Principles of Micro- and Nanofabrication for Electronic and Photonic Devices

Photolithography 光刻
Part I: Optics

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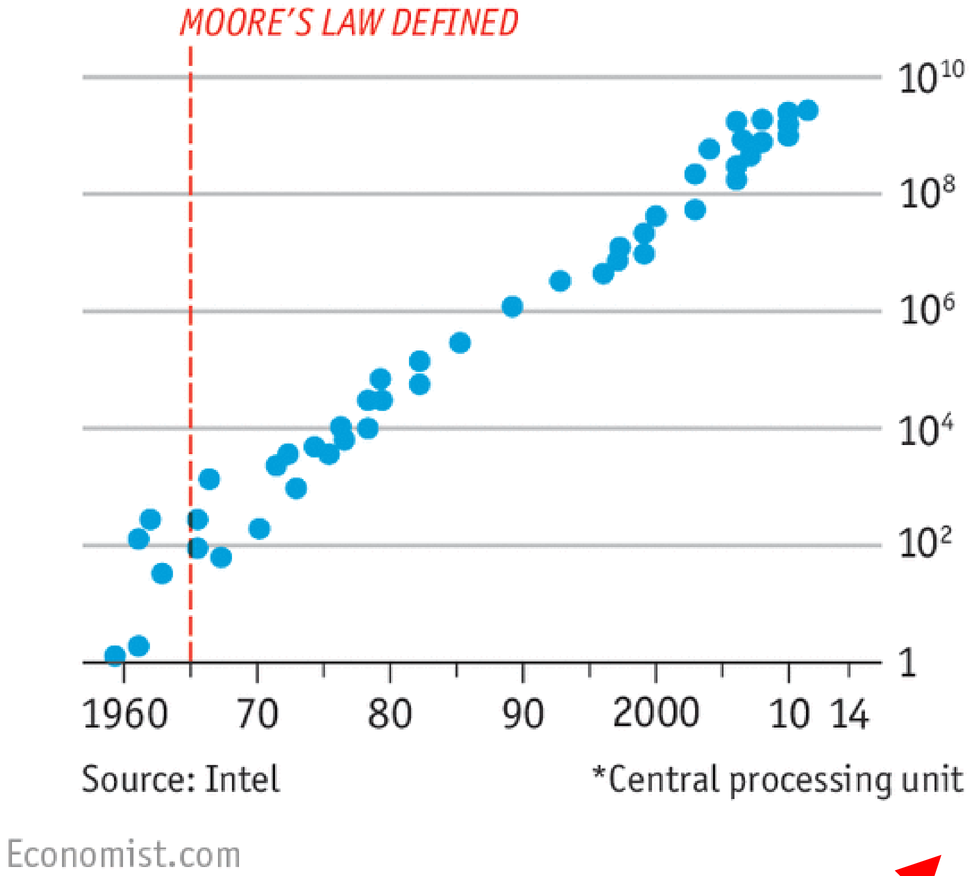
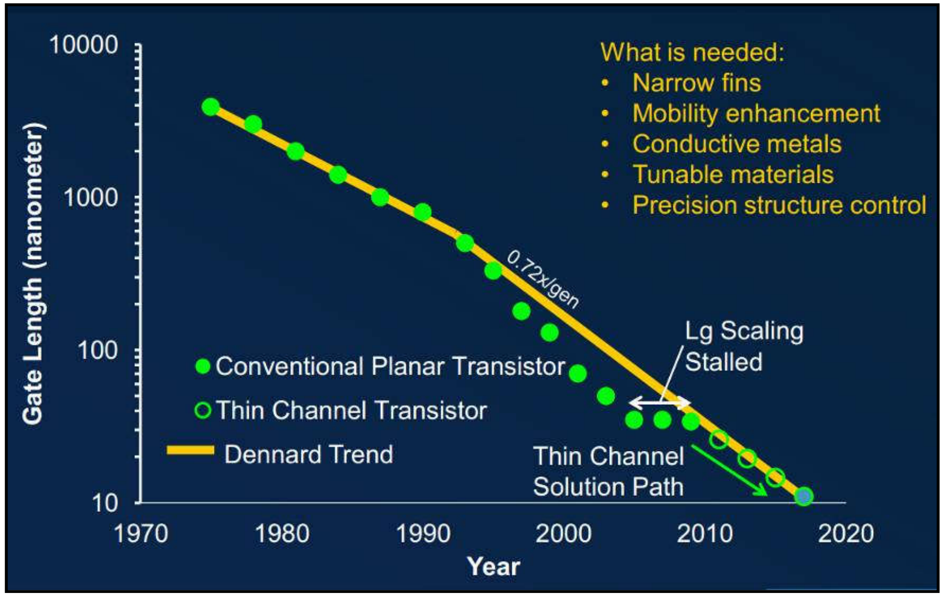
Integrate Circuits

- **Moore's law**

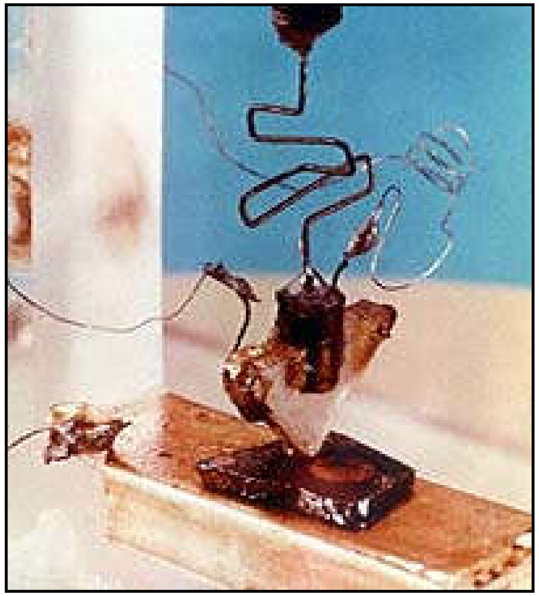
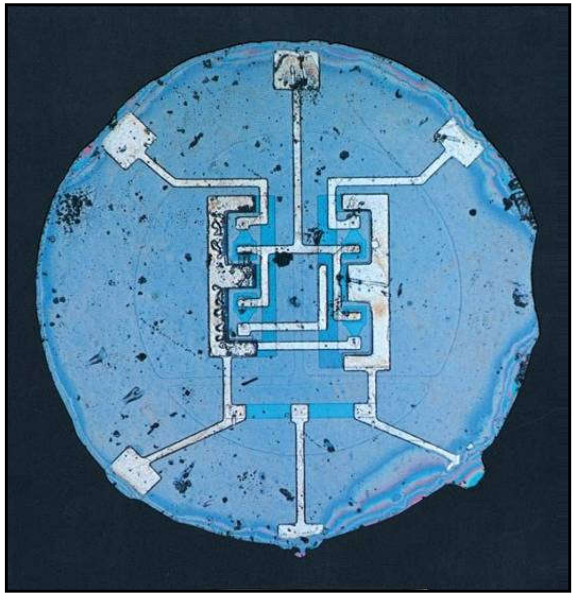
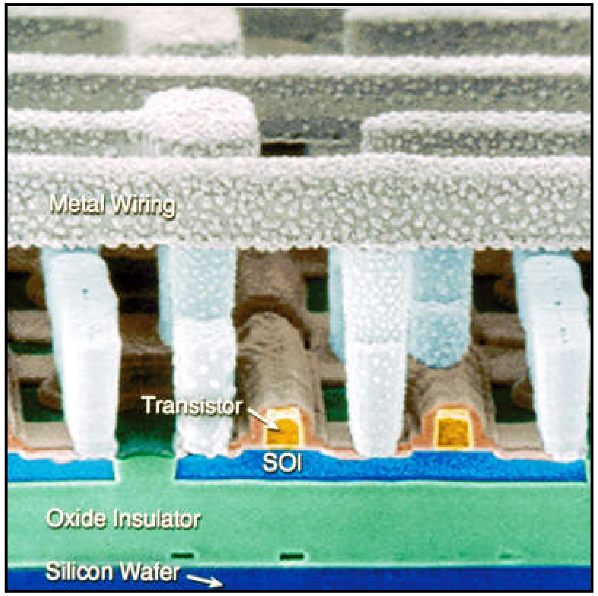




transistor number

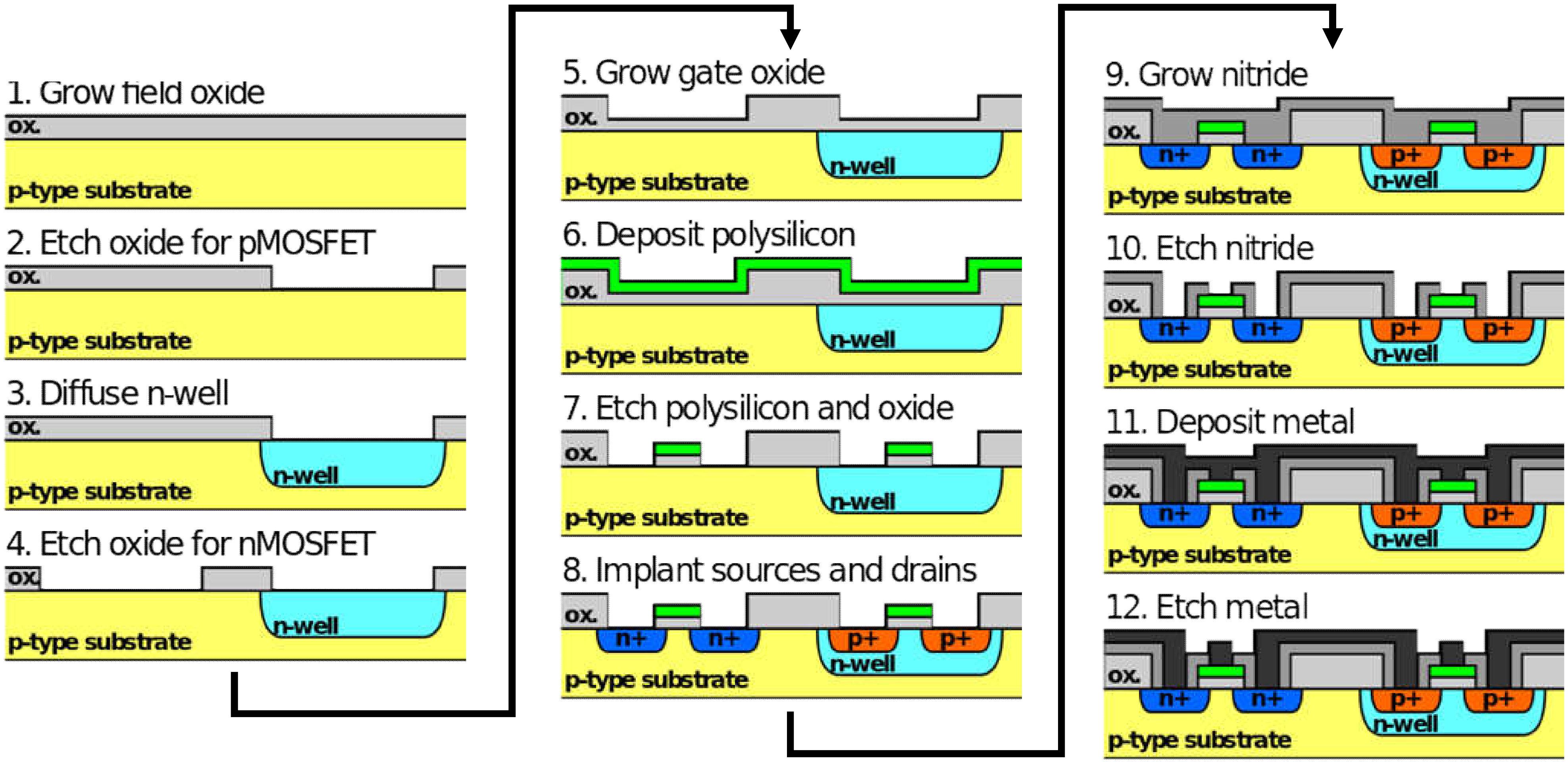
transistor size

Transistor Size

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

revolution → *evolution*

CMOS Process



'Lithography is the cornerstone of modern IC technology'

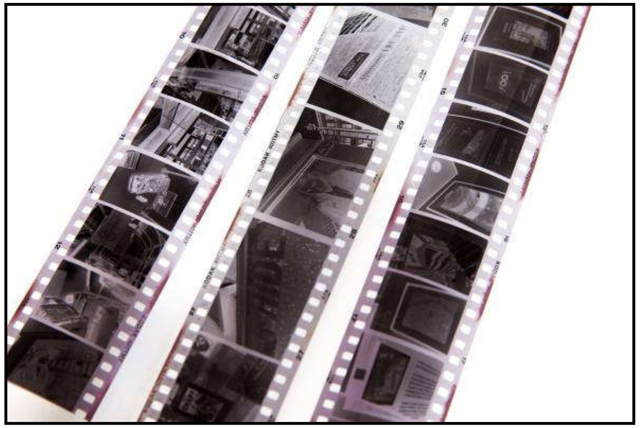
---- Silicon VLSI, Plummer et al.,

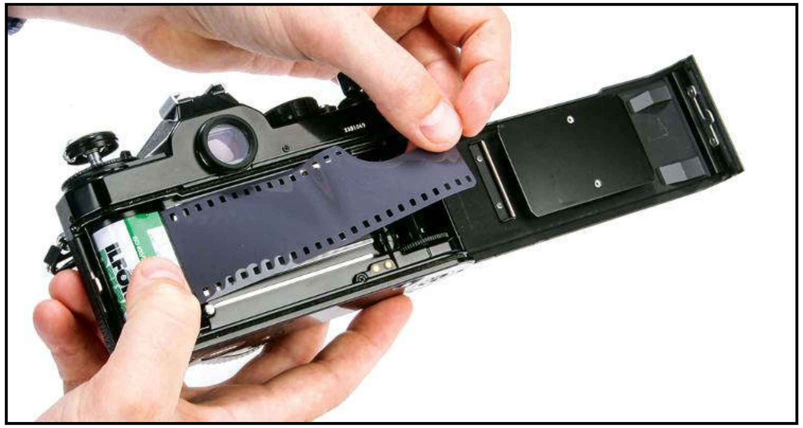
Lithography

litho-　石头
-graph 图案

石版画

Photography

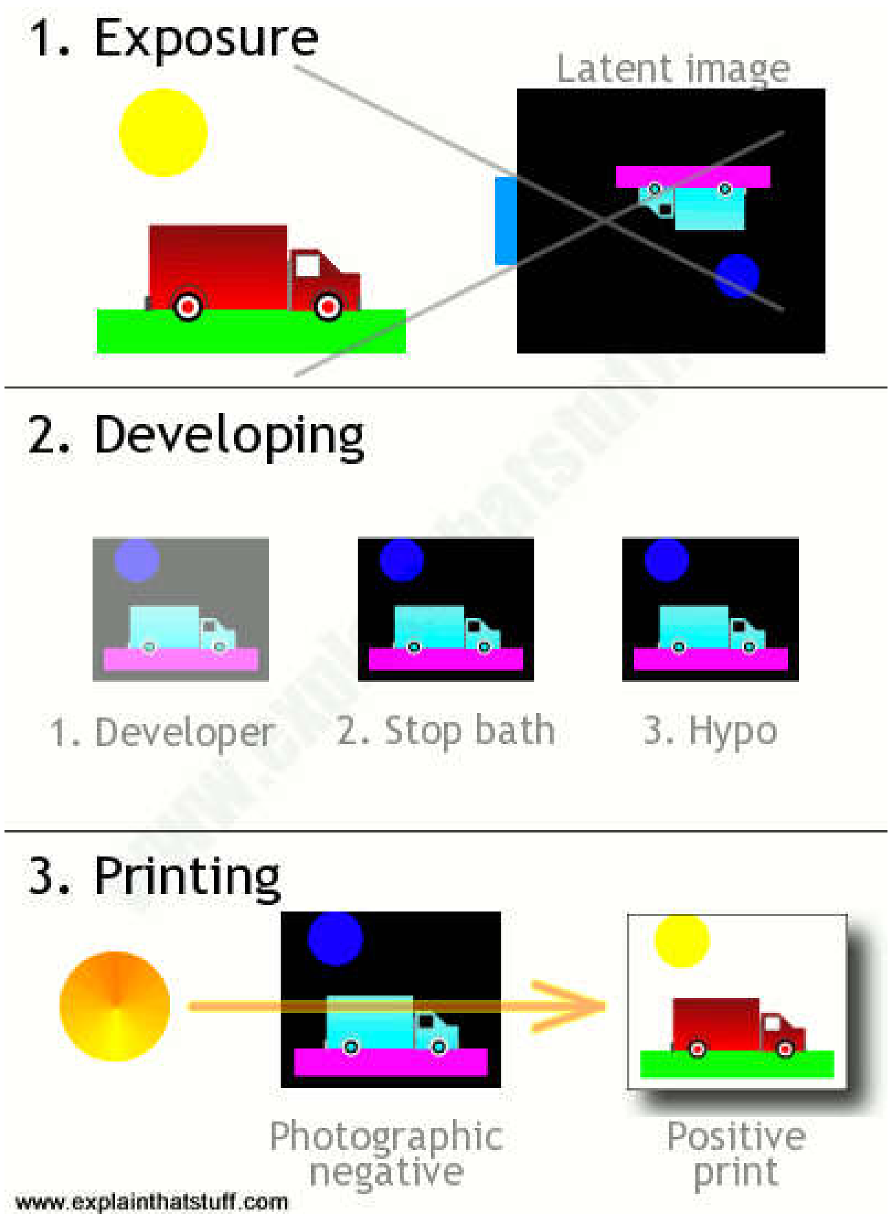




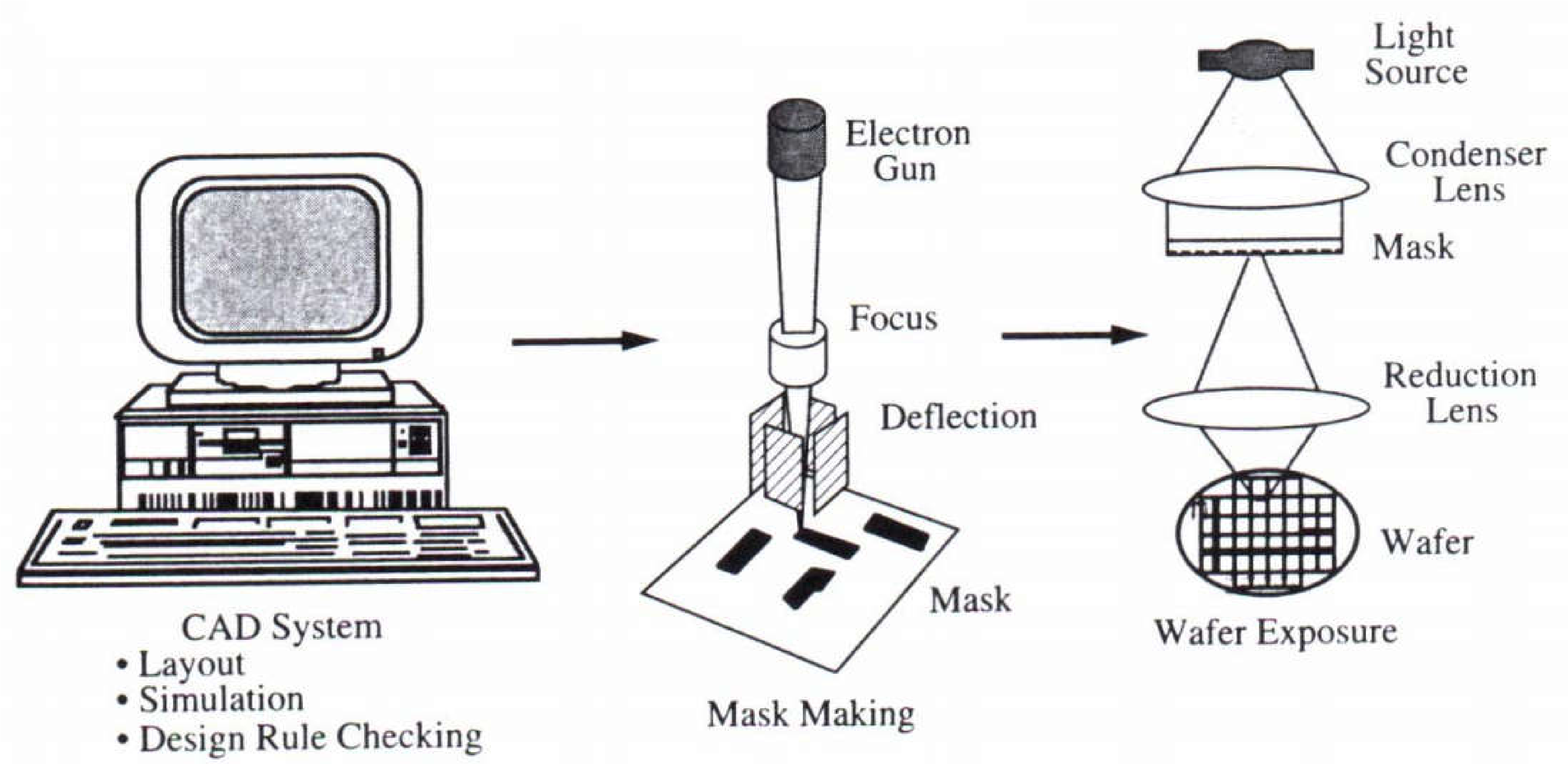
曝光

显影

打印



Photolithography（光刻）

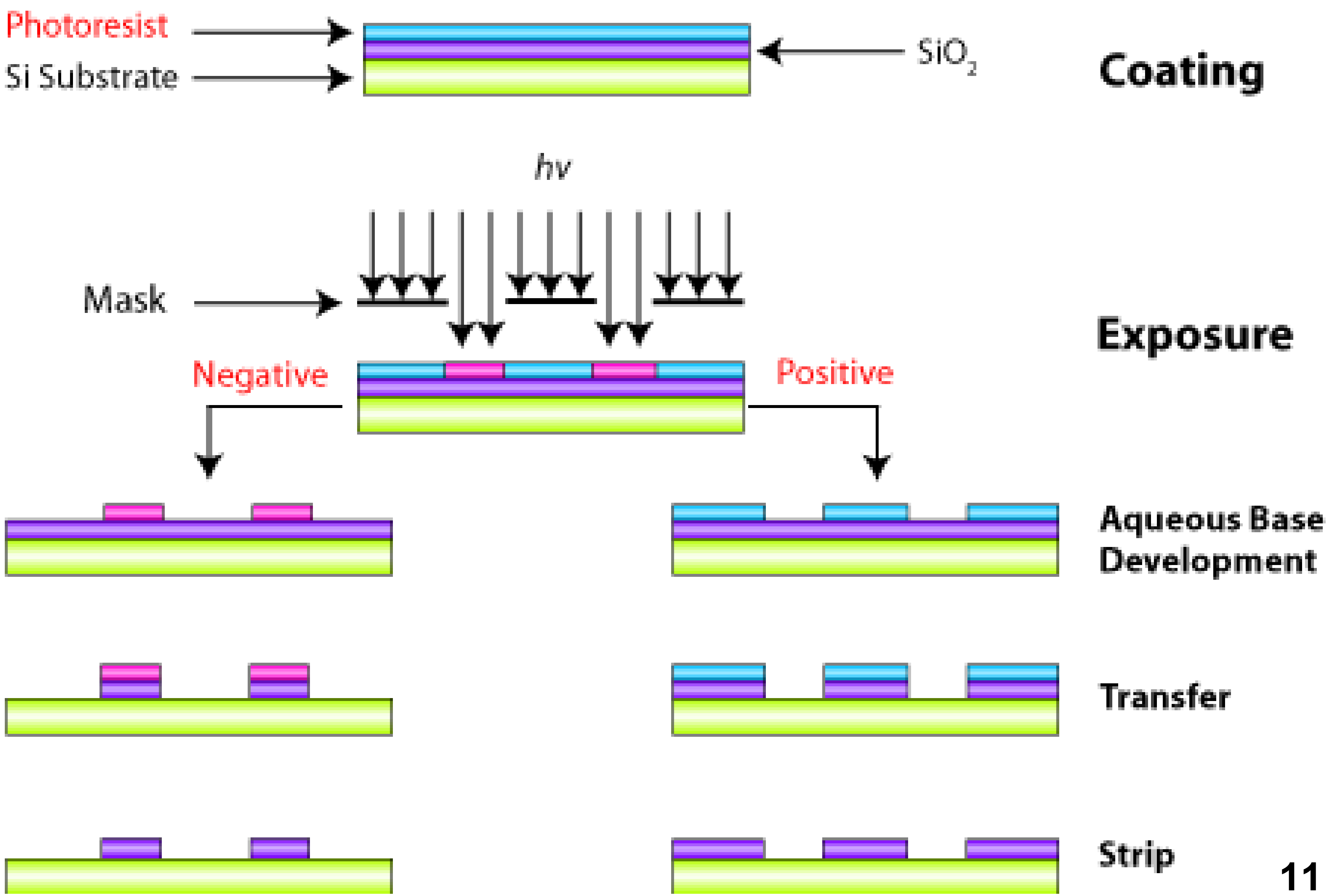


Photolithography（光刻） Video

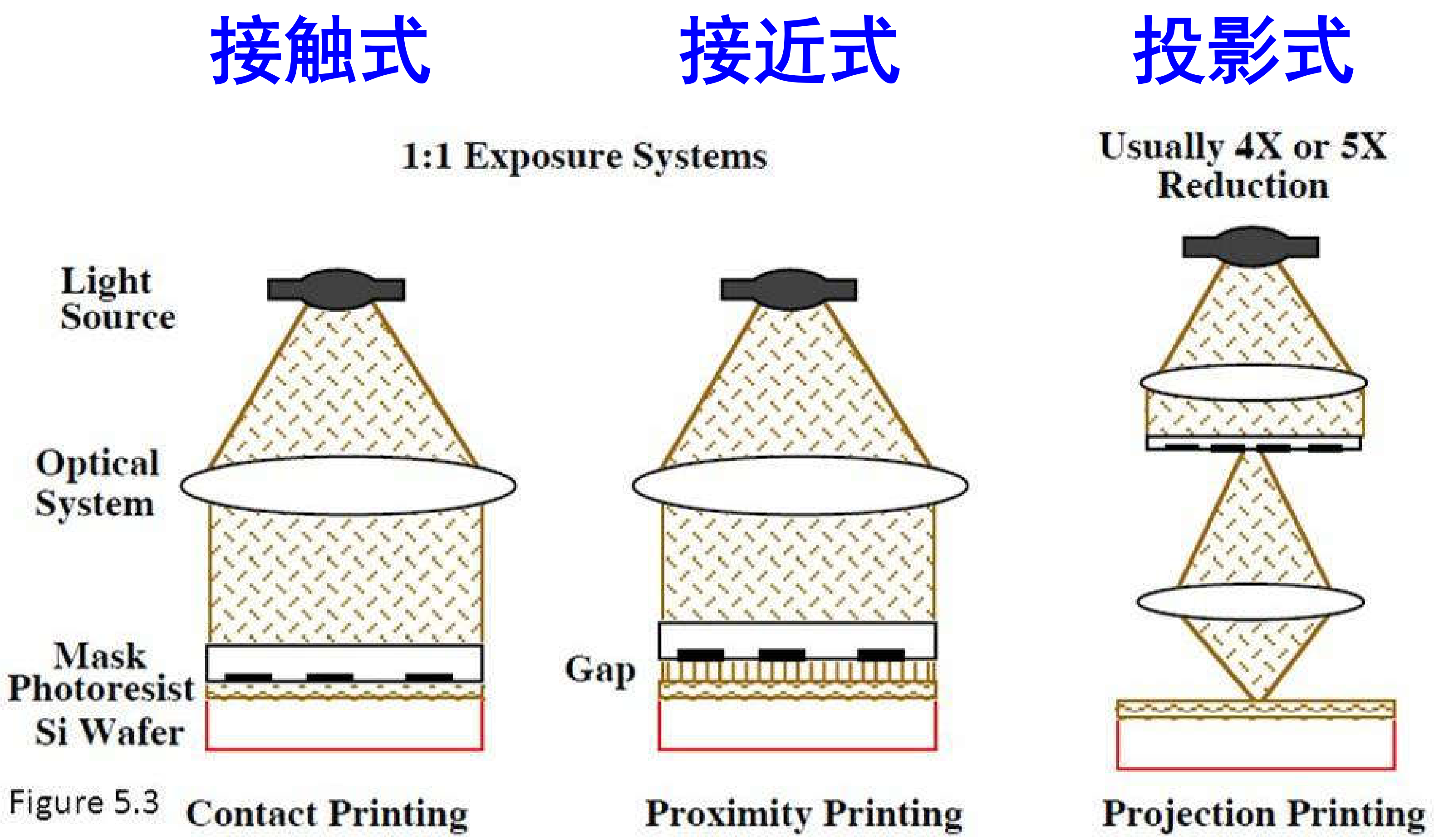
光刻胶

光源

掩膜



Exposure (曝光)



High resolution. But mask wear, defect generation.

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

No mask wear/contamination, mask de-magnified 4× (resist features 4× smaller than mask).

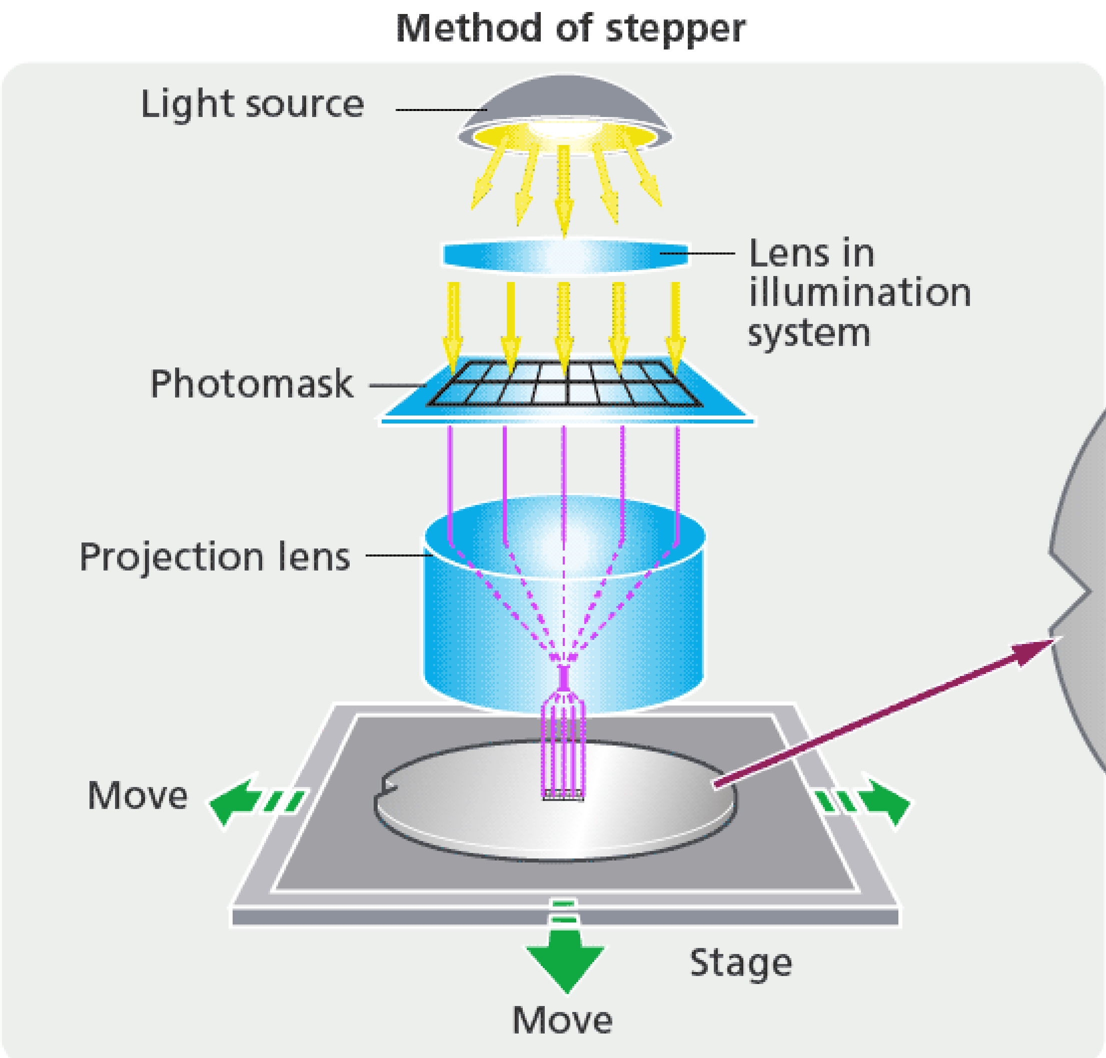
Fast, simple and inexpensive, choice for R&D.

Very expensive, mainly used for IC industry.

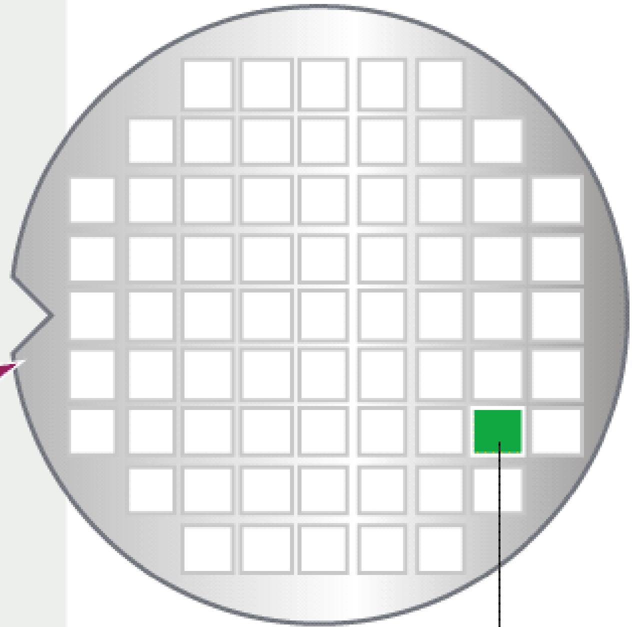
Exposure (曝光)

stepper (步进投影)

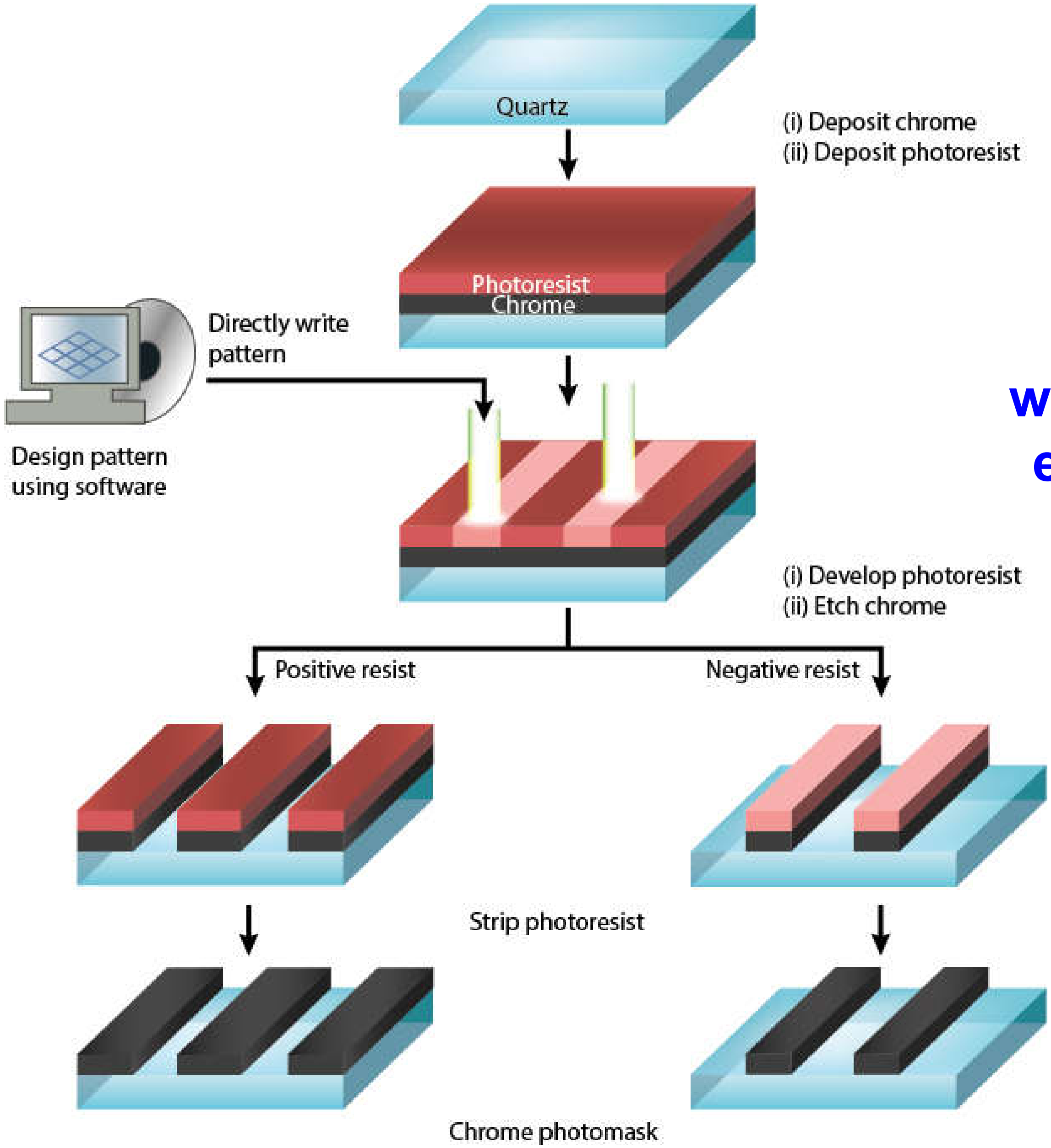
Video



mass chip production in industry

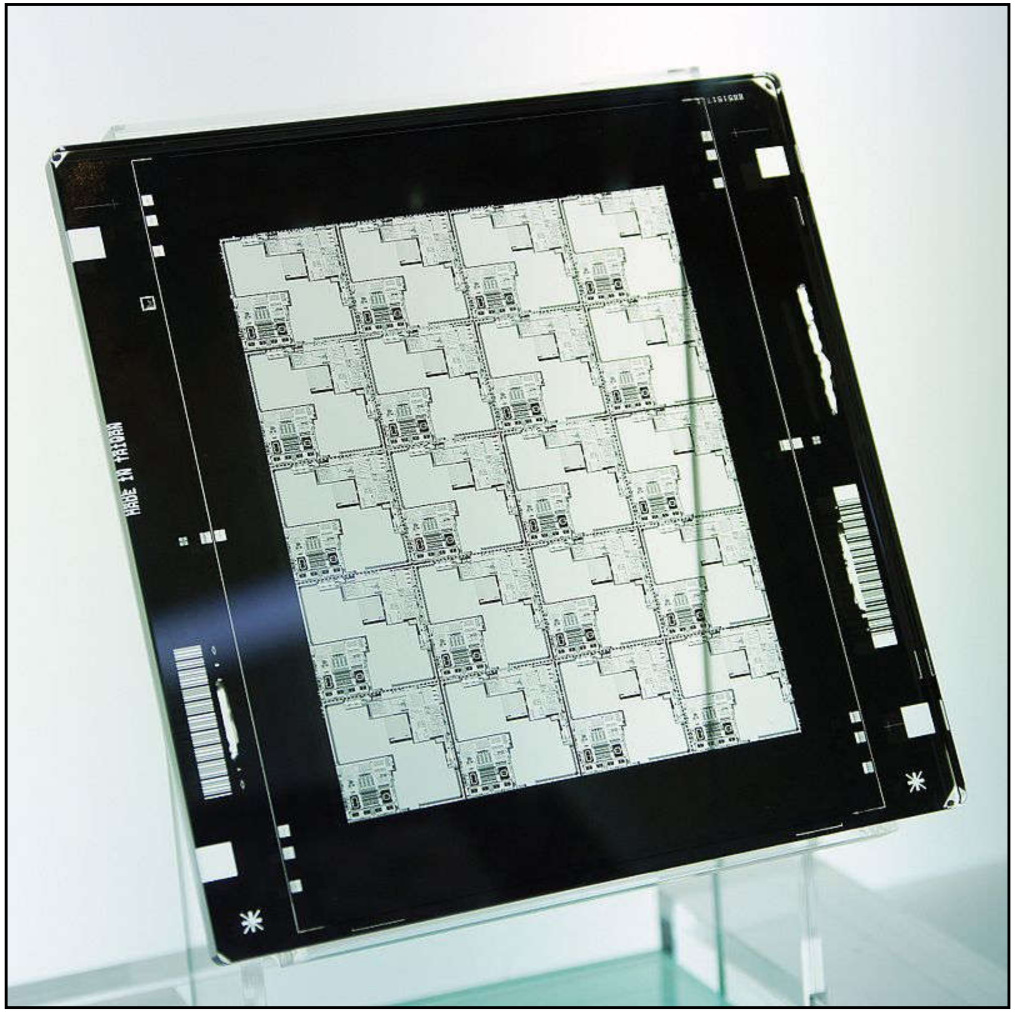


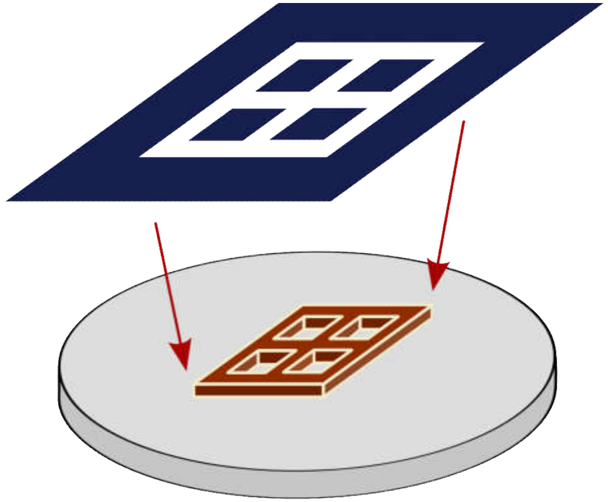
Photomasks (掩膜)

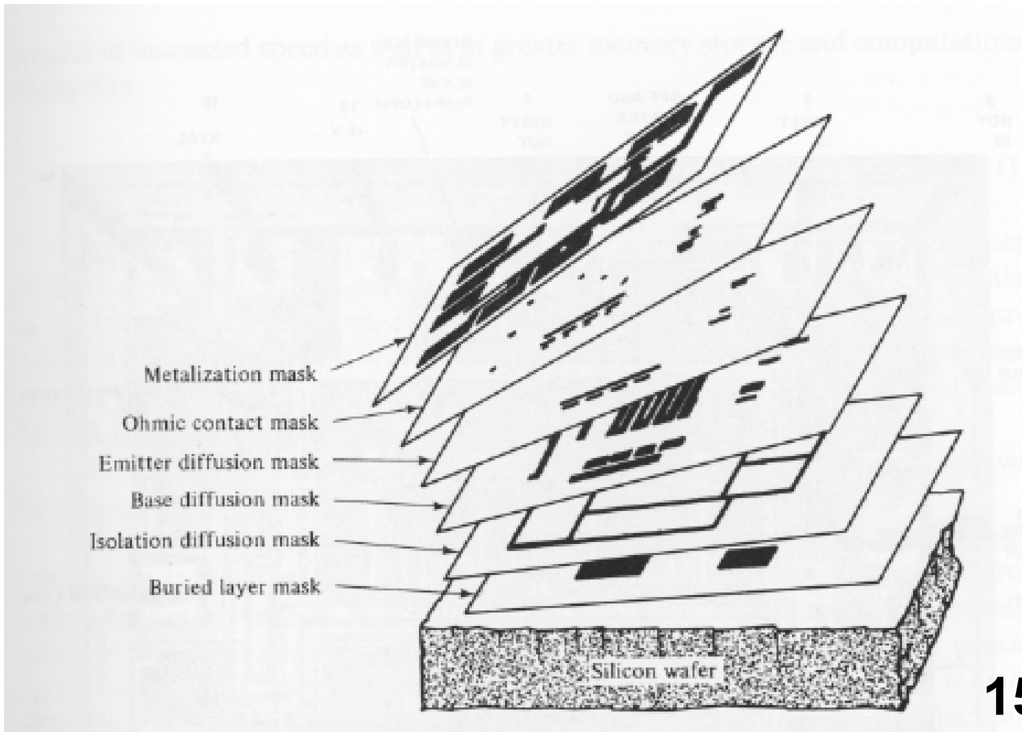


write by laser or electron beam

Photomasks (掩膜)



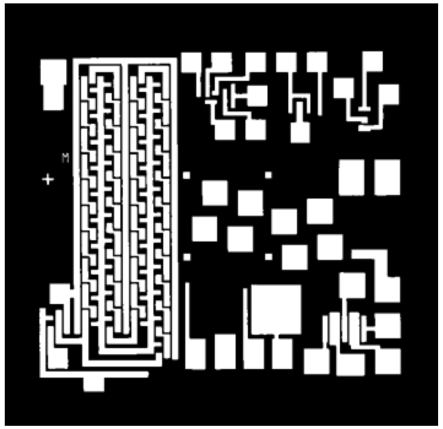




Photomasks (掩膜)

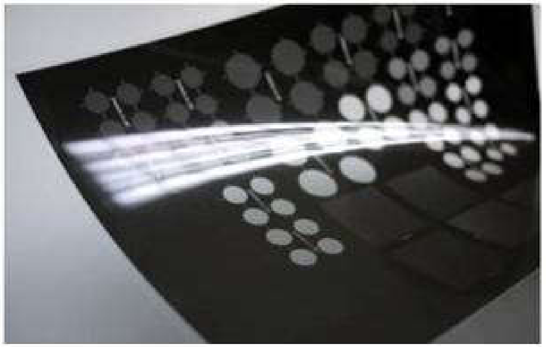
- Layout design
  - CAD tools
  - see examples

Example

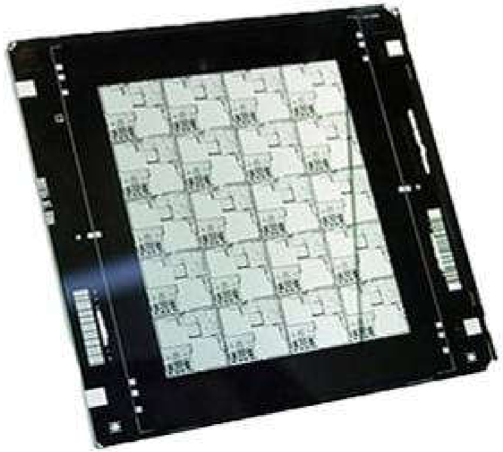


design layout

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

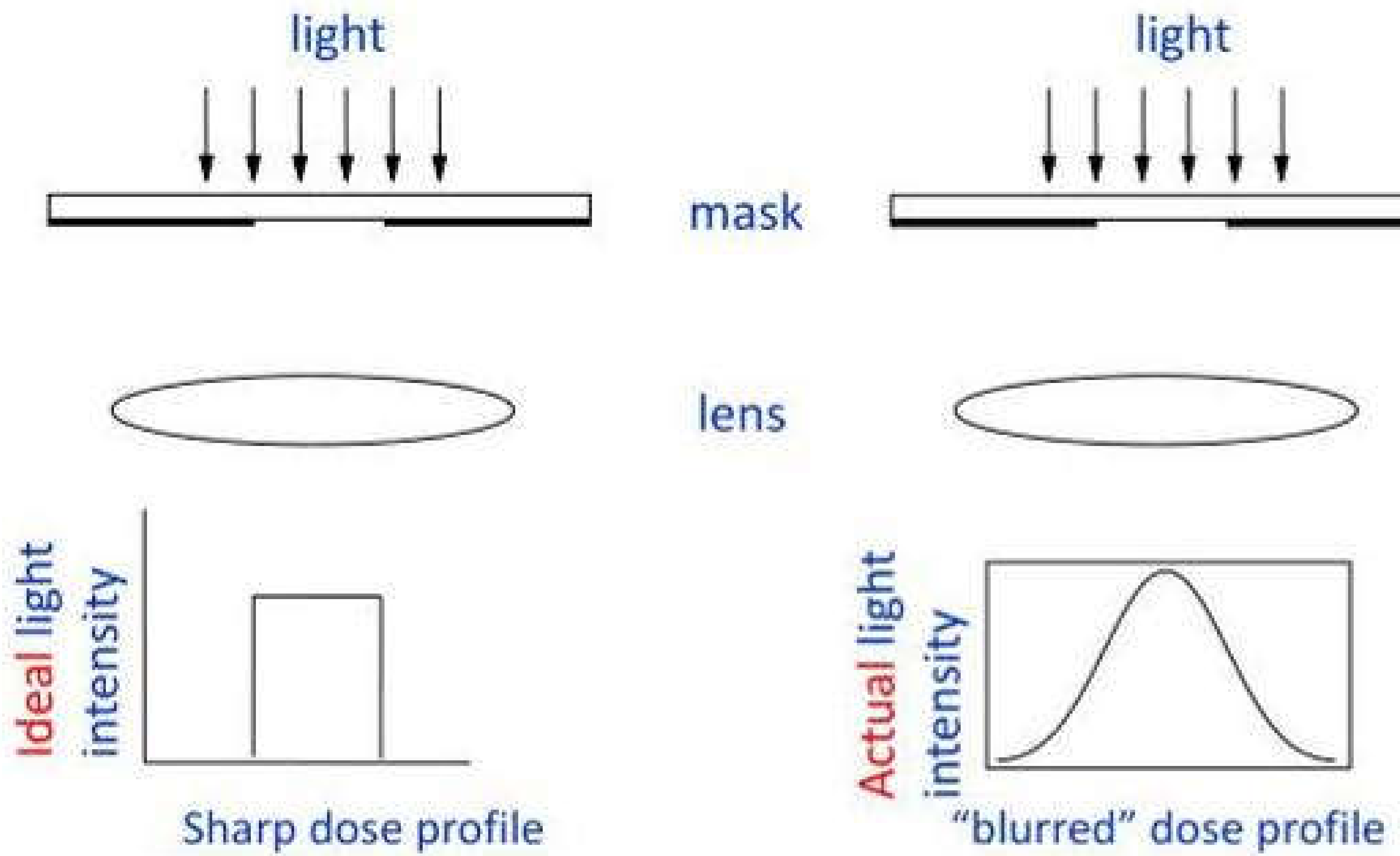


transparency film



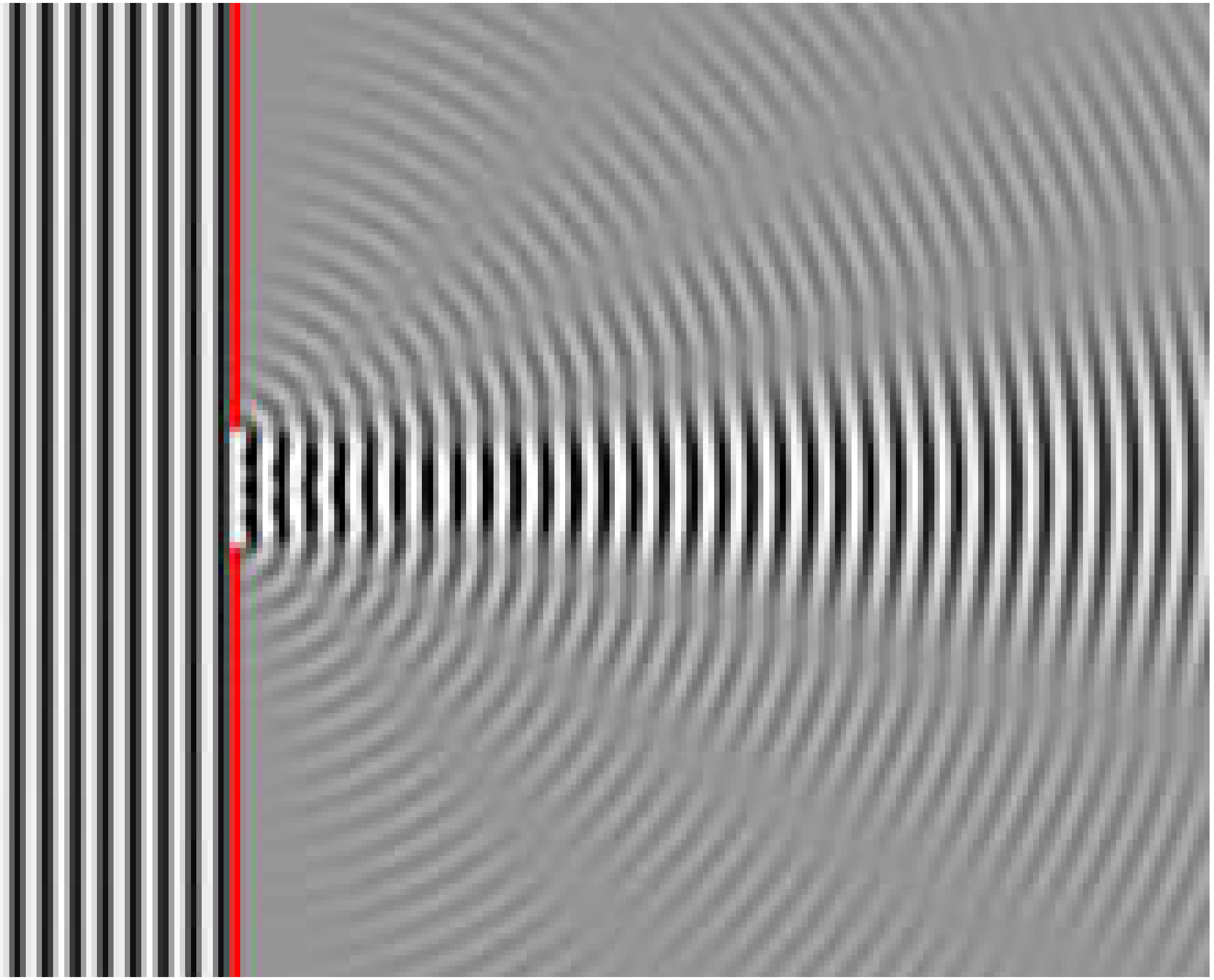
chrome mask

Resolution



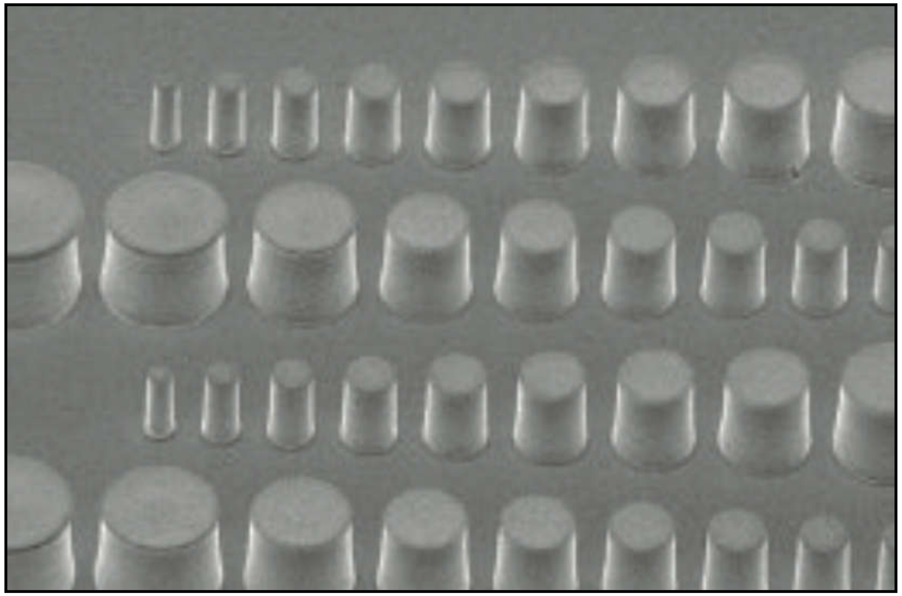
ideal case **actual case**

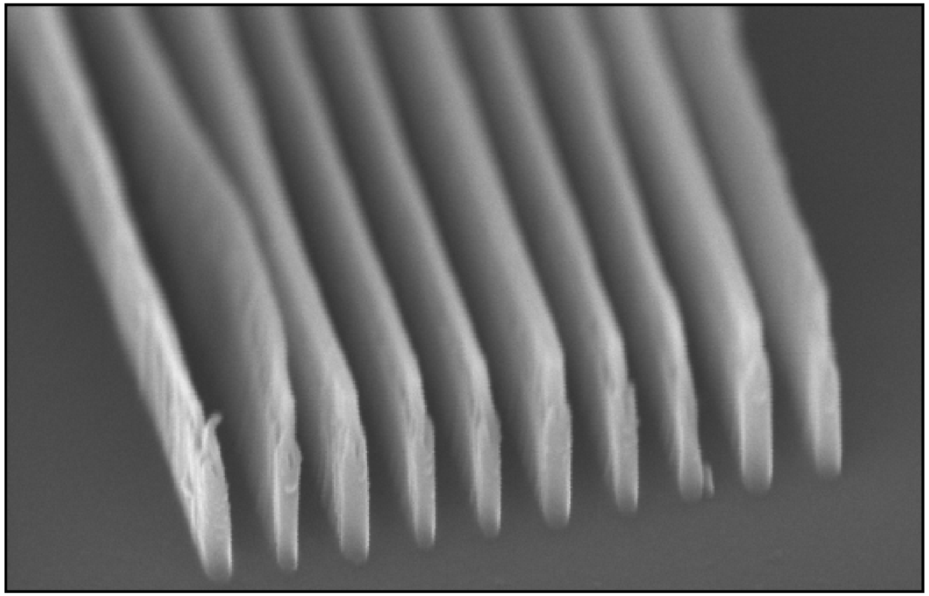
Resolution



diffraction: light is a wave!

Resolution

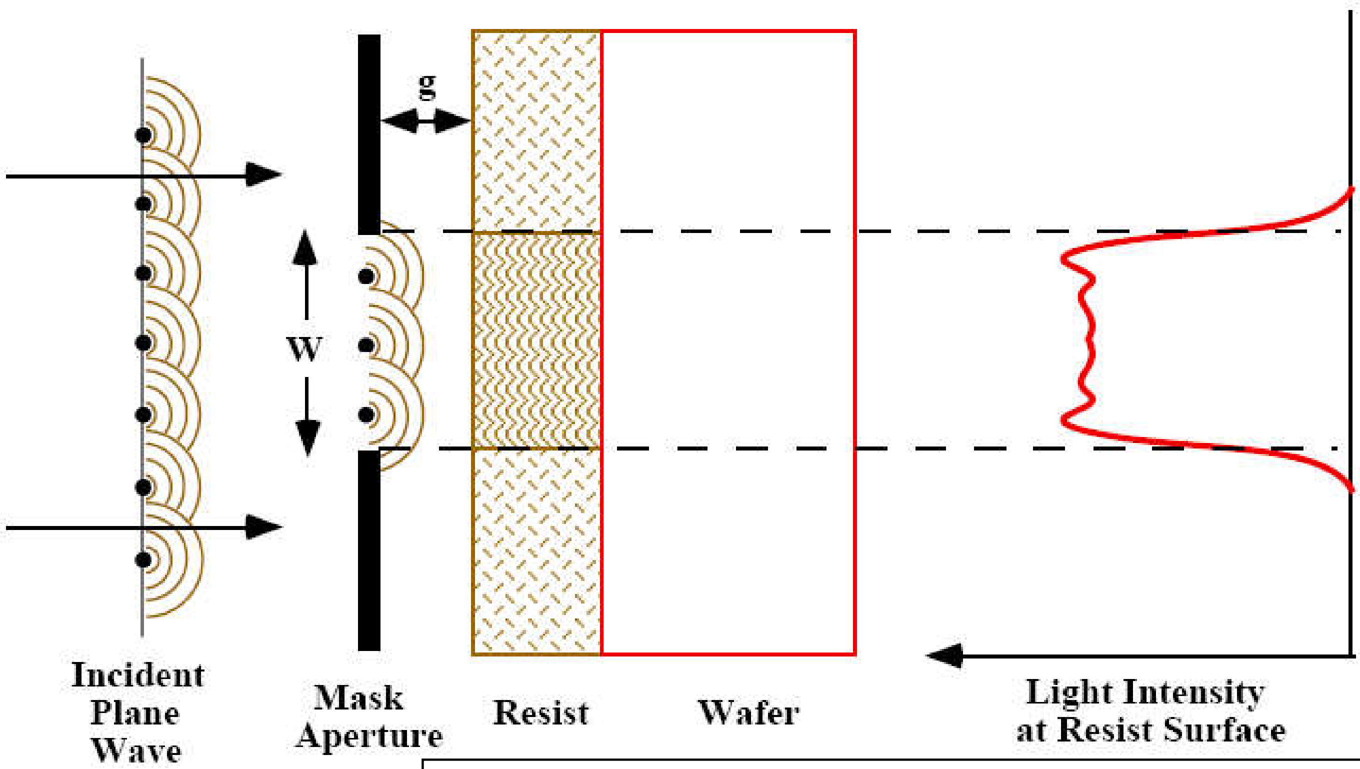




the smaller, the harder

Resolution

contact and proximity mode



R resolution

λ wavelength

g gap size

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

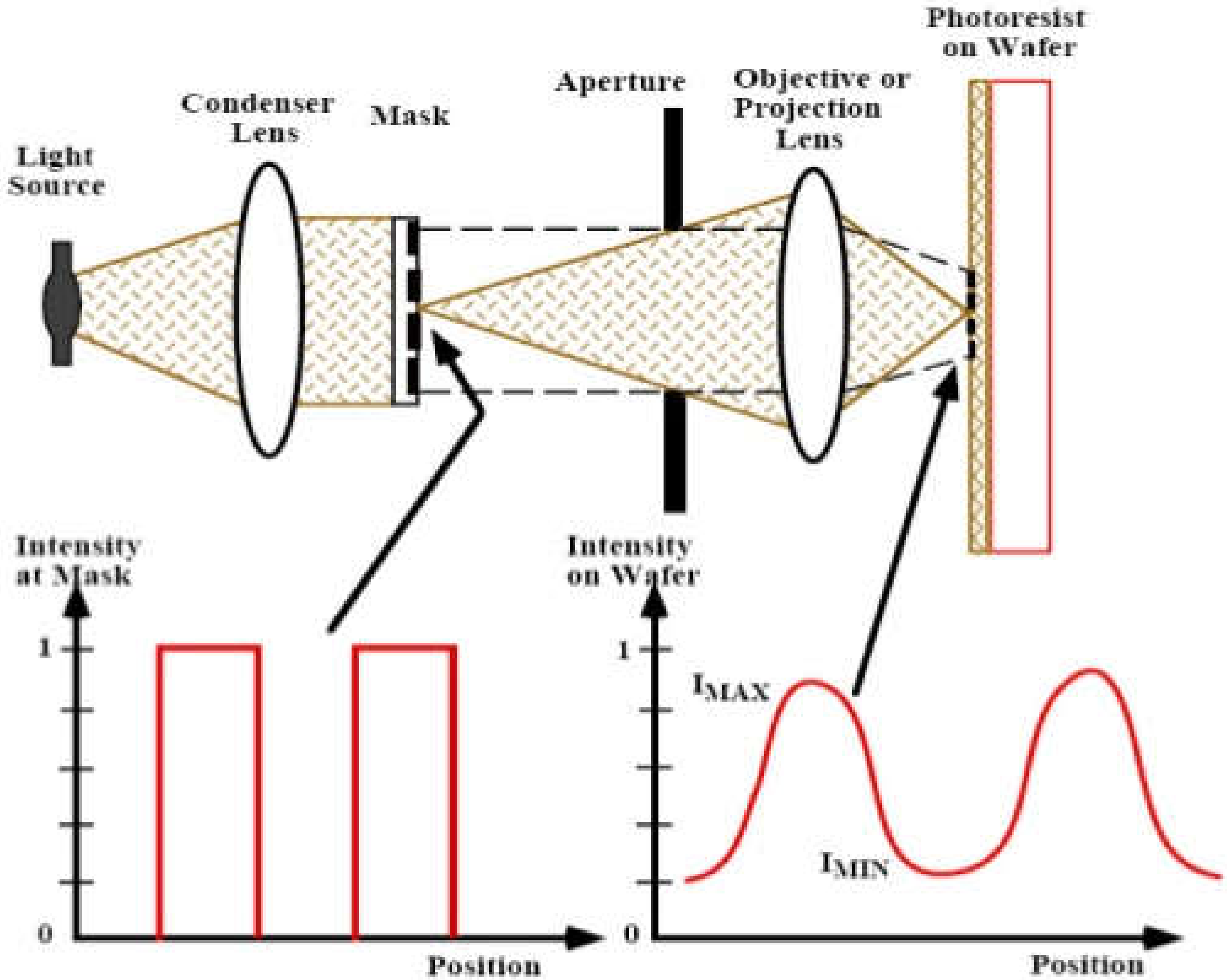
smaller *λ*, *g* ---> smaller *R*

λ UV, DUV, EUV, x-ray, ...

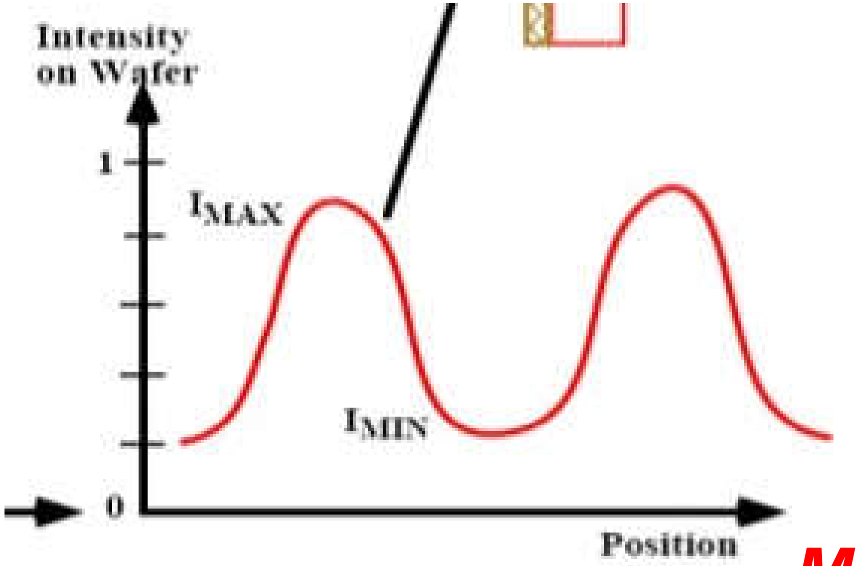
g minimum: resist film thickness

Resolution

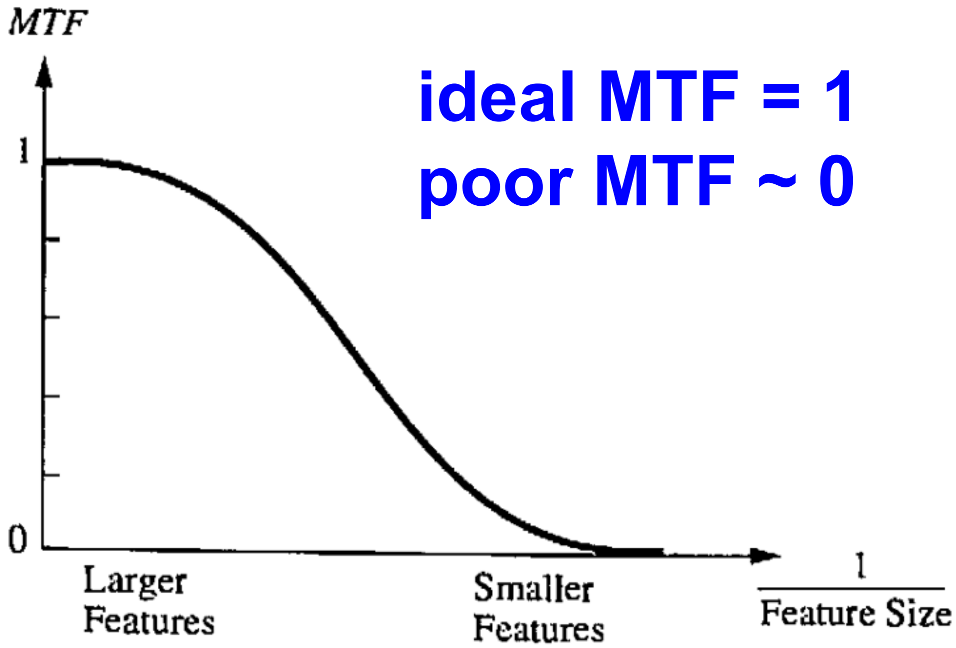
projection mode



Resolution



MTF = ?



ideal MTF = 1
poor MTF ~ 0

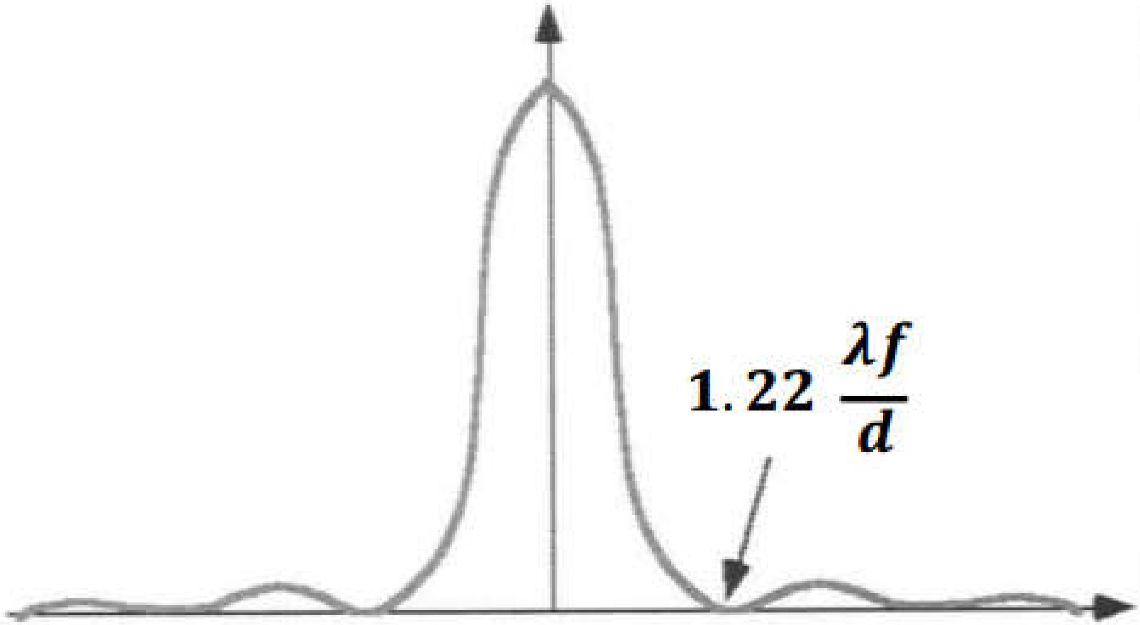
modulation transfer function (MTF)

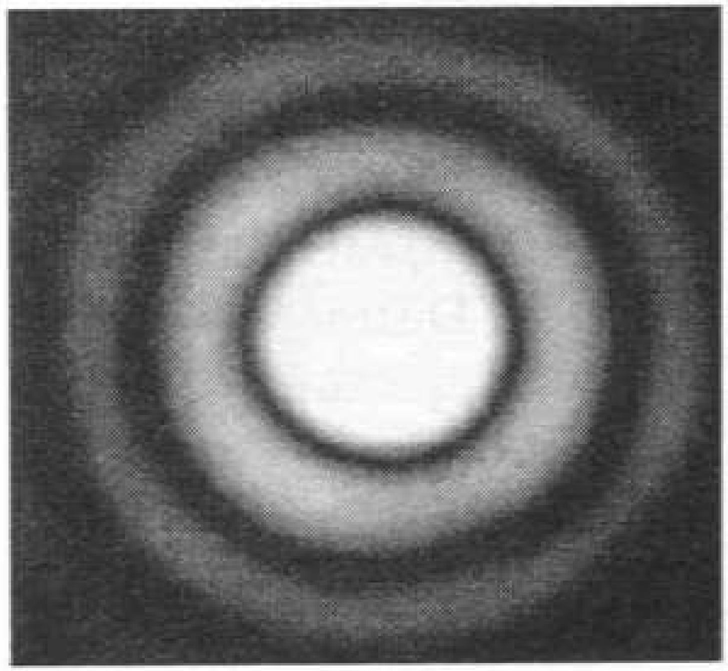
$$MTF = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Resolution

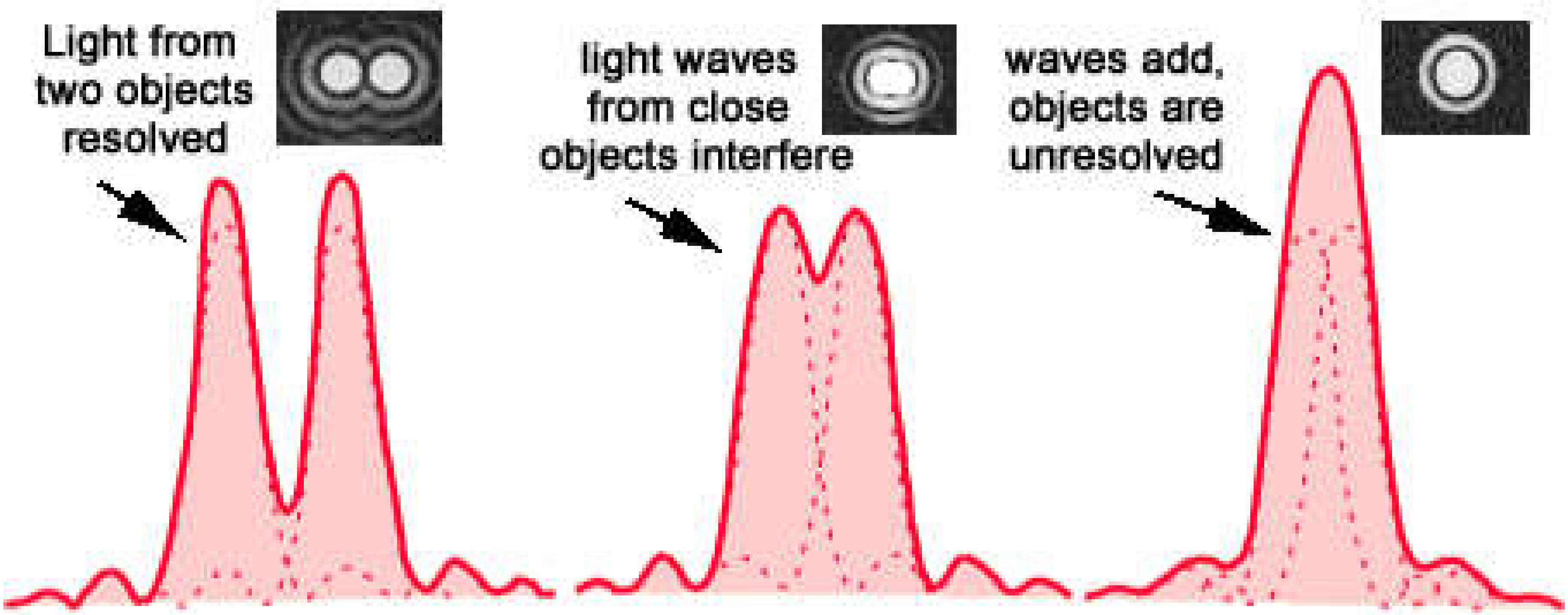
diffraction pattern (Airy's disk)

f = focal distance
d = lens diameter





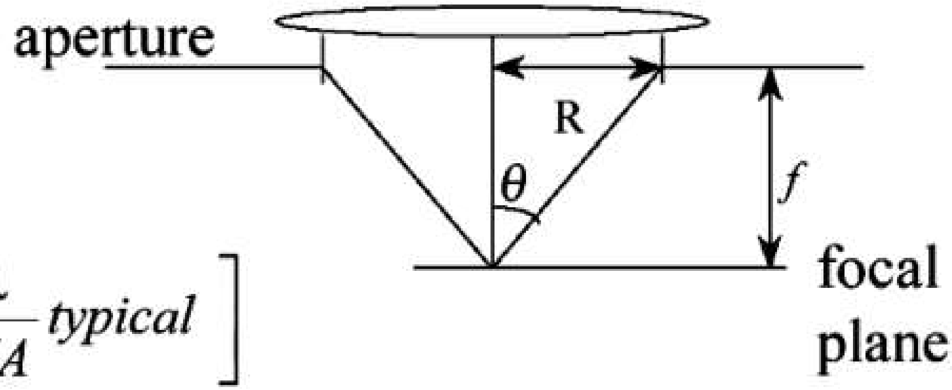
Resolution



Rayleigh Criterion:

the first diffraction minimum of one source coincides with the maximum of another

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

$$\boxed{R \sim 0.6 \cdot \frac{\lambda}{n \sin\theta}}$$

smaller λ, larger NA ---> smaller resolution

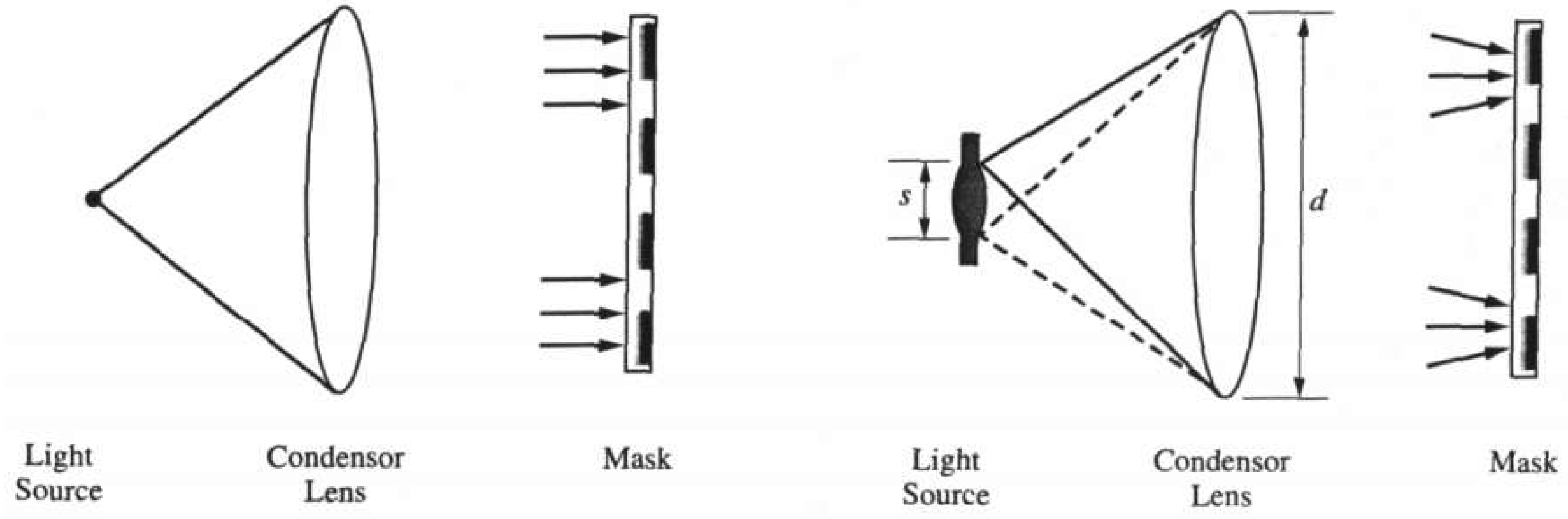
λ	**UV, DUV, EUV, x-ray, ...**
n	**refractive index (air: 1, oil: 1.4~1.7)**
$\sin\theta$	**maximum = 1.0**

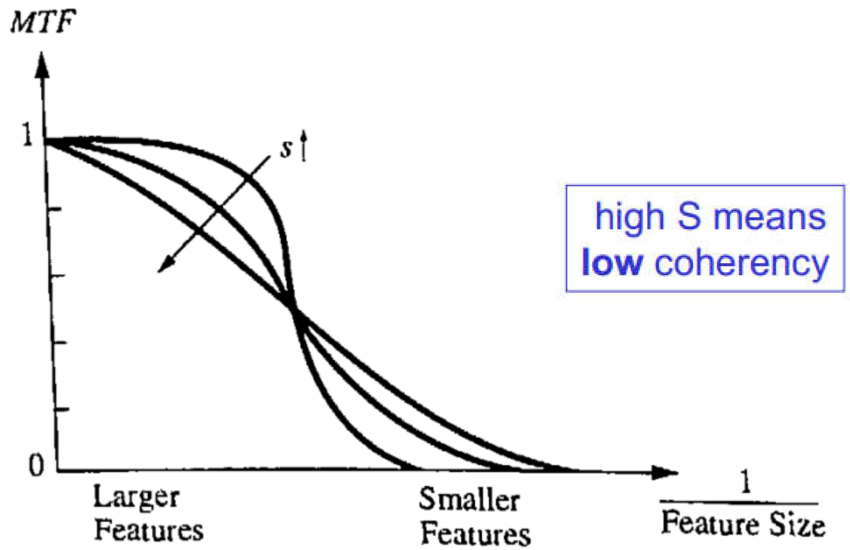
Spatial Coherence

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

$$\boxed{R \sim 0.6 \cdot \frac{\lambda}{n \sin \theta}}$$

decrease λ

increase θ

increase n

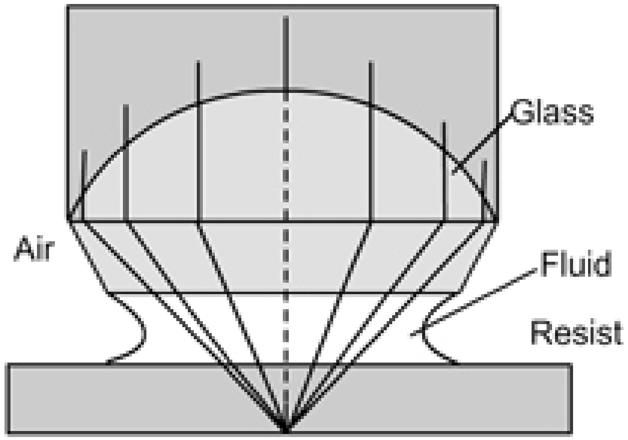
???

Large Aperture

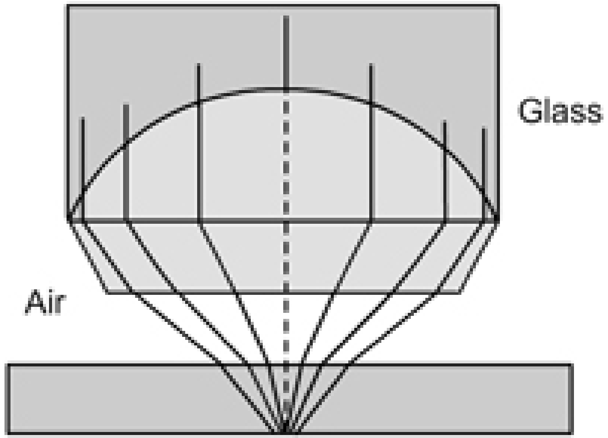
FAST (天眼，贵州)

Immersion Lithography

$$\boxed{R \sim 0.6 \cdot \frac{\lambda}{n \sin \theta}}$$



***n* > 1.0**



***n* = 1.0**

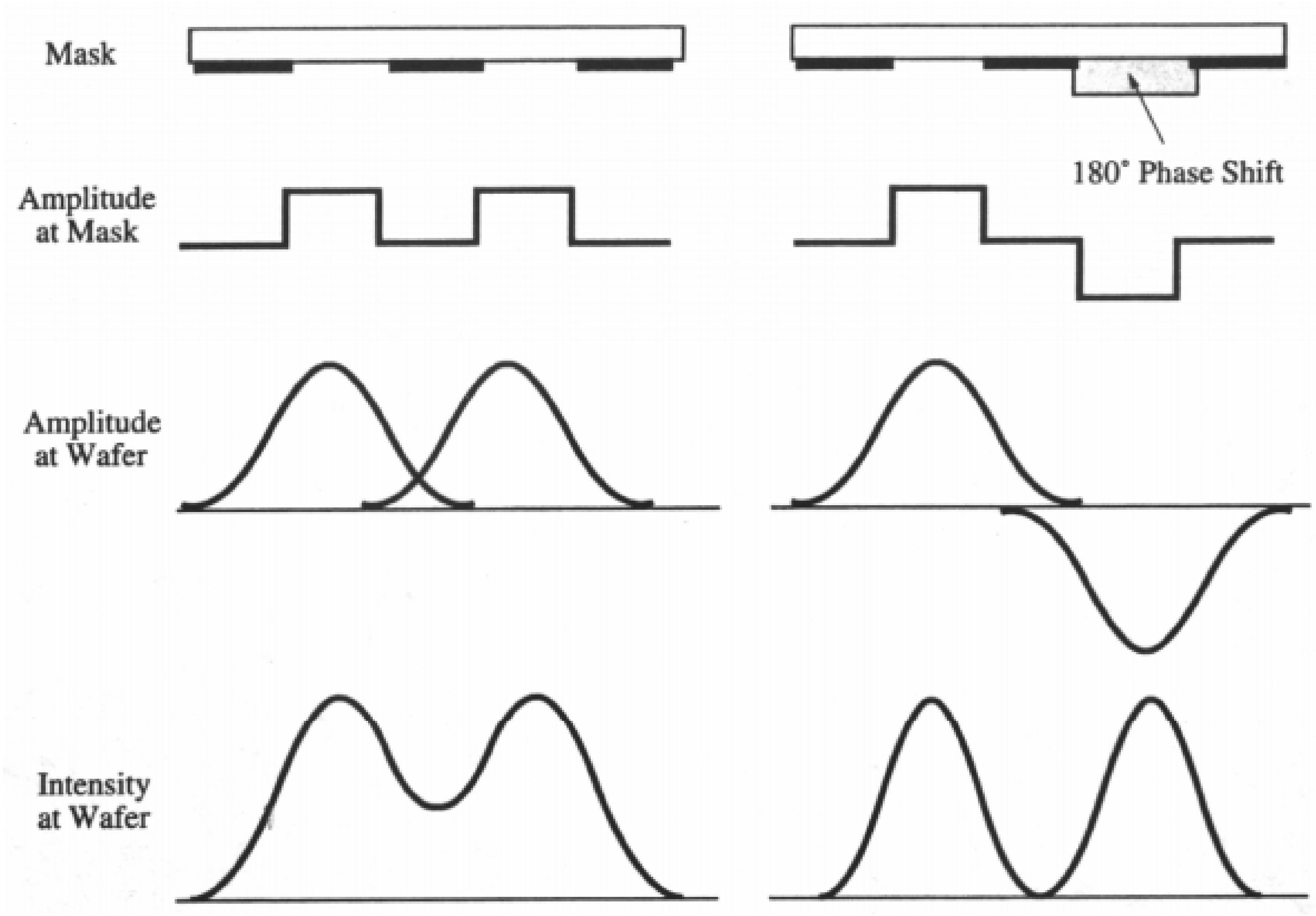
If high index fluid *n* = 1.7, resolution is reduced by ~40%

B. J. Lin (林本坚)
2018 未来科学大奖

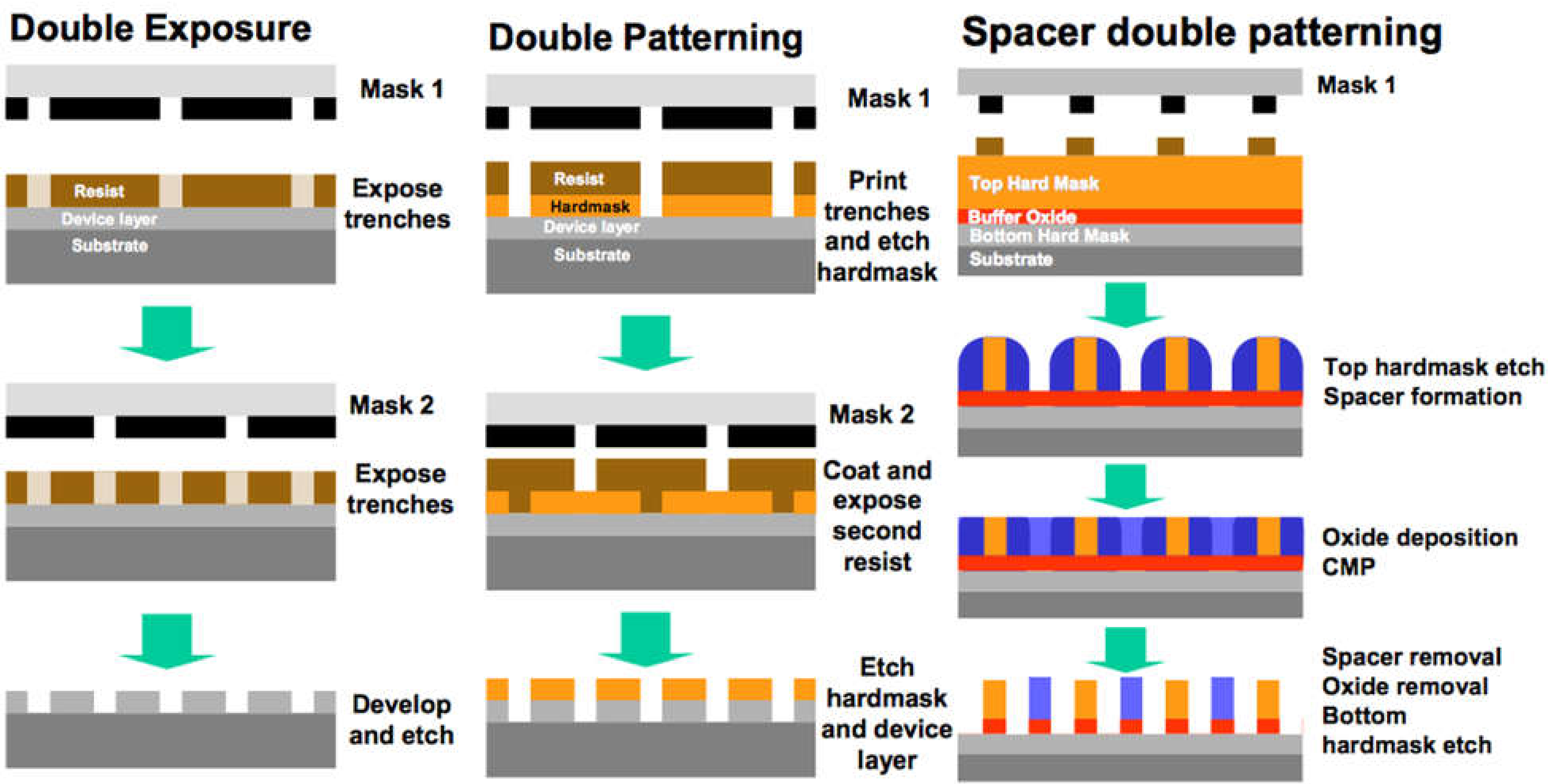

袁隆平、林本坚等7人获百万美元“未来科学大奖”
The ChinaPress · 21 hours ago

B. J. Lin, *Microelec. Eng.* **6,** 31 (1987)

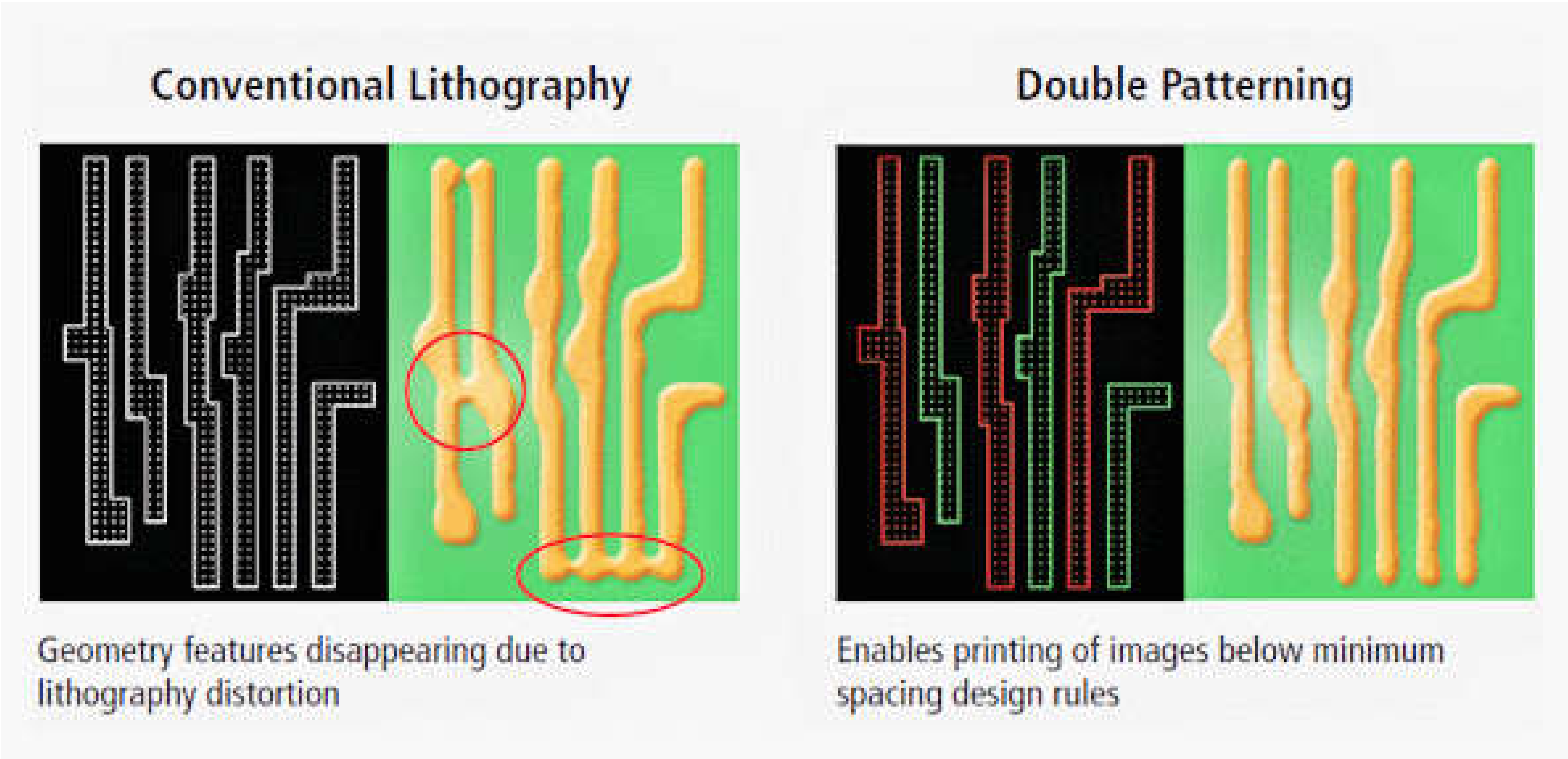
Phase Shift Mask



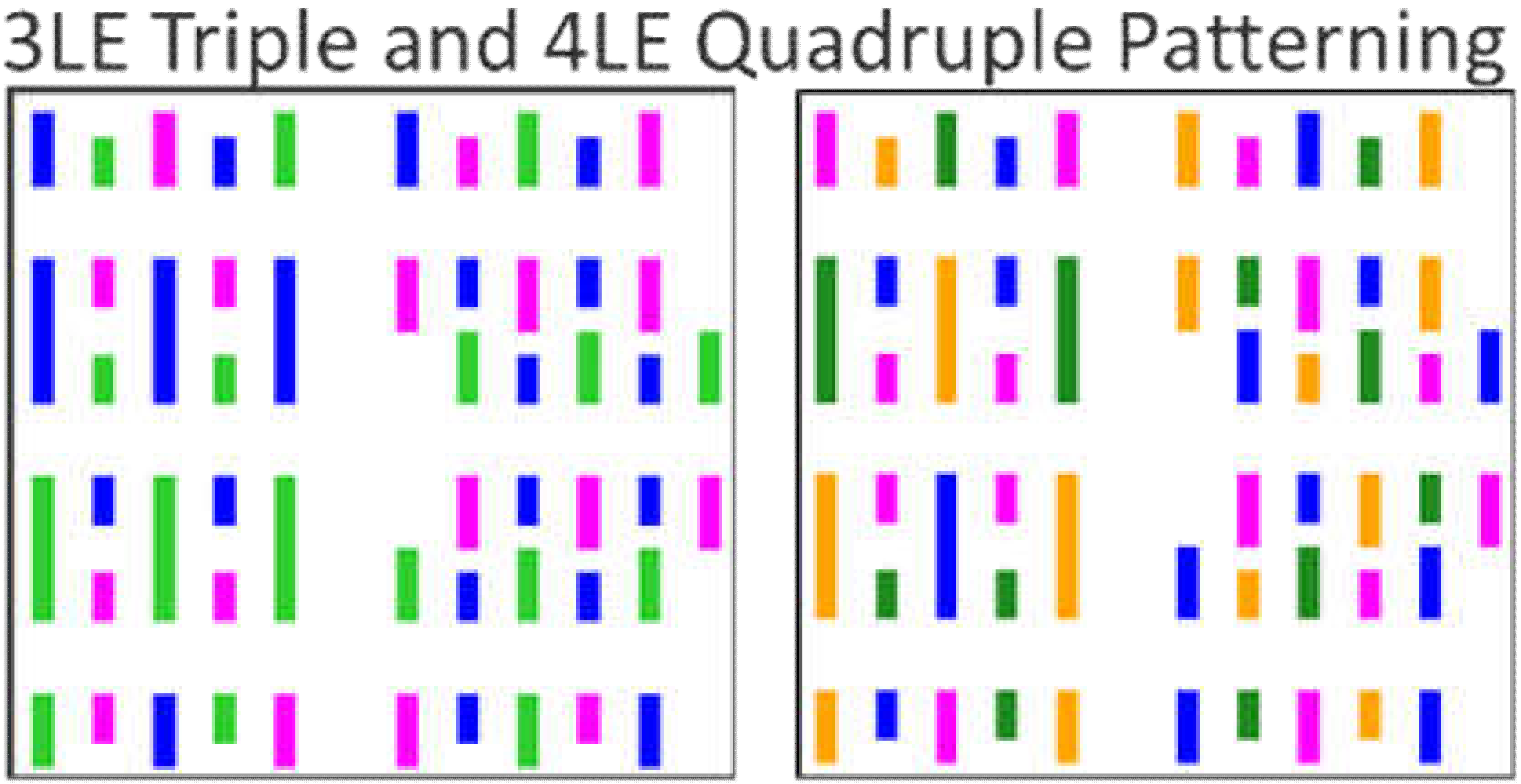
Double Patterning



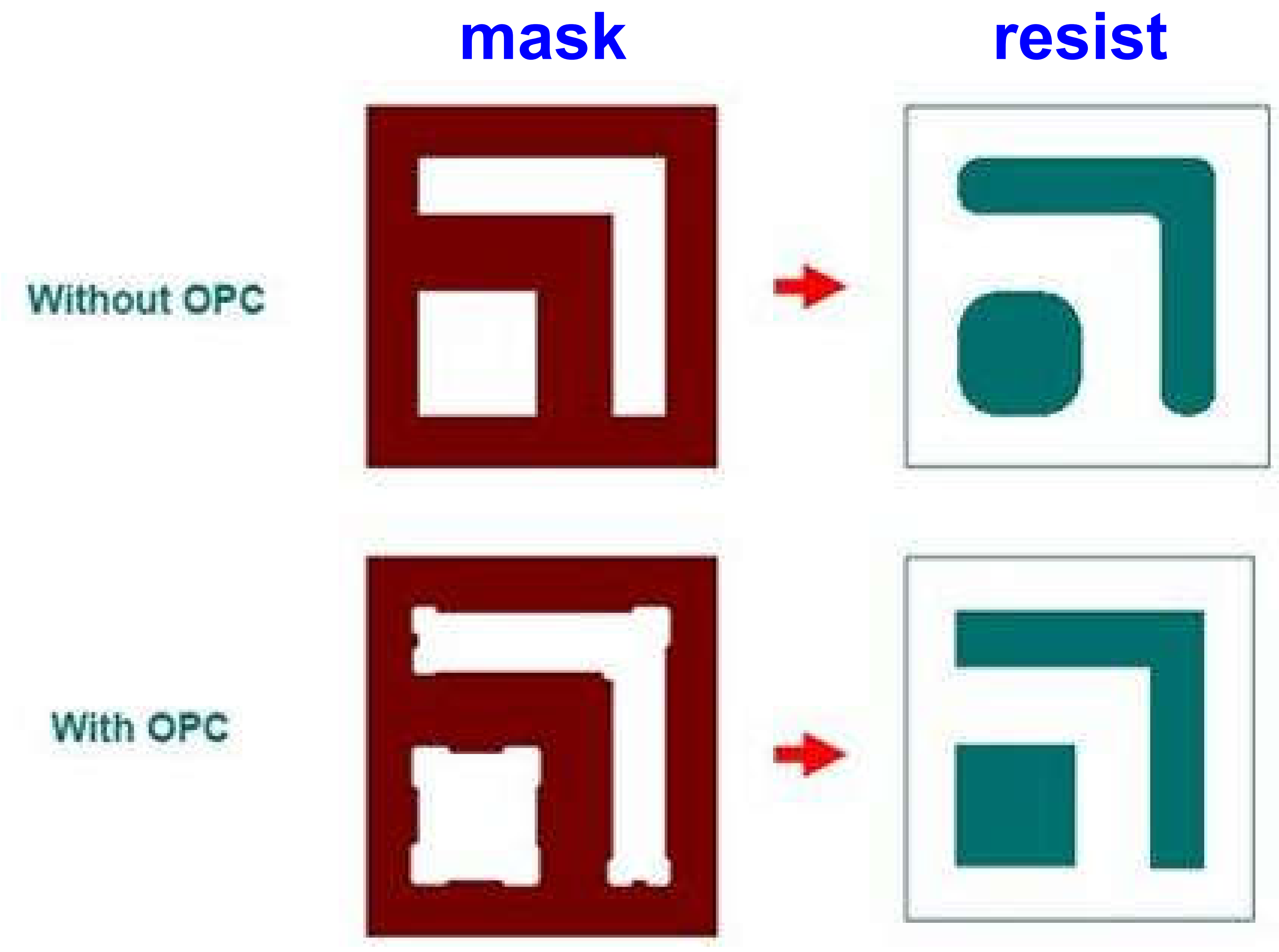
Double Patterning



Multiple Patterning



Optical Proximity Correction (OPC)



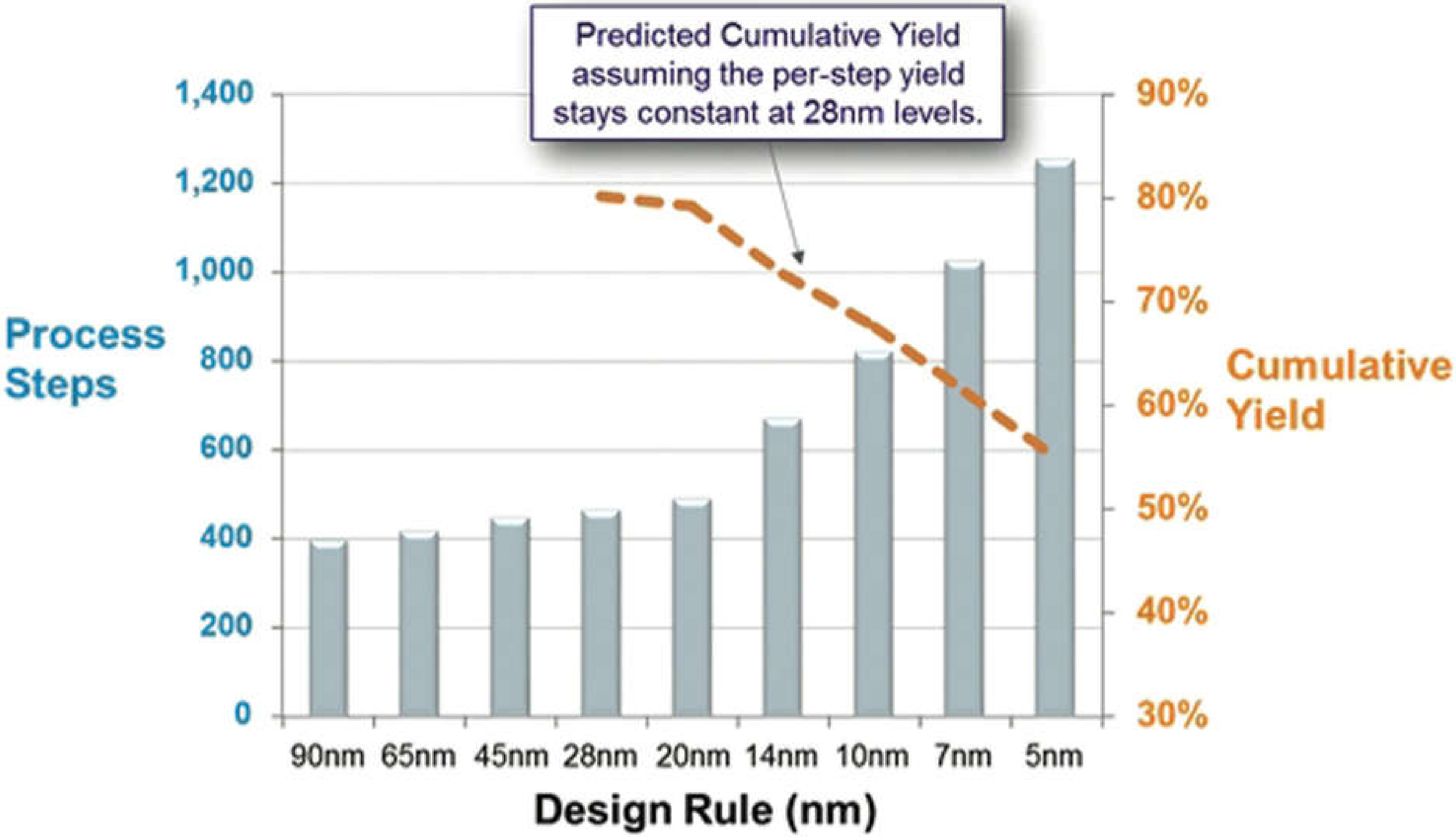
Resolution Improvement

$$\boxed{R \sim 0.6 \cdot \frac{\lambda}{n \sin\theta}}$$

For deep-UV, λ = 193 nm

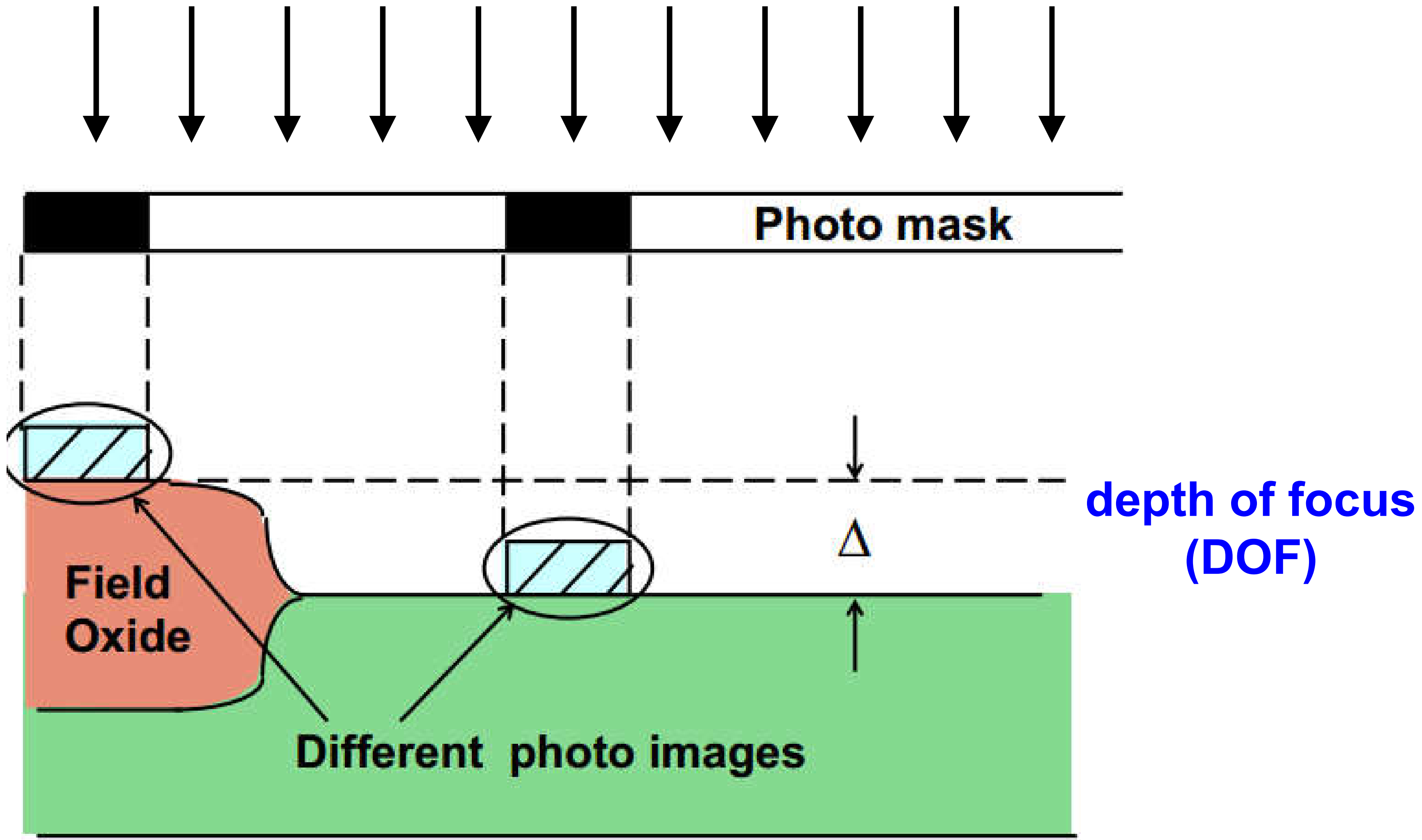
normal *R*	**116 nm**
+ immersion (*n* = 1.7)	**68 nm**
+ immersion (*n* = 1.7) + double pattern	**34 nm**
+ immersion (*n* = 1.7) + quad pattern	**17 nm**
...	**...**

Manufacturing Gets Complicated

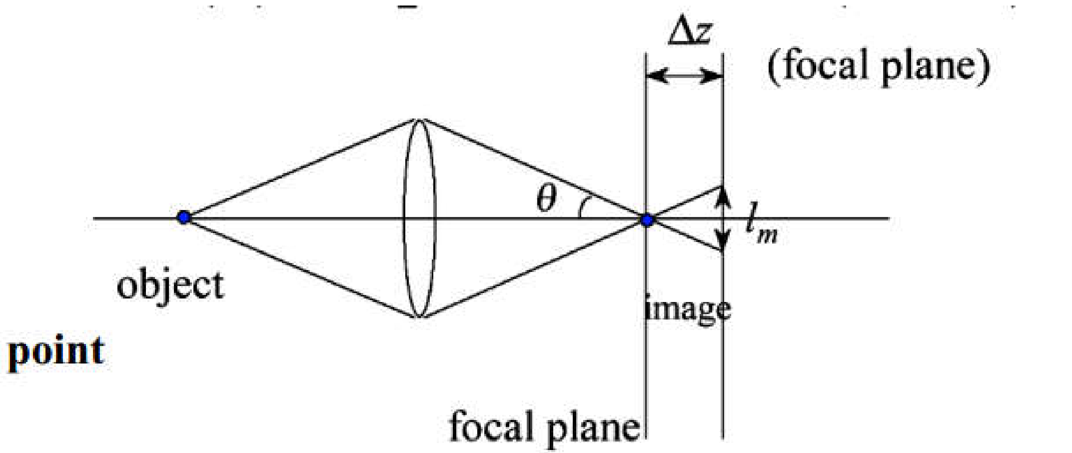


→ ***multiple patterning steps***

Depth of Focus (DOF)



Depth of Focus (DOF)



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

$$0.5 < k_2 < 1$$

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

$$for\ \ small\ \theta$$

off focus

on focus

off focus

large NA (光圈)

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

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

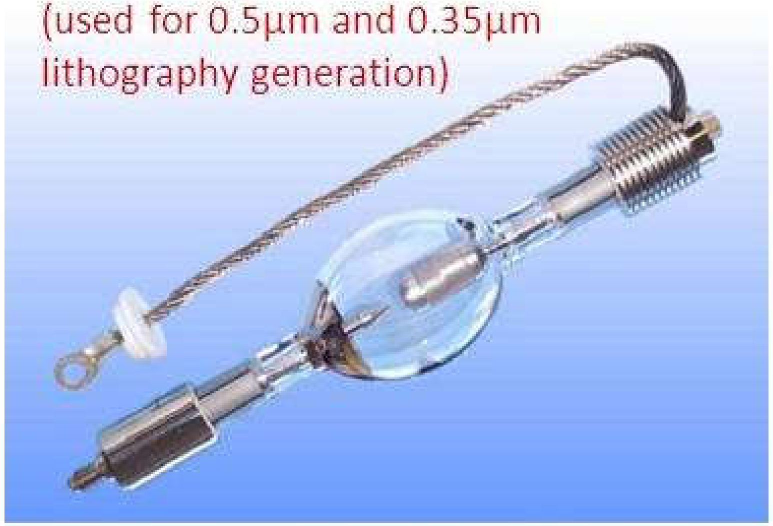
trade-off between resolution and DOF

Light Sources

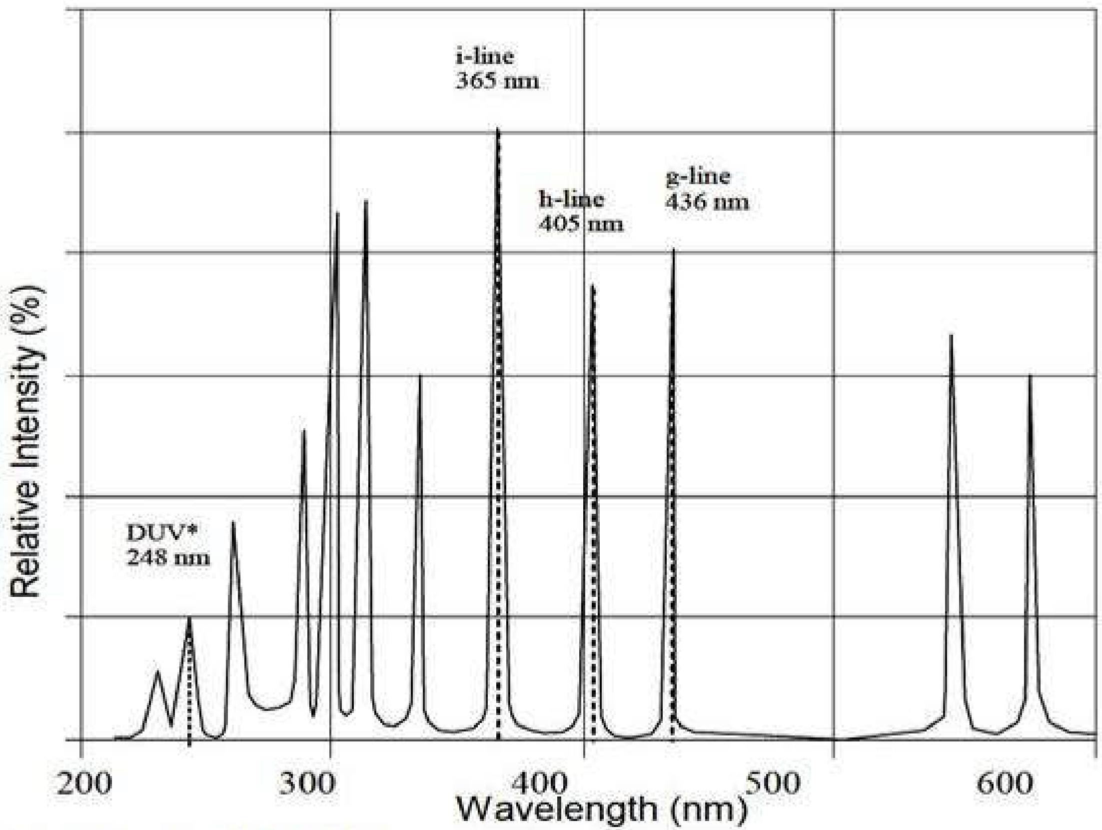
- **Mercury (Hg) arc lamp**
  - **g-line 436 nm, h-line 405 nm, i-line 365 nm**

$$R \sim 0.6 \cdot \frac{\lambda}{n \sin\theta}$$

g line λ=436 nm
i line λ=365 nm
(used for 0.5μm and 0.35μm lithography generation)



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



- Filters can be used to limit exposure wavelengths.

Light Sources

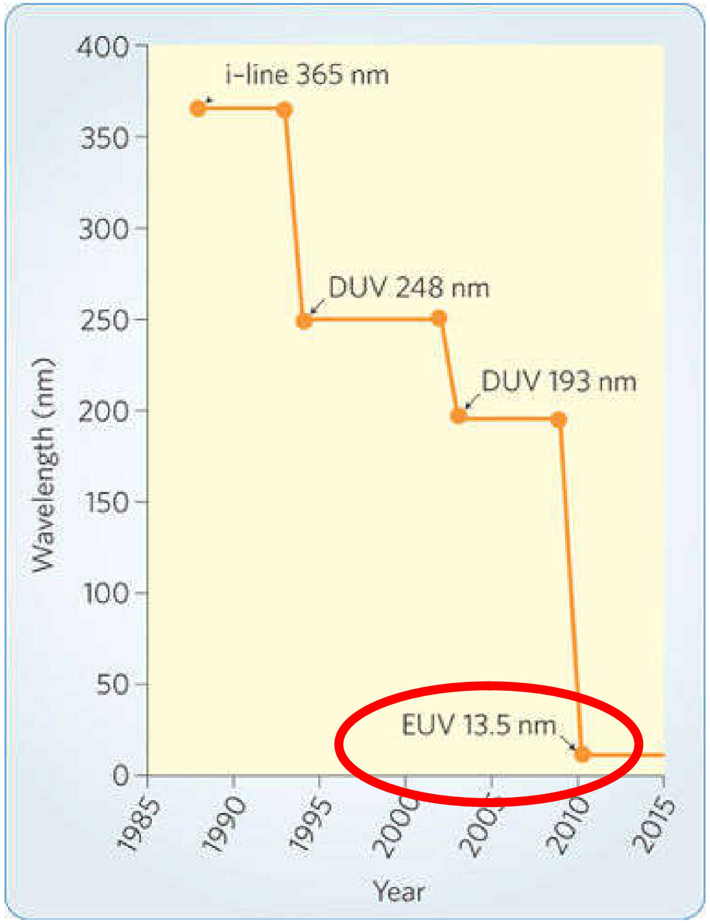
- **Mercury (Hg) arc lamp**
  - **g-line 436 nm, h-line 405 nm, i-line 365 nm**

yellow light in cleanroom

Light Sources

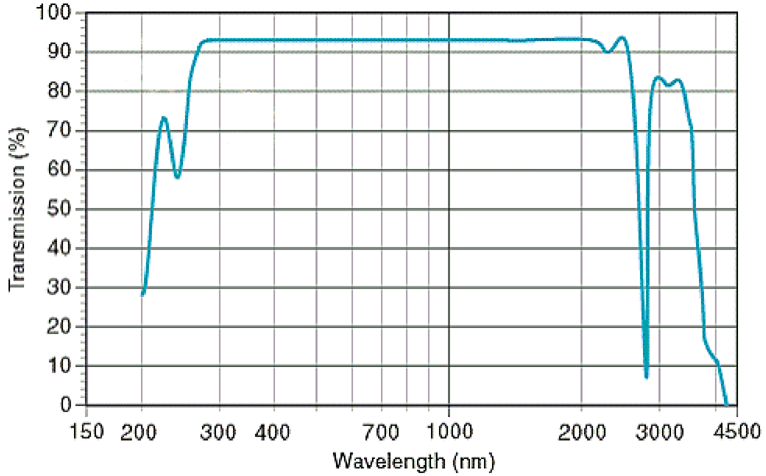
$$R \sim 0.6 \cdot \frac{\lambda}{n \sin \theta}$$

- 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)
- ...

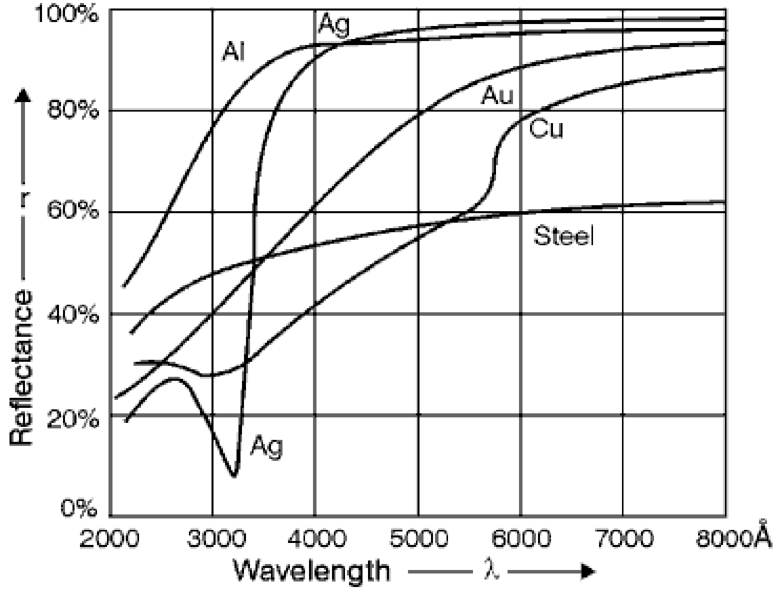


Optics for EUV

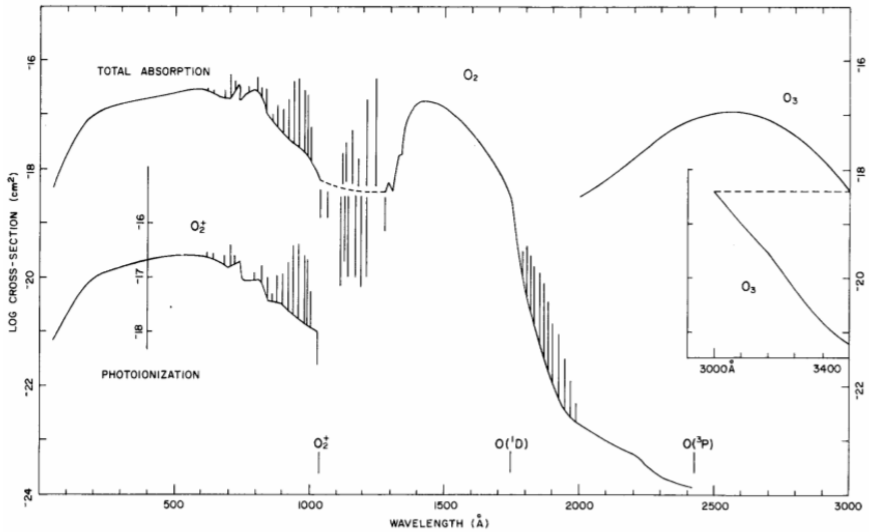
quartz glass



metals



air



at EUV (λ = 13.5 nm):

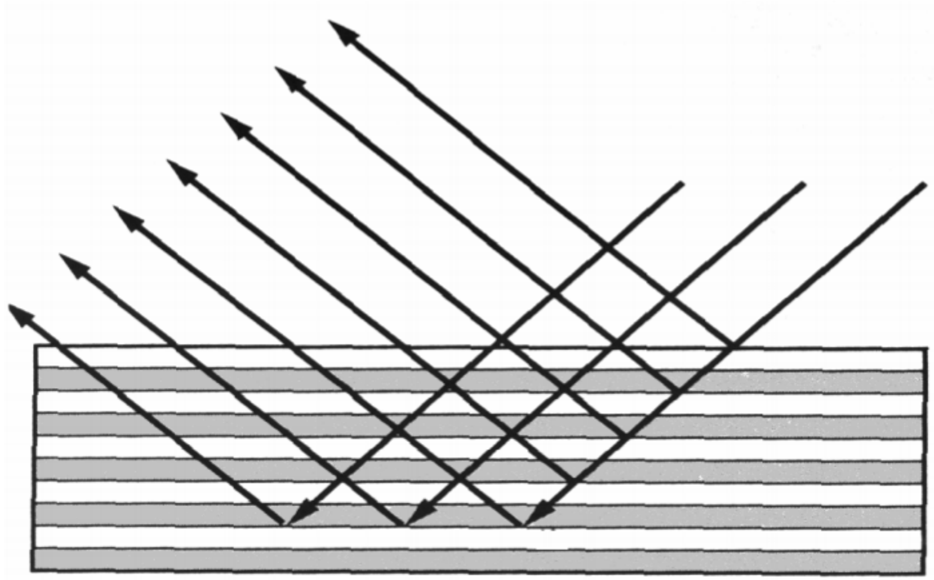
glass is not transparent

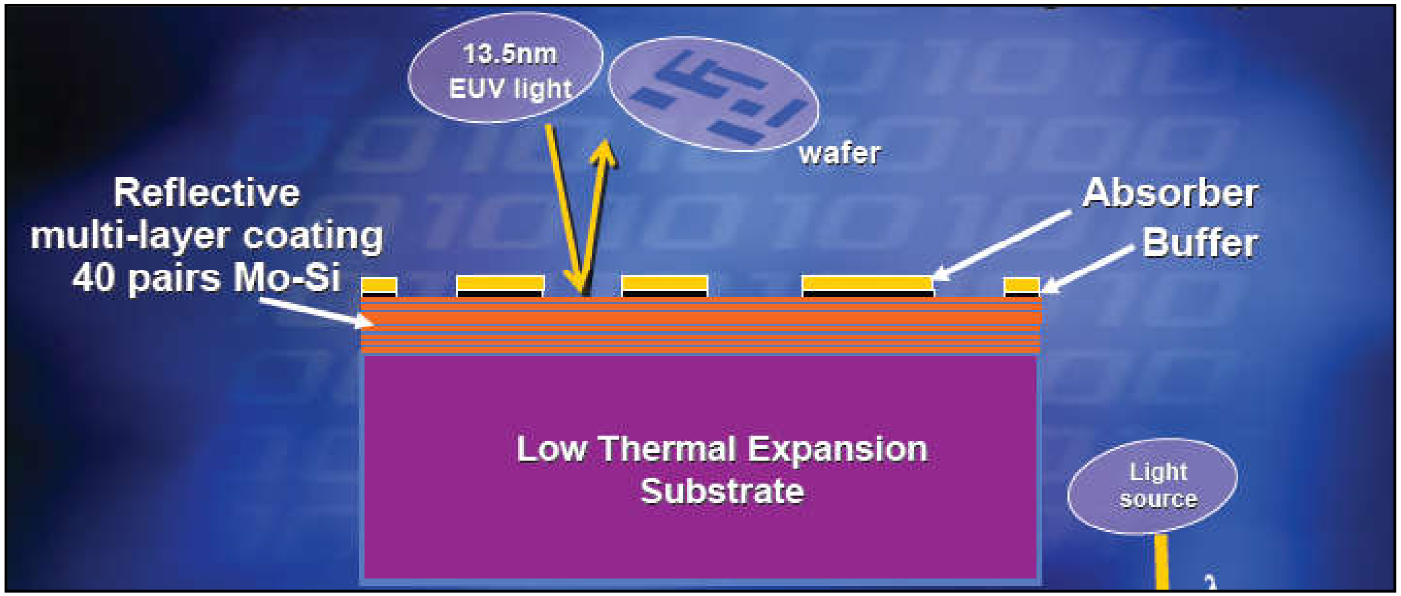
metal is not reflective

even air is absorptive

Optics for EUV

multilayer mirrors (Mo/Si)

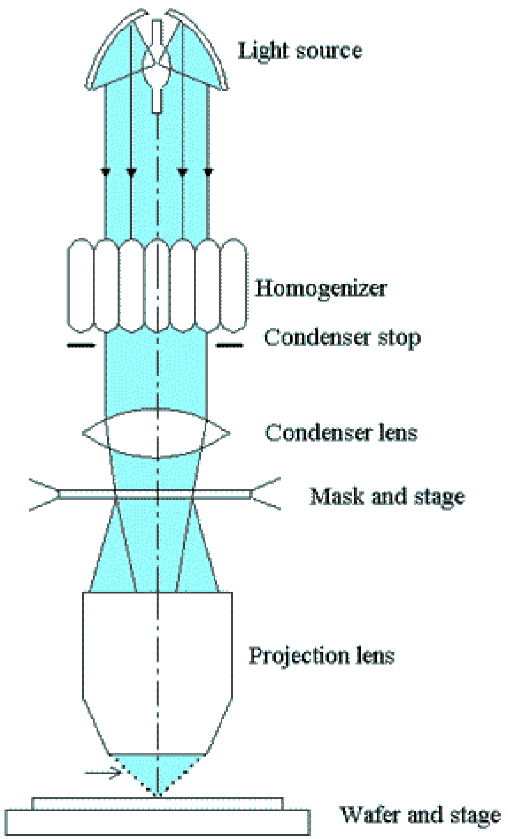


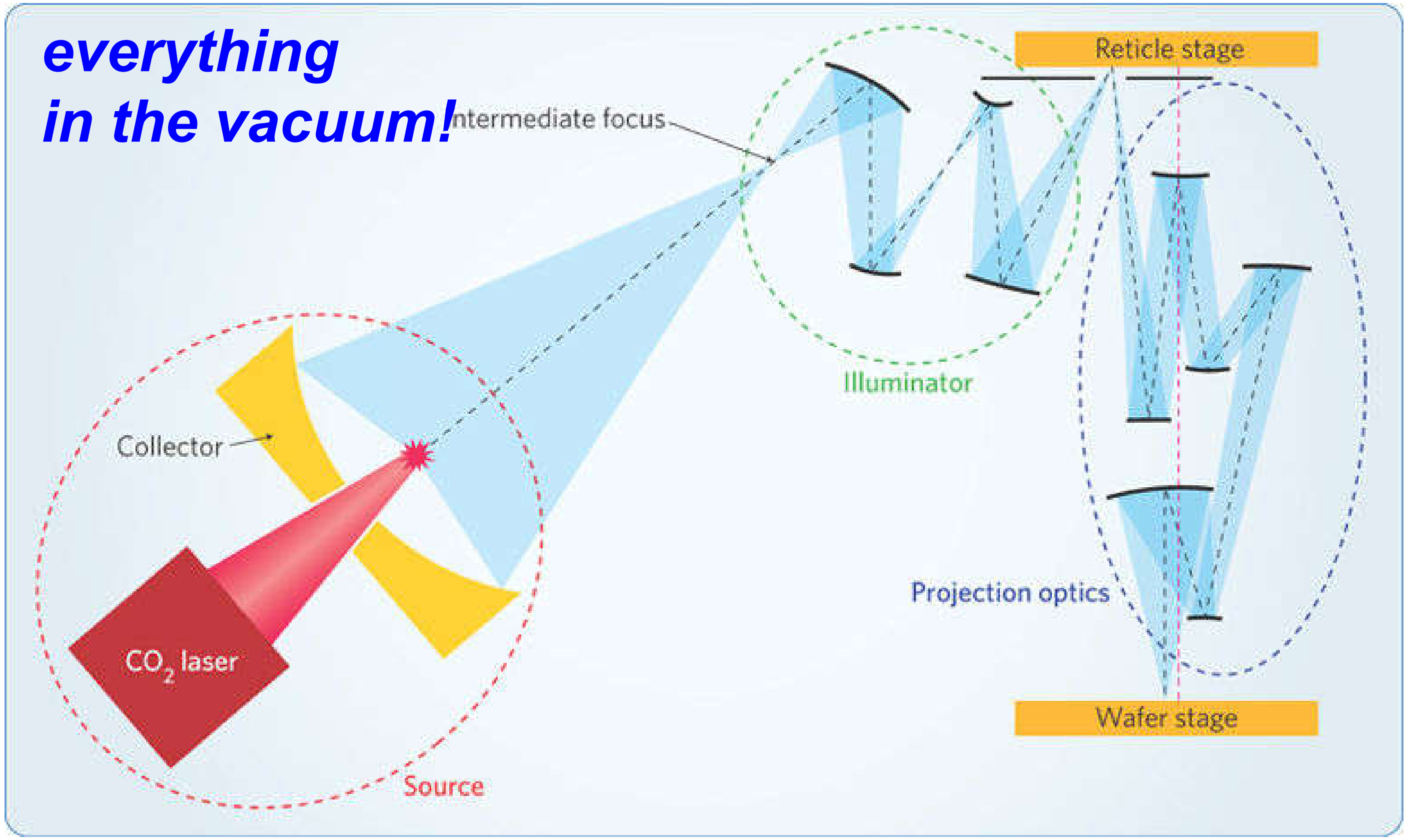


reflective masks

Optics

optical loss > 95%





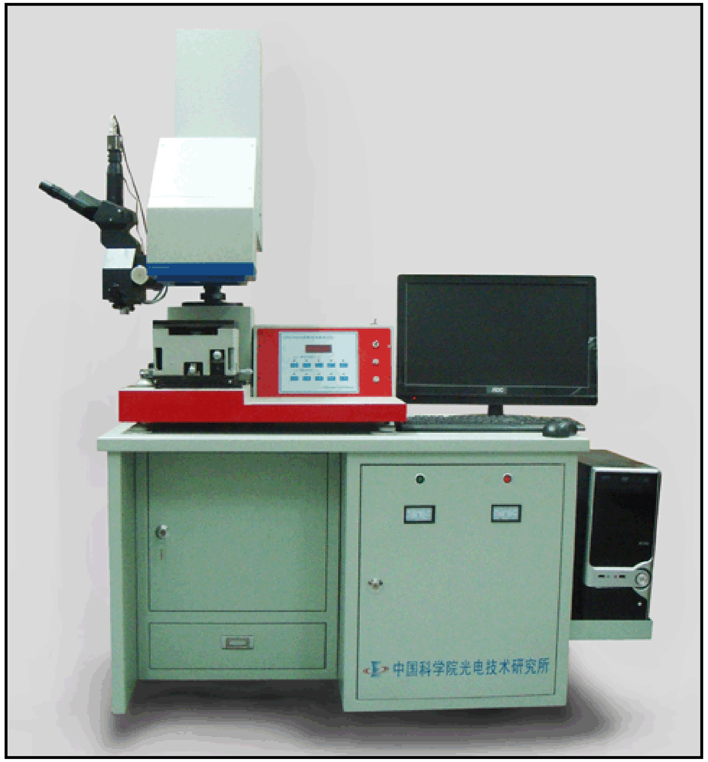
UV (365 nm)

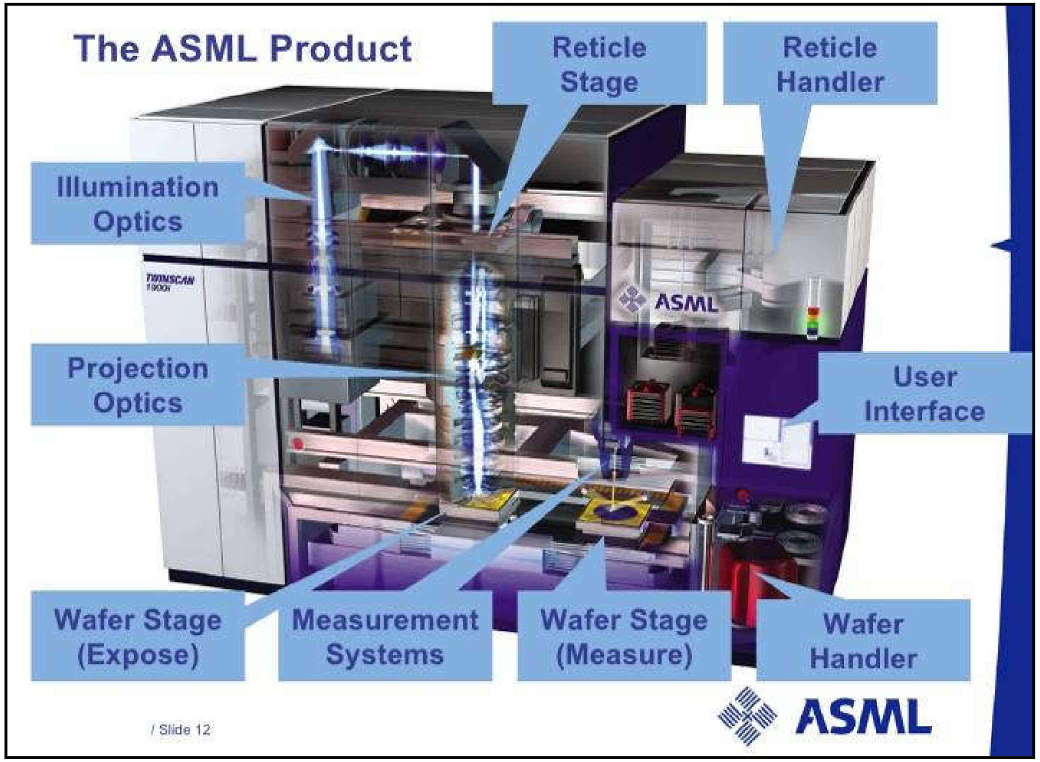
EUV (13.5 nm)

Equipment

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

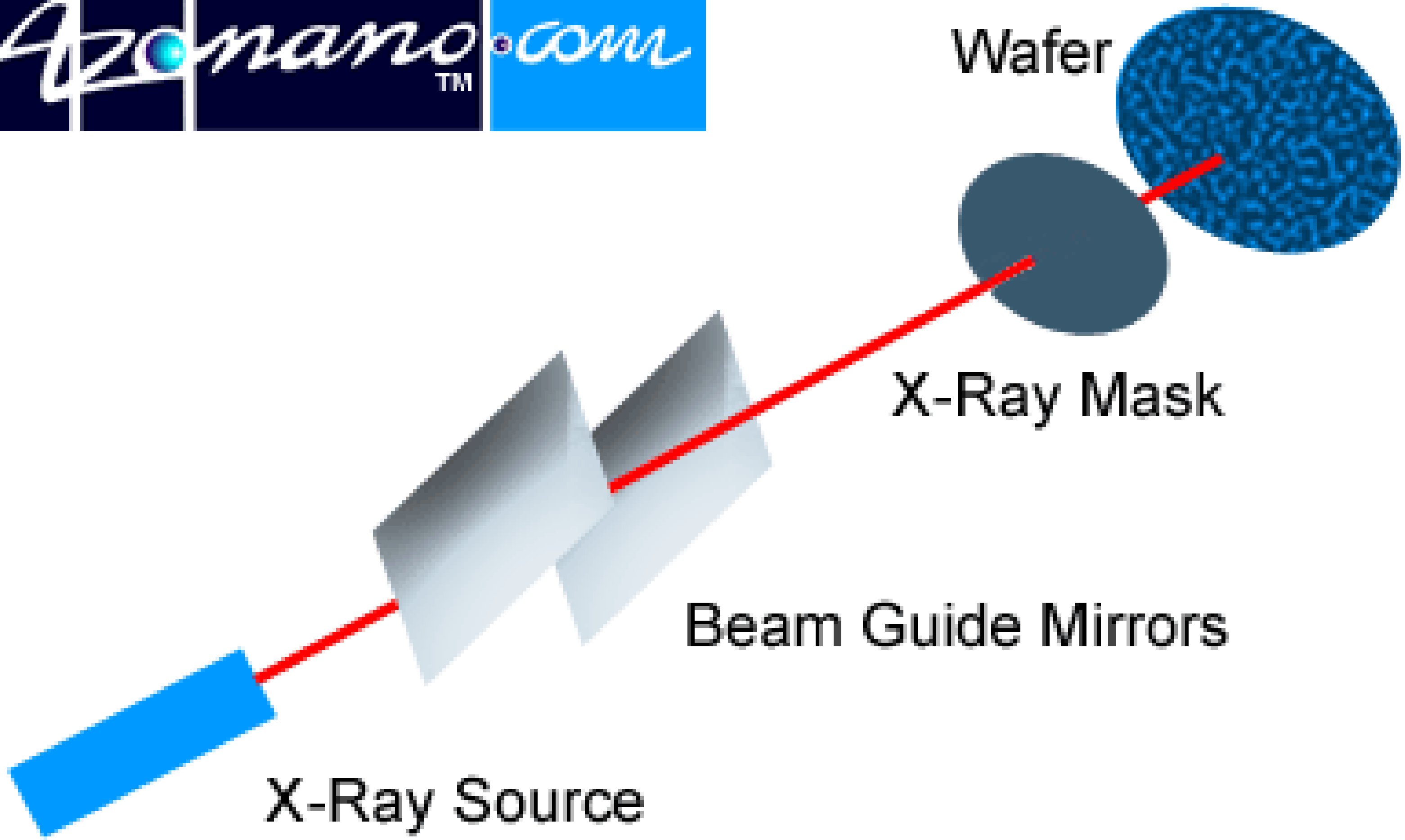
EUV (13.5 nm)
resolution ~ 10 nm
price ~ 100,000,000 $$$





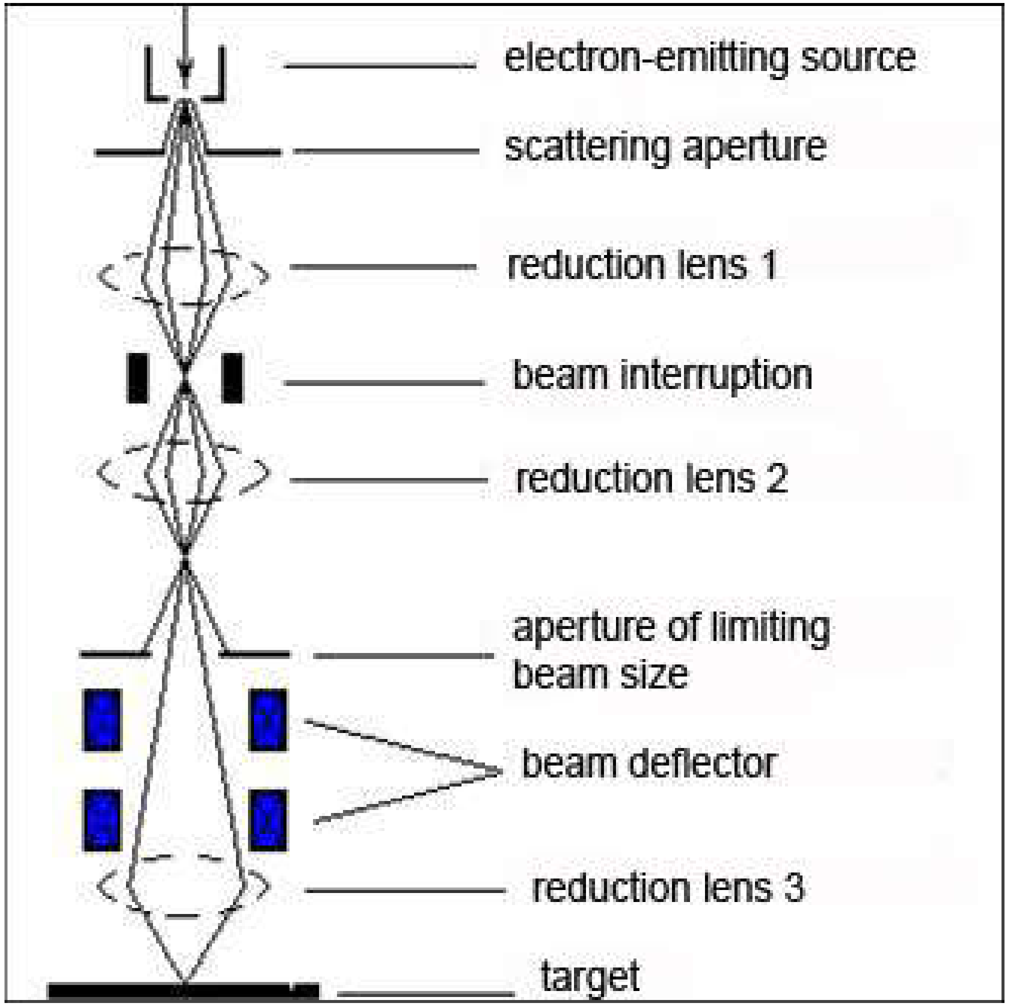
X-ray Lithography

wavelength 0.01~10 nm



Electron Beam (Ebeam) Lithography

similar to a scanning electron microscope (SEM)



wave-particle duality

$$\boxed{\lambda = \frac{h}{\text{momentum}}}$$

wavelength

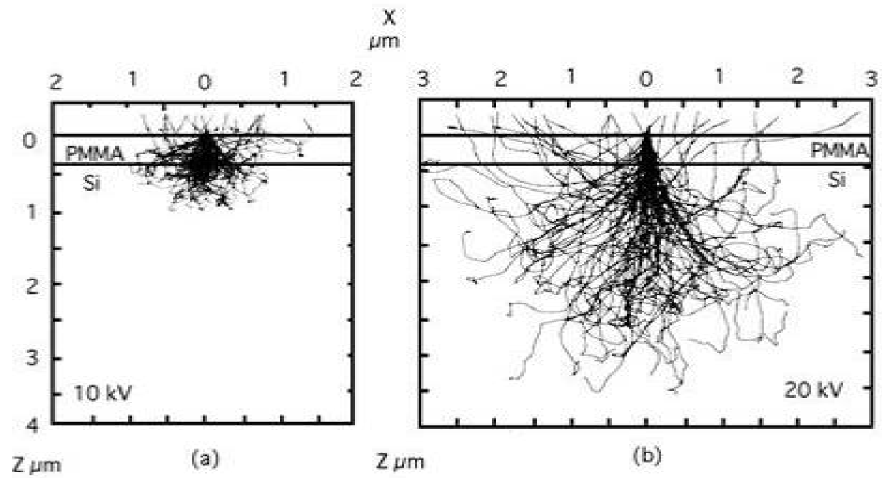
$$\lambda(\text{nm}) = \frac{1.23}{\sqrt{V}}$$

Example:
for V = 30 kV, λ = 0.007 nm

Electron Beam (Ebeam) Lithography

- The resolution is limited by secondary electrons
  - higher V -> lower resolution
  - resolution ~ 10 nm

proximity effect

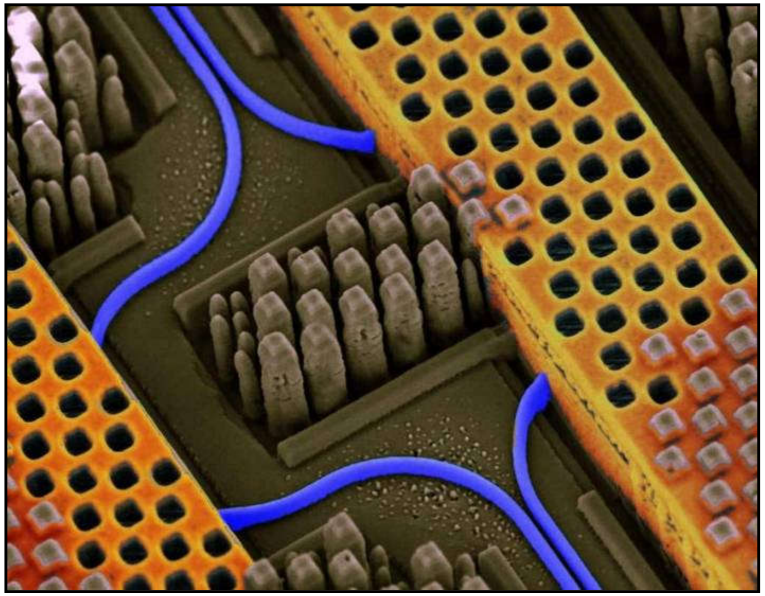


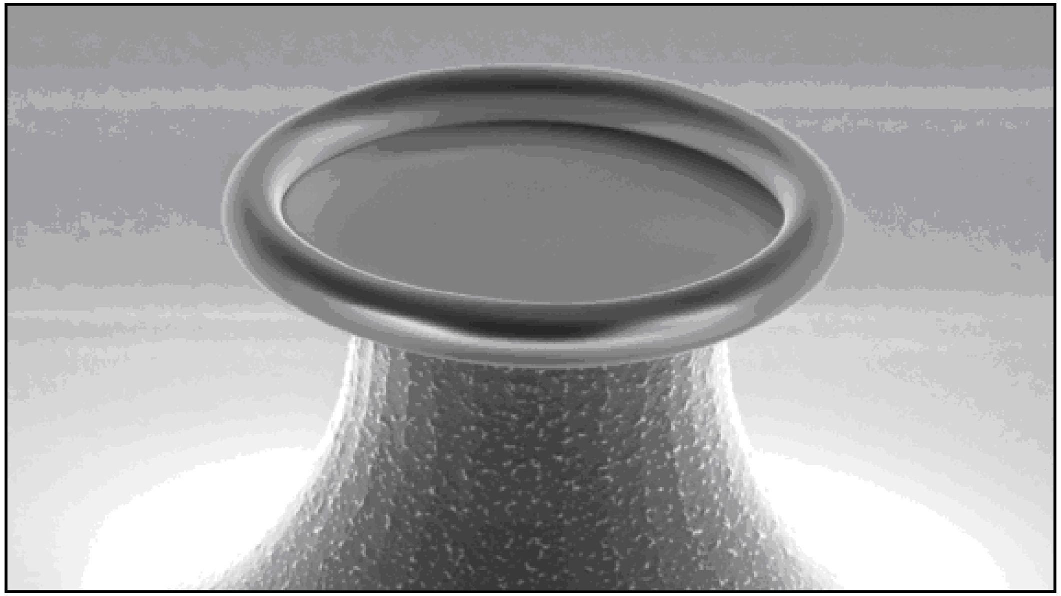
- No mask for electron, only direct writing!
  - slow process

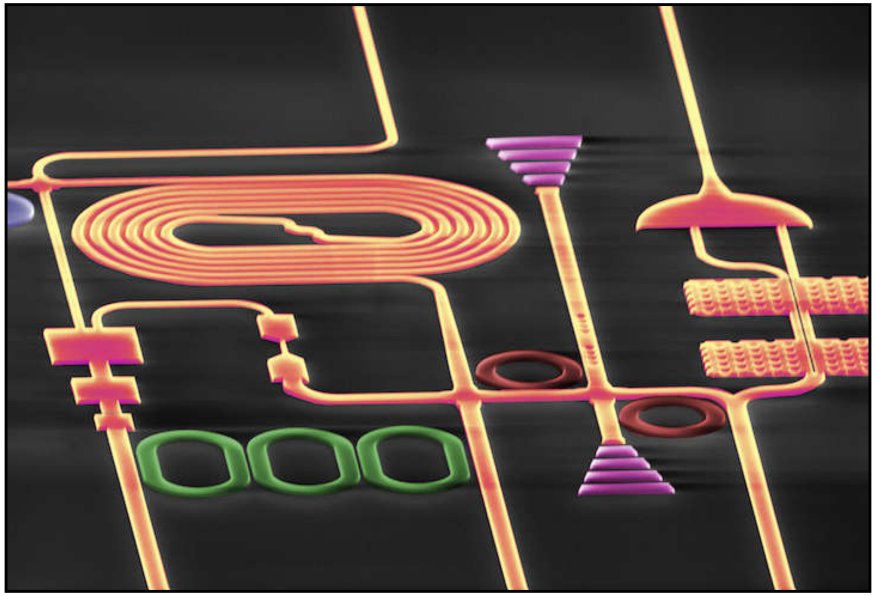
- Only for research purposes now

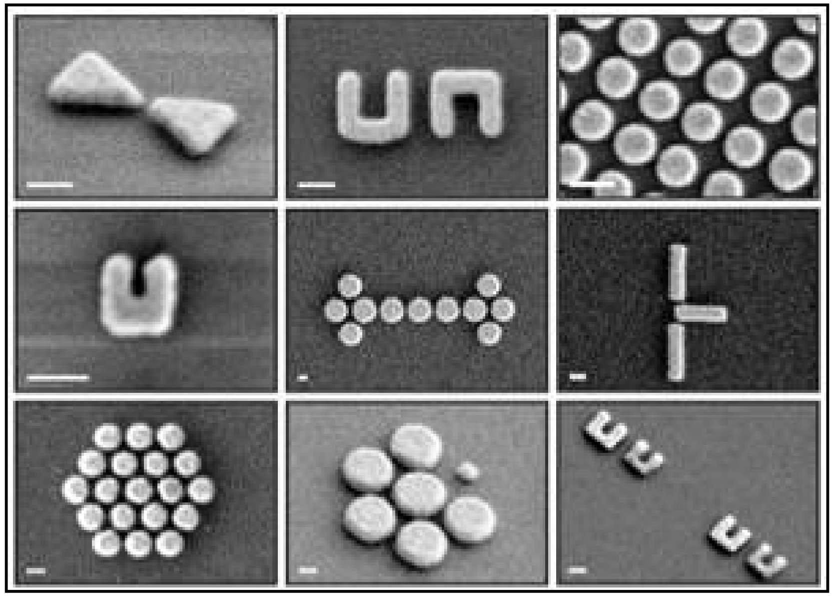
Video

NanoPhotonics







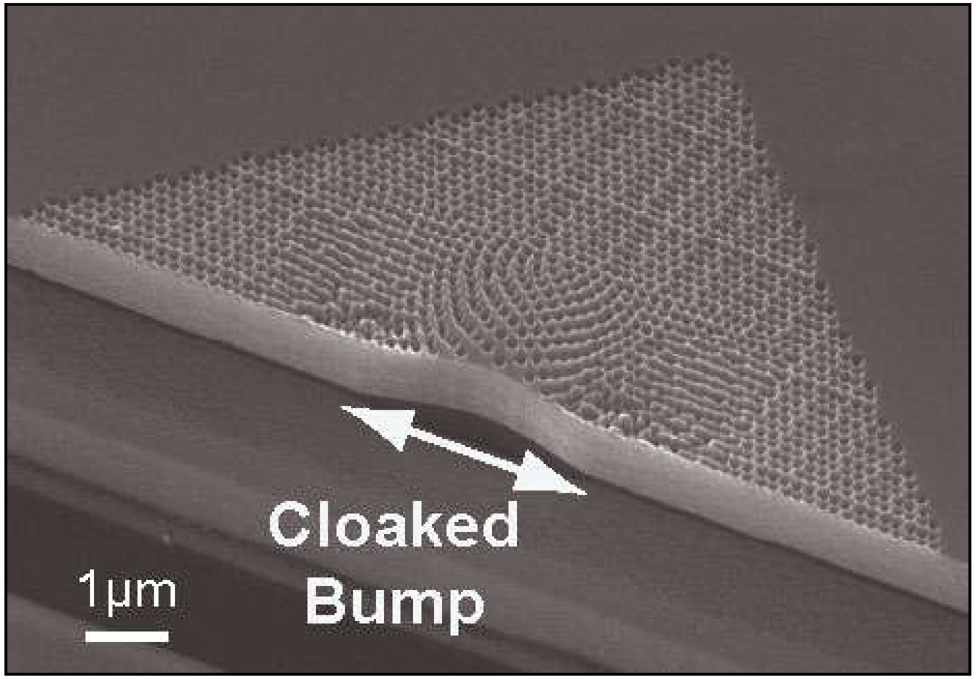


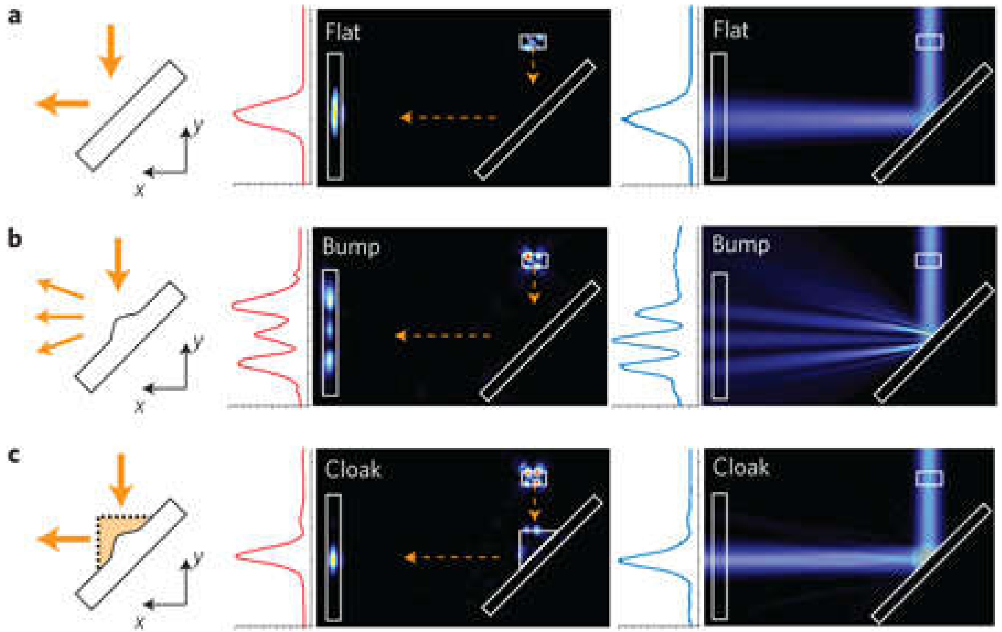
Optical Cloak

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

An optical cloak made of dielectrics

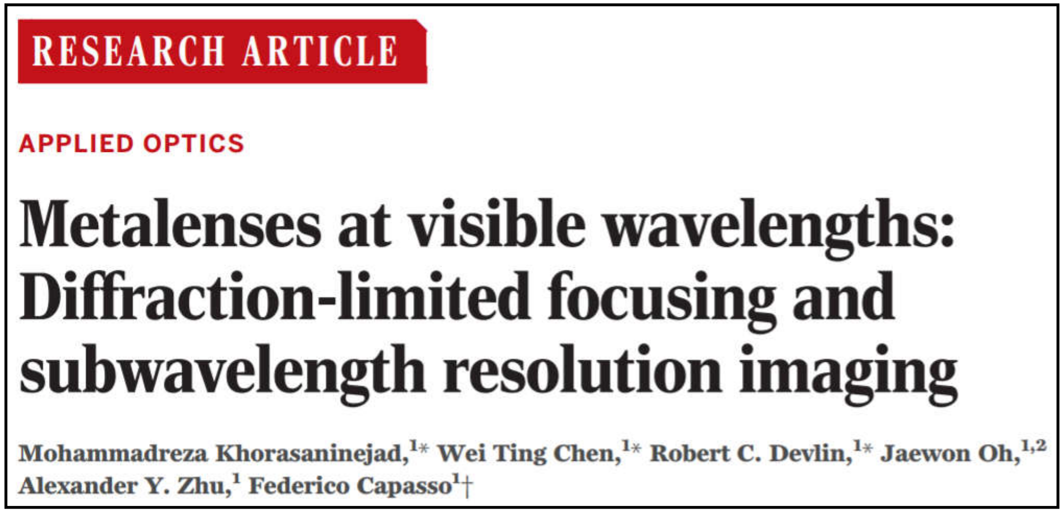
Jason Valentine[1]*, Jensen Li[1]*, Thomas Zentgraf[1]*, Guy Bartal[1] and Xiang Zhang[1,2]†





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

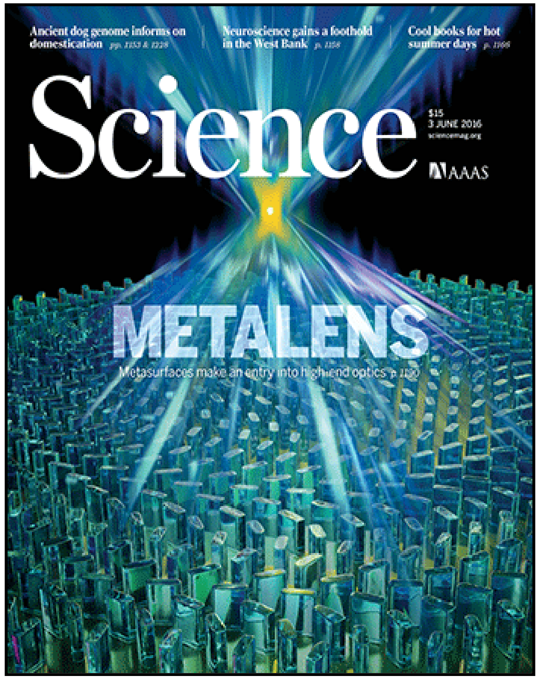
Metalens

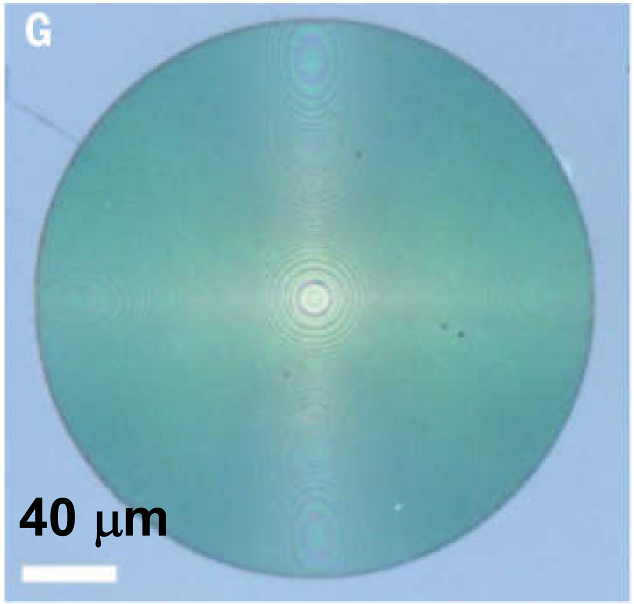

RESEARCH ARTICLE

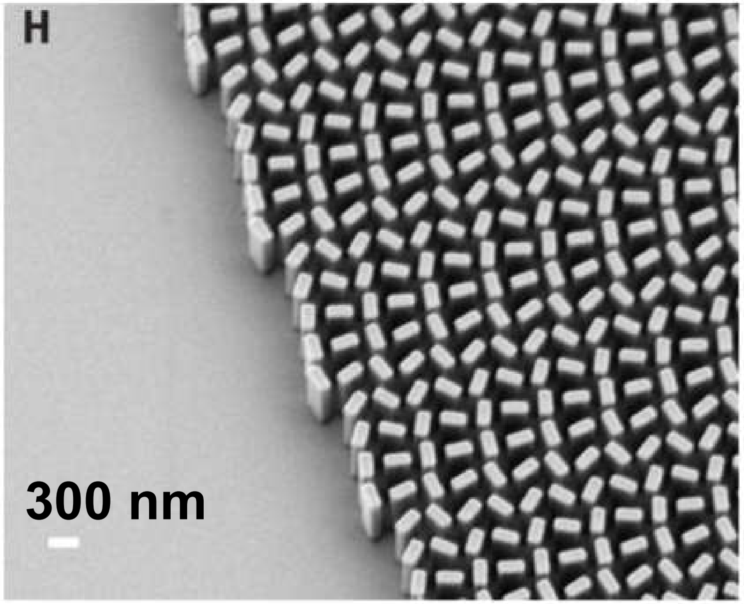
APPLIED OPTICS

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†]

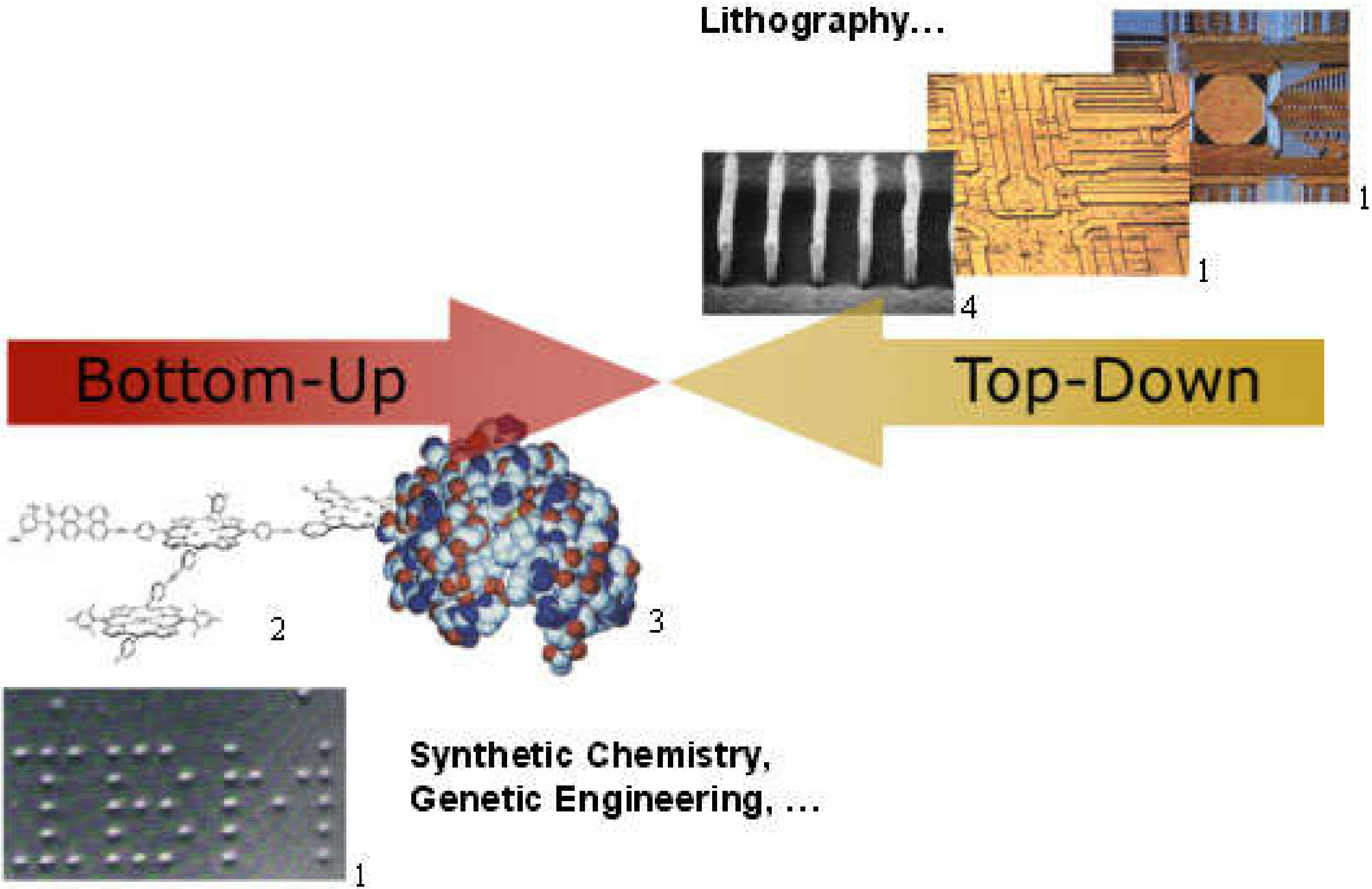




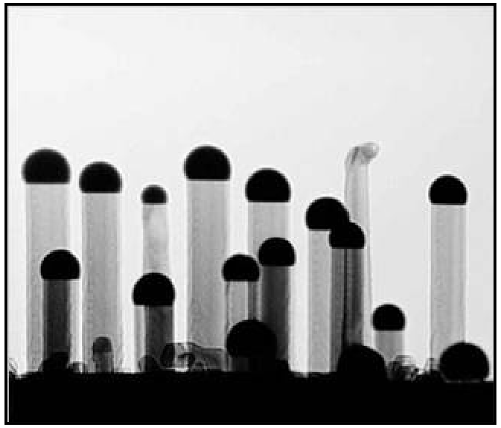


M. Khorasaninejad, *et al.*, *Science* **352,** 1190 (2016)

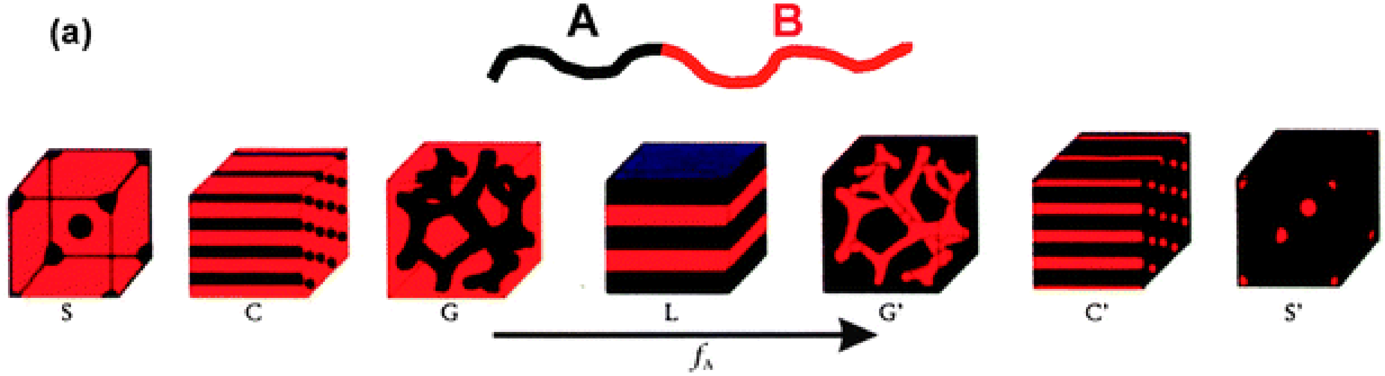
Top Down vs. Bottom Up



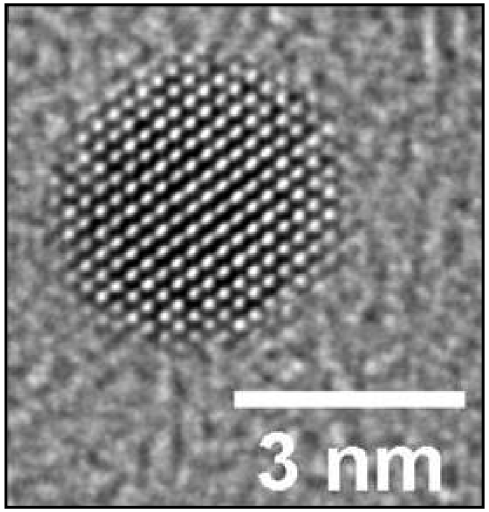
Bottom Up Approaches



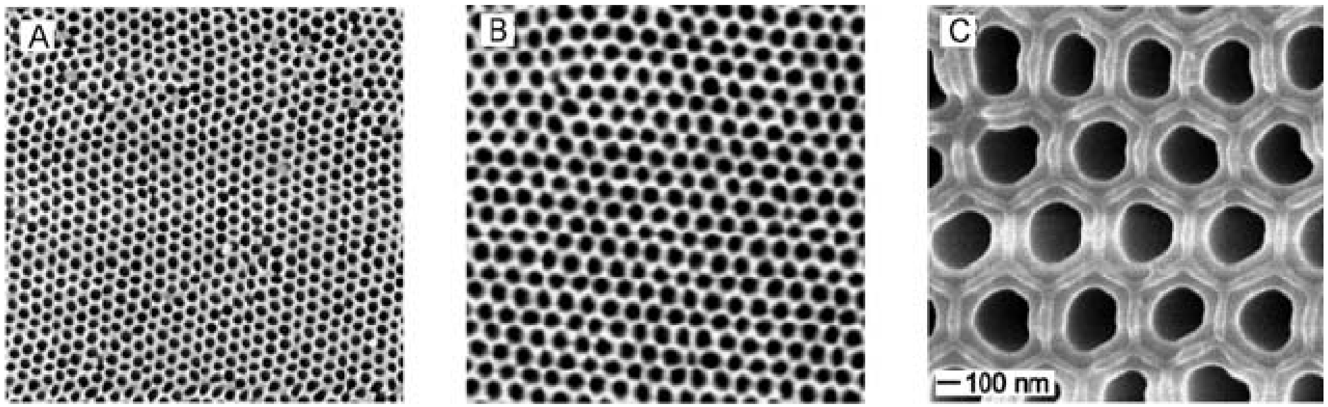
nanowire growth



block copolymer assembly



quantum dot



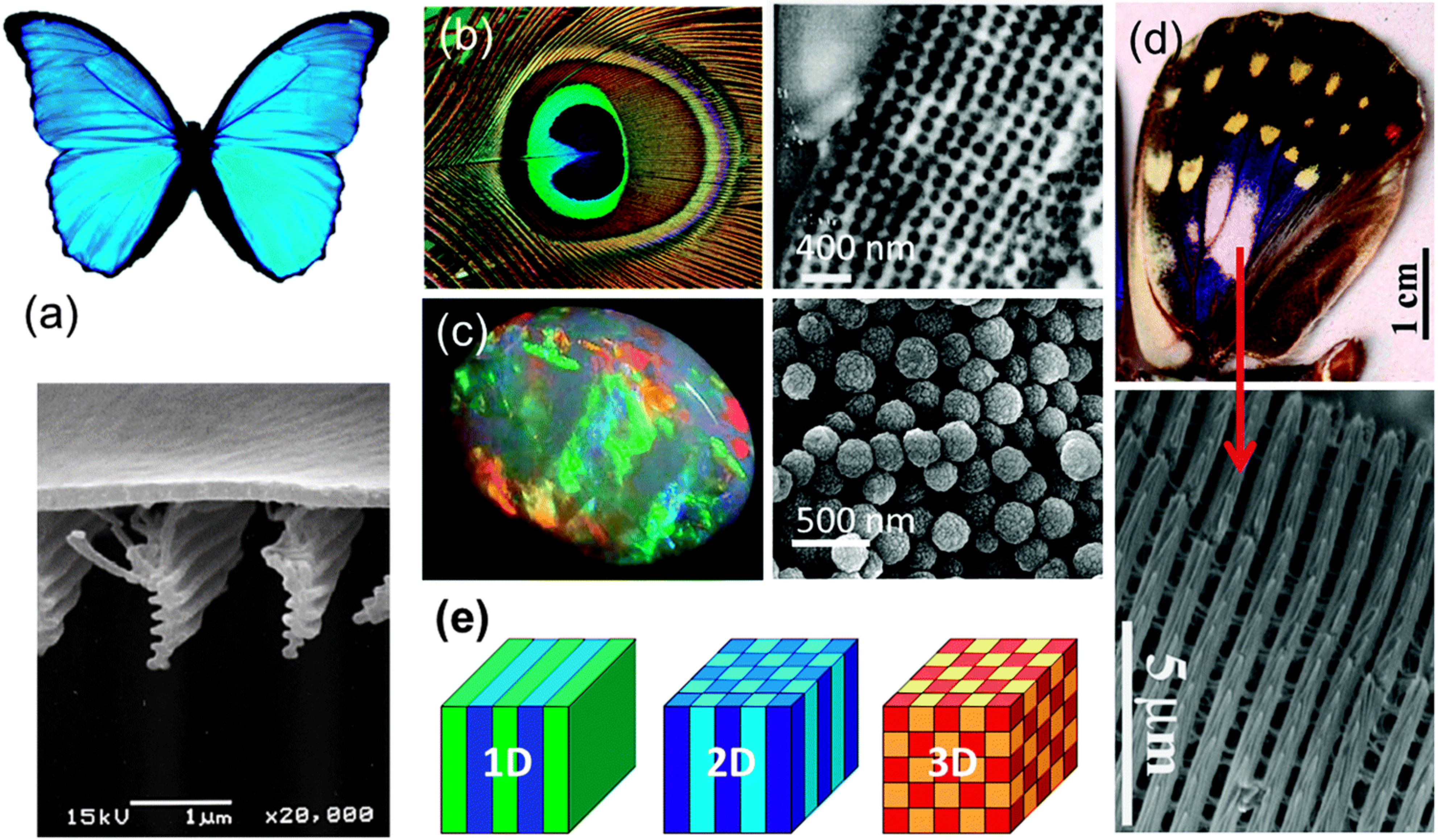
0.3 M H_2SO_4, 25 V
D_c = 60 nm

0.5 $C_2H_2O_4$, 40 V
D_c = 100 nm

1.1 M H_3PO_4, 160 V
D_c = 420 nm

anodized alumina

Nano Structures in Nature



E. Armstrong and C. O'Dwyer, *J. Mater. Chem. C* **3,** 6109 (2015)