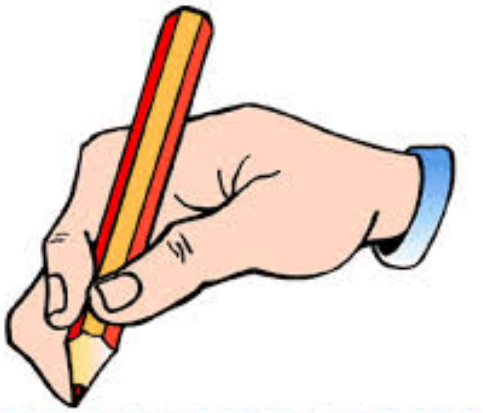
EEE6395 Photolithography



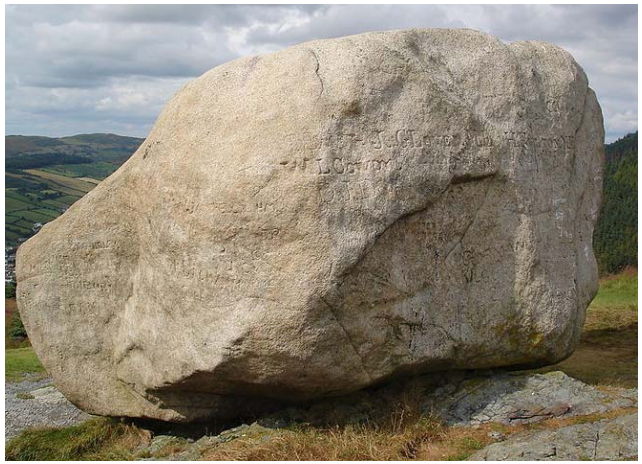
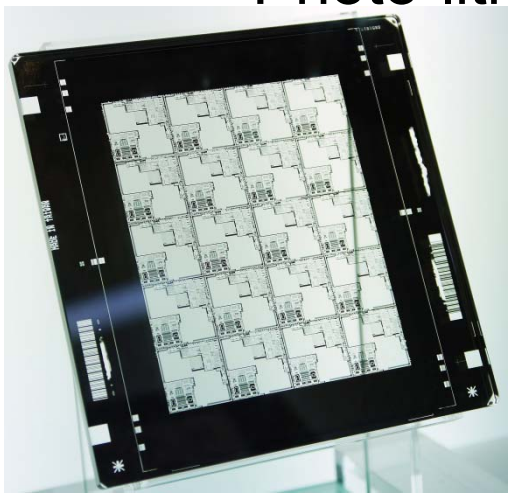
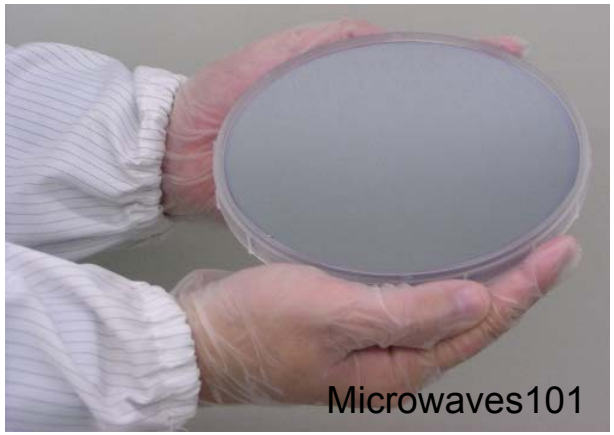


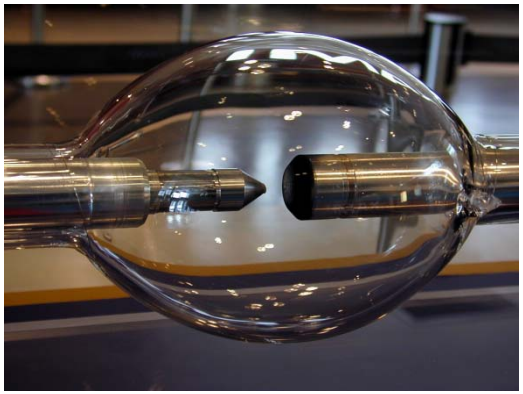
Photo-litho-graphy = Writing on stone using light



Mask

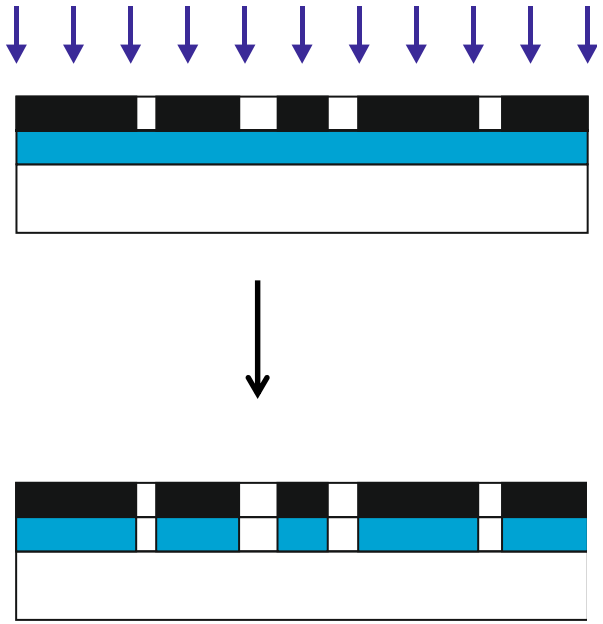


Wafer



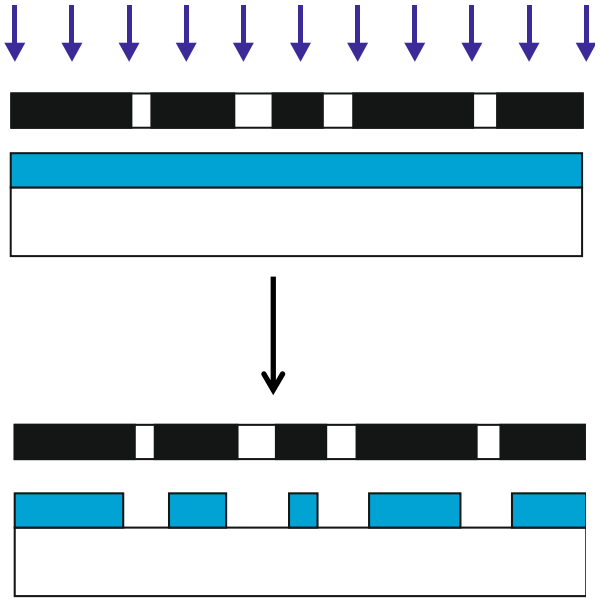
Arc lamp

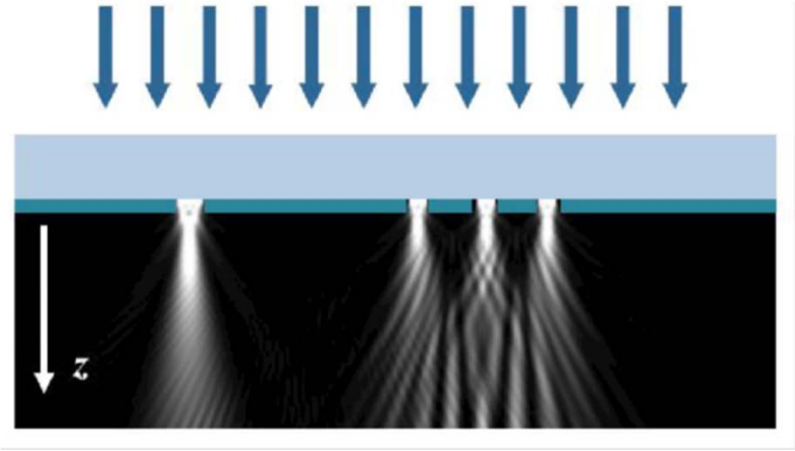
Contact Lithography



- 1:1 copy of mask
- Contact = damage!
- Gap needed for alignment…

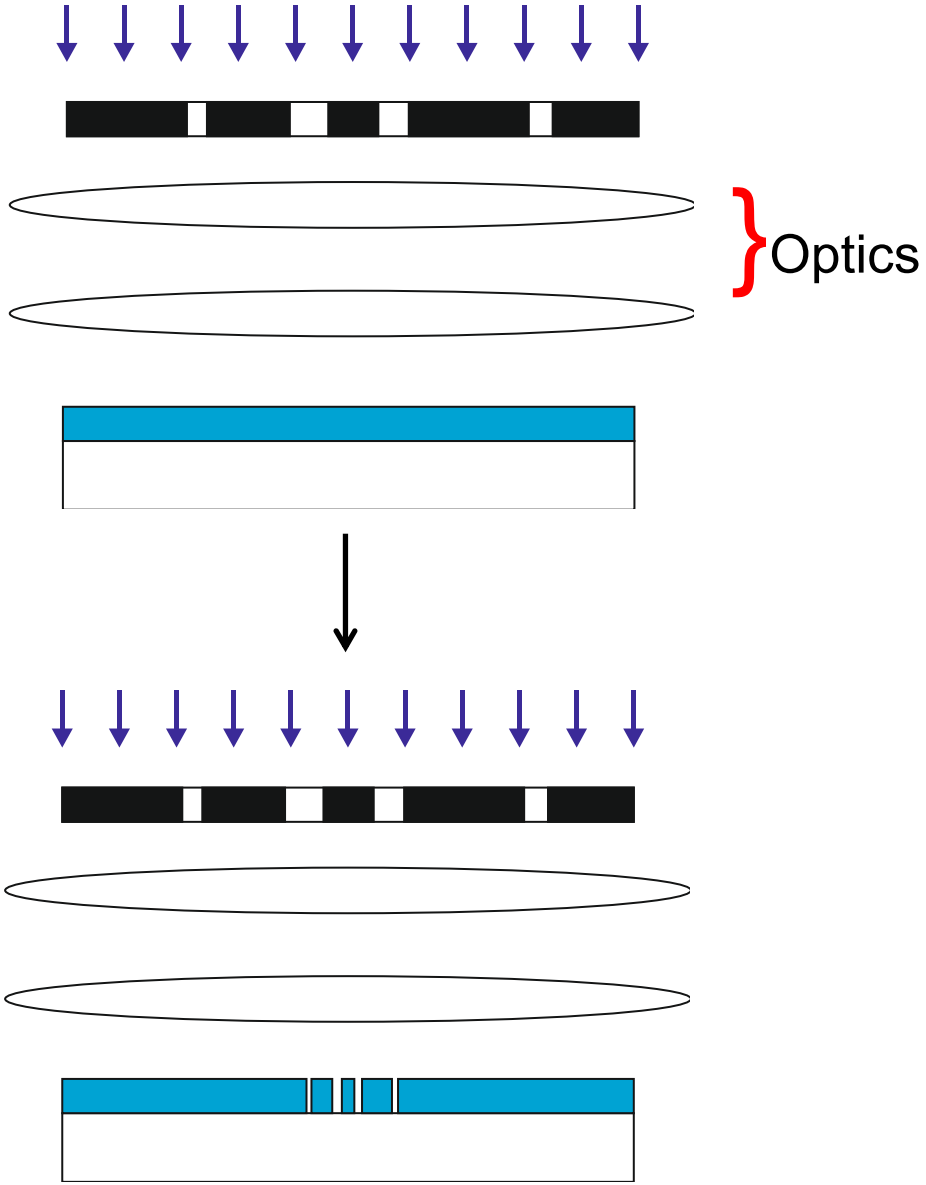
Proximity Lithography





- 1:1 copy
- Avoid damage
- Diffraction, hence loss of resolution

Projection Lithography



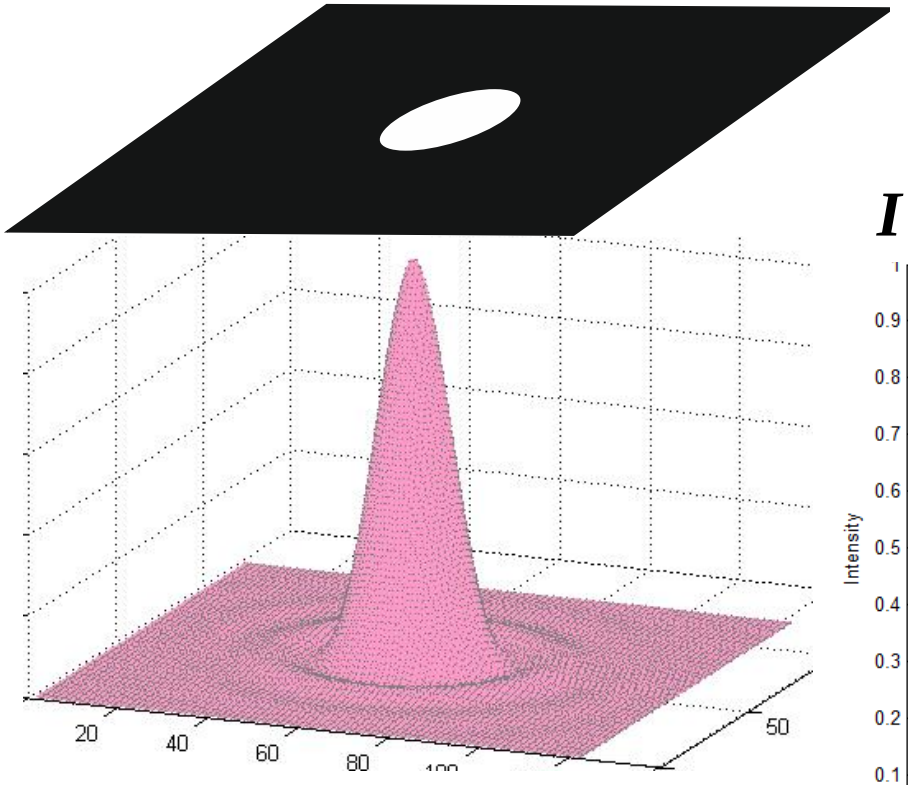
- Gap good!
- Many lenses!
- Stepper
- Scan
- Reduction possible

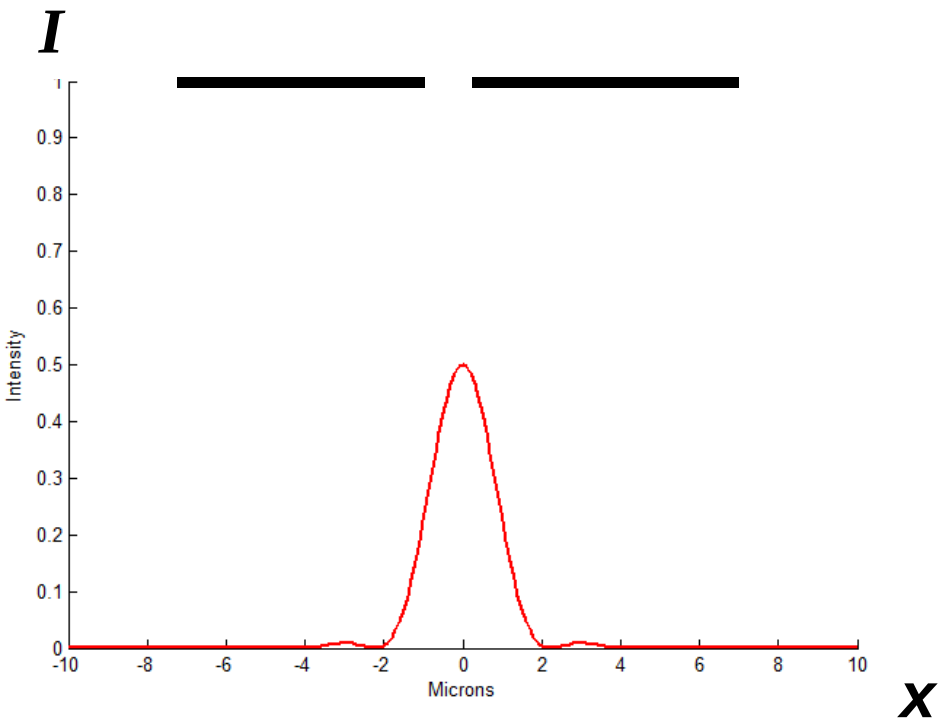
Airy disc cross-sections

Image formed by circular aperture…

Diffraction theory:

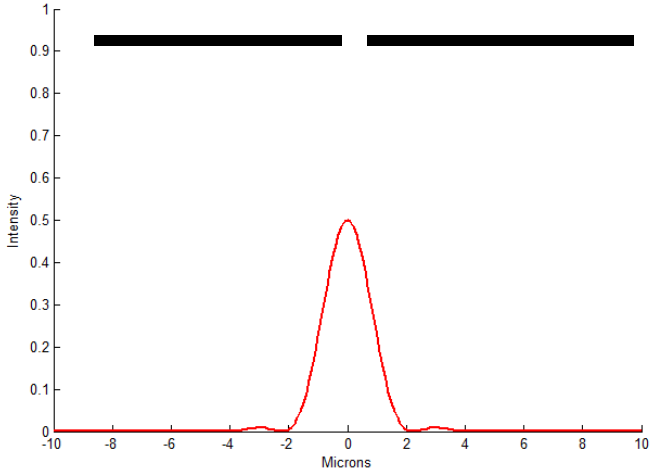
$$I(x) = I_0 \left(\frac{2J_1(x)}{x} \right)^2$$



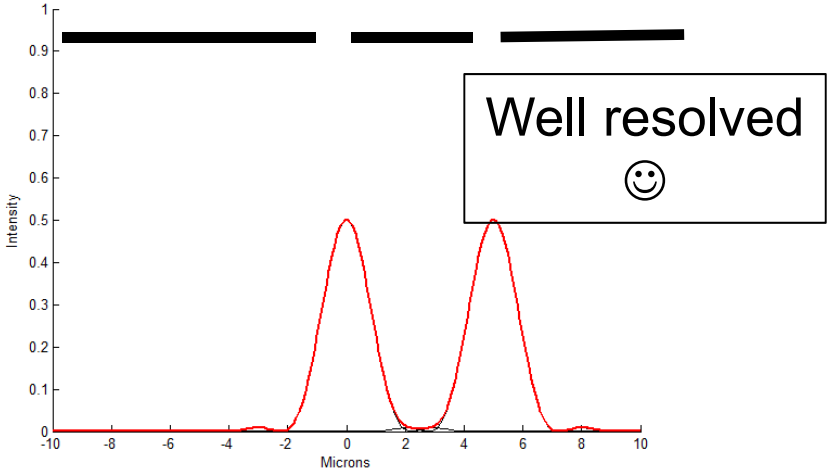


The University Of Sheffield.

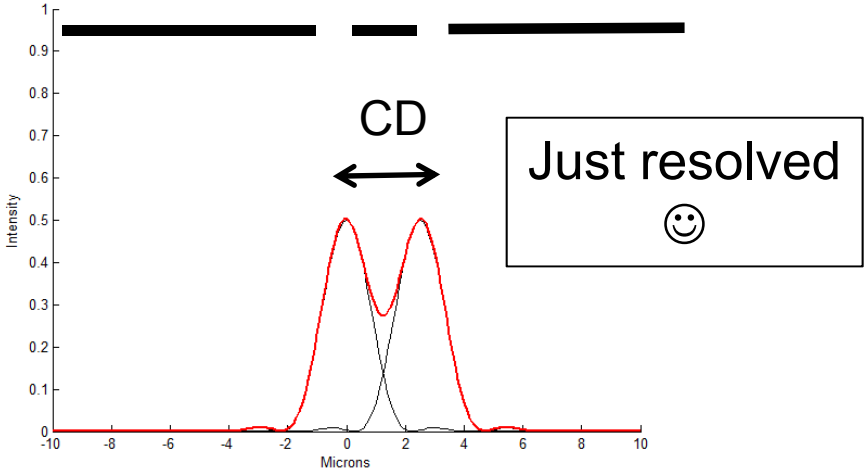
Airy disc cross-sections



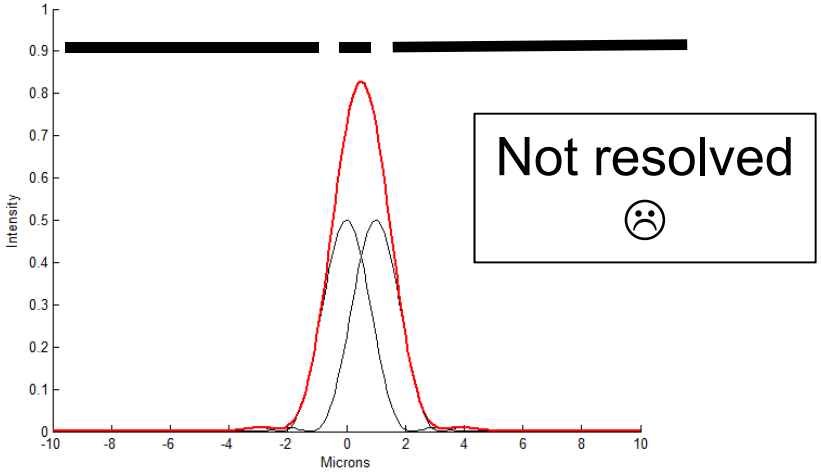
Single (circular) aperture



Two separate apertures

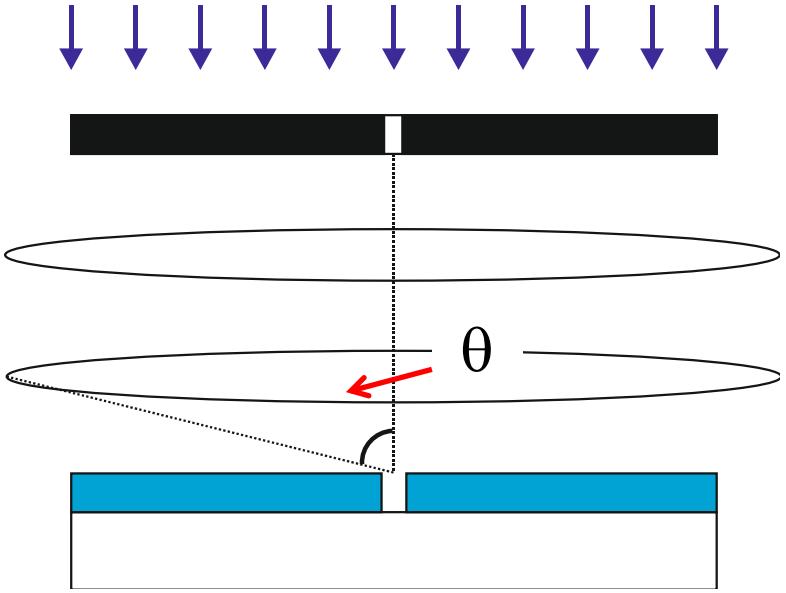


Close apertures



Very close apertures

Critical dimension *CD*



From diffraction theory, critical dimension*:

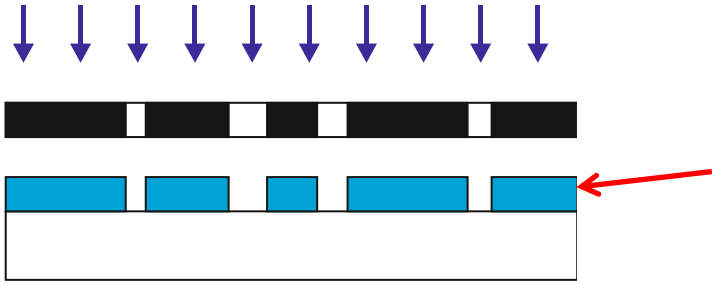
$$CD = k_1 \frac{\lambda}{n \sin\theta}$$

(* i.e. minimum feature size)

k_1 = process-dependent constant
λ = wavelength of light
n = refractive index of surroundings (air)
θ = maximum angle for light collection

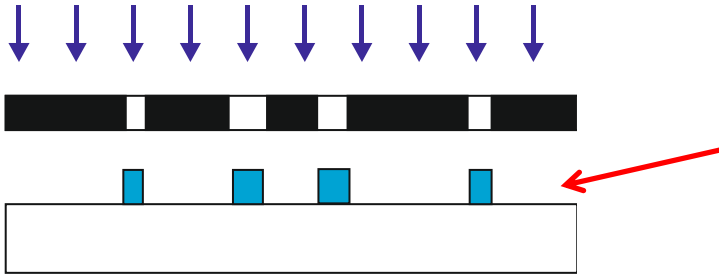
Define numerical aperture: $NA = n \sin\theta$

Two photoresist ‘flavours’



Light makes resist *more* soluble in developer

1. Positive-acting resist
(hole in mask → hole in resist)



Light makes resist *less* soluble in developer

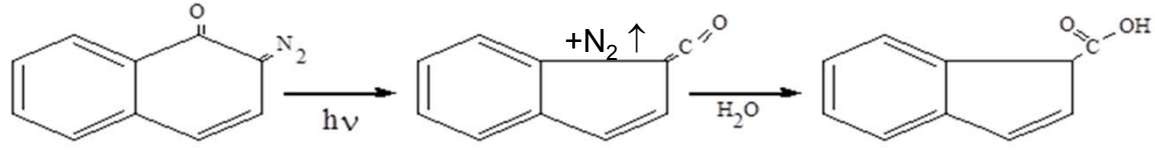
2. Negative-acting resist
(hole in mask → resist remains)

Positive resist

Example:

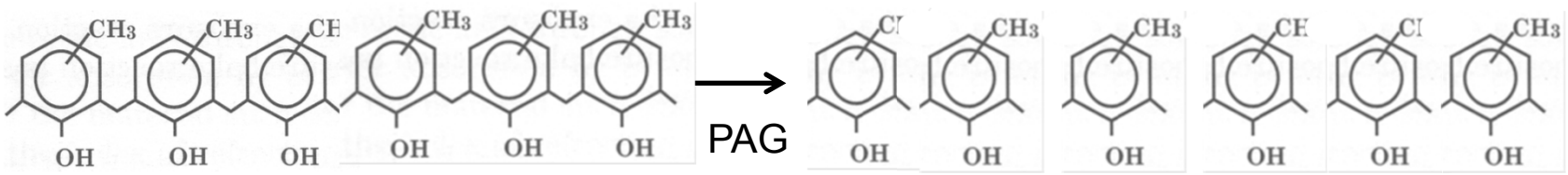
- Polymer: 'Novolak'
- Photoactive compound: diazonapthoquinone (DNQ)
- Solvent

- Light (+water) causes photo-acid generation (PAG)



DNQ (photoinitiator) → Ketene → Indene carboxylic acid (photo-acid)

- Photo-acid breaks polymer chains



- Developer* dissolves monomers

*aqueous alkali solution e.g. $(CH_3)_3OH$ (TMAH)

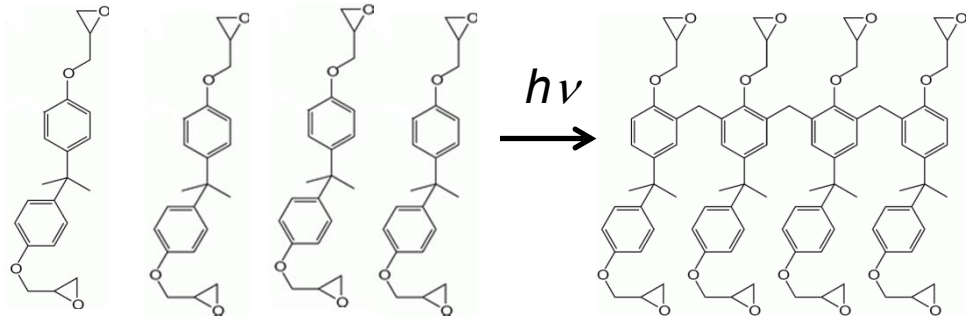
- Sensitivity can be increased by using acid + heat to *catalyse* breaking of polymer chains (chemically amplified resist CAR)

Negative resist

Example:

Photosensitive epoxy resin ‘SU-8’
Solvent

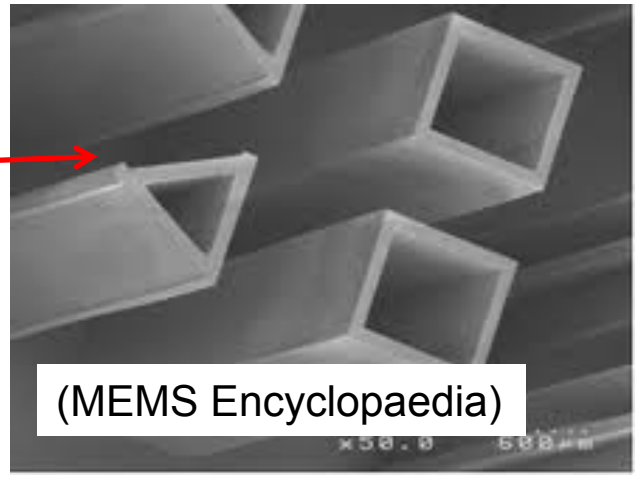
- Light causes 3d cross-linking of polymer chains



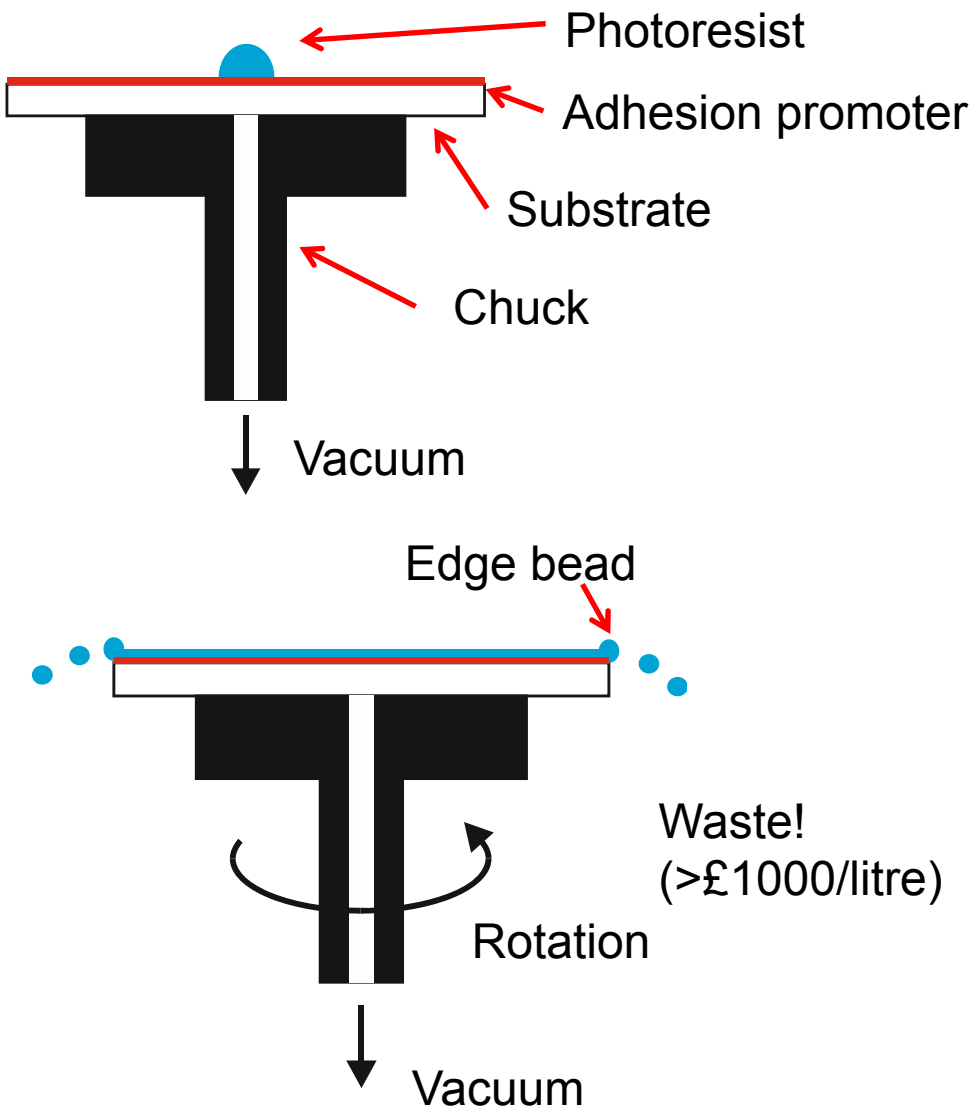
- Developer* removes uncross-linked chains

(* organic solvent)

- Very high aspect ratios possible
- Strong – used for permanent structures in MEMS and MOEMS
- Difficult to strip!

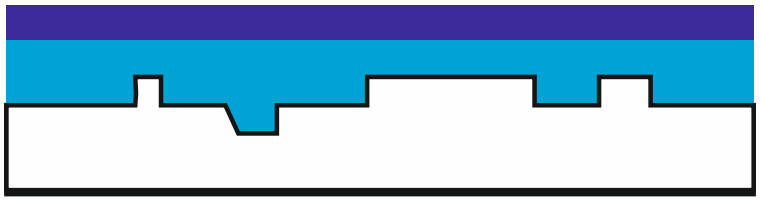


Resist deposition



- Dehydration bake (~100°C)
- Adhesion promoter –vapour or liquid (mainly for Si)
- Photoresist dispense (~ 1 ml)
- Spin at optimum speed
- Soft bake - to drive off solvent and generate PAG (~ 100 °C)
- Expose (see later…)
- Develop
- Post-exposure ‘hard’ bake – to make resist more robust, prior to implantation, etch, etc. (> 100°C)

Planarization and Lift-off



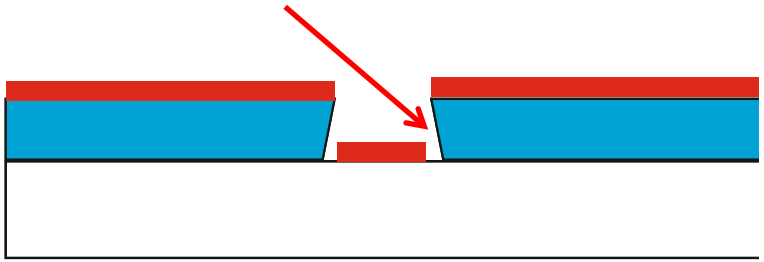
Photoresist

Planarization layer

Micro-structured (or warped) substrate

- Enables patterning of (slightly) structures substrates

No metal here!



Metal from directional source

Resist with vertical/negative-slope edge

Substrate

- Undercutting of resist prevents metal coverage on side walls
- Photoresist stripper can attack resist
- Enables ‘lift-off’ process

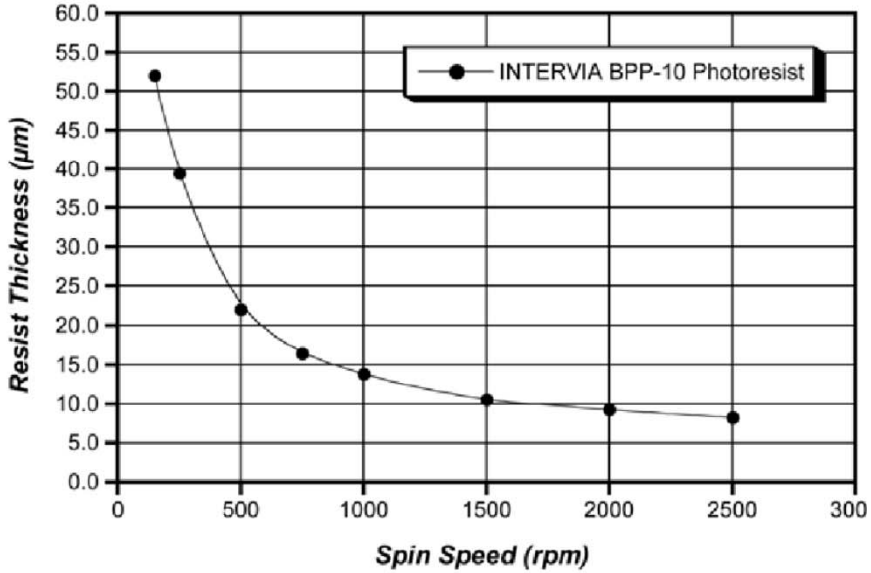
Resist datasheet (Intervia BPP10)

Table 1. Recommended Process Conditions

	1.1–4.0 µm Thickness*
Thickness	1.1–4.0 µm
Softbake	115°C/90 sec. Contact Hotplate
Expose	ASML™ PAS 5500™/200 i-Line (0.48 NA, 0.50s)
PEB	115°C/90 sec. Contact Hotplate
Developer	MF™-24A at 21°C, 60 sec. single spray puddle

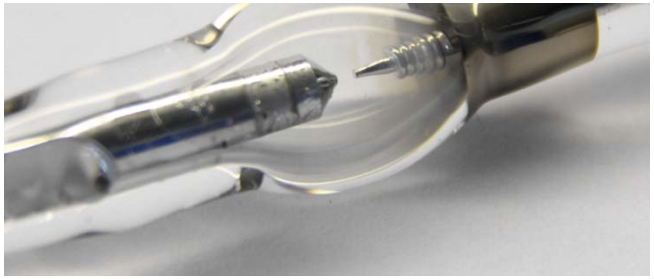
Table 2. Photospeed and Linearity of Dense Line/Spaces

Light	Film Thickness	Photospeed*
g-Line	1.2 µm	210 mJ/cm^2
g-Line	3.0 µm	320 mJ/cm^2
g-Line	7.0 µm	470 mJ/cm^2
i-Line	1.2 µm	160 mJ/cm^2
i-Line	3.0 µm	310 mJ/cm^2
i-Line	5.0 µm	380 mJ/cm^2



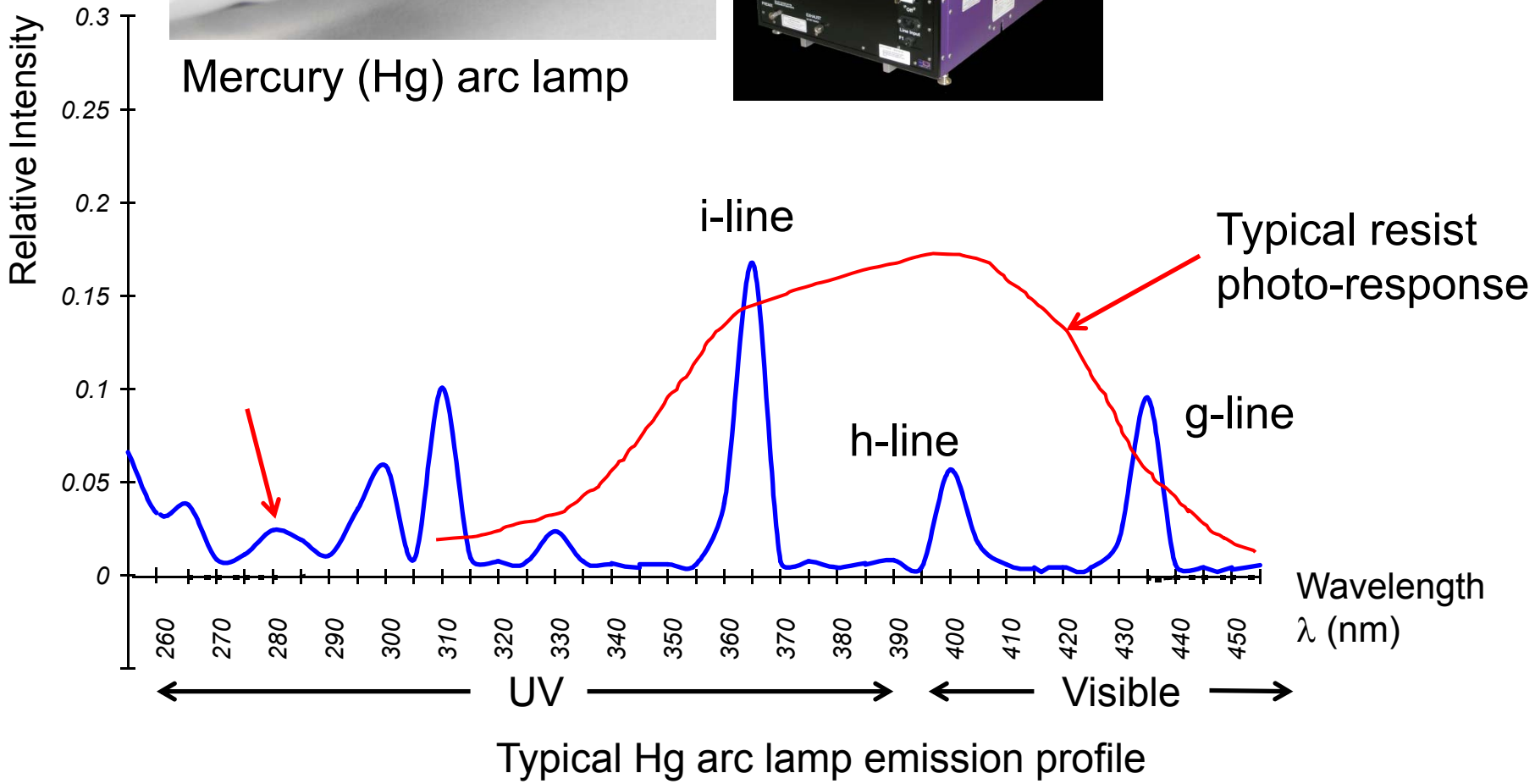
The University Of Sheffield.

Light sources



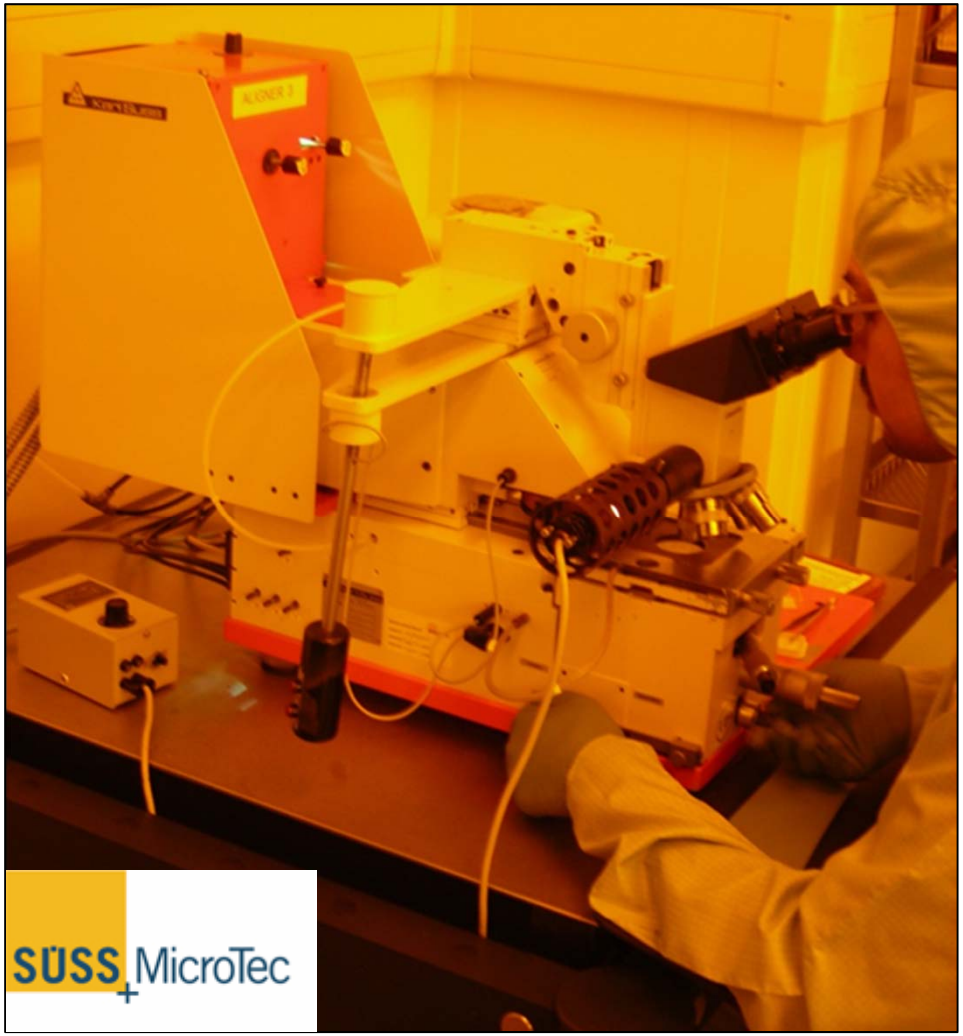
Mercury (Hg) arc lamp

Excimer laser
λ = 248/193/157 nm
Pulsed operation



Typical Hg arc lamp emission profile

Proximity Exposure Tool



SUSS MJB-3

Modes:
a) Proximity (‘soft’ or hard’)
b) Contact (‘vacuum’)

Wavelength: 254 - 440 nm

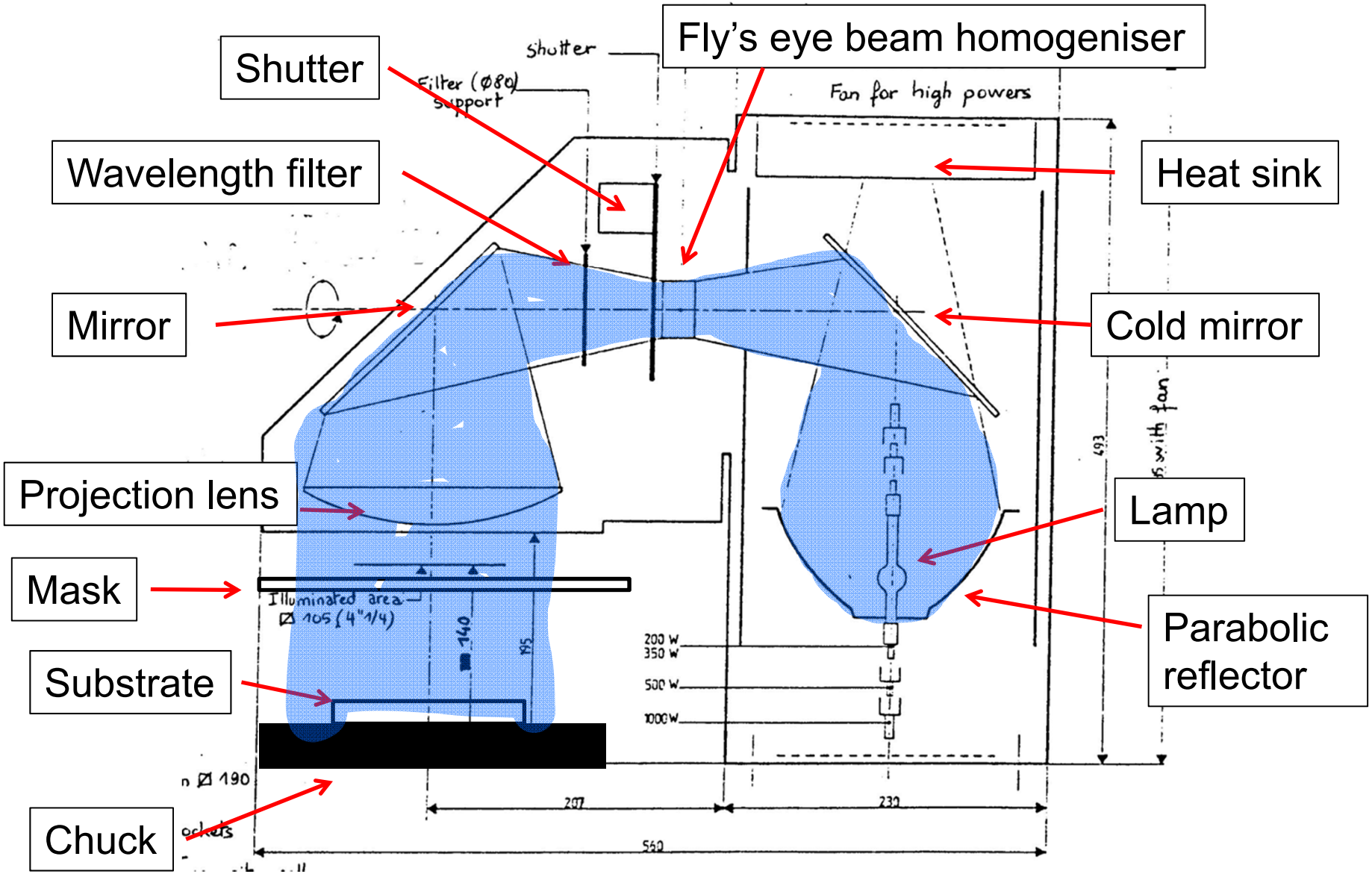
Resolution: ~1 µm

Power density at substrate:
2 mW/cm^2

Exposure time: ~ 2 sec.

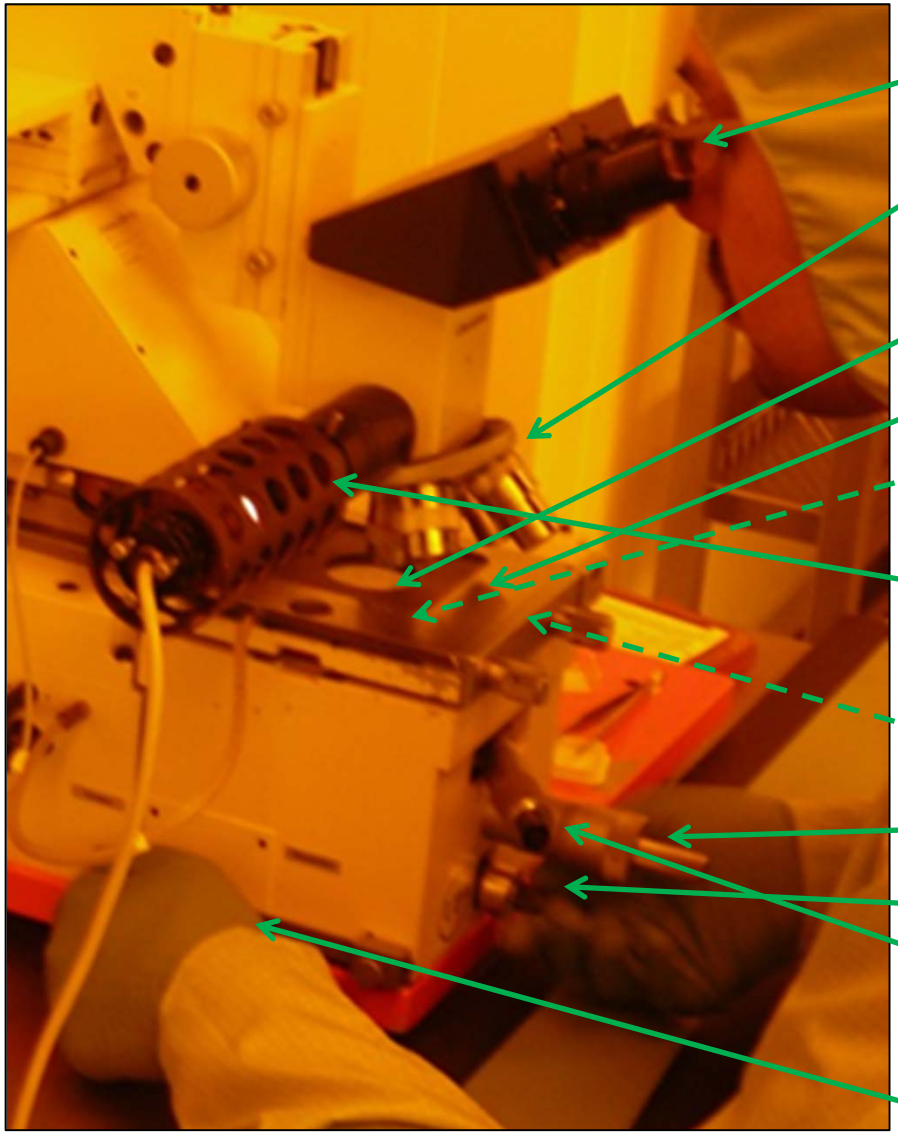
Throughput:
~10 exposures/h

MJB3 optical system



The University Of Sheffield.

MJB-3 Alignment System



Binocular viewing
Objective lenses (x5,10,20)

Mask
Mask holder (vacuum)
Substrate (hidden)

Illumination (yellow light)

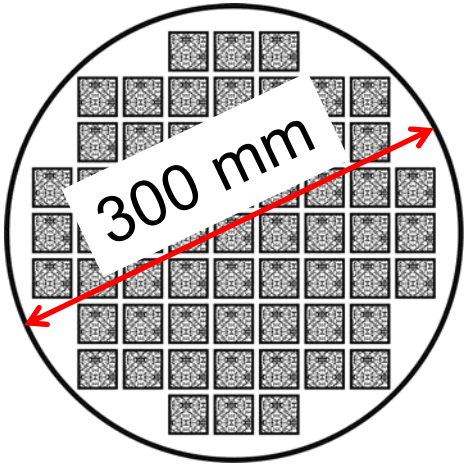
X-axis micrometer (hidden)
Y-axis micrometer
Z-axis micrometer
θ-axis micrometer

Contact lever (δZ)

Projection exposure tool

Mask (x4)

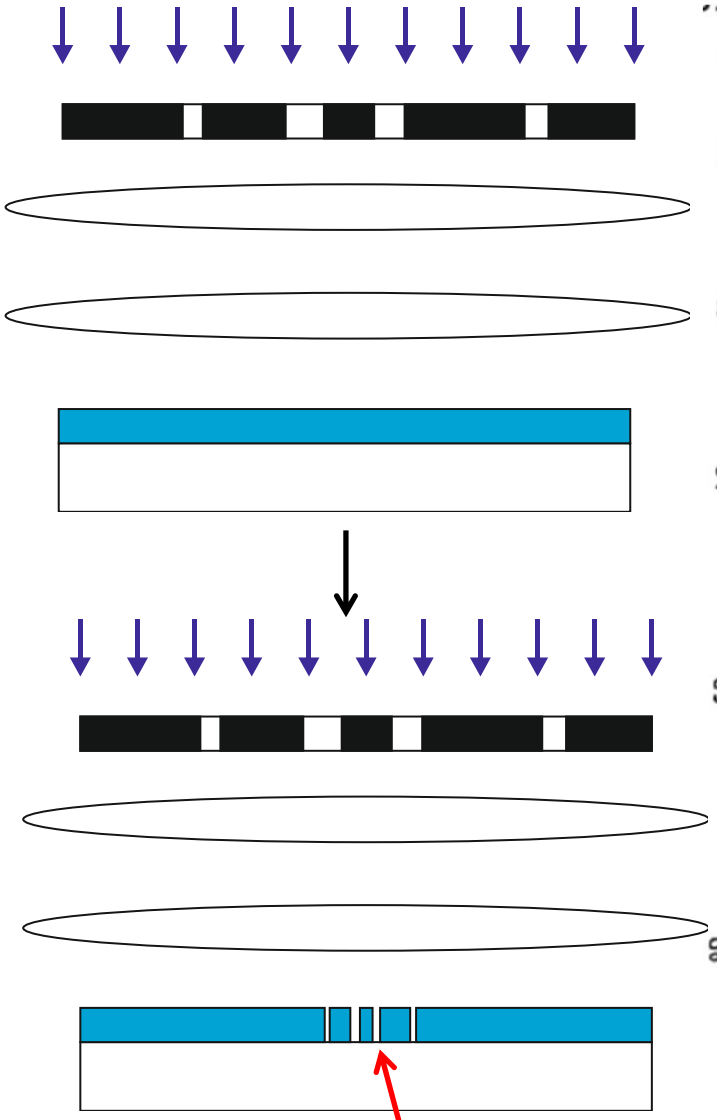
Multiple copies on wafer

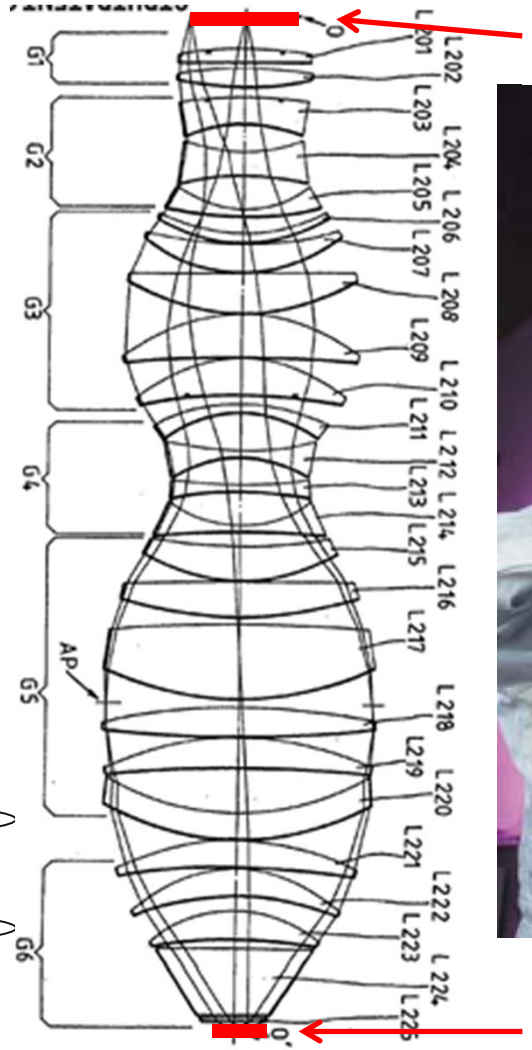


‘Stepper’ (i.e multiple copies from same mask)
Wavelength = 193 nm Resolution ~ 90 nm
Throughput > 135 wafers/hour

!

Projection optics

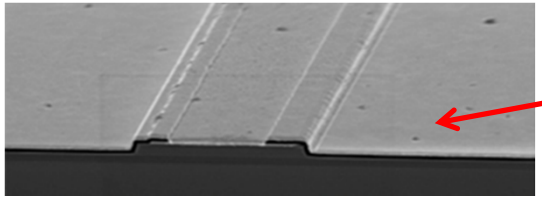


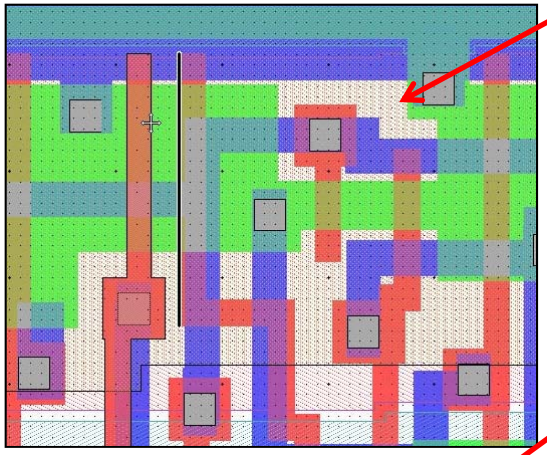


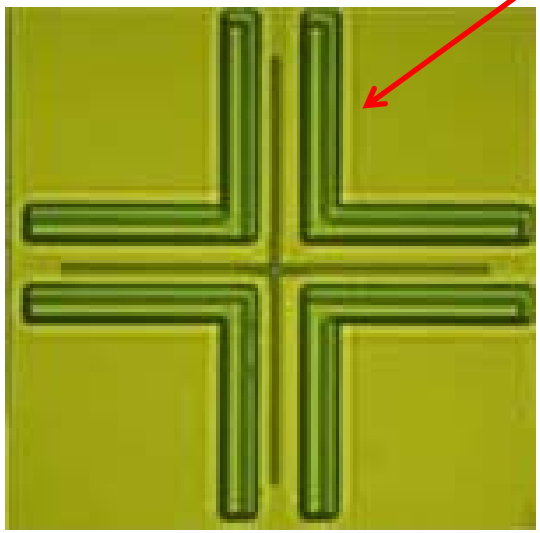
Note image size reduction

Very complicated/expensive optics!

Alignment







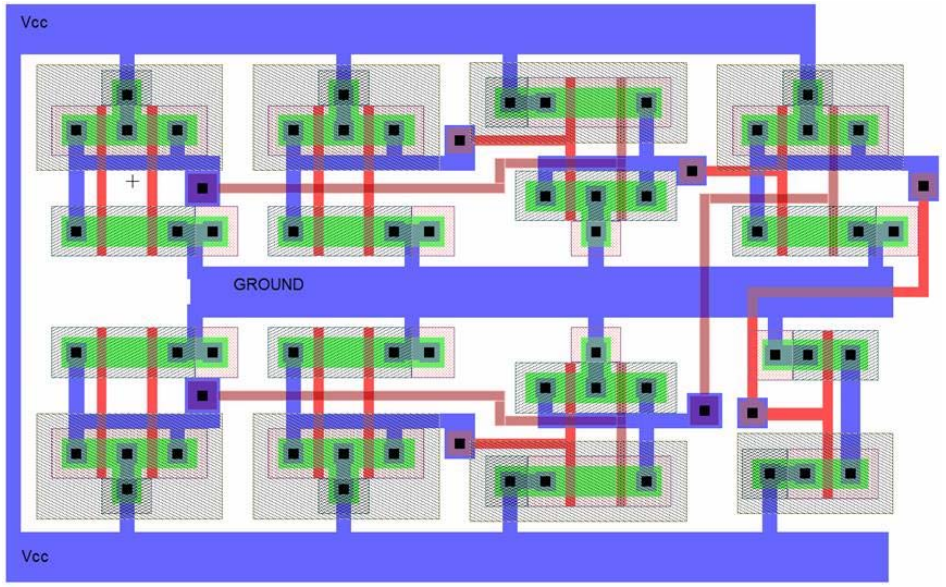
- Your substrate may have surface features (e.g. ridges)
- Your design may contain may have many layers (e.g. for implantation or contacts)
- Precision alignment needs between mask and substrate ('overlay')
- X,Y alignment achieved using alignment marks on mask and substrate
- Z alignment also necessary for projection systems, since depth of focus (*DOF*):

$$DOF = k_2 \frac{\lambda}{NA^2} \sim 1\ \mu m$$

- achieved using interferometry

Mask design and manufacture

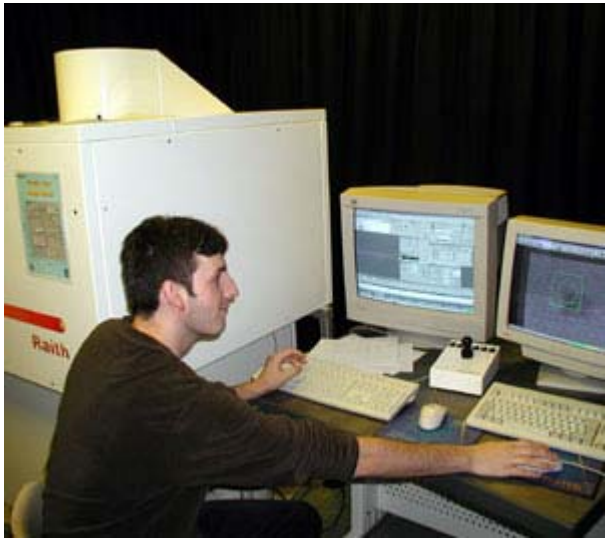
Mask design:
CAD software
('Wavemaker', 'L-Edit', etc…



Raster format

'tape out'

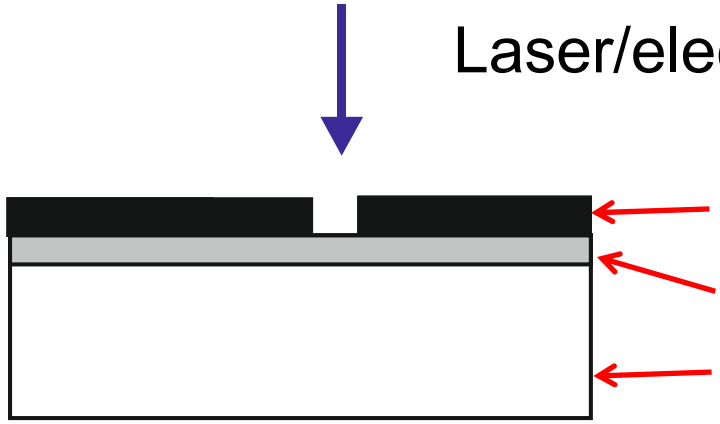
Mask writing:
Laser or electron beam



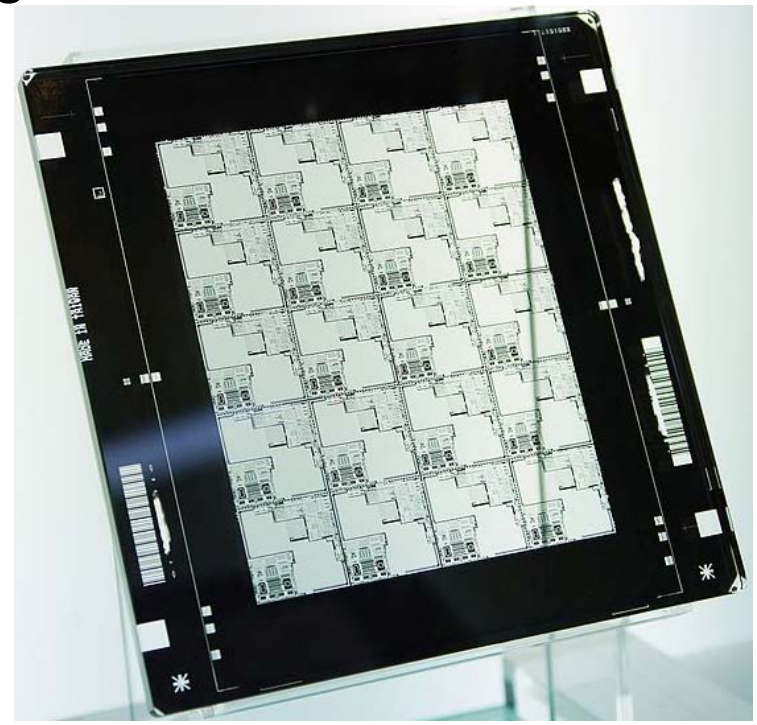
Vector format
(GDSII, Gerber,
DXF, OASIS)

```
…
Y20000D01*
X0D01*
Y15000D01*
G37*
G36*
Y20000D02*
X1005000D01*
Y25000D01*
X0D01*
Y20000D01*
G37*
G36*
Y25000D02*
X1005000D01*
Y30000D01*
X0D01*
Y25000D01*
G37*
G36*
Y30000D02*
…
```

Photo-mask



Minimum feature size ~ 20 nm
Write time ~ hours!



The University Of Sheffield.

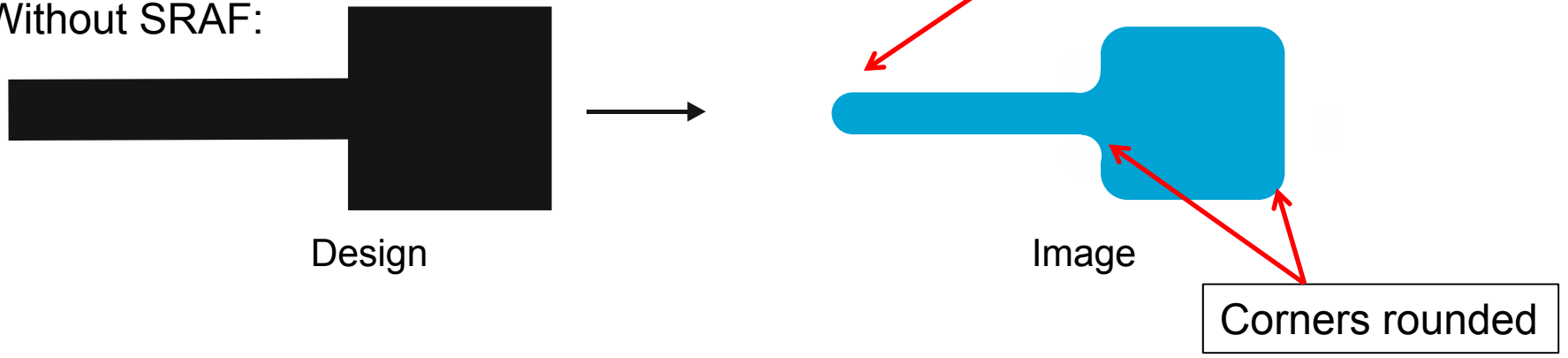
It's a big research area…

… because it's the main reason why electronics products continue to shrink!

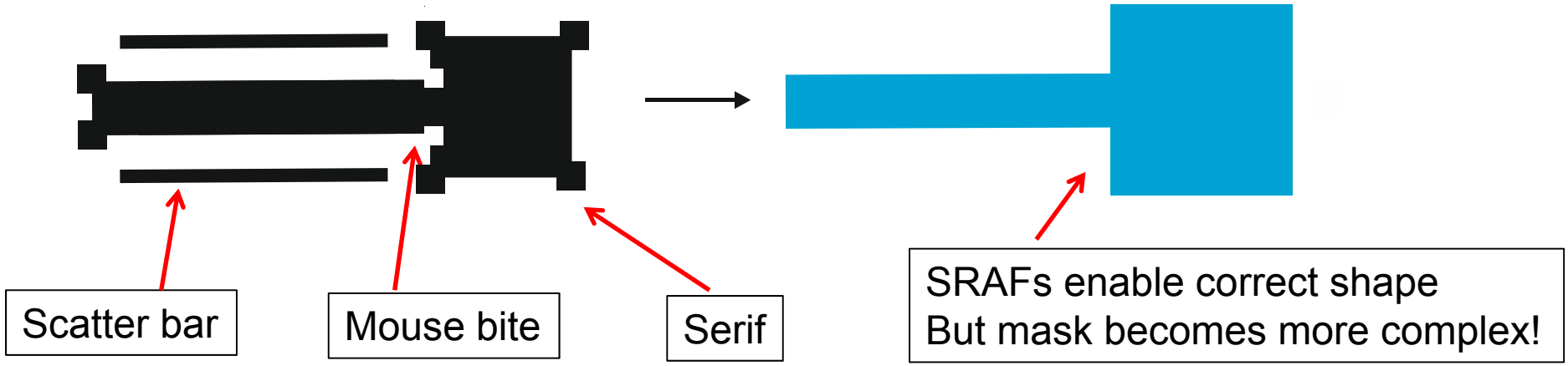
Sub-resolution assist features (SRAF)

$$CD = k_1 \frac{\lambda}{n \sin\theta}$$

Without SRAF:

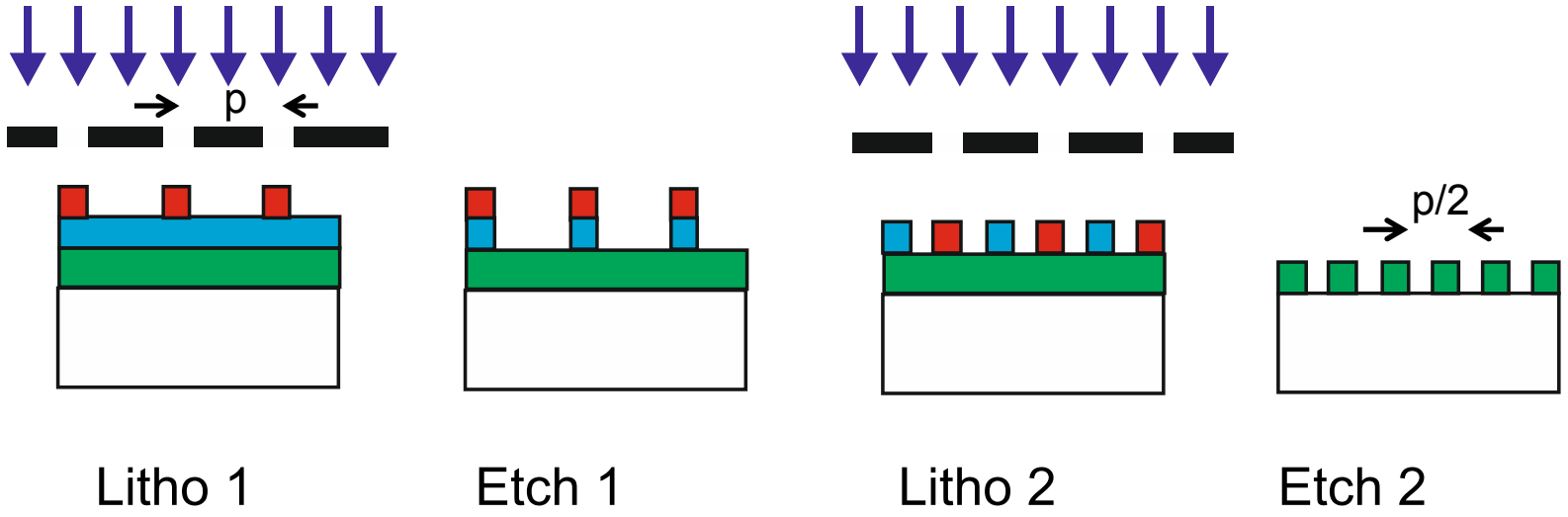


With SRAF:



Double patterning

$$CD = k_1 \frac{\lambda}{n \sin\theta}$$

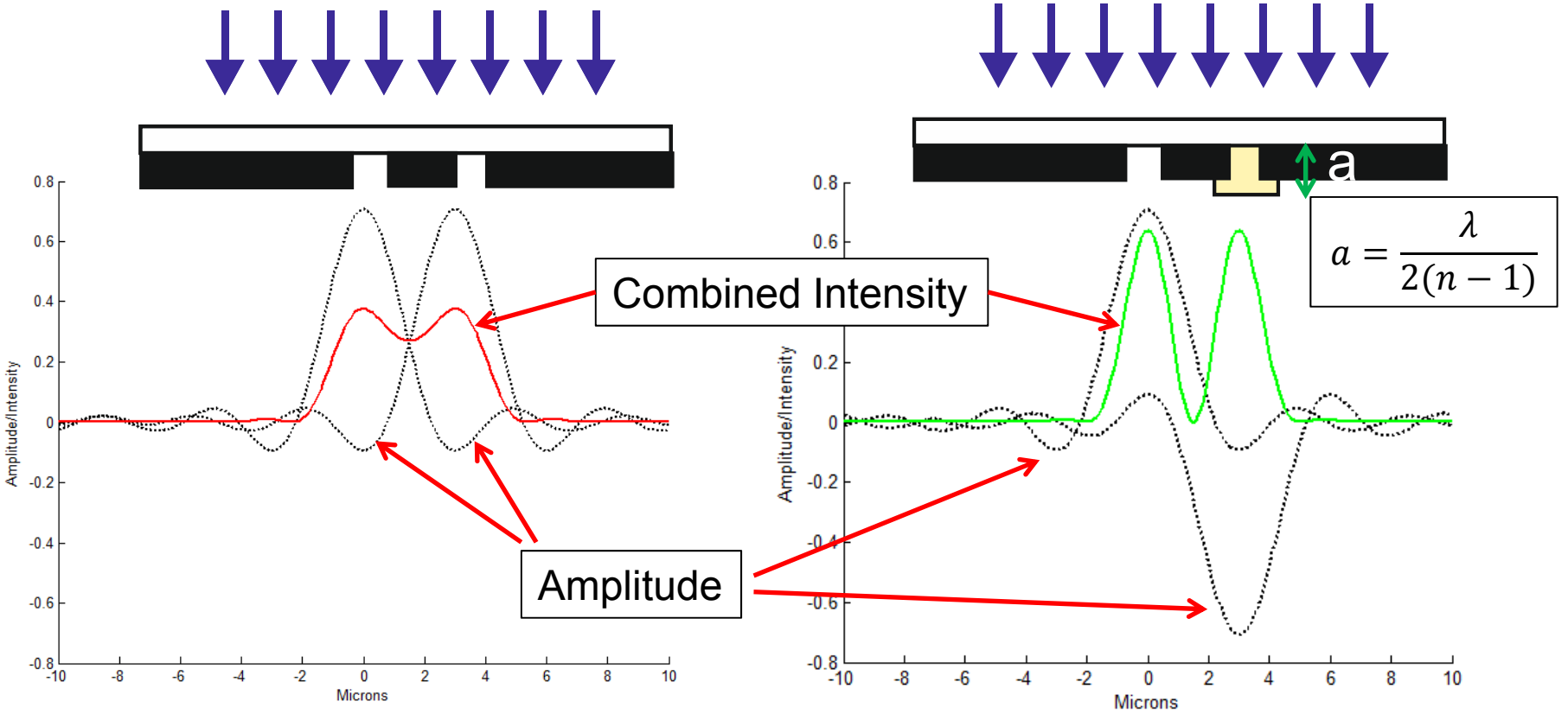


- Final pitch on substrate = ½ pitch on masks ☺
- Two masks needed to produce one pattern ☹

Phase masks

$$CD = k_1 \frac{\lambda}{n \sin\theta}$$

- Apply π radians *phase shift* to alternate lines by adding or subtracting material (*n*) to/from mask
- Intensity ~ (Amplitude)^2



Lines unresolved ☹

Lines resolved ☺

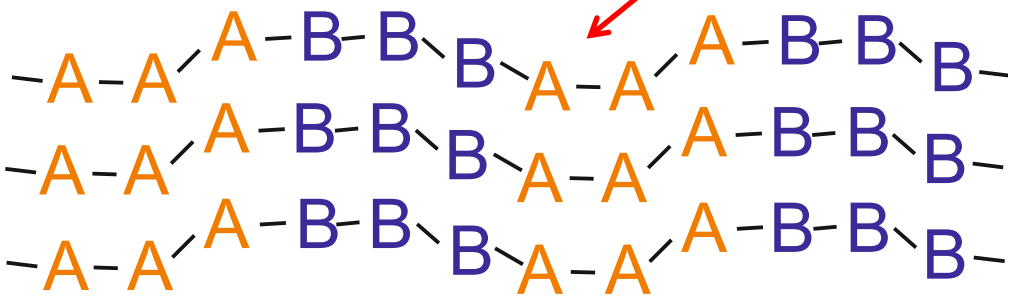
Directed self-assembly

$$CD = k_1 \frac{\lambda}{n \sin\theta}$$

Lithography

Block co-polymer with self-assembled lamellar structure

Frequency doubled pattern

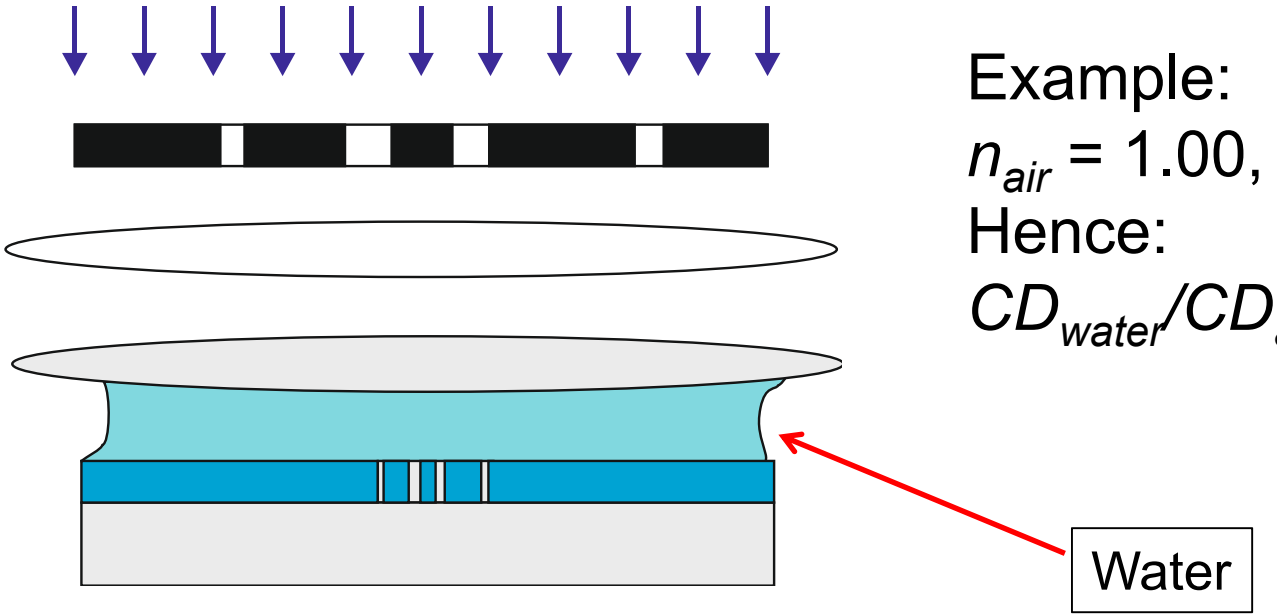


A – polymer 1
B – polymer 2

Immersion lithography

$$CD = k_1 \frac{\lambda}{n \sin\theta}$$

Decrease CD by increasing refractive index (n) of medium between substrate and final lens



Example:

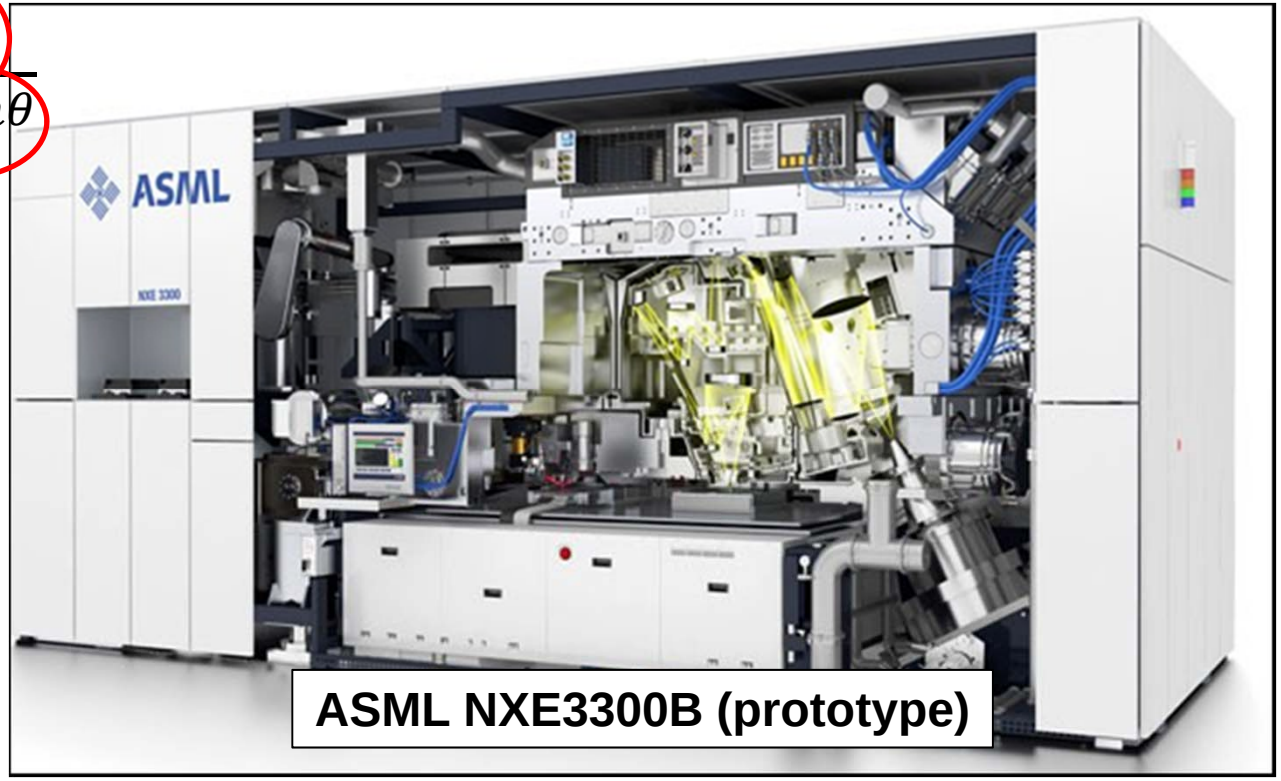
n_{air} = 1.00, n_{water} = 1.33

Hence:

CD_{water}/CD_{air} = 1/1.33 = <u>0.75</u>

Extreme UV lithography #1

Recall: $CD = k_1 \frac{\lambda}{n \sin\theta}$



ASML NXE3300B (prototype)

NA = 0.33
k_1 = 0.53
CD = 22 nm
Dose = 15 mJ/cm^2
Throughput (design) = 125 wafers/h

Extreme UV lithography #2

- New light source:

Tin plasma λ = 13.5 nm (x-ray!)

Issues:

1 No x-ray lenses, hence:

- Optics- curved mirrors
- Mask – reflective, illuminated off-axis

2 Tin droplets produced

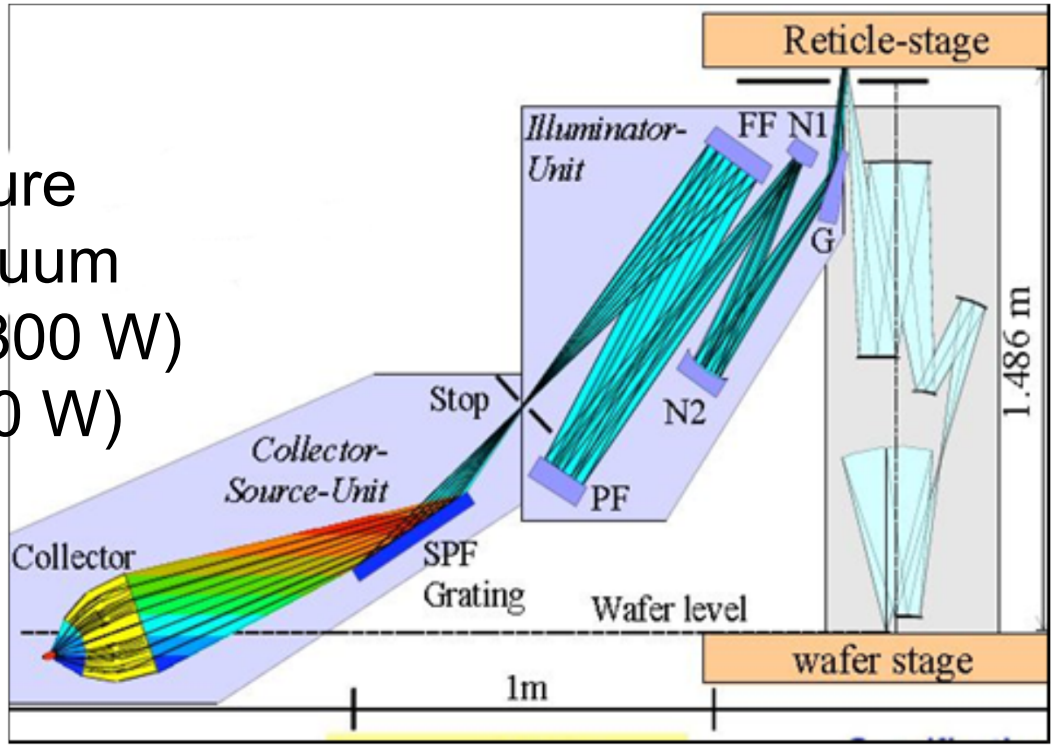
- Mirror damage

3 Plasma needs low pressure

- Entire system under vacuum

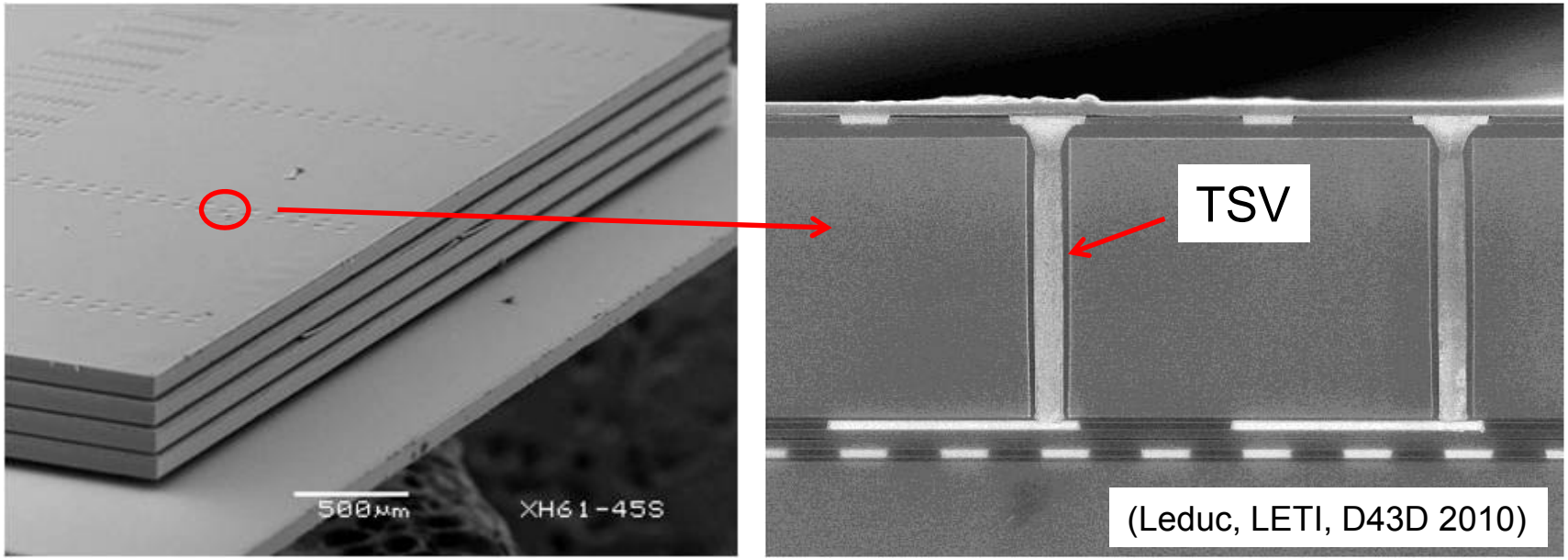
4 Bright source needed (~300 W)

- Currently low power (~50 W)



The University Of Sheffield.

Die stacking using TSVs



Hybrid Memory Cube

- Chips stacked vertically
- Connected using through-silicon vias (TSVs)
- Increased functionality *without* decrease in CD

The University Of Sheffield.

Photolithography on *non-planar* surfaces

Attraction:

- Enables *rapid* patterning of 3d shapes

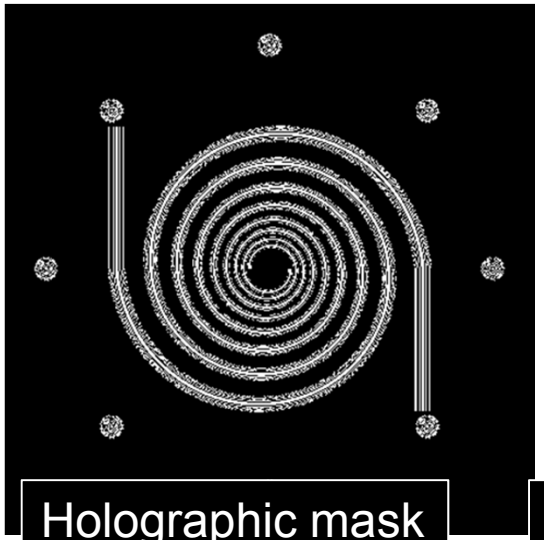
Issues:

- Can't deposit resist by spinning
- Diffraction destroys image

Solutions:

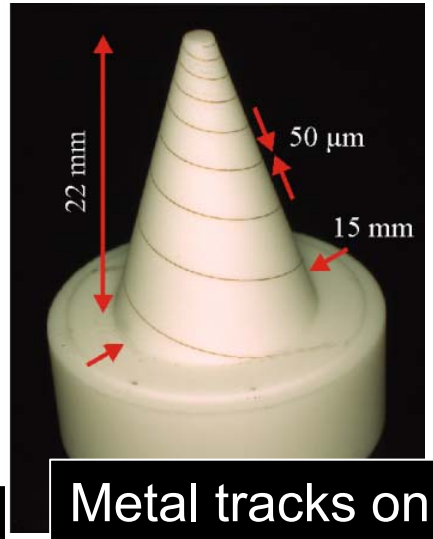
- Use electroplated or spray-deposited photoresist
- Use computer-designed holographic masks

Example: Bi-helical antenna



Holographic mask

Illuminated substrate



Metal tracks on substrate

(Reference: Purvis, Williams et al, SPIE J. MMM 6(4) 043015 (2007).)

The University Of Sheffield.

References

Journals:

Elsevier	*Microelectronic Engineering*
IEEE	*Trans. Components, Packaging and Manufacturing*
IOP	*Journal Micromechanics and Micro-Engineering*
OSA	*Journal Optical Society of America*
SPIE	*Journal Micro/Nanolithography, MEMS and MOEMS*

Books:

Levinson HJ *'Principles of Lithography'* SPIE Press 2005.

Lin BJ *'Optical Lithography'* SPIE Press 2010.

Mack CA *'Field Guide to Optical Lithography'* SPIE Press 2006.

Wong AK-K *'Optical Imaging in Projection Microlithography'* SPIE 2005.

Websites:

chipscalereview.com

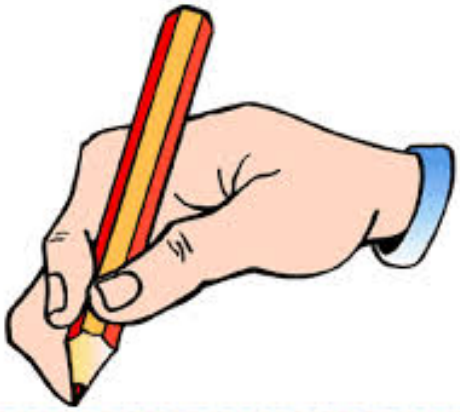
electroniq.com

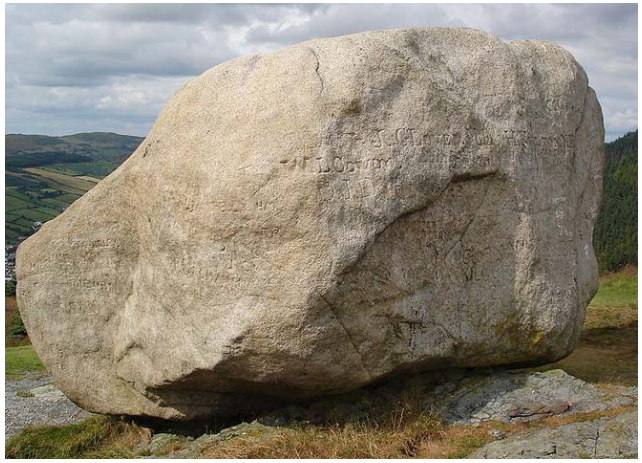
i-micronews.com

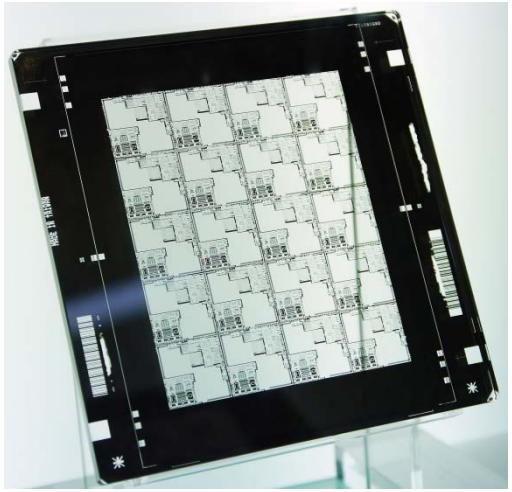
semiconductorpackagingnews.com

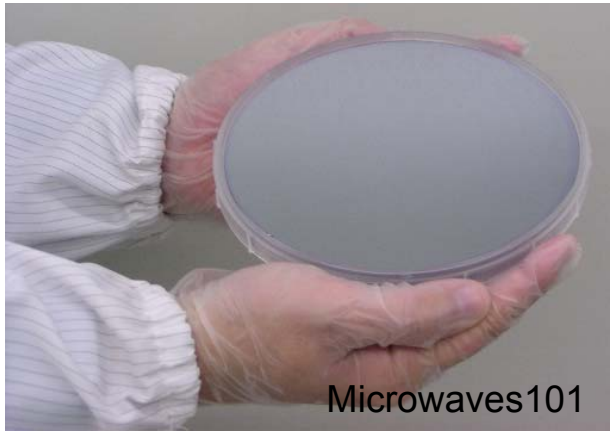
semiengineering.com

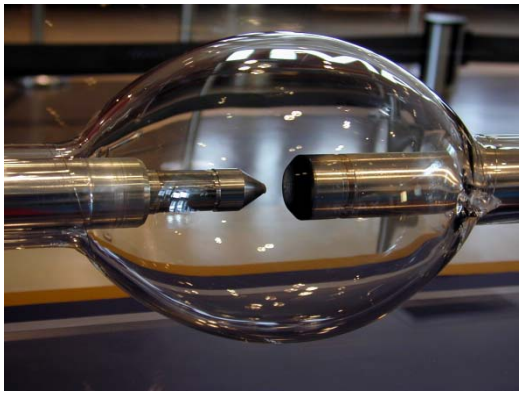
Photo-litho-graphy











Mask

Wafer

Arc lamp

Contact: Dr Gavin Williams g.williams@sheffield.ac.uk