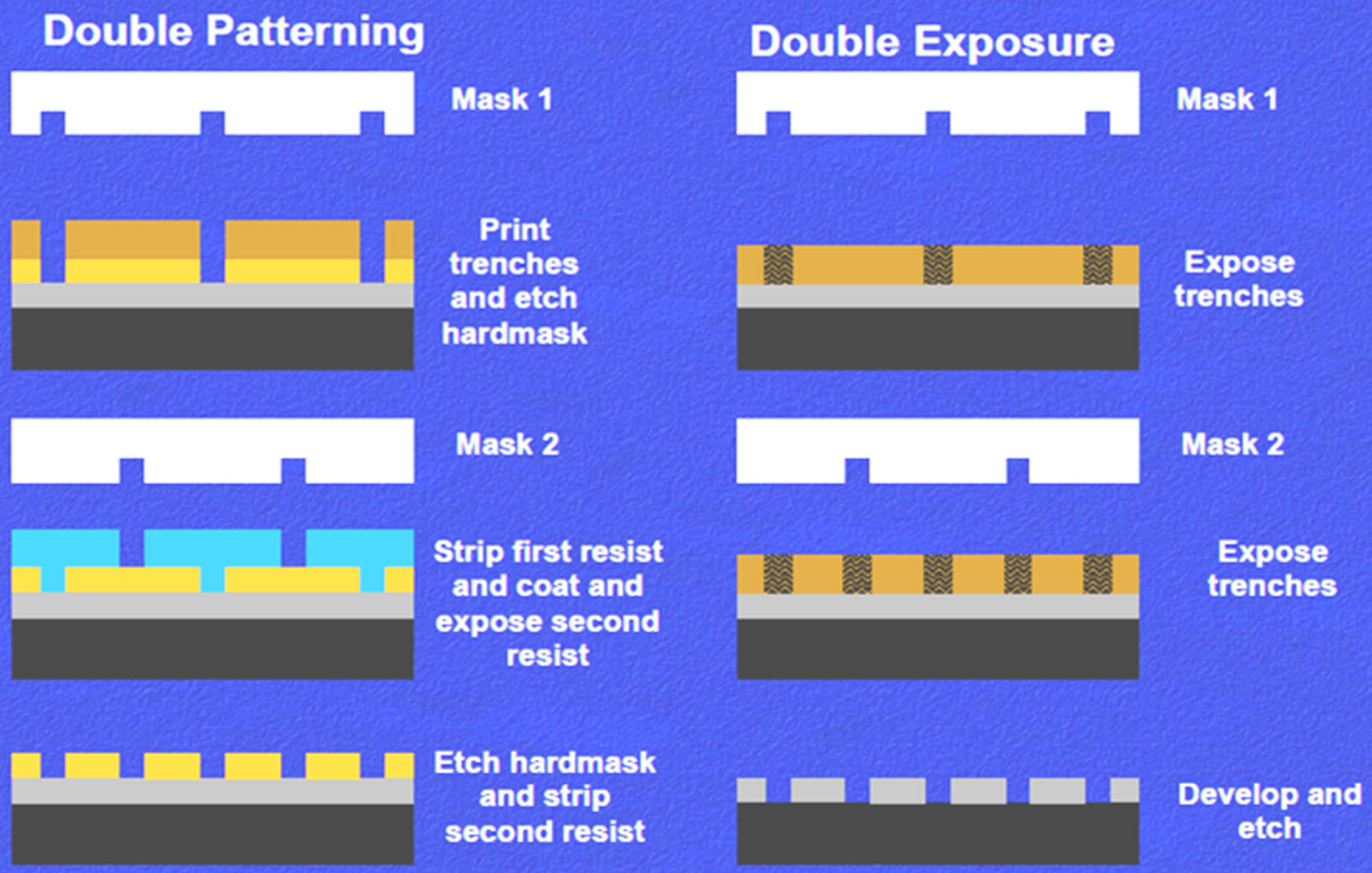
OPC is meant to correct for these effects through adjusting sub wave-length features in the mask.

➔ Either shortening or extending corners.

OPC can also be done by adjusting the transmission of local regions ➔grey scale patterns in the mask.

Now we need sub wavelength or ~100 nm features in the mask!

RET Optical Lithography



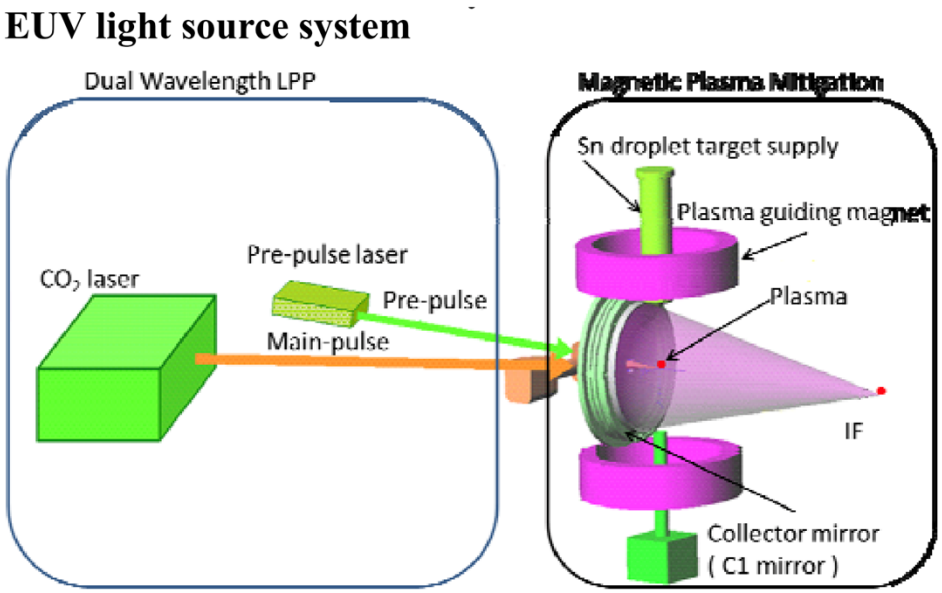
2 Masks
2 Expose steps
2 Etch steps

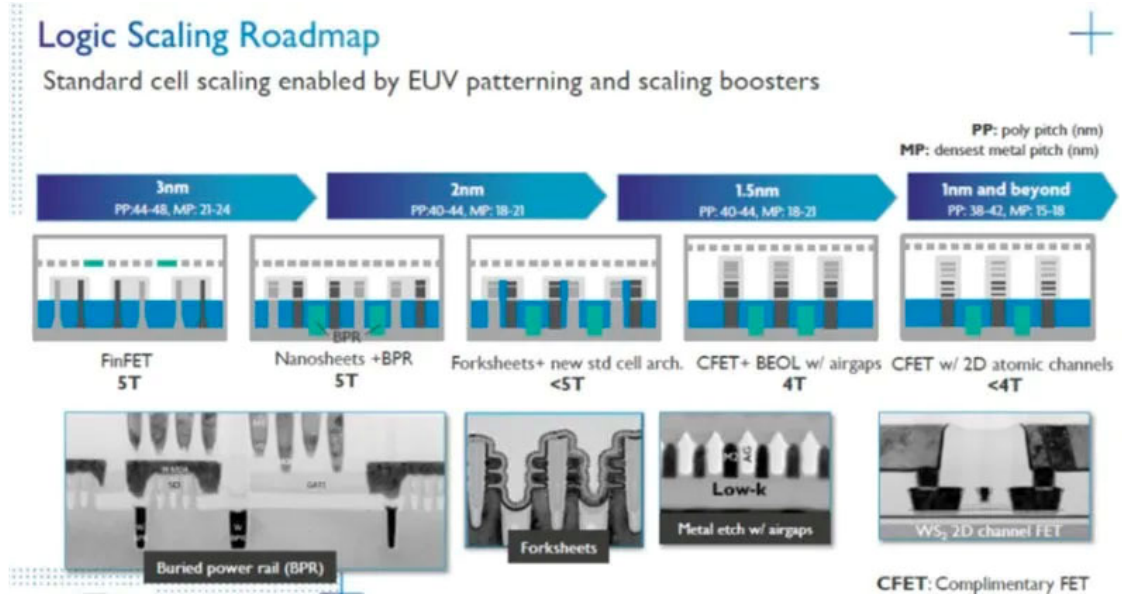
2 Masks
2 Expose steps
1 Etch step

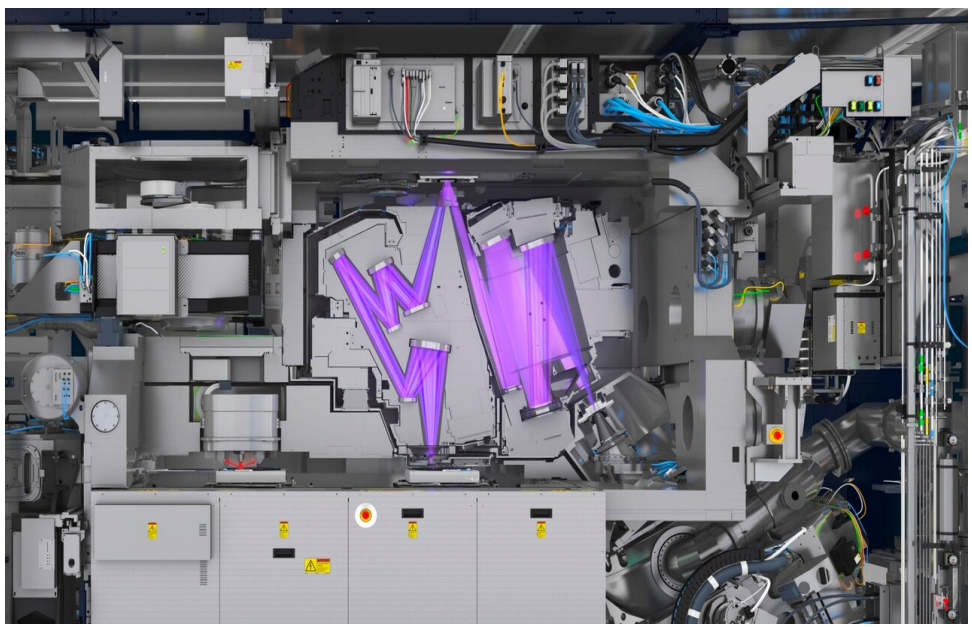
SEMATECH
Accelerating the next technology revolution.

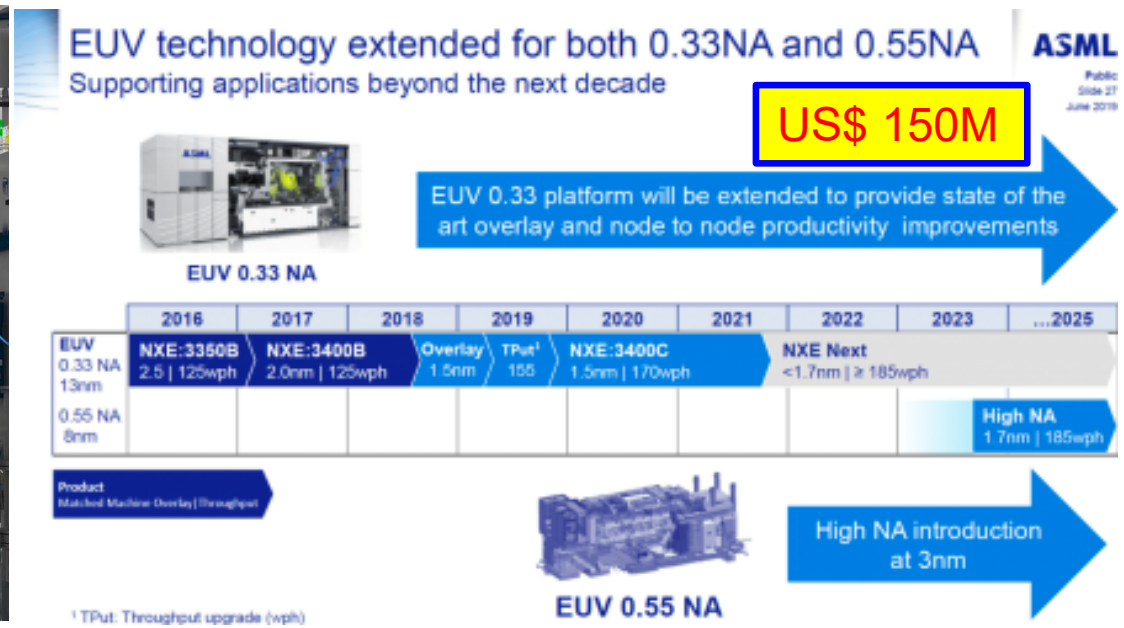
Optical Lithography

Extreme UV Lithography Technology, λ = 13.5 nm





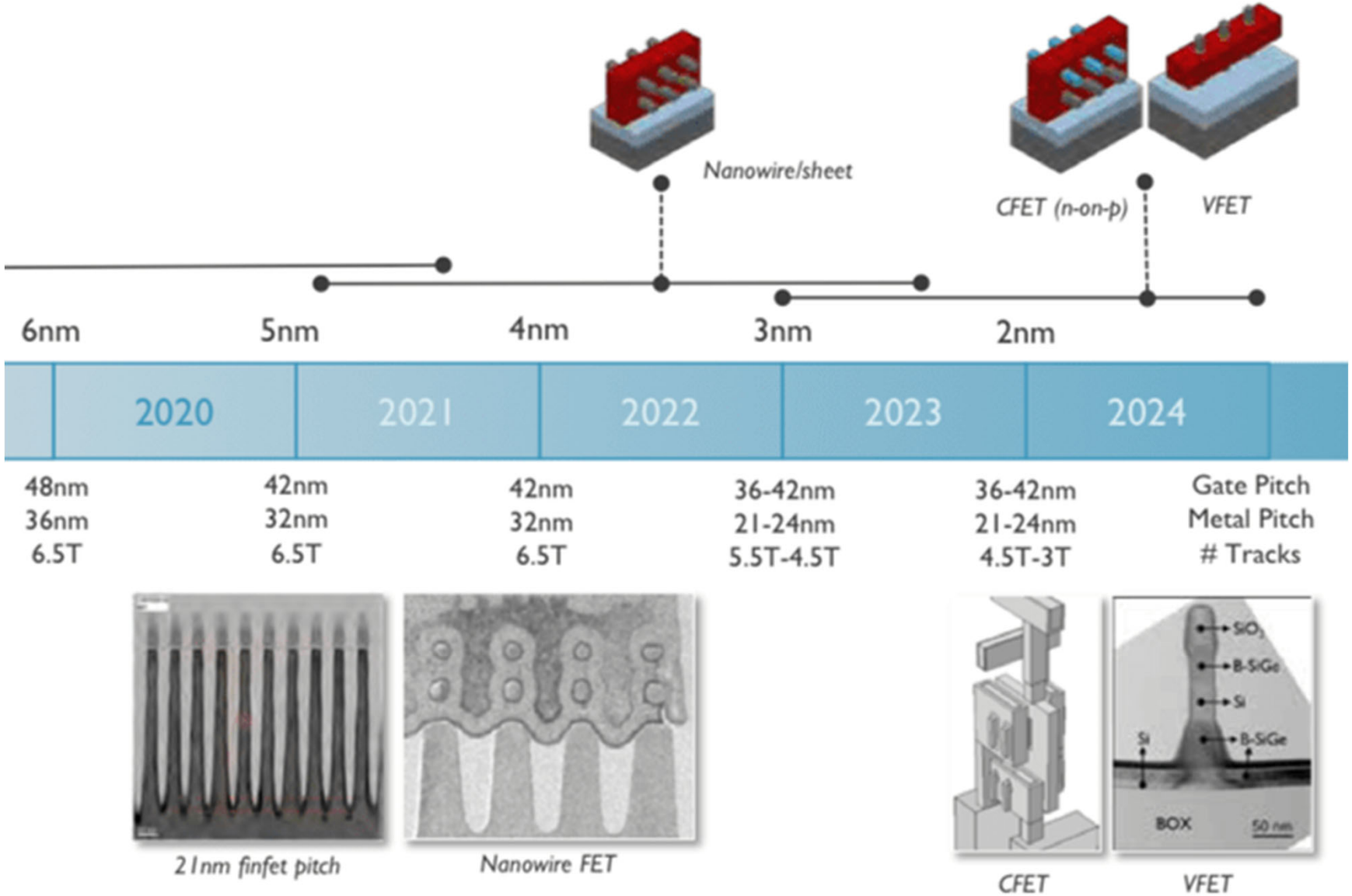




https://www.asml.com/en/technology/lithography-principles/light-and-lasers

❑ Market Trend:

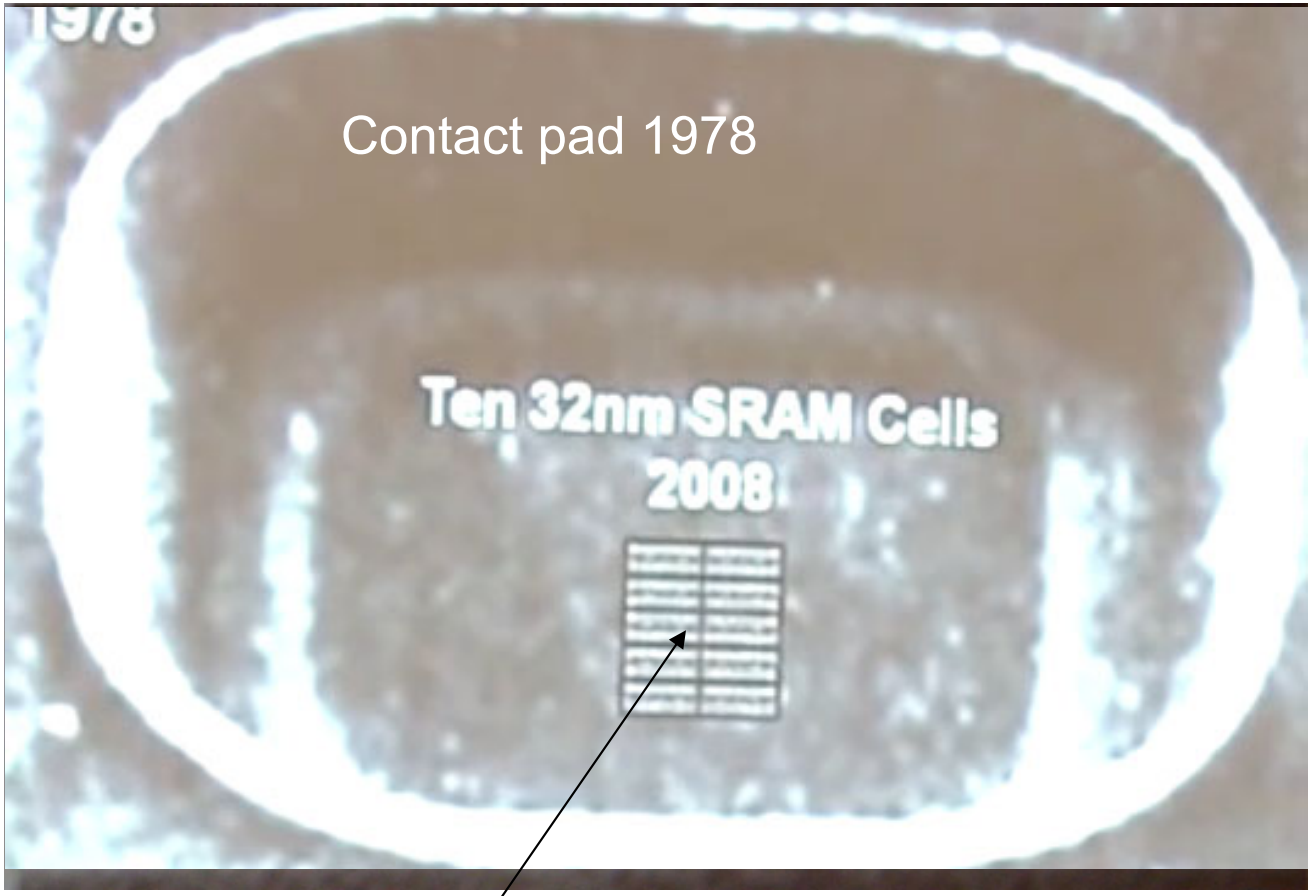
Smaller structures are needed in IC circuits



imec July 2020

Optical Lithography (History)

30 Years of Transistor scaling (1978 ➔ 2008)



Year	Node (nm)	Lithography Technology
1957	254000	Camel's Hair Brush
1958	127000	Silk Screen Printer
1959	76200	Contact Printer – Emulsion plates
1964	16000	Contact Printer – Chrome plates
1972	8000	Proximity Aligner
1974	5000	Projection Aligner
1982	2000	g-line Stepper
1990	800	i-line Stepper
1997	250	248nm Scanner
2003	90	193nm Scanner
2009	32	193nm Immersion Scanner
2019	7	EUV Scanner

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32 nm SRAM Cells (2008) ~21 month to double density

<u>Moore's Law:</u>
The semiconductor industry was able to **<u>double the density</u>** of **<u>transistors</u>** on a unit area of silicon chip in **<u>every 18 months</u>**.

China plans to build a giant chip factory driven by particle accelerator

- Scientists said this unprecedented technology can overstep US sanctions and make China a new leader in semiconductor chip industry

- Plans are now in progress to construct a huge particle accelerator to help researchers put into practice the cutting-edge technology