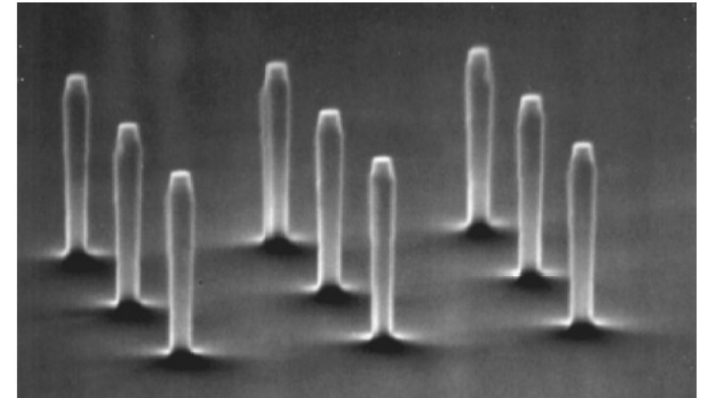


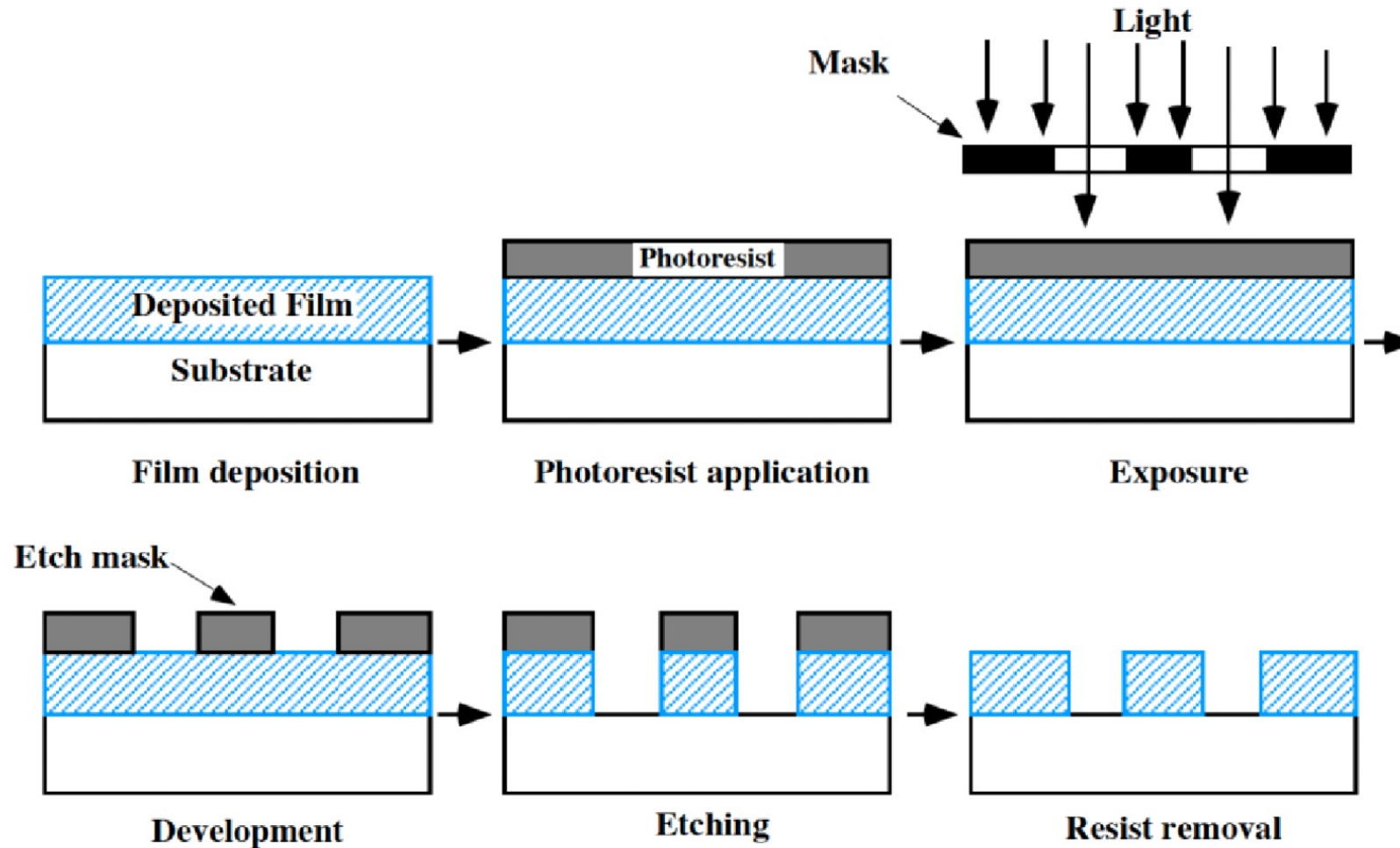
Pattern Transfer Techniques

Dry and Wet

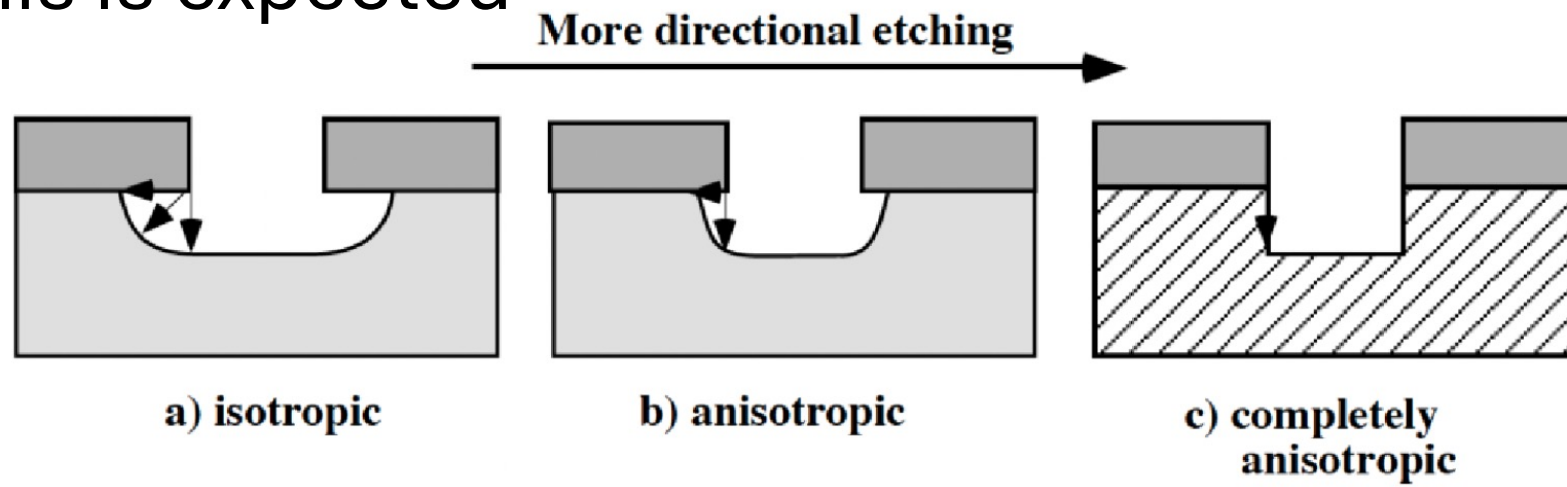
250 nm wide cavities etched using
Dry etching techniques



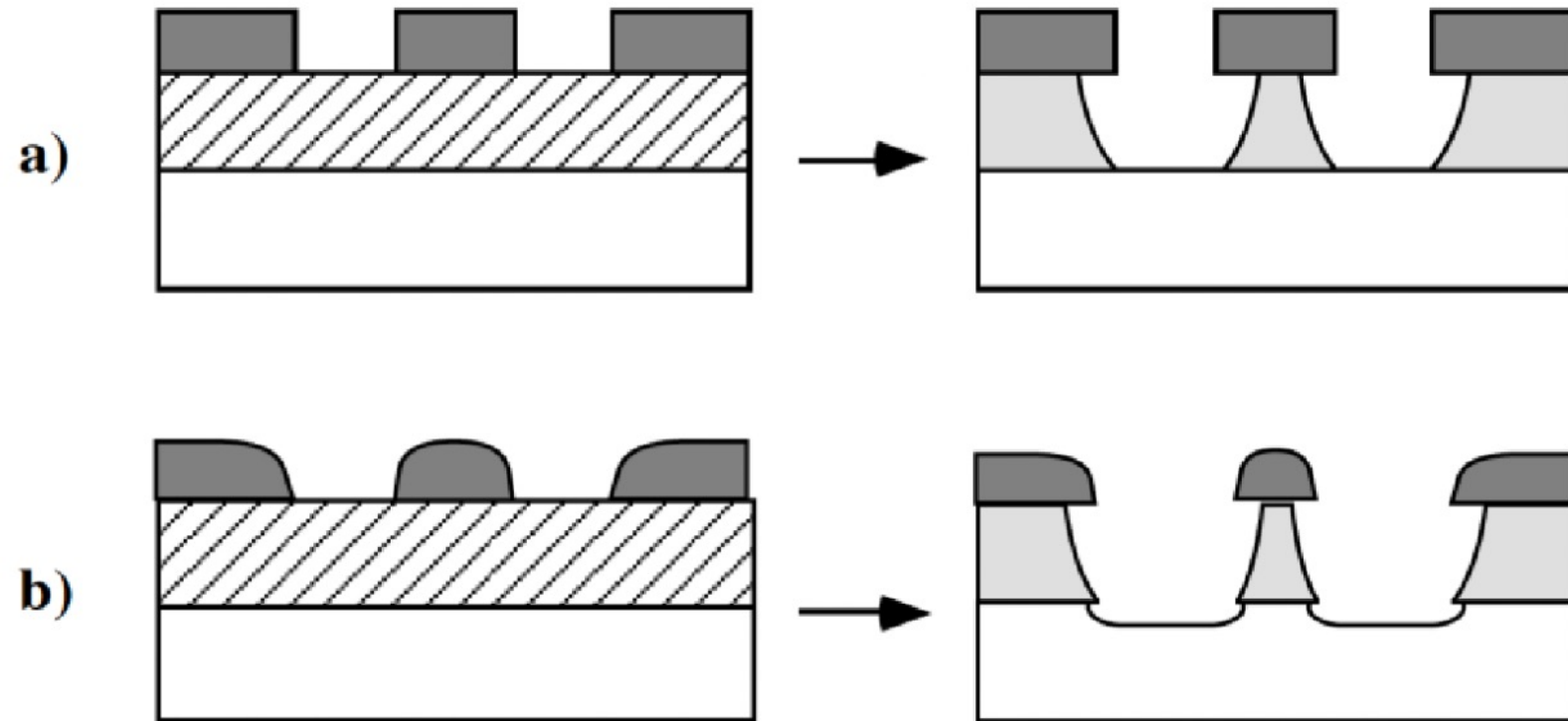
A typical Etching process



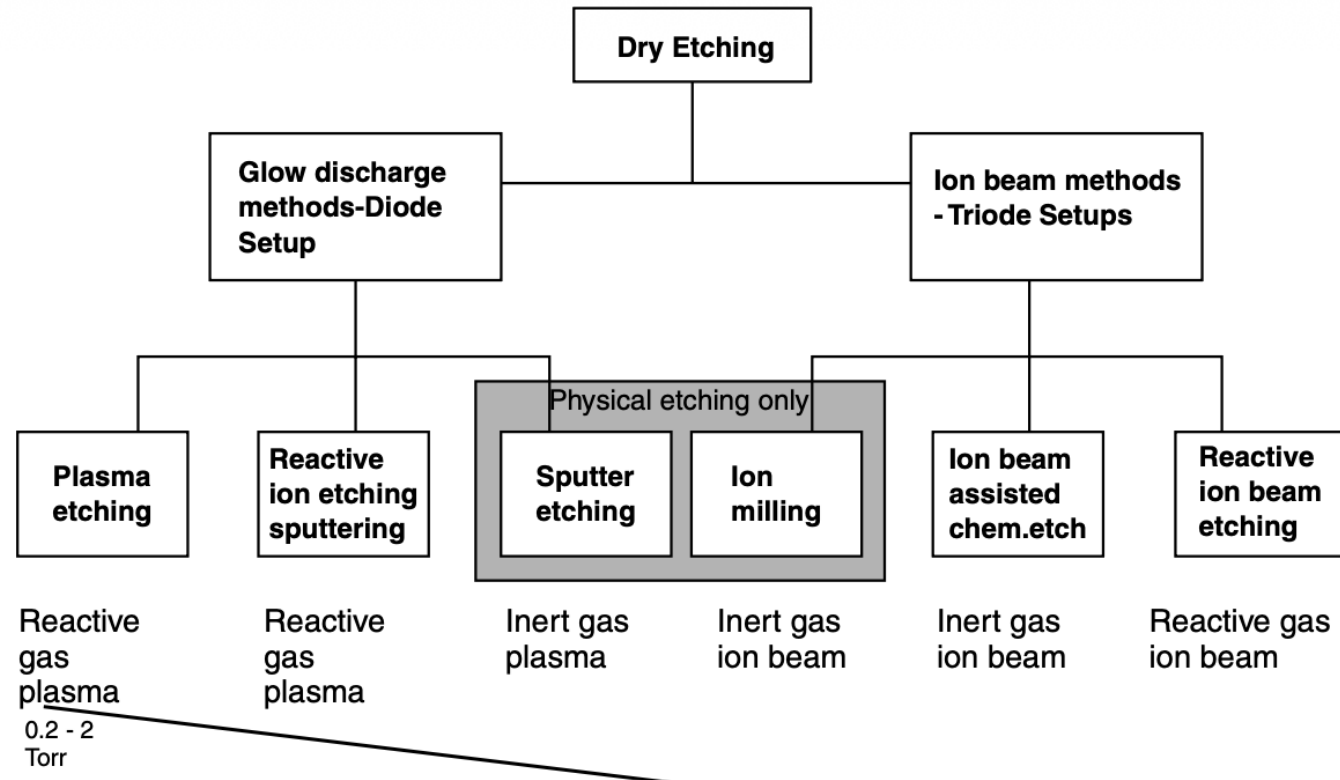
This is expected



This is obtained



Dry Etching Practices



Plasma dynamics

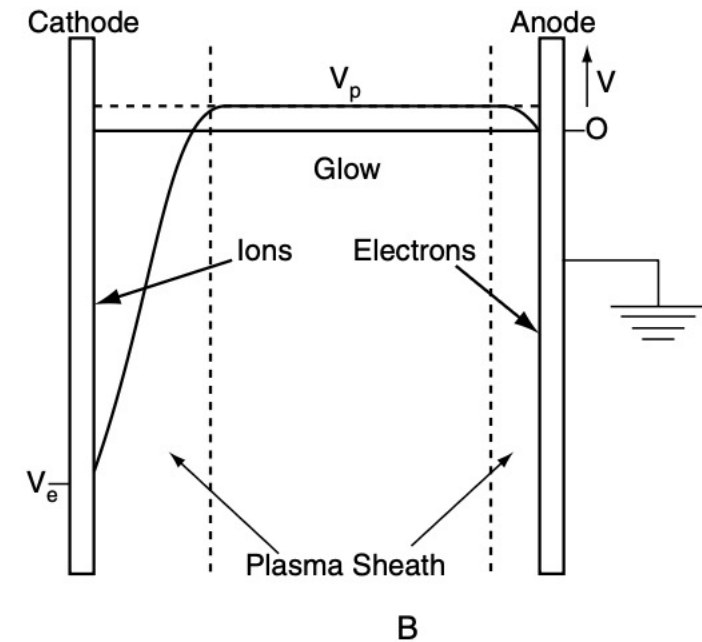
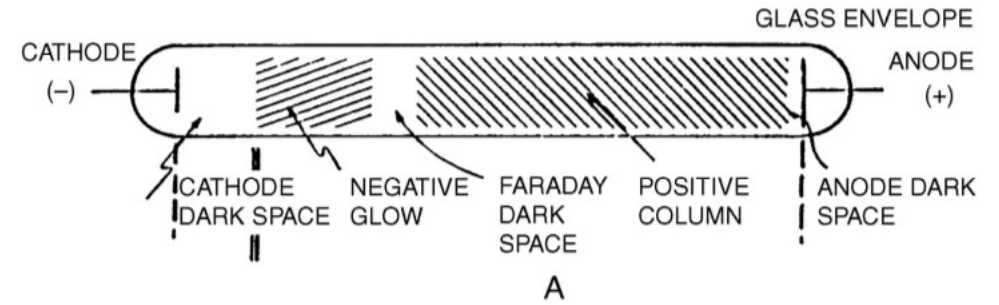
- The flux of ions is given by

$$j = qn_i\mu_i E$$

E – Electric field

n_i – ion density

μ - ion mobility



Ionization of gases under Fixed DC bias

TABLE 2.3 Minimum Breakdown Voltage (V_{min}) and Pressure/Distance Product ($P \times d$) at the Minimum Voltage for Various Gases, as Deduced from Their Paschen Law Curves

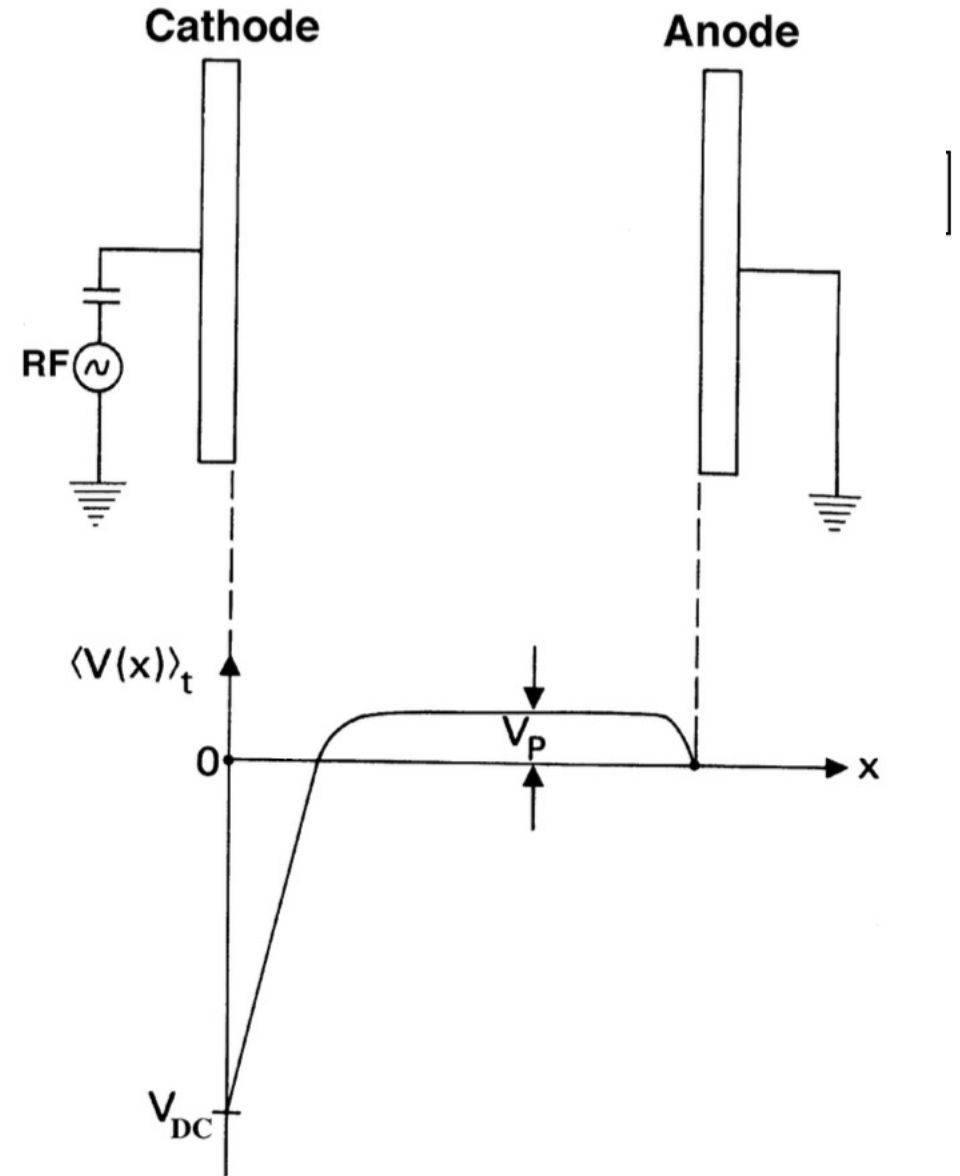
Gas	V_{min} in Volts (V)	$P \times d$ at V_{min} (Torr cm)
Air	327	0.567*
Ar	137	0.9
H ₂	273	1.15
He	156	4.0
CO ₂	420	0.51
N ₂	251	0.67
N ₂ O	418	0.5
O ₂	450	0.7
SO ₂	457	0.33
H ₂ S	414	0.6

*At 1 atmosphere = 760 mm Hg or 760 Torr, $d = 7.460 \times 10^{-4}$ cm or ~8 μm .

Source: After Naidu et al., 1995.²⁷

Physics of RF Plasma

- Ionization is achievable at lower pressures
- Dielectrics can also generate plasma
- As the neutral gas molecules get ionized, the electrons move closer to the cathode, separating the positive ions.
- A self-bias (-ve) is obtained near the cathode.



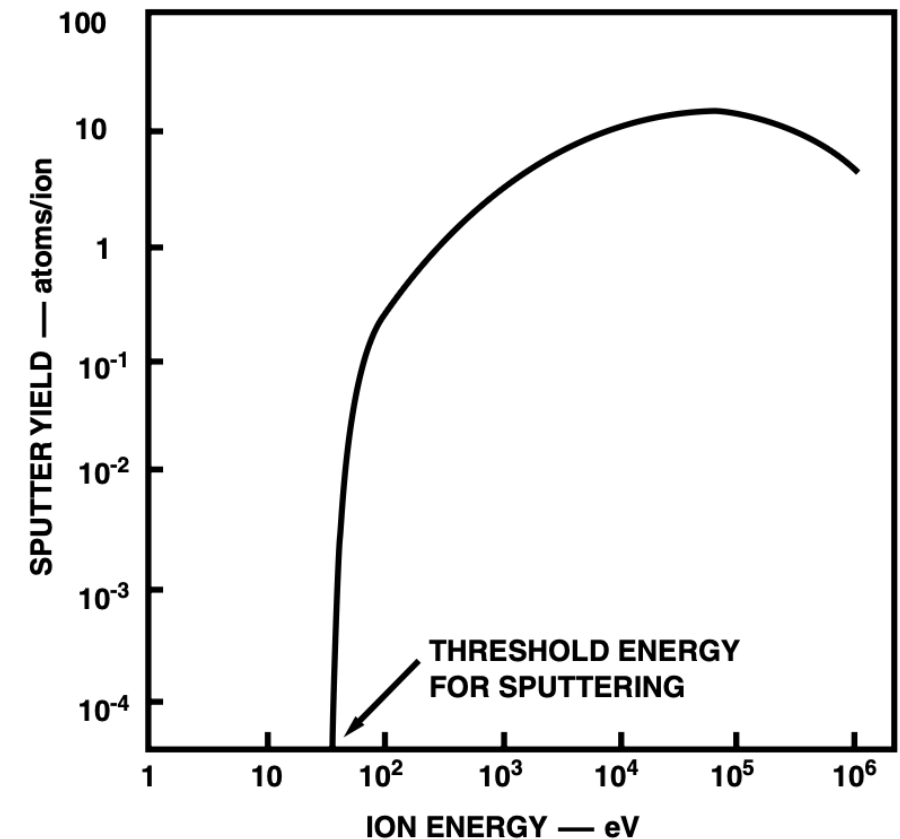
Plasma Etching - Physical

- Physical etching is possible when the ion energy is > 10 eV
- Billiard ball removal of atoms
- No volatile chemical etching is expected.
- Material non-selective
- Some directional anisotropy is possible
- Small etch rates! (few hundred Å/min)
- A magnetron can help confining the electrons to a smaller region – better plasma.

Etching is purely impact controlled.

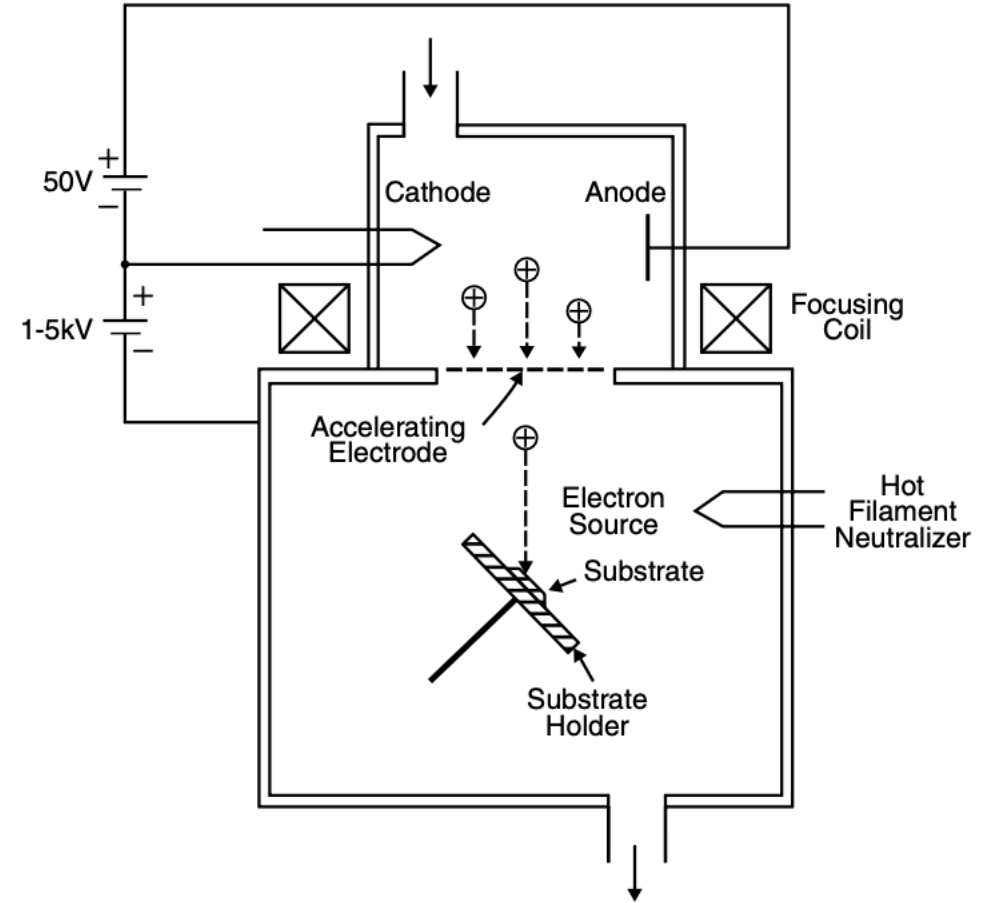
TABLE 2.4 Energy Requirements
Associated with Various Physical Processes

Ion energy (eV)	Reaction
<3	Physical adsorption
4–10	Some surface sputtering
10–5000	Sputtering
10k–20k	Implantation



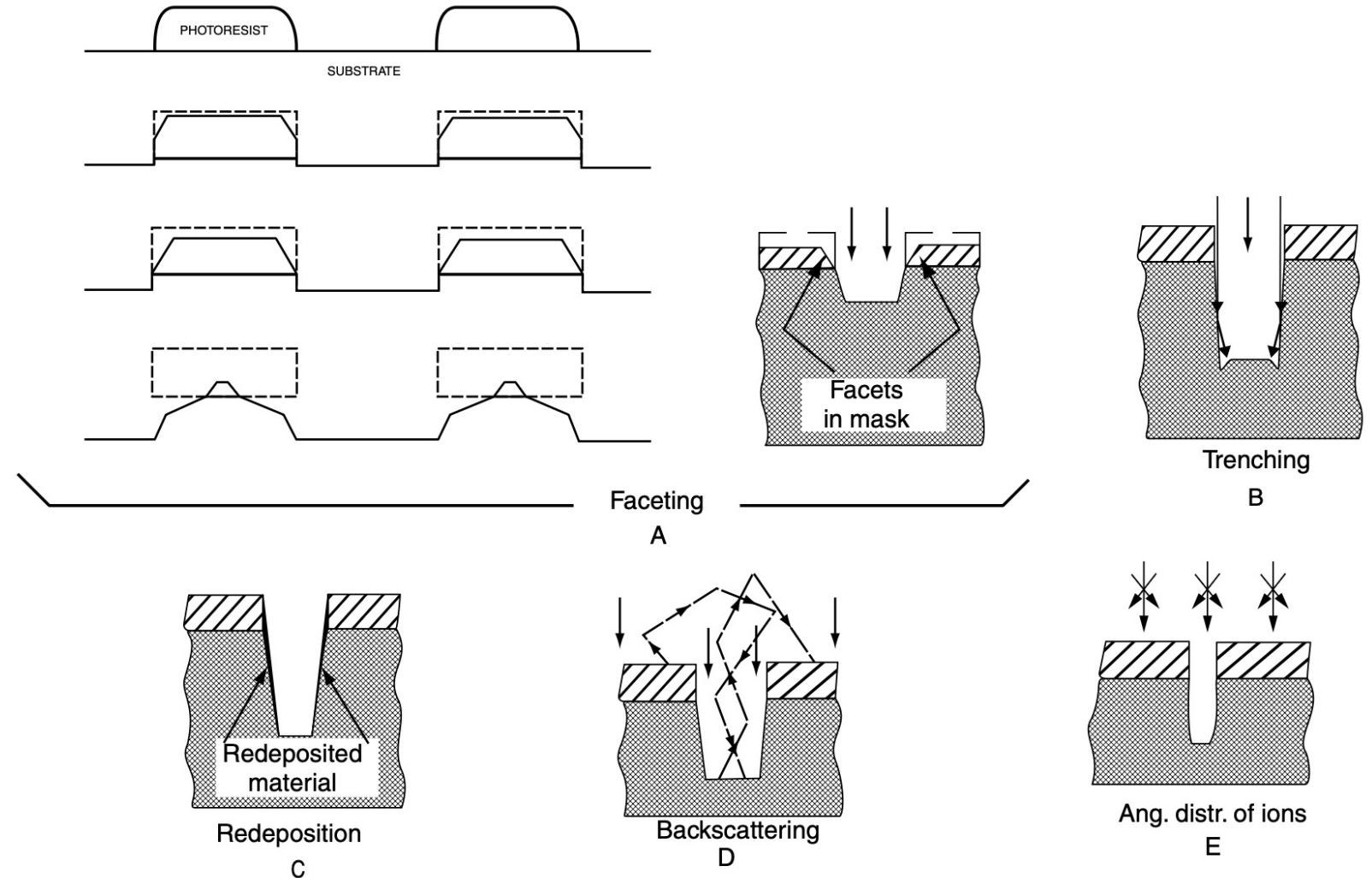
Ion-beam milling

- A triode is setup
- Ions are generated separately and are extracted, neutralized and then made to incident on the target.
- Energies from 30 eV – keV are possible
- Etch rates of 3000 Å/min are possible



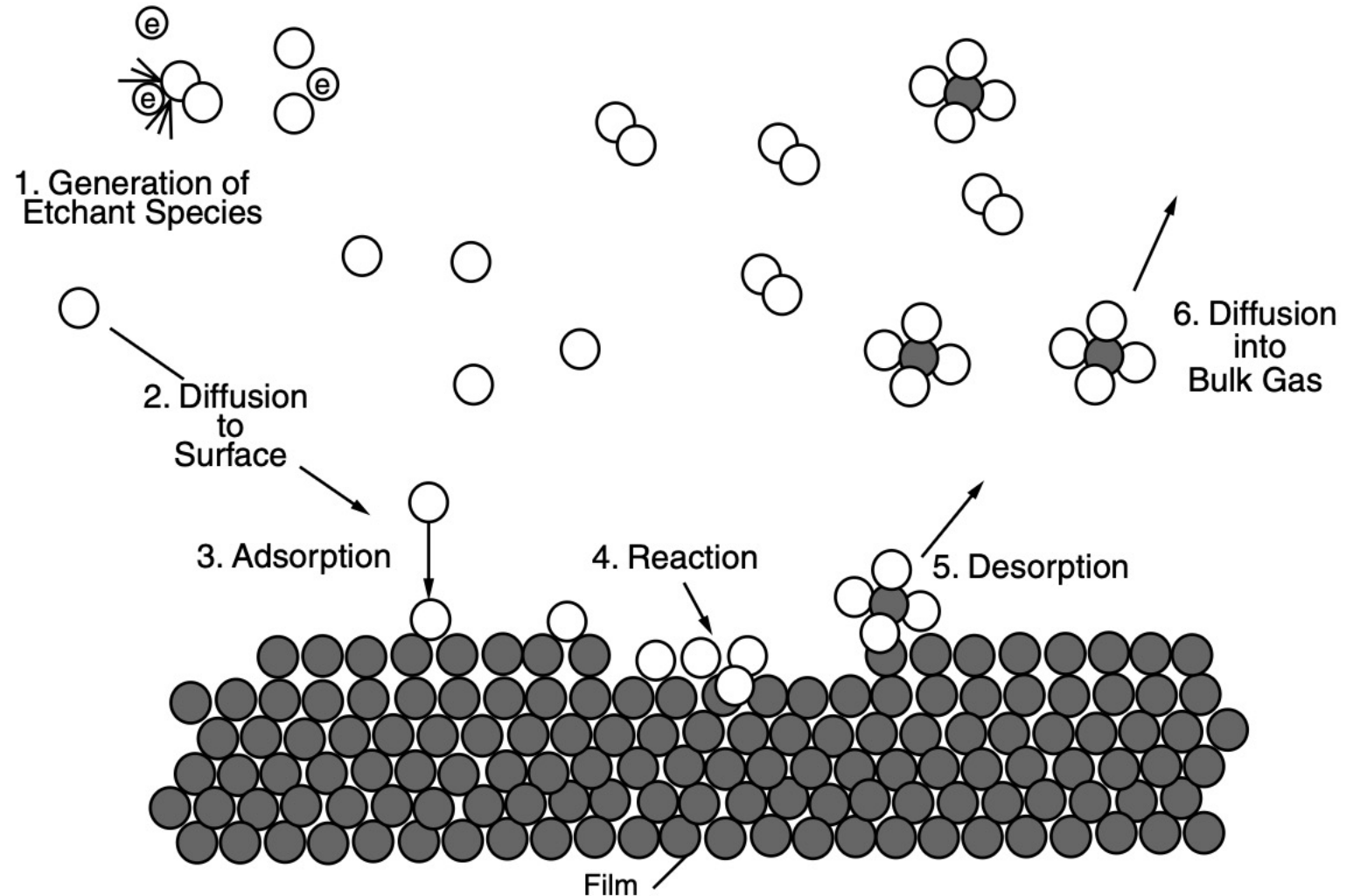
Resist Profiles issues

- Faceting
- Trenching
- Re-deposition
- Back-scattering



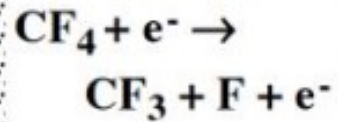
Plasma Etching (Radical Etching)

- At lower ion energies
 - Largely chemical reaction of radicals are possible
 - Leading to volatile radicals
- Radicals are more stable than ions.
- Radicals are more in number than ions.
- Eg: A gas like CF_4 dissociates into CF_3 , F , CF_3^+
- The radical diffuses into the solid
- The reacted products leave the surface

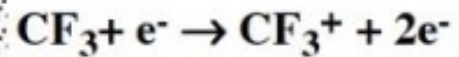


Silicon etching in CF₄

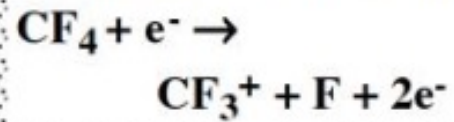
Dissociation:



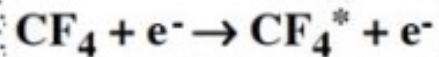
Ionization:



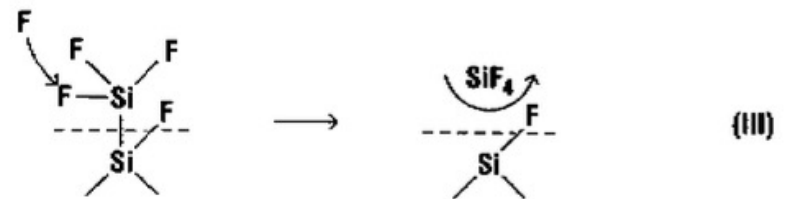
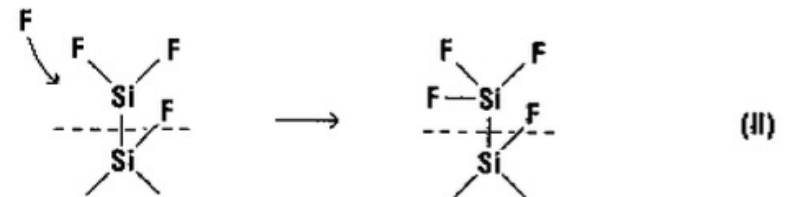
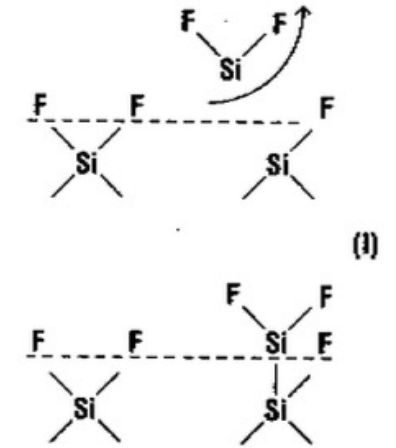
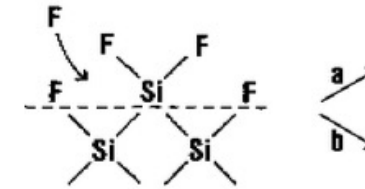
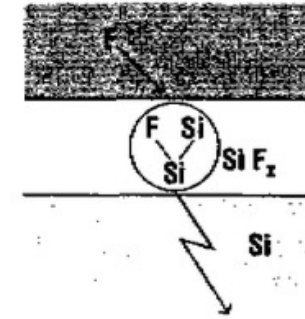
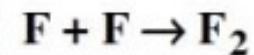
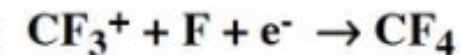
Dissociative ionization:



Excitation:



Recombination:

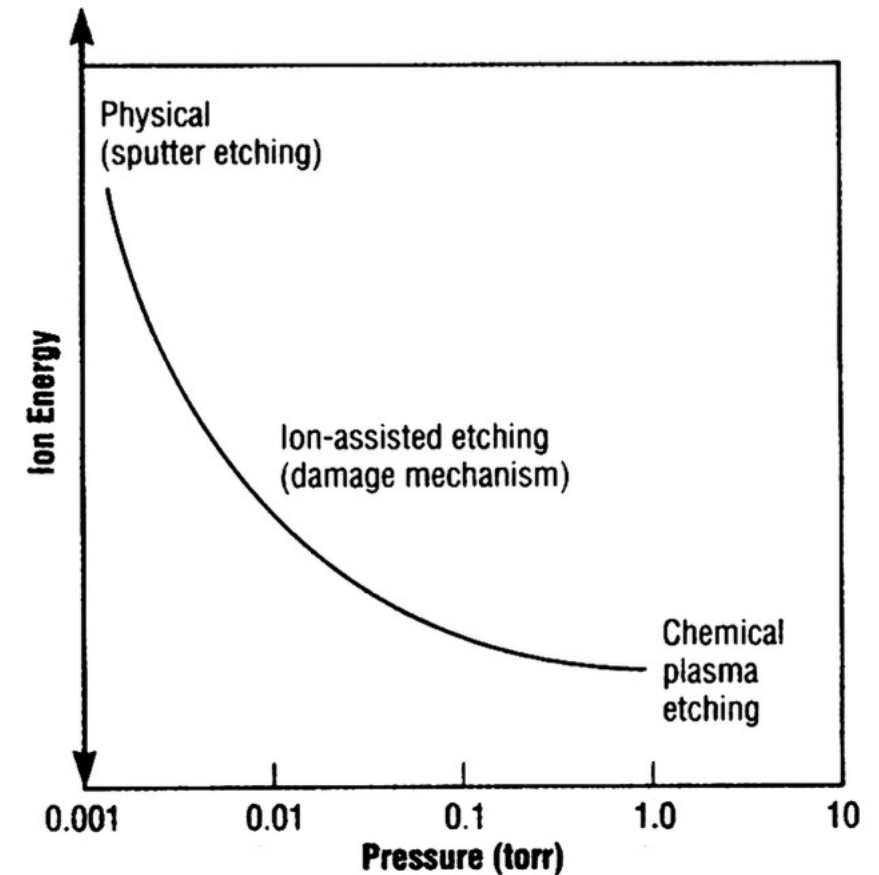


Material Selectivity

Material	Etchant	Comments
Polysilicon	CF ₄	Isotropic or near isotropic (significant undercutting); fair to no selectivity over SiO ₂
	CF ₄ /H ₂	Very anisotropic, non-selective over SiO ₂
	SF ₆ , CF ₄ /O ₂	Isotropic or near isotropic, good selectivity over SiO ₂
	HBr, Cl ₂ , Cl ₂ /HBr/O ₂	Very anisotropic, most selective over SiO ₂
Single crystal Si	same etchants as polysilicon	
SiO ₂	SF ₆ , NF ₃ , CF ₄ /O ₂ , CF ₄	Can be isotropic or near isotropic (significant undercutting); anisotropy better with higher ion energy and lower pressure; poor or no selectivity over Si
	CF ₄ /H ₂ , CHF ₃ /O ₂ , C ₂ F ₆ , C ₃ F ₈	Very anisotropic, selective over Si
	CHF ₃ /C ₄ F ₈ /CO	Anisotropic, selective over Si ₃ N ₄
Si ₃ N ₄	CF ₄ /O ₂	Isotropic, selective over SiO ₂ but not over Si
	CF ₄ /H ₂	Very anisotropic, selective over Si but not over SiO ₂
Al	CHF ₃ /O ₂ , CH ₂ F ₂	Very anisotropic, selective over Si and SiO ₂
	Cl ₂	Near isotropic (significant undercutting)
W	Cl ₂ /CHCl ₃ , Cl ₂ /N ₂	Very anisotropic; BCl ₃ often added to scavenge oxygen.
	CF ₄ , SF ₆	High etch rate, non-selective over SiO ₂
Ti	Cl ₂	Selective over SiO ₂
TiN	Cl ₂	
TiSi ₂	Cl ₂ /CHCl ₃ , CF ₄ /O ₂	
Photoresist	O ₂	Very selective over other films

Ion Energy vs Pressure Dependency

- Low pressure of the gas
 - Increased mean free path
 - Higher velocity of ions/radicals
 - More physical etching.
 - Anisotropic etching
 - Increasing the power increases etch rate
- At high pressure
 - Lower mean free path
 - Low bias – isotropic etching
 - Under-cutting can be observed.



< 100 MILLITORR

PHYSICAL SPUTTERING
(and Ion Beam Milling)

- Physical momentum transfer
- Directional etch (anisotropic) possible
- Poor selectivity
- Radiation damage possible

**HIGHER
EXCITATION
ENERGY**

RIE (Halocarbon Gas)

**100 MILLITORR
RANGE**

- Physical (ion) and chemical
- Directional
- More selective than sputtering

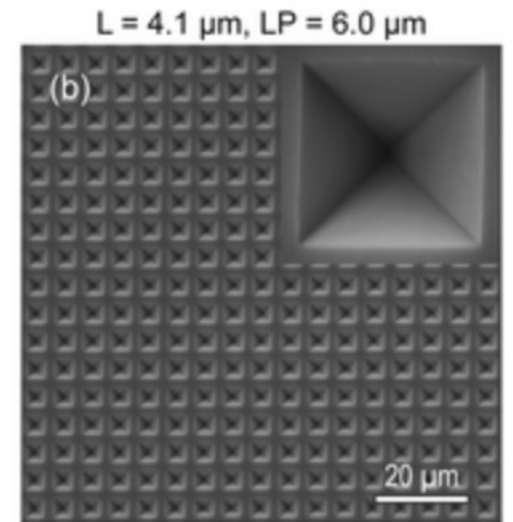
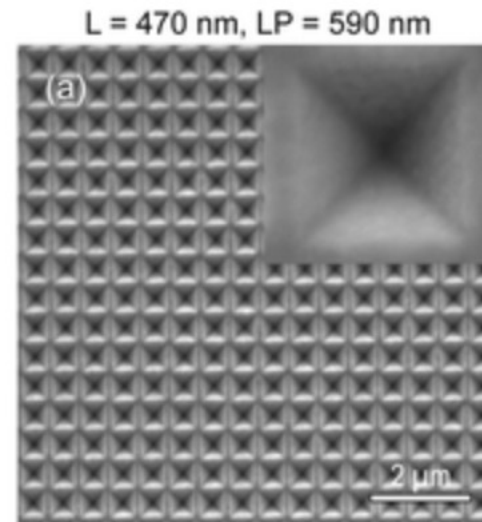
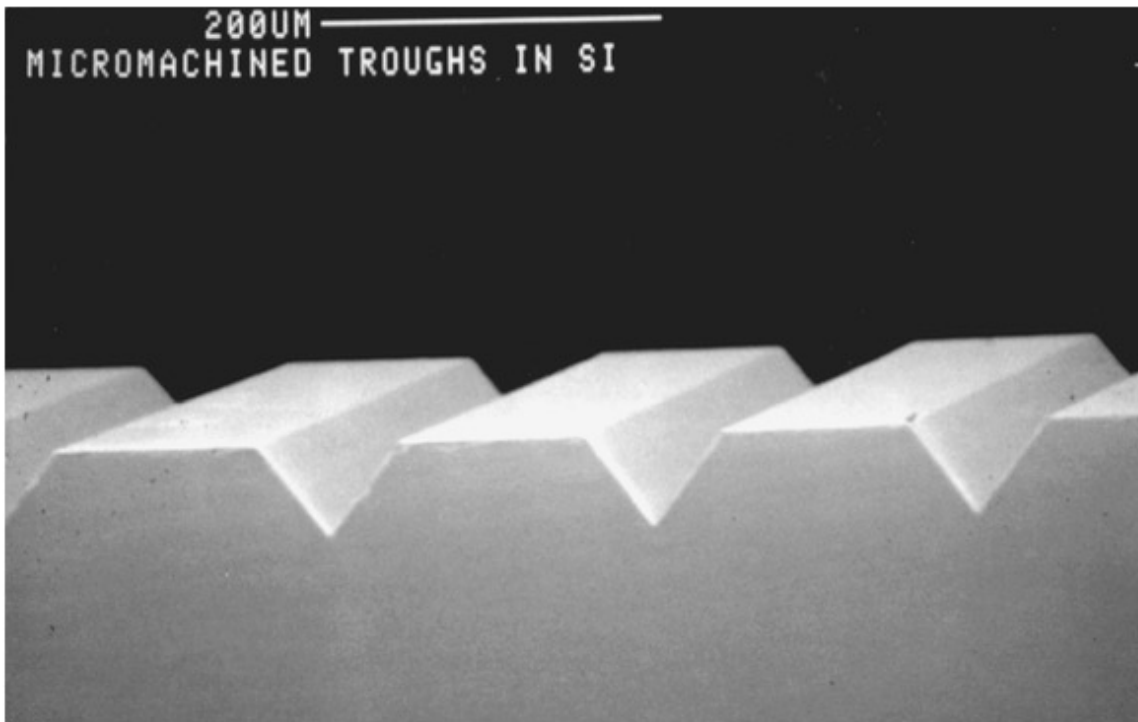
PLASMA ETCHING

**HIGHER
PRESSURE**

- Chemical, thus faster by 10-1000X
- Isotropic
- More selective
- Less prone to radiation damage

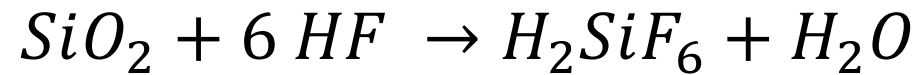
Wet Chemical Etching

*Long V-shaped grooves in a
(100) Si wafer*



Some simple wet-chemical etching

- How to remove SiO₂ ?



The product is highly soluble in water and hence removes SiO₂.

Buffered HF

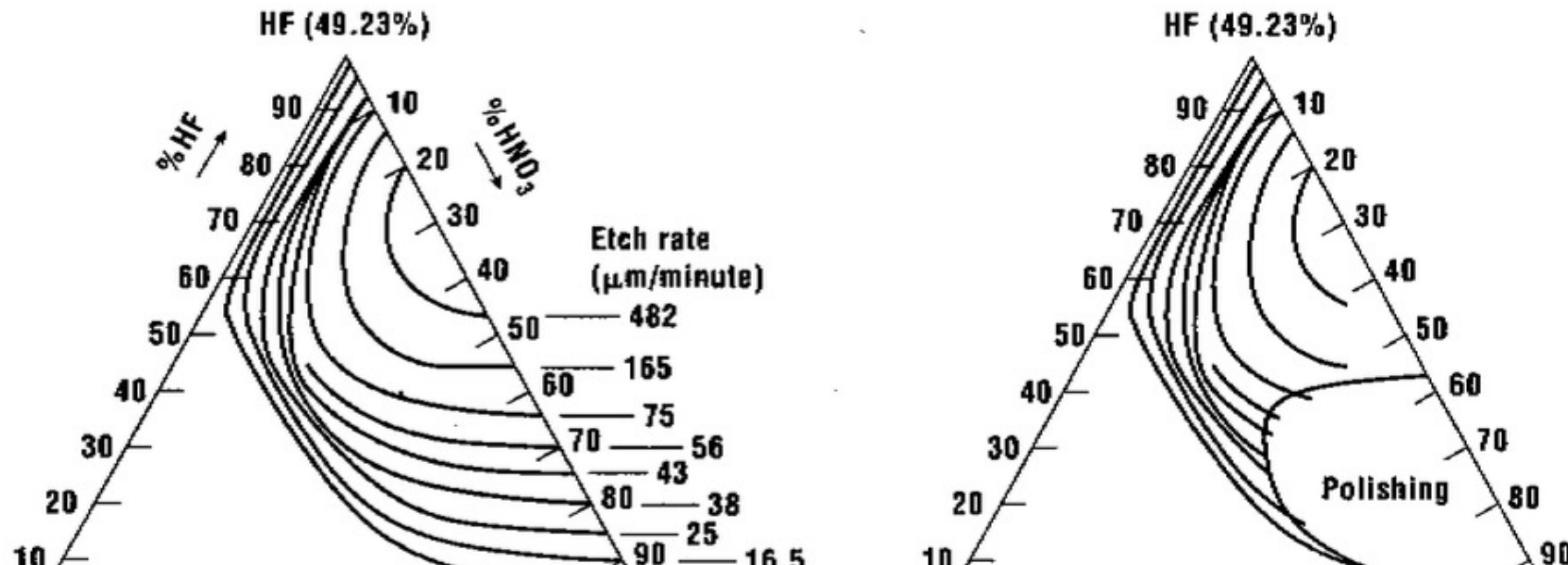
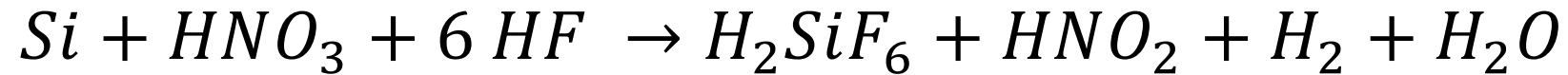
However, this consumes HF. So, it is common process to buffer this



Thus, if HF concentration reduces, the ammonium fluoride decomposes to maintain constant HF concentration.

This provides a clue to remove Si.

To remove Si, Can we simply, oxidize it first ?



A delicate balance between oxidation and etching has to be met to have good etching rates

Material	Etchant	Comments
SiO ₂	HF (49% in water) “straight HF”	Selective over Si (i.e. will etch Si very slowly in comparison) Etch rate depends on film density, doping
	NH ₄ F:HF (6:1) “Buffered HF” or “BOE”	About 1/20th the etch rate of straight HF Etch rate depends on film density, doping Will not lift up photoresist like straight HF
Si ₃ N ₄	HF (49%)	Etch rate depends strongly on film density, O, H
	H ₃ PO ₄ :H ₂ O (boiling @ 130-150°C)	Selective over SiO ₂ Requires oxide mask
Al	H ₃ PO ₄ :H ₂ O:HNO ₃ :CH ₃ COOH (16:2:1:1)	Selective over Si, SiO ₂ , and photoresist
Polysilicon	HNO ₃ :H ₂ O:HF (+ CH ₃ COOH) (50:20:1)	Etch rate depends on etchant composition
Single crystal Si	HNO ₃ :H ₂ O:HF (+ CH ₃ COOH) (50:20:1) KOH:H ₂ O:IPA (23 wt. % KOH, 13 wt. % IPA)	Etch rate depends on etchant composition Crystallographically selective; relative etch rates: (100): 100 (111): 1
Ti	NH ₄ OH:H ₂ O ₂ :H ₂ O (1:1:5)	Selective over TiSi ₂
TiN	NH ₄ OH:H ₂ O ₂ :H ₂ O (1:1:5)	Selective over TiSi ₂
TiSi ₂	NH ₄ F:HF (6:1)	
Photoresist	H ₂ SO ₄ :H ₂ O ₂ (125°C)	For wafers without metal
	Organic strippers	For wafers with metal

Anisotropy in wet chemical etching

A wide variety of etchants are used

NaOH, LiOH, CsOH, NH₄OH

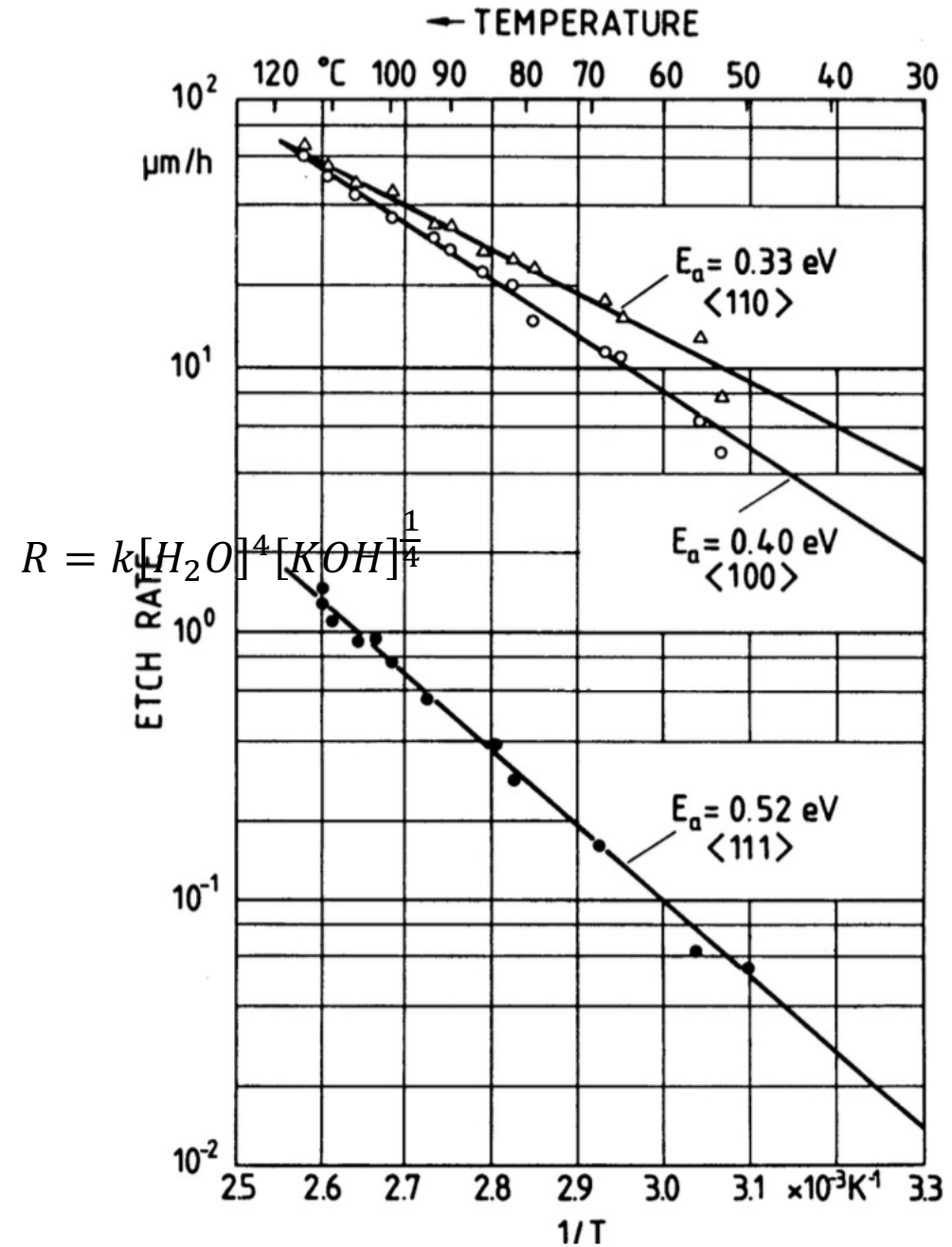
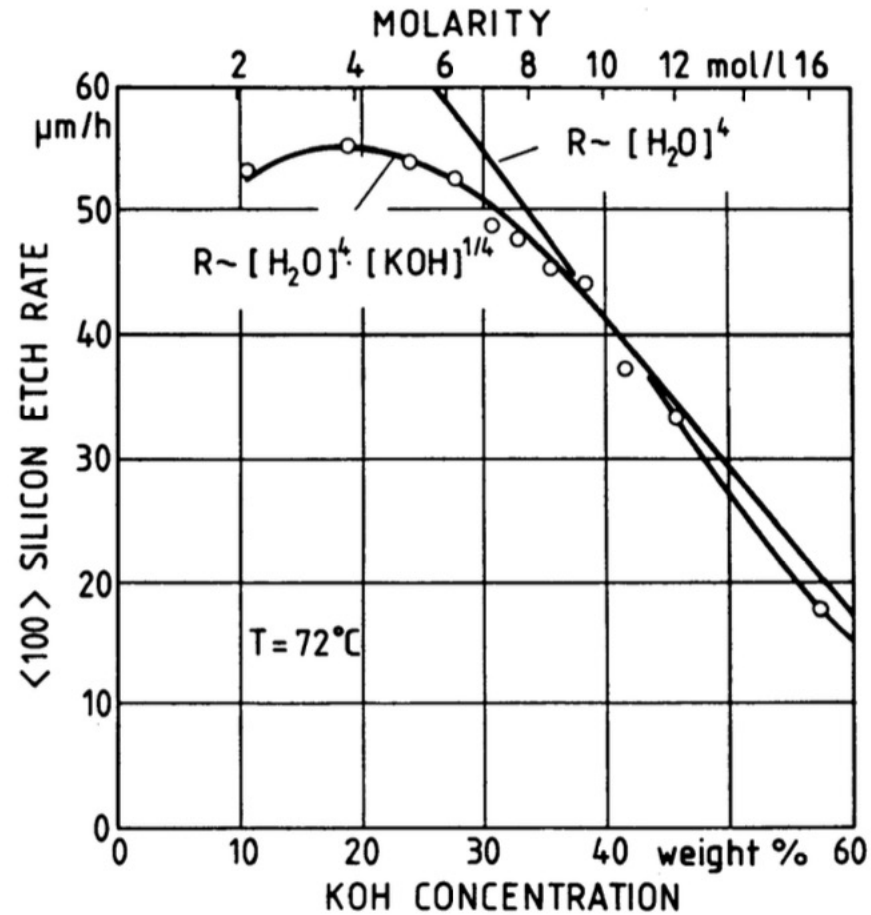
- Water is reduced at the Si surface:
 - $4H_2O + 4e^- \rightarrow 4[OH]^- + 2H_2$
- Imagine Si is in basic solutions:
 - Now that we have a lot of $[OH]^-$ groups
 - $Si + 2[OH]^- \rightarrow Si(OH)_2^{2+} + 2e^-$
 - $Si(OH)_2^{2+} + 2[OH]^- \rightarrow Si(OH)_4 + 2e^-$

Oh, so just water dissolves Si ?



This is a water-soluble complex!

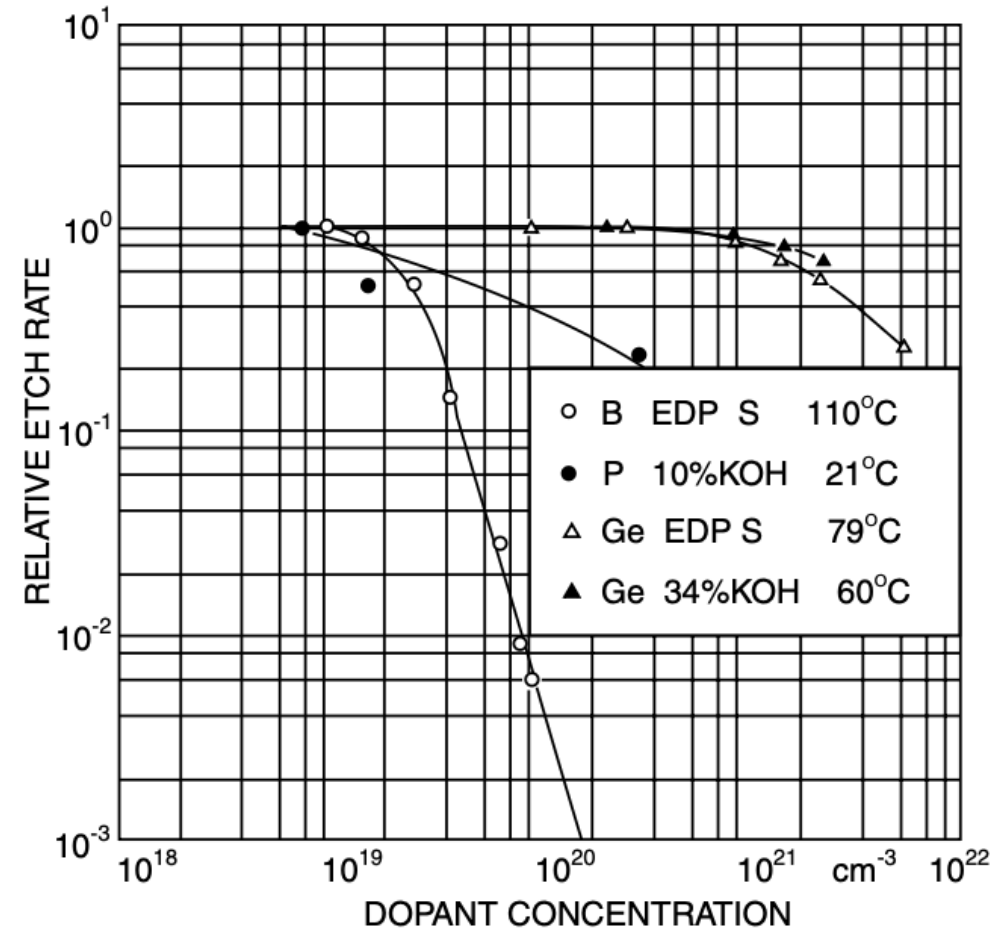
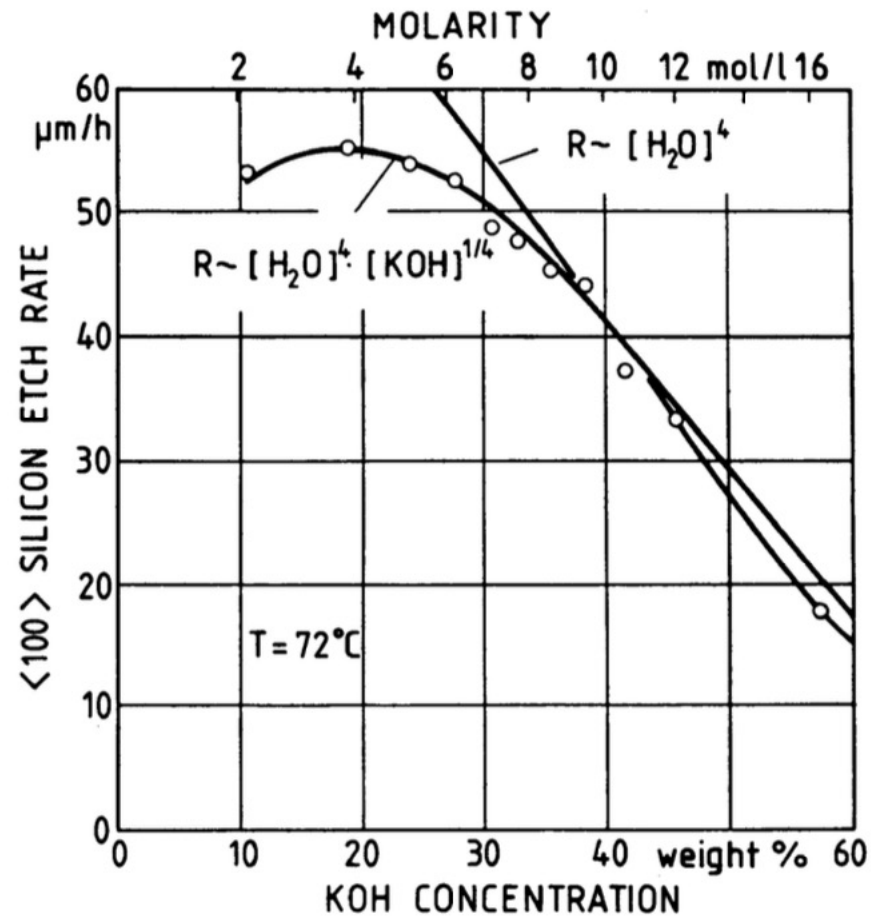
KOH is very specific



Higher concentration does not mean more etching!

KOH is very specific

$$R = k[H_2O]^4[KOH]^{\frac{1}{4}}$$

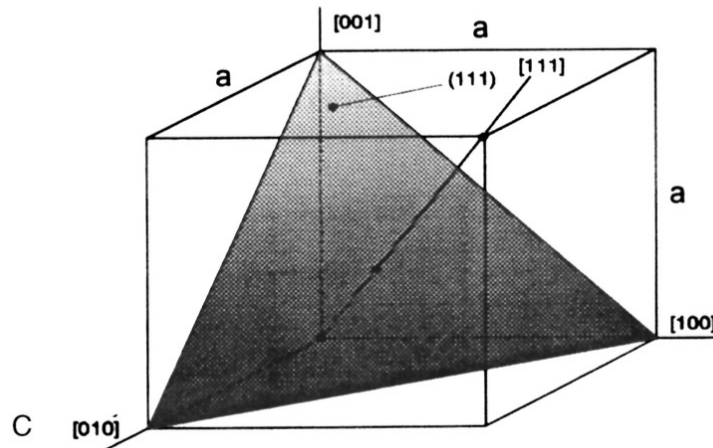
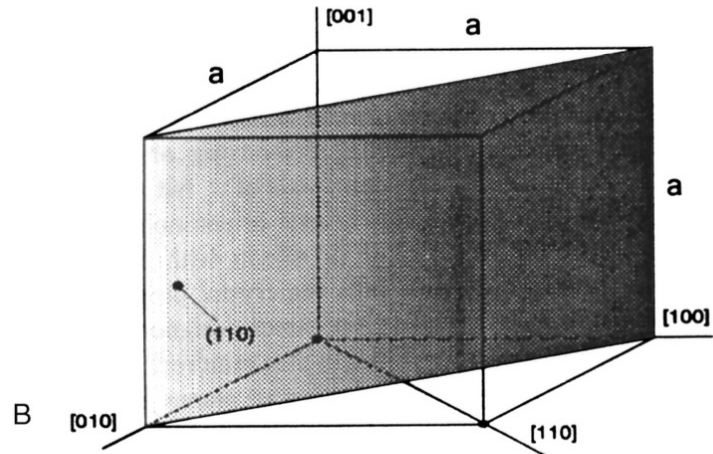
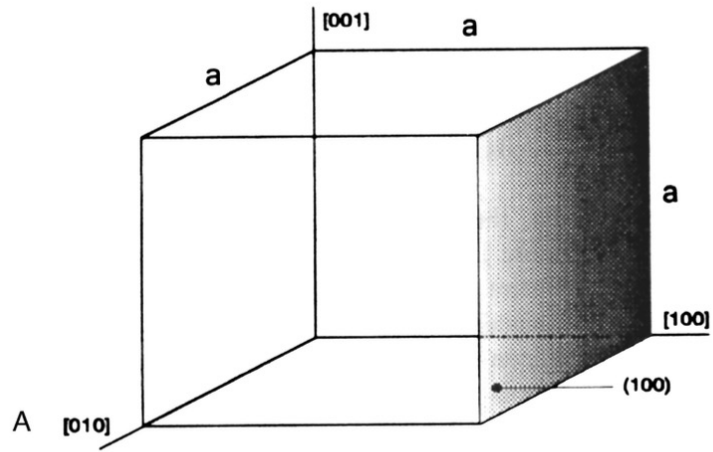


Higher concentration does not mean more etching!

Silicon crystallography

Angular orientation between

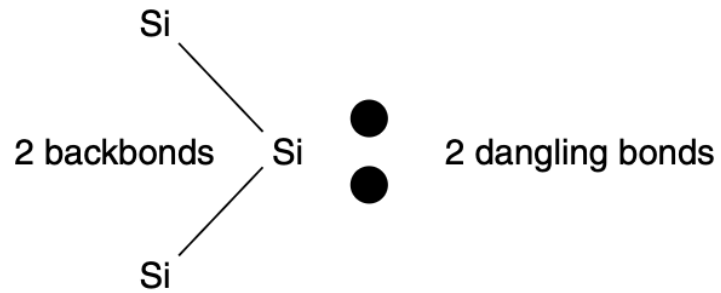
- (100) family of planes – 90
- (100) and (110) planes – 45
- (100) and (111) is 54.7
- (111) and (110) can intersect at 35.2, 90 and 144.7 degrees



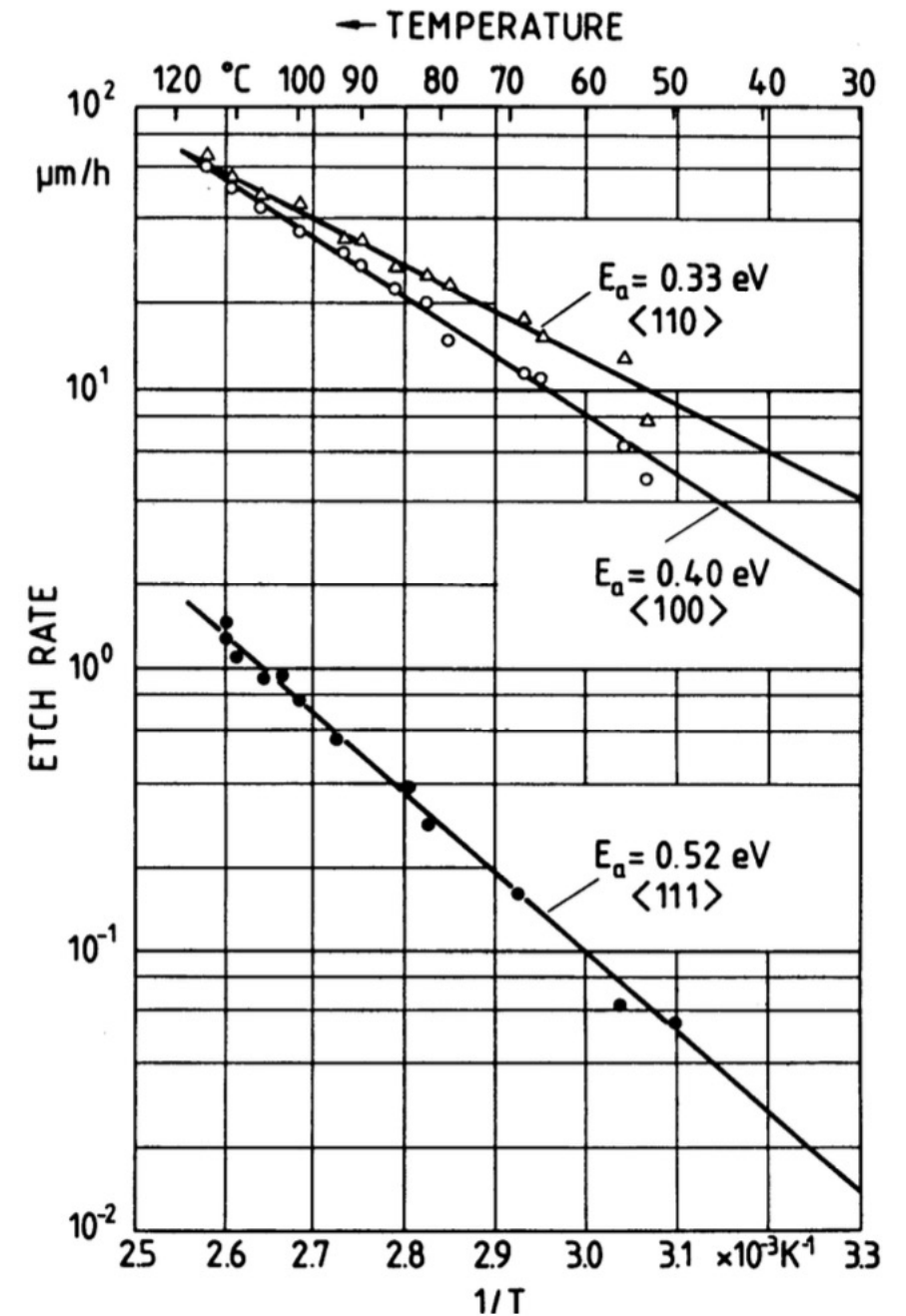
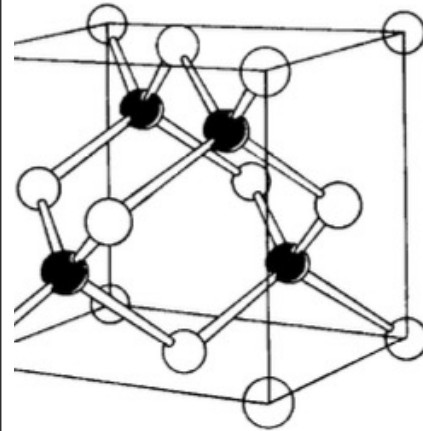
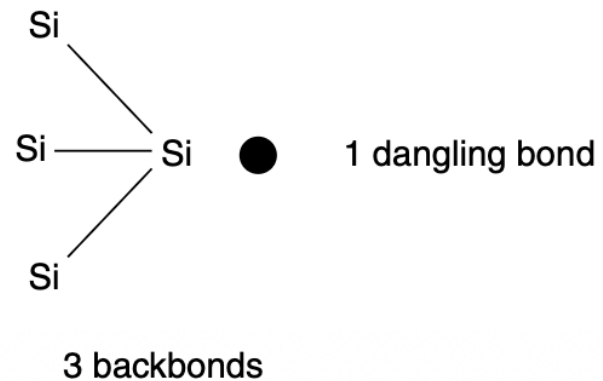
Orientation dependence

Dangling Bonds

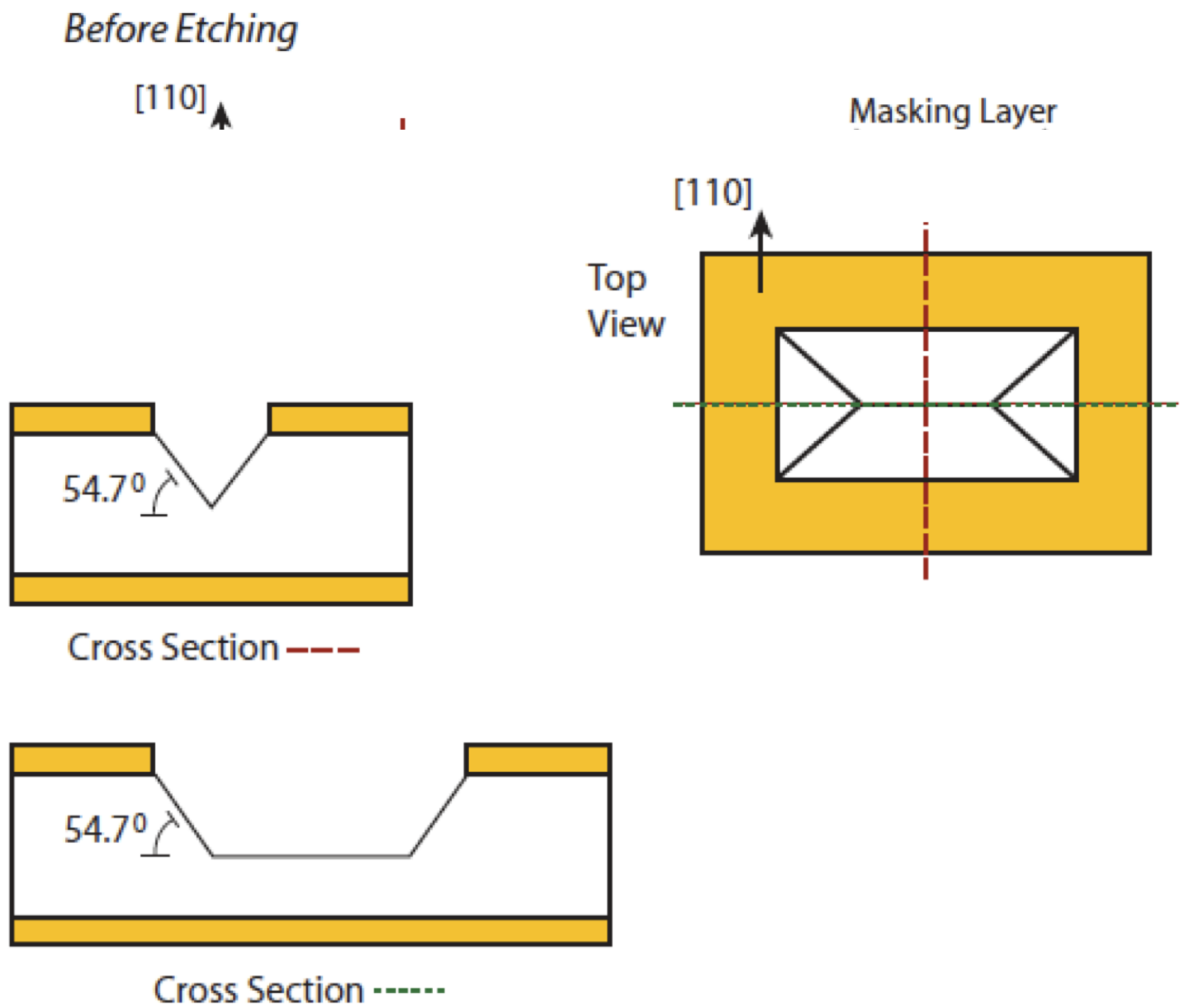
Si atoms on a (100) plane



Si atoms on a (111) plane



Pyramidal pattern



What pattern does it form

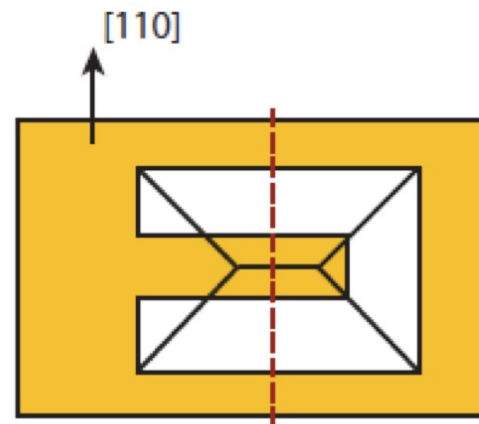
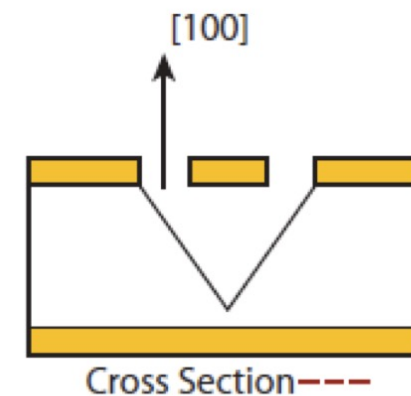
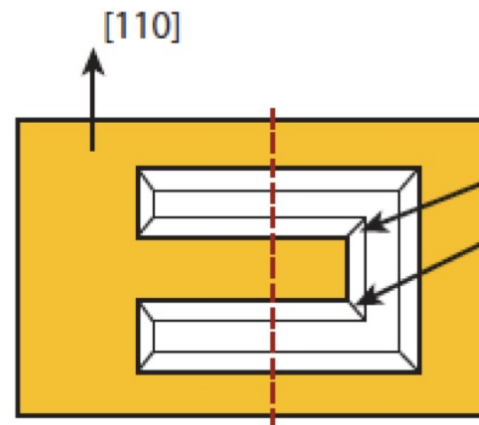
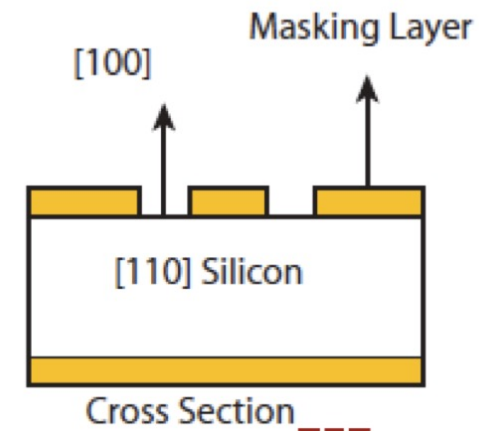
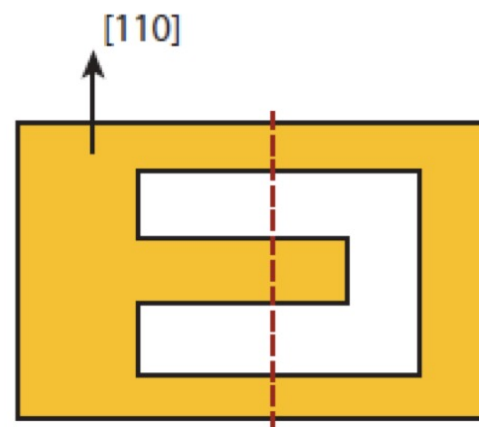
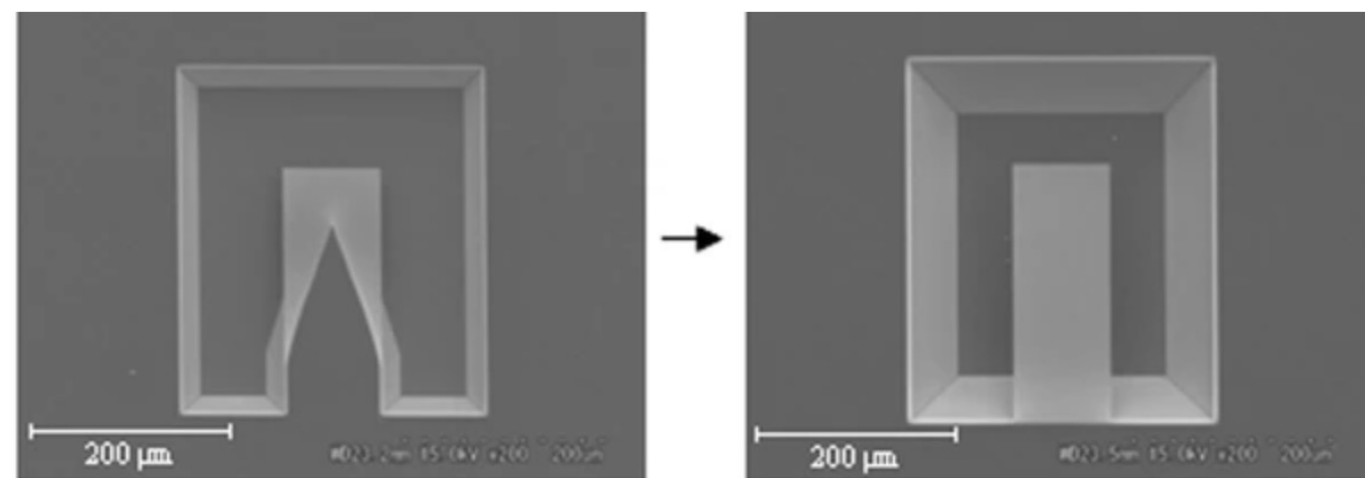
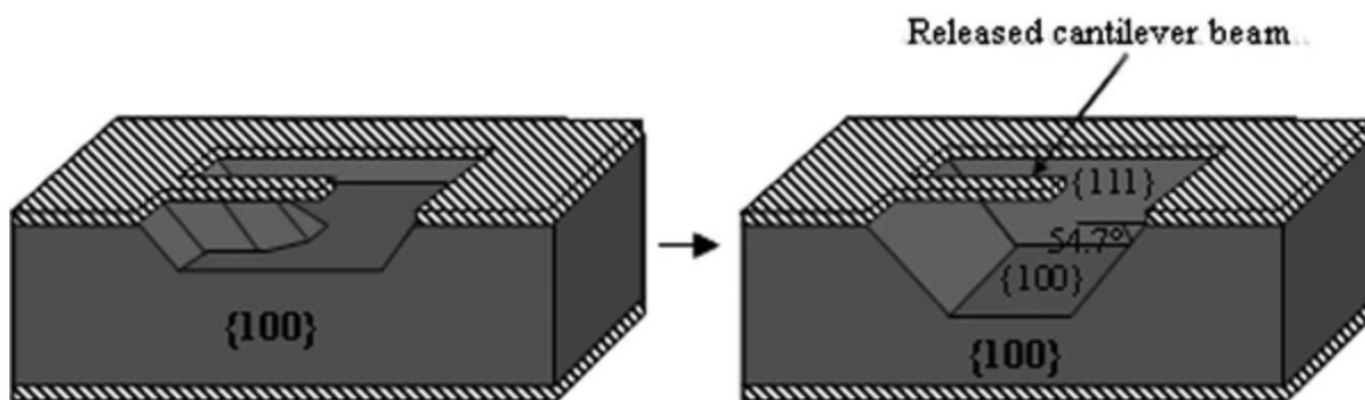


Fig. 10



SEM Pictures (beam length = 250 μm , width = 100 μm)



Schematic view {100}Si SiO₂

