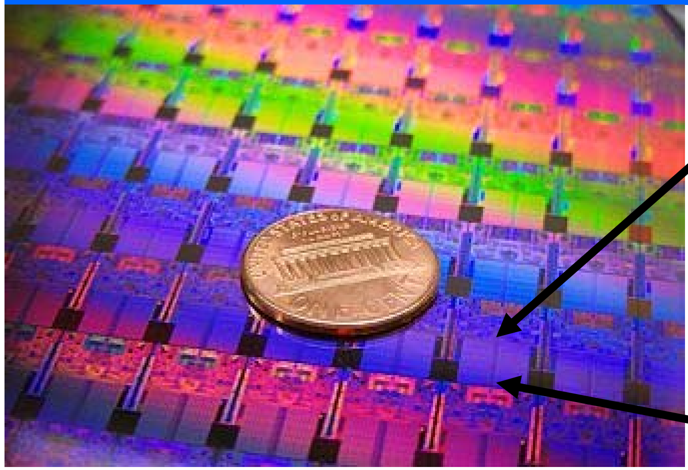
Lecture 5

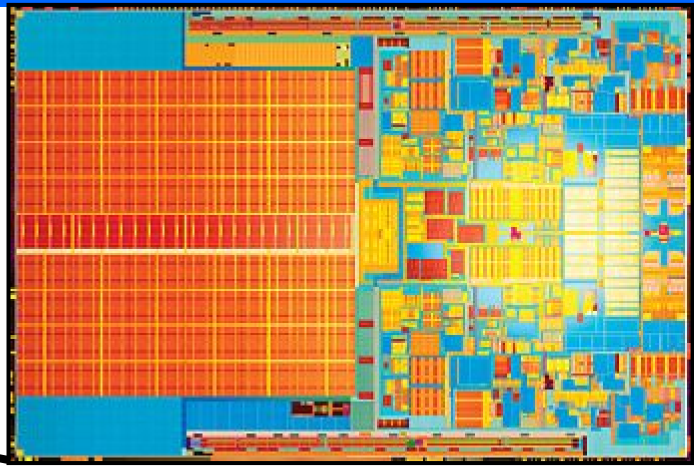
Optical Lithography

Intro

- For most of microfabrication purposes the process (e.g. additive, subtractive or implantation) has to be applied selectively to particular areas of the wafer: **patterning** is required;
- Predominately done by **optical lithography**

Intro

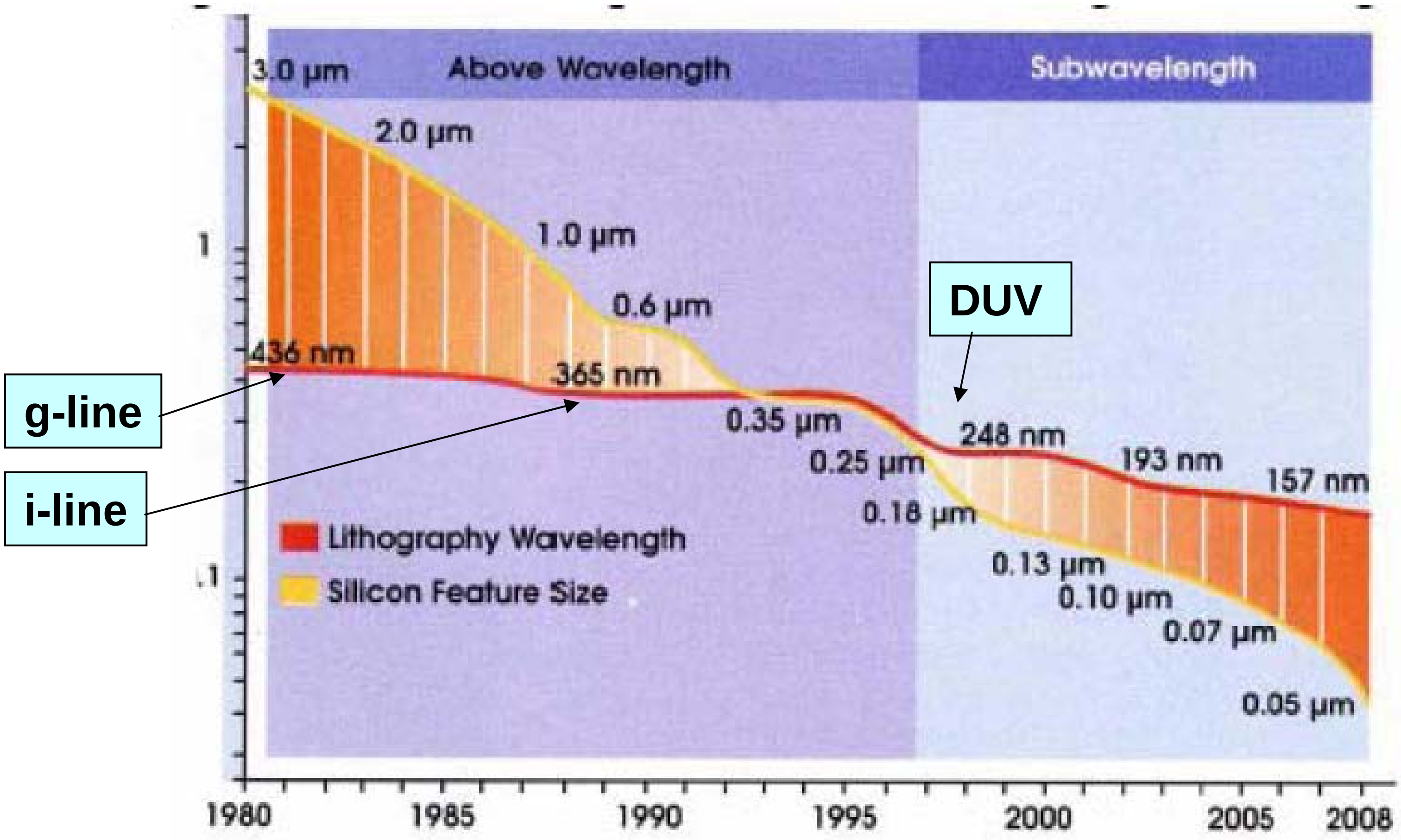




Intel's Dual core CPU, 45nm tech, 420mln transistor each

- Patterns for lithography are usually designed where **cells** are assembled in the devices and repeated on the wafer
- Layout of cells is designed according to layout or **design rules**:
  - smallest feature allowed
  - smallest spacing allowed
  - minimum overlap between the layers
  - minimum spacing to underlying topology
  - etc.

Optical Lithography Roadmap



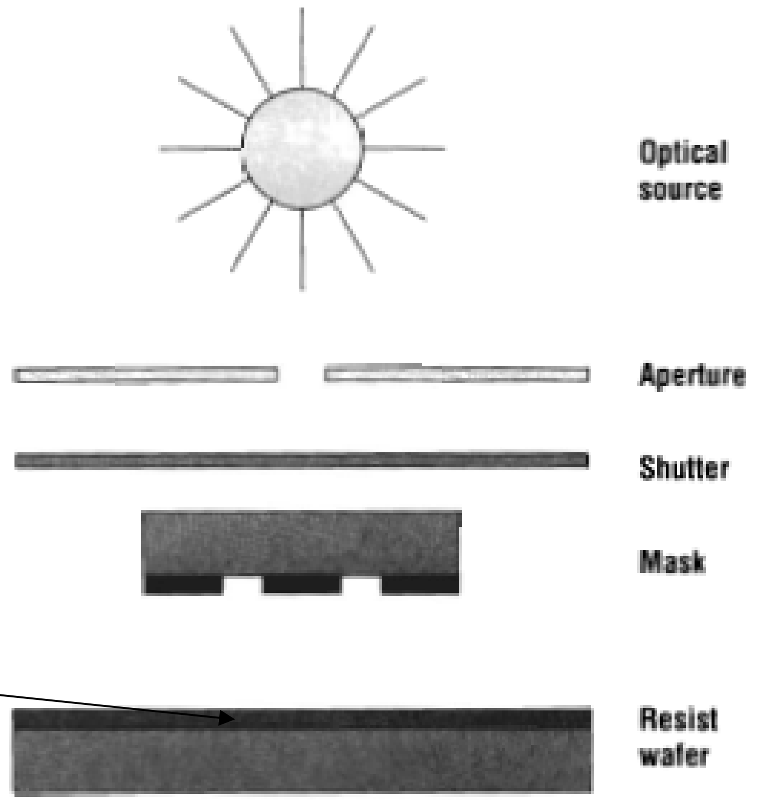
Today: Intel 45nm process, 157nm source
wafer in use: 300mm diam
processing steps per wafer: ~40

Costs:
Mask cost: $15000 - $300000 (!!!)
Optical tool: $20M

Lecture plan

- Diffraction and the resolution limits
- Modulation transfer function
- Light sources
- Contact/proximity printers: Mask Aligners
- Projection printers: Steppers
- Advanced techniques:
  - Phase-shift masks
  - Immersion lithography
  - Maskless lithography
  - Stencil lithography (“Resistless”)

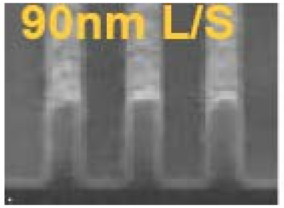
Simple exposure system



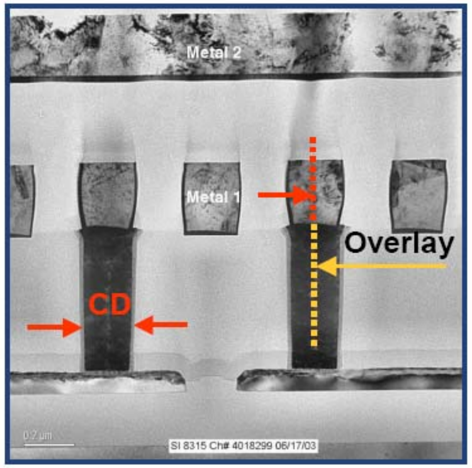
areal image of the mask

Figure 7.4 Schematic of a simple lithographic exposure system.

Performance issues



- Resolution: quoted as minimum feature size resolved maintaining a tolerance 6σ<10%



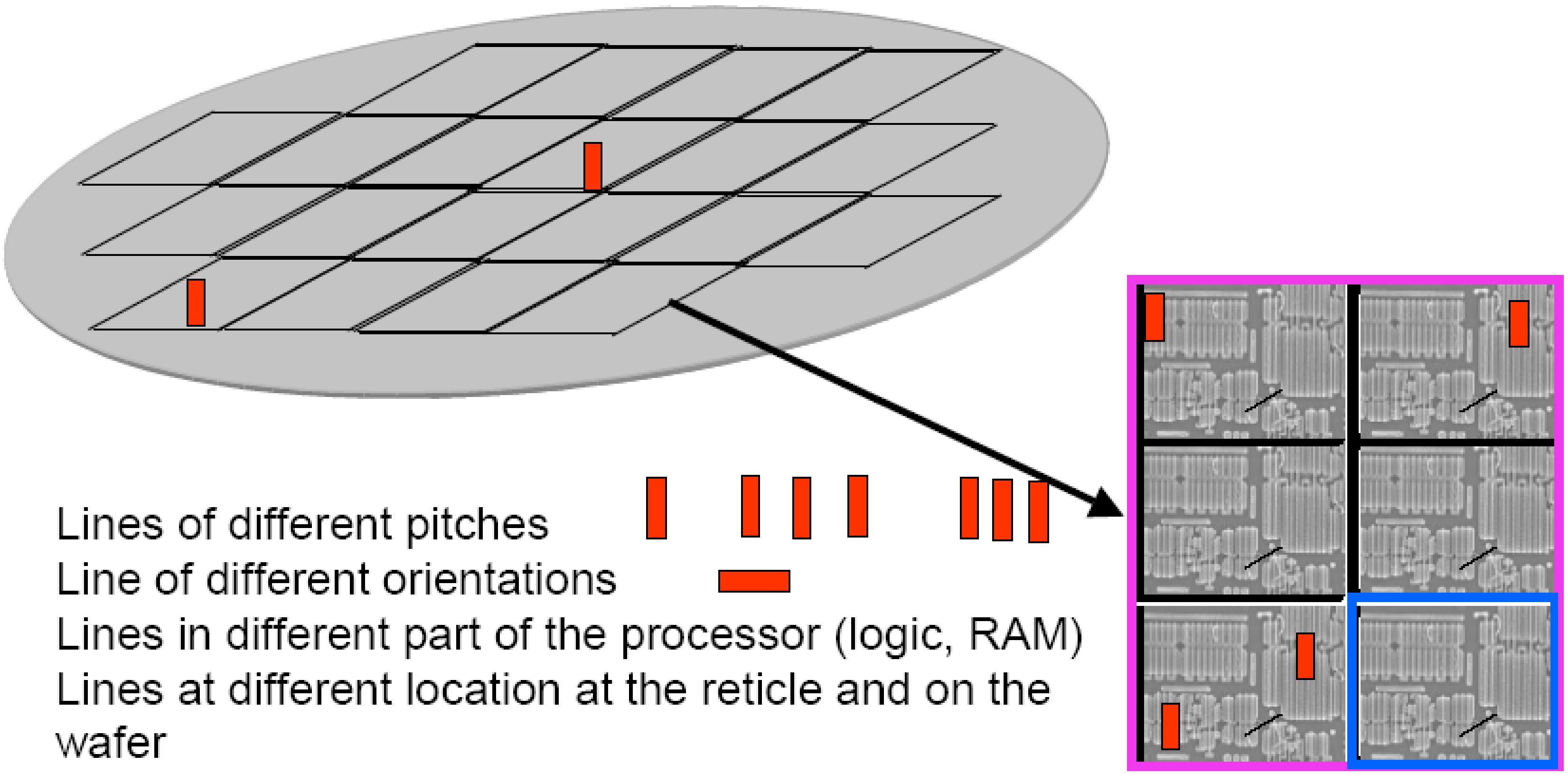
- Registration: measure of overlay accuracy, usually 6σ;
- Throughput: 50-100 wafer/h for optical, <1 for ebeam
- Variation (within the chip, within the waferm wafer to wafer etc.)

Table 7.2 The effects of some of the resist parameters on process outcomes

	Resolution	Registration	Wafer to Wafer Control	Batch to Batch Control	Throughput
Exposure system	XX	XX	X	XX	XX
Substrate	X	X	XX	X	X
Mask	X	X	—	X	X
Photoresist	XX	X	XX	XX	XX
Developer	X	—	XX	XX	X
Wetting agent	—	—	XX	X	—
Process	X	X	XX	XX	XX
Operator[a]	X	XX	XX	X	XX

Performance issues

Across chip linewidth variation:	**ACLV**	**goal: <5nm (3s)**
Across wafer linewidth variation.	**AWLV**	



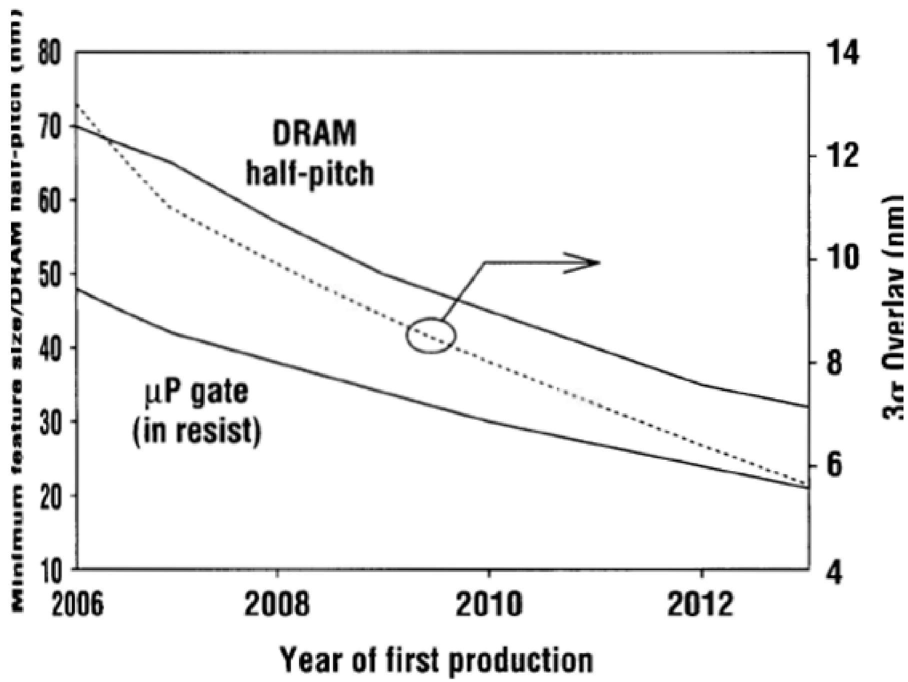
Lines of different pitches
Line of different orientations
Lines in different part of the processor (logic, RAM)
Lines at different location at the reticle and on the wafer

Where we are now?

- as in 2003 reported by AMD

	Development	Production
wavelength	193	193
NA	0.80	0.75
Resolution	70nm	90nm
Overlay	20nm	30nm
CD-uniformity	6nm	8nm

- current projections

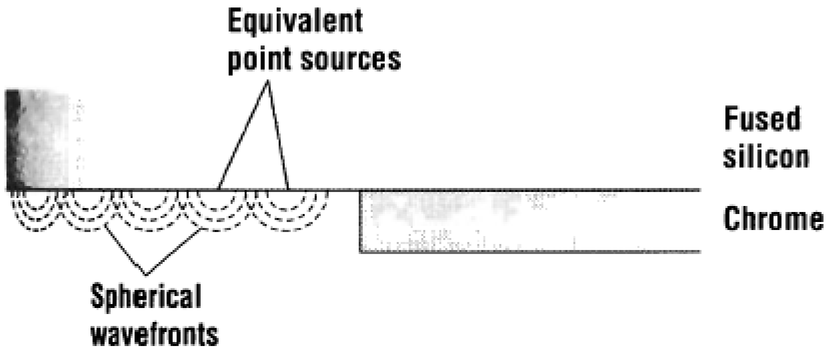


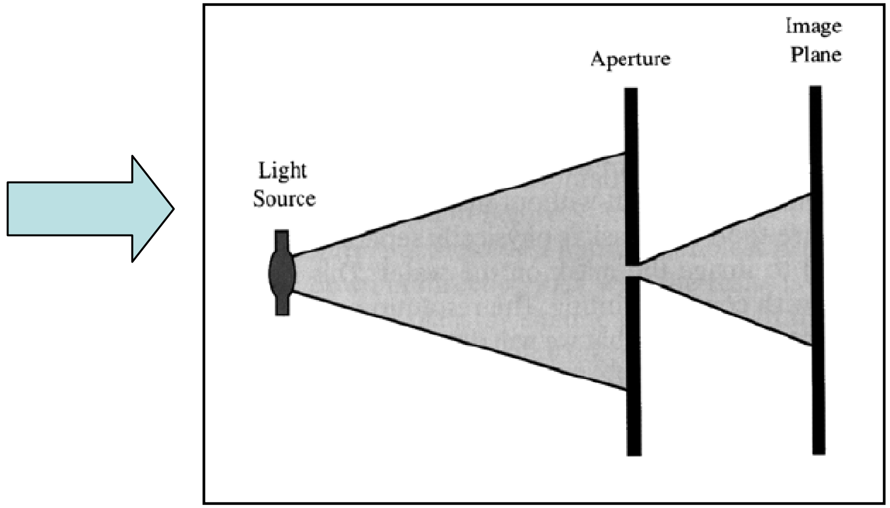
Requirements for the mask

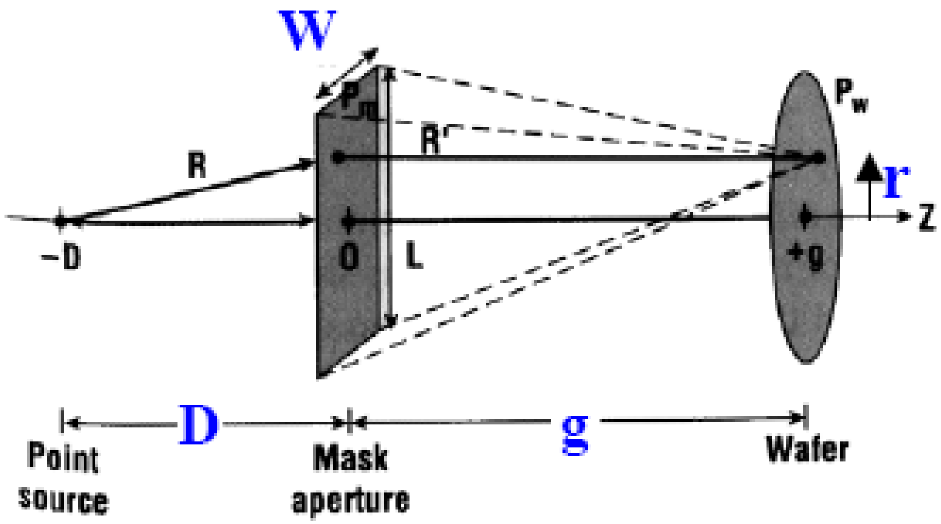
- Required properties:
  - high transparency at the exposure wavelength
  - small thermal expansion coefficient
  - flat highly polished surface
- Photomask material:
  - fused silica
  - glass (soda-lime) for NUV applications;
  - opaque layer: usually chromium

Resolution issues

- Huygens' Principle







Generally, at a point **r:**

$$E(\overline{r},\nu) = E_0(\overline{r})\exp(j\phi(\overline{r},\nu))$$

$$I(r) = \varepsilon_0 E^2(r)$$

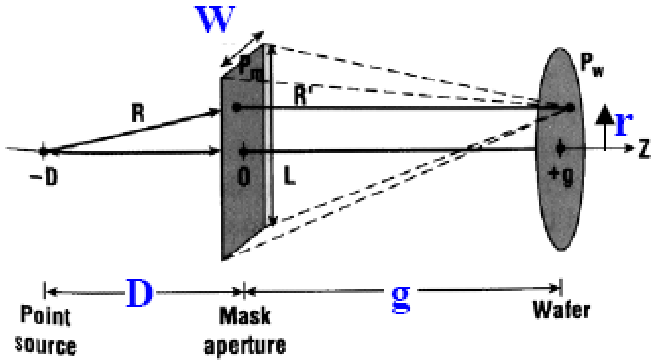
Waves from different sources will interfere with each other

$$I = E_1^{\ 2} + E_2^{\ 2} + E_1E_2\cos(\phi_1 - \phi_2)$$

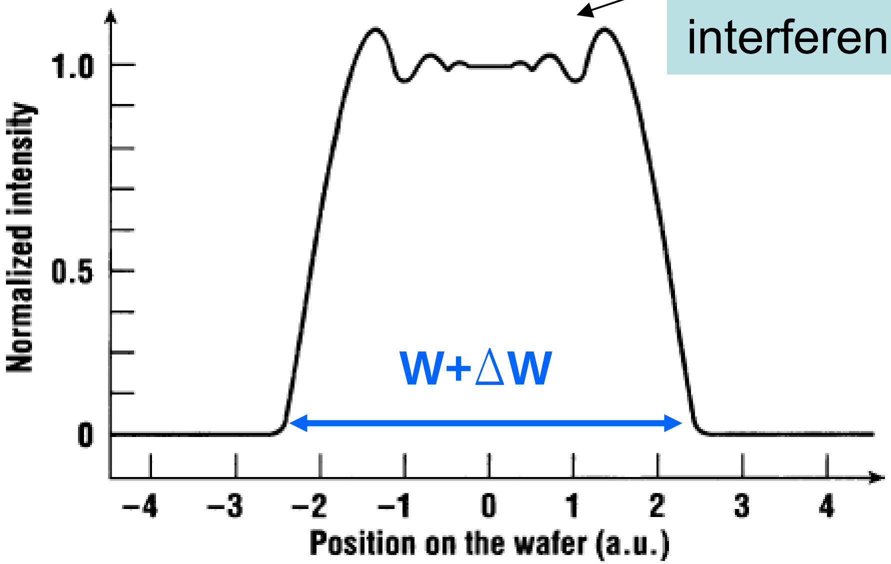
Resolution issues

- Near field (Mask close to wafer)
  Fresnel diffraction

$$W^2 \gg \lambda\sqrt{g^2 + r^2}$$



oscillations due to interference



if W is very large and ray tracing can be used:

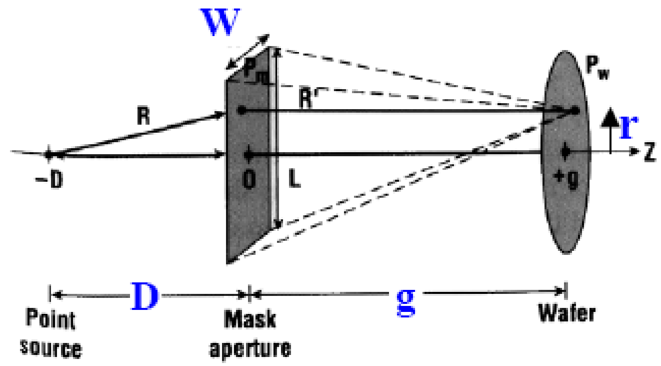
$$\Delta W = W\frac{g}{D}$$

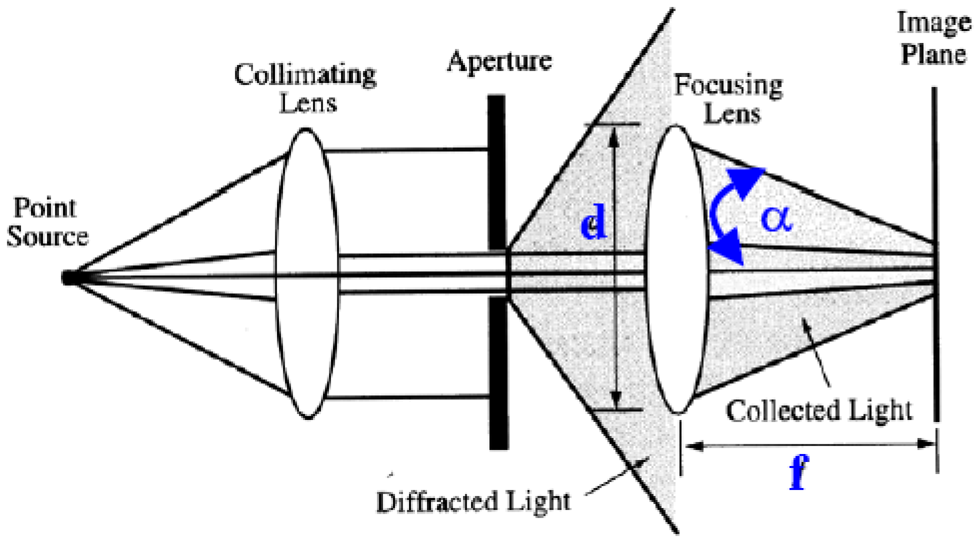
Resolution issues

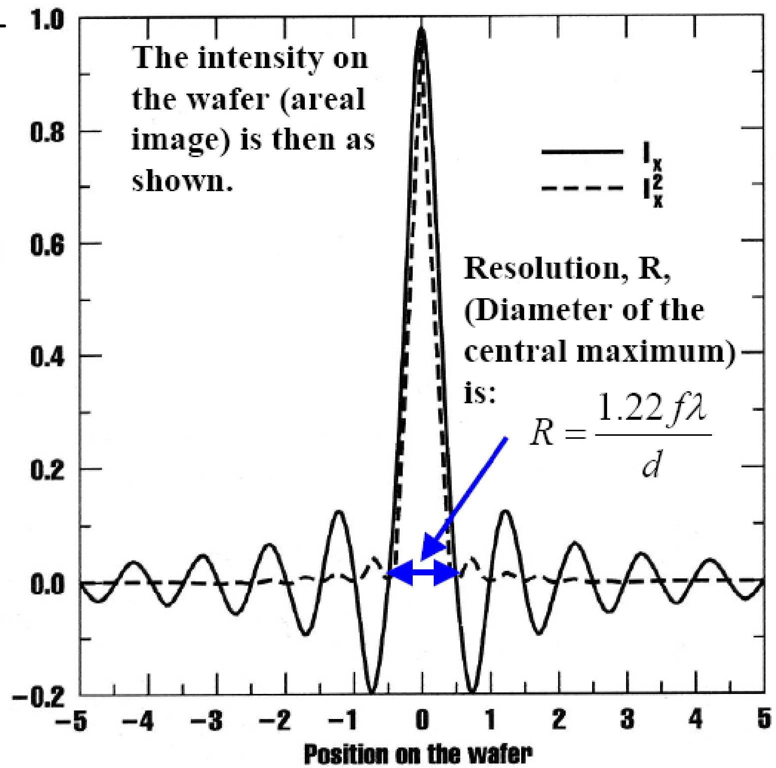
- Far field
  (Fraunhofer diffraction)

$$W^2 \ll \lambda\sqrt{g^2 + r^2}$$

$$I_x = \frac{\sin\left(2\pi xW/\lambda g\right)}{2\pi xW/\lambda g}; I_y = \frac{\sin\left(2\pi yL/\lambda g\right)}{2\pi yL/\lambda g}$$







Resolution issues

- Other complications:
  - light source is not a point
  - imperfection of optical components
  - reflection, adsorption, phase shift on the mask
  - reflection on the wafer
  - etc…

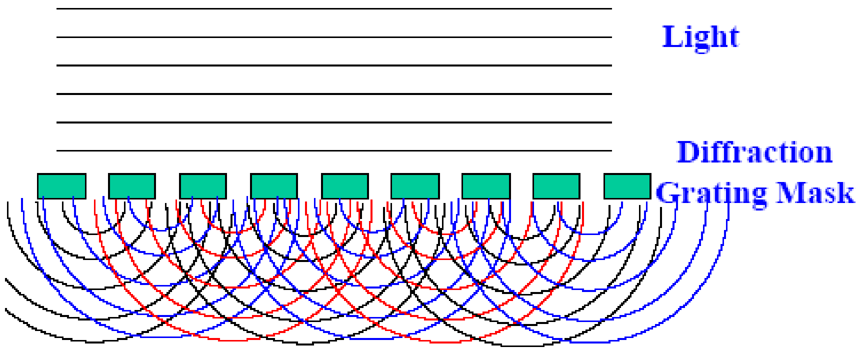
Resolution issues

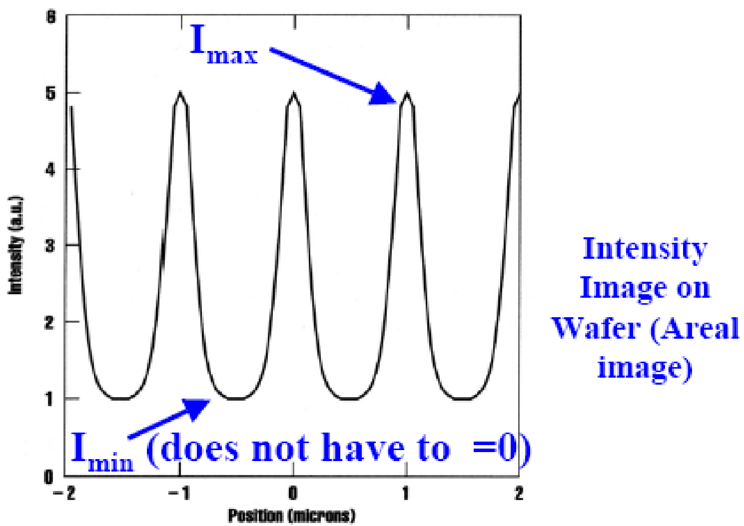
- Modulation transfer function (MTF)

$$MTF = \left(\frac{I_{max} - I_{\min}}{I_{max} + I_{\min}} \right)$$

⇦ measure of the optical contrast in the areal image

- The higher the MTF the better the contrast;
- The smaller the period of the grating, the lower is the MTF





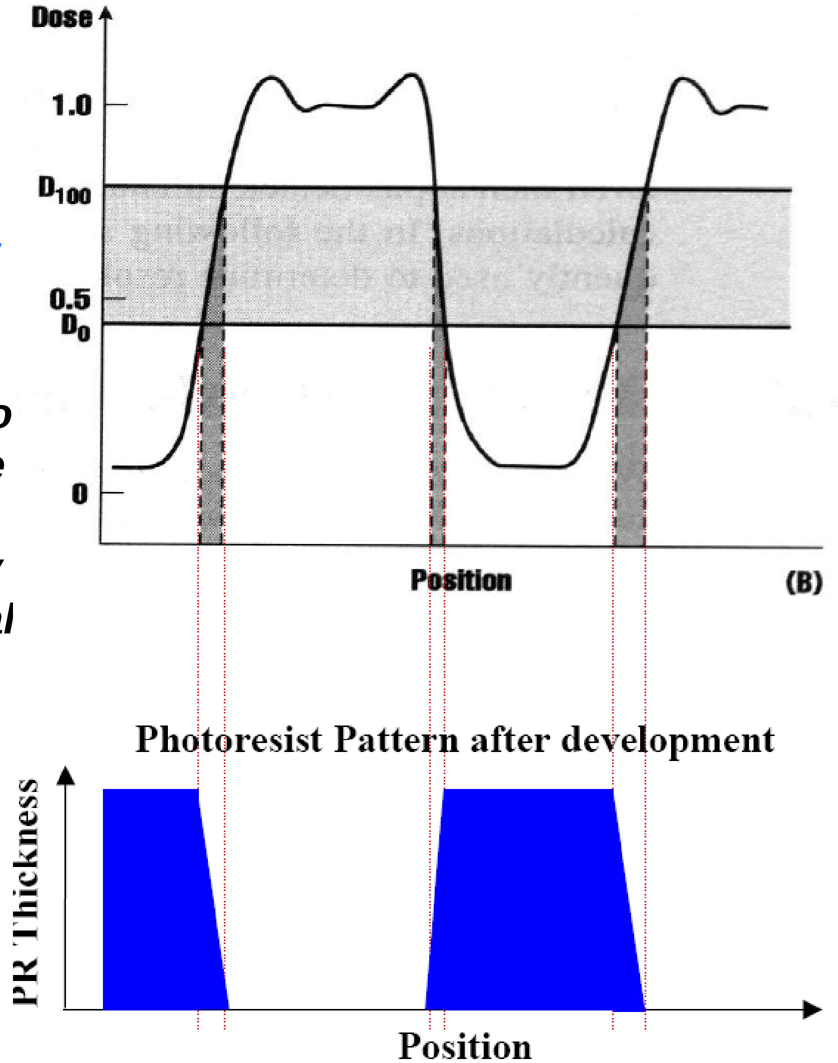
Resolution issues

The MTF uses the power density (W/cm2 or (J/sec)/cm^2). The resist responds to the total amount of energy absorbed.

Thus, we need to ***define the Dose, with units of energy density (mJ/cm^2), as the Intensity (or power density) times the exposure time.***

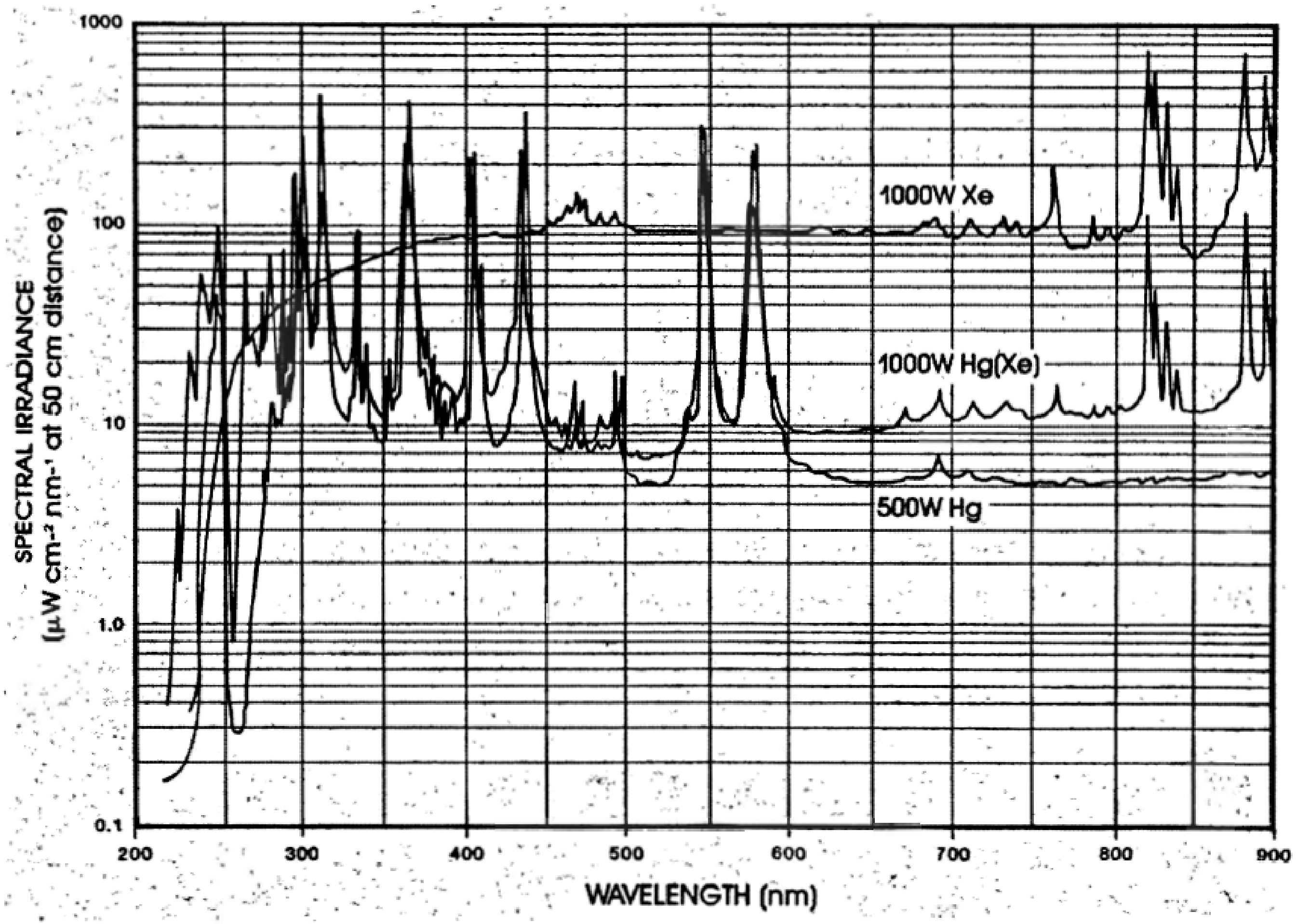
- We can also define ***D_{100}= the minimum dose fo which the photoresist will completely dissolve when developed***.
- We define ***D_0 as the maximum energy density for which the photoresist will not dissolve at al when developed***.
- Between these values, the photoresist will partially dissolve.

Commonly, image with the MTF lower than 0.4 cannot be reproduced (of course depend on the resist system



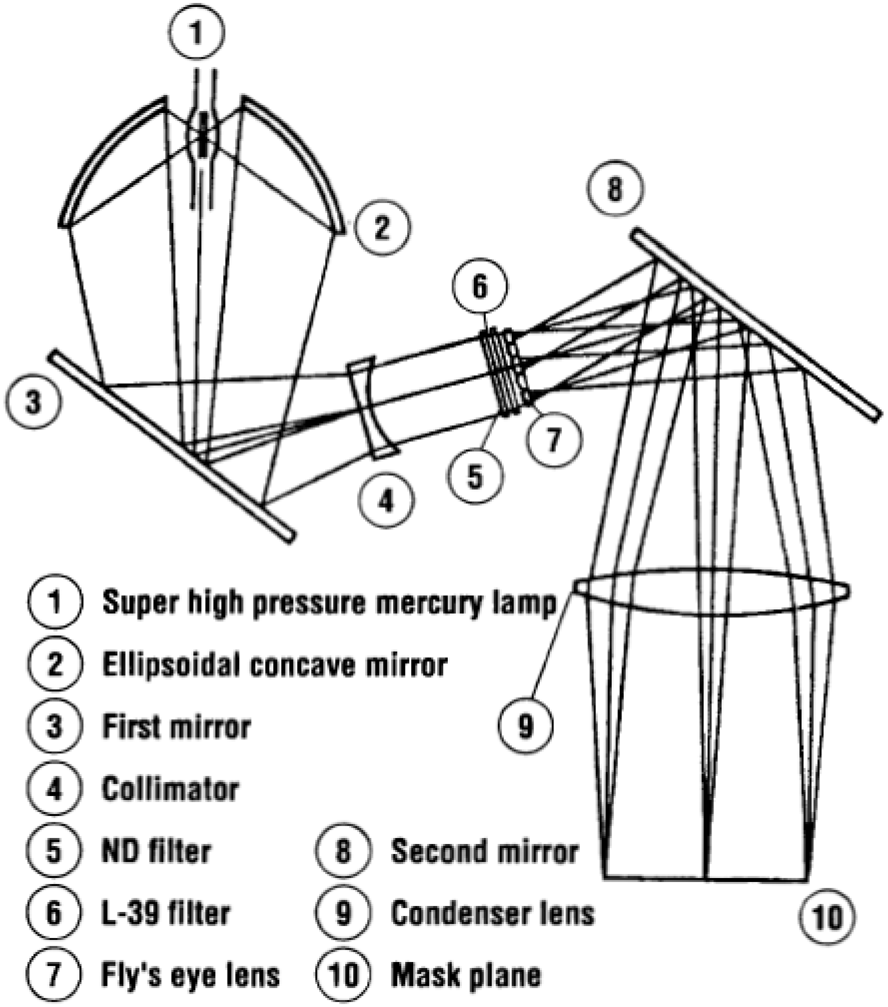
Light Source

- Typically mercury (Hg)- Xenon (Xe) vapor bulbs are used as a light source in visible (>420 nm) and ultraviolet (>250-300 nm and <420 nm) lithography equipment.
- Light is generated by: gray body radiation of electrons (40000K, lmax=75nm, absorbed by fused silica envelop, impurities added to reduce ozon production) and electron transitions in Hg/Xe atoms
- Often particular lines are filtered: 436 nm (g-line), 365 (i-line), 290, 280, 265 and 248 nm.



Light Source

- Schematics of contact/proximity printer

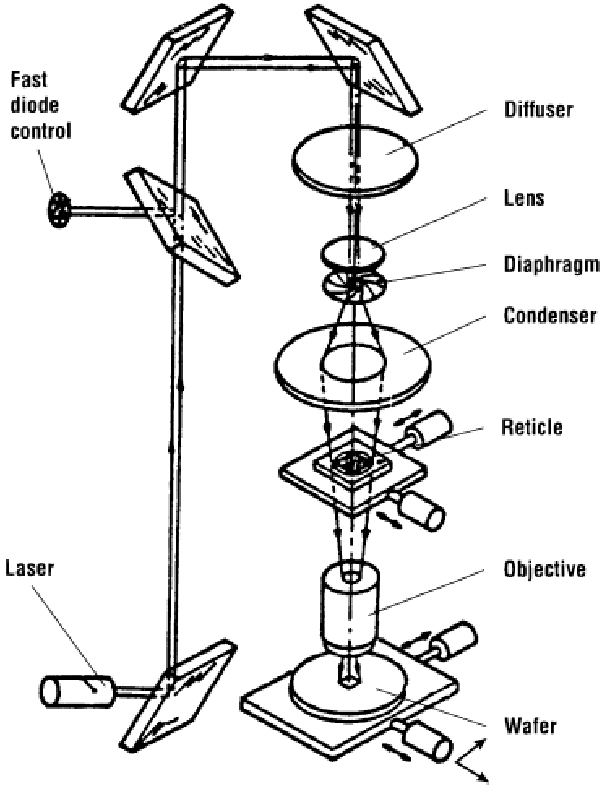


Light Sources

- Excimer lasers (excited dimers):
  - brightest optical sources in UV
  - based on excitation and breakage of dimeric molecules (like F_2, XeCl etc.)
  - pumped by strobed 10-20 kV arc lamps

$$Xe^* + Cl_2 \rightarrow XeCl^* + Cl$$

Material	Wavelength (nm)	Max Output (mJ/pulse)	Frequency (pulse/sec)
F_2	157	40	500
ArF	193	10	2000
KrF	248	10	2000

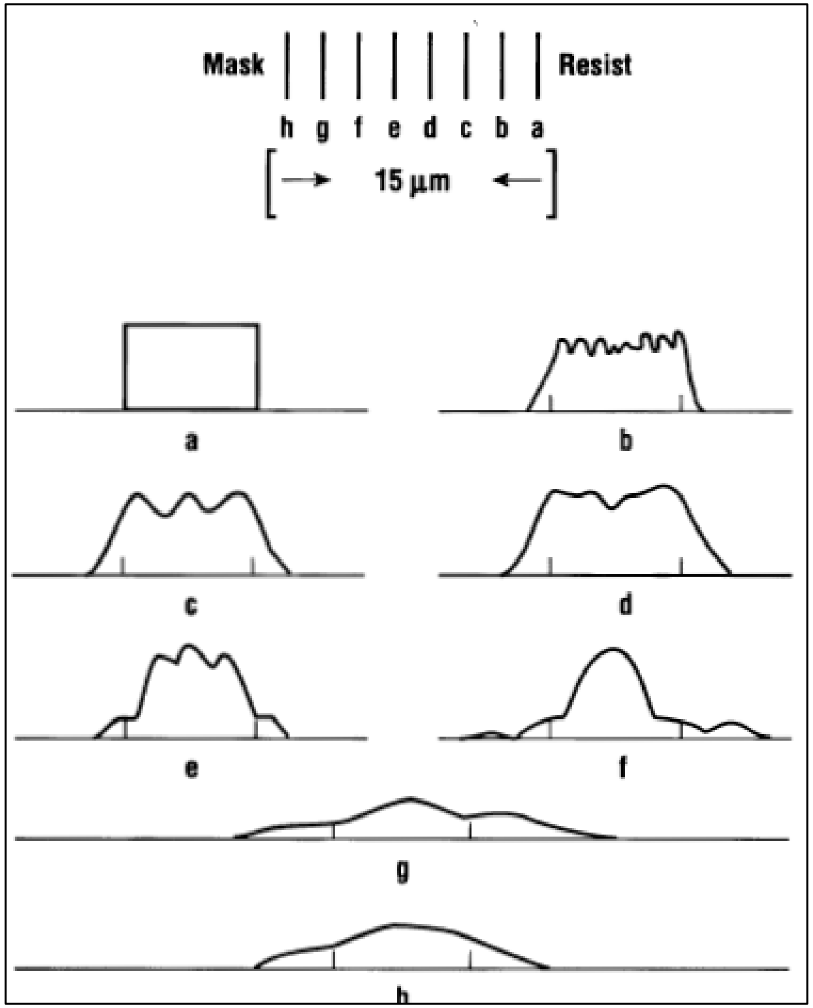


Contact/proximity printers

- Example: Carl Suss MA6 system

MA6 Resolution	UV400	UV300	UV250
Vacuum Contact	0.7 µm 0.6 µm*	0.5 µm 0.4 µm*	< 0.5 µm 0.3 µm*
Hard Contact	1.0 µm	<1.0 µm	–
Soft Contact	2.0 µm	<2.0 µm	–
Proximity	2.5 µm	<2.5 µm	–

Contact/proximity printers



- intensity vs. wafer position

$$W \approx \sqrt{k\lambda g}$$

constant ~1, depending on resist process

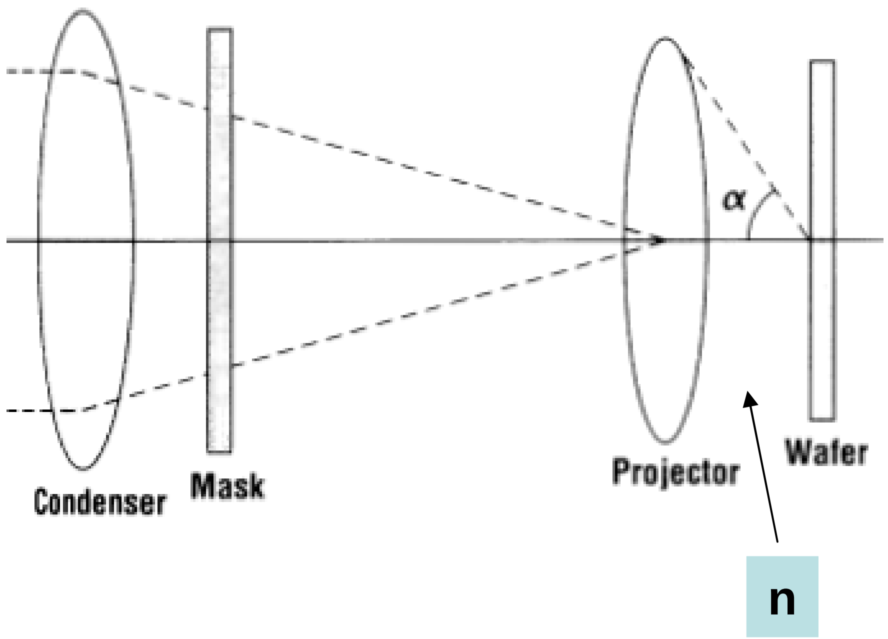
Example: for k=1 and λ=0.365

W_{min}	g (gap)
2.7 um	20 um
1.9 um	10 um
1.35 um	5 um
0.6 um	1 um

Projection printers

- Rayleigh's criteria

$$NA = n\sin(\alpha)$$

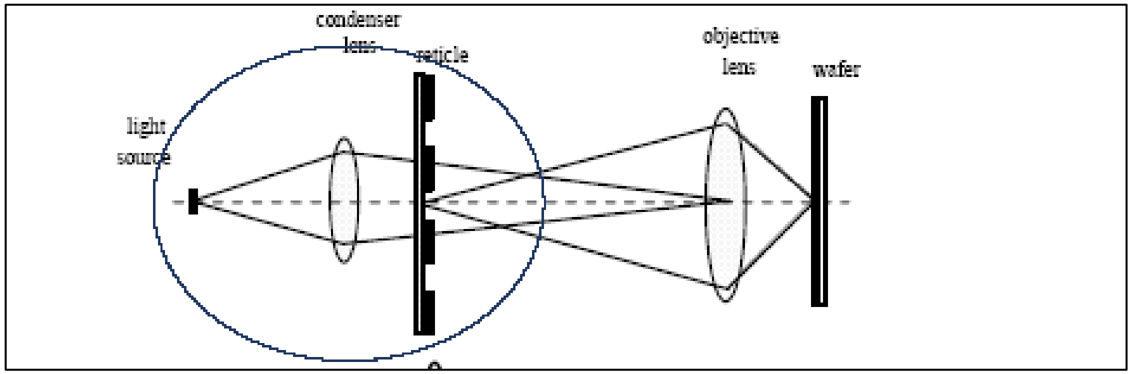


$$W_{\min} \approx k\frac{\lambda}{NA}$$

k is typically 0.8 – 0.4

$$DOF \approx \frac{n\lambda}{NA^2}$$

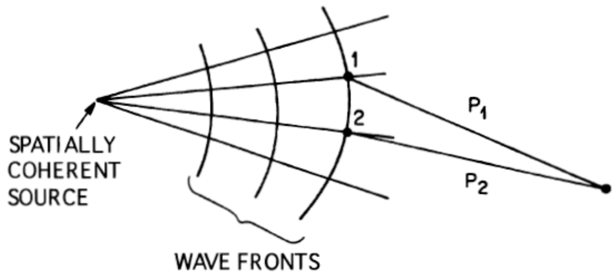
Köhler illumination

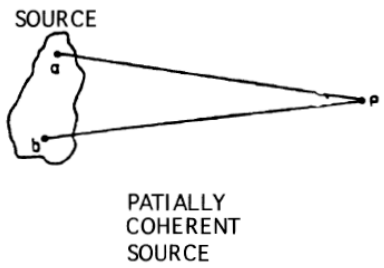


Projection printers

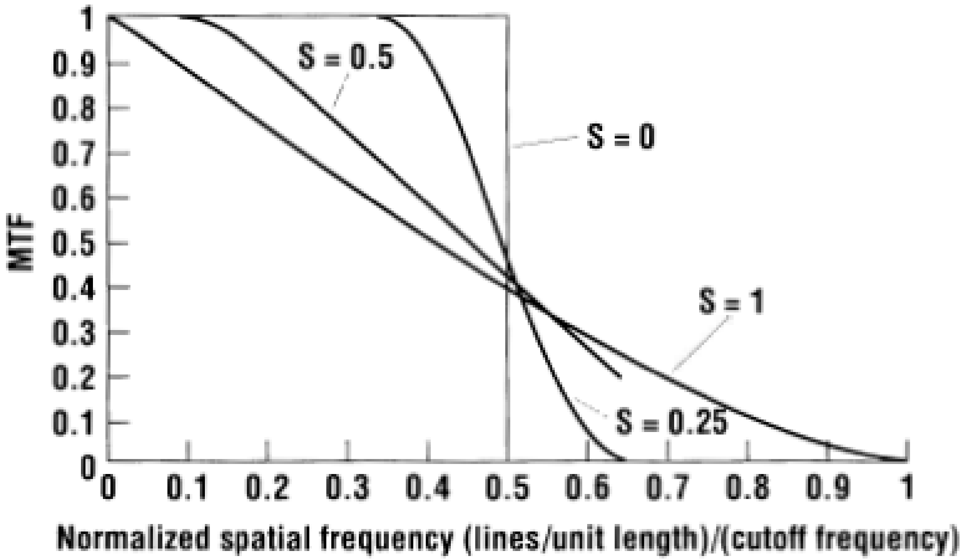
- Finite source effect: Dependence on the spatial coherence of the source

For a source of finite size light will arrive with a different phase from different parts





$$S = \frac{\text{source image diameter}}{\text{pupil diameter}}$$



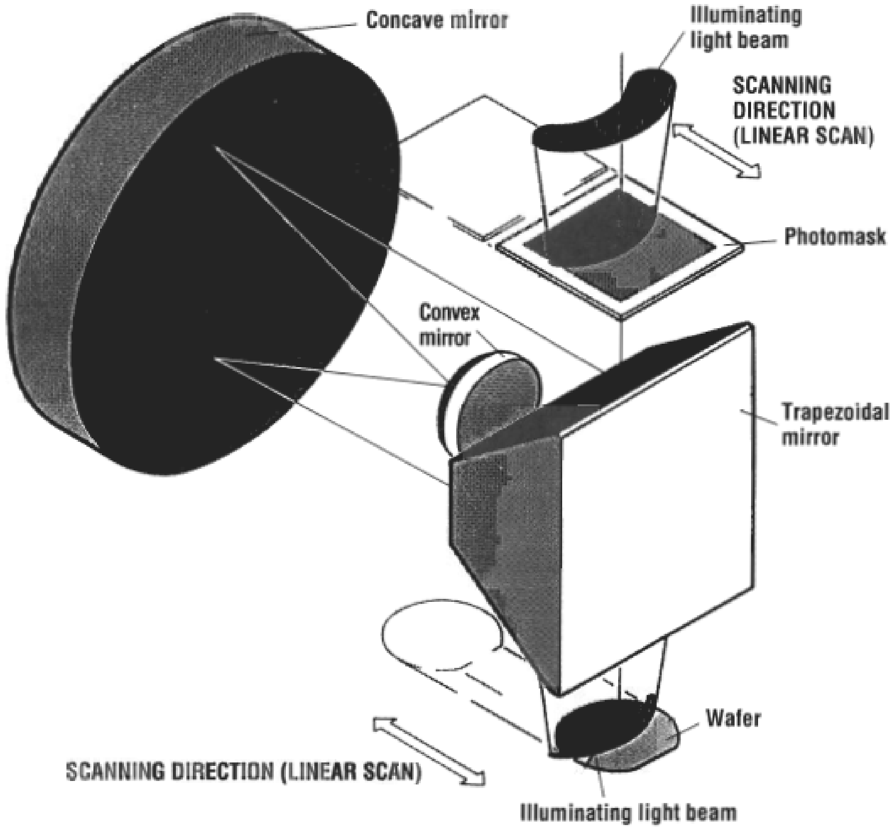
spatial frequency:

$$\nu_{ap} = \frac{1}{2W}$$

$$\nu_0 = \frac{1}{W_0} = \frac{NA}{0.61\lambda}$$

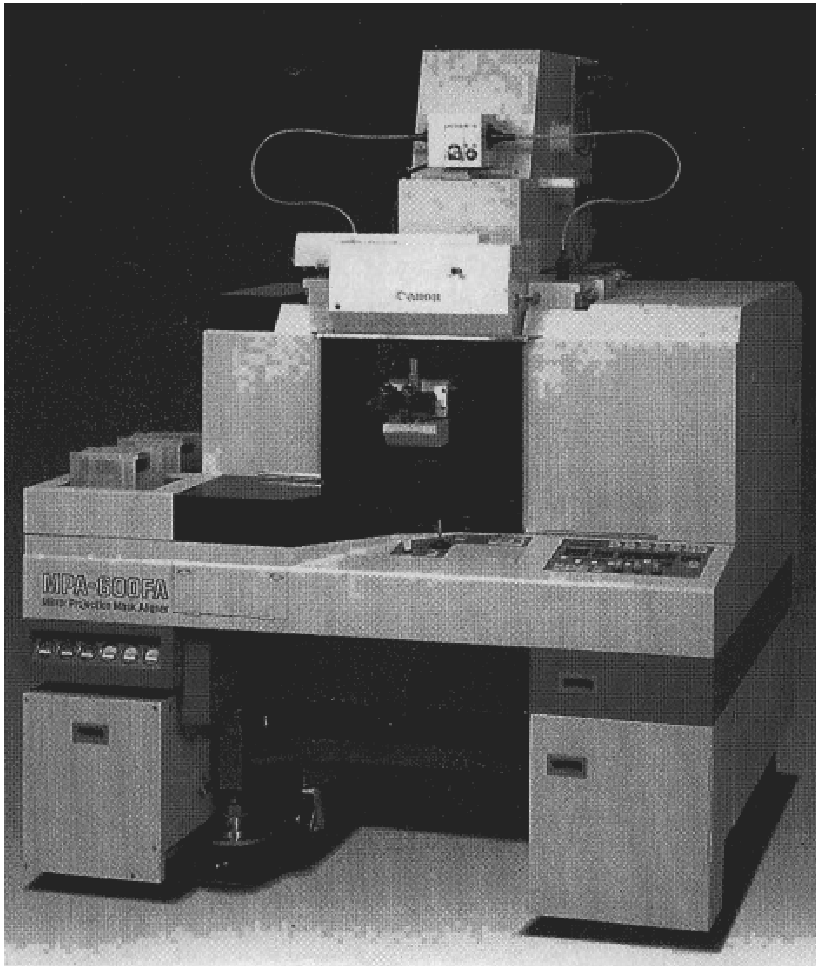
Projection printers

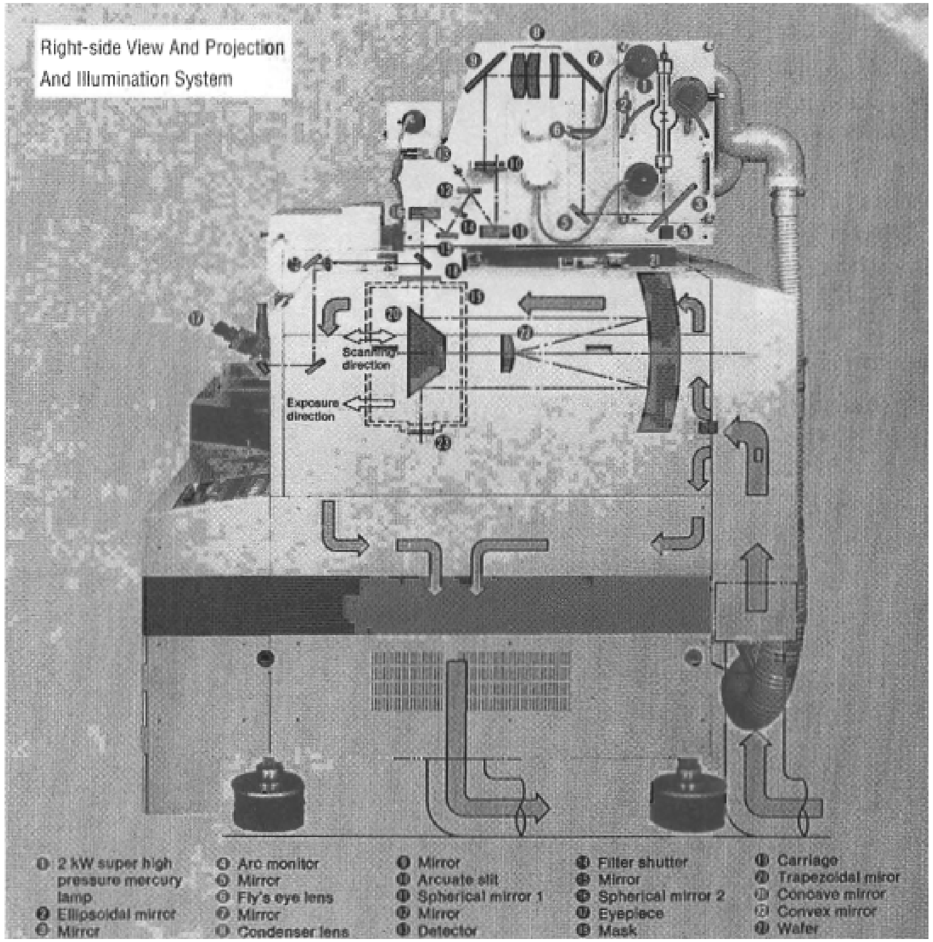
- 1:1 projection printers (1970)
  - completely reflective optics (+)
  - NA~0.16
  - very high throughput
  - resolution ~2um
  - global alignment



Projection printers

- Canon 1x mirror projection system





Projection printers: steppers

- small region of wafer (field 0.5-3 cm2) is exposed at a time
- high NA possible
- field leveling possible (so, high NA can be used)
- Throughput

$$T = \frac{1}{O + n*[E + M + S + A + F]}$$

PAS 5500/750F DUV Step & Scan system

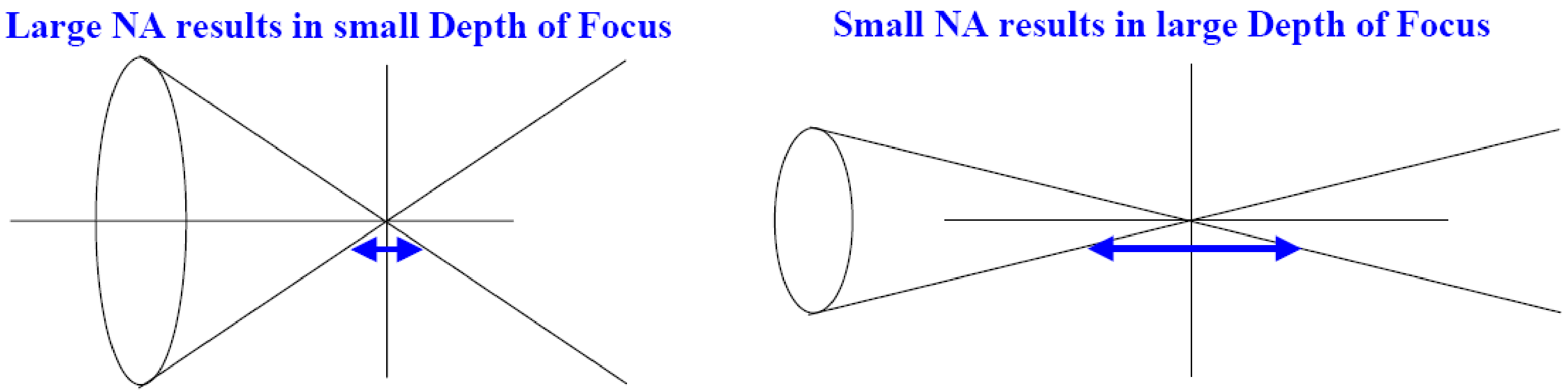
- 1:4 reduction of patterns
- Resolution down to 65 nm

- Very expensive (20 Mio. €)
- High throughput (50 wafers/h)

Resolution improvement

$$W_{\min} \approx k \frac{\lambda}{NA}$$

- reducing wavelength (193nm -> 157nm ->13.6 nm)
- increasing NA (but also decreasing the DOF)



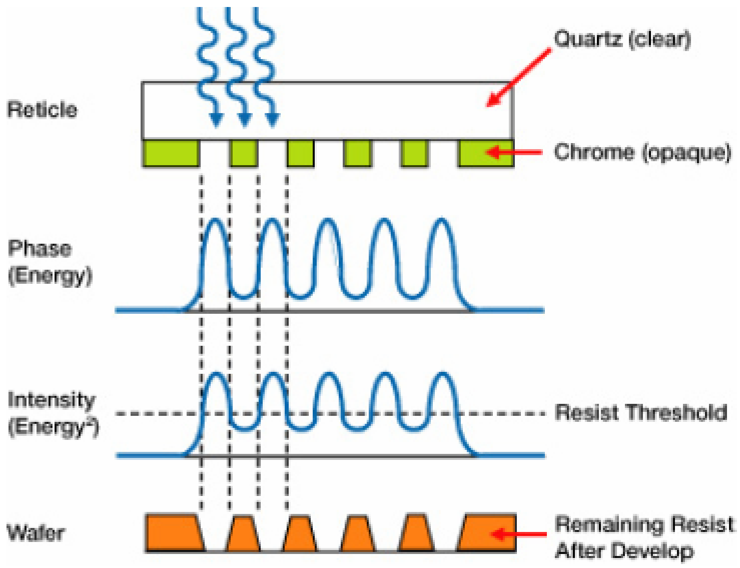
Variations in surface heights of a processed wafer must be less than the optical Depth of Focus. Thus, for high resolution lithography the surface must be planar (flat).

- reducing **k** (depends on resist, mask, illumination, can be decreased from 1 down to 0.3….)

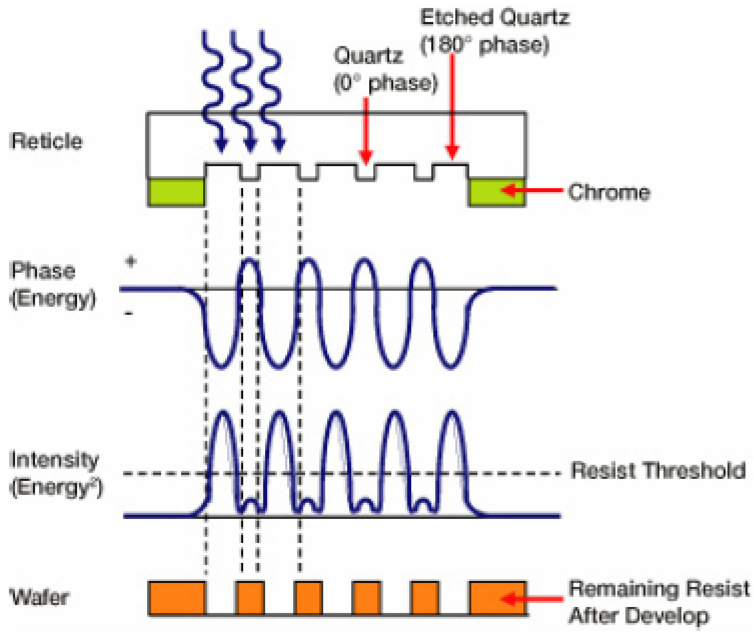
Advance mask concepts

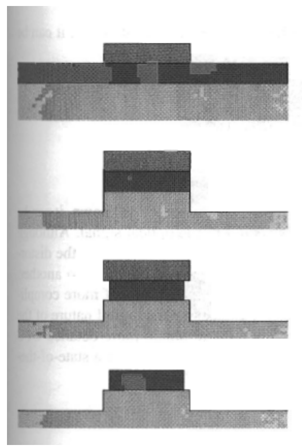
- resolution improvement: phase shift mask

Amplitude mask



Phase shift mask



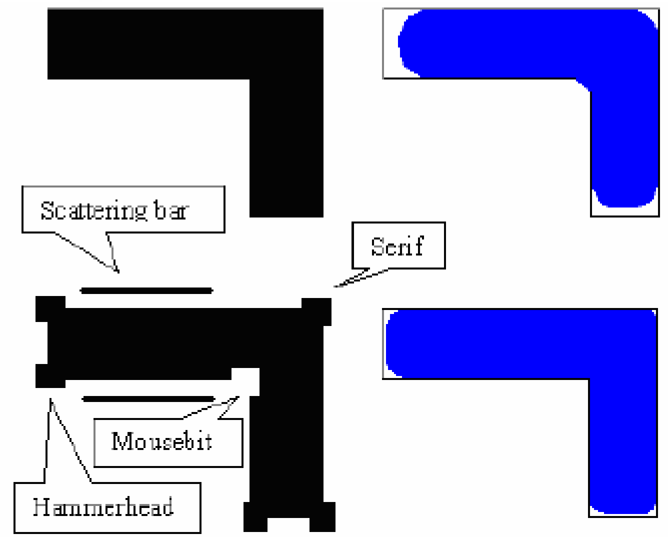


Introduction of phase shifting regions on mask creates real zeros of the electrical field on the wafer => increased contrast

Advance mask concepts

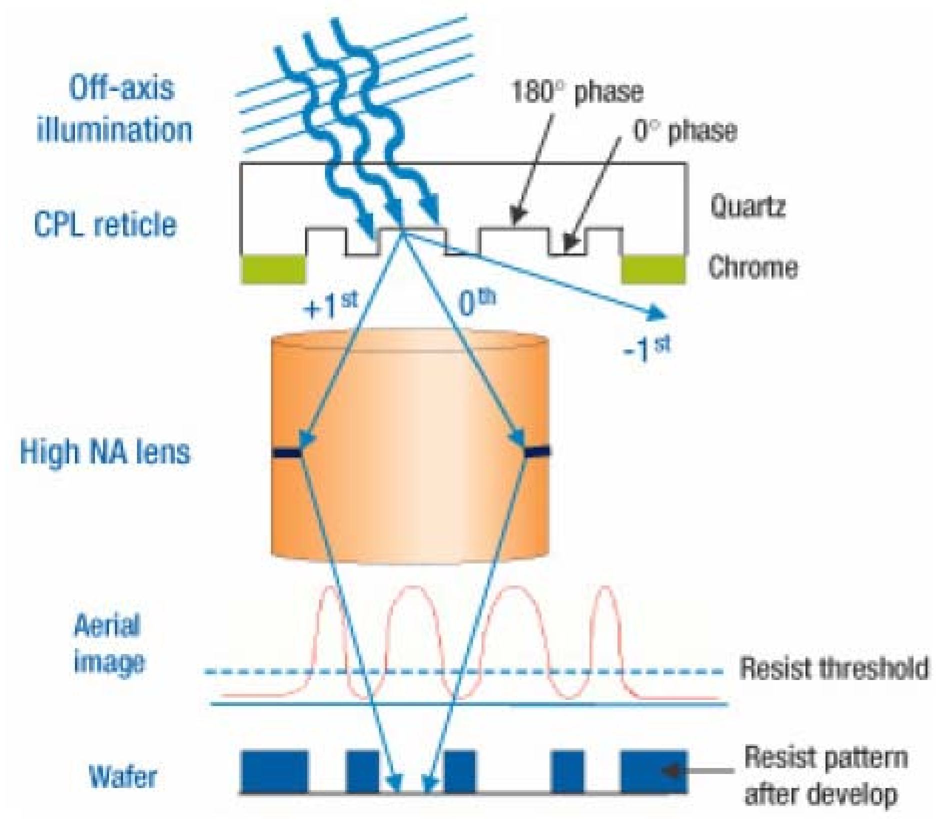
- Optical proximity correction (OPC)

Patterns are distorted on mask in order to compensate limited resolution of optical system



Advance mask concepts

- Off-axis illumination



Illumination under an angle brings enables transmission of first diffraction order through optical system

Surface reflection and standing waves

- reflection of surface topography features leads to poorly controlled linewidth

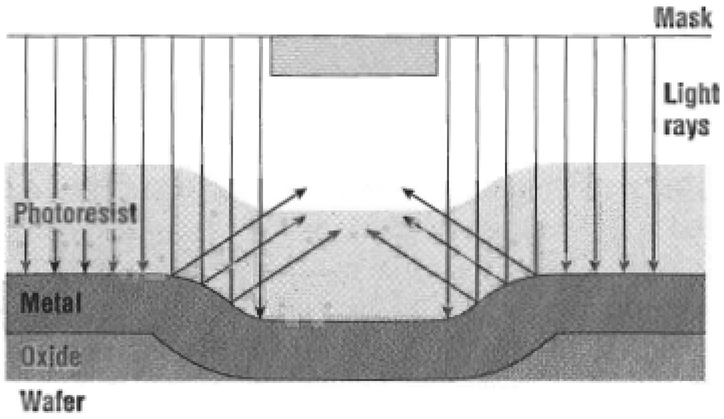
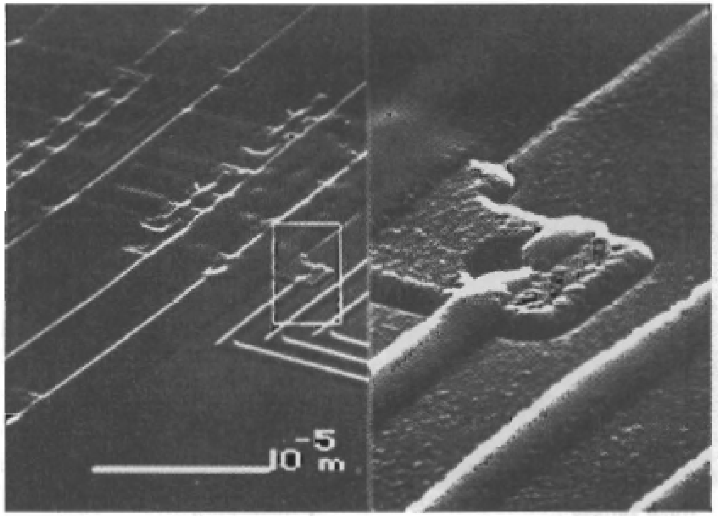


Figure 7.24 Light from the exposed regions can be reflected by wafer topology and be absorbed in the resist in nominally unexposed regions.



- standing waves can be formed

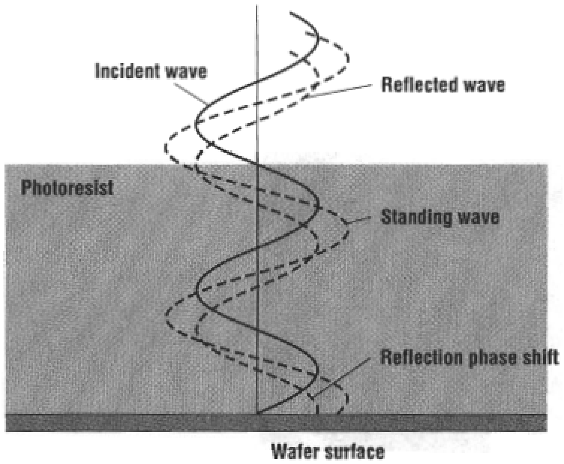
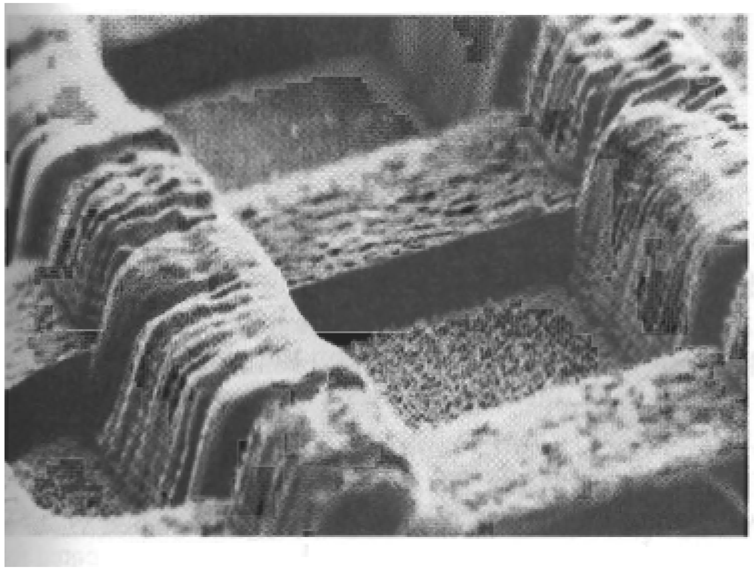
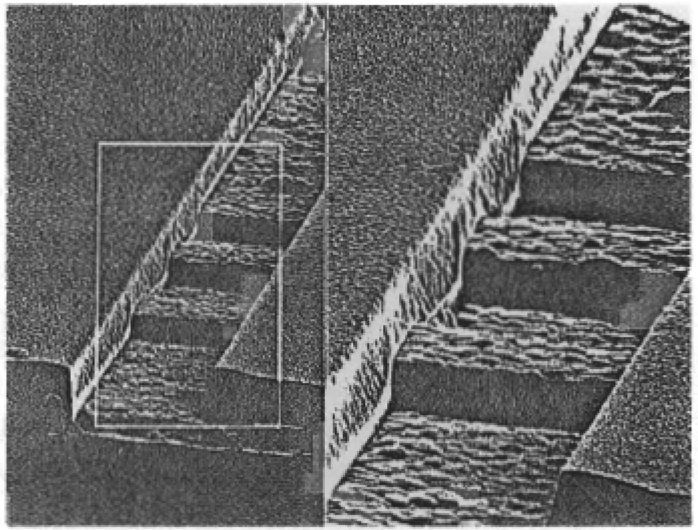


Figure 7.27 The formation of standing waves in the resist.

Surface reflection and standing waves

- Solution: antireflection coating on the wafer and/or on the resist (bottom/top ARC)



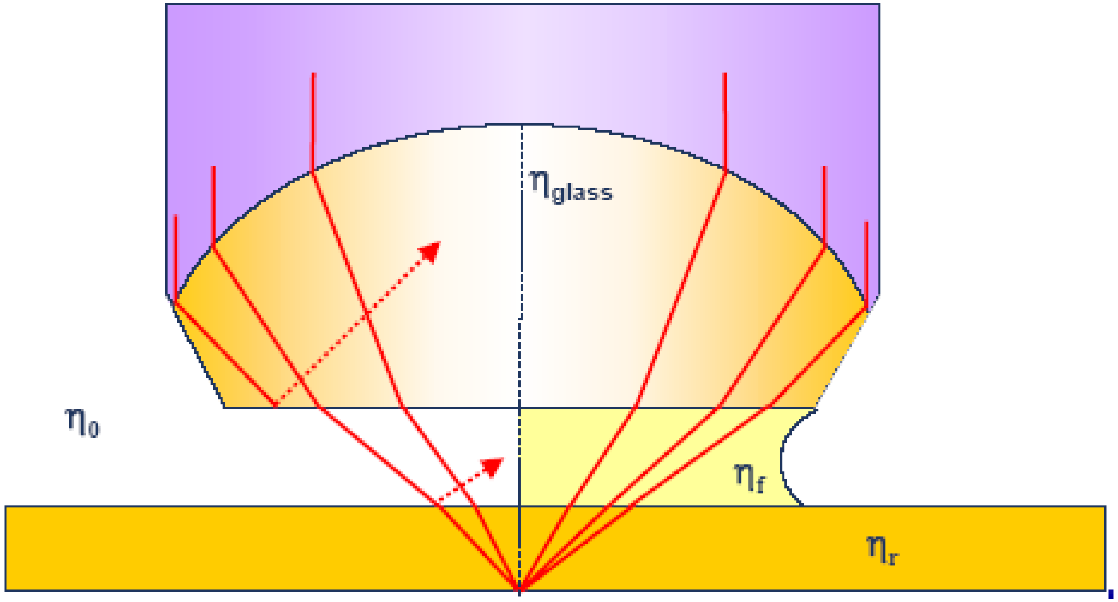


Immersion lithography

Immersion lithography

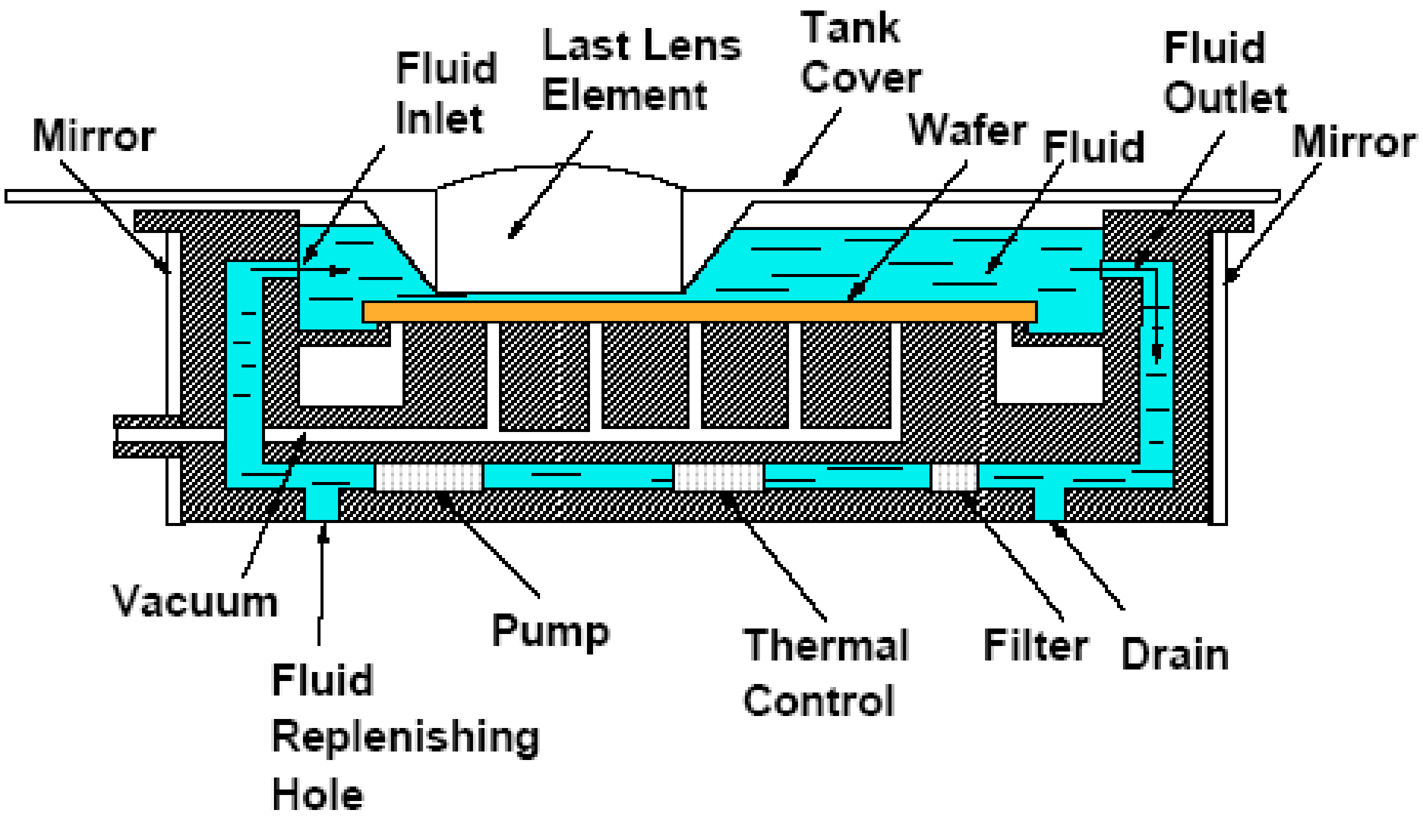
- **improvement in resolution**

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



Immersion lithography

- **concept**

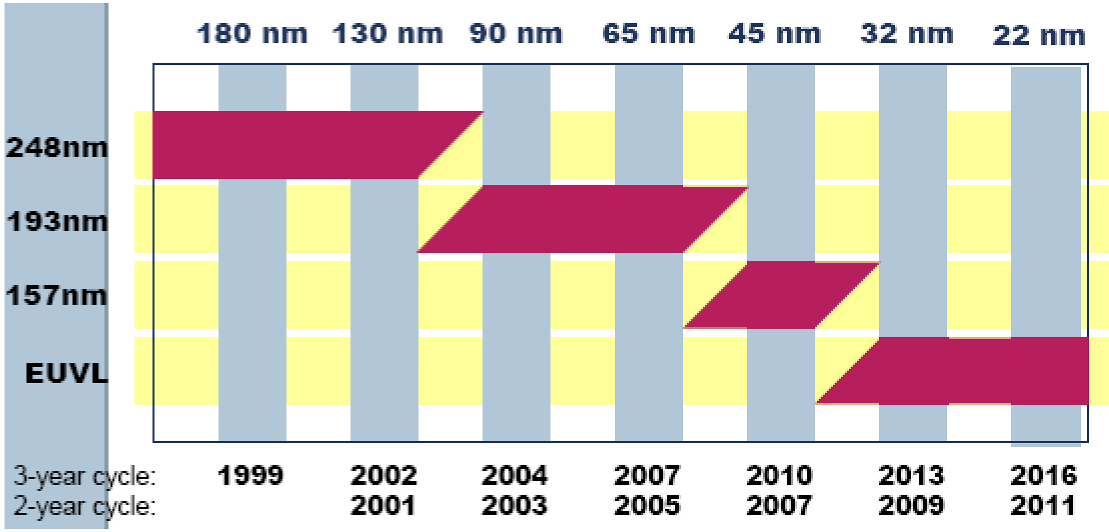


After B.J. Lin

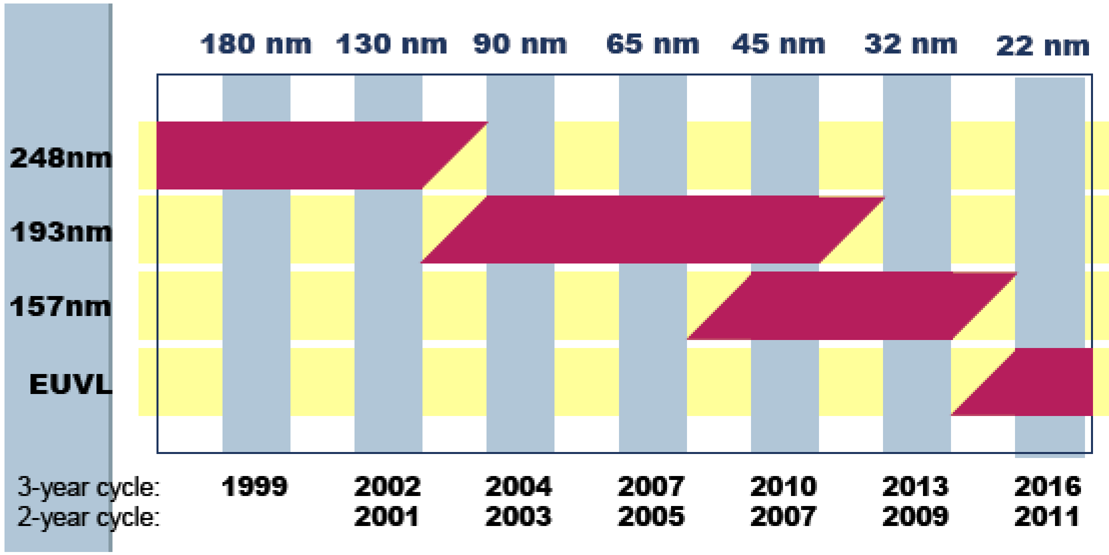
Fluid:	193nm	water
	157nm	polyfluoropolyether

Immersion lithography roadmap

without immersion



with immersion



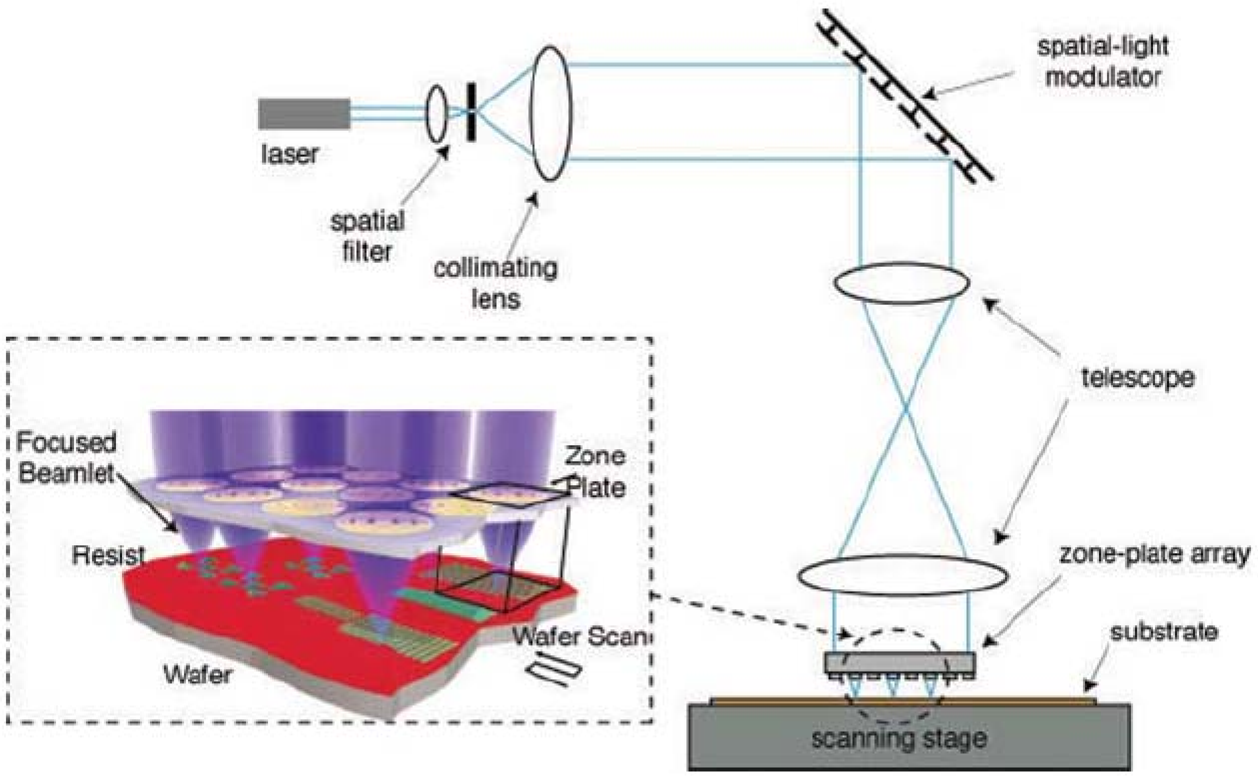
Current Technology and Trends

Half pitch	Max NA	K_1 today	K_1 ultimate	K_1 phys. limit
ArF 193nm	0.92	0.35 73 nm	0.3 63 nm	0.25 52 nm
F2 157nm	0.92	0.35 60 nm	0.3 51 nm	0.25 43 nm
EUV 13.6nm	0.25	0.7 38 nm	0.5 27 nm	0.25 14 nm

new systems under development → (EUV 13.6nm)

Maskless lithography

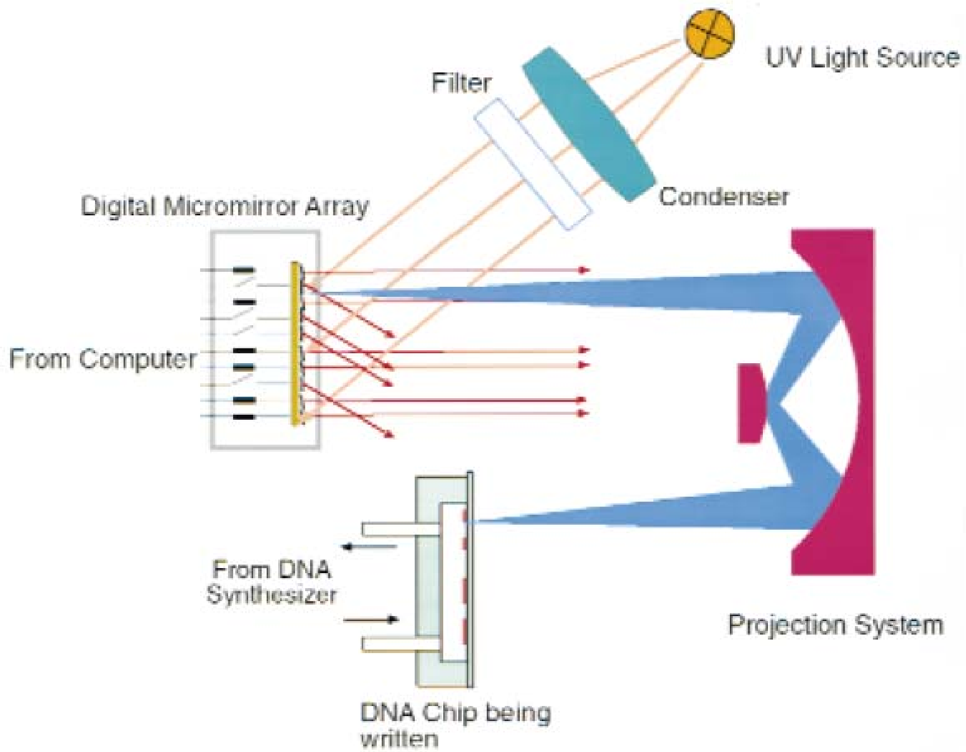
- For low volume production maskless lithography can be advantageous (mainly due to high mask cost: per wafer cost ~$500 ($300 for the mask!)

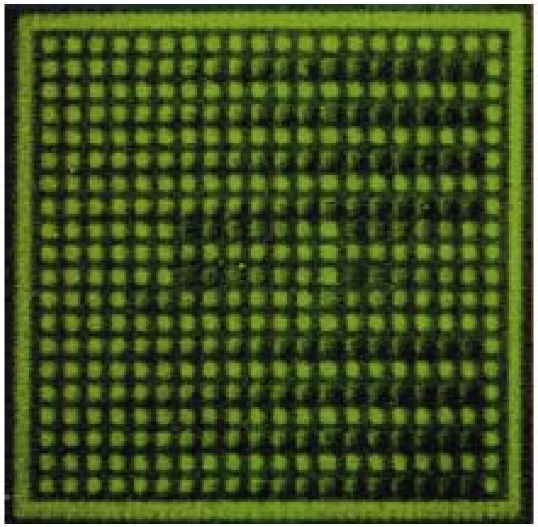


H. Smith, MIT
see R. Menon et al, Materials Today 4, p.26 (2005)

Fabrication of DNA arrays w. maskless lithography

Fabrication of DNA array requires many lithographic steps (equal to number of bp), arrays are made on demand ⇨ good candidate for maskless lithography

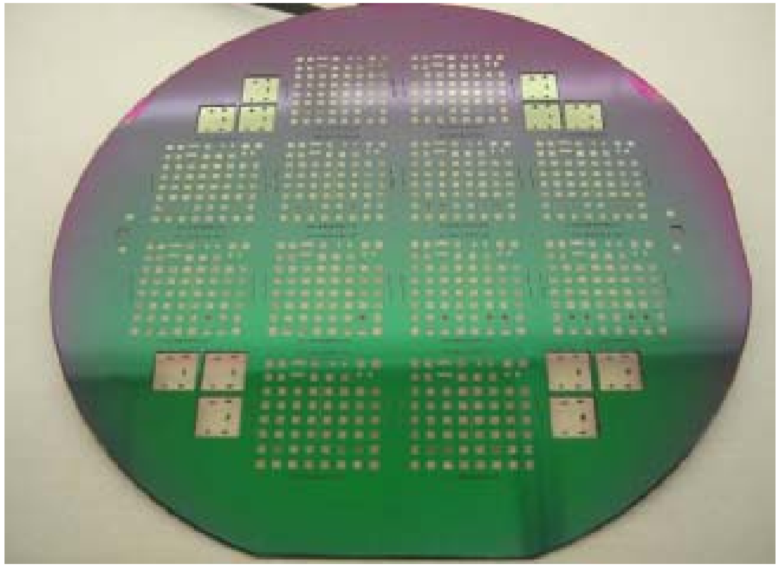


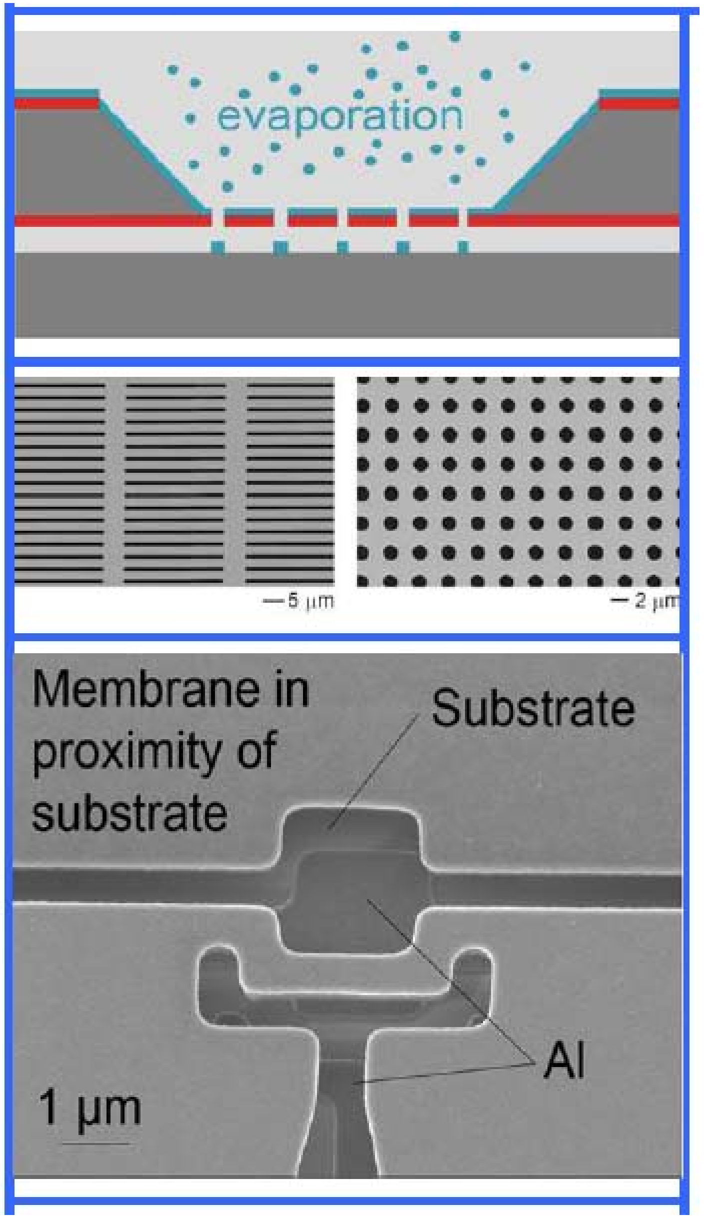


S. Singh-Gasson et al, Nature Biotech., 17, p.974 (1999)

Stencil lithography

biological or fragile object (e.g. membranes) might be damaged by standard resist processing techniques. Stencil lithography ("resistless") can be advantageous for those objects.





ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Problems

- Campbell 7.4:
  In an effort to make a relatively inexpensive aligner, capable of producing very small features an optical source of a simple contact printer is replaced with ArF laser.
  - list 2 problems that the engineer is likely to encounter in trying to use this device, assume yield is unimportant
  - assume the resist constant 0.8 for the process and the gap equal to resist thickness in hard contact. What is the minimum feature size for 1um resist
  - How thin the resist should be made to achieve 0.1um resolution
- Campbell 7.8
  A particular resist process is able to resolve features whose MTF≥0.3. Using fig 7.22 calculate the minimum feature size for an i-line aligner with NA=9.4 and S=0.5