Lithography and etching 2023

sami.franssila@aalto.fi

Chapters 9,11

Outline

- lithography = photoresist pattern formation
- etching = transfer of photoresist pattern into solid material
- stripping = removal of photoresist after etching the pattern
- isotropic (wet) etching
- anisotropic (plasma) etching

Patterning process: lithography and etching

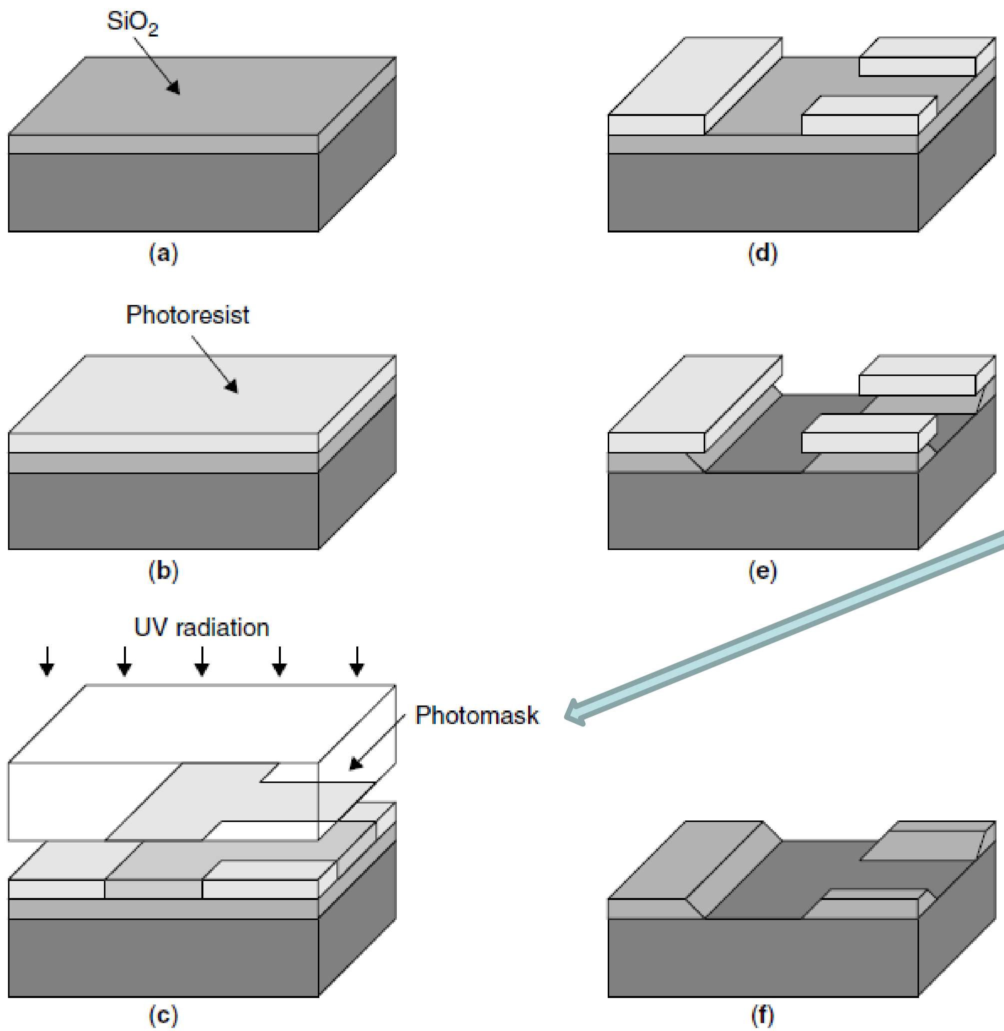
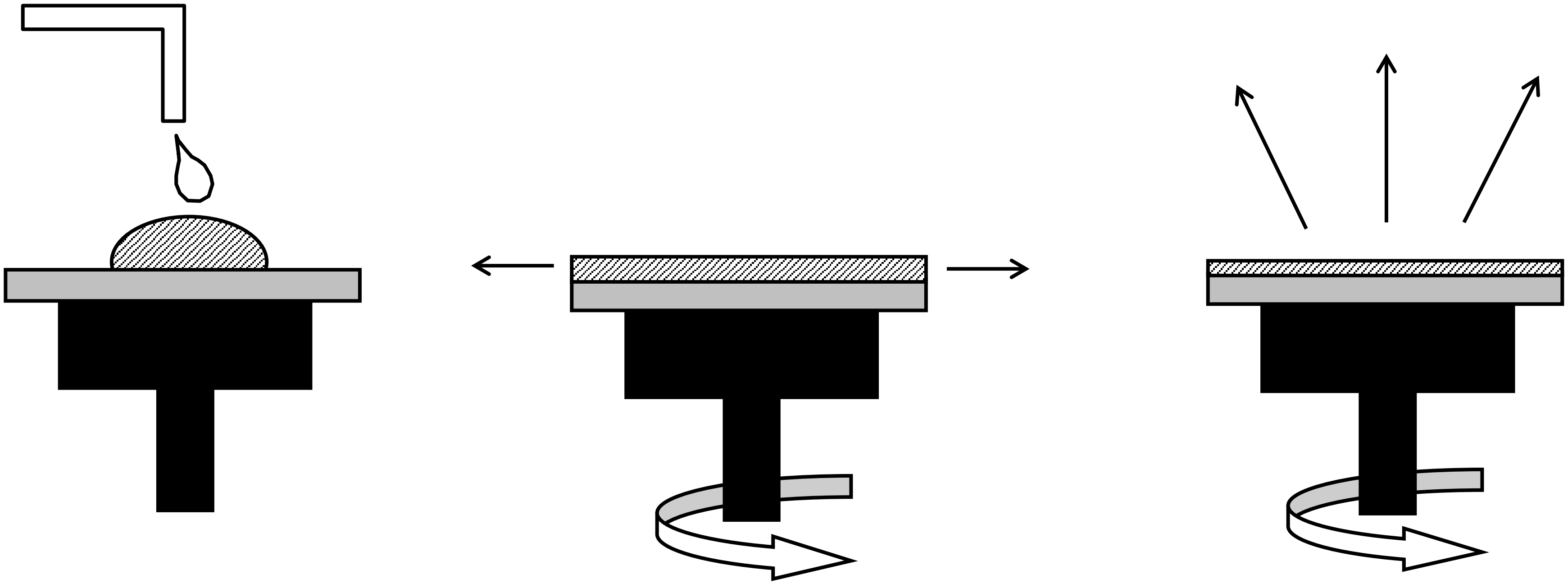


Fig. 9.1

Photoresist spin coating



Resist dispensing (a few milliliters)

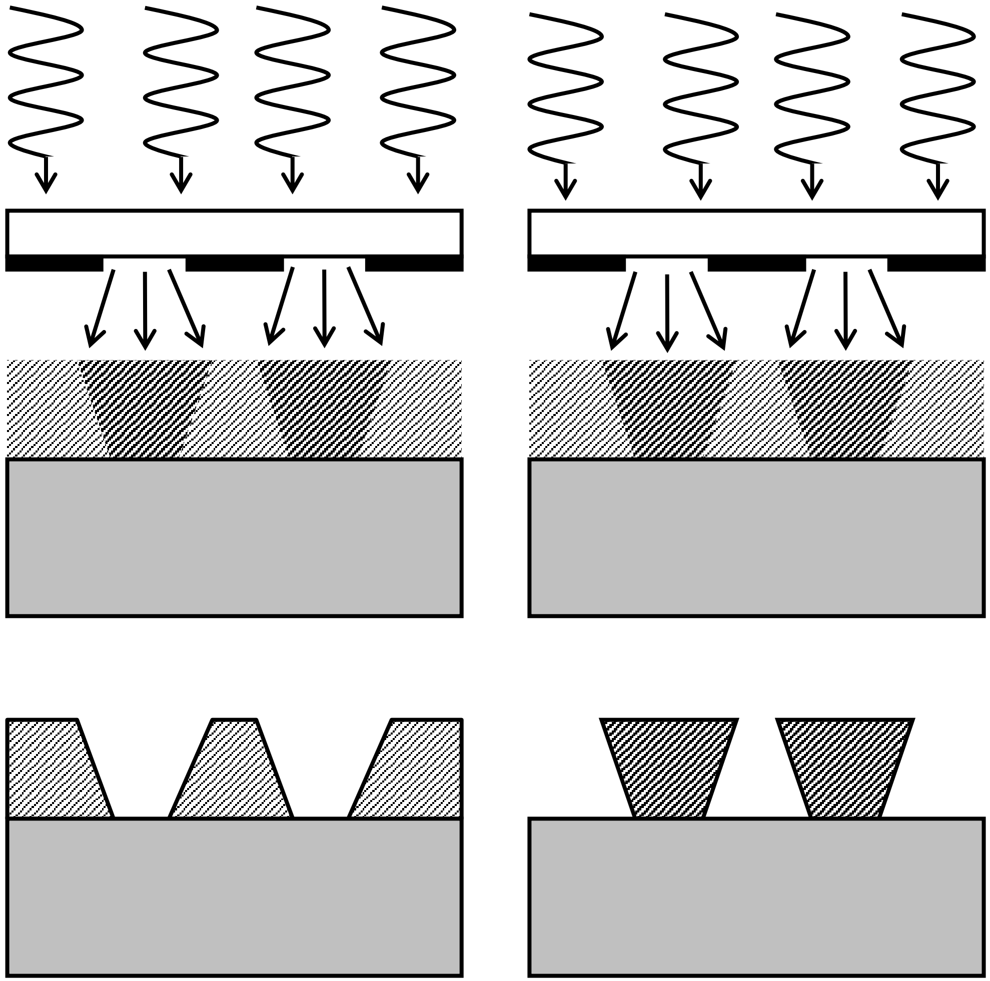
Acceleration (resist expelled)

Final spinning (5000 rpm) (partial drying via evaporation)

Photoresist exposure

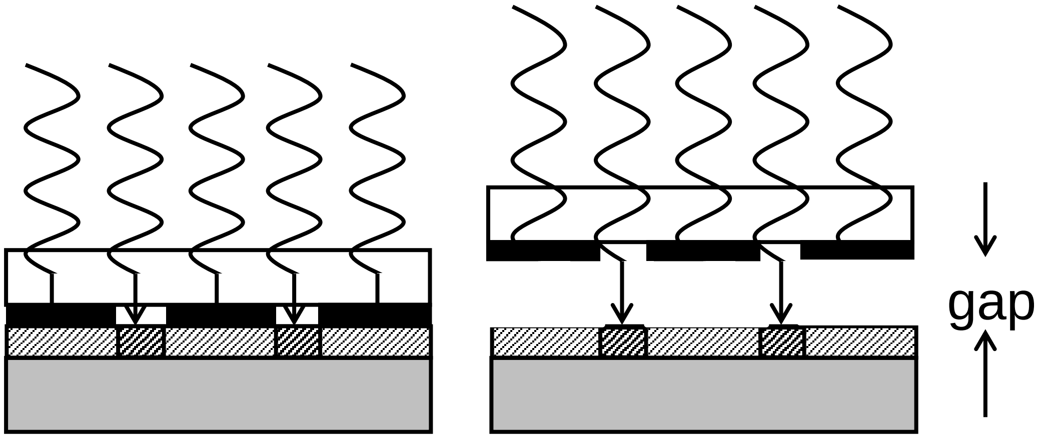
Positive resist: exposed parts become soluble (because polymer breaks into small, soluble pieces)

Negative resist: exposed parts photo-polymerize and cross-link and become insoluble



Typically 1 µm thick

Contact/proximity lithography



$$linewidth \approx \sqrt{\lambda \cdot \left(g + \frac{d}{2} \right)}$$

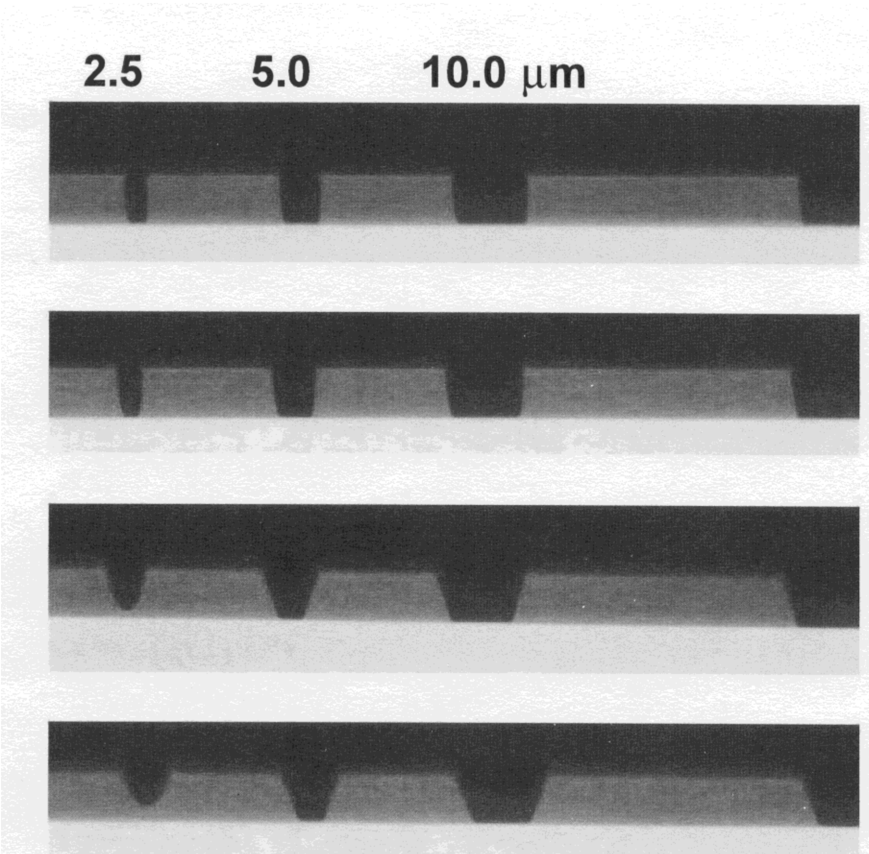
λ = 436 nm

d = 1 μm (standard resist)

Linewidth min ≈ 0.5 μm   gap = 0 (contact)

Linewidth min ≈ 2 μm   gap = 10 μm (proximity)

Contact/proximity resolution



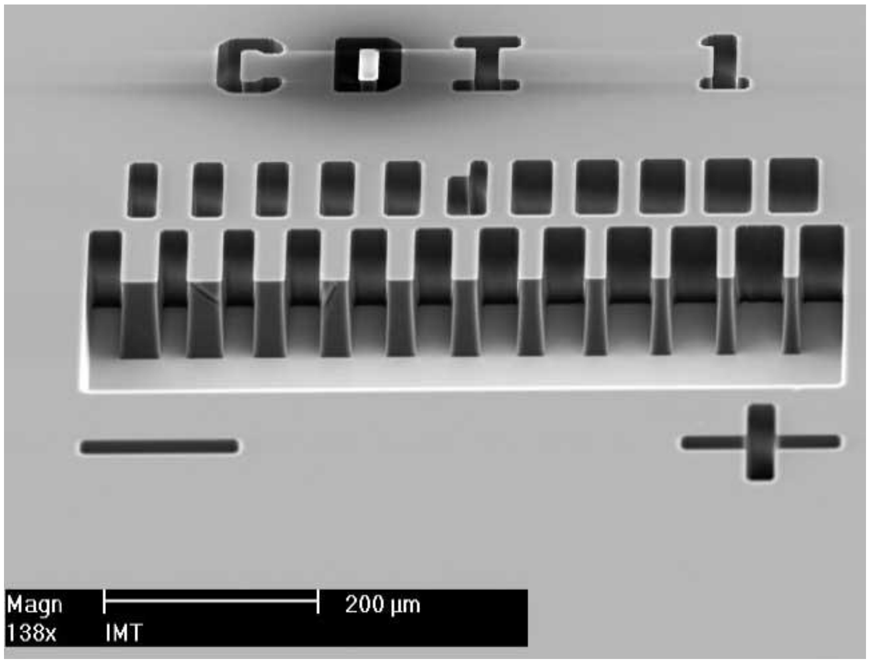
Vacuum contact

Hard contact

Soft contact

20 μm proximity gap

Lithography test structures



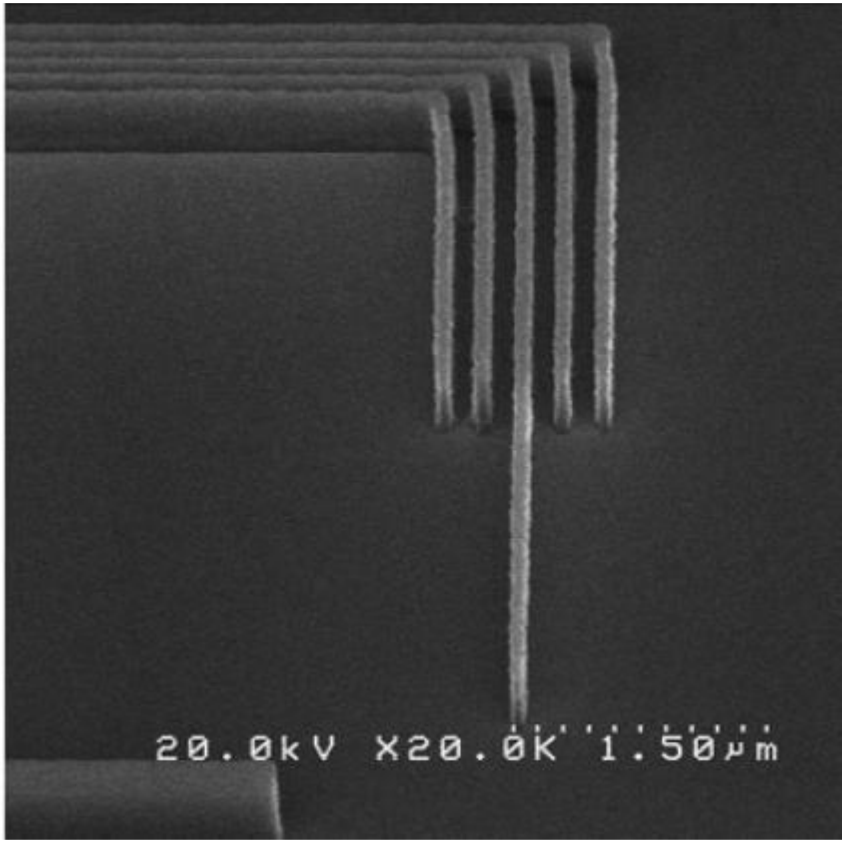
Test which lines can be resolved ➔ find process capability

Test lines in different “neighborhoods”

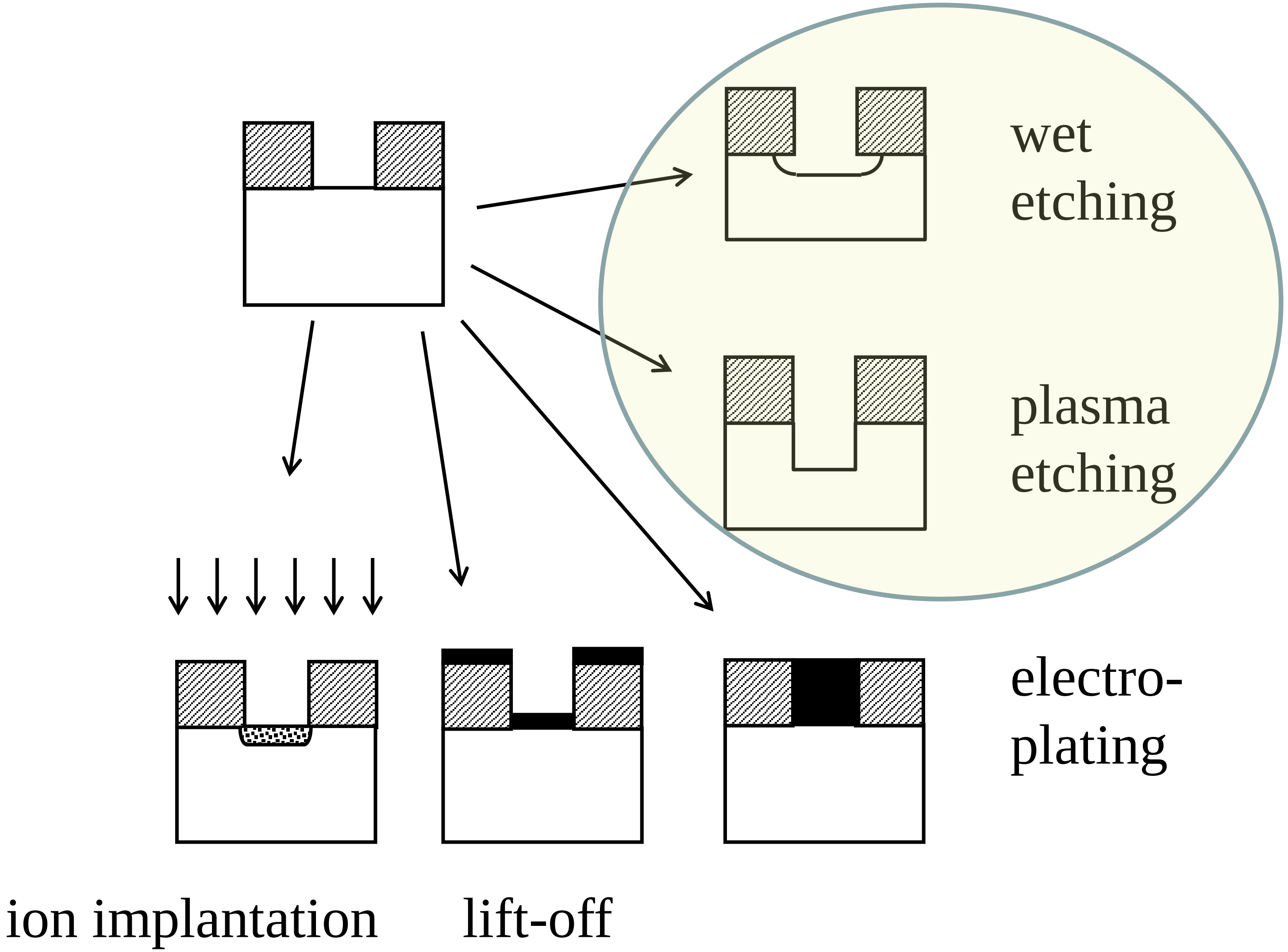
Linewidth and pitch

The goal of lithography is to make lines **and** spaces small (only this will increase device packing density).

In making microprocessor gates, line is smaller than space, e.g. 100 nm pitch results in 30 nm gate and 70 nm space.

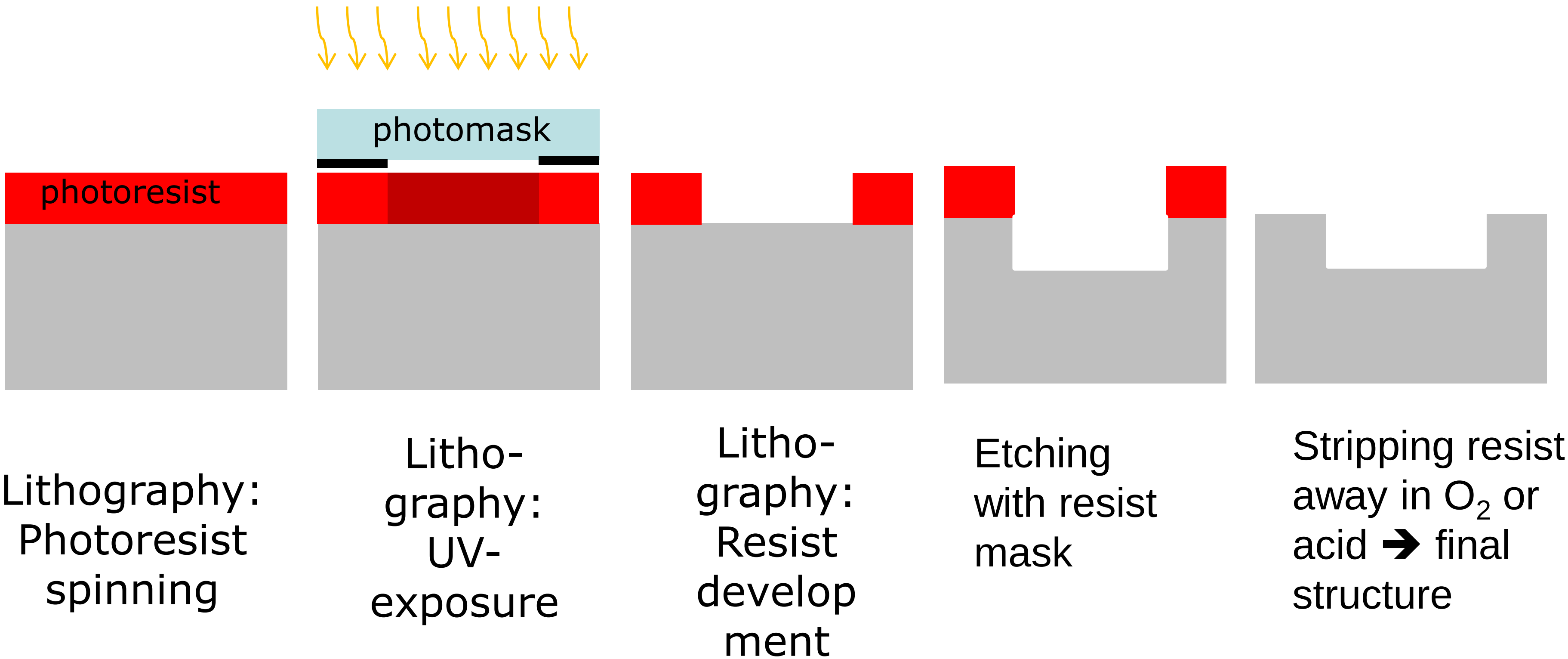


Processing after lithography



Photoresist as an etch mask

– Most simple to use
– Will be consumed during etching
– Suitable for most etching processes but not all



Lithography and etching

1) Lithographic pattern

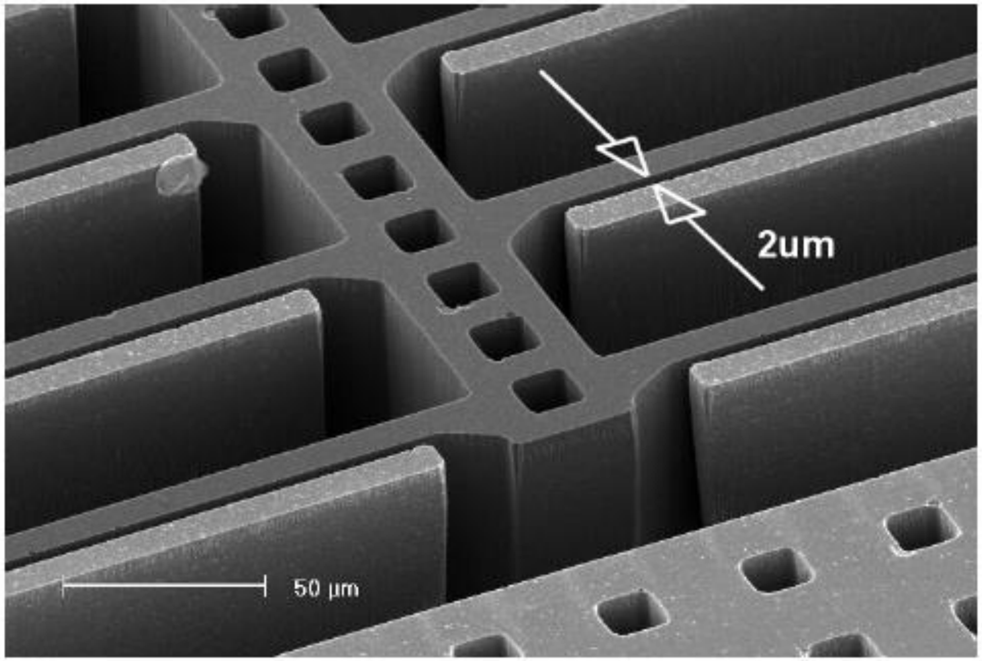
2) etching with reactive chemicals (acids, bases, plasmas)

Etching thin film

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

Etching bulk silicon

Structure in silicon after etching



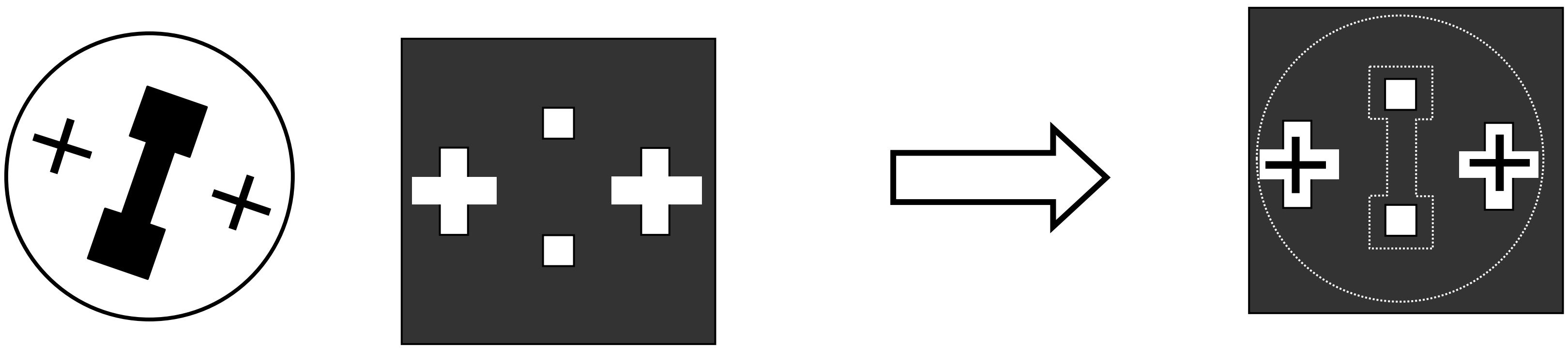
Plasma etching (=RIE)

Deep vertical walls

Narrow gaps

Alignment

- Alignment (overlay of patterns made in different steps) must be considered whenever two or more patterns are needed for the final structure
- Alignment is done with separate alignment marks (e.g. hair crosses); not by the structures themselves
- Alignment mark size is irrelevant !

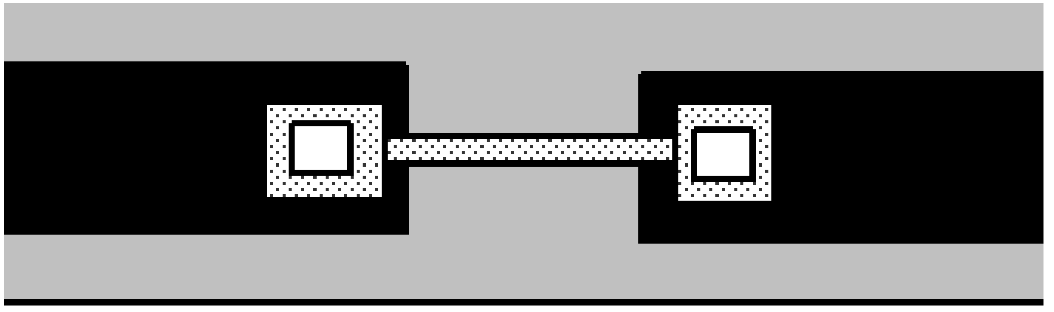


1st pattern on wafer 2nd pattern on photomask Translation & rotation Alignment of patterns

Alignment in resistor fabrication

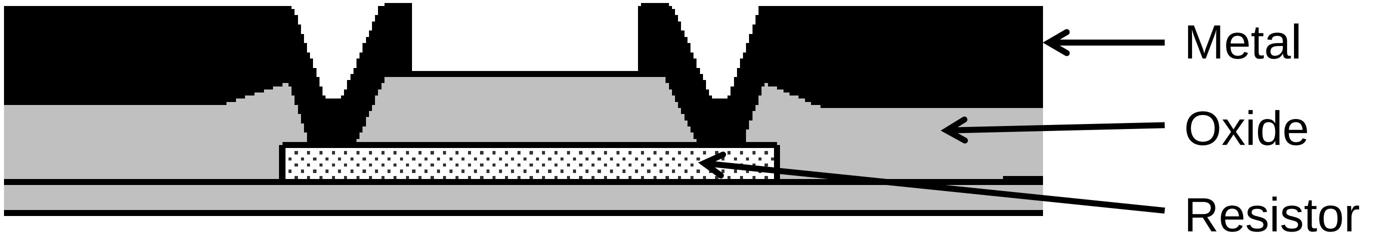
Top view

(=mask layout)



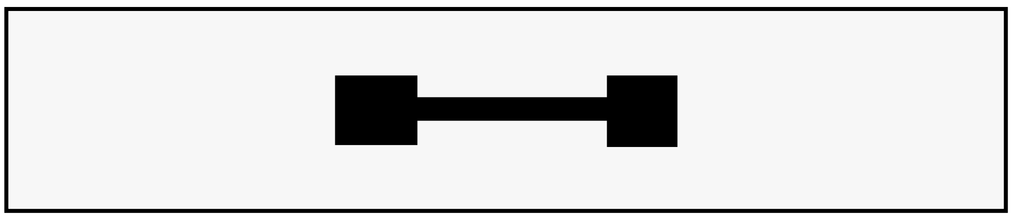
Sideview

(=cross section)



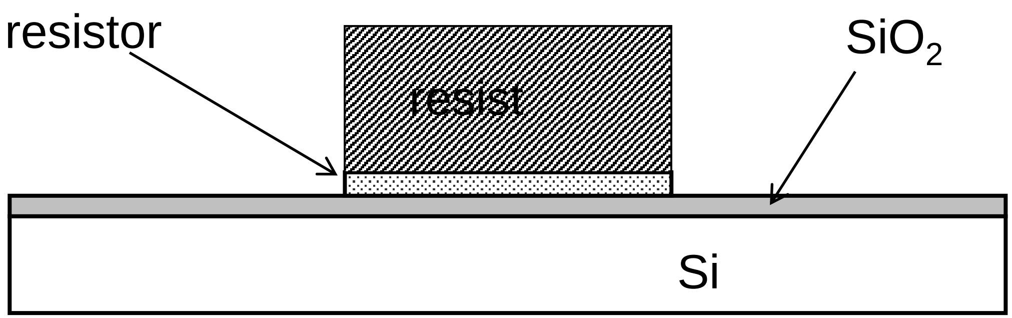
1. Contact hole in oxide must be aligned to resistor
2. Metal must be aligned to resistor

Patterning the resistor



Photomask

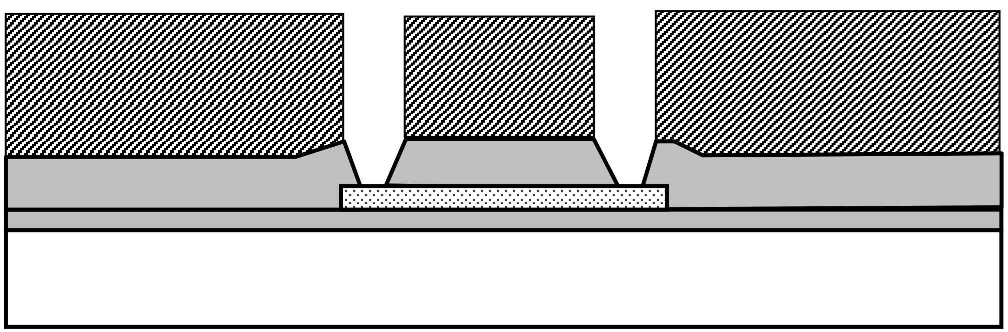
pattern



Cross section view after resistor etching; before photoresist removal

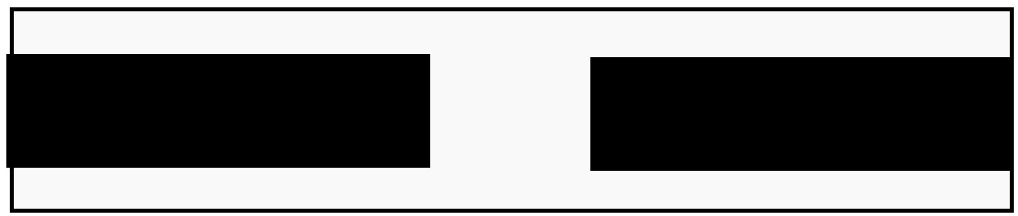
Oxide deposition & patterning

Photomask

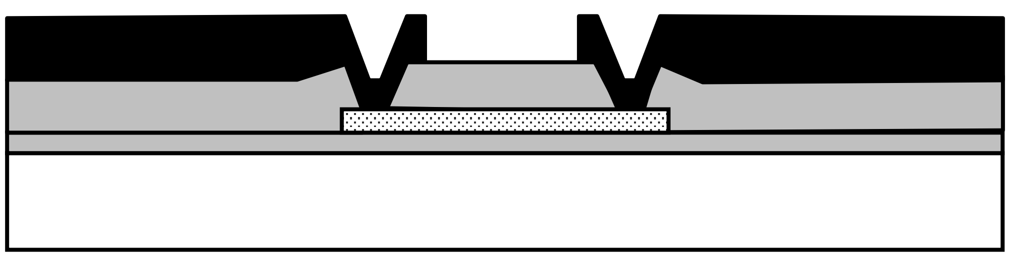


Oxide etched in holes (photoresist still in place)

Metal deposition & patterning



Photomask

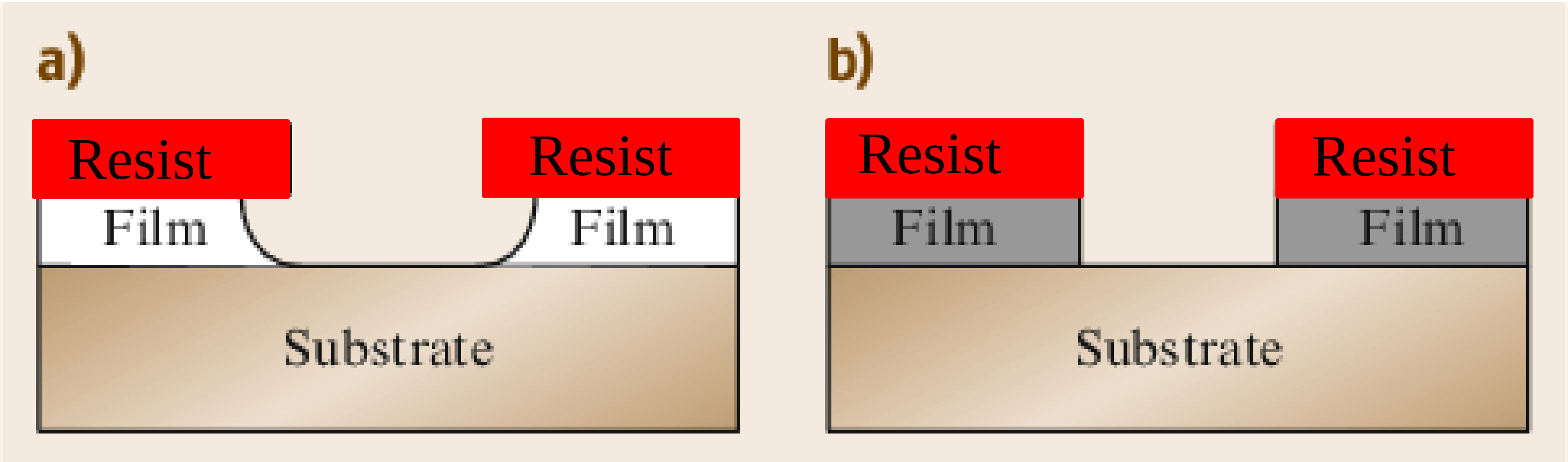


Metal etched to make runners (photoresist removed)

Etching terminology

- Etching mask – patterned protective layer (typically photoresist) on the top of material to be etched
- Undercut – lateral etching of material below etch mask
- Selectivity – etch rate ratio of two materials
- Aspect ratio – ratio of height to width for a microstructure
- Anisotropy – different etching rate in different directions

Etch profiles



Isotropic profile
Rate lateral = rate vertical
Wet etching

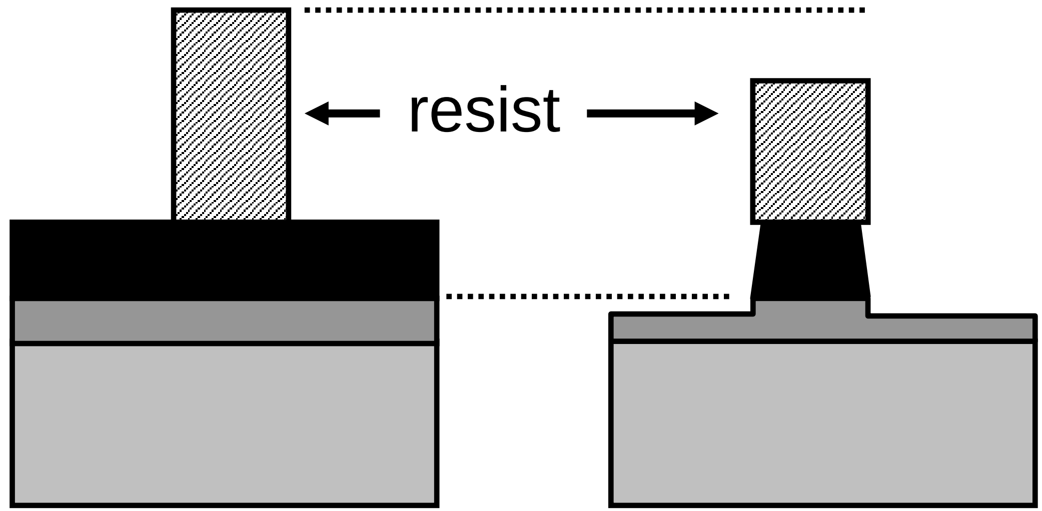
Anisotropic profile
Plasma etching
(vertical profile needs optimization: isotropic profile comes easily)

Etch selectivity = etch rate ratio

S= rate 1 / rate 2

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

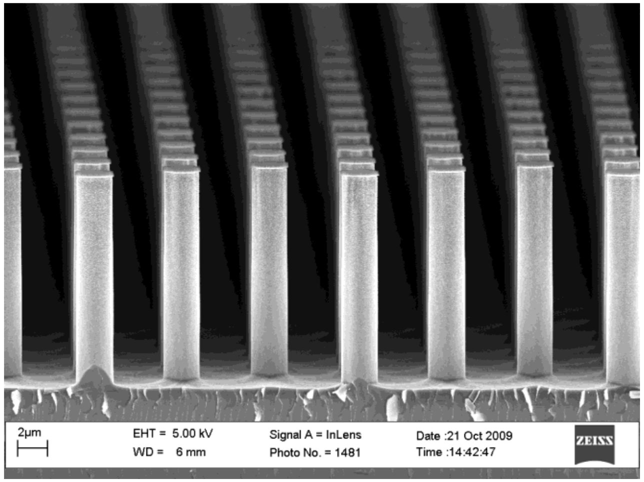
Photoresist etch rate 100 nm/min
➔ Si:PR = 5:1



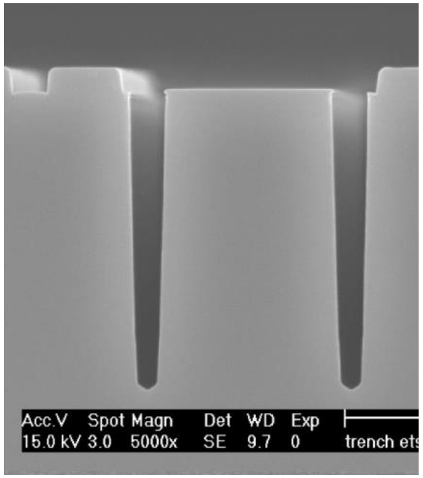
Selectivity can be defined between mask and film; film and substrate; film and film

Aspect ratio

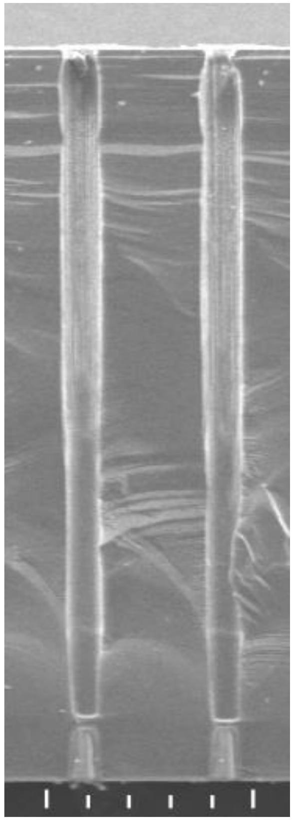
AR is the ratio of height to width



Si pillars AR 6:1



Si trenches AR 6:1



Circular holes AR=20:1

Lauri Sainiemi,
Aalto university

Markus Forsberg *et al* 2004 *J. Electrochem. Soc.* **151** G839

Tang et al: JMEMS 2018 p.686

Quizz

- What is a photomask ?
- How does it relate to etch mask ?

3 methods of etching

Wet etching

solid + liquid etchant ➔ soluble products

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

Plasma etching

solid + gaseous etchant ➔ volatile products

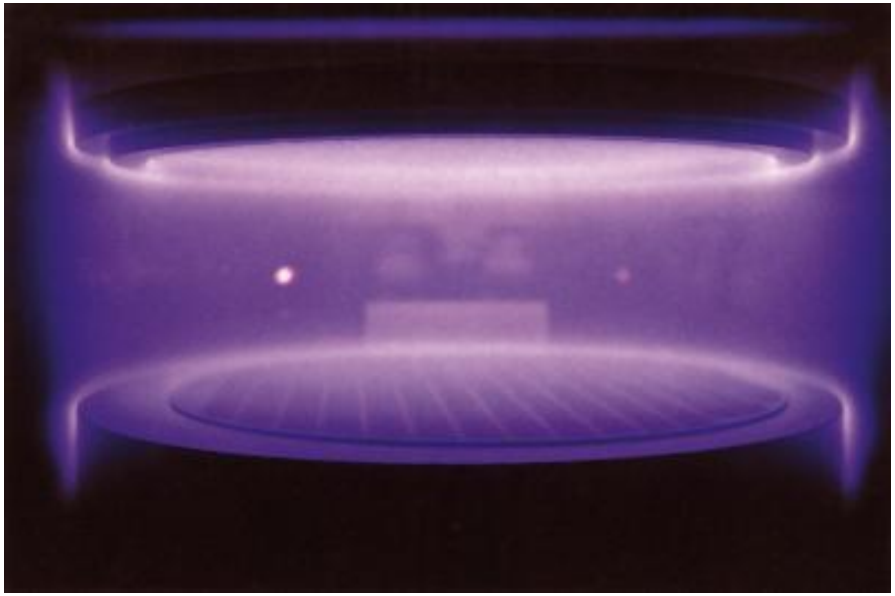
$SiO_2\ (s) + CF_4\ (g) \rightarrow SiF_4\ (g) + CO_2\ (g)$

Ion beam etching

solid + energetic ion ➔ energetic atom + reflected ion

$Au + Ar^+ \rightarrow Au^* + Ar^+$

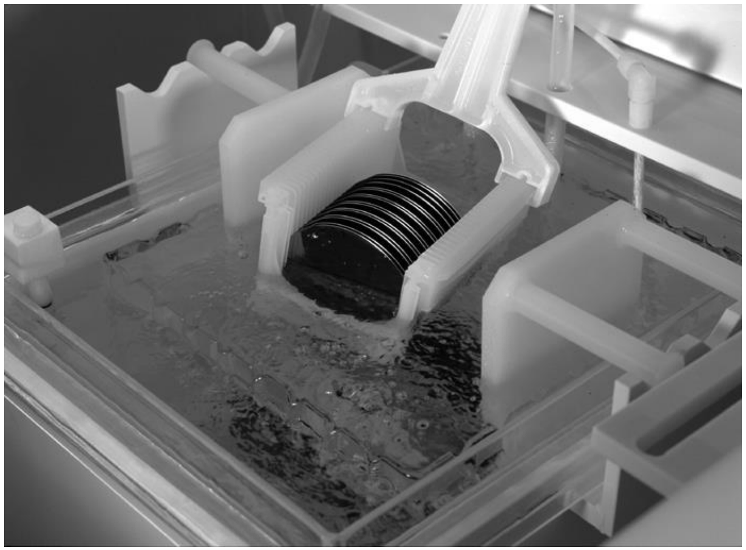
Wet etching vs. plasma etching



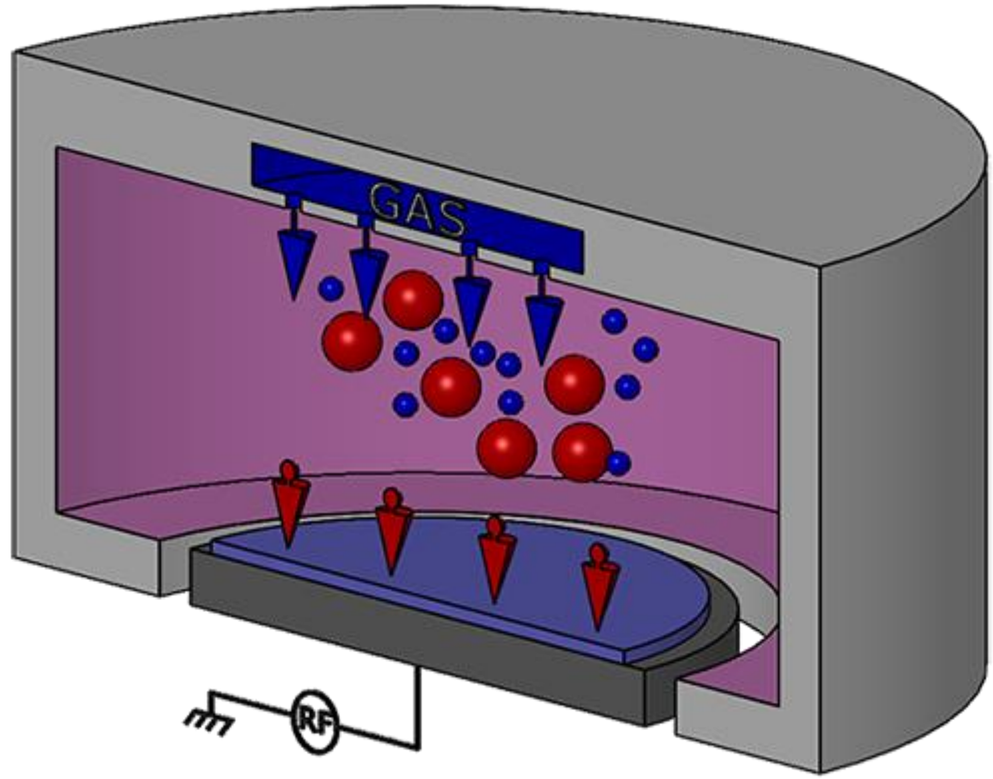
Wet etching:
chemical reaction; simple wet bench and acids or bases needed

Plasma etching:
chemical and physical processes; requires RF-generator, vacuum system and reactive gases

Wet vs. plasma (2)



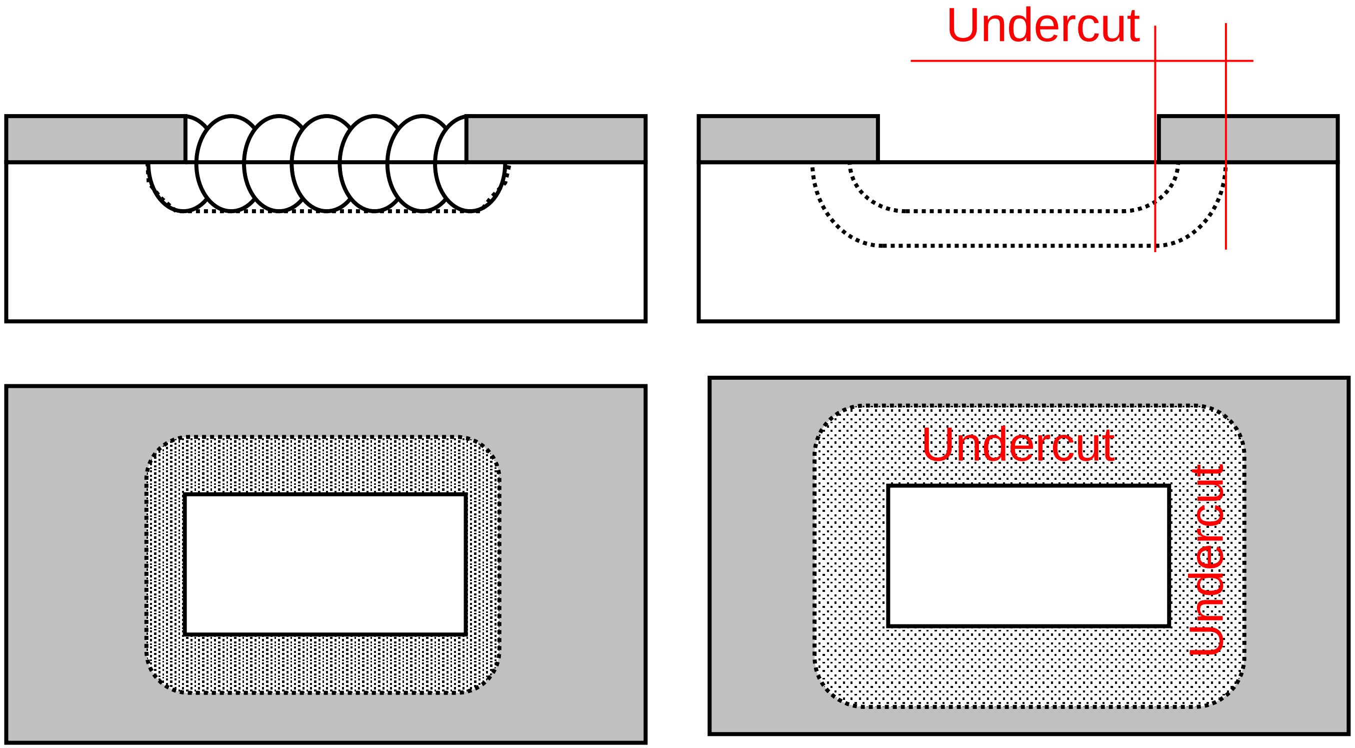
Both sides of the wafer exposed to etchant liquid



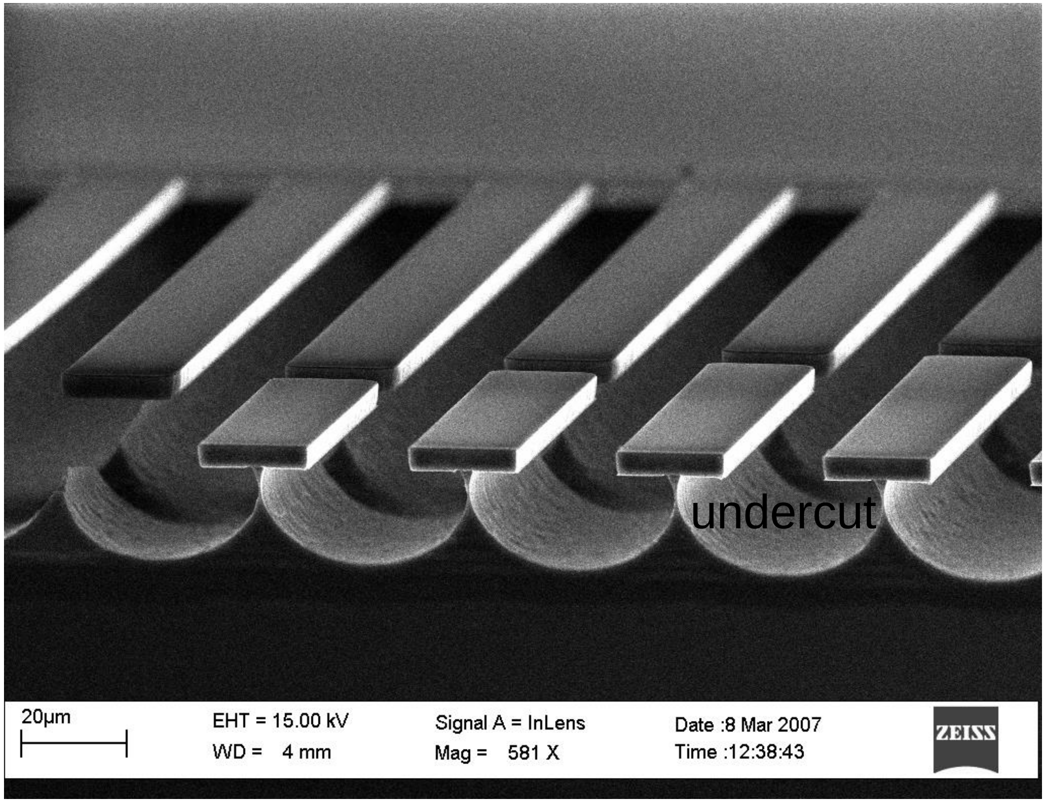
Only wafer topside exposed to plasma

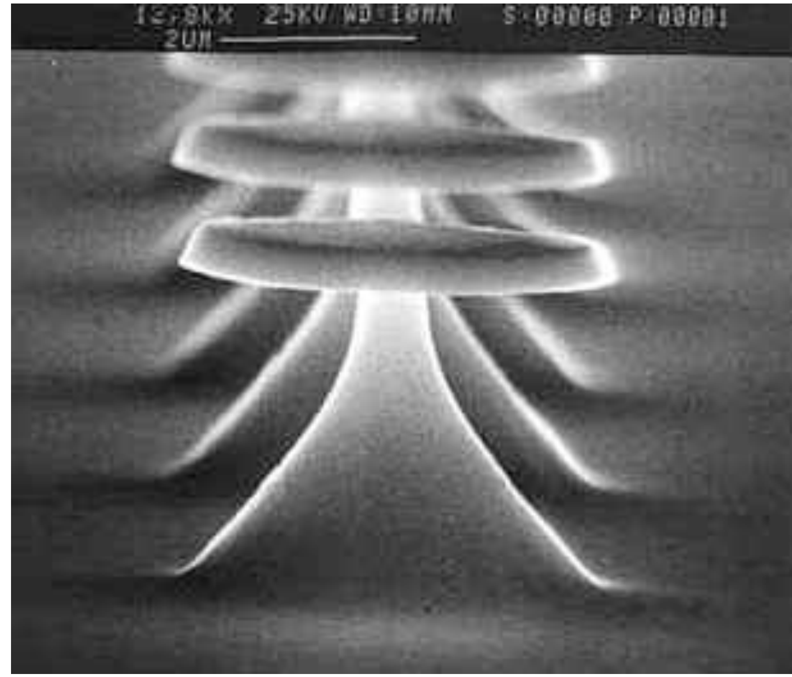
Wet etching

- 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



Wet etch profiles





Hemispherical in theory,
in practise variable sloped shape

Typical wet etchants

- SiO_2 HF
- <Si> HNO_3:HF:CH_3COOH
- 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"

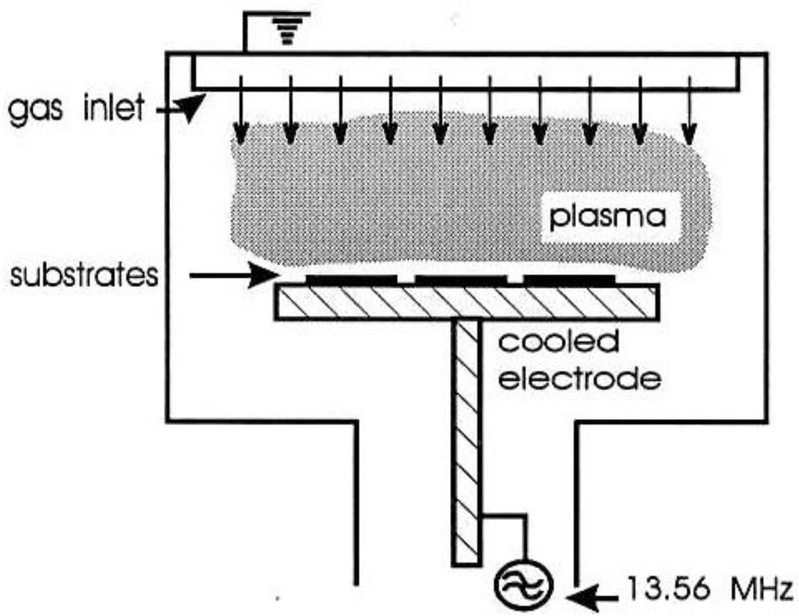
Etch rate goes up if heated, but resist mask often damaged or delaminated

Wet etching

- Usually isotropic
- (Near) perfect selectivity
- Each material needs different etch chemistry
- Surface finish smooth
- High throughput because batch process
- Cheap equipment

- Not suitable for narrow lines and spaces !!!
- But if film is very thin, undercut is negligible !

Plasma etching
= Reactive Ion Etching



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

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

Sorry about the name RIE: reactive neutrals are more abundant and important

Chemical effect: radicals are (very) reactive
Physical effect: ion bombardment gives directionality
Physical effect: ion bombardment detaches loosely bound material

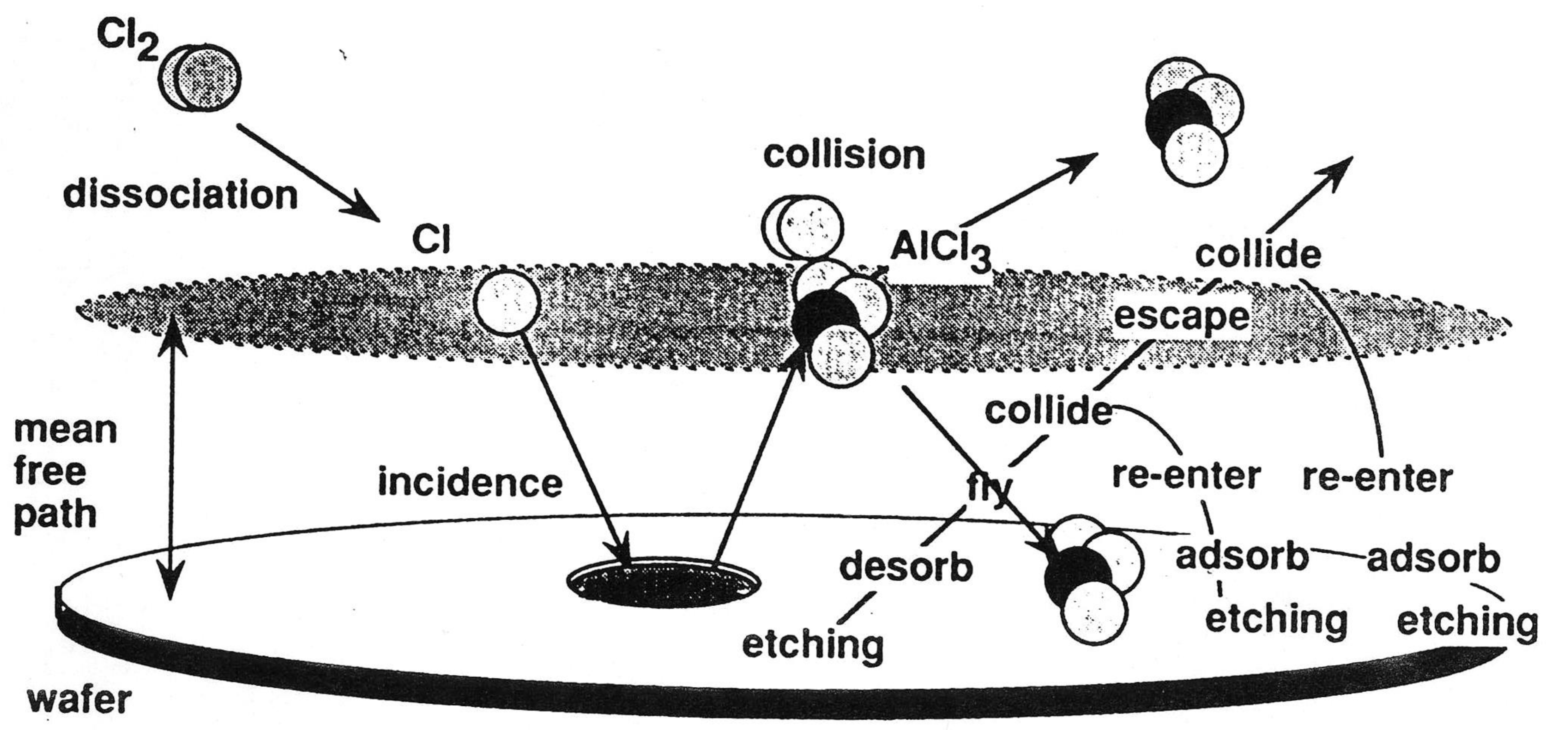
Gases for plasma etching

Material	Etch gas	Volatile product gases
• Silicon	SF_6 or Cl_2	SiF_4 or $SiCl_4$
• 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 plasma etching practical ←	

halogenides non-volatile, e.g. $CuCl_2$ boiling point 993^{o}C

Plasma – surface interaction

Al etching in Cl_2

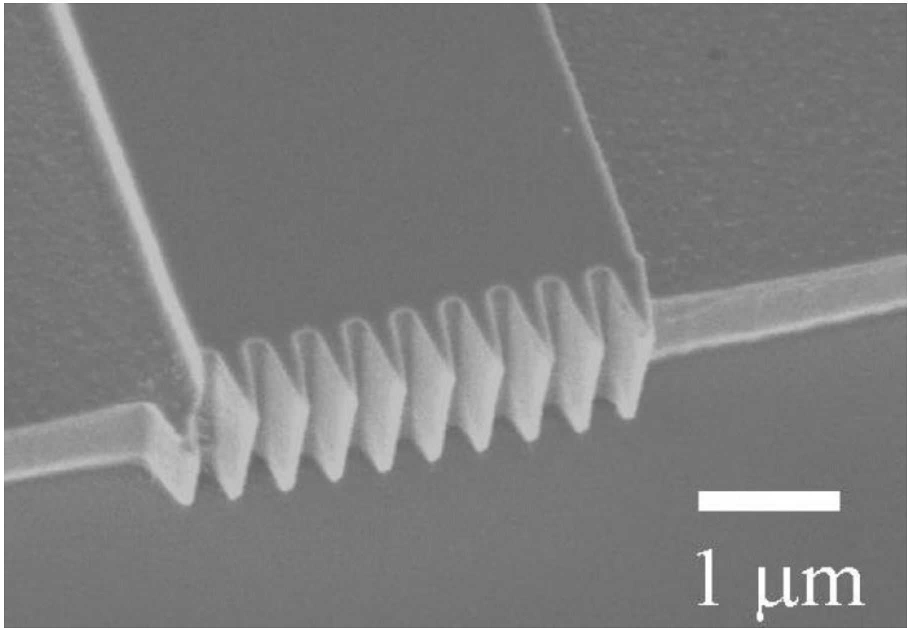


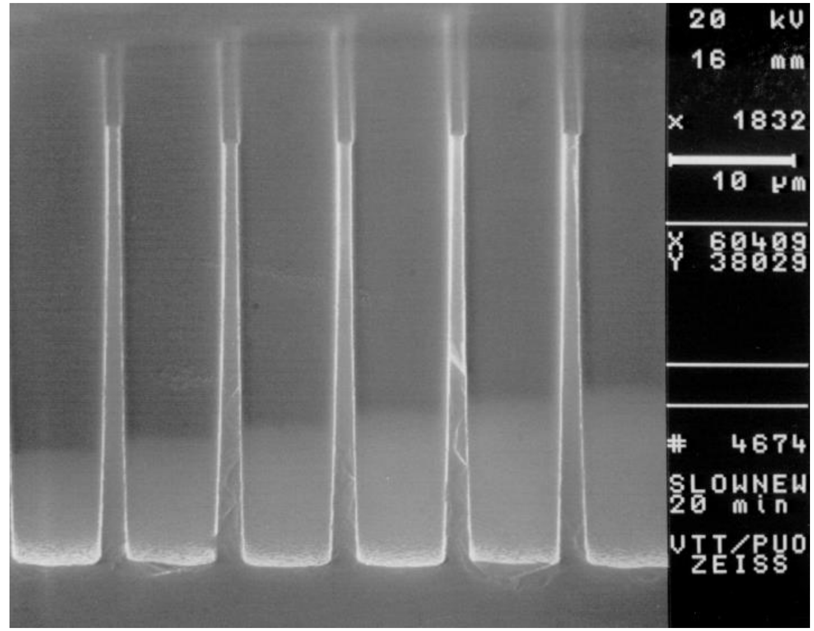
Reaction product volatility important to avoid redeposition of. $AlCl_3$ boiling point 180^{o}C

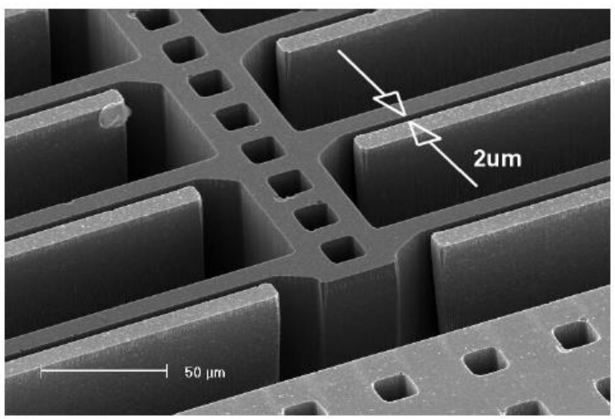
Plasma etching

- Can be anisotropic when optimized
- Near vertical walls
- Easily isotropic profile if needed
- Sidewalls and bottom rough
- Slow, because single wafer process
- Expensive equipment

Plasma etched profiles



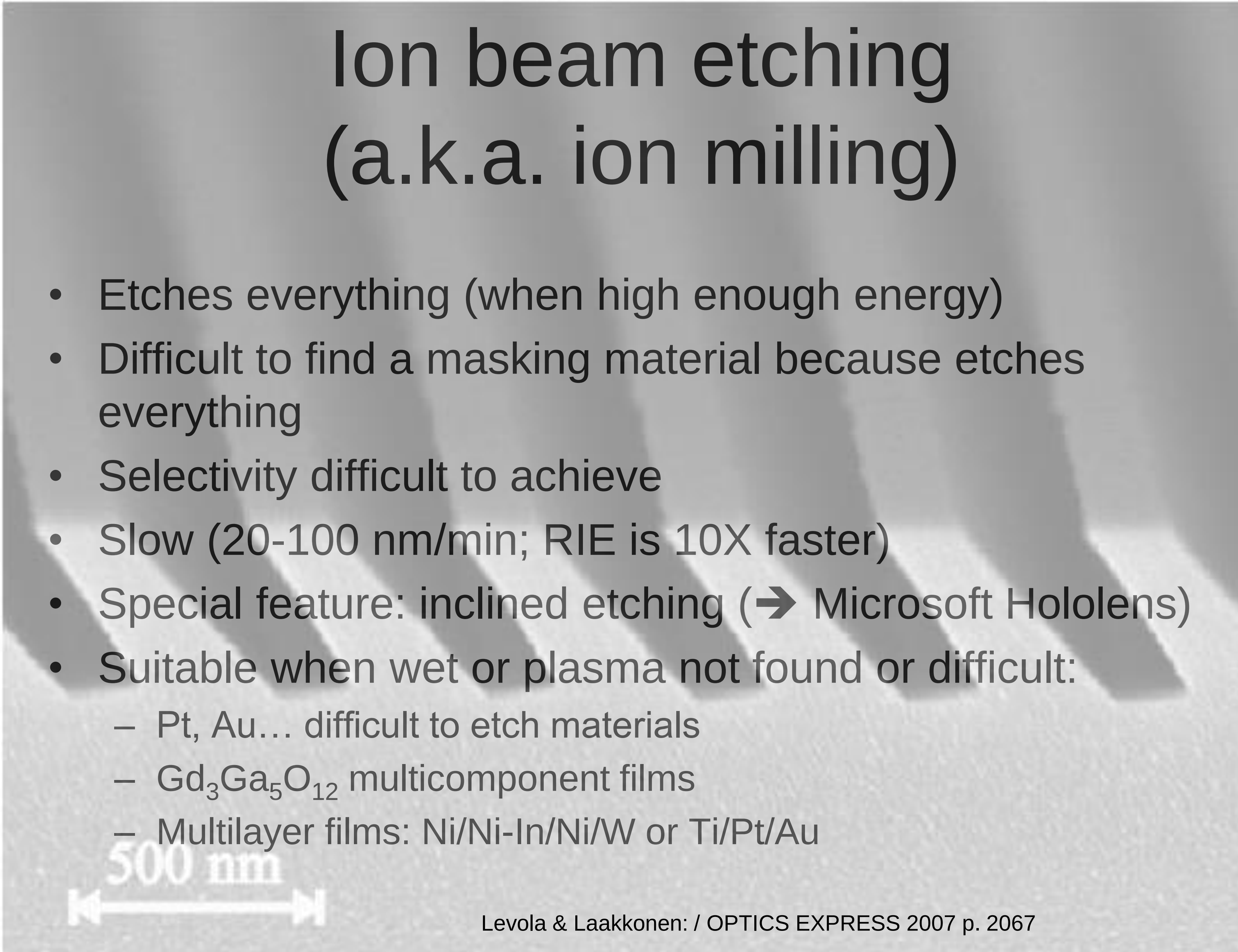




Anisotropic by RIE/plasma

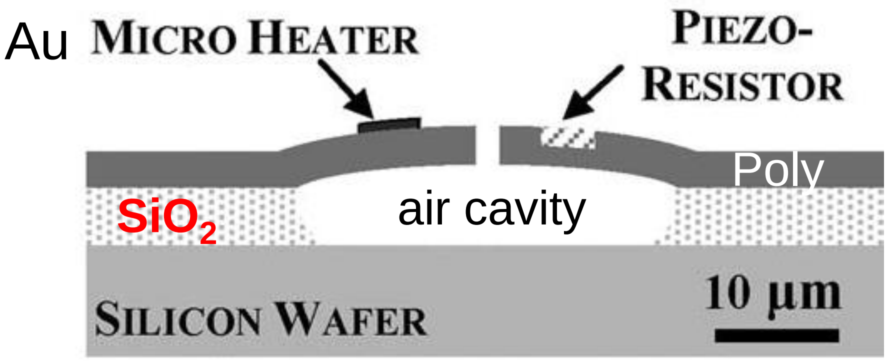
Ion beam etching (a.k.a. ion milling)

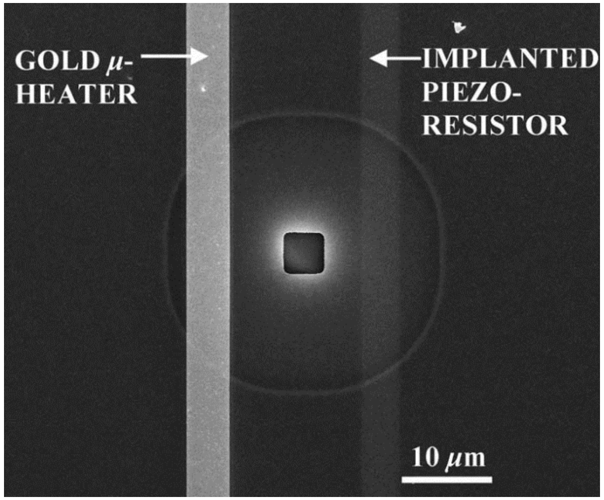
- Etches everything (when high enough energy)
- Difficult to find a masking material because etches everything
- Selectivity difficult to achieve
- Slow (20-100 nm/min; RIE is 10X faster)
- Special feature: inclined etching (➔ Microsoft Hololens)
- Suitable when wet or plasma not found or difficult:
  - Pt, Au… difficult to etch materials
  - $Gd_3Ga_5O_{12}$ multicomponent films
  - Multilayer films: Ni/Ni-In/Ni/W or Ti/Pt/Au



Levola & Laakkonen: / OPTICS EXPRESS 2007 p. 2067

Etching in action: dome resonator



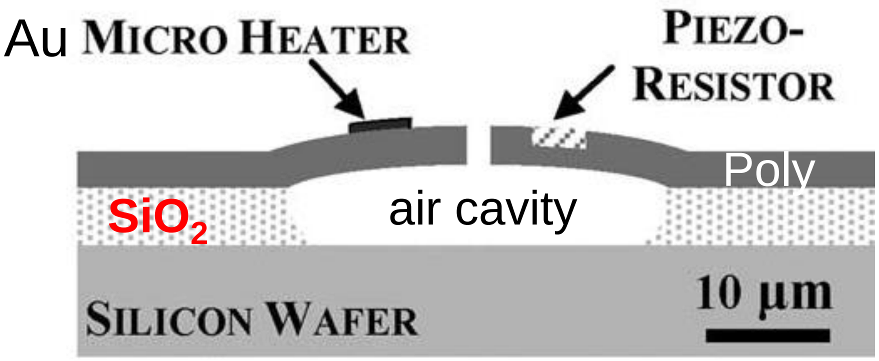


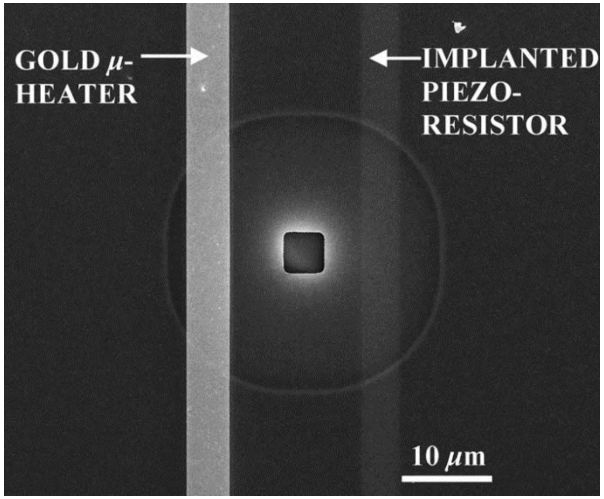
1) RIE etching a small hole in polysilicon

2) Isotropic HF wet etching of oxide under polysilicon
➔ Air cavity formed
➔ Poly membrane can resonate up and down

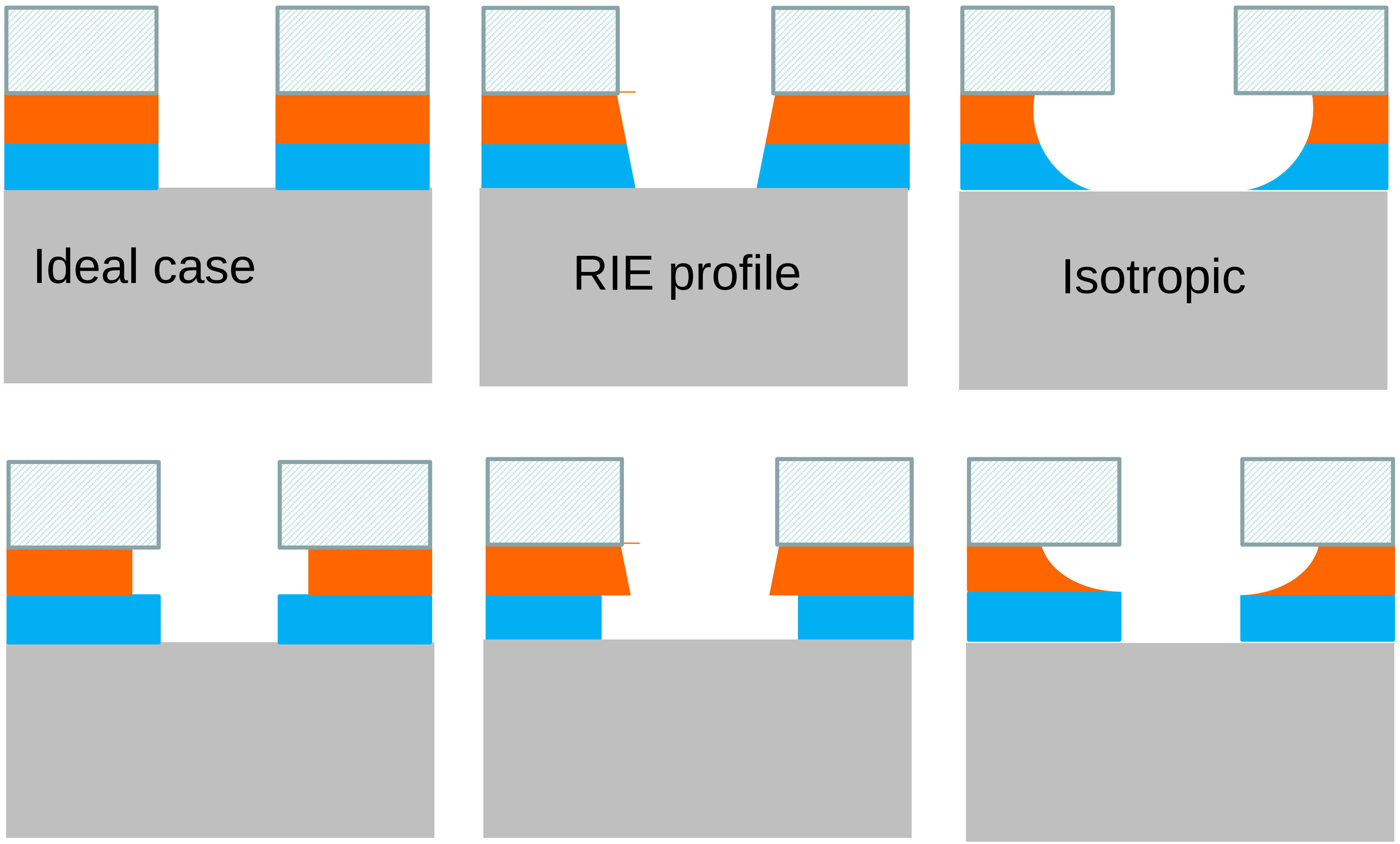
H. G. Craighead

Dome resonator:
How many lithography steps needed ?

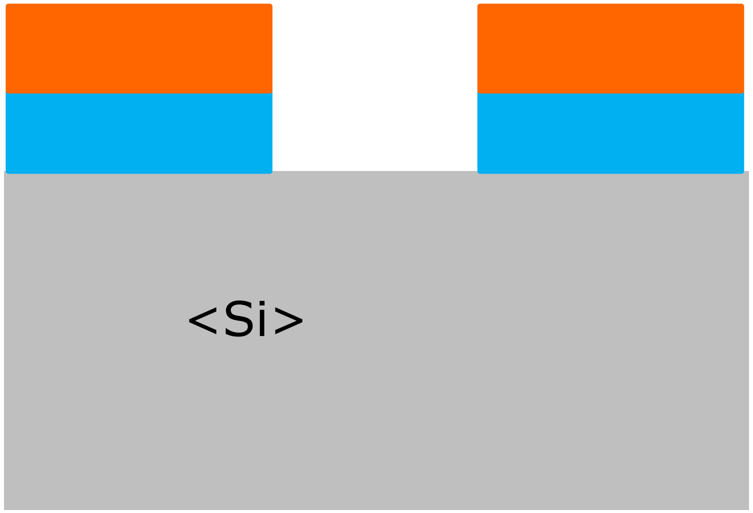




Etching two-layer films



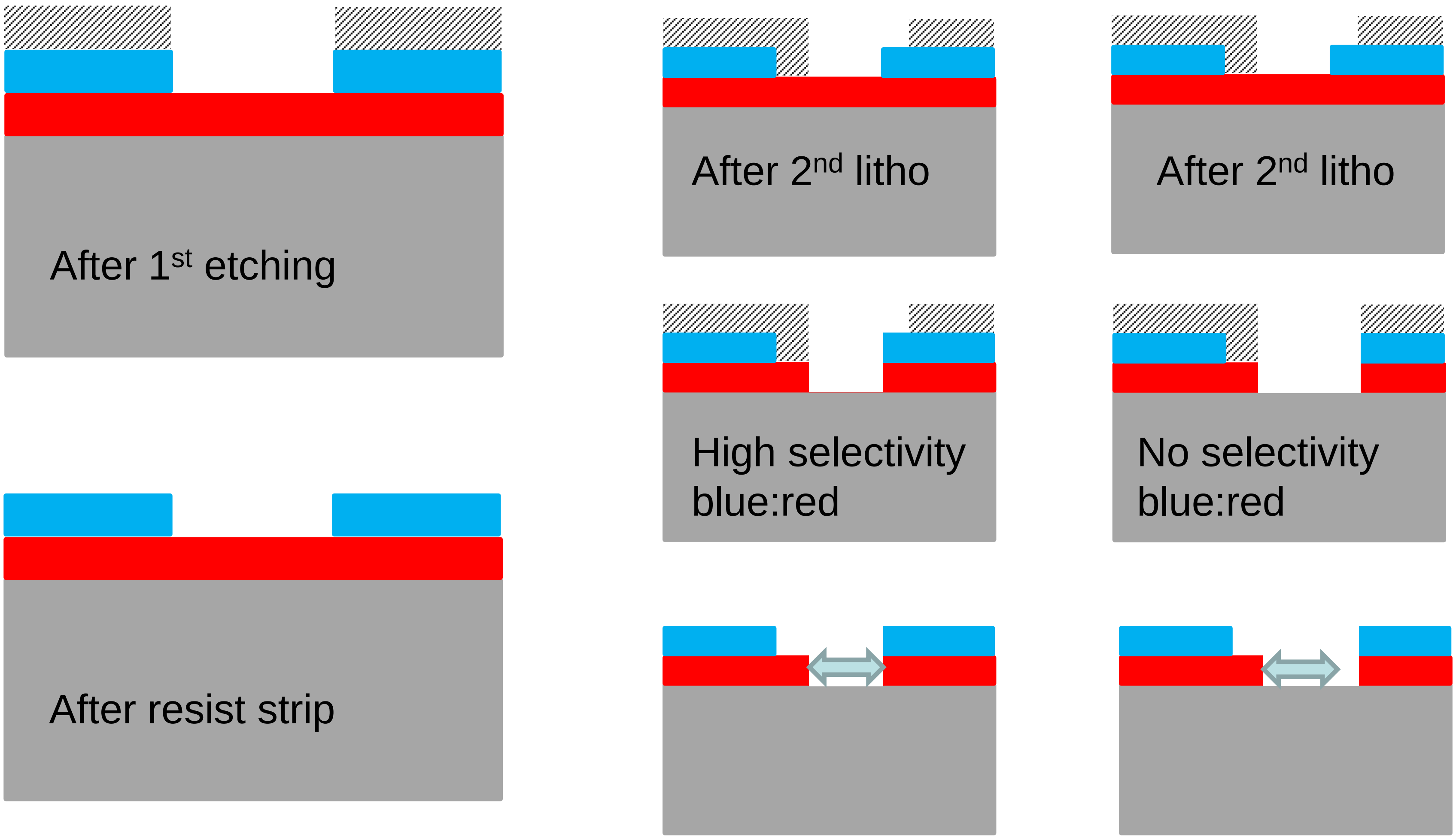
Perfect alignment ?



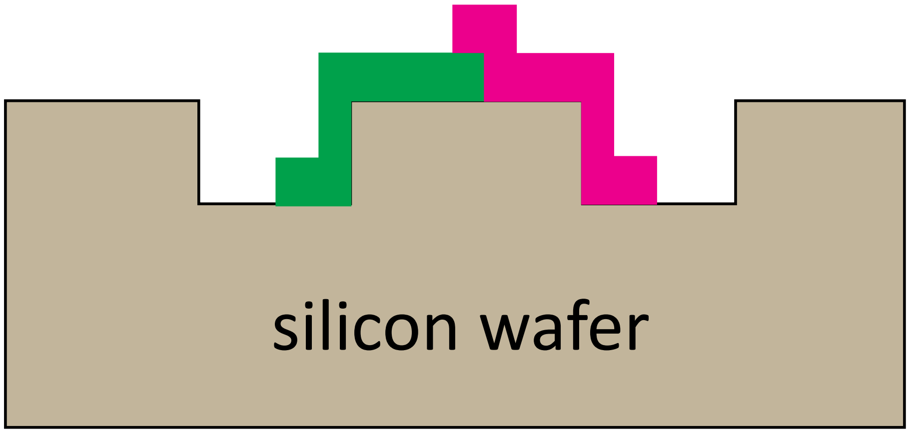
If two layers are perfectly aligned, they were made in the same etch step.

Otherwise alignment error would be visible.

Alignment error and etch profile



Example



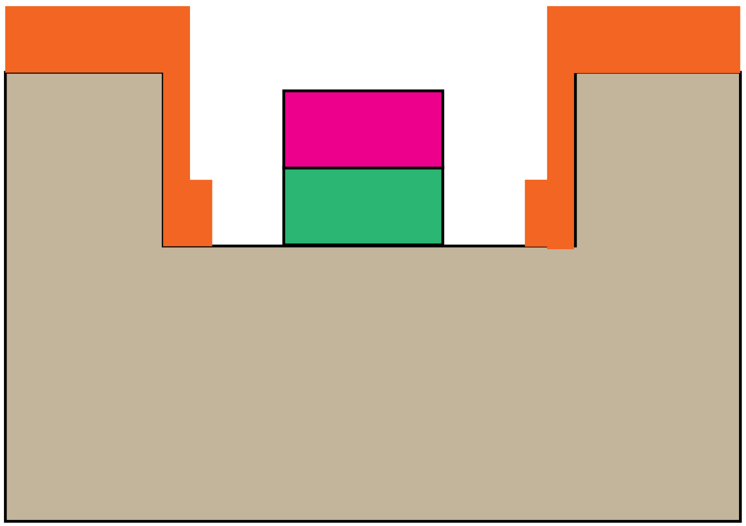
Comment:

Strictly chronological (imagine this as a list of instructions that you give to a laboratory technician, and she will carry out processing.

Process flow:

Litho (trenches)
Etch (silicon)
Strip resist
Film deposition (green)
Litho (green)
Etch (green)
Strip resist
Film deposition (red)
Litho (red)
Etch (red)
Strip resist

Example 2



Or:

After trench formation, it does not matter whether green/red or orange is done first.

Litho trench
Etch silicon
Strip resist
Film deposition green & red
Litho
Etch red and green
Strip resist
Film deposition orange
Litho
Etch orange
Strip resist

Lithographic patterning

- Photoresist is UV-exposed.
- It serves as an interim mask.
- Etching produces permanent pattern in metal/silicon/oxide.
- Photoresist is stripped in the end.

- Smaller linewidth require more expensive lithography.
- Large linewidths can be wet etched.
- Small linewidths require plasma etching.
- Undercut is smaller when film is thinner, so sometimes wet etching is good enough.