微纳光电子材料与器件工艺原理

Photolithography 光刻
Part I: Optics

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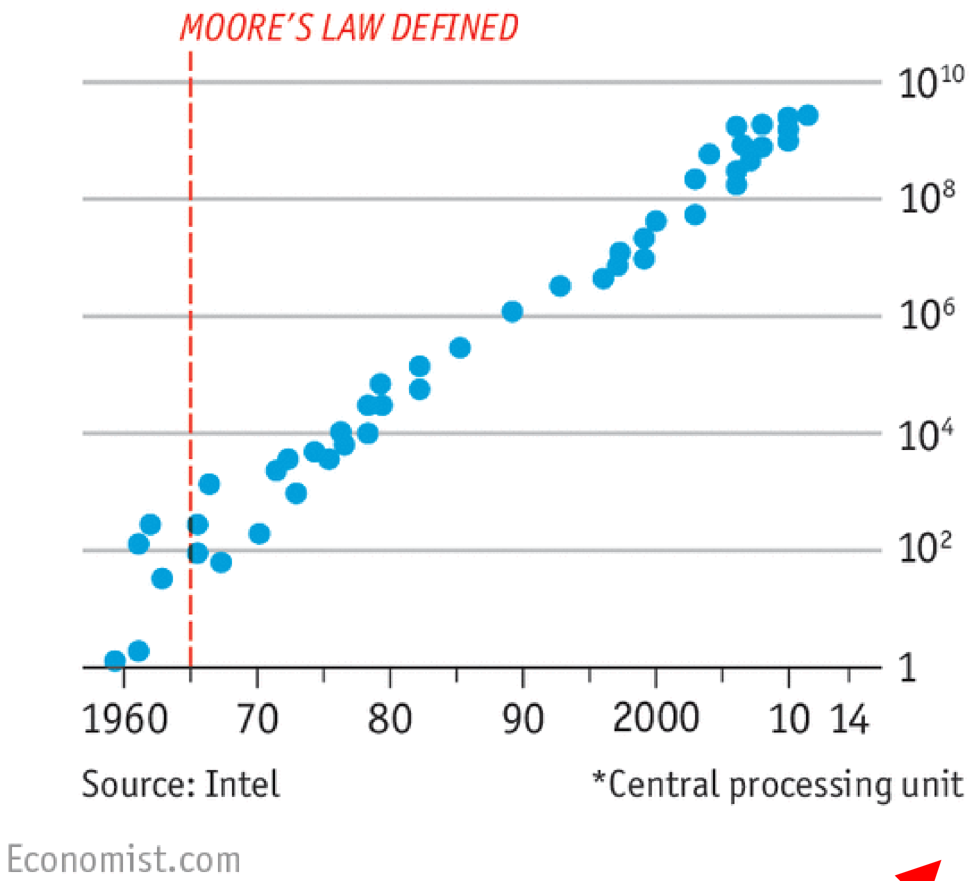
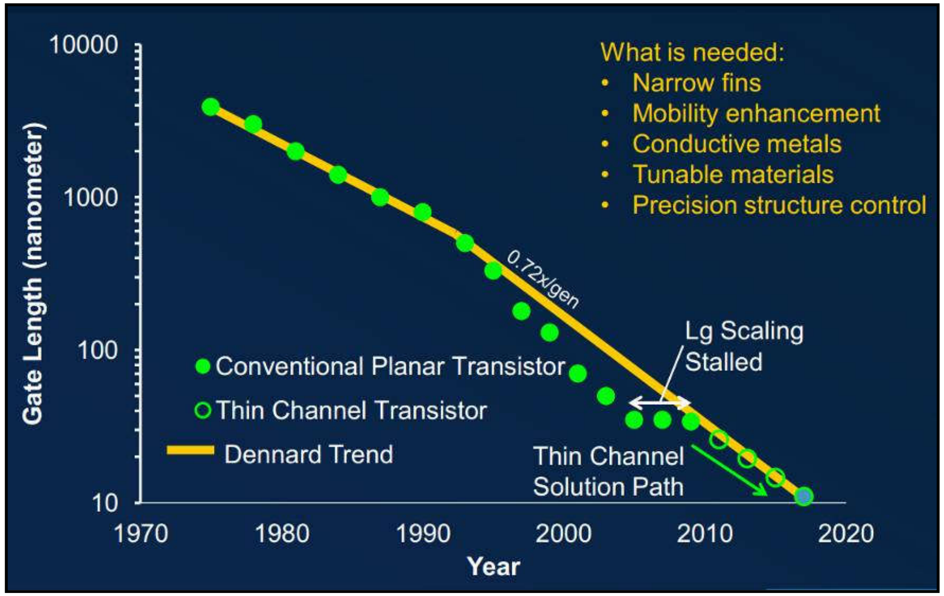
Integrate Circuits

- **Moore's law**

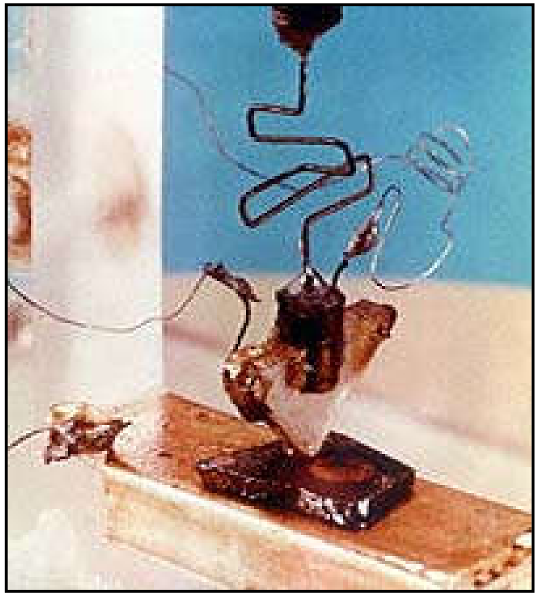
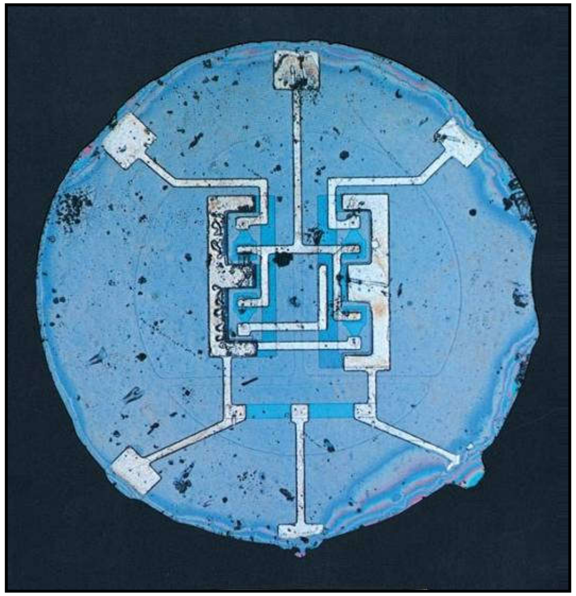
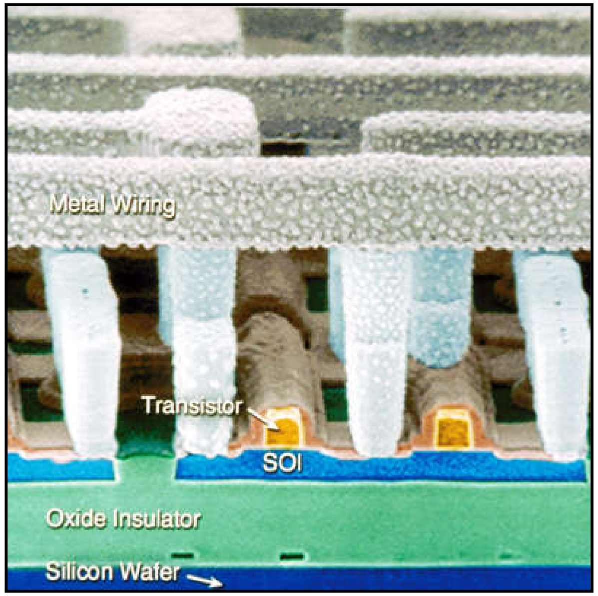




transistor number

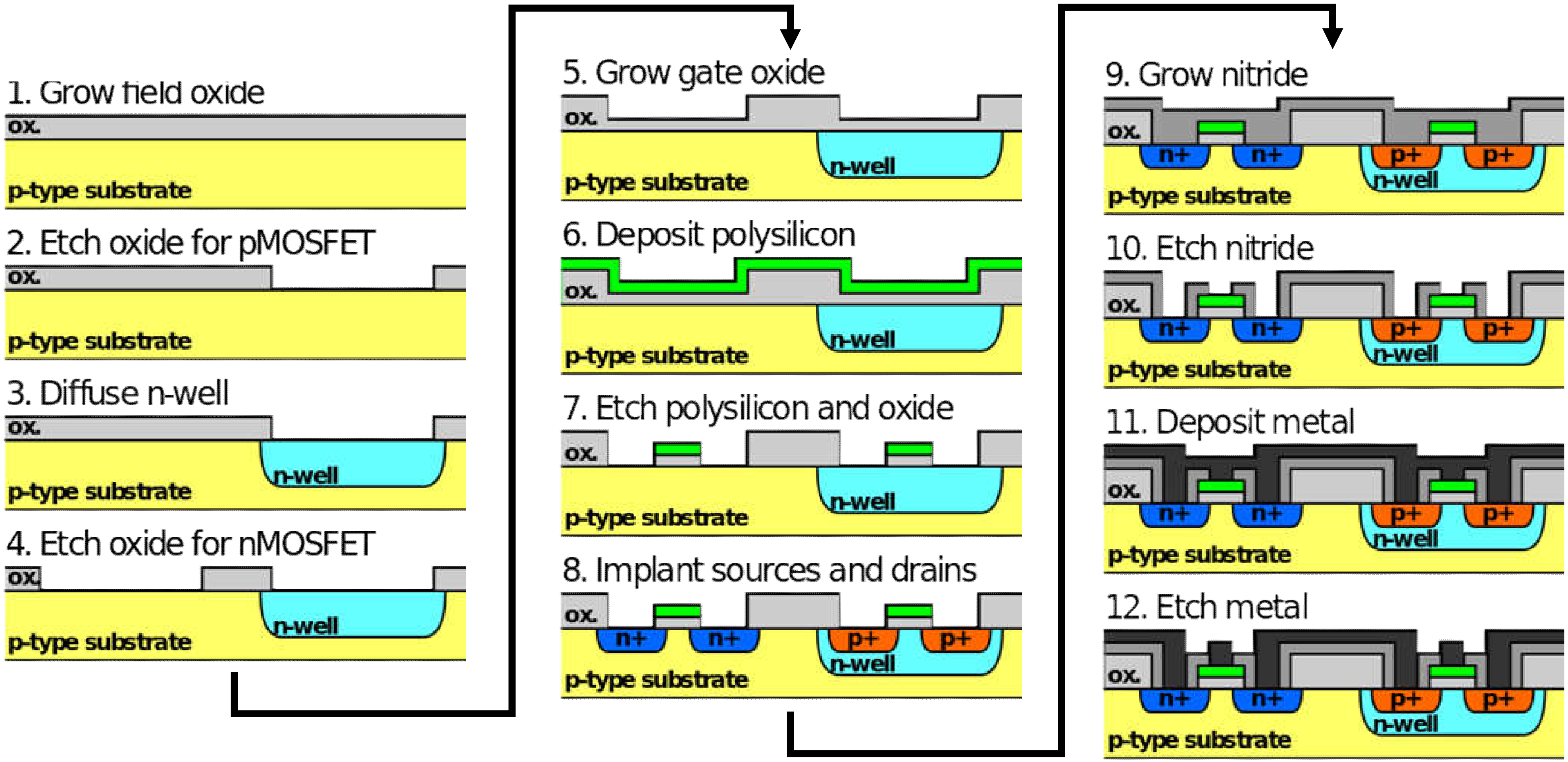
transistor size

Transistor size

1947	1961	2000s
		
1 cm	~ 2 mm	< 100 nm

revolution → *evolution*

CMOS Process



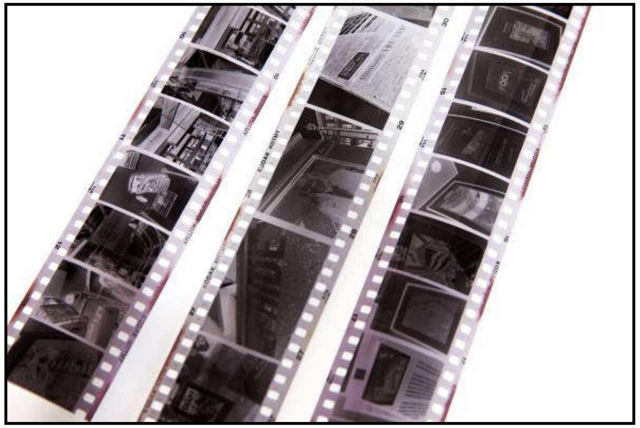
'Lithography is the cornerstone of modern IC technology'

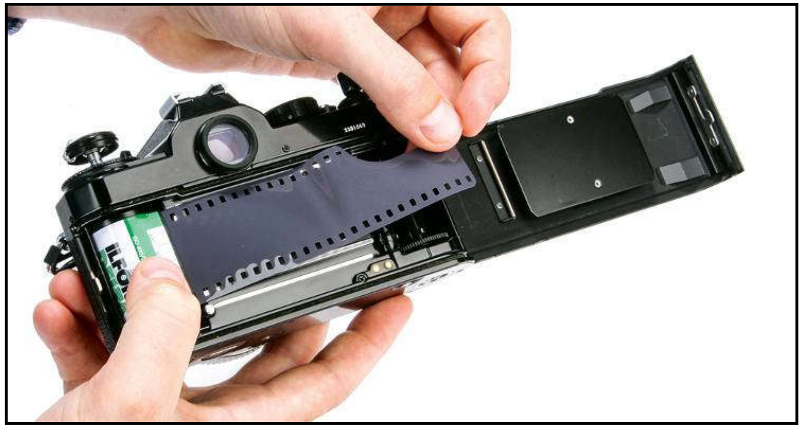
---- Silicon VLSI, Plummer et al.,

Lithography

litho-　石头
-graph 图案

Photography

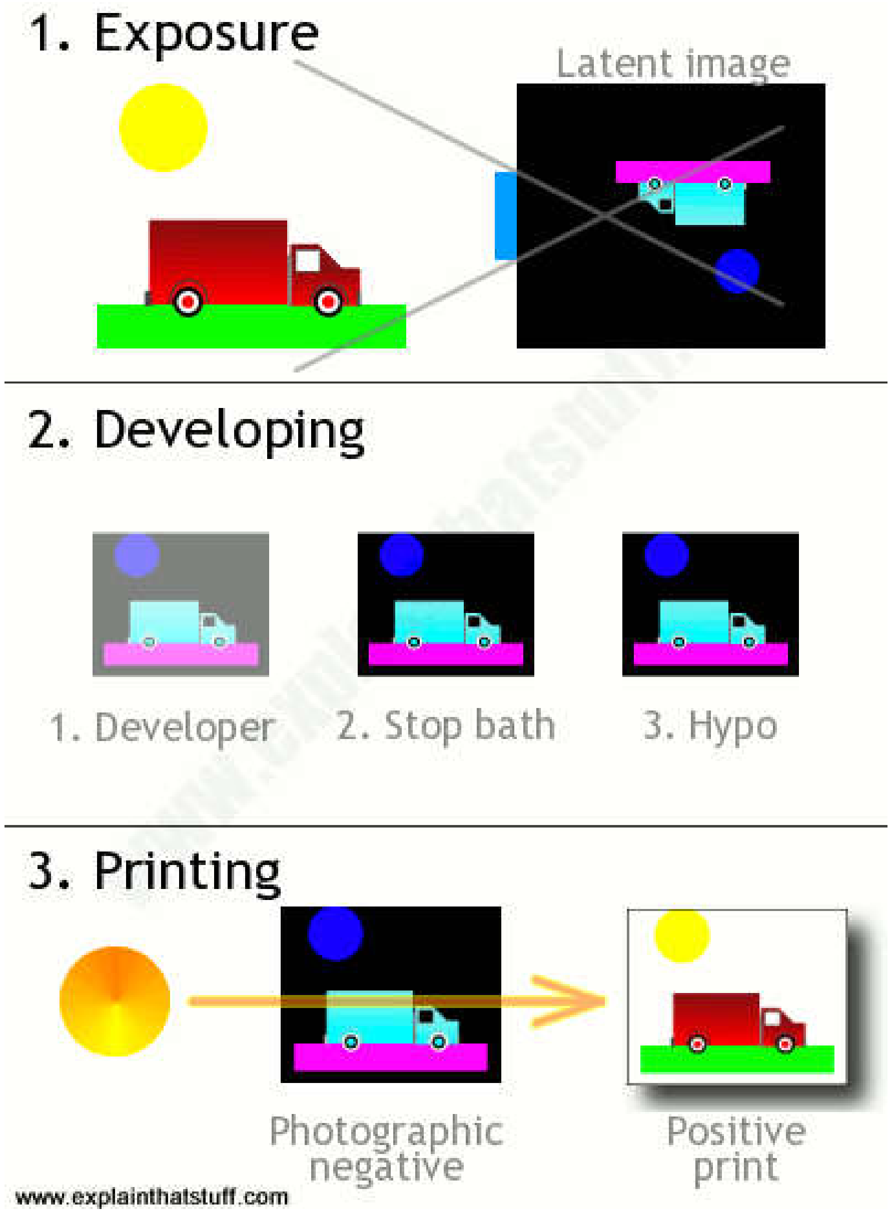




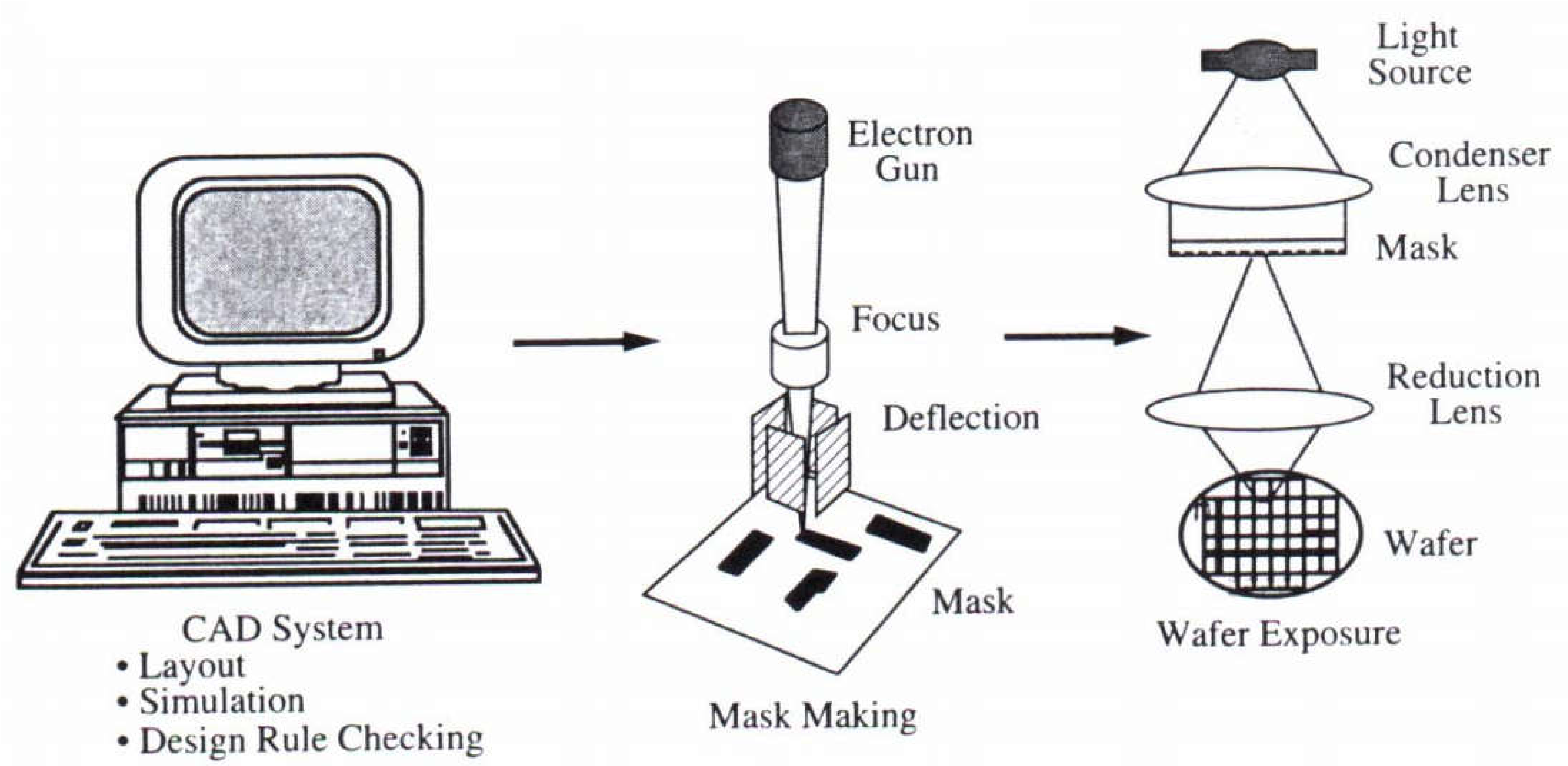
曝光

显影

打印



Photolithography（光刻）

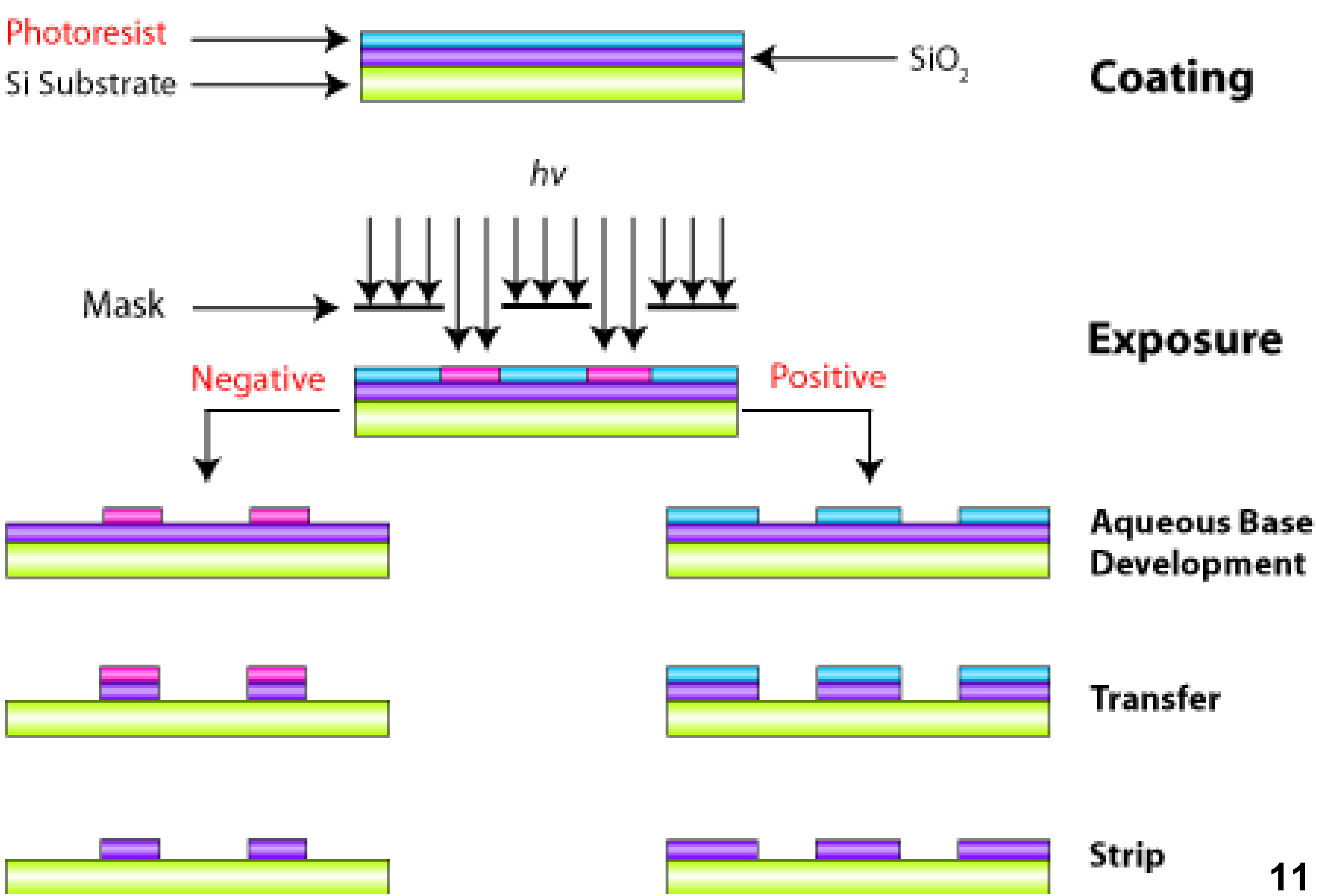


Photolithography（光刻） Video

光刻胶

光源

掩膜



Exposure (曝光)

接触式 接近式 投影式

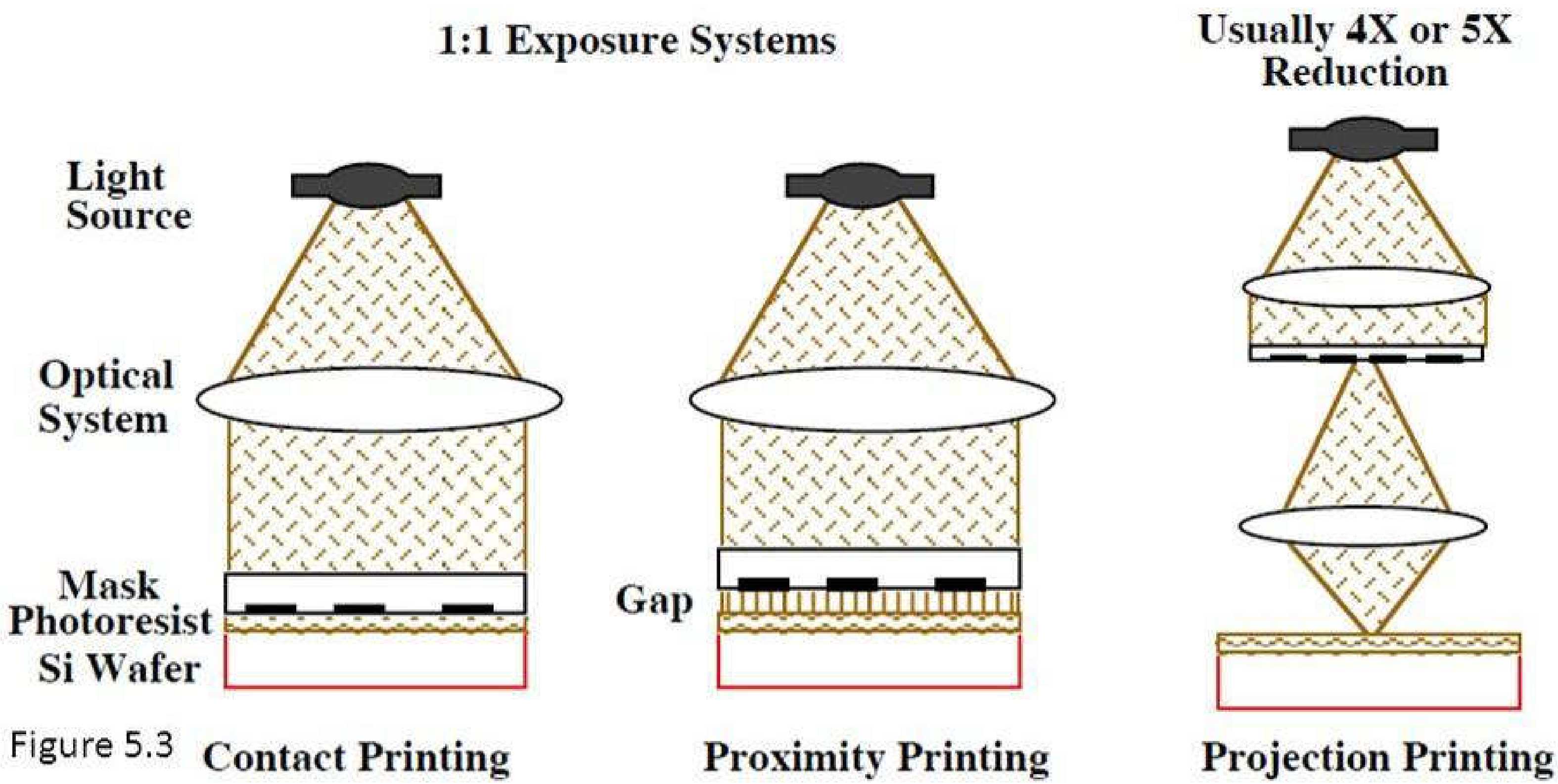


Figure 5.3

High resolution. But mask wear, defect generation.

Less mask wear /contamination, less resolution (depend on gap).

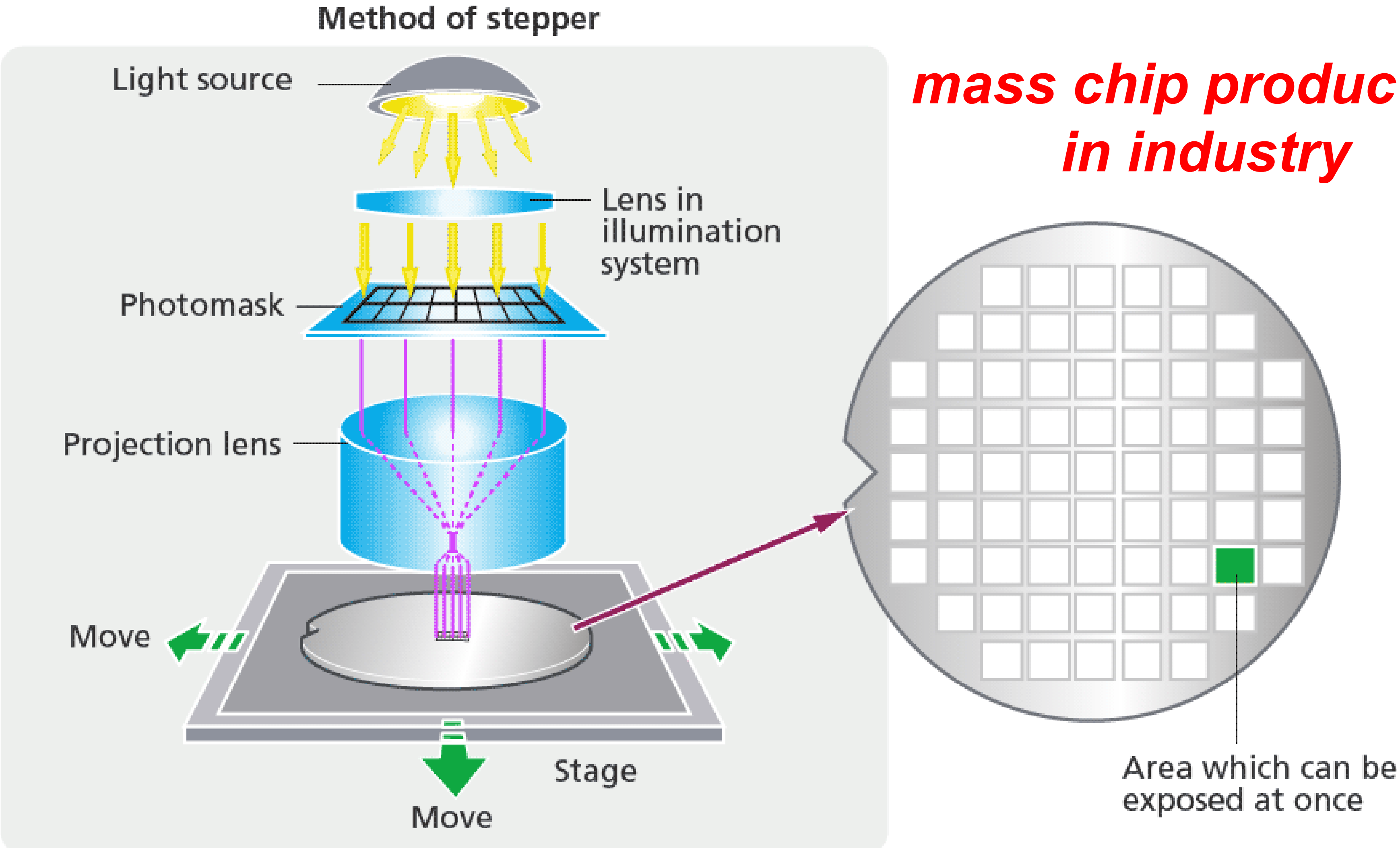
Fast, simple and inexpensive, choice for R&D.

No mask wear/contamination, mask de-magnified 4× (resist features 4× smaller than mask). Very expensive, mainly used for IC industry.

Exposure (曝光)

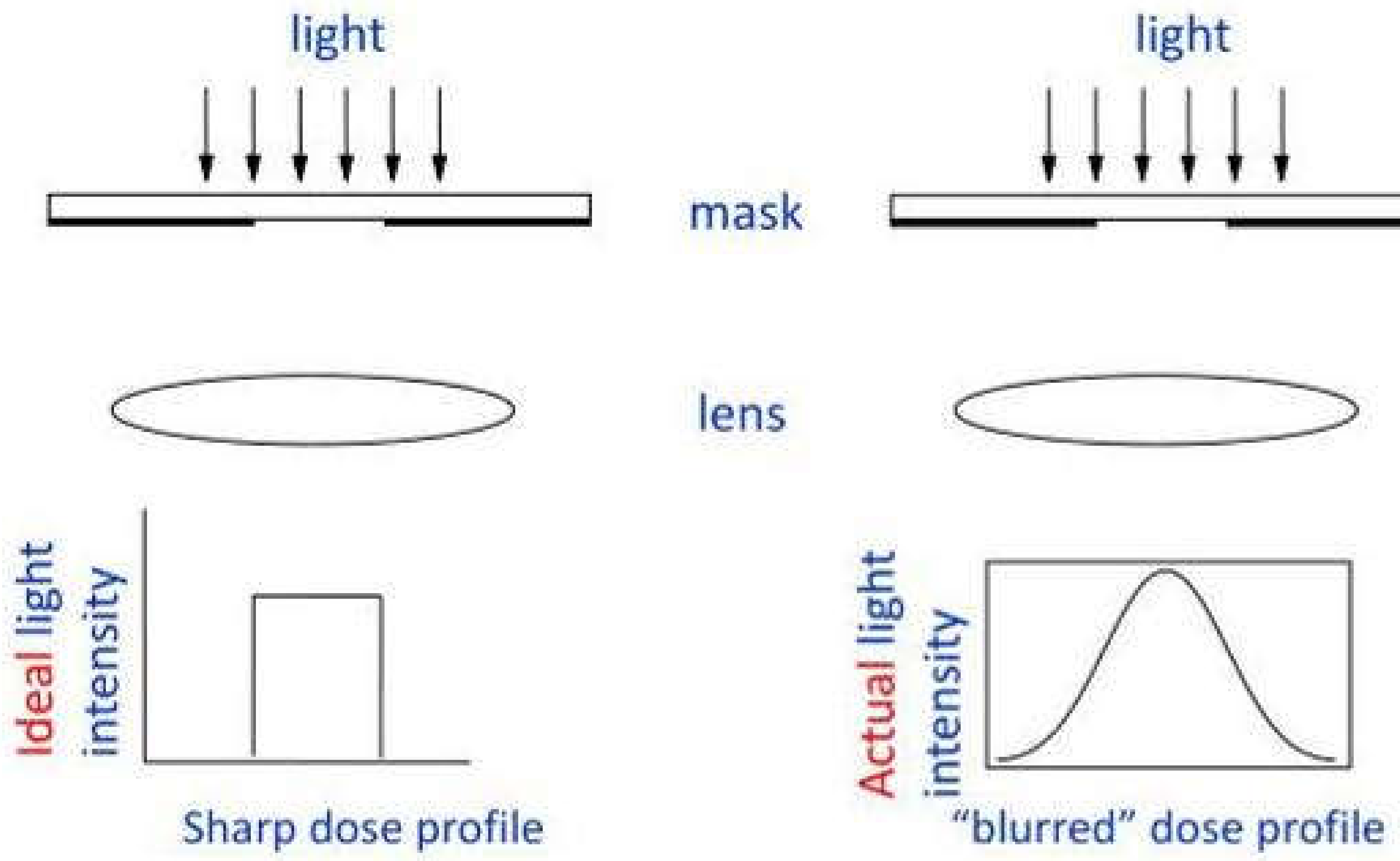
stepper (步进投影)

Video



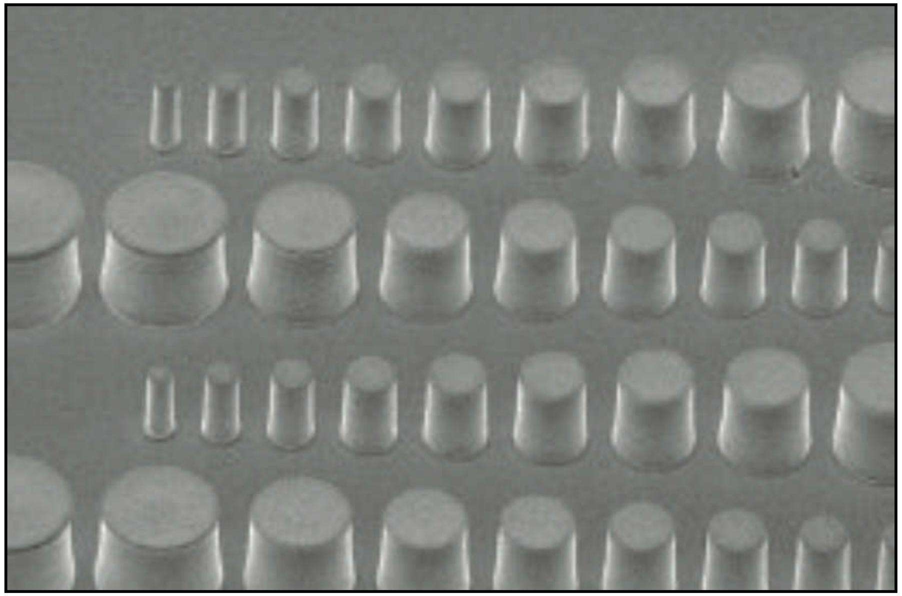
mass chip production in industry

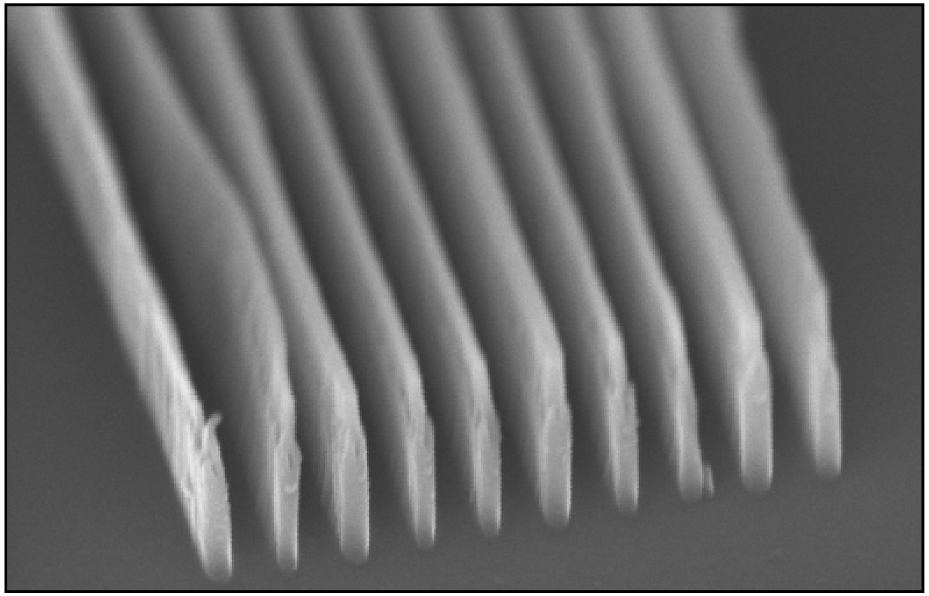
Resolution



ideal case **actual case**

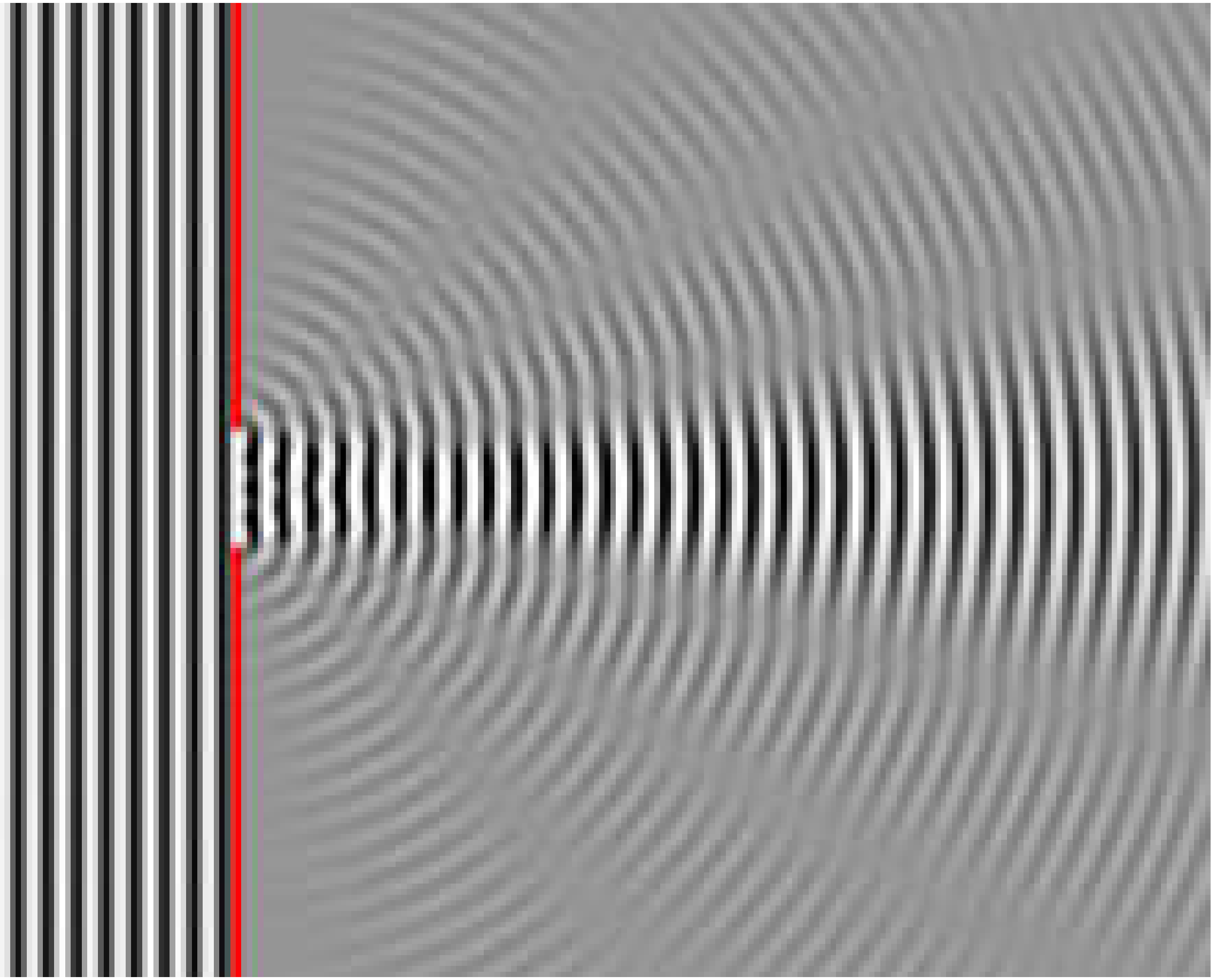
Resolution





the smaller, the harder

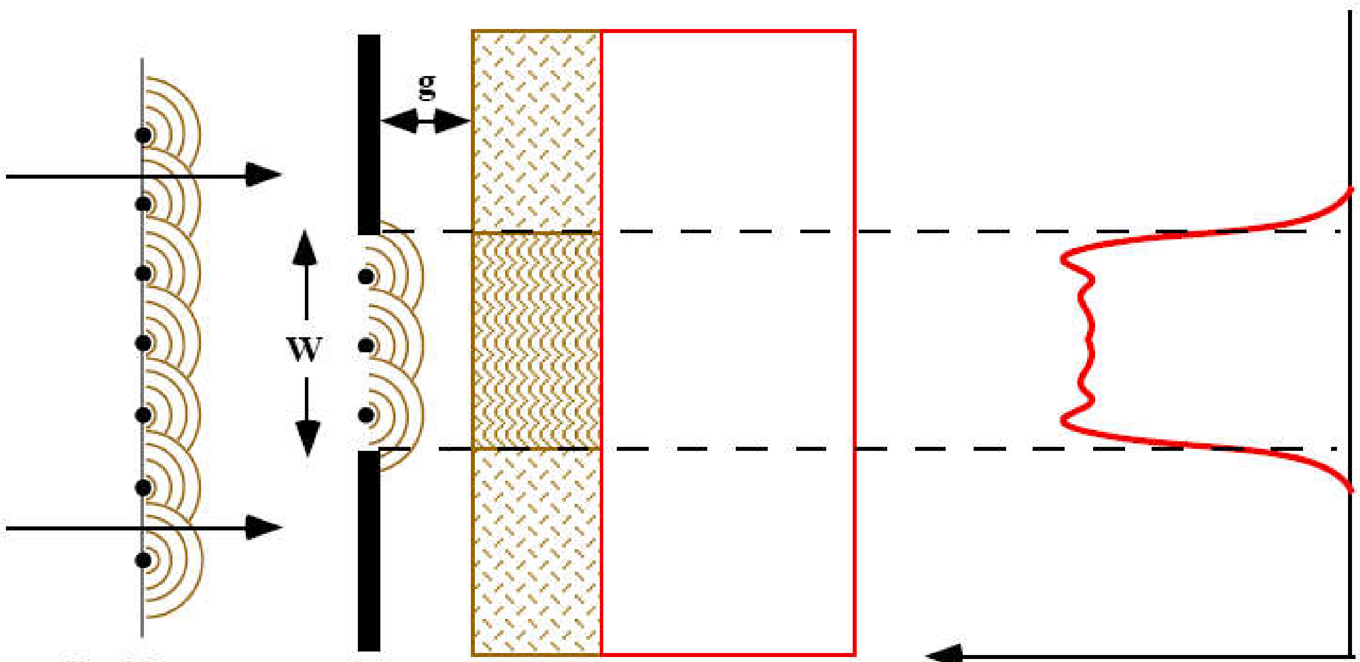
Resolution



diffraction: light is a wave!

Resolution

contact and proximity mode



R resolution

λ wavelength

g gap size

$$R \sim \sqrt{\lambda \cdot g}$$

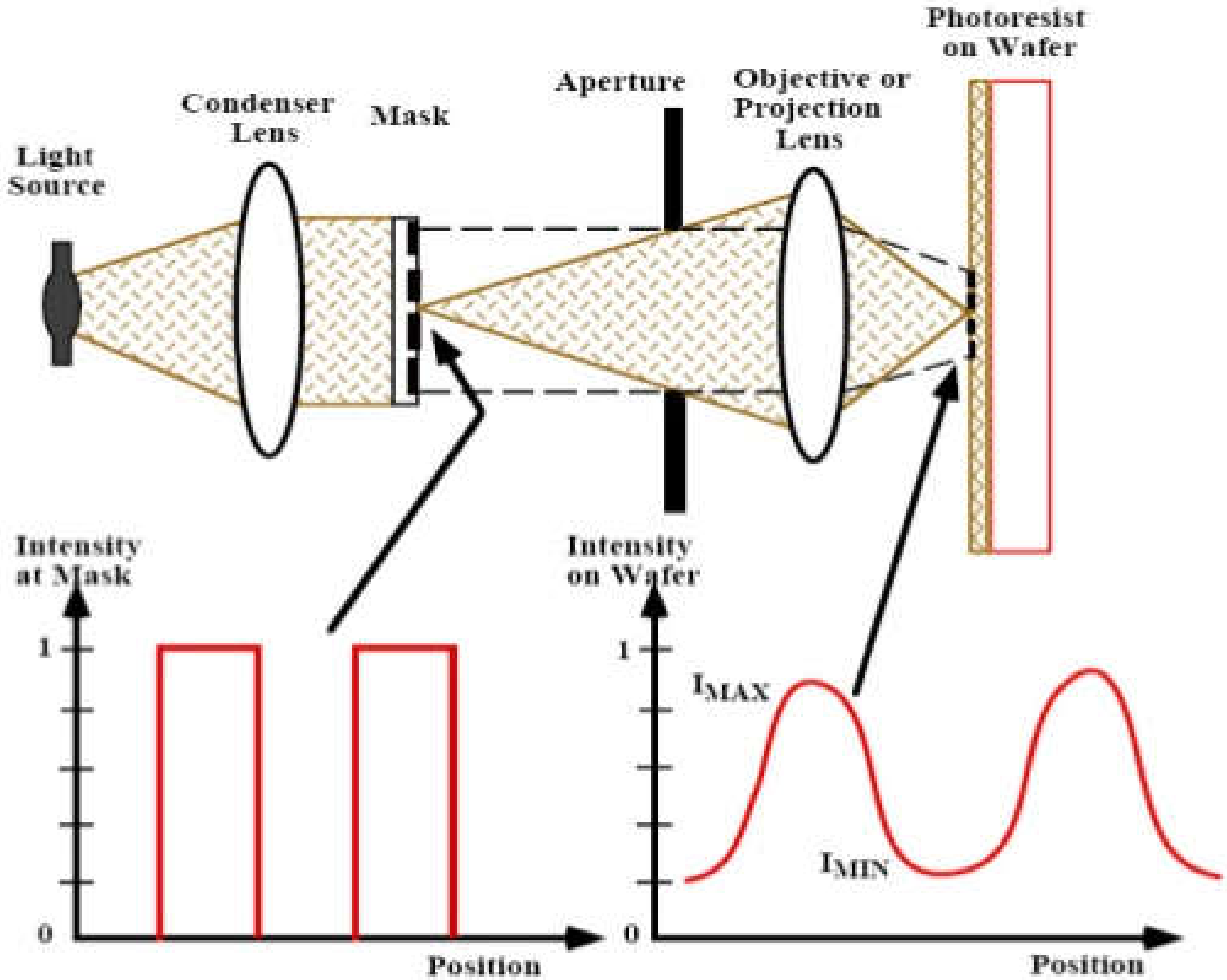
smaller *λ*, ***g*** ---> smaller ***R***

λ UV, DUV, EUV, x-ray, ...

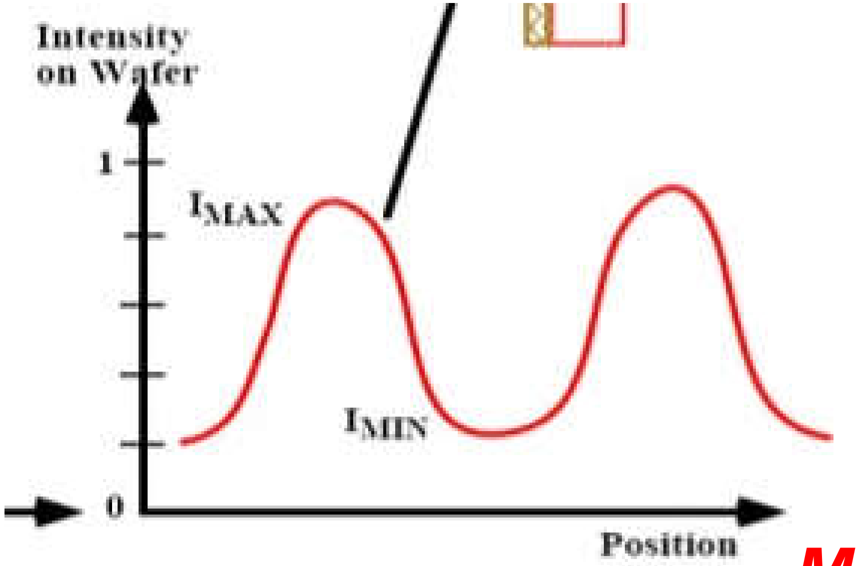
g minimum: resist film thickness

Resolution

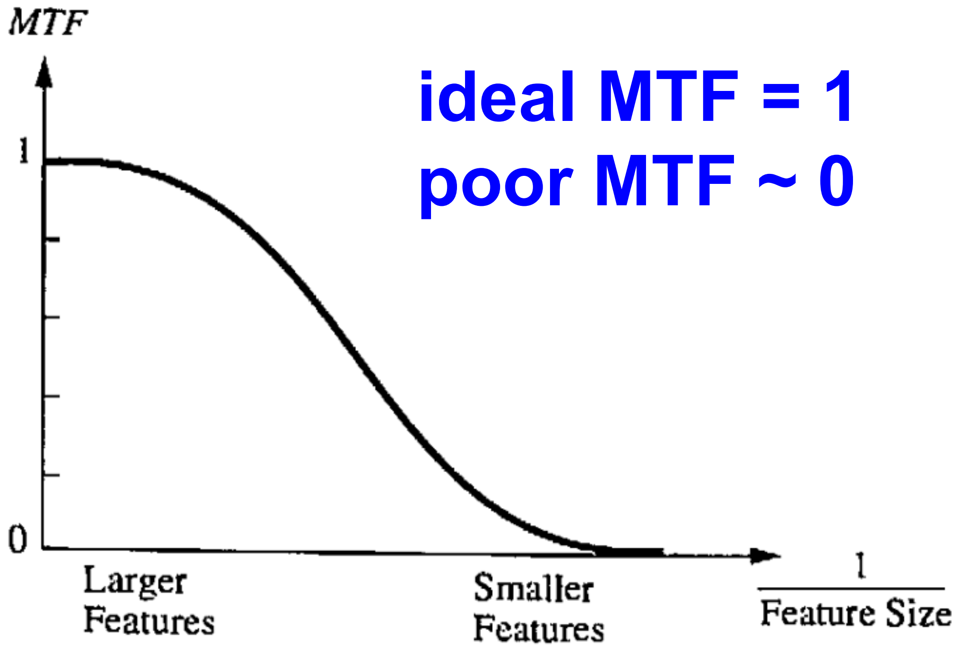
projection mode



Resolution



MTF = ?



ideal MTF = 1
poor MTF ~ 0

modulation transfer function (MTF)

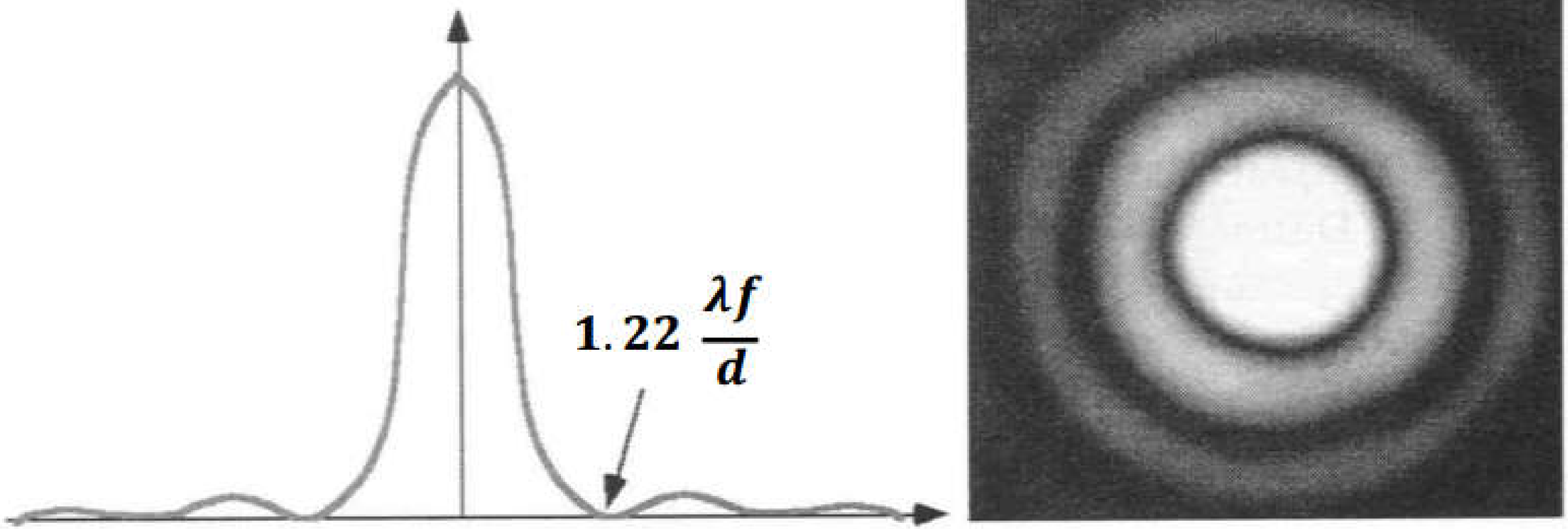
$$MTF = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Resolution

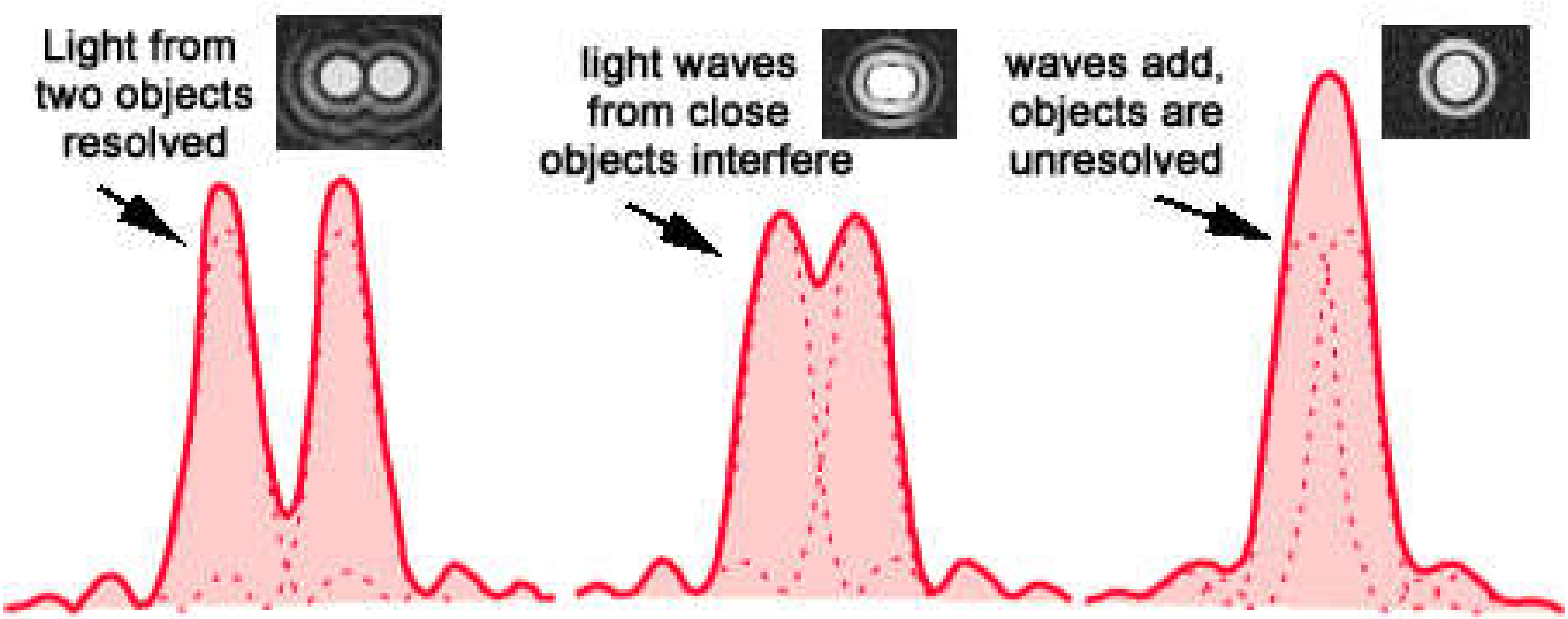
diffraction pattern (Airy's disk)

f = focal distance

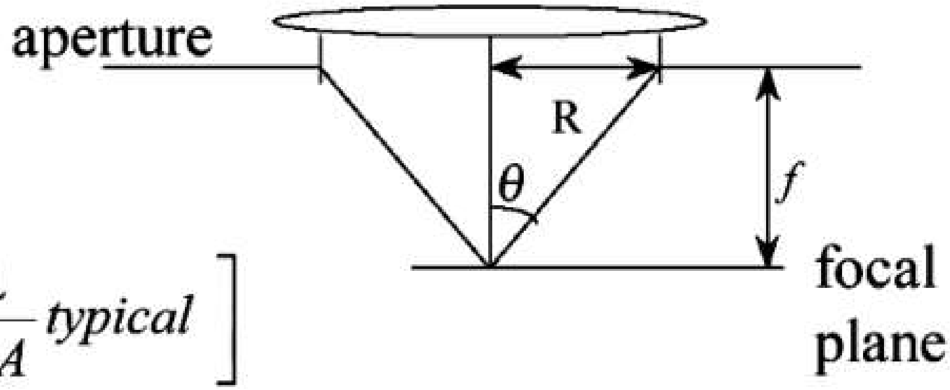
d = lens diameter



Resolution


Light from
two objects
resolved
light waves
from close
objects interfere
waves add,
objects are
unresolved

Resolution



resolution

$$l_m = k_1 \frac{\lambda}{NA} \qquad \left[0.6 \frac{\lambda}{NA} \; typical \right]$$

$NA \equiv numerical \;\; aperture \;\; of \;\; lens.$

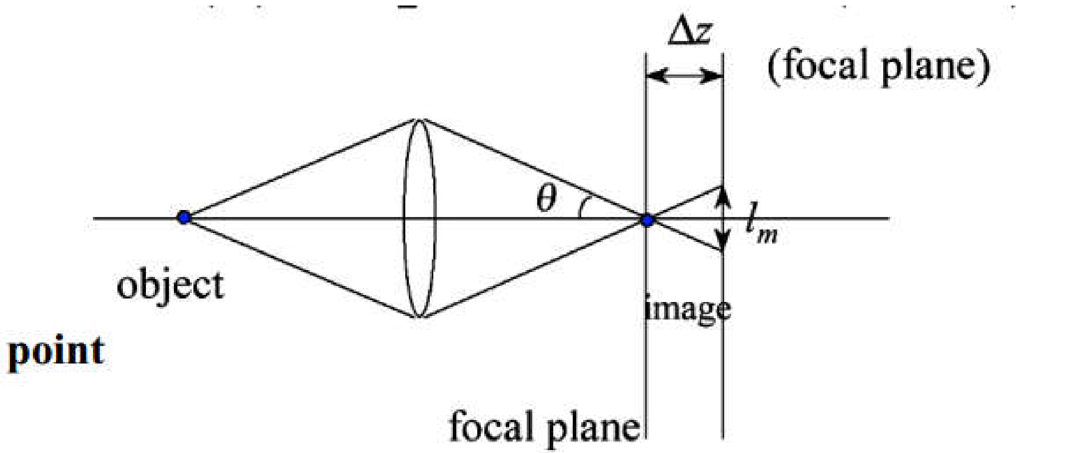
$= n.\sin\Theta$, where n is the index of refraction

k_1 = a constant between 0.25 and 1, depending on optics, resist, and process latitude

smaller λ, larger NA ---> smaller resolution

λ	**UV, DUV, EUV, x-ray, ...**
n	**refractive index (air: 1, oil: 1.4~1.7)**
sinθ	**maximum = 1.0**

Depth of Focus (DOF)



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

$$0.5 < k_2 < 1$$

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

$$\text{for small } \theta$$

off focus

on focus

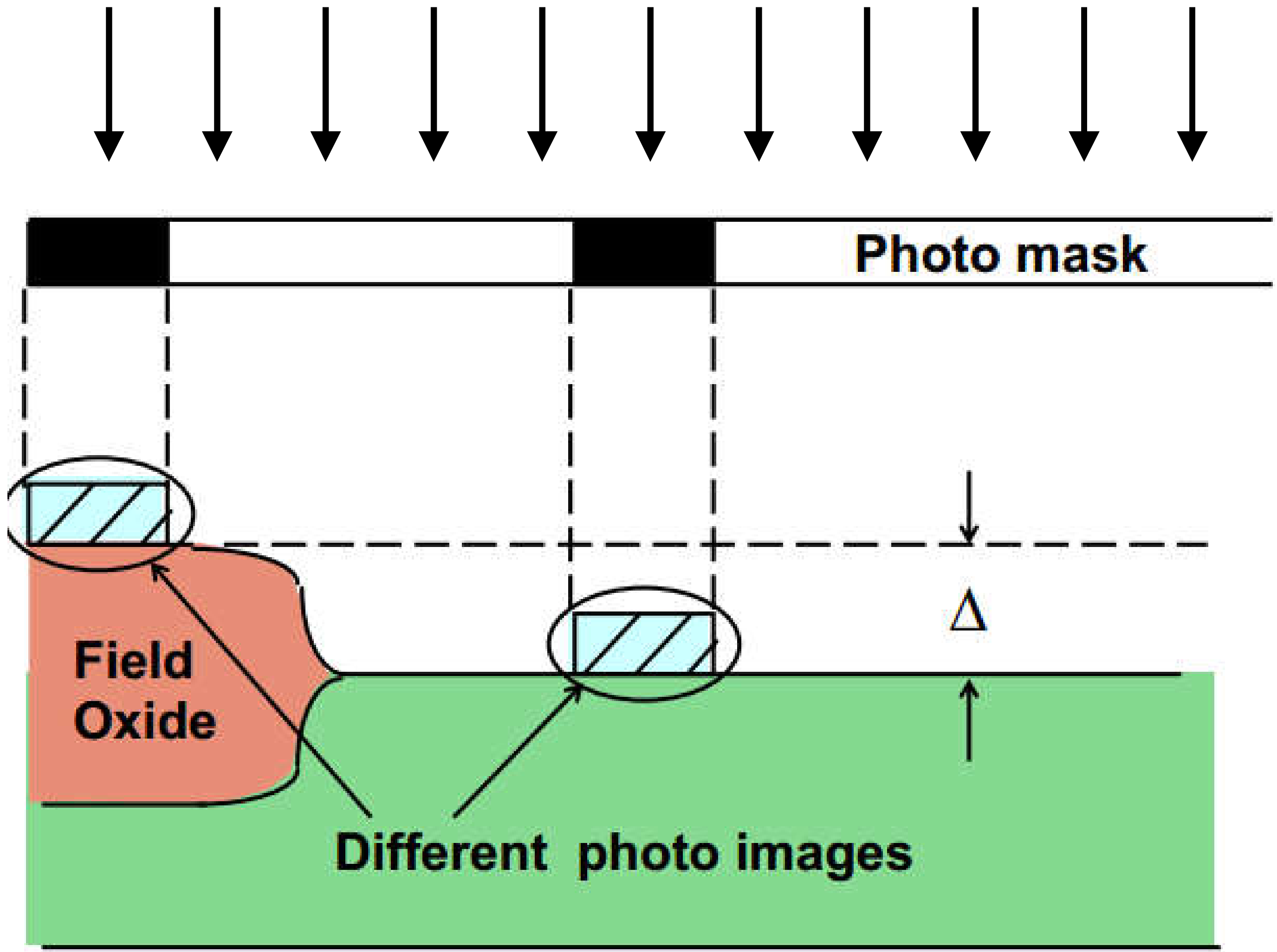
off focus

$$(1)\ l_m \cong 0.6\frac{\lambda}{NA} \quad \text{want small } l_m$$

$$(2)\ DOF = \pm\frac{\lambda}{2(NA)^2} \quad \text{want large } DOF$$

trade-off between resolution and DOF

Depth of Focus (DOF)

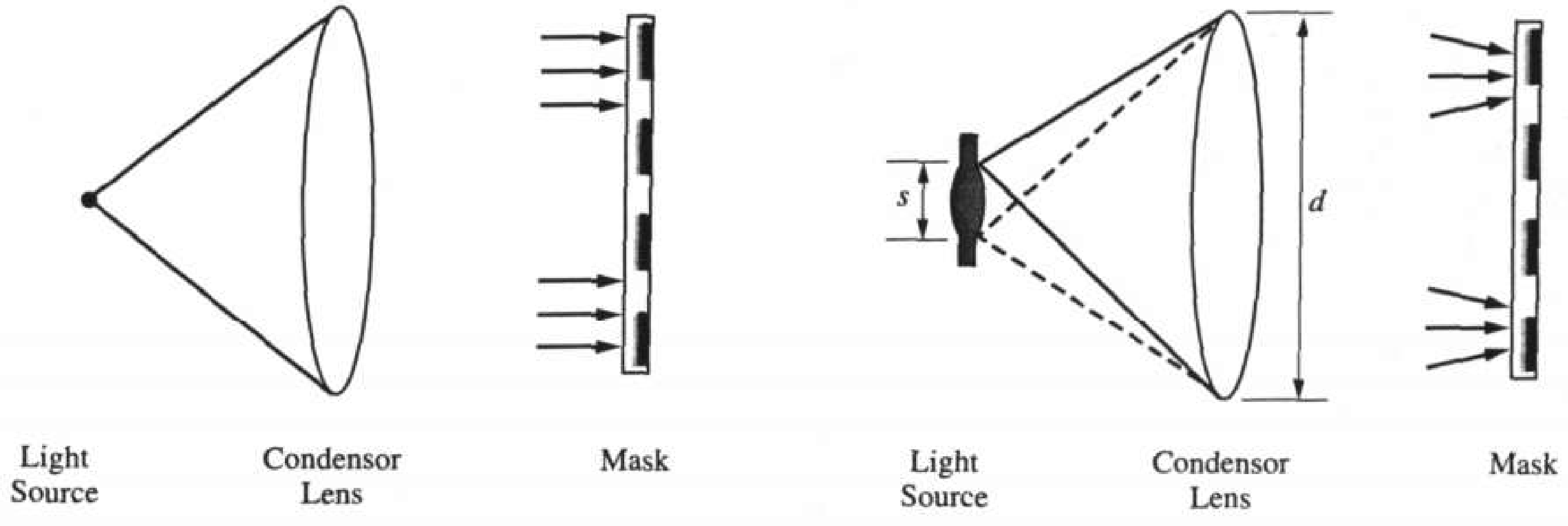


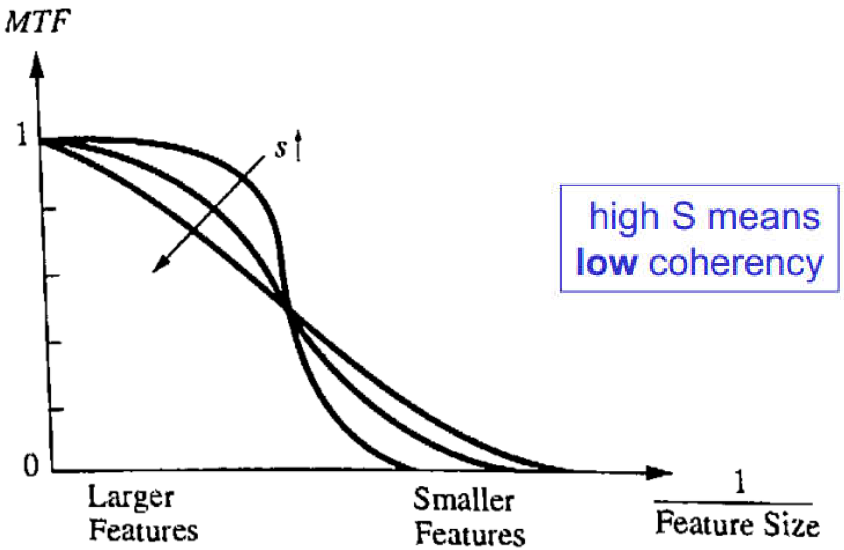
Spatial Coherence

Spatially coherent

small source size s

Partially coherent





high S means **low** coherency

S = spatial coherence of light source

$$S = \frac{\text{light source diameter}}{\text{condenser lens diameter}} = \frac{s}{d}$$

Resolution Improvement

$$\boxed{R \sim \frac{\lambda}{n \sin\theta}}$$

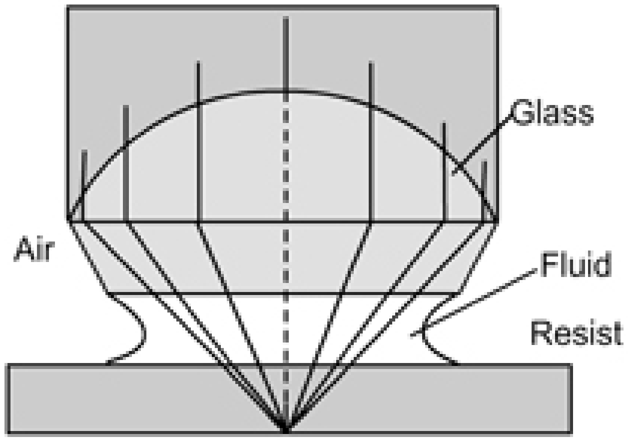
reduce λ

increase *n*

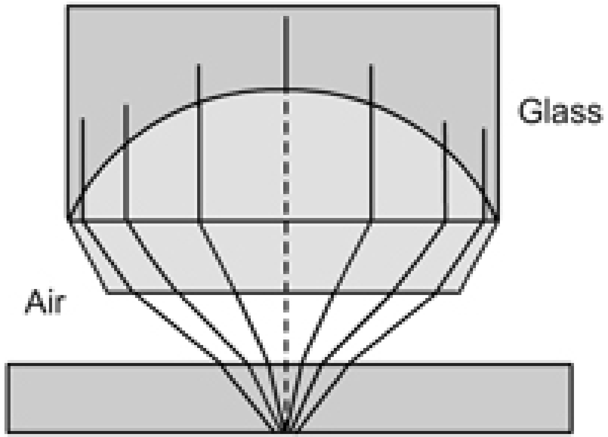
???

Immersion Lithography

$$R \sim \frac{\lambda}{n \sin\theta}$$



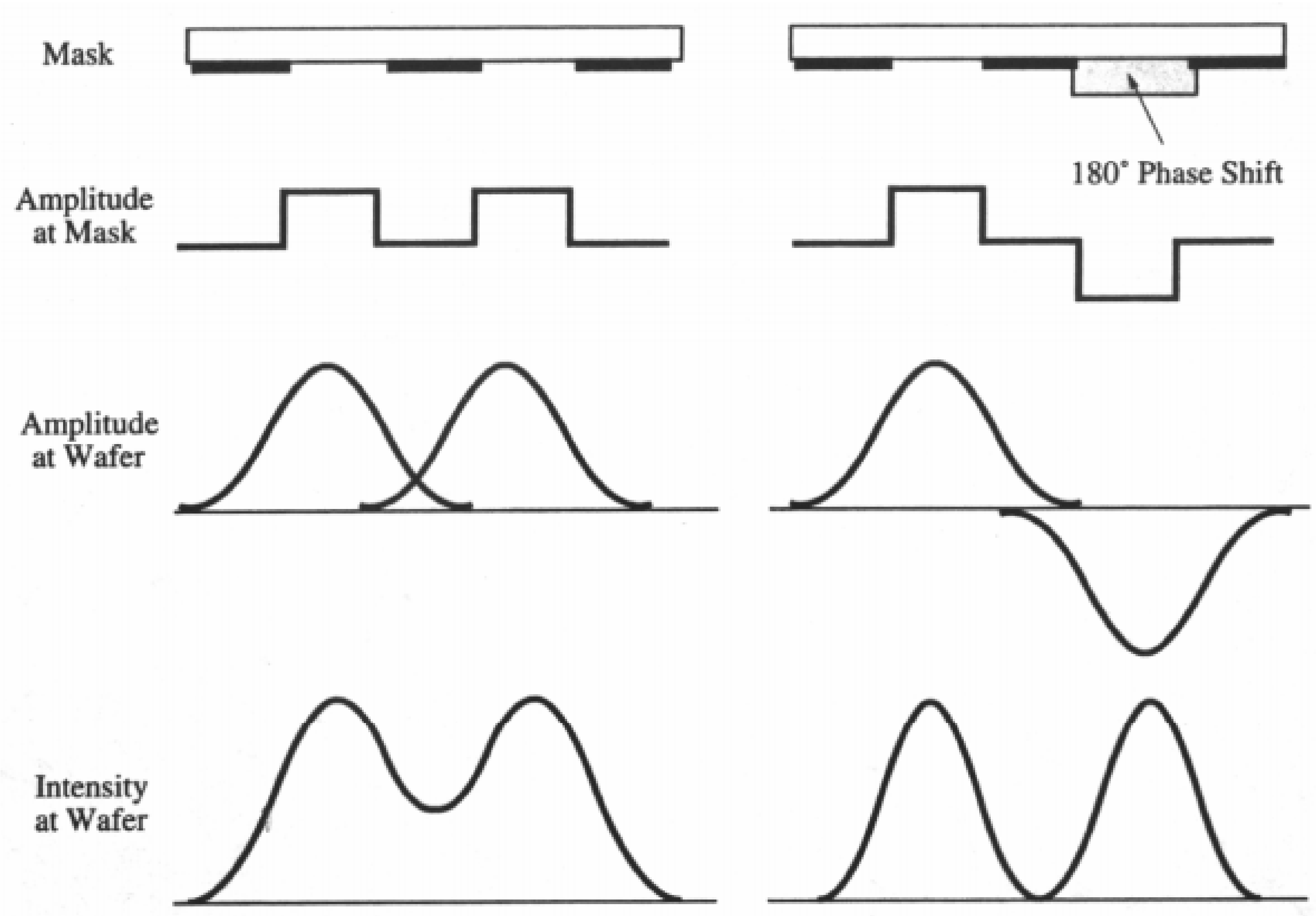
n **> 1.0**



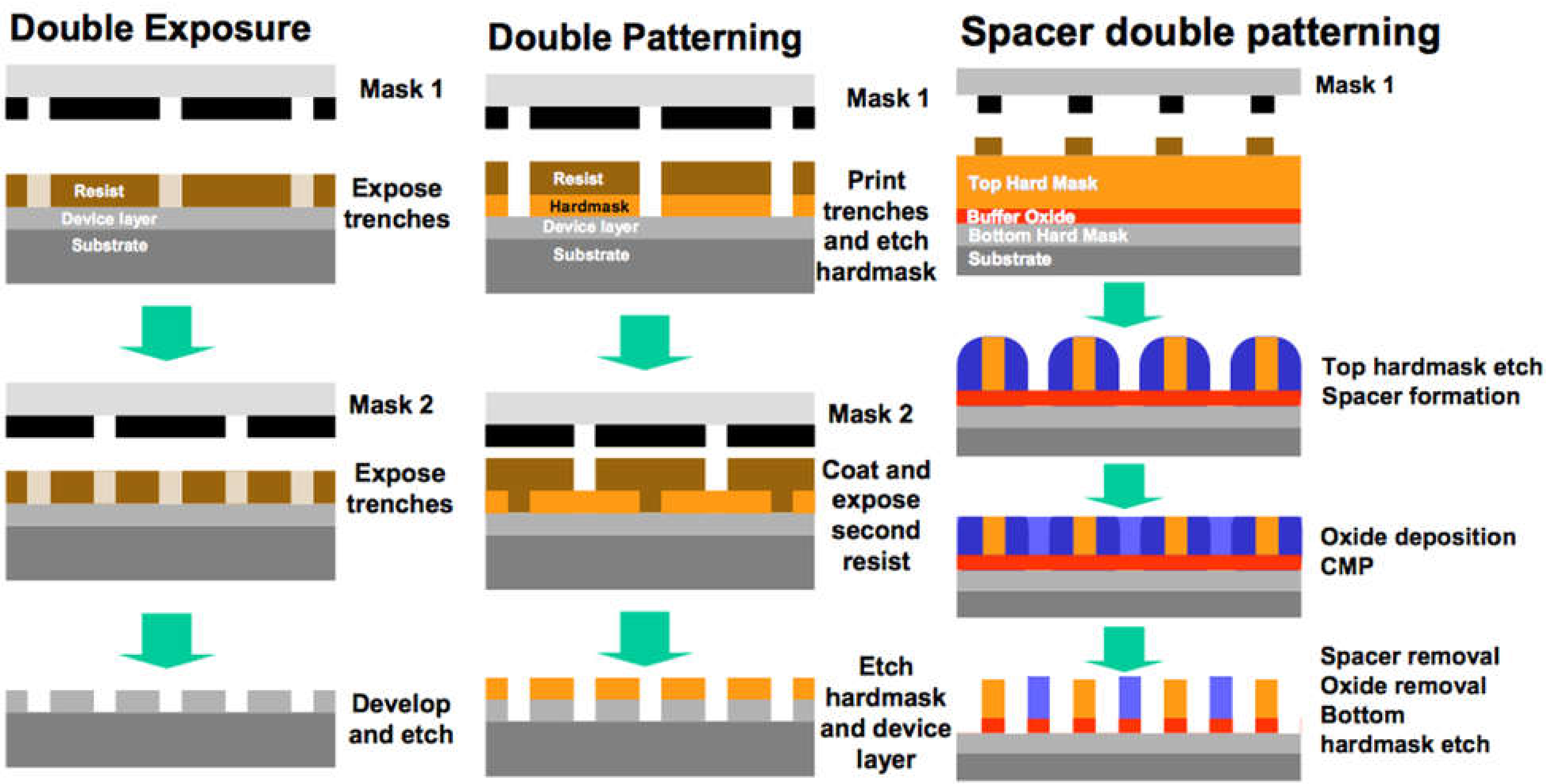
n **= 1.0**

high index fluid *n* = 1.7
resolution is reduced by ~40%

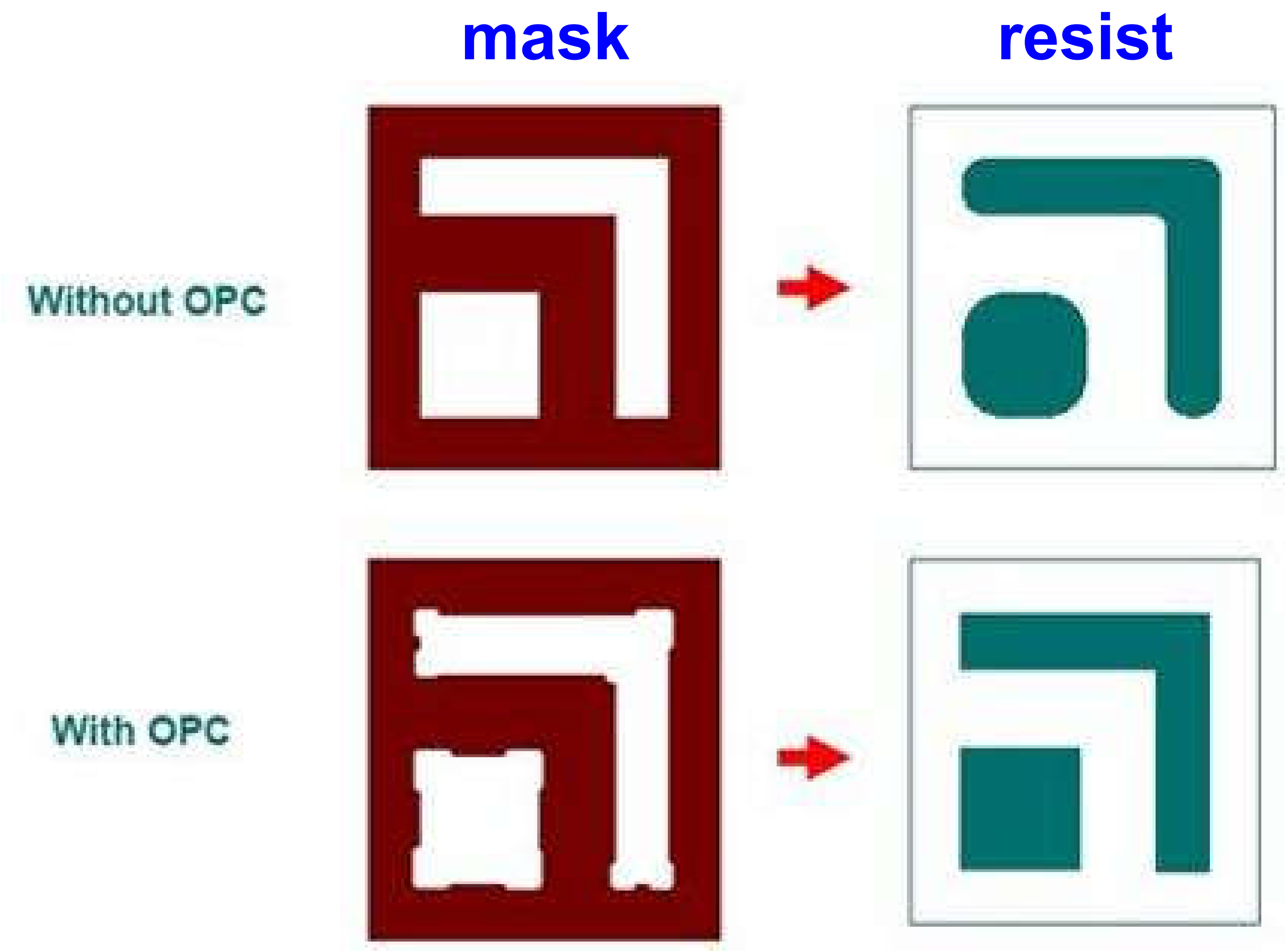
Phase Shift Mask



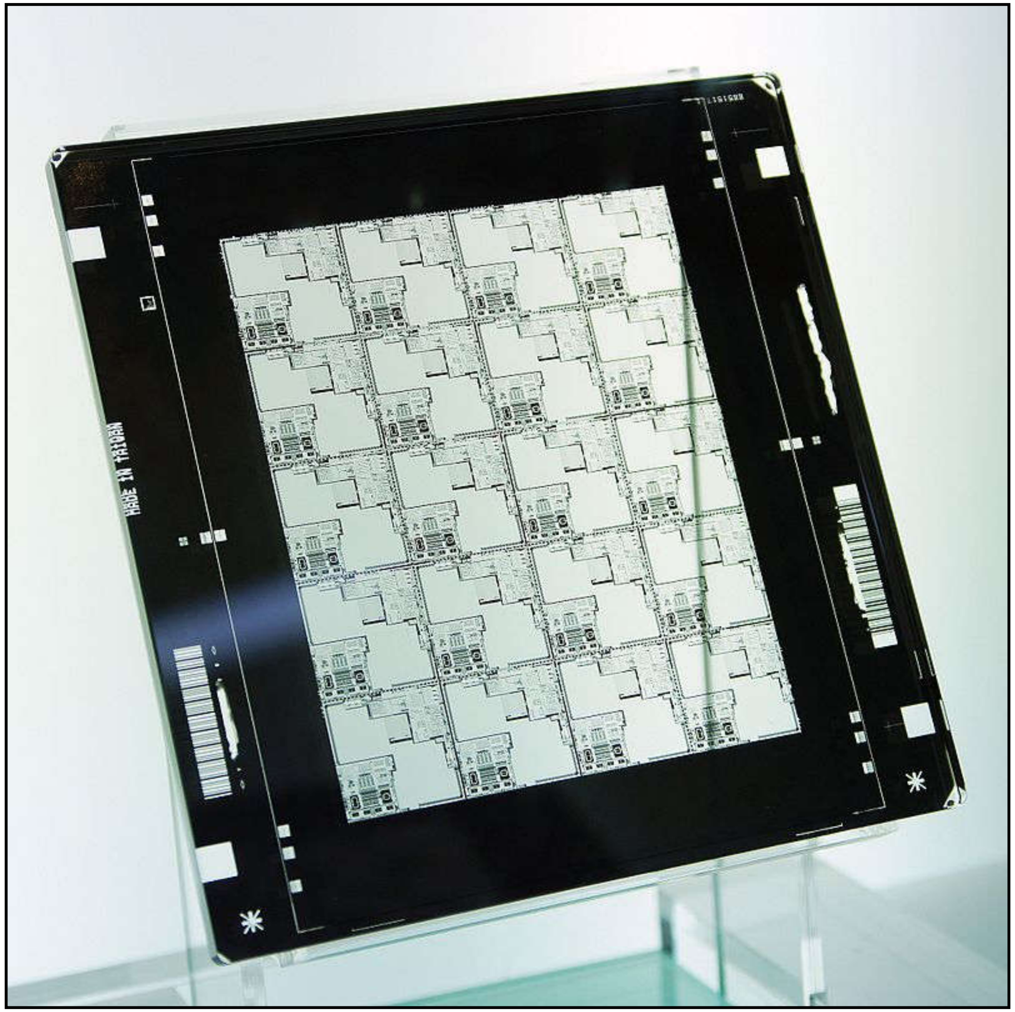
Double Patterning

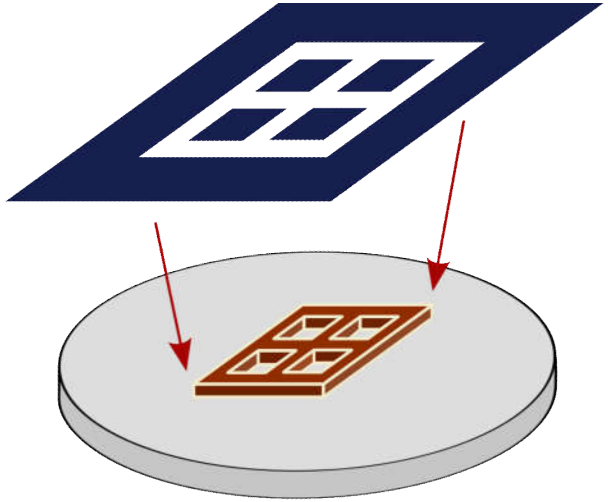


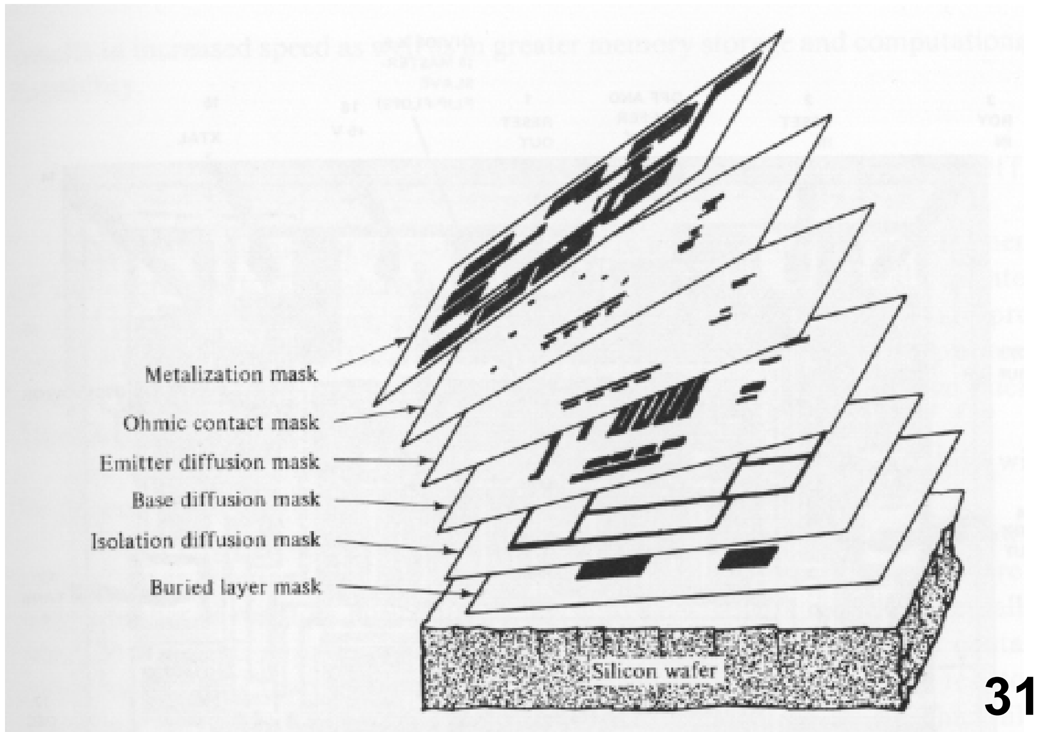
Optical Proximity Correction (OPC)



Photomasks (掩膜)



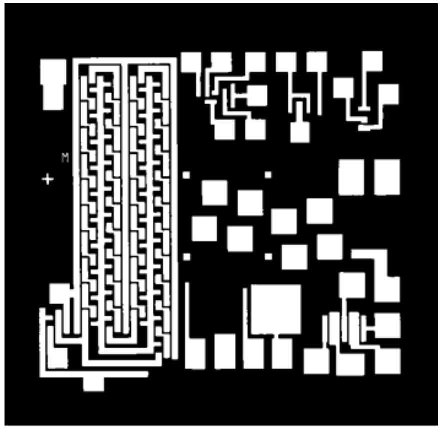




Photomasks (掩膜)

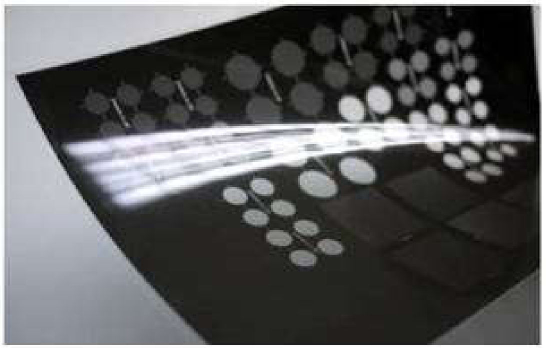
- Layout design
  - CAD tools
  - see examples

Example

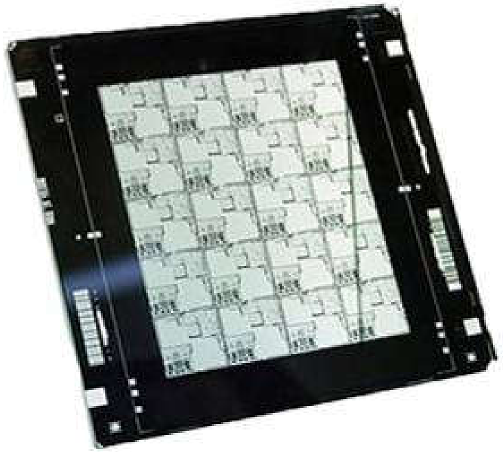


design layout

- Transparency film
  - flexible mask
- Chrome mask
  - glass substrate
  - chrome coating

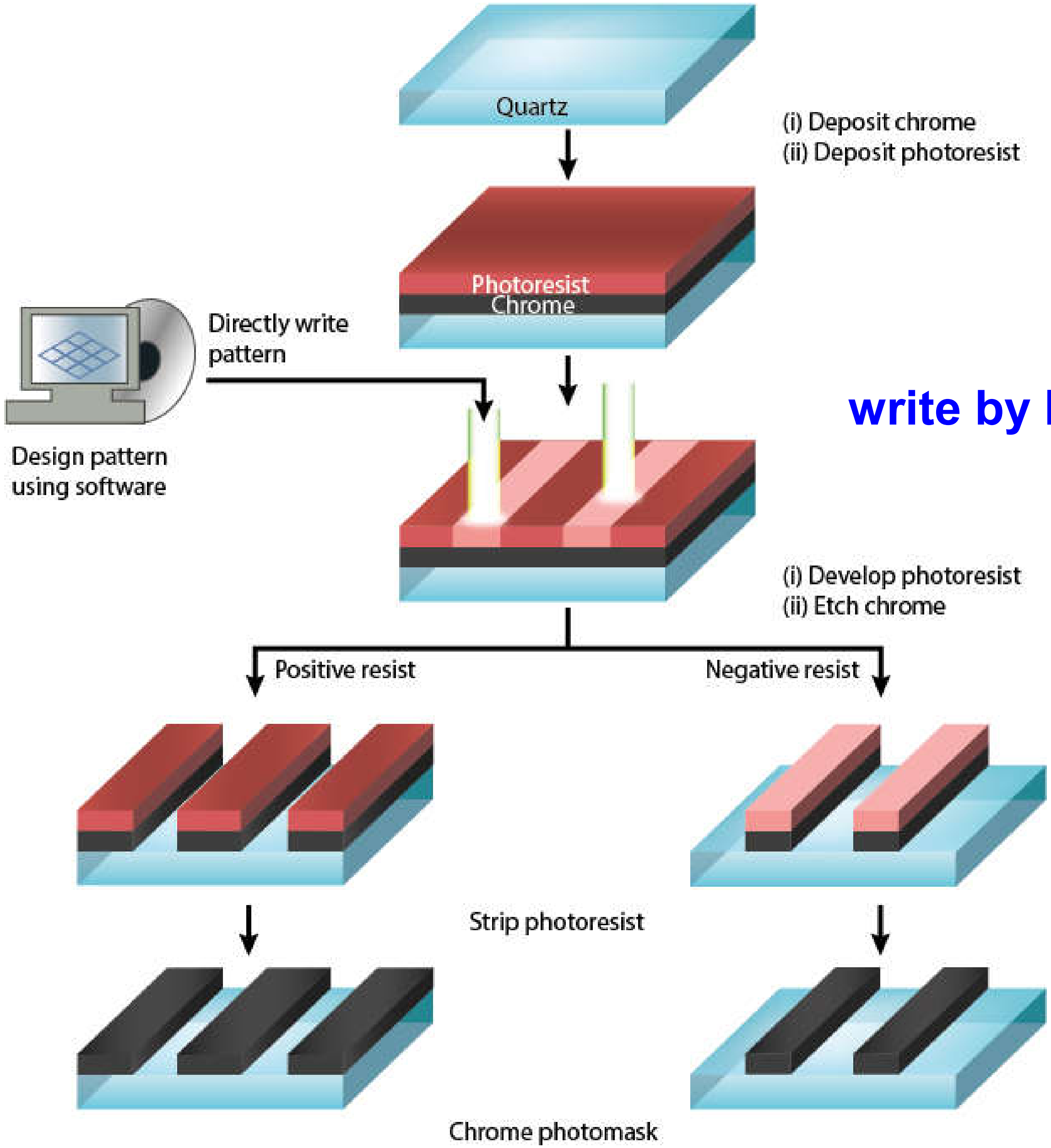


transparency film



chrome mask

Photomasks (掩膜)



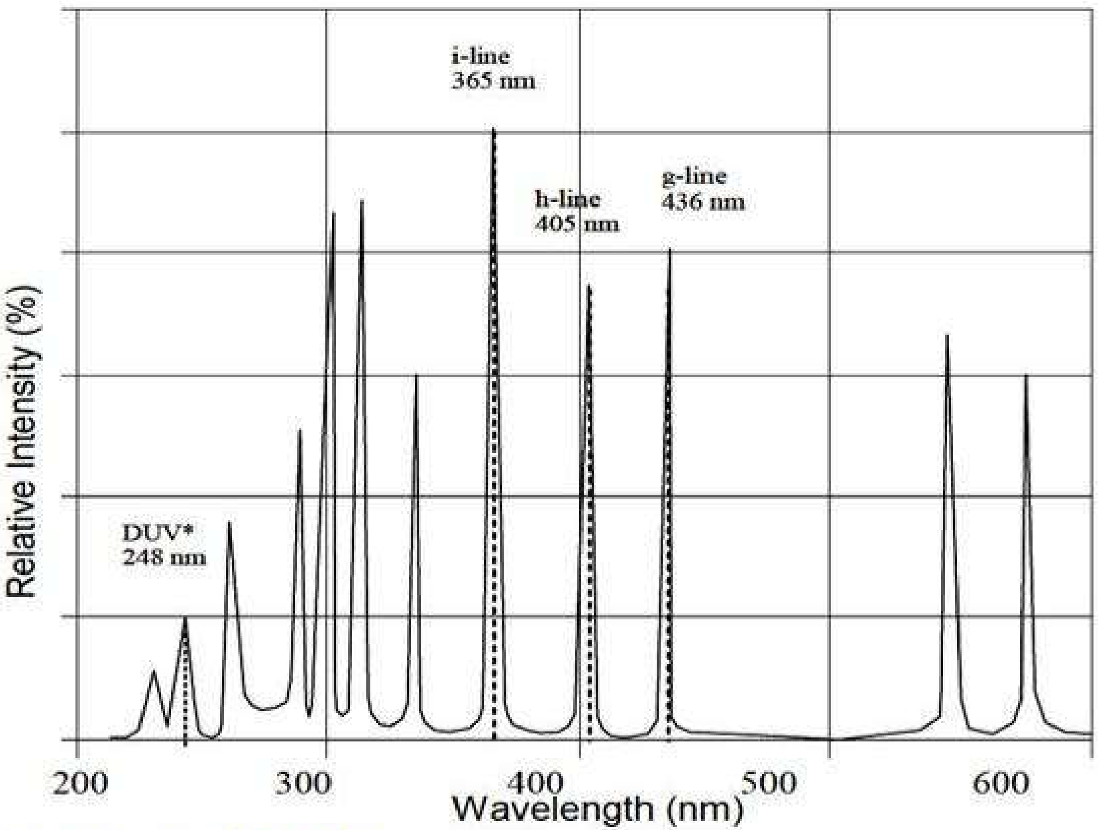
write by laser or Ebeam

Light Sources

- **Mercury (Hg) arc lamp**
  - **g-line 436 nm, h-line 405 nm, i-line 365 nm**

$$R \sim \frac{\lambda}{n \sin \theta}$$

High pressure Hg-vapor lamps
Order $1000, lasts ~1000 hours.



- Filters can be used to limit exposure wavelengths.

Light Sources

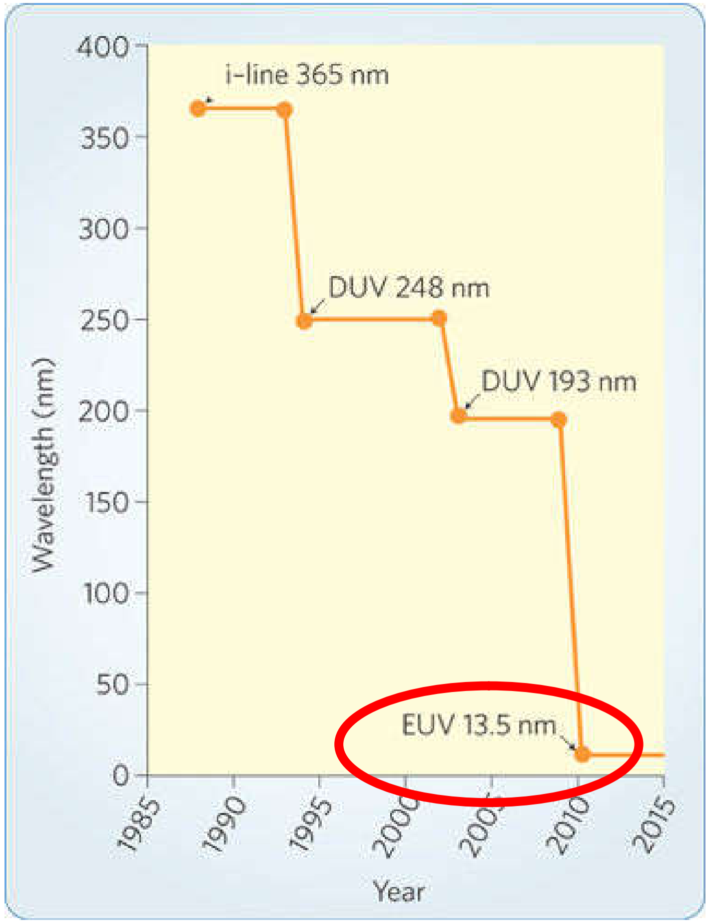
- **Mercury (Hg) arc lamp**
  - **g-line 436 nm, h-line 405 nm, i-line 365 nm**

yellow light in cleanroom

Light Sources

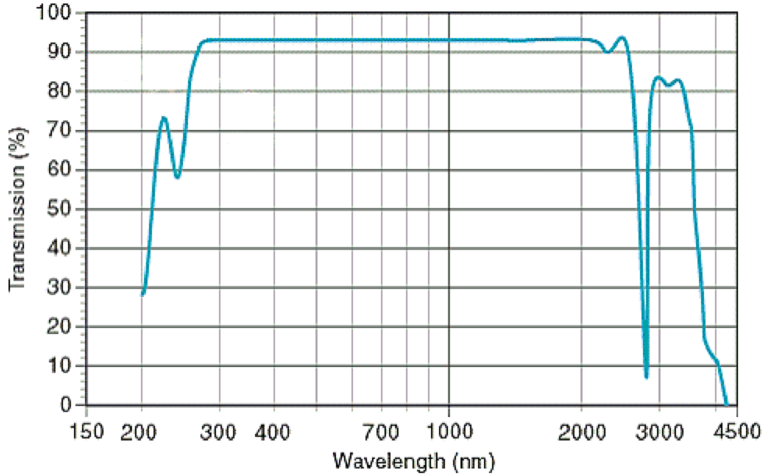
$$R \sim \frac{\lambda}{n \sin\theta}$$

- Deep UV (DUV)
  - excimer lasers, KrF (248 nm), ArF (193 nm)
- Extreme UV (EUV)
  - Tin (Sn) plasma lasers, 13.5 nm
- X-ray
  - 0.01 ~ 10 nm
- Electron beam (E-beam)
- ...

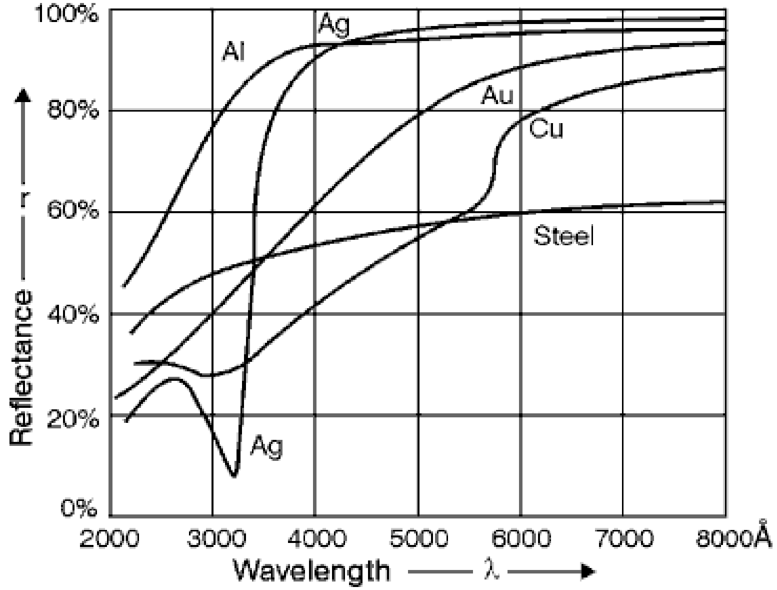


Optics for EUV

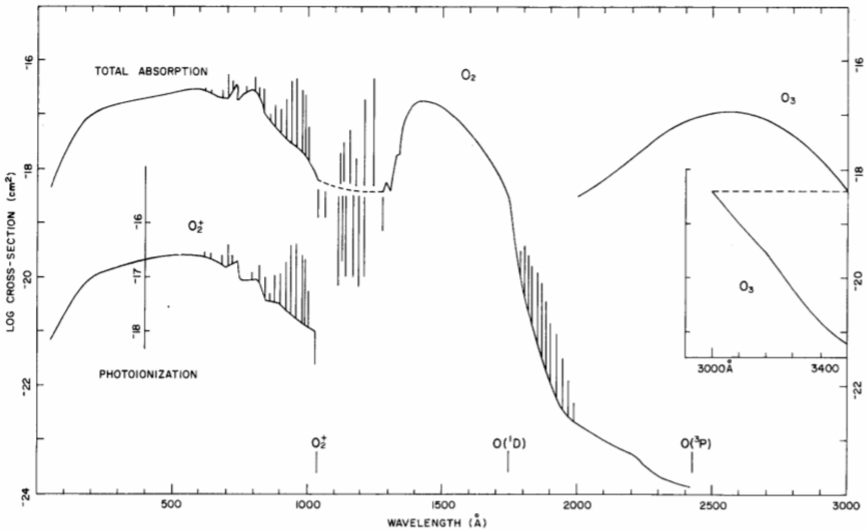
quartz glass



metals



air

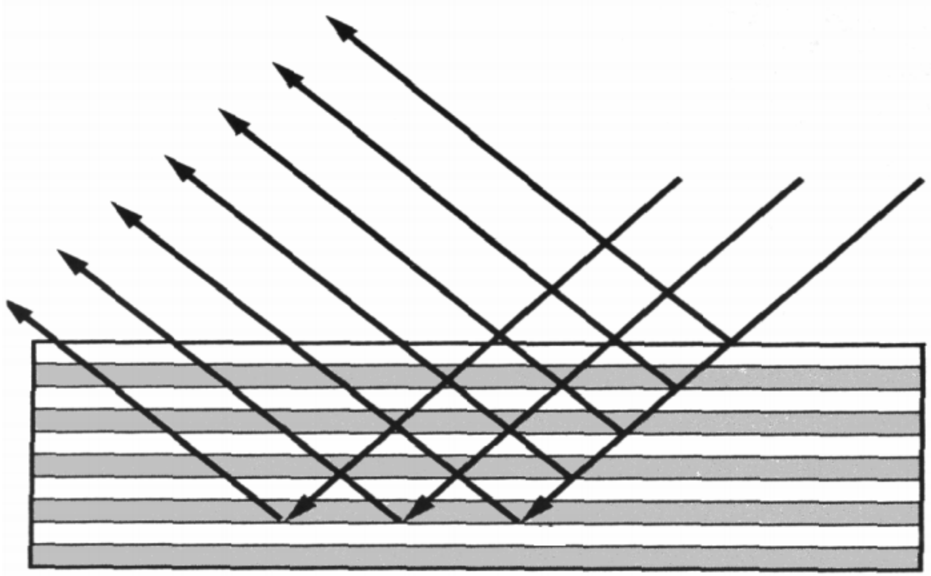


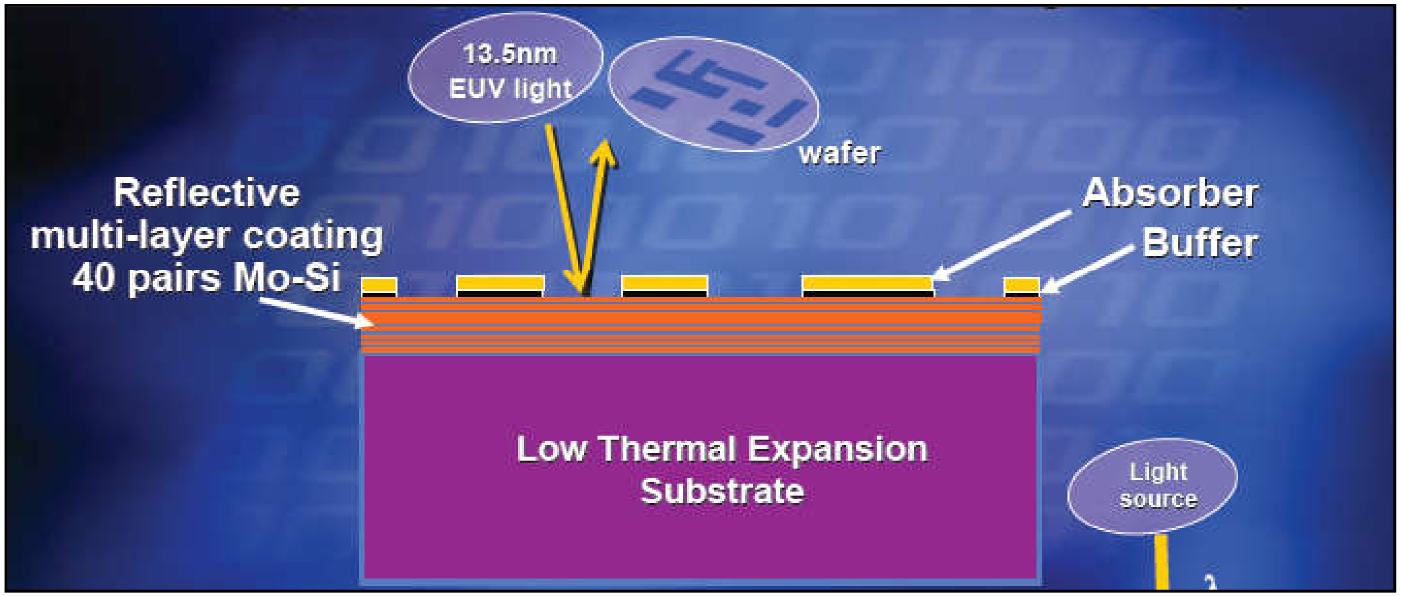
at EUV:

glass is not transparent
metal is not reflective
even air is absorptive

Optics for EUV

multilayer mirrors (Mo/Si)

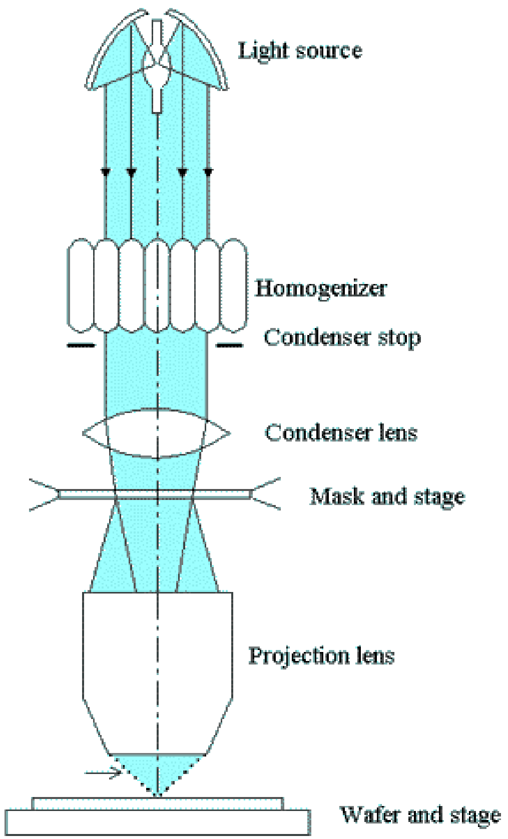


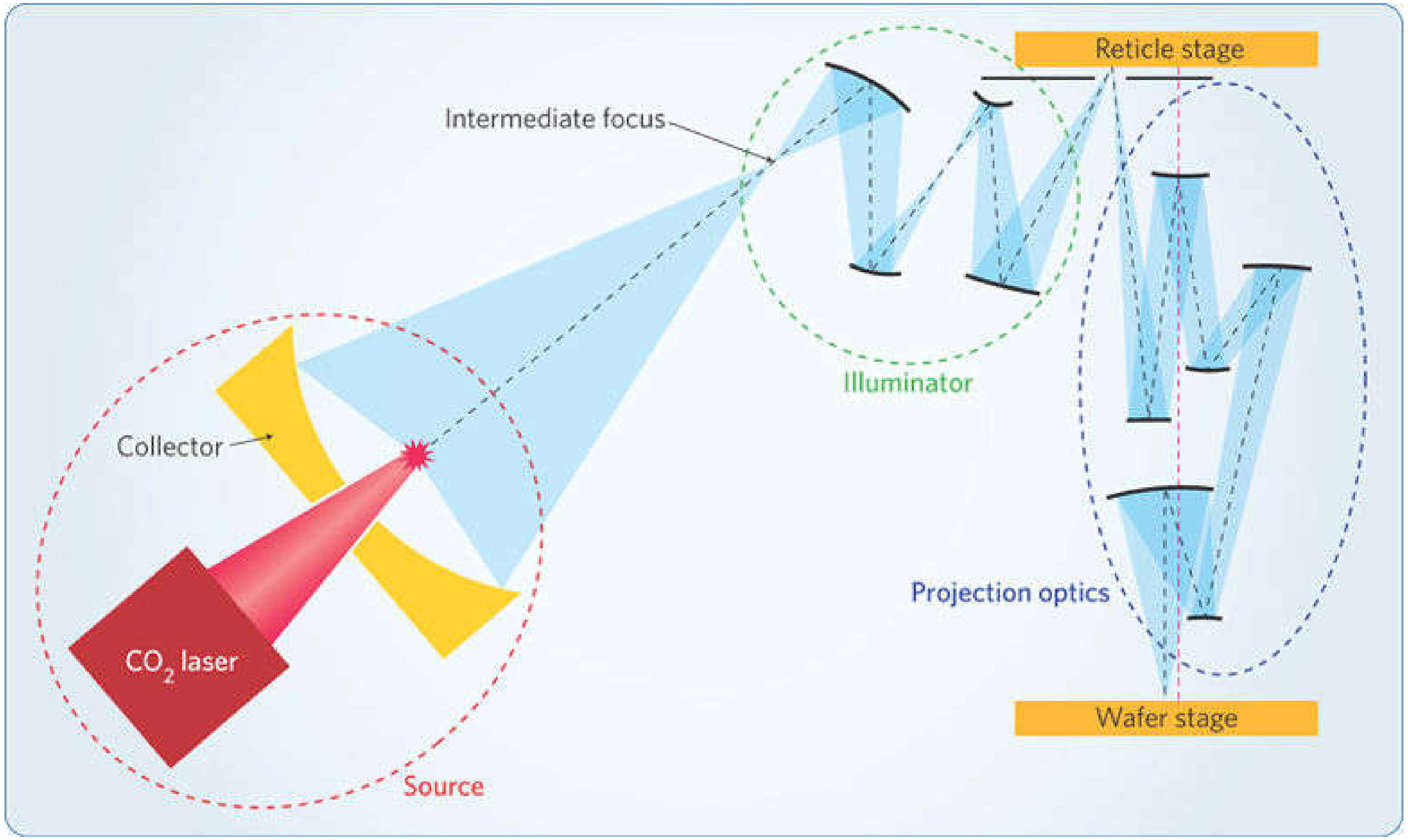


reflective masks

Optics

optical loss > 95%





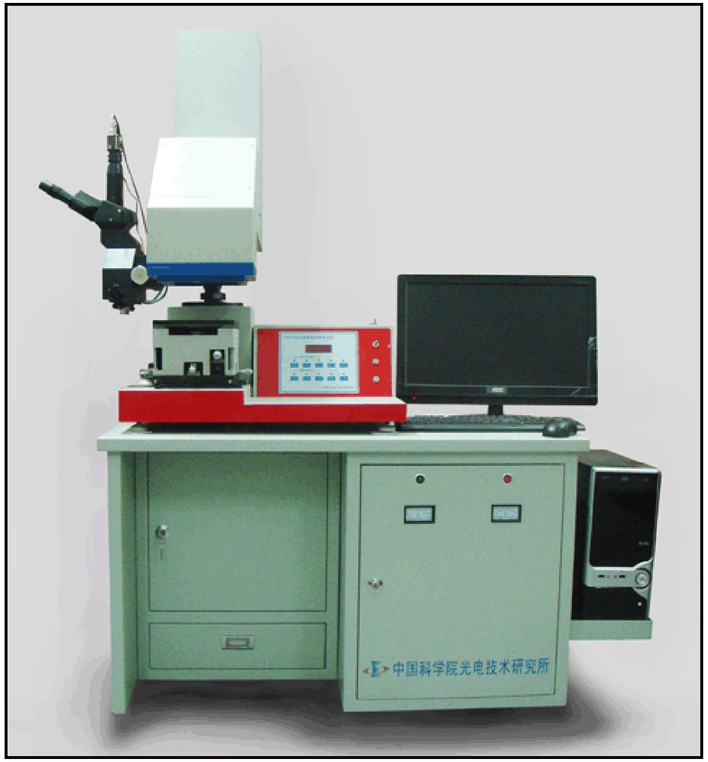
UV (365 nm)

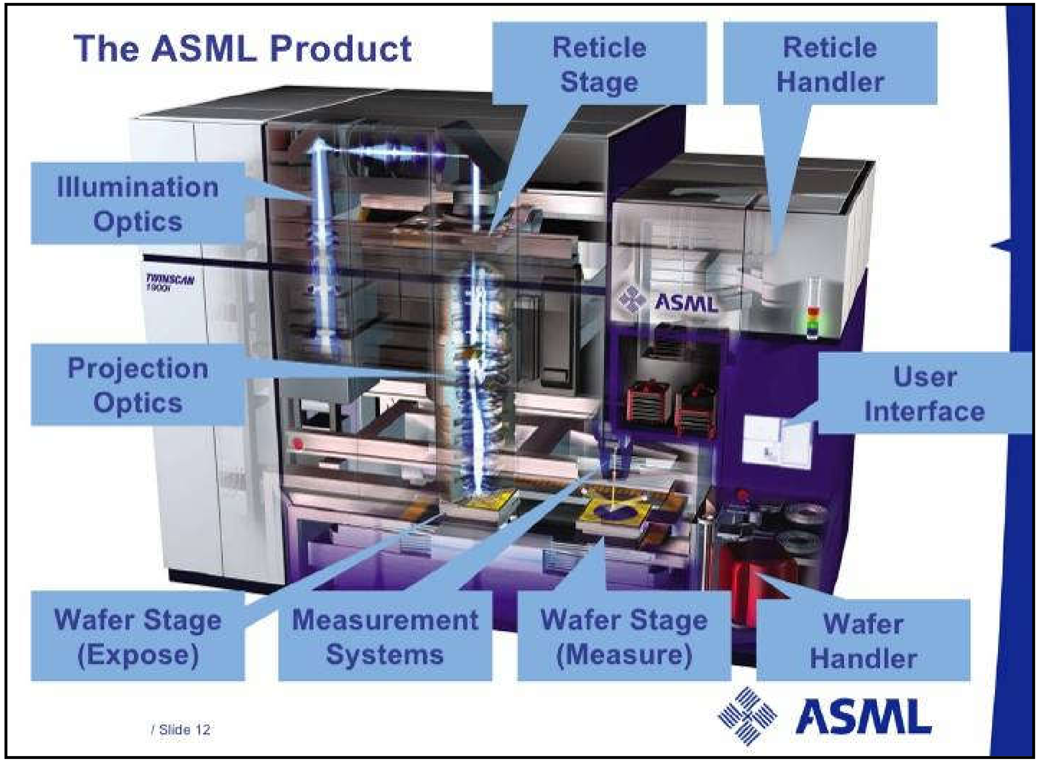
EUV (13.5 nm)

Equipment

UV (365 nm)
resolution ~ 2 μm
price ~ 200,000 RMB

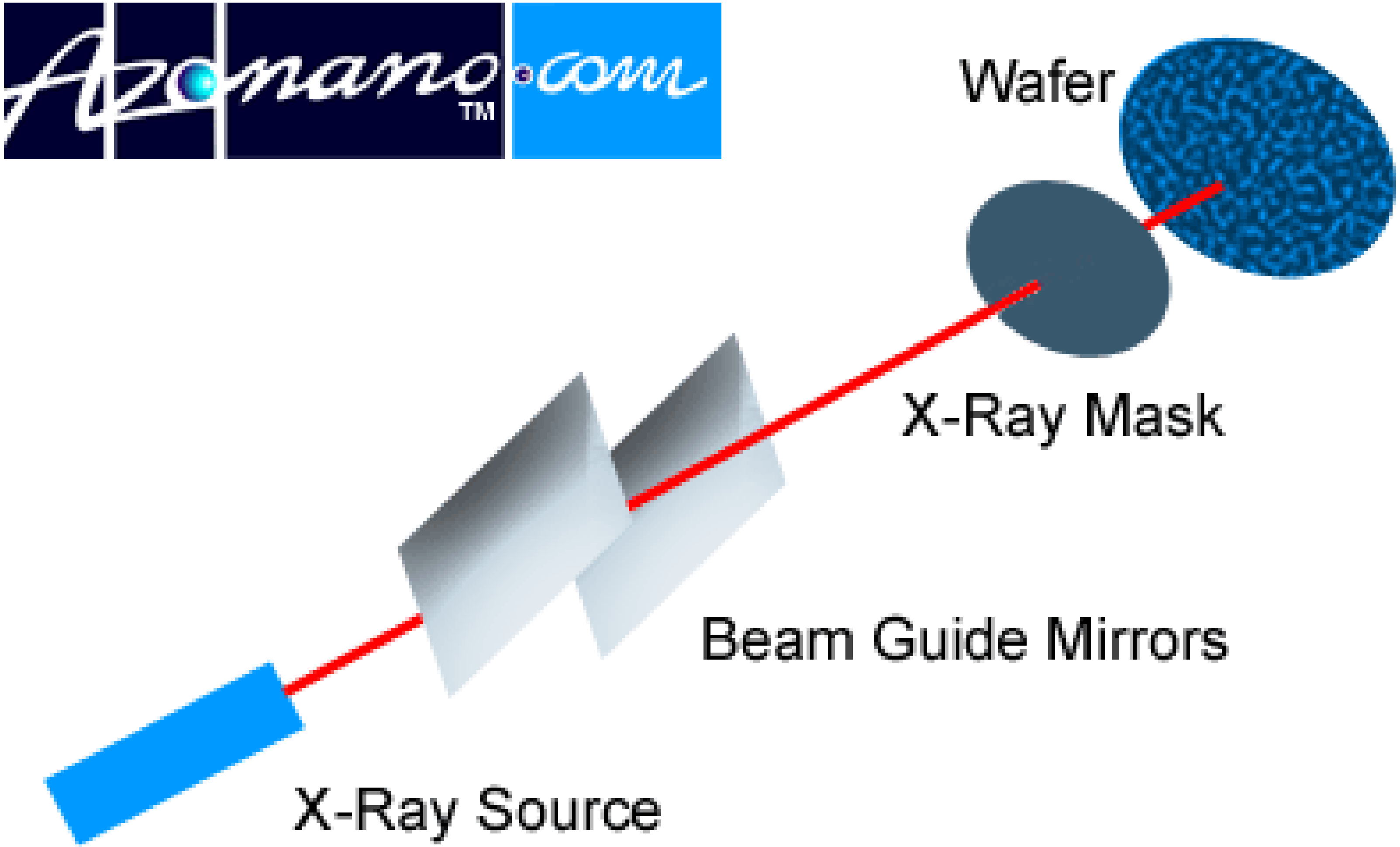
EUV (13.5 nm)
resolution ~ 10 nm
price ~ 100,000,000 $$$





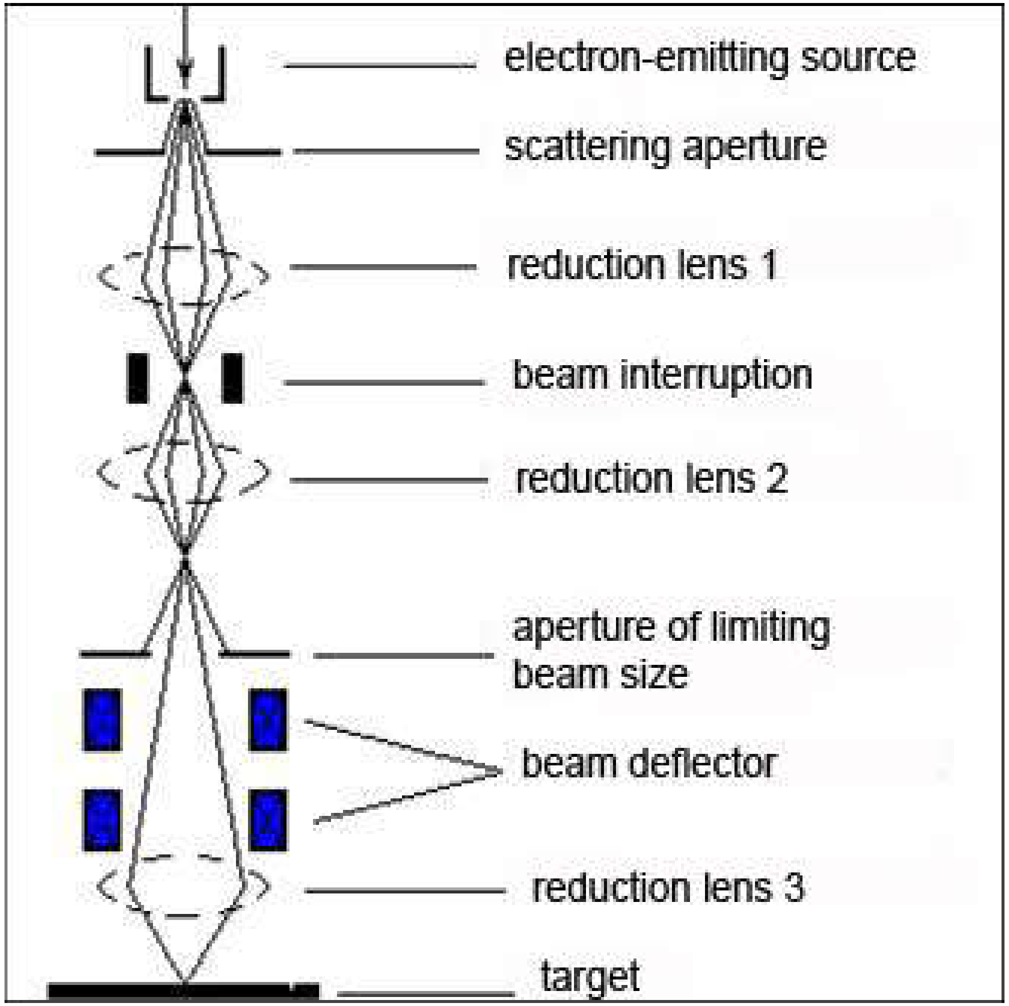
X-ray Lithography

wavelength 0.1~10 nm

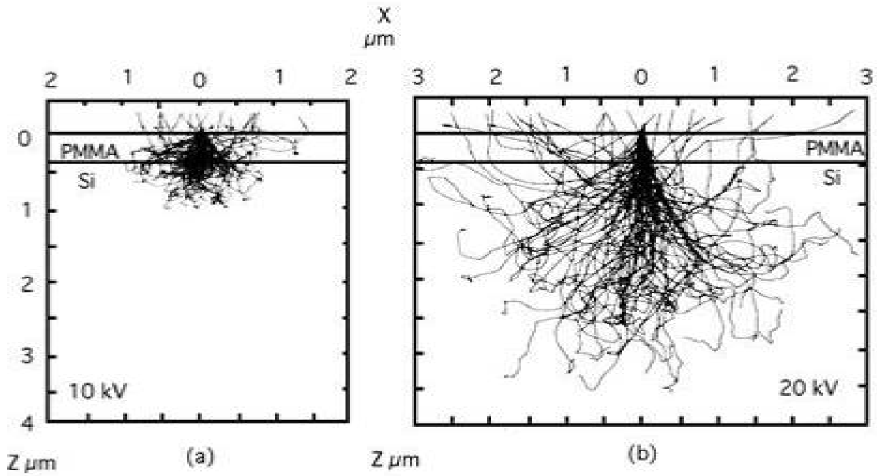


Electron Beam (Ebeam) Lithography

similar to a scanning electron microscope (SEM)



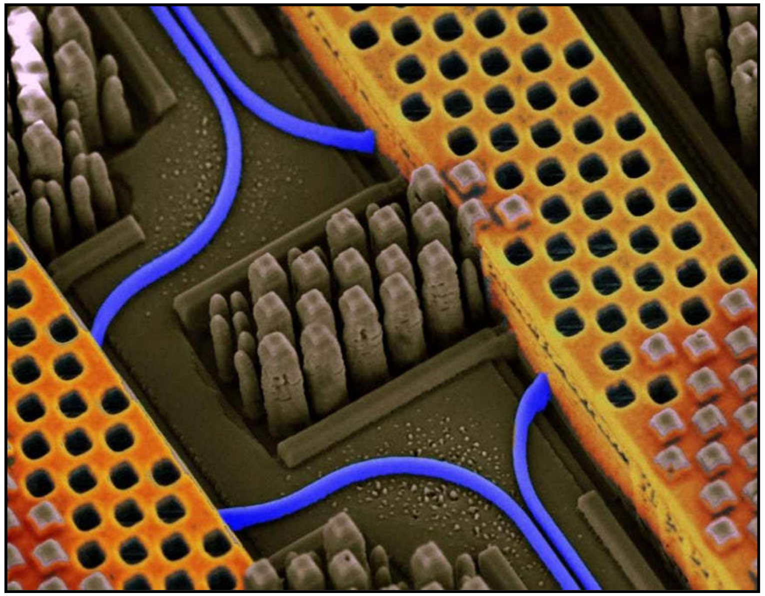
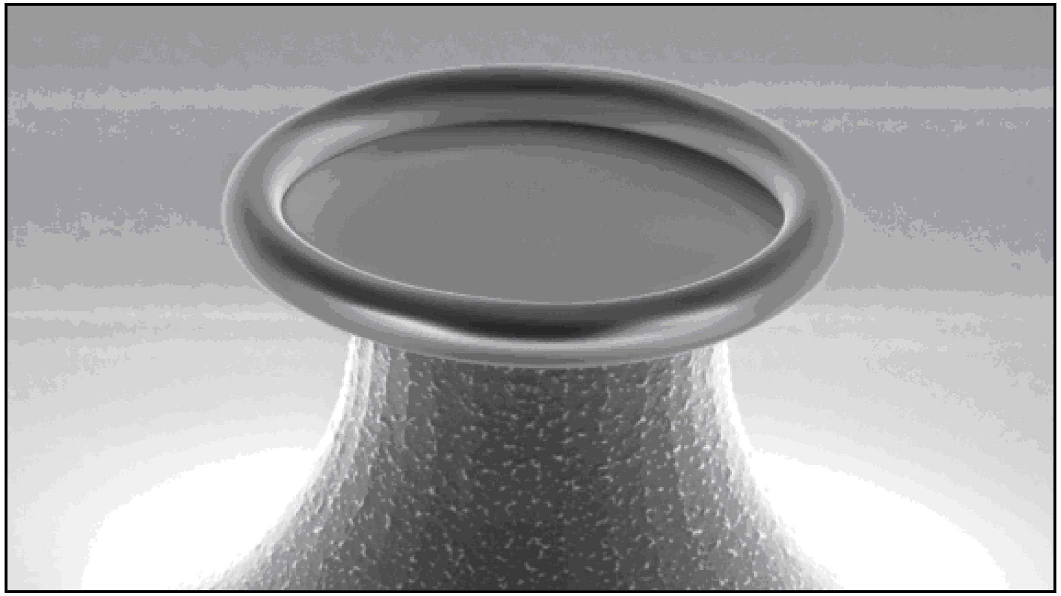
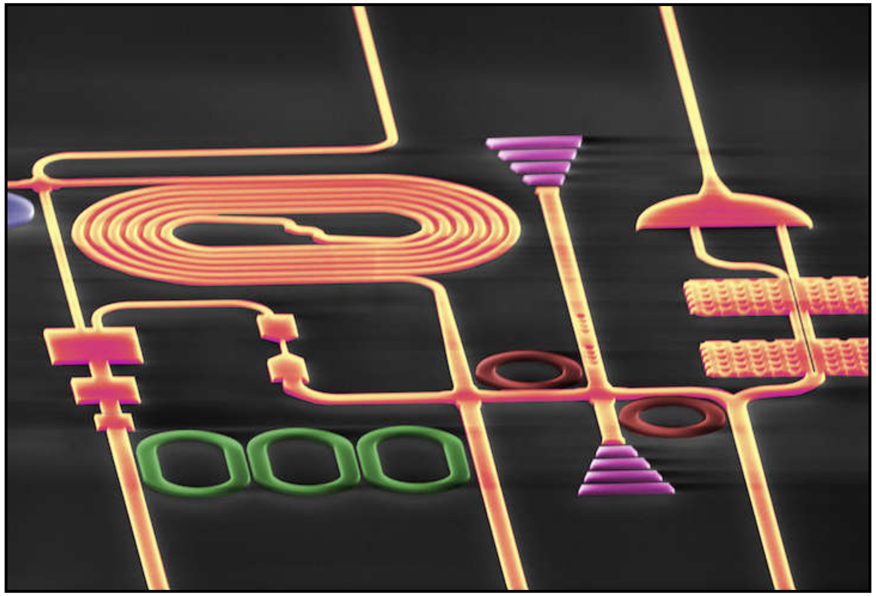
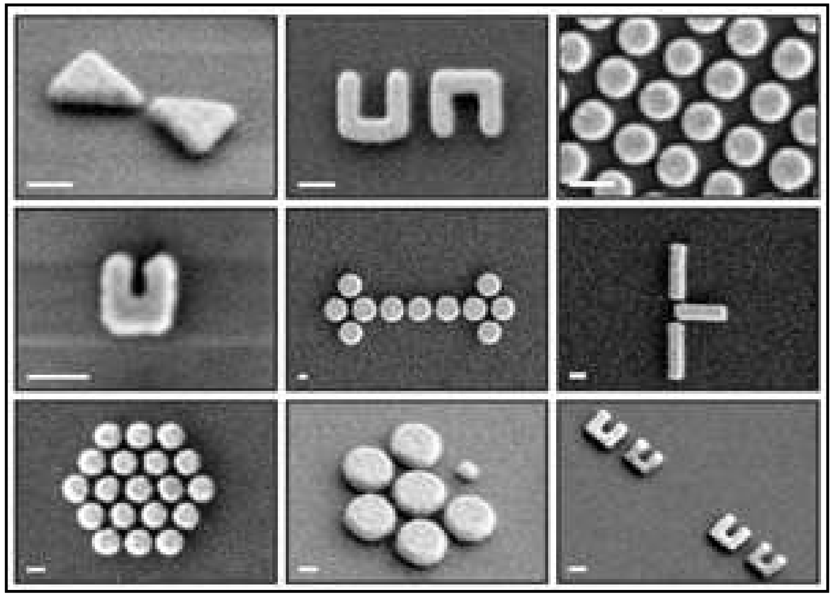
proximity effect



Electron Beam (Ebeam) Lithography

- **Wavelength** $$\lambda(\text{nm}) = \frac{1.23}{\sqrt{V}}$$
  - **example: for V = 30 kV, λ = 0.007 nm**
- **The resolution is limited by secondary electrons**
  - **resolution ~ 10 nm**
- **No mask for electron, only direct writing!**
  - **"*To cover the 700 cm^2 surface area of a 300 mm silicon wafer, the minimum write time would extend to 7*10^8 seconds, about 22 years*." - Wikipedia**
- **Only for research purposes now**

NanoPhotonics

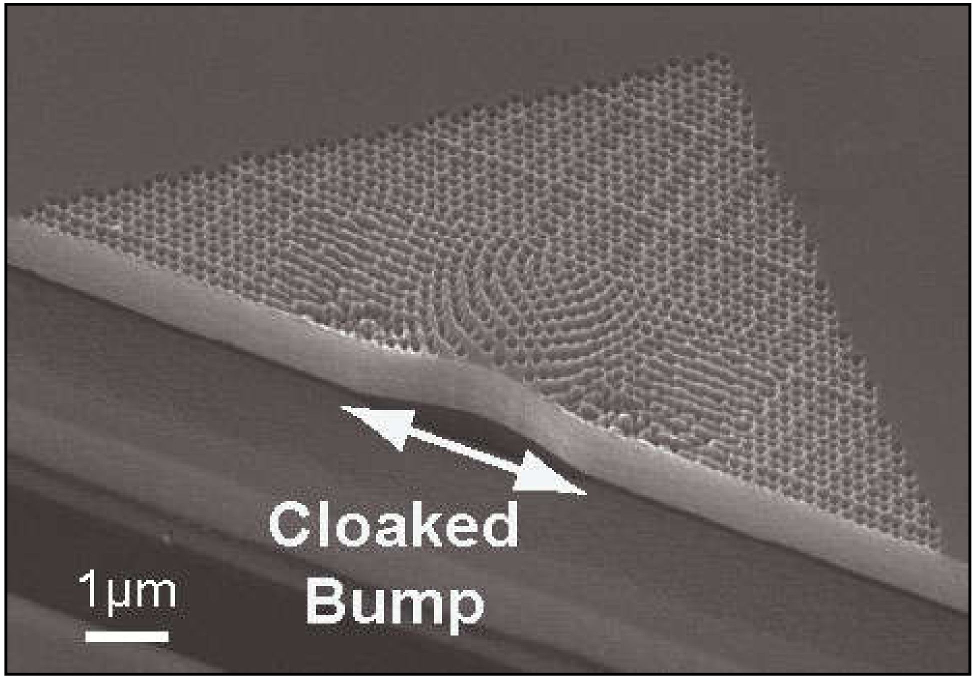





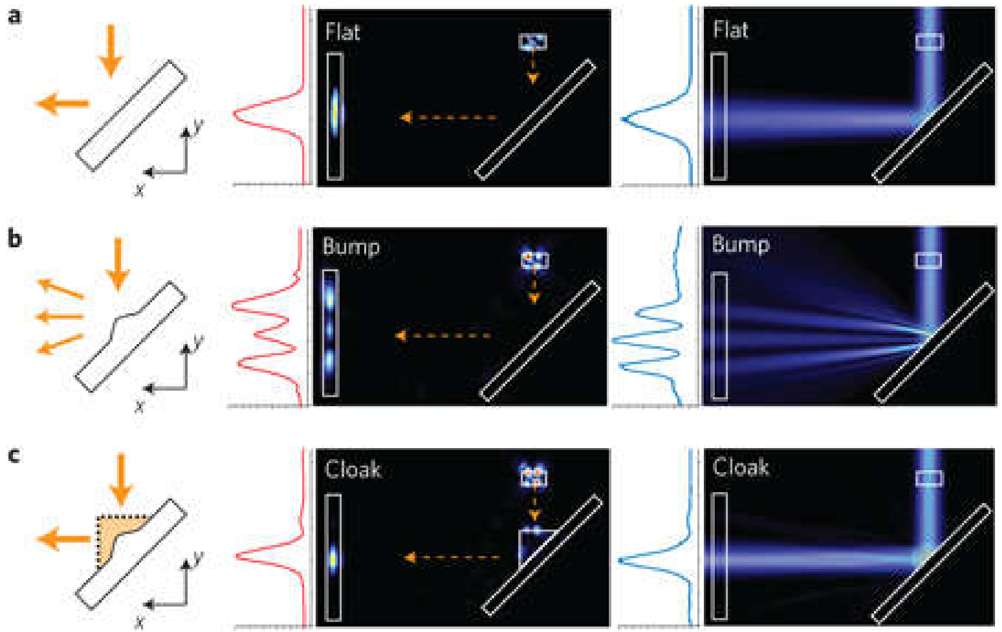
Optical Cloak

LETTERS
PUBLISHED ONLINE: 29 APRIL 2009 | DOI: 10.1038/NMAT2461
nature materials

An optical cloak made of dielectrics

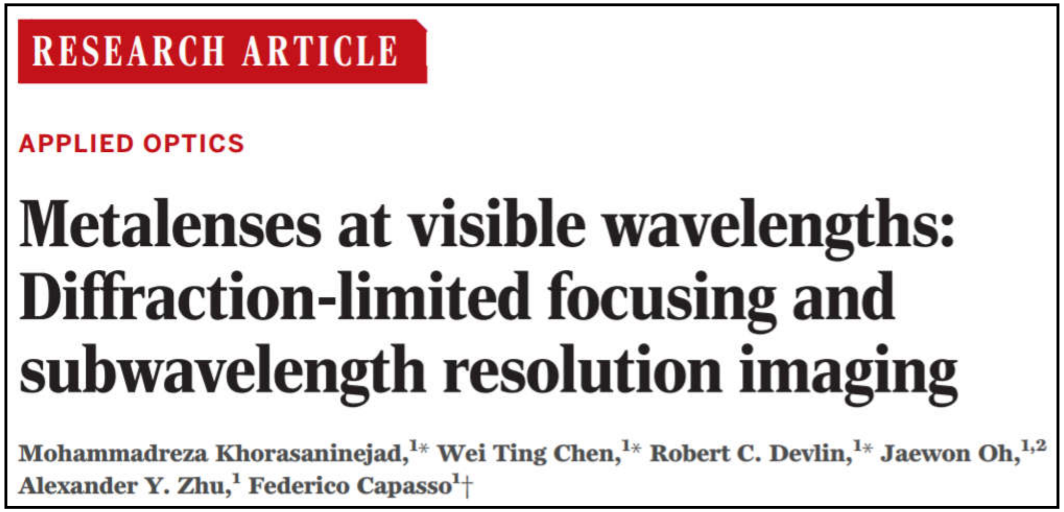
Jason Valentine[1]*, Jensen Li[1]*, Thomas Zentgraf[1]*, Guy Bartal[1] and Xiang Zhang[1,2]†





J. Valentine, *et al.*, *Nature Mater.* **8,** 568 (2008)

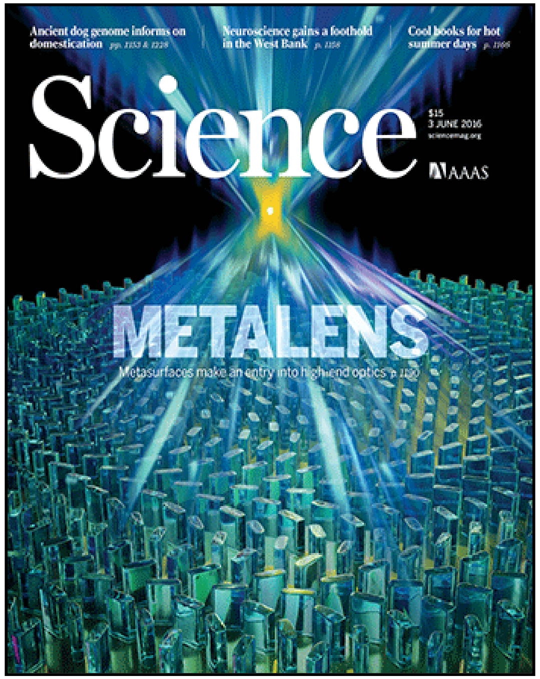
Metalens

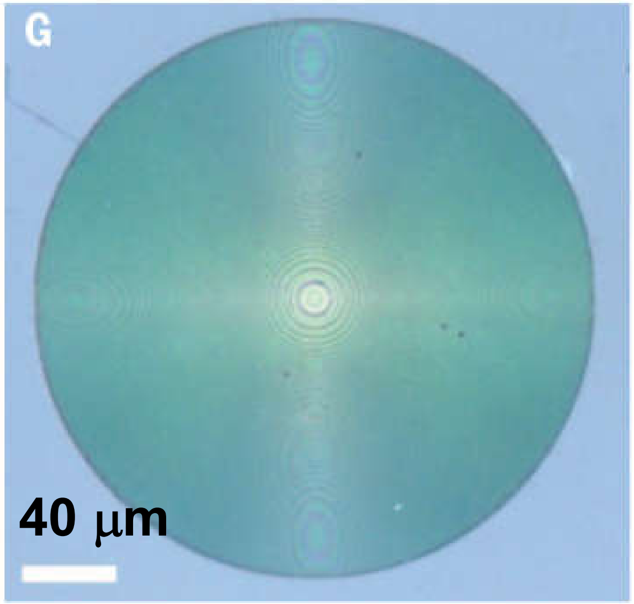

RESEARCH ARTICLE

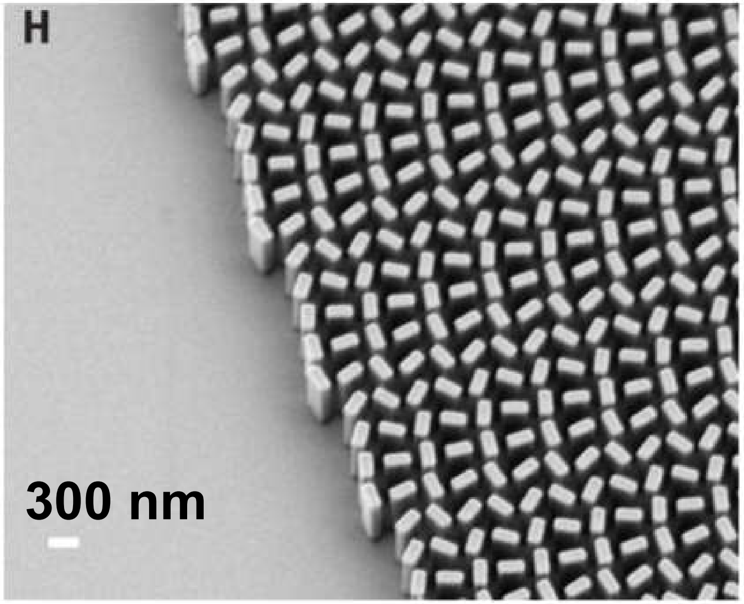
APPLIED OPTICS

Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging

Mohammadreza Khorasaninejad,[1]* Wei Ting Chen,[1]* Robert C. Devlin,[1]* Jaewon Oh,[1,2] Alexander Y. Zhu,[1] Federico Capasso[1]†







M. Khorasaninejad, *et al.*, *Science* **352,** 1190 (2016)

Thank you for your attention