Etching Techniques in Nanotechnology

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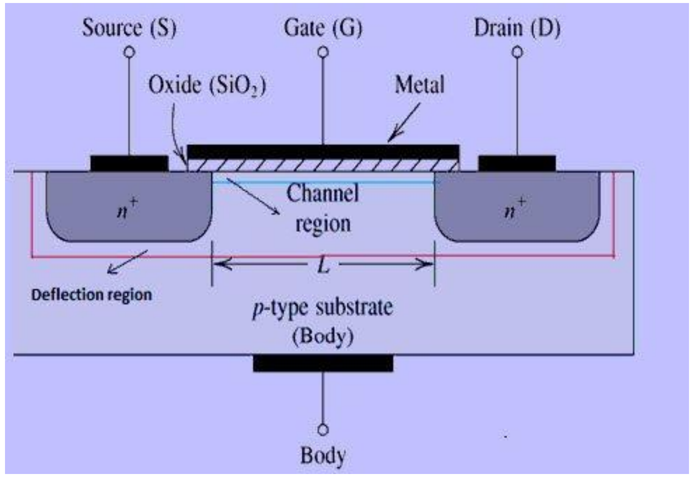
Etching is an important process in SEMICONDUCTOR FAB

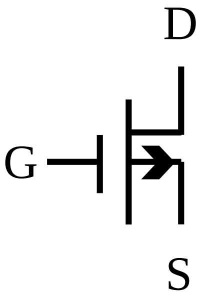
GATE METAL WIDTH defines technology node



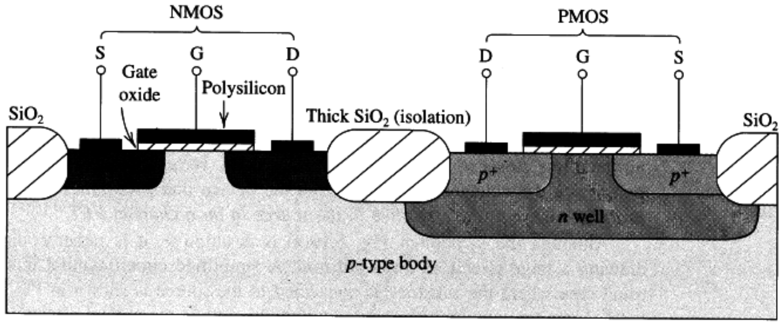
NMOS

So where are we now?.....7 nm node

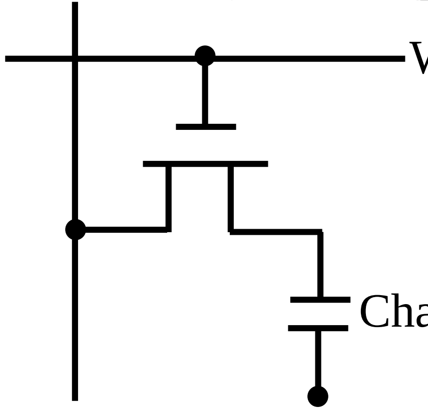
Where are we headed?
5 nm node using EUVL 2020 mass priduction



A typical computer processor involves close to half a billion of such transistors. Other active elements of any digital or analog device is also based on large scale integration of transistors in some form or the other.
e.g: DRAM, CMOS, NAND Flash



CMOS



World line

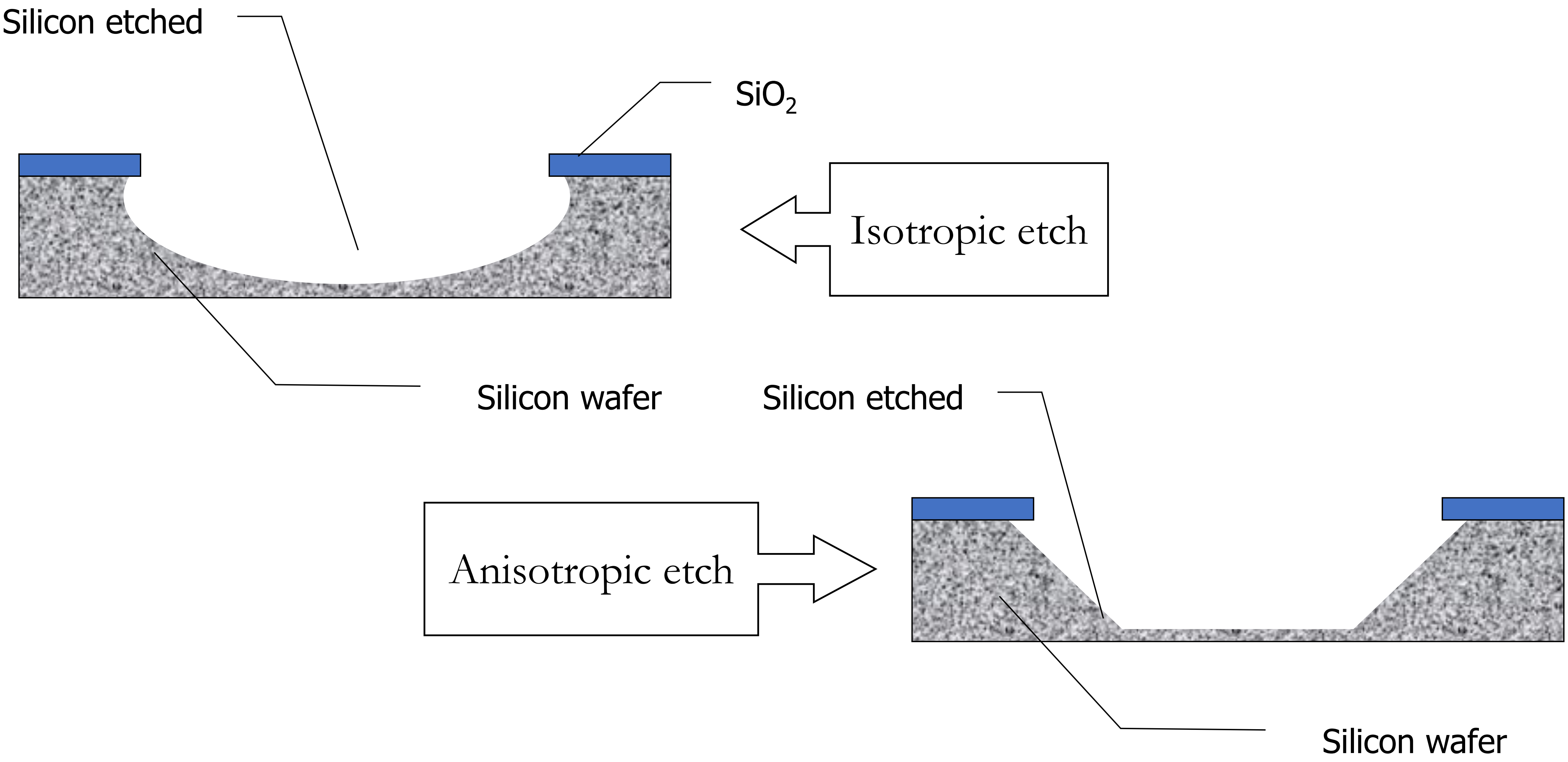
DRAM

Charging and discharging of capacitor

BIT line

Ground

Bulk micromachining



Silicon etched

SiO_2

Isotropic etch

Silicon wafer

Silicon etched

Anisotropic etch

Silicon wafer

Etching

Etching: Chemical reaction resulting in the removal of material

Wet etching: etchants in liquid form

Dry etching: etchants contained is gas or **plasma**

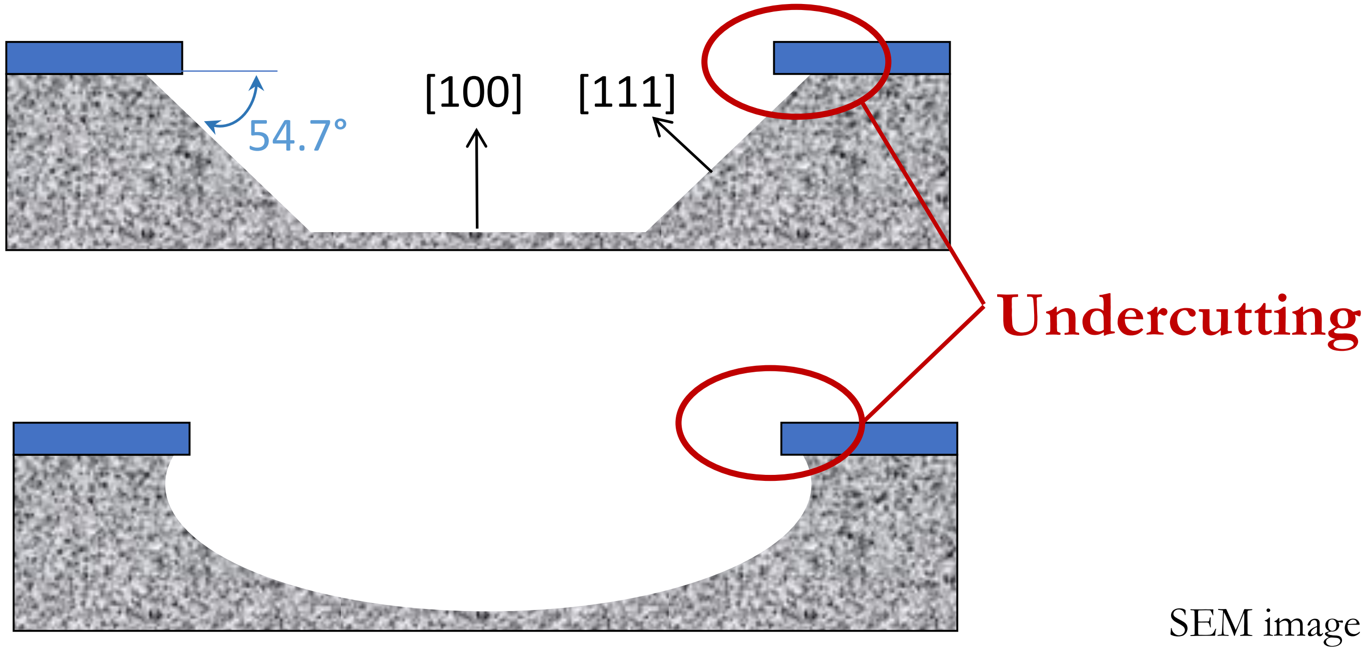
→ ionized gas

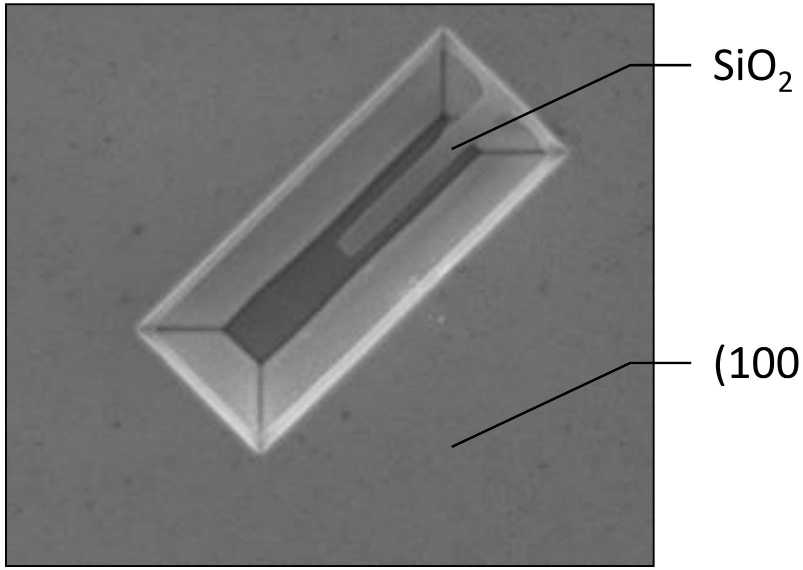
Etch rate: material removed per time (µm/min)

Selectivity and undercutting

Selectivity:

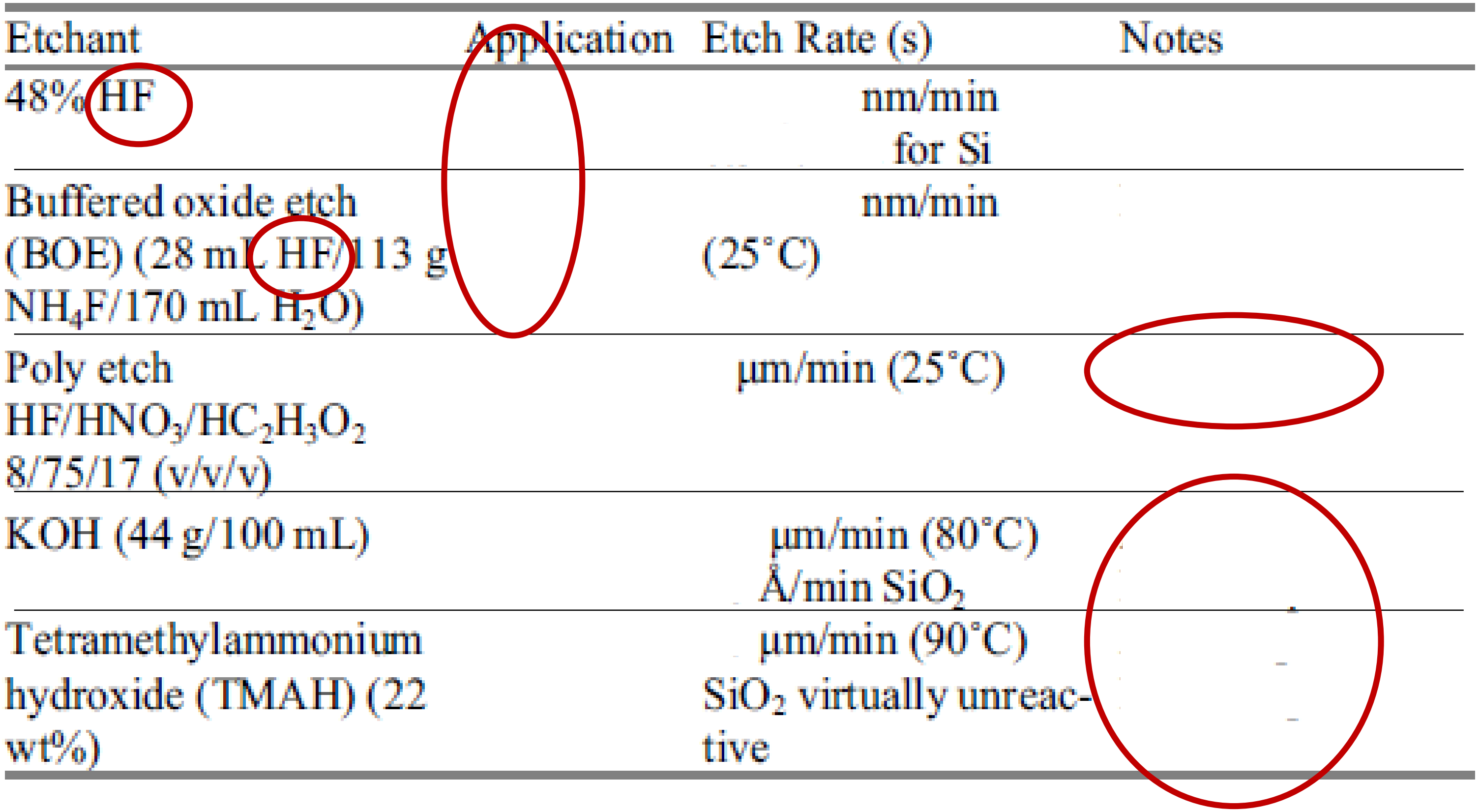
- etch rate of one material compared to another
- etch rate of one crystalline direction compared to another





SEM image of a SiO_2 cantilever formed by undercutting (S. Mohana Sundaram and A. Ghosh, Department of Physics, Indian Institute of Science, Bangalore)

Application and properties of different wet etchants



Etchant	Application	Etch Rate (s)	Notes
48% HF		nm/min for Si	
Buffered oxide etch (BOE) (28 mL HF/113 g NH_4F/170 mL H_2O)		nm/min (25°C)	
Poly etch $HF/HNO_3/HC_2H_3O_2$ 8/75/17 (v/v/v)		µm/min (25°C)	
KOH (44 g/100 mL)		µm/min (80°C) Å/min SiO_2	
Tetramethylammonium hydroxide (TMAH) (22 wt%)		µm/min (90°C) SiO_2 virtually unreactive	

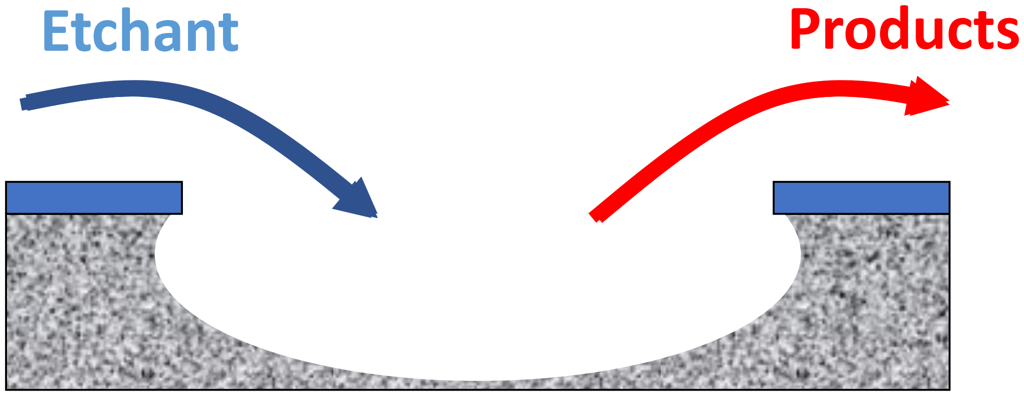
High HF tends to etch SiO_2

Acidic etchants tend to etch Si isotropically

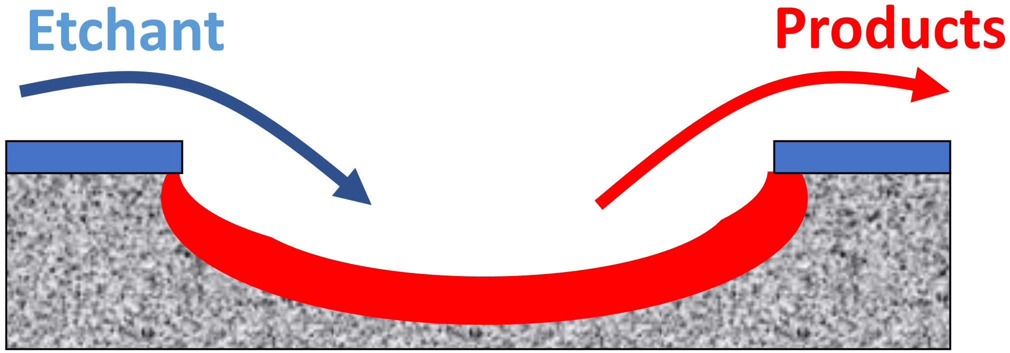
Basic etchants tend to etch Si anisotropically

Depend on concentration and temperature

Rate versus diffusion limited etching



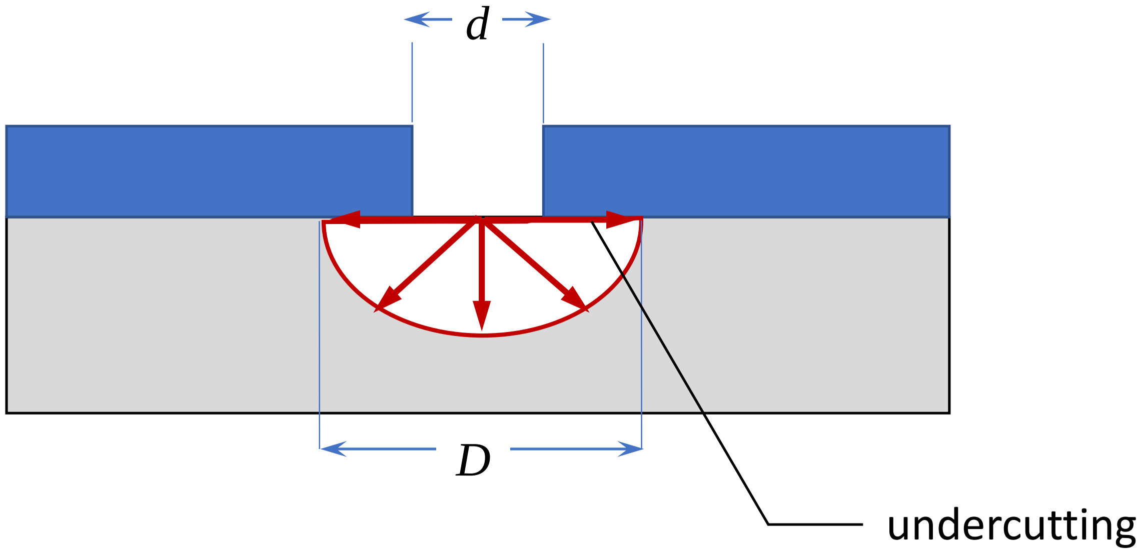
Rate limited reaction



Diffusion limited reaction

Rate limited reactions are preferred → easier to control and more repeatable

Isotropic etching



Estimate of etch depth

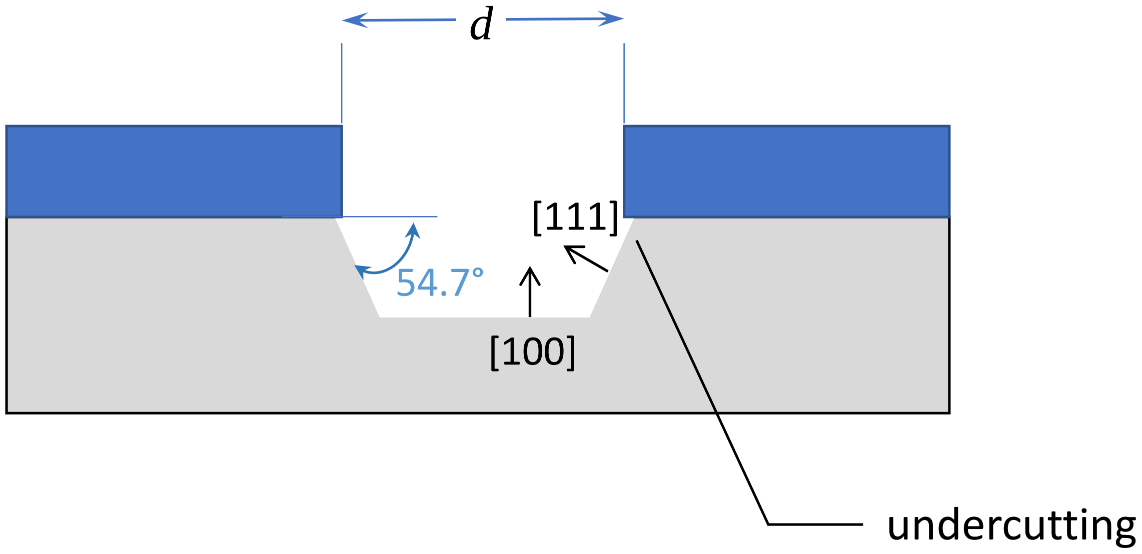
$$\text{depth} \approx (D\text{-}d)/2$$

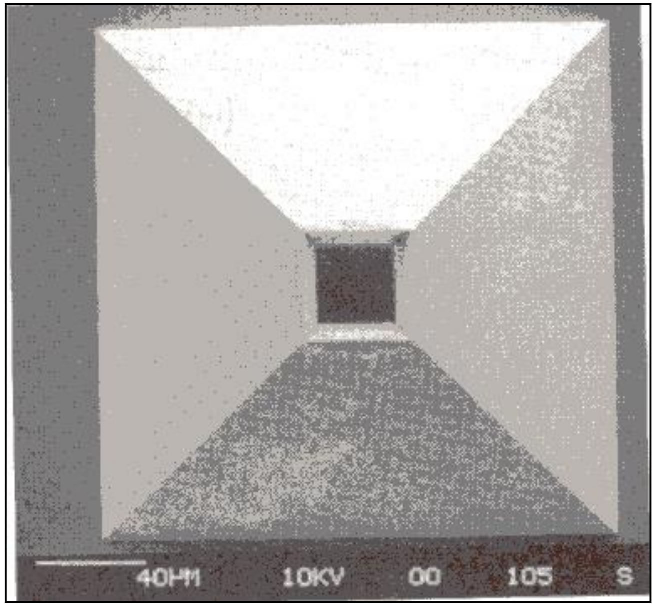
- Etch rate is the same in all directions
- Typically acidic
- Room temperature
- Isotropy is due to the fast chemical reactions

→ Reaction or diffusion limited?

- X µm/min to XX µm/min

Anisotropic etching

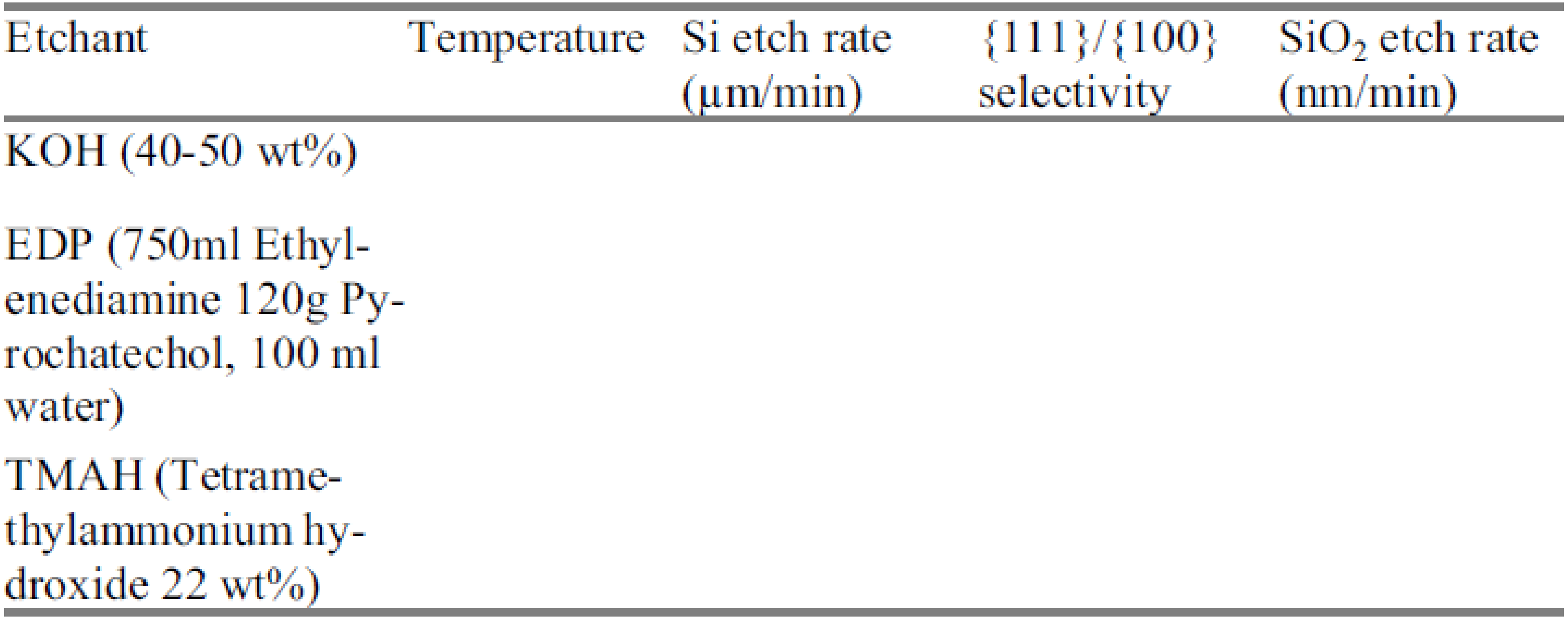




- Etch rate is different for different crystal plane directions
- Typically basic etchants
- Elevated temperatures (70-120°C)
- Different theories propose for anisotropy
- Slower etch rates, ~ 1 μm/min → Reaction or diffusion limited?

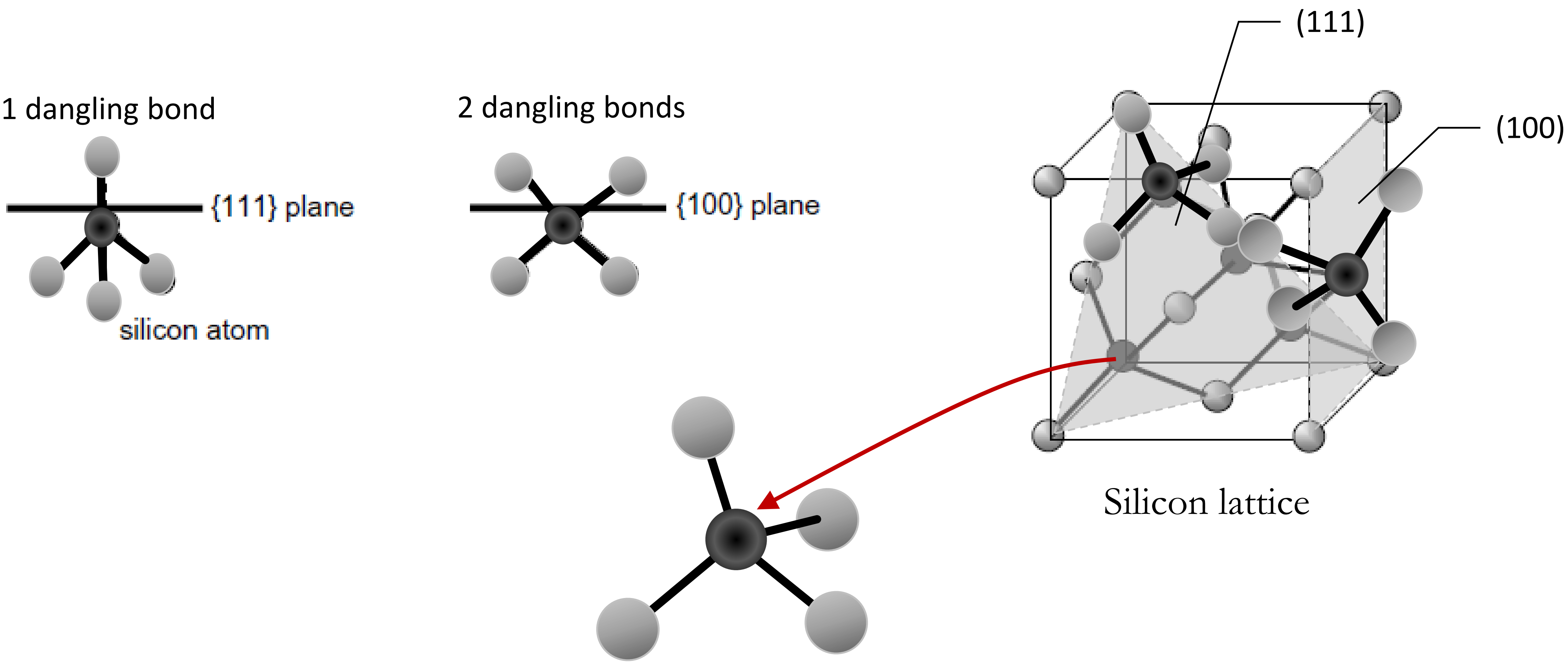
- Etch depths depend on geometry
- Undercutting also depends on geometry

Properties of different anisotropic etchants of Si



Etchant	Temperature	Si etch rate (μm/min)	{111}/{100} selectivity	SiO_2 etch rate (nm/min)
KOH (40-50 wt%)				
EDP (750ml Ethylenediamine 120g Pyrochatechol, 100 ml water)				
TMAH (Tetramethylammonium hydroxide 22 wt%)				

Theories for anisotropic etching



Silicon lattice

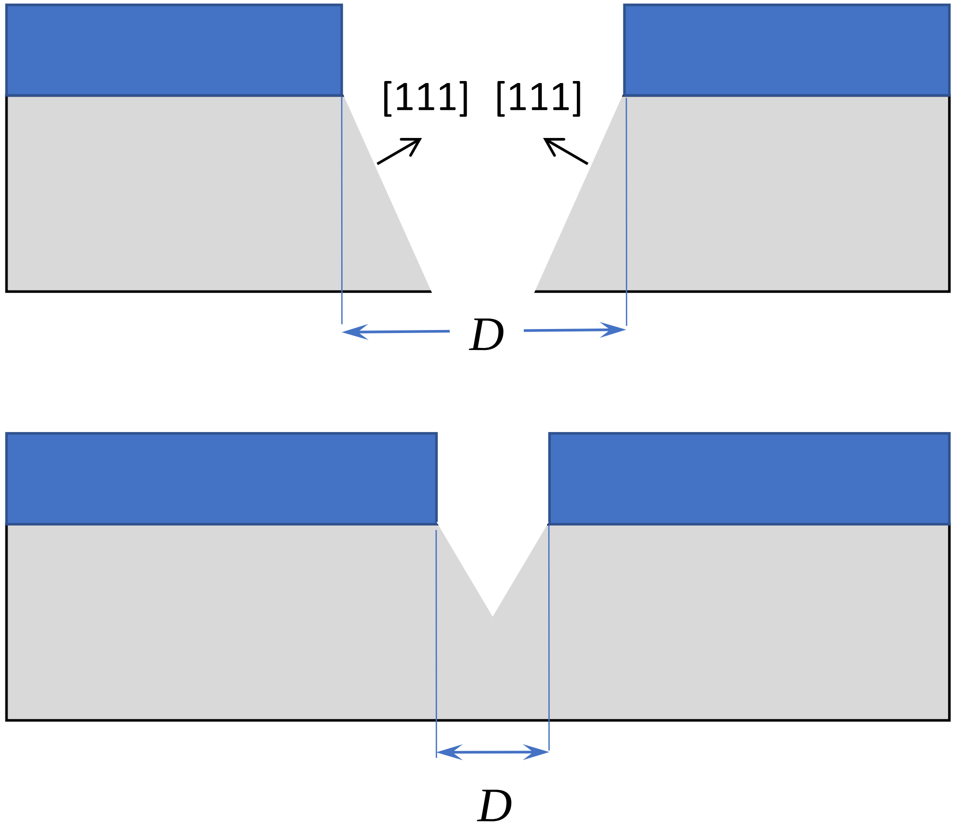
The lower reaction rate for the {111} planes is caused by the larger **activation energy** required to break bonds behind the etch plane. This is due to the larger bond density of silicon atoms behind the {111} plane.

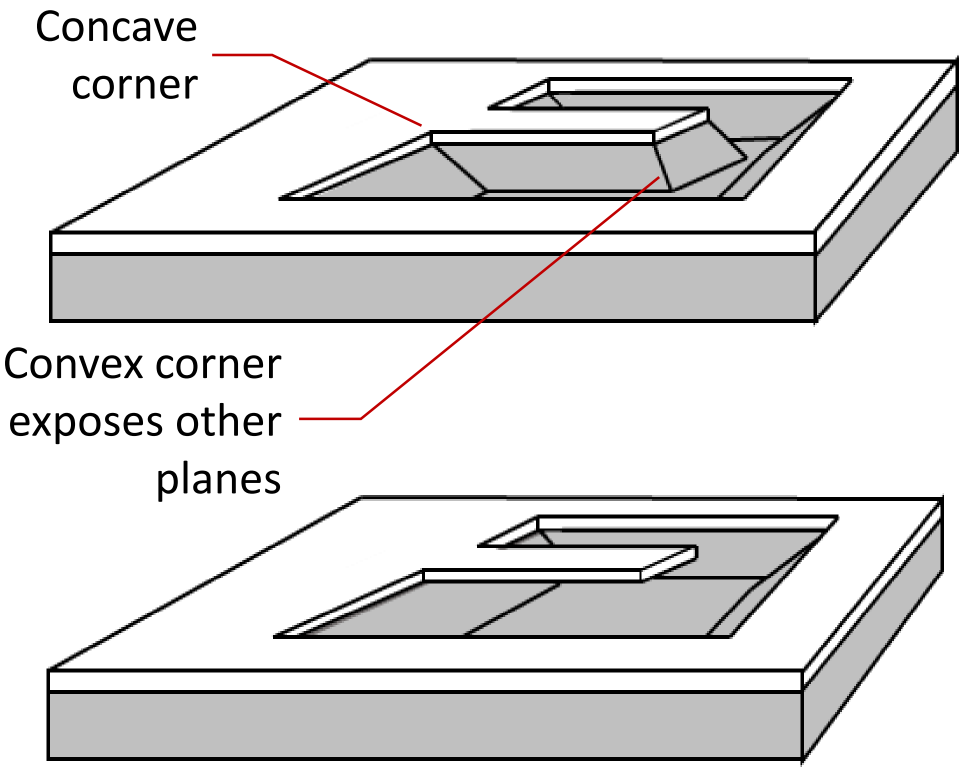
Theories for anisotropic etching of Si in aqueous based basic solvents

- Reduction of water believed to be the rate determining step
- OH^- believed to be provided by H_2O near Si surface

$$SiOH_2^{++} + 4\,e^- + 4\,H_2O \rightarrow Si(OH)_6^{--} + 2\,H_2 \qquad \text{(reduction step)}$$

Self-limiting etch and undercutting

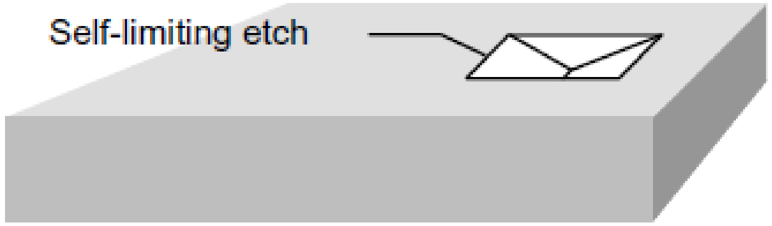



Concave corner

Convex corner exposes other planes

Resulting undercutting can be used to create suspended structures

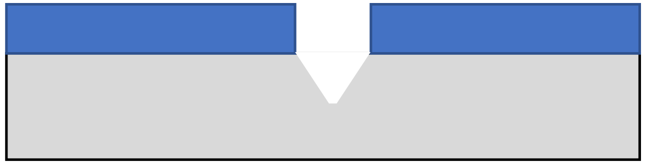
- Intersection of {111} planes can cause **self-limiting** etch.
- Only works with concave corners



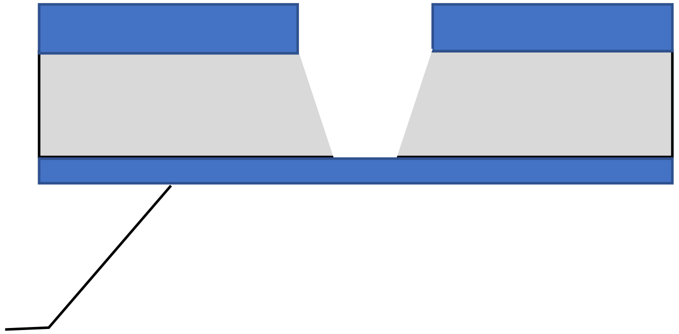
Etch stop

Etch stop: Technique to actively stop the etching process

Self-limiting etch

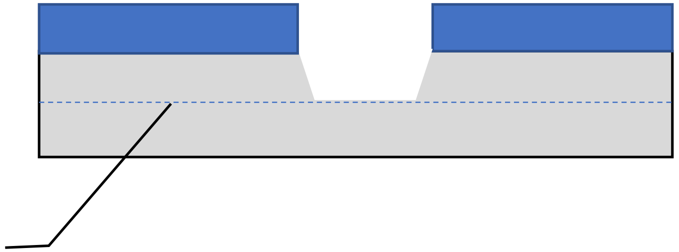


Insulator etch stop



Timed etch

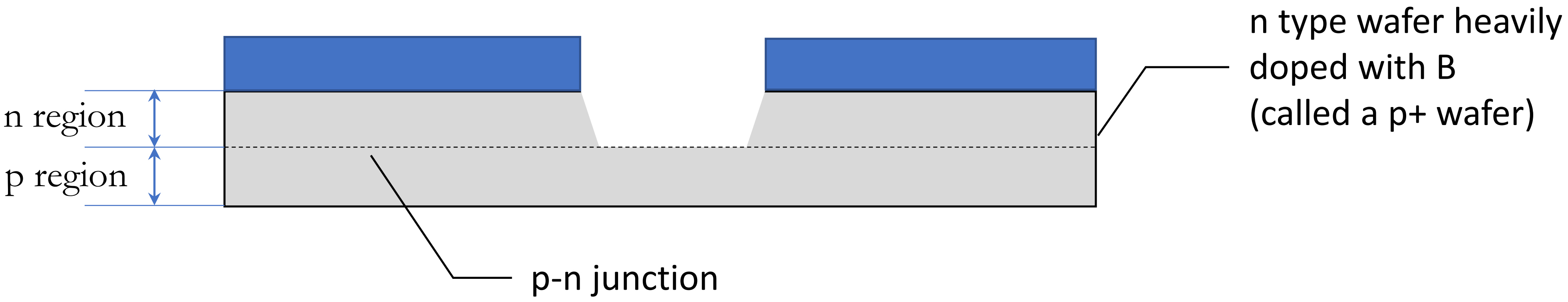
Etch stop via doping



Etch stop via doping

Boron etch stop

$SiOH_2^{++} + 4\,e^- + 4\,H_2O \rightarrow Si(OH)_6^{--} + 2\,H_2$ (reduction step)



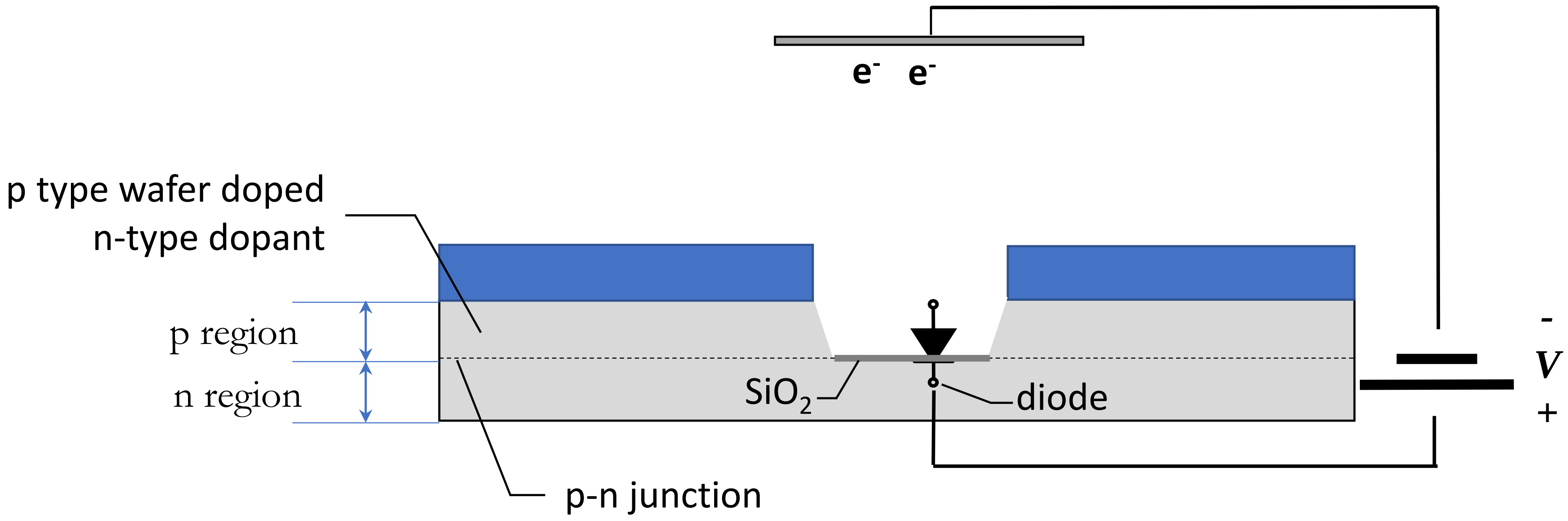
n type wafer heavily doped with B (called a p+ wafer)

p region Si deficient in e^-

Etch stop via doping

Electrochemical etch stop (ECE)

$\mathrm{SiOH_2^{++}} + 4\,e^{-} + 4\,\mathrm{H_2O} \rightarrow \mathrm{Si(OH)_6^{--}} + 2\,\mathrm{H_2}$ (reduction step)



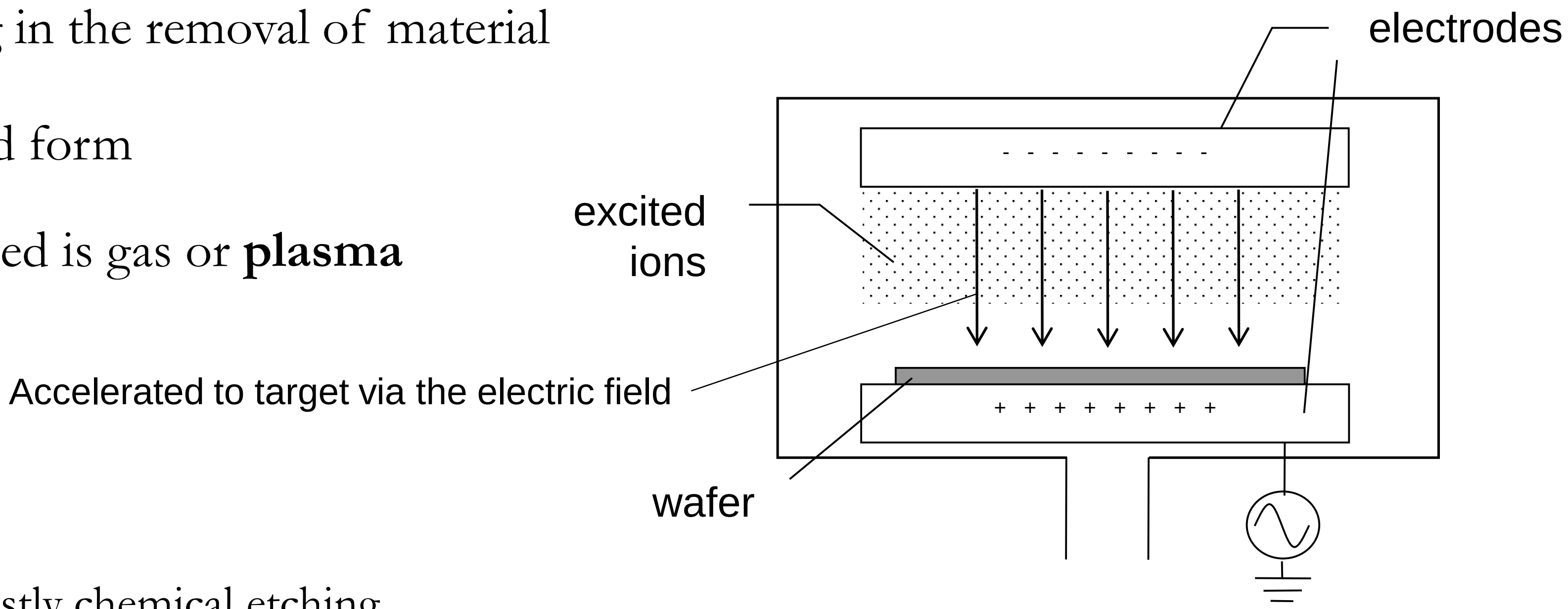
"Reverse bias" voltage applied to p-n junction keeps current from flowing

Dry etching

Etching: Chemical reaction resulting in the removal of material

Wet etching: etchants in liquid form

Dry etching: etchants contained is gas or **plasma**



Plasma etching: mostly chemical etching

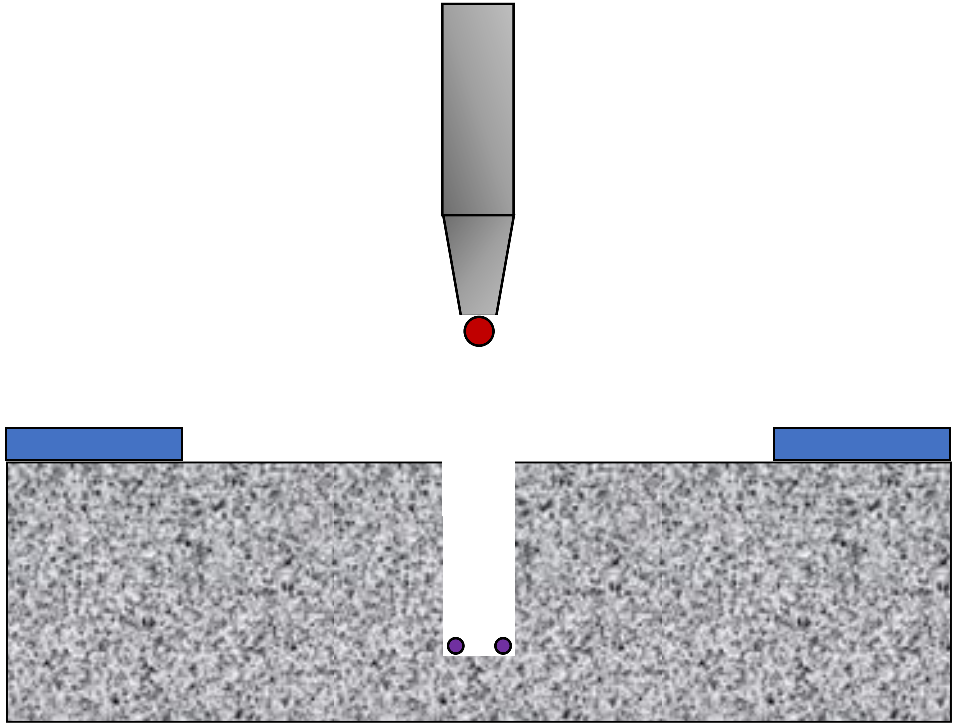
Reactive ion etching (RIE):

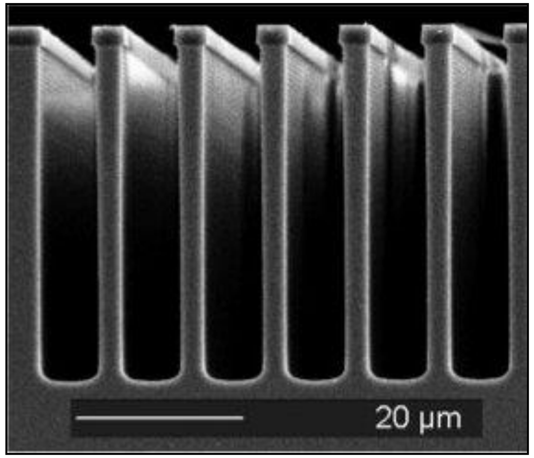
In addition to the chemical etching, accelerated ions also physically etch the surface

Chemically reactive gas formed by collision of

- molecules of reactive gas with
- energetic electrons
- Excited/ignited be RF (radio frequency) electric field ~ 10-15 MHz

Reactive ion etching





(Intellisense Corporation)

Plasma hits surface with large energy

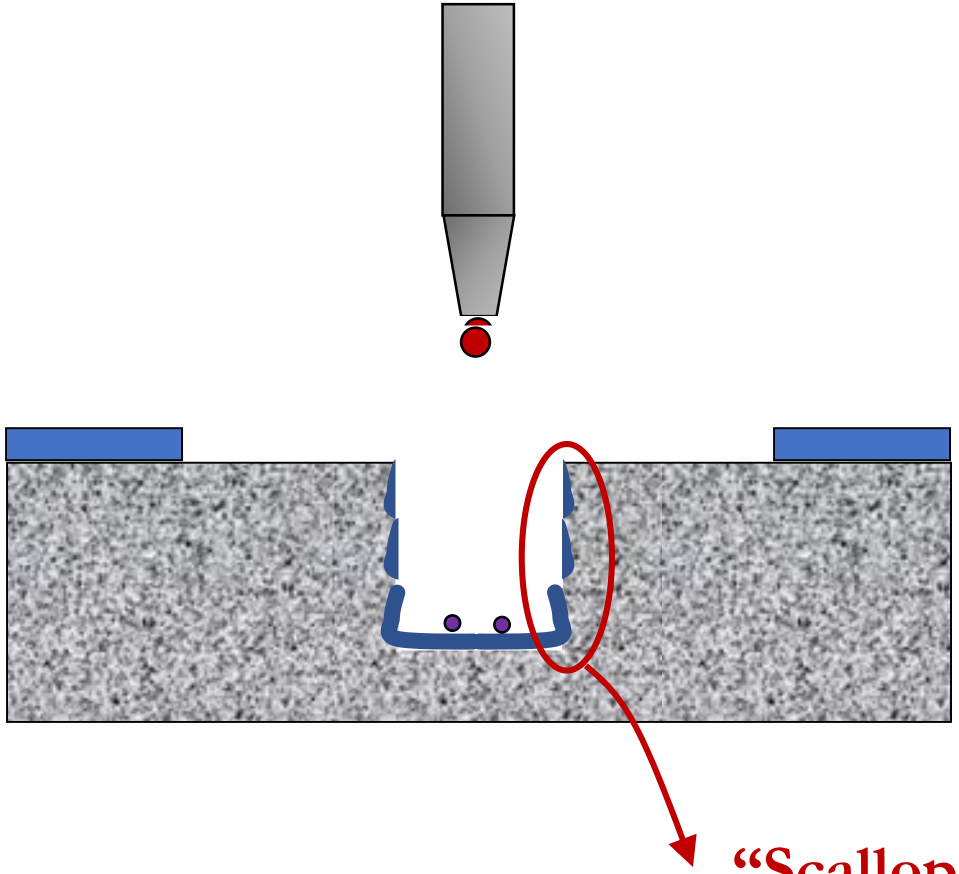
- In addition to the chemical reaction, there is physical etching
- Can be very directional—can create tall, skinny channels

If there is no chemical reaction at all, the technique is called **ion milling.**

Common dry etchant/material combinations

Material	Reactive gas
Silicon (Crystalline or polysilicon)	
SiO_2	
Al	
Si_3N_4	
Photoresist	

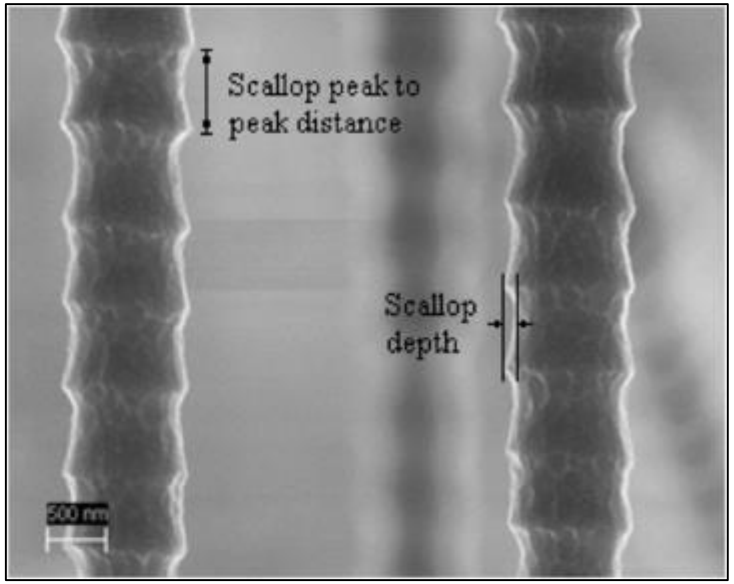
Deep reactive ion etching (DRIE)



“Scalloping”

Bosch process

- 1st, reactive ion etching step takes place
- 2nd, fluorocarbon polymer deposited to protect sidewalls



Kane Miller, Mingxiao Li, Kevin M Walsh and Xiao-An Fu, **The effects of DRIE operational parameters on vertically aligned micropillar arrays**, *Journal of Micromechanics and Microengineering*, **23** (3)