Lithography and Etching

Victor Ovchinnikov

Chapters 8.1, 8.4, 9, 11

Previous lecture

- Microdevices
- Main processes:
  - Thin film deposition
  - Patterning (lithography)
  - Doping
- Materials:
  - Single crystal (monocrystal)
  - Polycrystals
  - Thin film
- Process flow
- Cleanroom
- Yield

Outline

- Optical lithography
- Beam lithography:
  - e-beam writing
  - laser writing
  - focused ion beam
- Etching:
  - wet etching
  - plasma etching

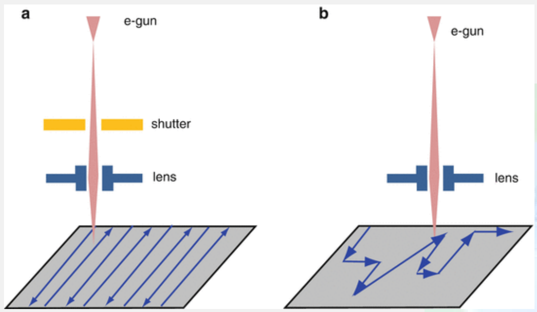
How do we create images?

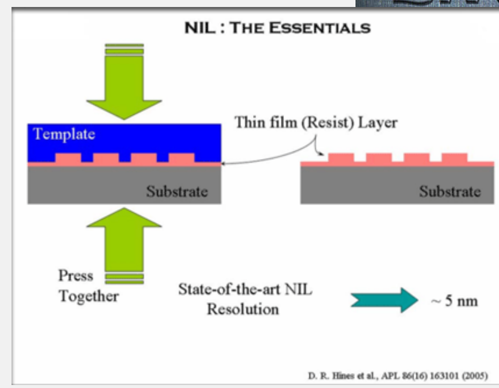
Embossing

Direct writing

Drawing

Nanoimprint



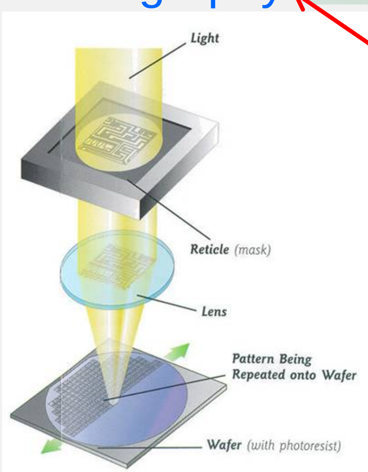


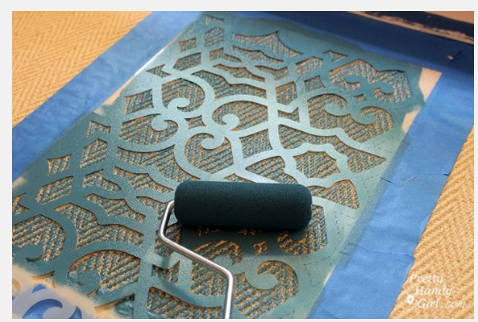
Shadow mask

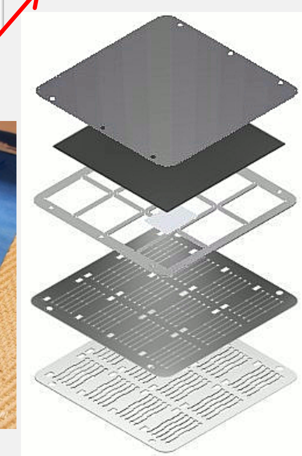
Photolithography

Offset printing

Stencil process

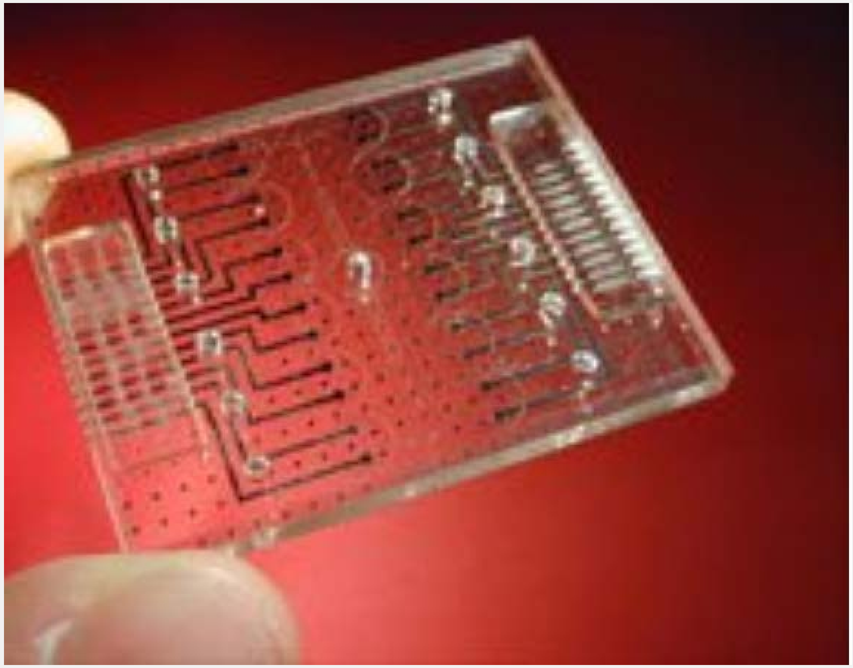






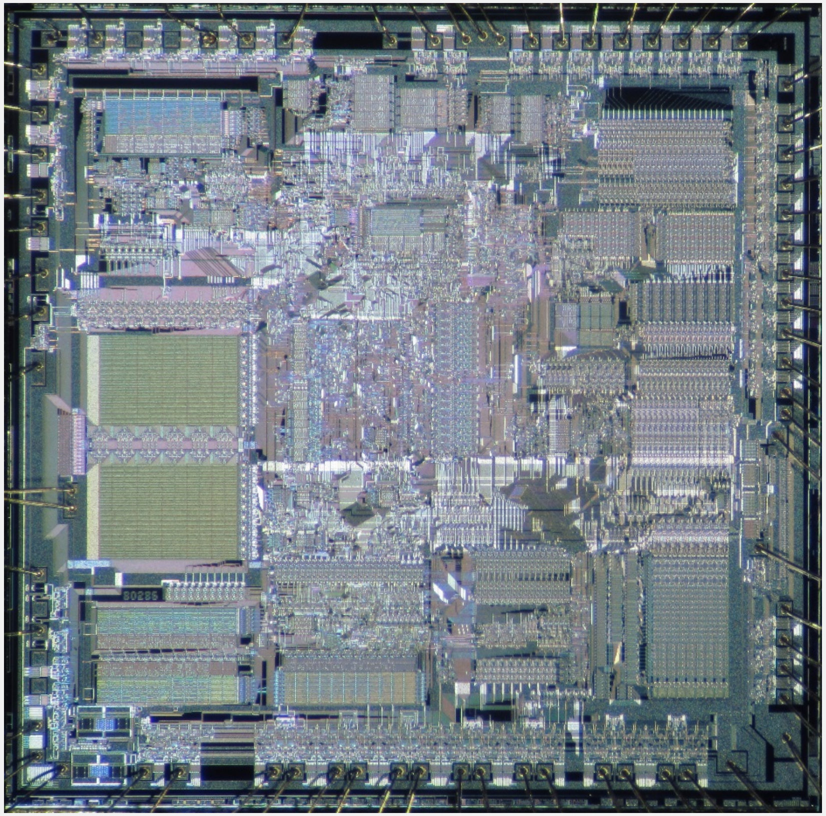
Photolithography results

Microfluidic chip



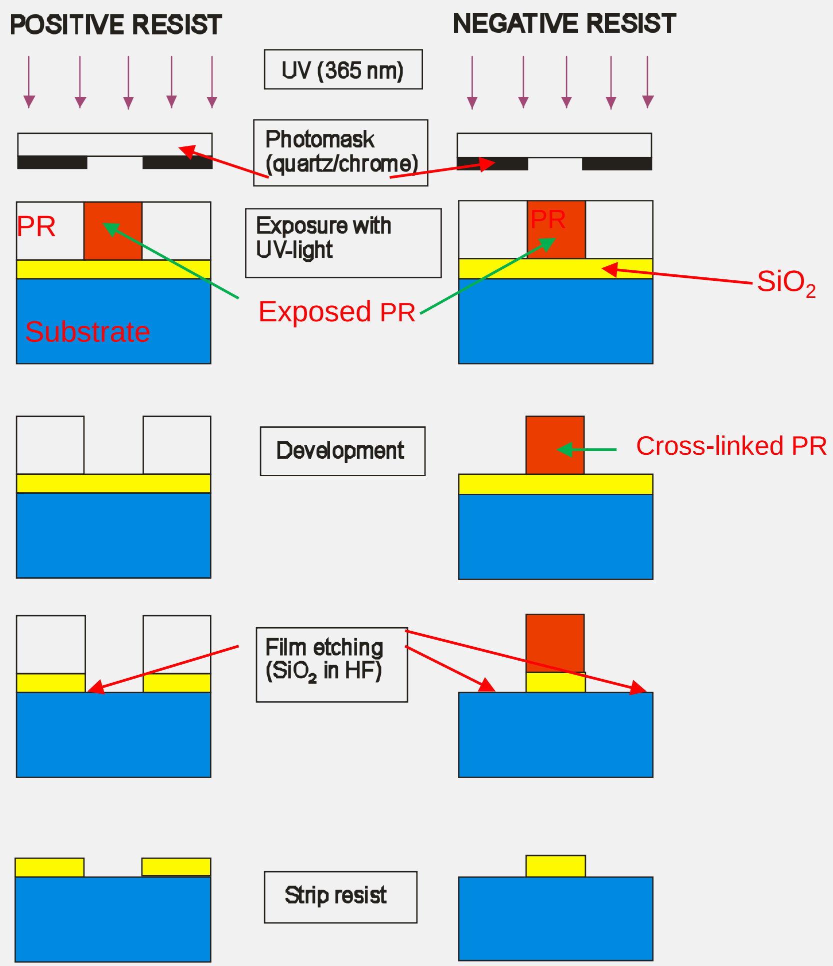
Critical dimension – 50 μm
Chip size – 50 x 50 mm
Glass substrate

Intel 80286, a 16-bit microcontroller



Critical dimension – 1.5 μm
Chip size – 7 x 7 mm
Silicon substrate

The photolithography patterning



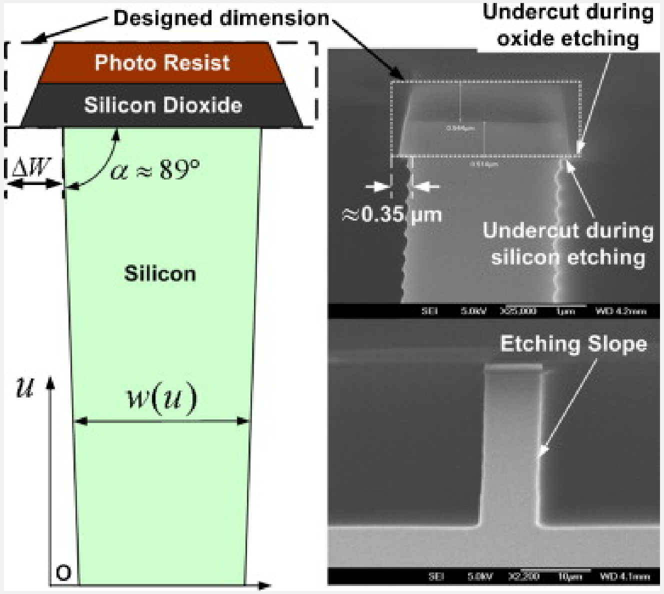
Three parts in one:

Optics - exposure

Chemistry - development

Mechanics - alignment

PR mask after etching



Sensors and Actuators A: Physical
Volume 156, Issue 1, November 2009, Pages 134-144

Patterning terminology

Photolithography - photoresist pattern

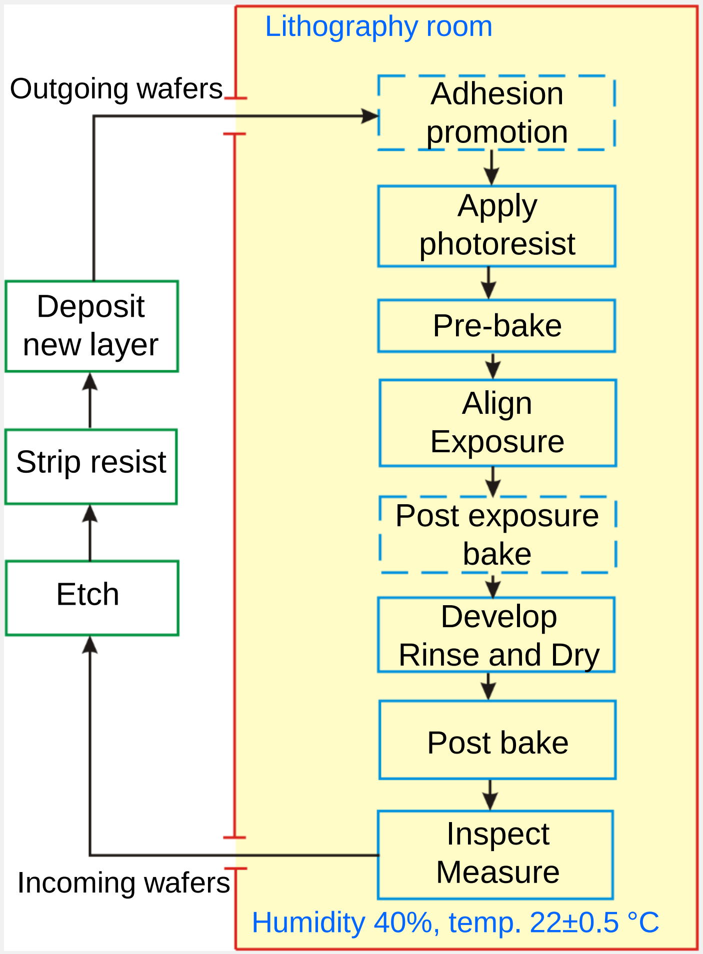
Etching - transfer of photoresist pattern into solid material

Stripping - removal of photoresist after etching the pattern

Photomask – fabricated image on transparent holder in 1x scale

Patterning – lithography + etching

Lithography steps



Baking 30 minutes, 150 °C, HMDS

Spin-on, spray, dip, roller. 1.5 µm

90 °C, 1 min - hotplate, 20 min – convection furnace

Maskaligner, 1-2 seconds, UV

105 °C, 20 min – convection furnace

1 min – wetbench, 5 min – spin rinse drier

120 °C, 1 min - hotplate, 20 min – convection furnace

Possible rework

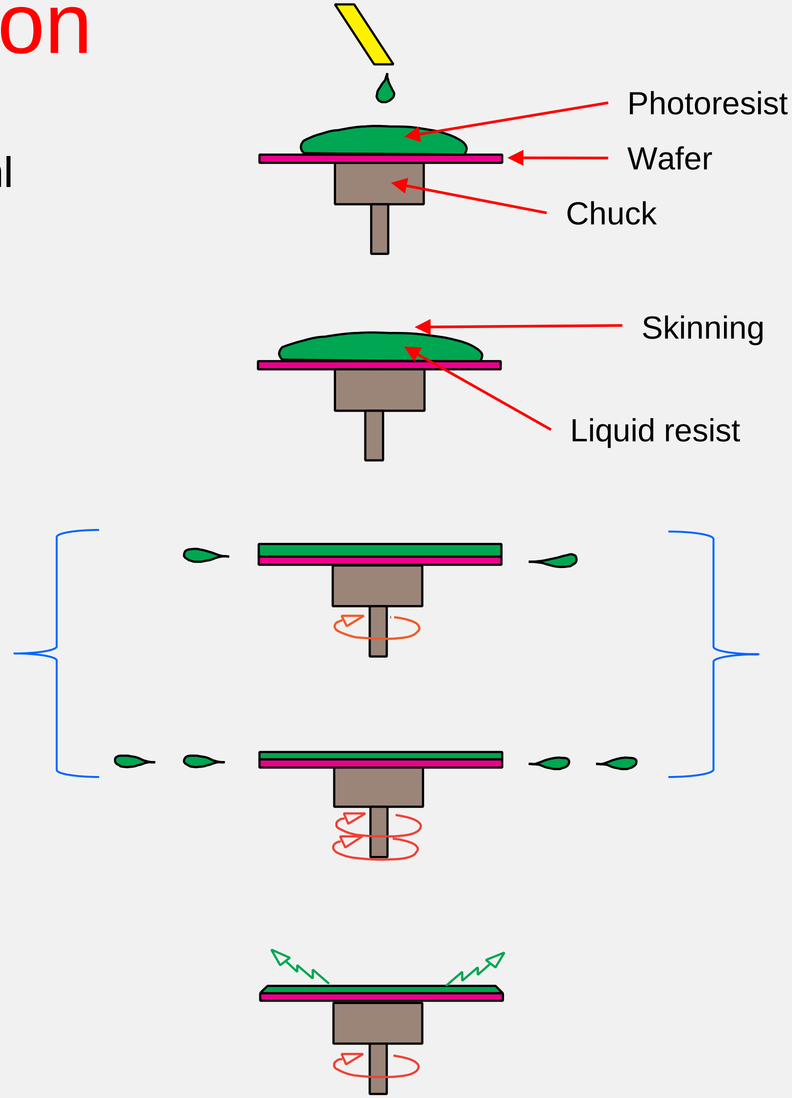
Spin-on

Static dispense, 1-10ml

Spread cycle

Ramp-up

Final spin coat speed



Liquid resist expelled from beneath the surface skin

Evaporation of residual solvent

Film thickness 100 nm – 500 µm

Spin coating thickness of PR

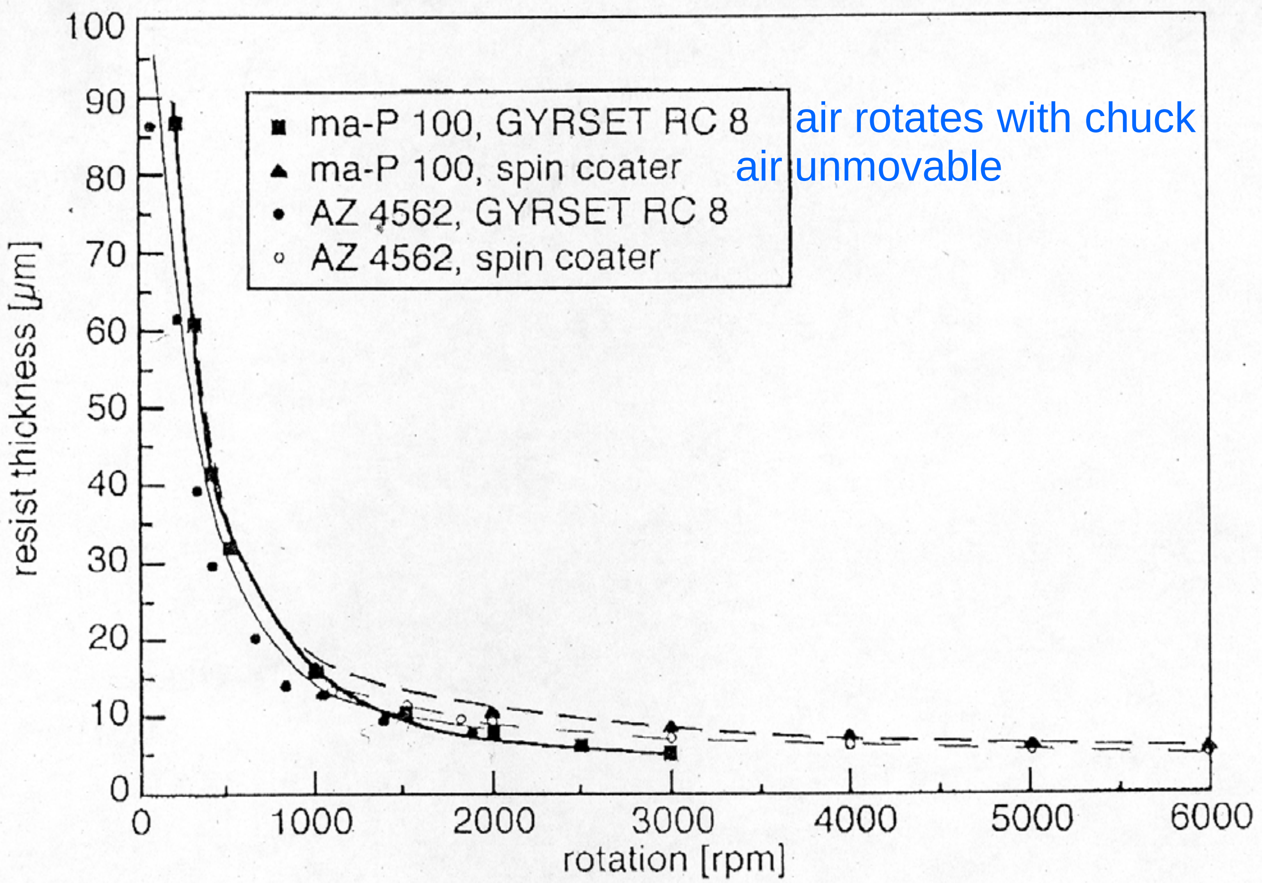
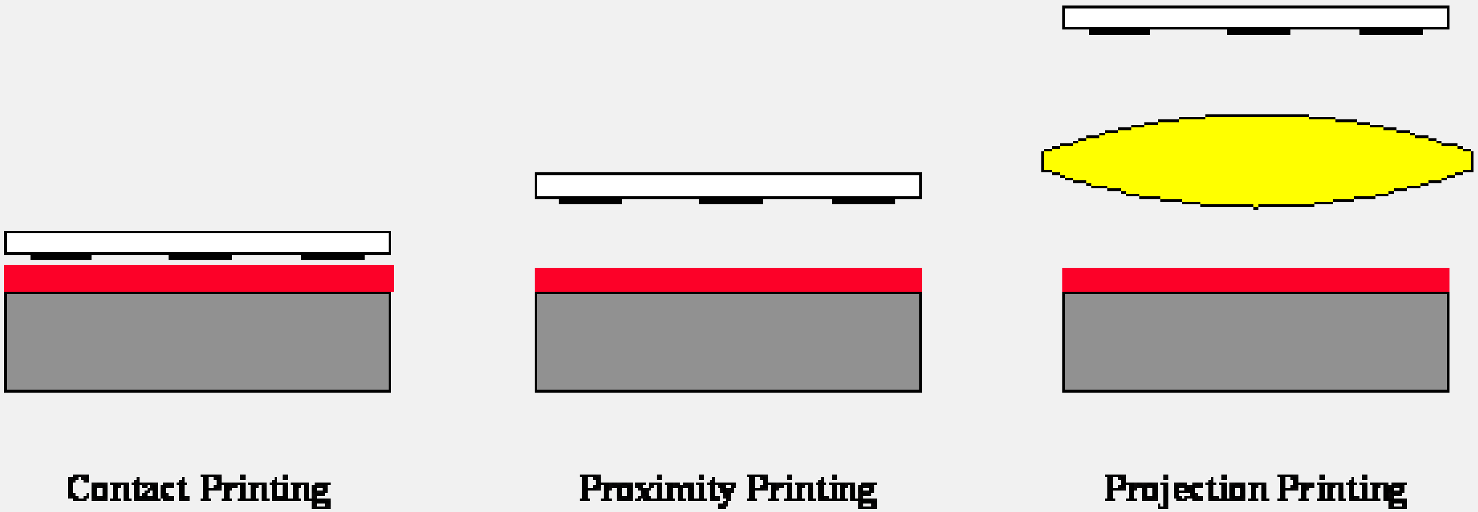


Figure 2. Spin coating curves for AZ 4562 and ma-P 100.

Three types of lithography



Contact Printing	Proximity Printing	Projection Printing
	Intact mask	High resolution
Mask contamination, Mask damage	Low resolution	Exposure of small area Stepper

http://www.lithoguru.com/scientist/lithobasics.html

Proximity lithography

Valid for $\lambda < g < \dfrac{b^2}{\lambda}$

λ = 365 nm, *i*-line
d = 1.4 µm (standard resist)

b ≈ 0.6 µm   g = 0 (contact)

b ≈ 2.3 µm   g = 10 µm (proximity)

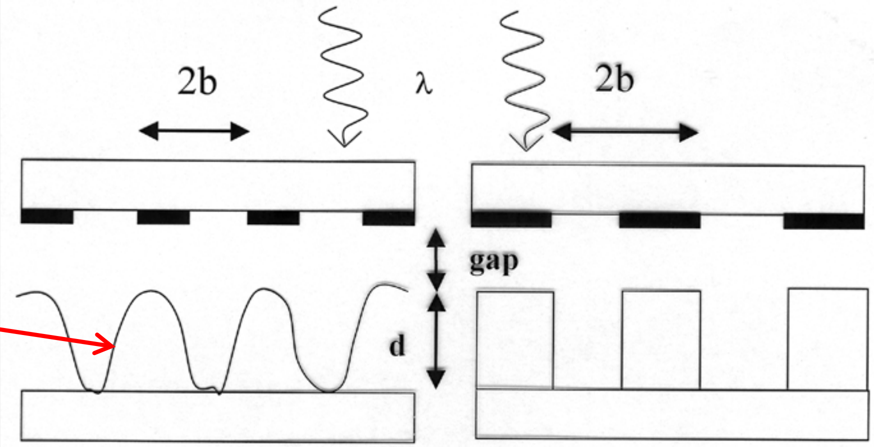
b is half-pitch

Can be improved
by phase-shift mask

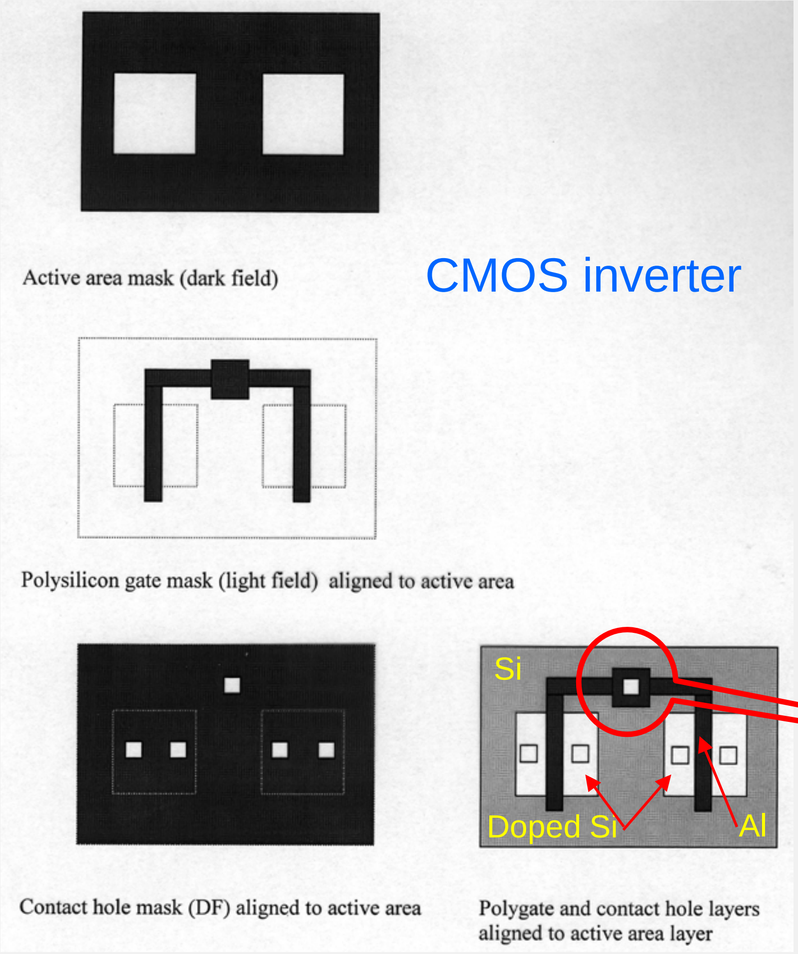
Resolution in proximity lithography

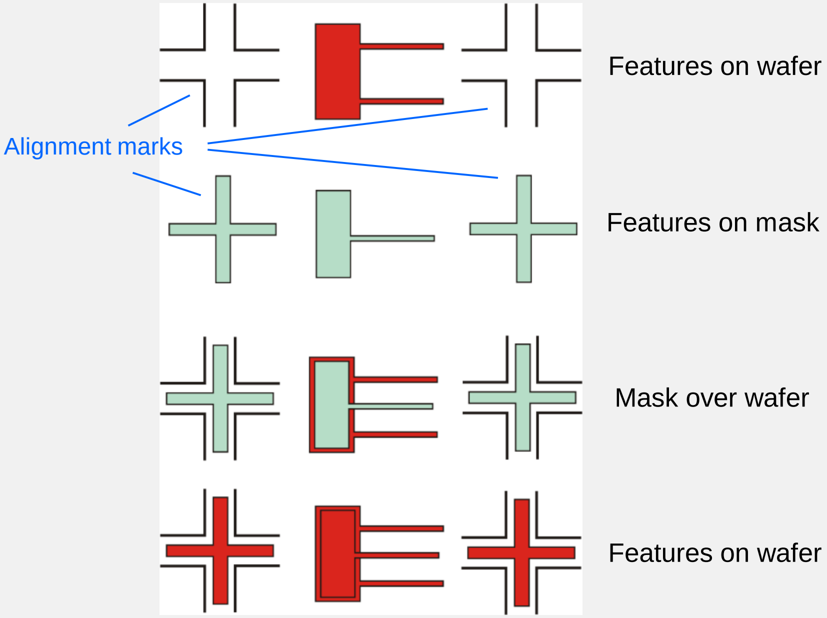
$$2b_{min} = 3\sqrt{(\lambda/n_r) * (g + (d/2))}$$

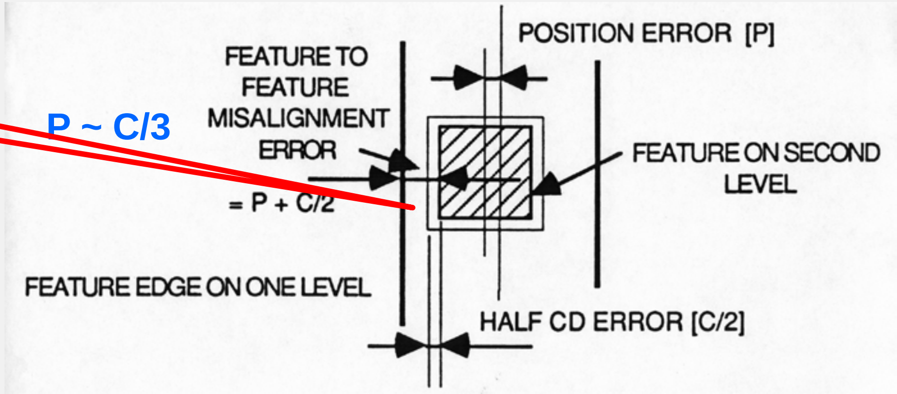
$2b_{min}$ = minimum period
λ = vacuum wavelength
n_r = refractive index of resist
g= gap between mask and resist
d = resist thickness



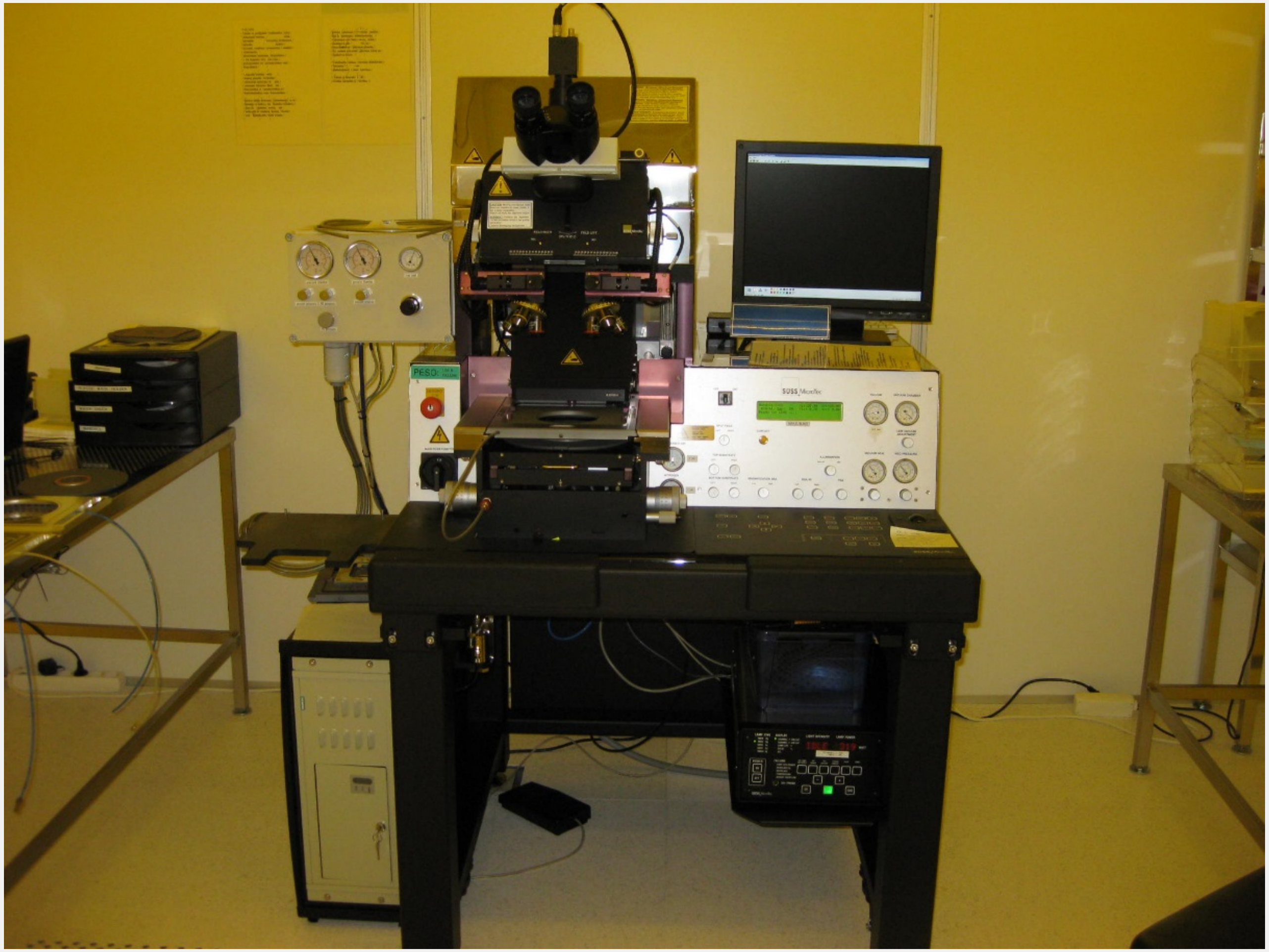
Alignment and overlay







MICRONOVA maskaligner



365 nm, i-line, Hg

Summary I

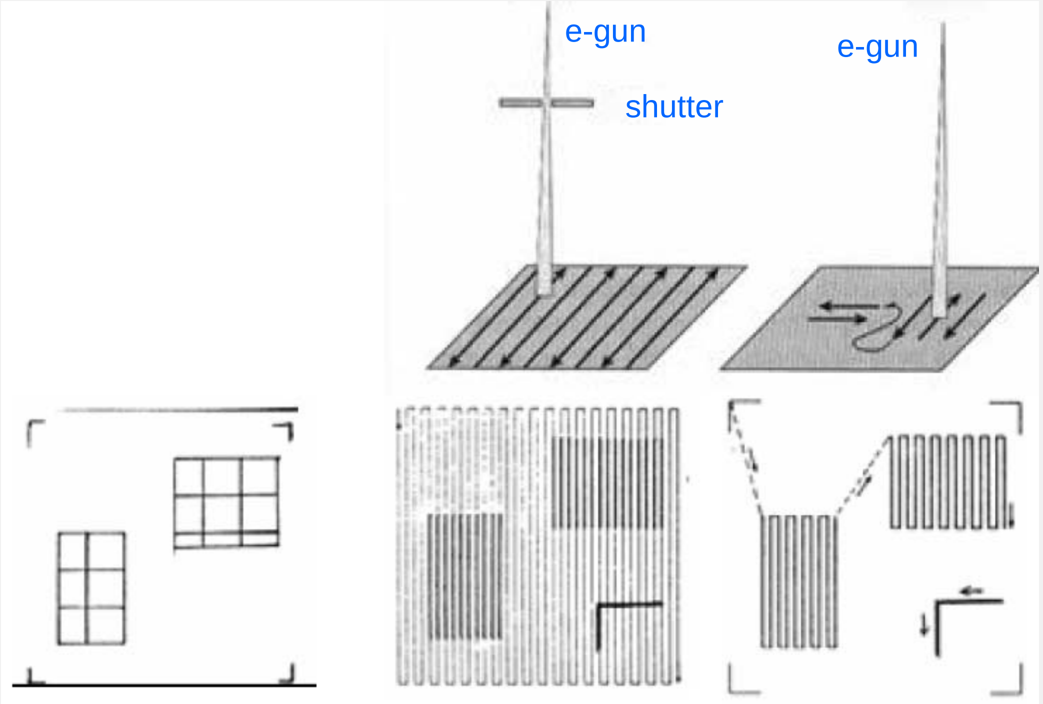
- Photolithography provides:
  - required CD
  - exact control over shape and size
  - easy alignment
  - parallel processing, i.e., patterns over an entire surface at the same time

- Limitations of photolithography
  - works only on flat surface
  - only 2D shapes can be generated

Photomask fabrication

- Cr deposition and resist application
- Pattern writing by e-beam or laser
- PR development, Cr etching, PR stripping
- CD control
- Inspection of defects and fidelity
- Soft error reduction (particle removal)
- Reparing by ion beam (etching or deposition)
- Final inspection

Pattern generation by e-beam tool



Shaped beam Raster scan Vector scan

Applying of e-beam resist

A pattern generation tool transcribes the circuit design data into a physical structure.

Raster scan vs. vector scanning.

Variable shaped beam vs. Gaussian beam.

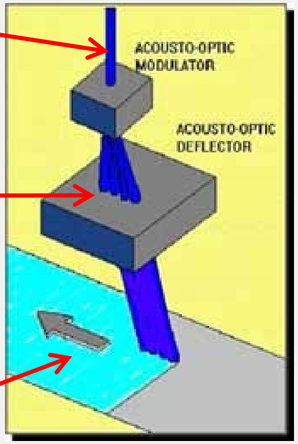
Global alignment vs. chip-alignment.

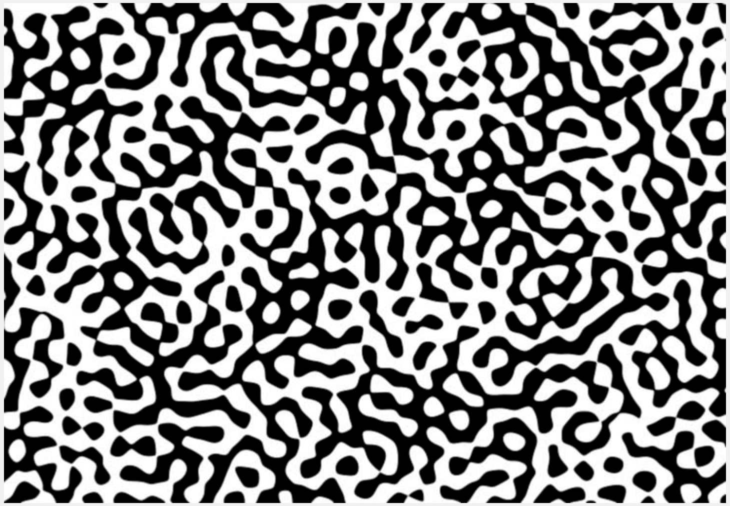
Laser beam sweep and a laser writer

Laser beam

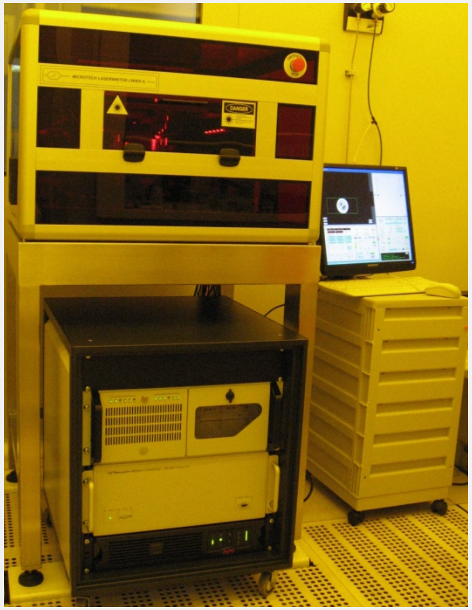
Four laser beams

Stage movement





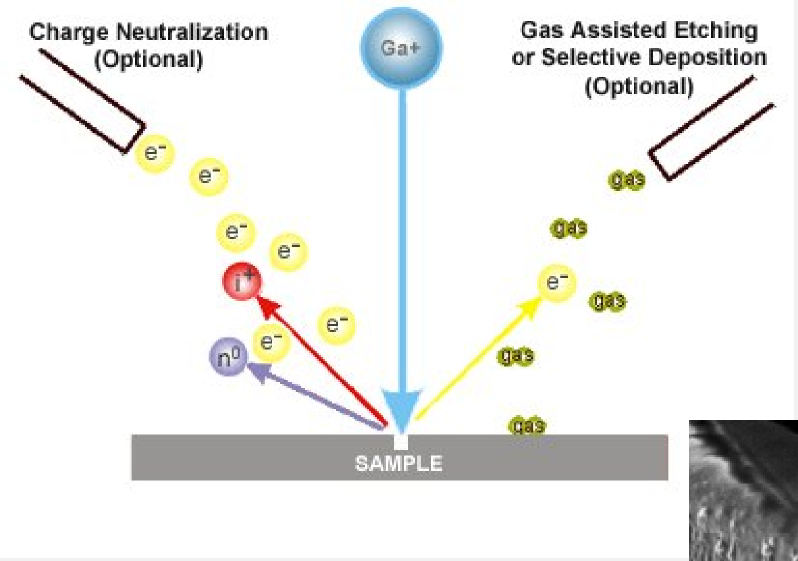
CD – 500 nm
Area 1x1 cm^2
Time 2 hours



MICRONOVA laser writer

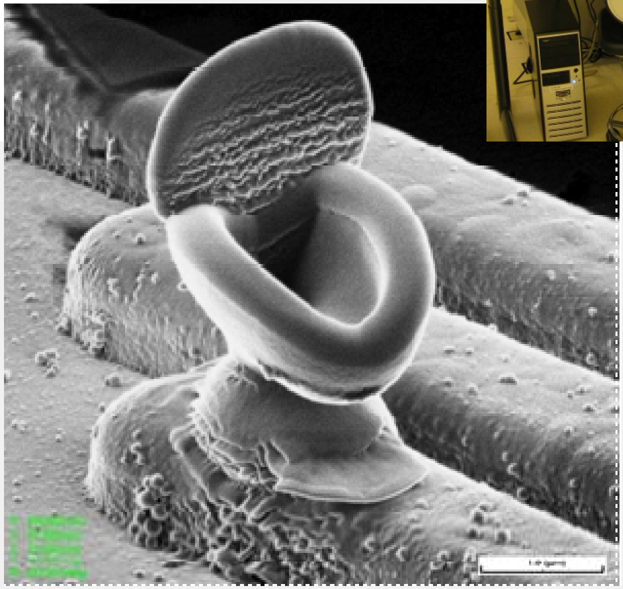
Beam wavelength 405 nm

Focused ion beam (FIB)



MICRONOVA FIB

Fabricated by FIB – 3D patterning!



DOI: 10.1017/S1431927605504884

Summary II

- Direct writing pros:
  - extremly small patterns
  - photomask is not required

- Direct writing cons:
  - serial processing, i.e., one element after another
  - alignment is problematic

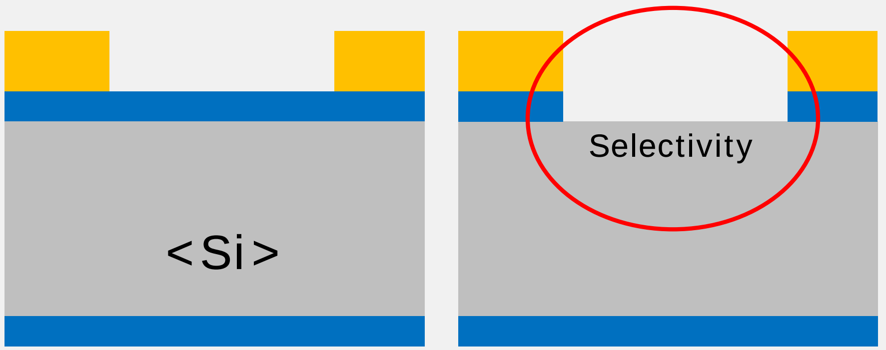
Lithography and etching

1) photoresist patterning

2) Etching with reactive chemicals (acids, bases, plasmas)

Same procedure applies both to etching thin films and to etching silicon wafer itself. Thicknesses and etch stop vary !

Photolithography can be redone if problems detected, but after etching no repair is available.



Etching thin film

Etching bulk silicon

Etching terminology

Etching mask – patterned protective layer on the top of etched material

Undercut – lateral erosion of etched material below protective layer

Selectivity – ratio of etching rates for two etched materials

Aspect ration – ratio of height to width for a microstructure

Anisotropy – different etching rate in different directions

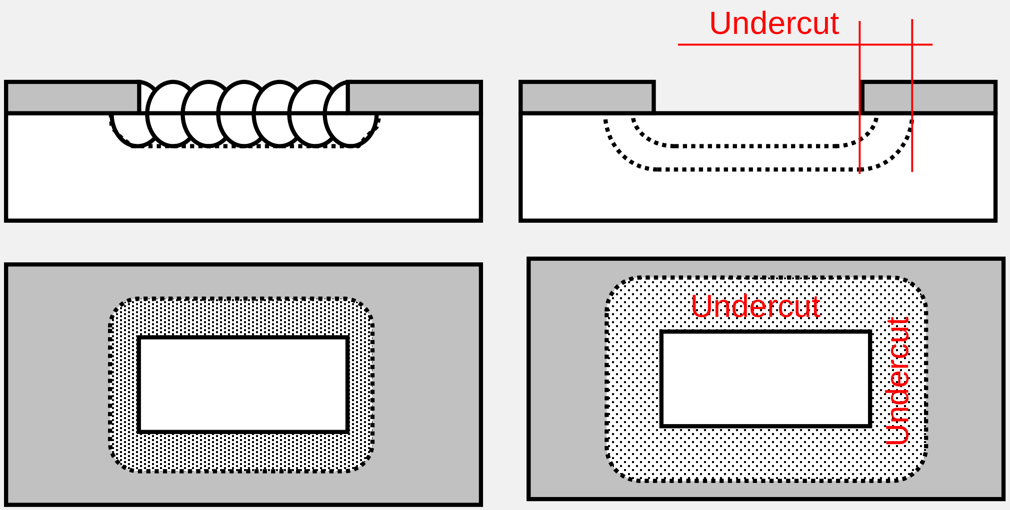
Etch mask

- Protective layer that is very slowly attacked by etchant
- Resist is the simplest etch mask to use ➔ always consider resist mask first
- Aggressive etchants (KOH) will prevent use of resist ➔ hard mask required

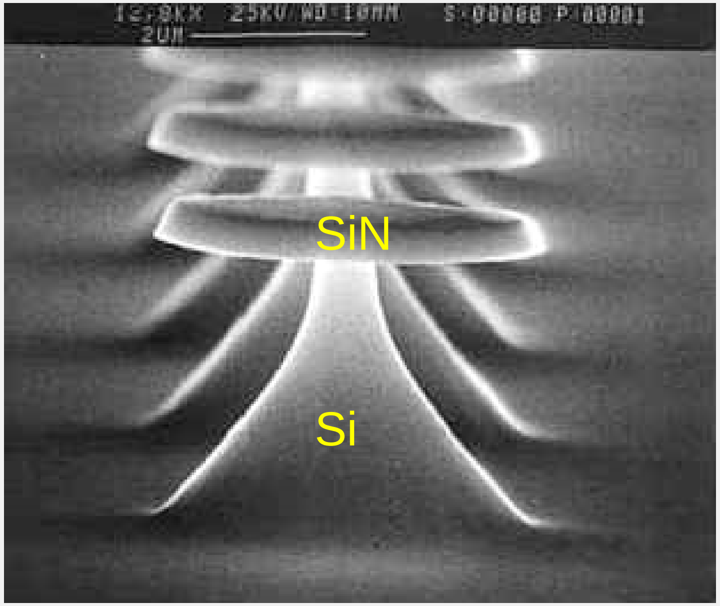
- Quiz: what is a photomask ? How does it relate to etch mask ?

Isotropic etching

- Proceeds as a spherical wave
- Undercuts structures (proceeds under mask)
- Most wet etching processes are isotropic, e.g., HF etching of oxide, H_3PO_4 etching of Al
- Some of dry etchings are isotropic, e.g., photoresist stripping



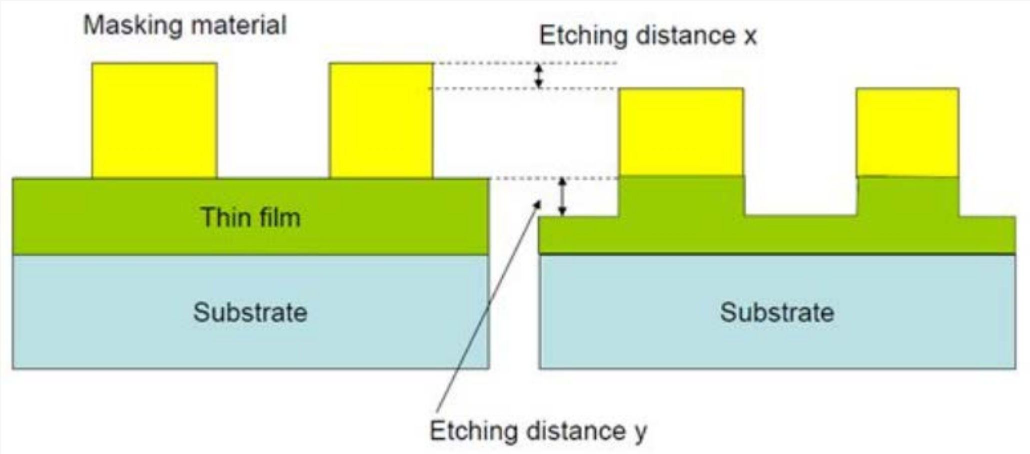
5 µm deep, isotropic etch →



Selectivity

Selectivity is defined as etch rate ratio:

S= rate film / rate mask = *y/x*



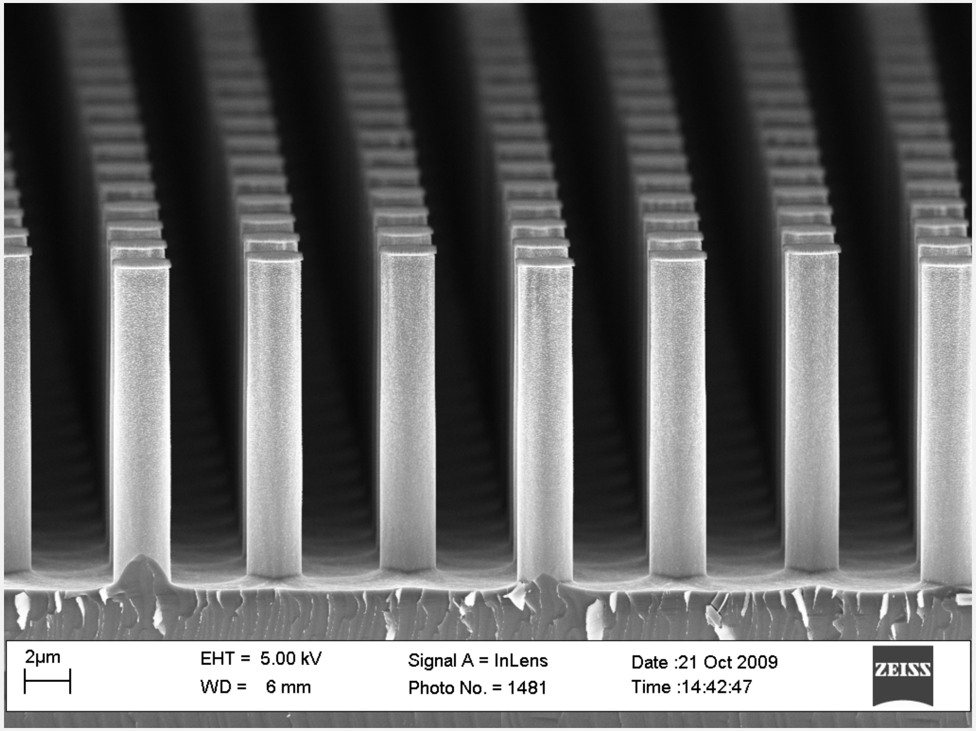
Silicon etch rate 500 nm/min
Oxide etch rate 15 nm/min
Selectivity 33:1

Silicon etch rate 500 nm/min
Resist etch rate 200 nm/min
Selectivity 2.5:1

$S \neq \infty$ ➔There is always some unintentional loss of material

Aspect ratio

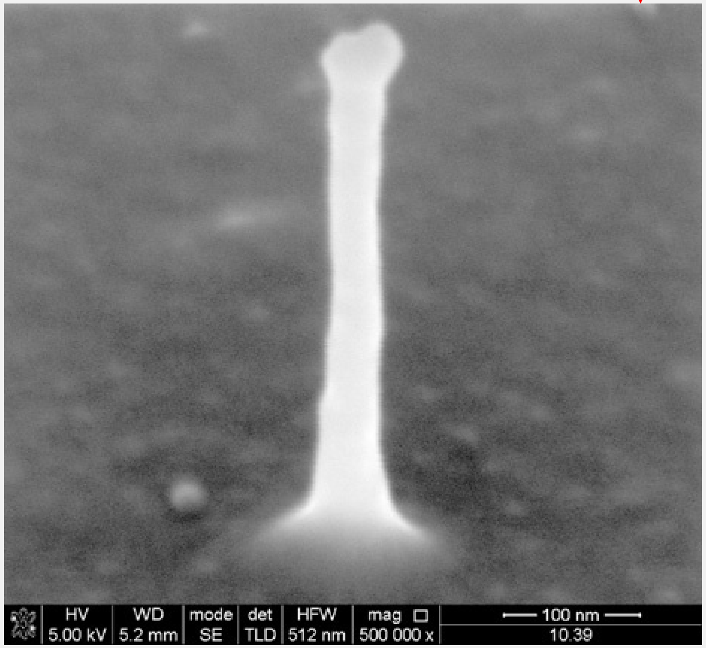
AR is the ratio of height to width



Lauri Sainiemi

Si pillar array AR 5:1

Si nanopillar AR 15:1



Nikolai Chekurov

Main methods of etching

Wet etching (usually, isotropic)

solid + liquid etchant ➔ soluble products

$Si\ (s) + 2\ OH^- + 2\ H_2O \rightarrow Si(OH)_2(O^-)_2\ (aq) + 2\ H_2\ (g)$

Plasma (dry) etching (usually, anisotropic)

solid + gaseous etchant ➔ volatile products

$SiO_2\ (s) + CF_4\ (g) \rightarrow SiF_4\ (g) + CO_2\ (g)$

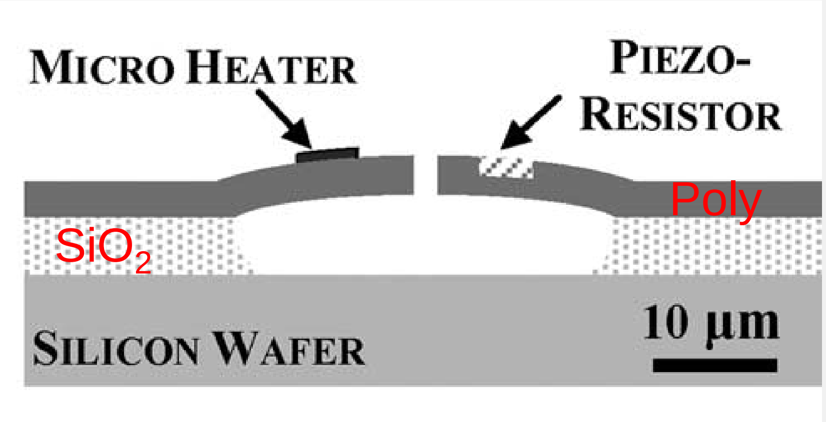
Typical etching rate 100 – 1000 nm/min in both cases

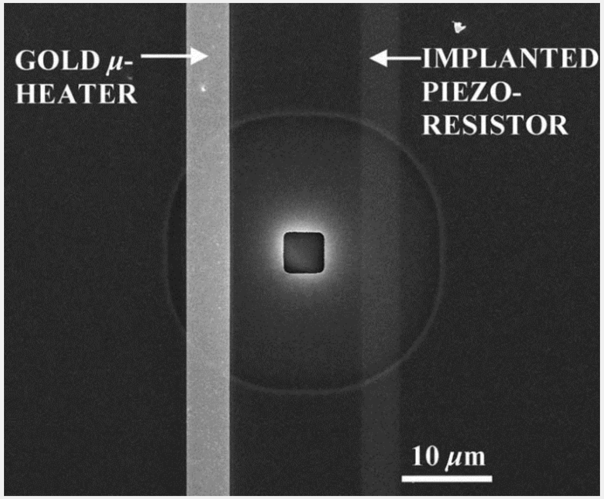
Wet etchants for common materials

• SiO_2	HF	
• <Si>	KOH (10-50%)	anisotropic etch
• <Si>	HNO_3:HF:CH_3COOH	isotropic etch
• poly-Si	HNO_3:HF: H_2O	
• Al	H_3PO_4:HNO_3:H_2O	
• W, TiW	H_2O_2:H_2O	
• Cu	HNO_3:H_2O (1:1)	
• Ni	HNO_3:CH_3COOH:H_2SO_4	
• Au	KI:I_2:H_2O	
• Pt, Au	HNO_3:HCl (1:3) "aqua regia"	

Everywhere, exclude Si etching, photoresist mask can be used

Undercutting in action: dome resonator





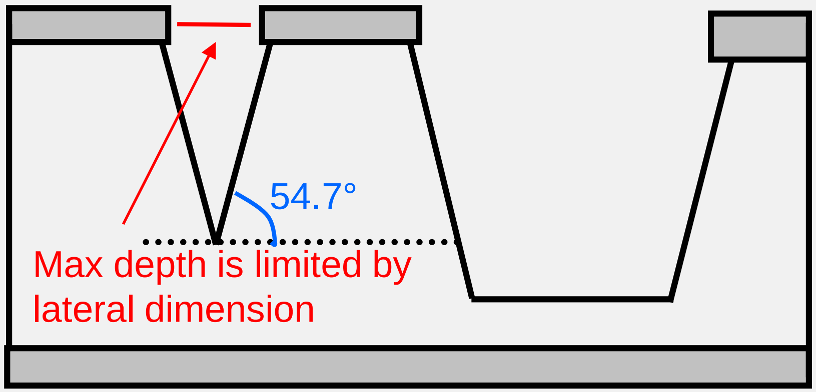
H. G. Craighead

1) RIE etching of a small hole in polysilicon

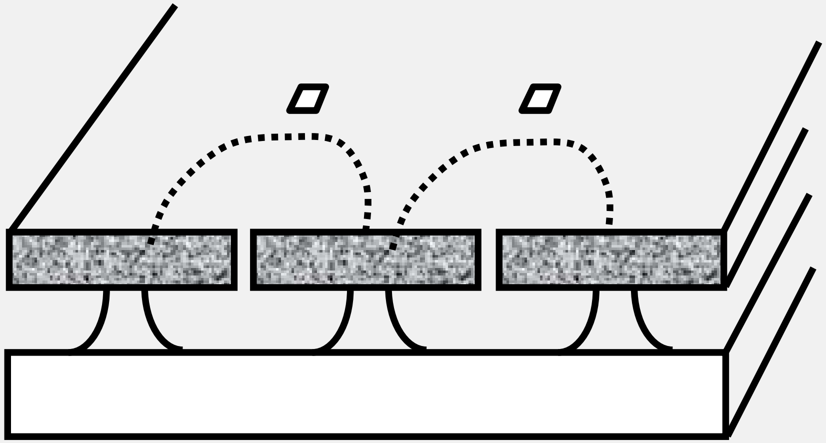
2) Isotropic HF wet etching of oxide under polysilicon
➔ Membrane can move

Anisotropic wet etching
(only for crystals)

Anisotropic etching



Isotropic etching



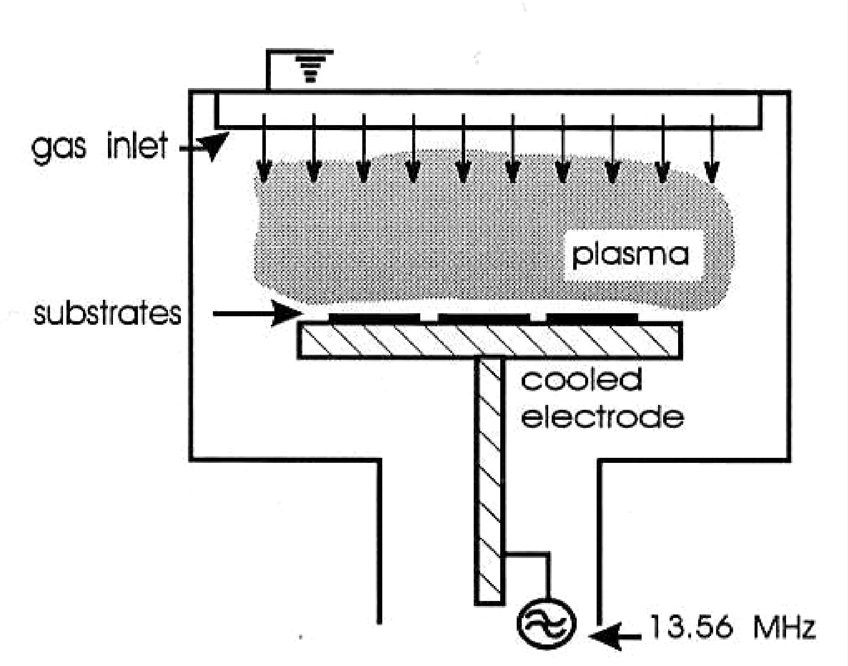
Accurate, but limited in shape;
Excellent surface finish

Wet etching

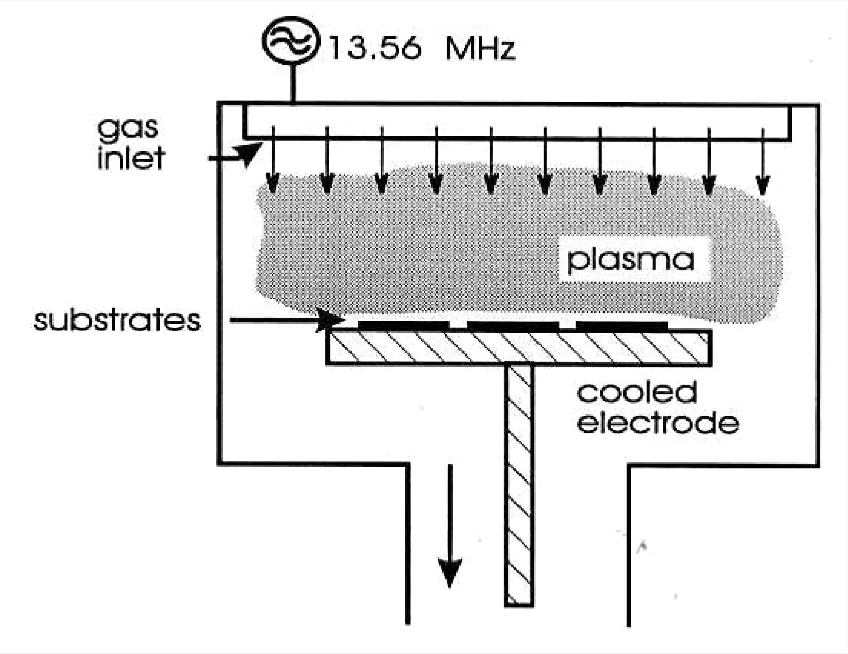
- Usually isotropic, but can be anisotropic for crystals, e.g., for *c*-Si
- Perfect selectivity
- Special etchant for each material
- Surface finish smooth
- Fast, because batch process
- Cheap equipment

Dry etching

RIE - Reactive Ion Etching



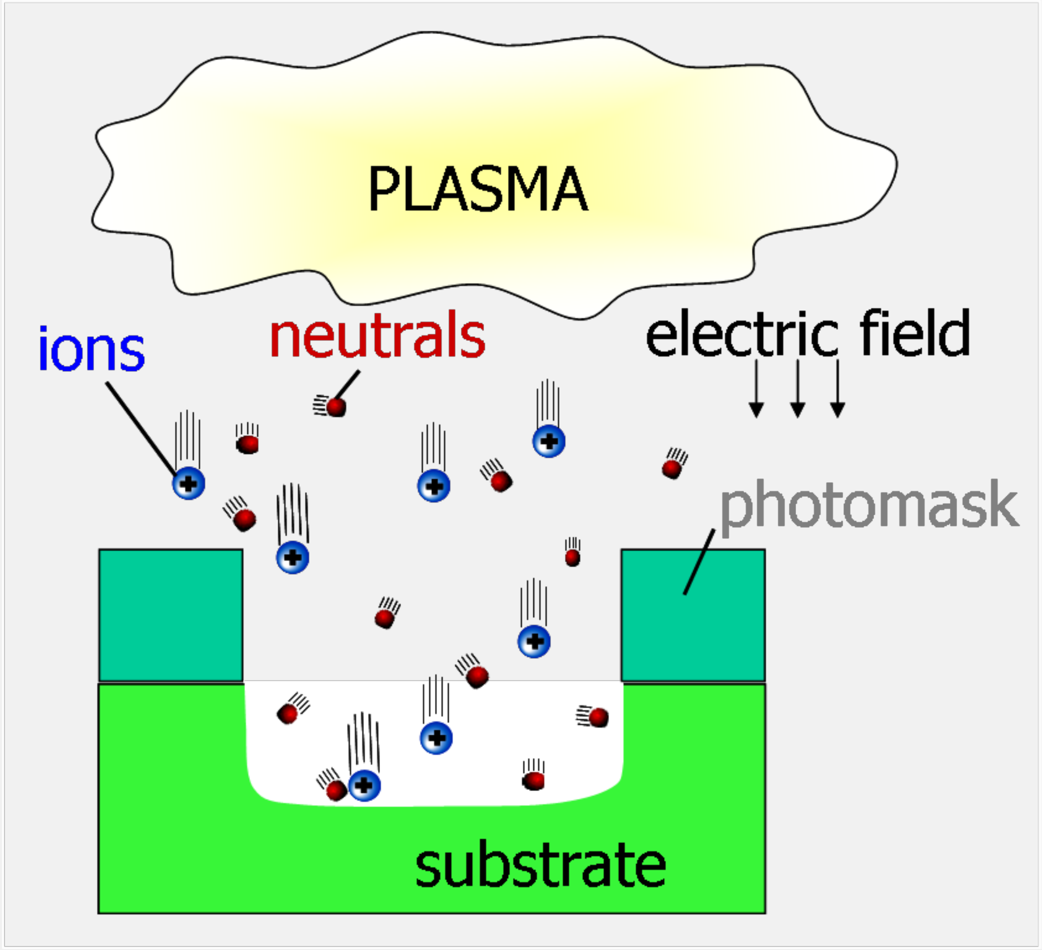
PE - Plasma Etching, also PECVD



Ion density 10^{10} ions/cm^{-3}

Reactive neutrals or active radicals density 10^{15} ions/cm^{-3}

Plasma – surface interaction in RIE

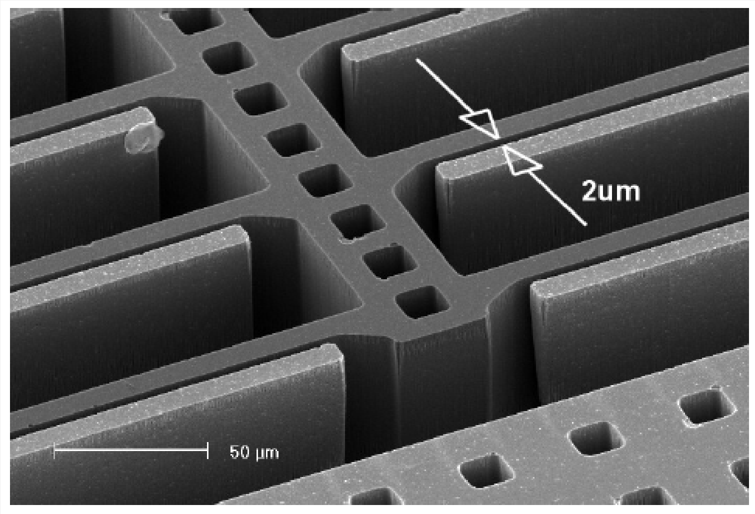


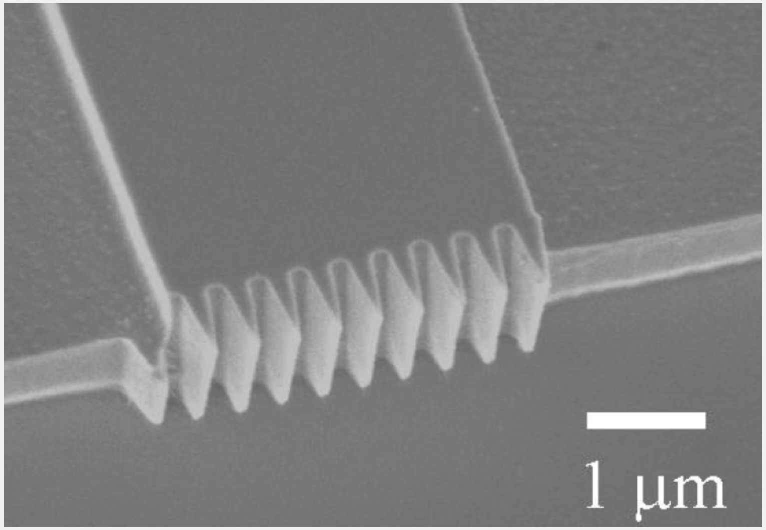
https://scorec.rpi.edu/research_plasmaetchmodeling.php

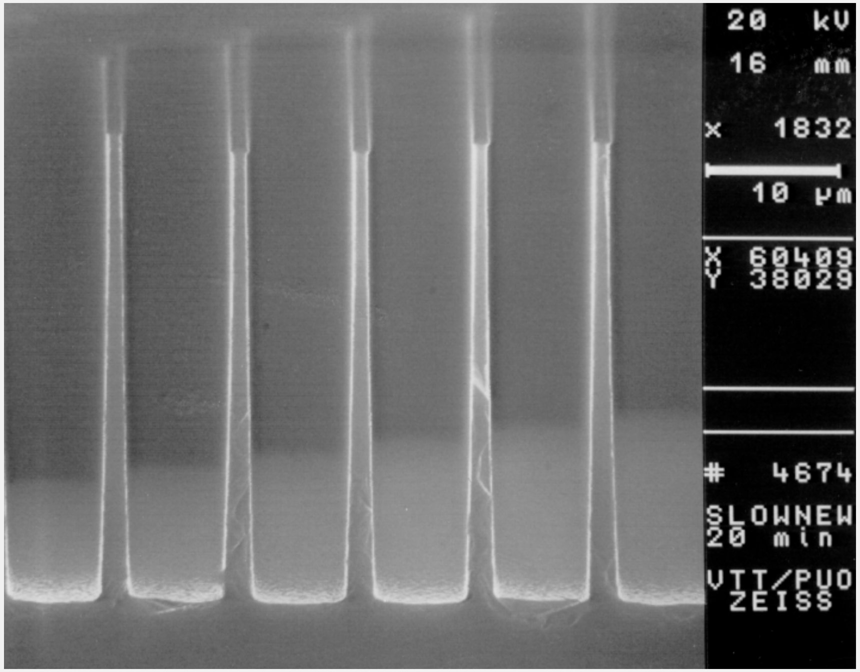
Chemistry of dry etching

Material	Etch gas	Product gases
• Silicon	SF_6 (or Cl_2)	SiF_4, $SiCl_4$
• Oxide	CHF_3 (or C_4F_8)	SiF_4, CO_2
• Nitride	SF_6 (or CF_4)	SiF_4, N_2
• Aluminum	Cl_2	$AlCl_3$
• Tungsten	SF_6	WF_6
• Copper	no practical plasma etching (Ar)	

Plasma etched (anisotropic) profiles





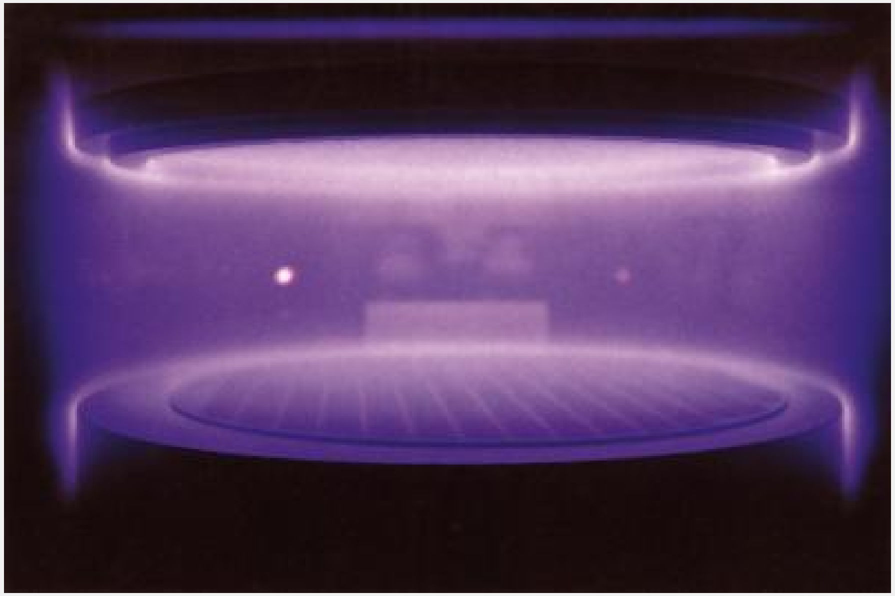


Franssila: Microfabrication

Plasma etching

- Usually anisotropic, but can be isotropic
- Near vertical walls
- Low selectivity
- Surface finish rough
- Slow, because single wafer process ?
- Expensive equipment

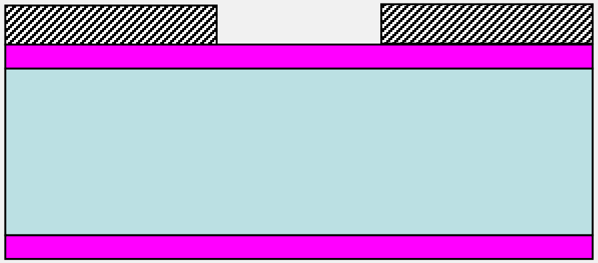
Wet etching vs. plasma etch I

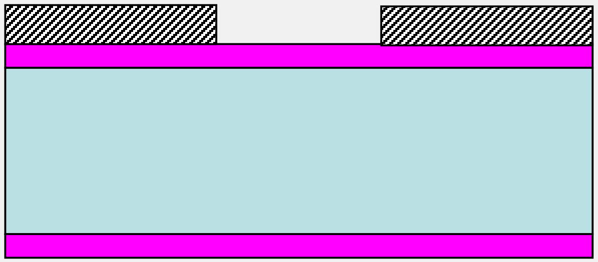


Wet etching: chemical reaction; simple wet bench and acids or bases needed

Plasma etching: chemical and physical processes; requires RF-generator, vacuum system and gas lines

Wet etch vs. plasma etch II



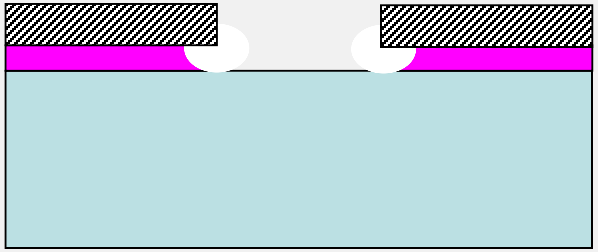


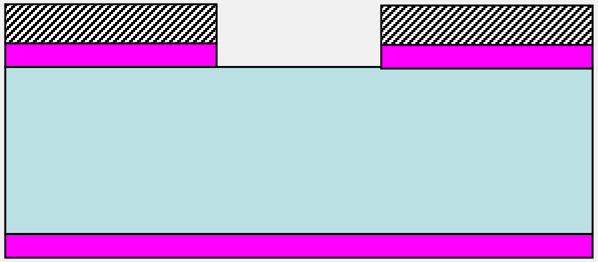
Oxide wet etch in HF

Undercut, isotropic

Oxide plasma etch in CHF_3

Vertical walls, no undercut



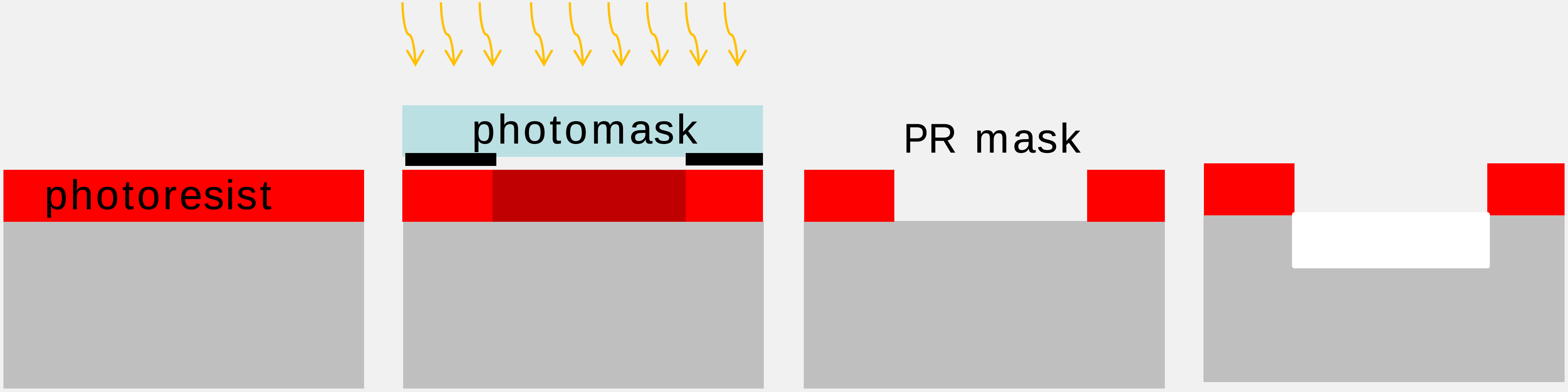


Film removed from backside

Film remains on backside

Photoresist as an etch mask

– Most simple to use
– Tolerates RIE: selectivity 10:1 at best
– Does not tolerate long RIE
– Does not tolerate most wet etchants such as KOH



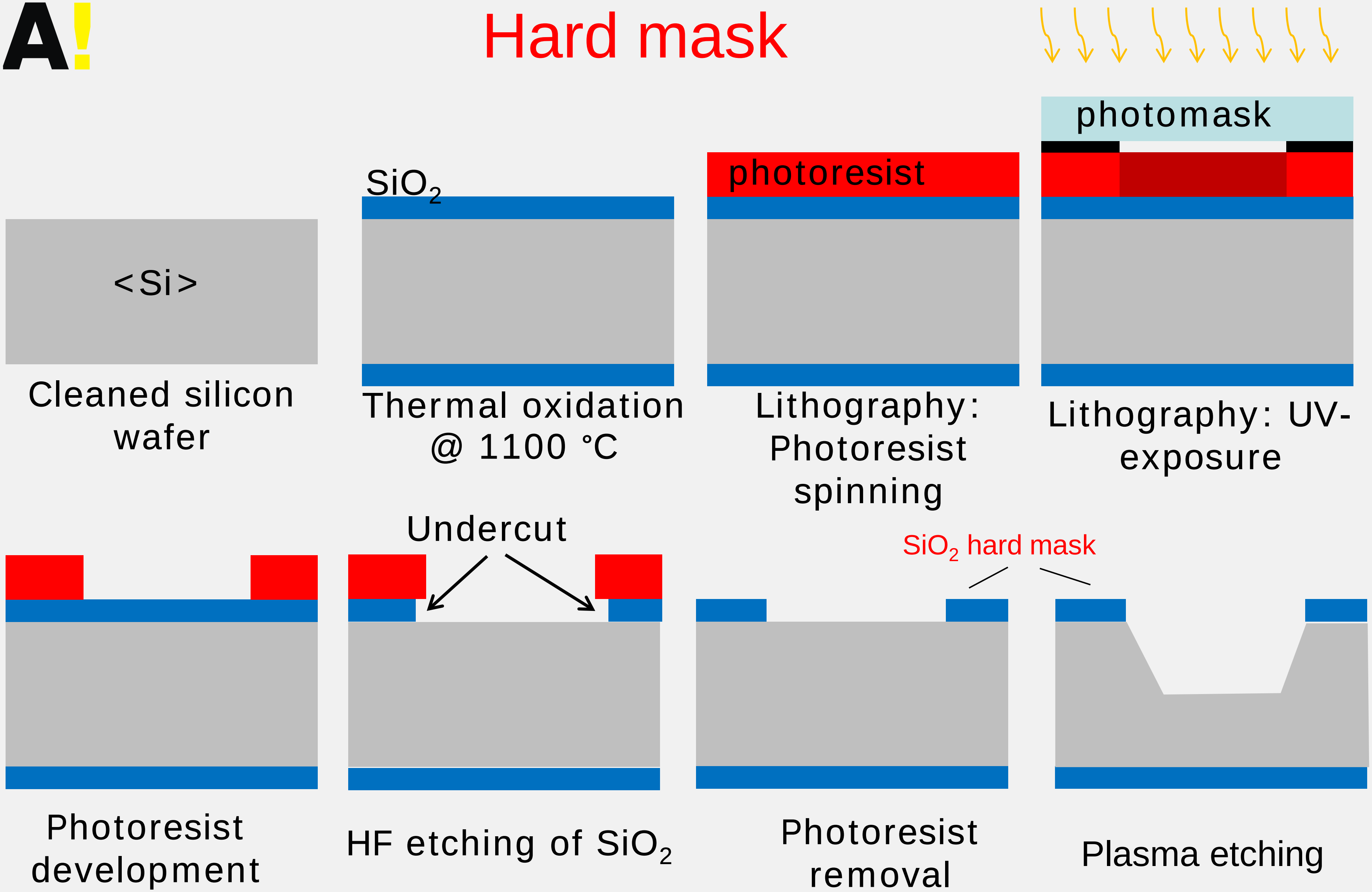
Lithography: Photoresist spinning

Lithography: UV-exposure

Photoresist development

Etching with resist mask

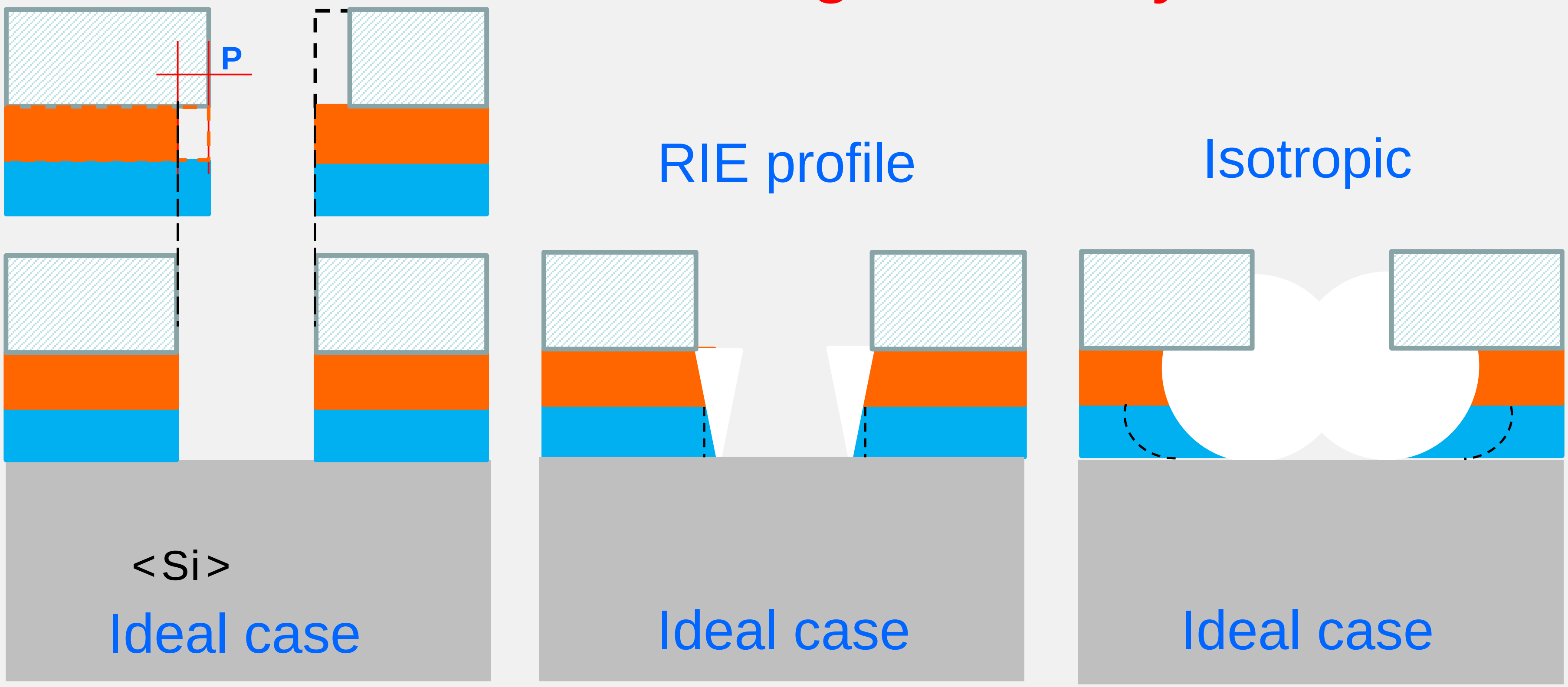
Hard mask



photomask
photoresist
SiO_2
<Si>
Cleaned silicon wafer
Thermal oxidation @ 1100 °C
Lithography: Photoresist spinning
Lithography: UV-exposure
Undercut
SiO_2 hard mask
Photoresist development
HF etching of SiO_2
Photoresist removal
Plasma etching

Etching of two-layer films

Misalignment

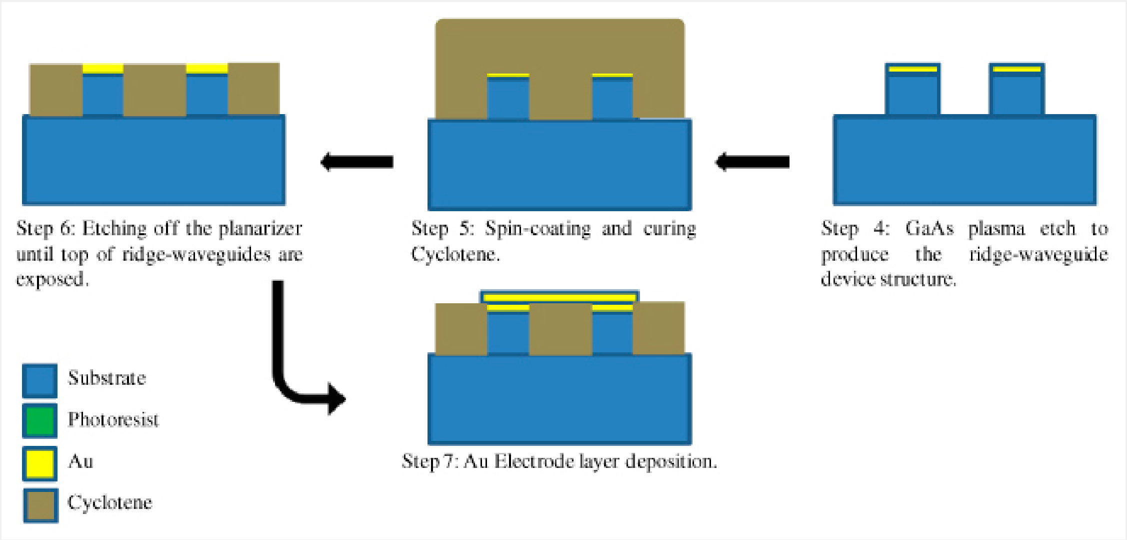


If two layers are perfectly aligned, they were made in the same etch step.

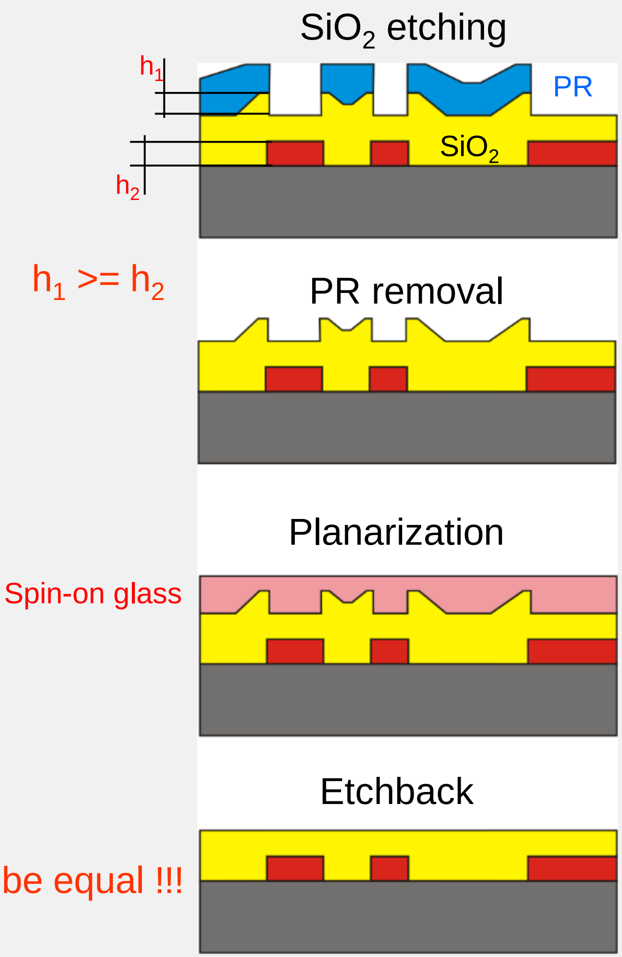
Otherwise alignment error would be visible.

Etchback

One layer surface planarization



Two layers surface planarization



Requirement: etching rates of glass and PR must be equal !!!