Etching

- Etching Terminology
- Etching Considerations for ICs
- Wet Etching
- Reactive Ion Etching (plasma etching)

Etch Process - Figures of Merit

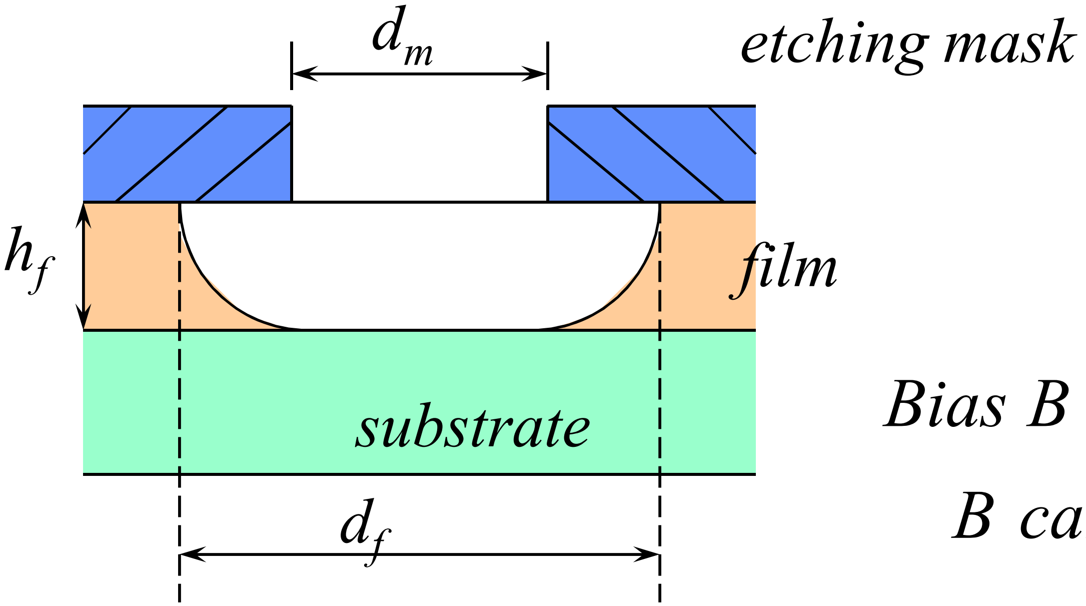
- Etch rate

- Etch rate uniformity

- Selectivity

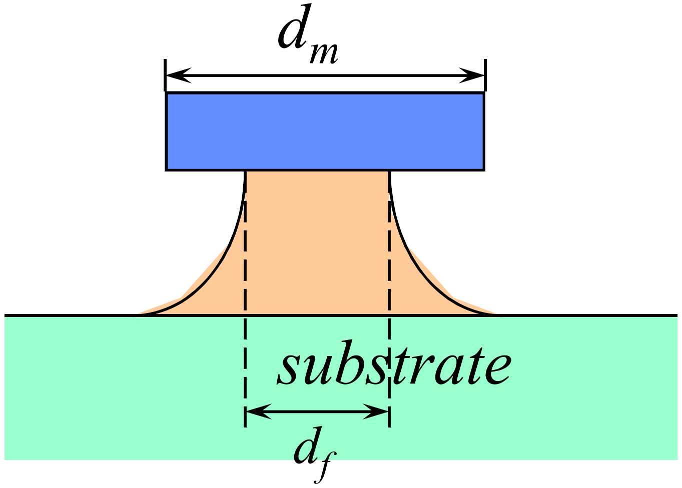
- Anisotropy

(1) Bias



$$Bias\ B \equiv d_f - d_m$$

$$B\ can\ be > 0\ or < 0.$$



Complete Isotropic Etching

Vertical Etching = Lateral Etching Rate

$B = 2 \times h_f$

Complete Anisotropic Etching

Lateral Etching rate = 0

$B = 0$

(2) Degree of Anisotropy

$$A_f \equiv 1 - \frac{|B|}{2h_f}$$

$$\underset{\substack{\uparrow \\ isotropic}}{0} \leq A_f \leq \underset{\substack{\uparrow \\ anisotropic}}{1}$$

$$\therefore \ |B| = 2h_f \qquad\qquad |B| = 0$$

(3) Etching Selectivity S

$$S_{AB} = \frac{v_A \text{(vertical etching velocity of materal A)}}{v_B \text{(vertical etching velocity of materal B)}}$$

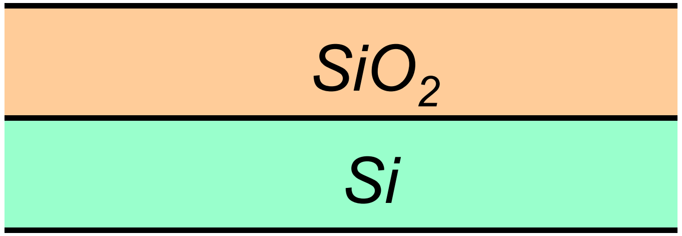
Wet Etching

S is controlled by:
chemicals, concentration, temperature

RIE

S is controlled by:
plasma parameters, plasma chemistry,
gas pressure, flow rate & temperature.

Selectivity Example



SiO_2/Si etched by HF solution

$S_{SiO2,\,Si}$ Selectivity is very large (~ infinity)

SiO_2/Si etched by RIE (e.g. CF_4 plasma)

$S_{SiO2,\,Si}$ Selectivity is finite (~ 10)

Etching of Steps with a Slope

* Etching velocity has vertical component v_v and lateral component v_l

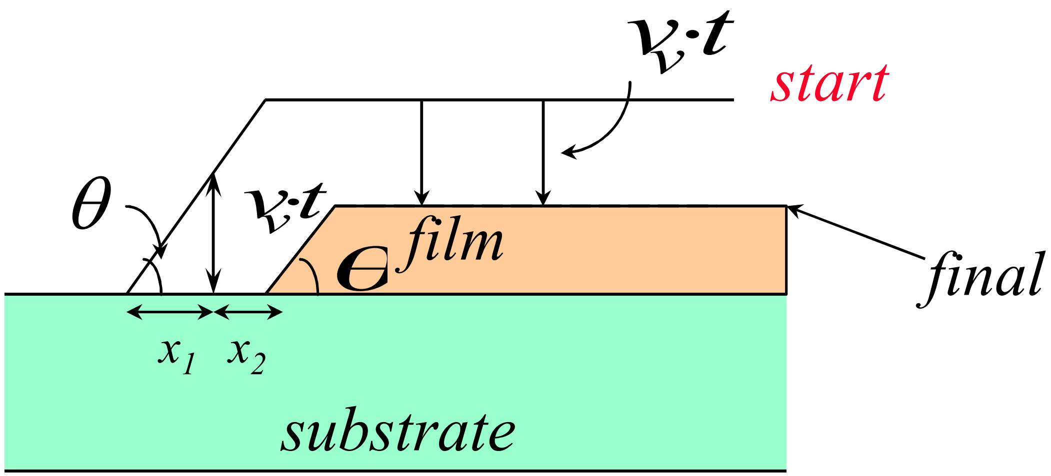
$$\text{Let etching time} = t$$

$$v_v = \text{vertical etch rate}$$

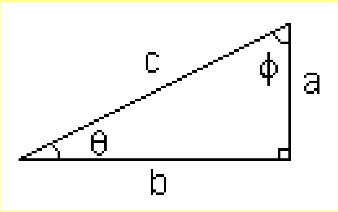
$$v_l = \text{lateral etch rate}$$

$$x_1 = v_v \cdot t \cot\theta$$

$$x_2 = v_l \cdot t$$



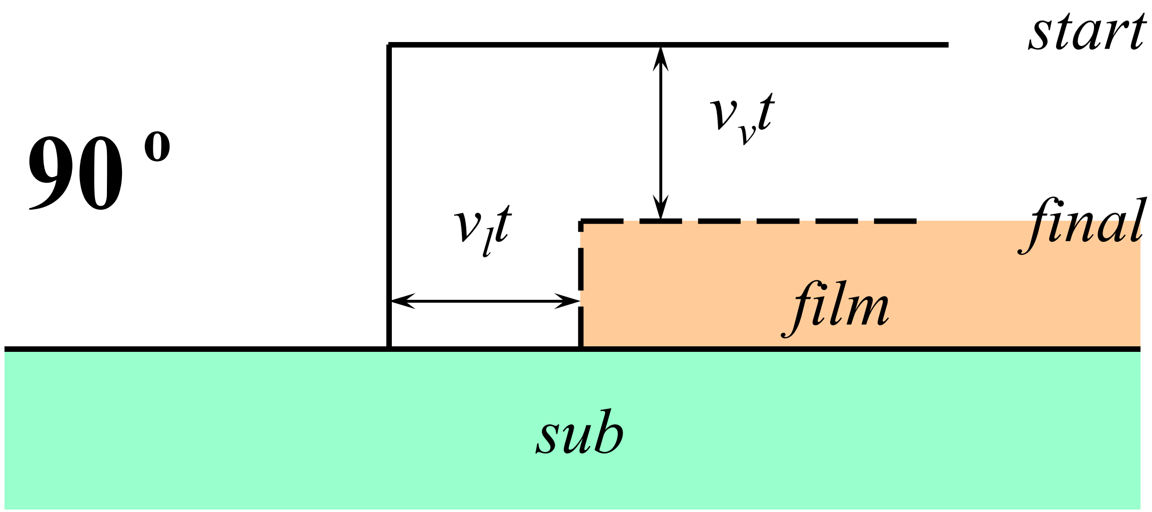
$$\boxed{\begin{aligned} x &= x_1 + x_2 \\ &= (v_v \cot\theta + v_l) \cdot t \end{aligned}}$$



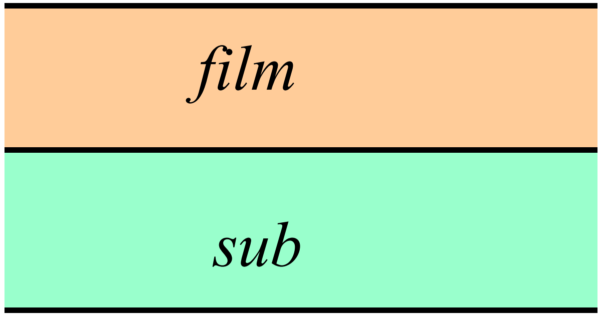
cot θ = 1/ tan θ = b / a

Slope etching examples

$\theta = 90^{o}$

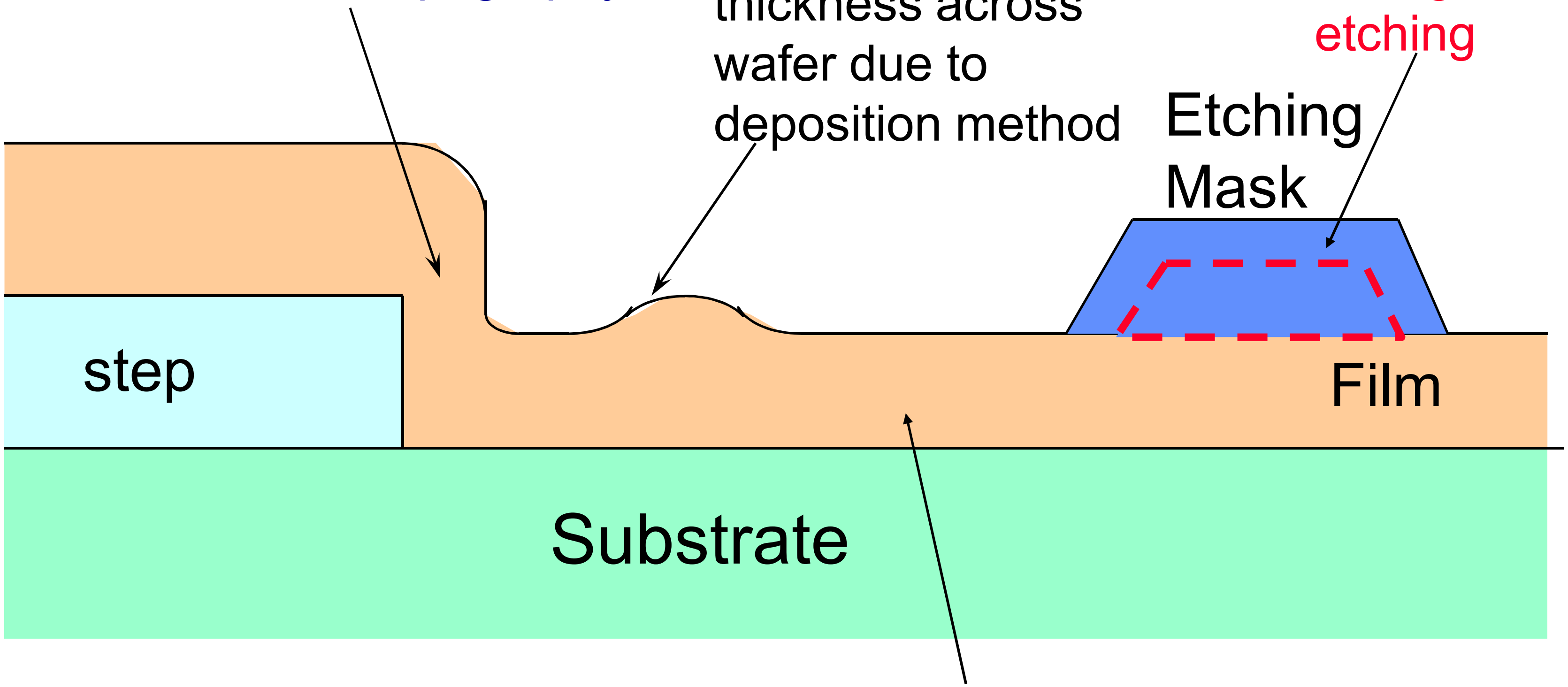


$\theta = 0^{o}$



Film etched uniformly laterally. Movement of “step” is “infinity”.

Worst-Case Design Considerations for Etching



Film thicker here due to surface topography

Variation of film thickness across wafer due to deposition method

Mask material can be eroded during film etching

Etching rate of film can vary from run-to-run

(a) Film thickness variation across wafer

$$h_{f(\max)} = h_f \cdot (1+\delta)$$

Thickness variation factor

Nominal thickness

- **The variation factor δ is dictated by the deposition method, deposition equipment, and manufacturing practice.**

- **Run-to-run variation of thickness data are recorded. Once the deposition process is under control, the maximum/minimum values will be used to define δ.**

(b) Film etching rate variation

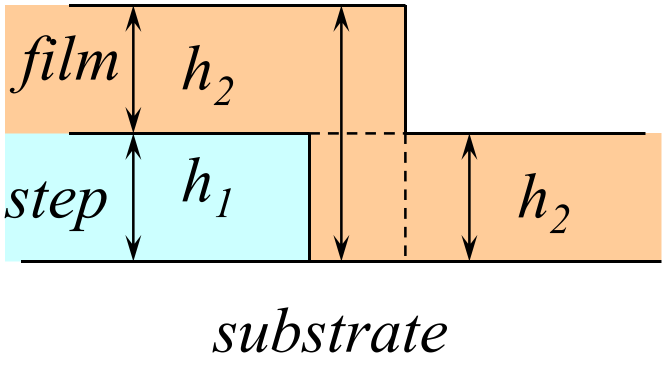
variation factor

$$\mathbf{v}_{\mathbf{f}(\mathbf{min})} = \mathbf{v}_{\mathbf{f}}\left(\mathbf{1} - \overset{\swarrow}{\phi}_{\mathbf{f}}\right)$$

Worst – case etching time required to etch the film

$$= \frac{\mathbf{h}_{\mathbf{f}(\mathbf{max})}}{\mathbf{v}_{\mathbf{f}(\mathbf{min})}} = \frac{\mathbf{h}_{\mathbf{f}}}{\mathbf{v}_{\mathbf{f}}} \cdot \frac{(\mathbf{1} + \delta)}{(\mathbf{1} - \phi_{\mathbf{f}})}$$

(c) Over-etch around step



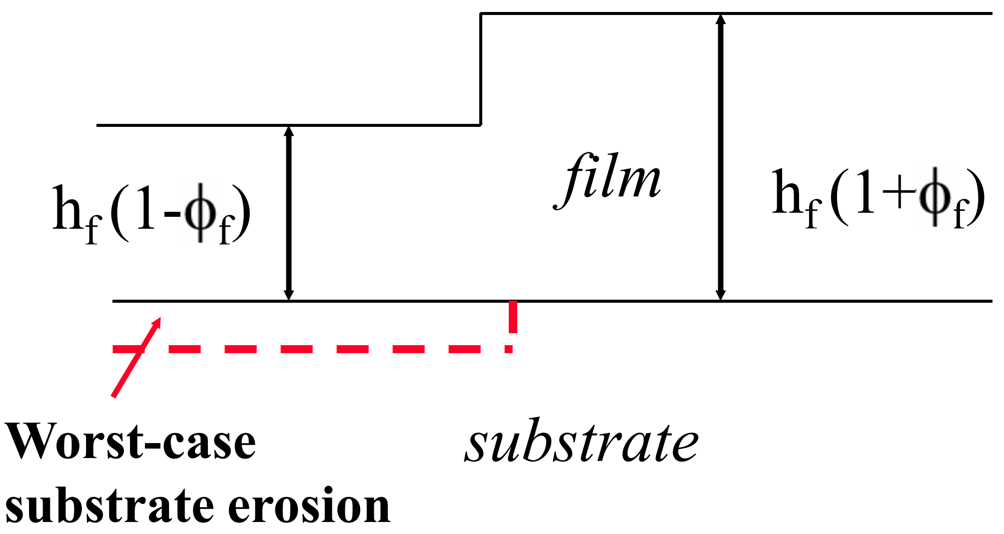
Fractional over-etch time to completely remove film $= h_1 / h_2$

Total worst-case etching time

$$\therefore \; \overset{\swarrow}{t_T} = \frac{h_f(1+\delta)}{v_f(1-\phi_f)} \cdot (1+\Delta)$$

$$\left(\Delta = \frac{h_1}{h_2}\right)$$

Example 1: Worst-case Consideration for substrate erosion



Film thickness has variation factor = δ

Film etching rate has variation factor = ϕ_f

Thinnest part of film with be completely removed in $t_1 = \frac{h_f(1-\delta)}{v_f(1+\phi_f)}$

Thickest part of film with be completely removed in $t_2 = \frac{h_f(1+\delta)}{v_f(1-\phi_f)}$

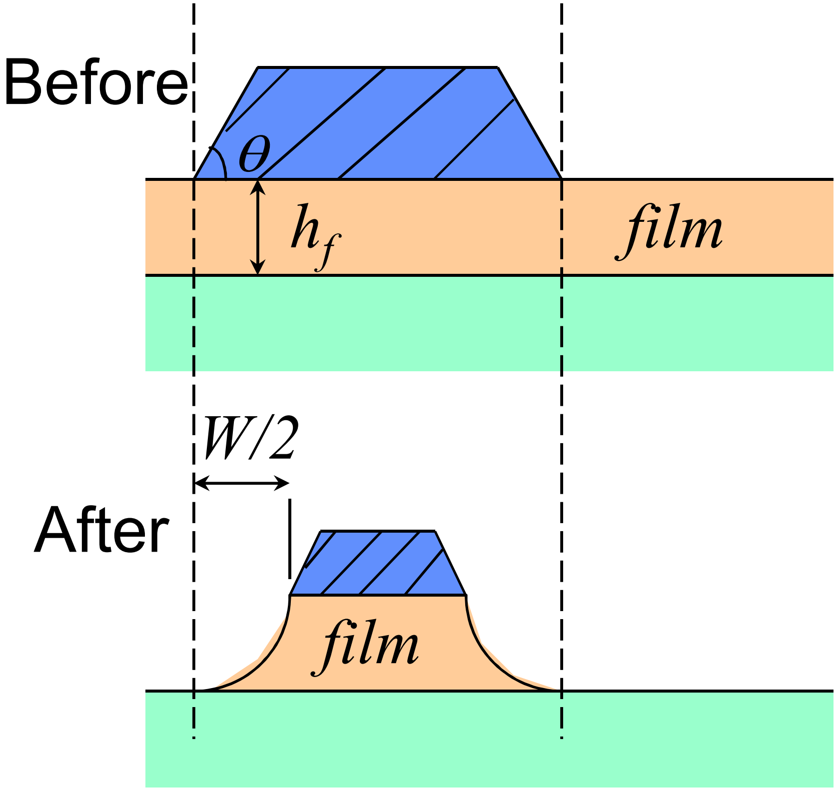
Worst-case substrate erosion = $v_{substrate} \bullet (t_2 - t_1)$

Example 2: Worst-case Design With Mask Erosion

State-of-problem:

Mask material can be eroded during film etching.

Top of film will be smaller than original mask size by an amount W/2.



Let $v_{m\perp}$, $v_{m//}$ be the vertical and lateral etching rates of the mask.

Let v_f be the vertical etching rate of the film.

(lateral film etch rate is ignored In this example for simplicity)

$$\frac{W}{2} = \left(v_{m\perp} \cot\theta + v_{m//}\right) \cdot t_T$$

$$= \left(\frac{v_{m\perp}}{v_f}\right) \cdot h_f \cdot \frac{(1+\delta)(1+\Delta)}{\left(1-\phi_f\right)} \left[\cot\theta + \frac{v_{m//}}{v_{m\perp}}\right]$$

To minimize W_

$\theta \to 90^o$

$v_f >> v_{m\perp}$

h_f *small*

Question: For a ***given*** allowable W/2 , what is the **minimum** etching selectivity between film and mask required?

$$\boxed{S_{fm(\min)} = \frac{h_f}{\left(W/2\right)} \frac{(1+\delta)(1+\Delta)}{\left(1-\phi_f\right)} \left[\cot\theta + \frac{v_{m//}}{v_{m\perp}}\right]}$$

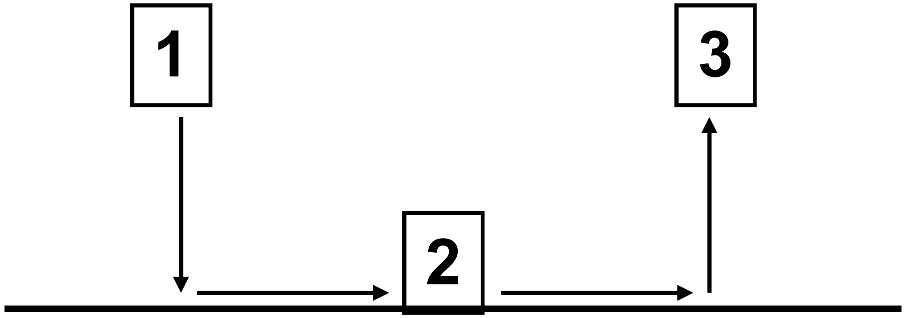
[Note] If $v_{m\perp}$ varies from run-to-run,

$$v_{m\perp(\max)} = v_{m\perp}(1+\phi_m)$$

$$\therefore S_{fm(\min)} = \frac{h_f}{W/2} \frac{(1+\delta)(1+\Delta)(1+\phi_m)}{1-\phi_f} \left[\cot\theta + \frac{v_{m//}}{v_{m\perp}}\right]$$

U_{fm} = *uniformity factor*

Wet Etching



1 Reactant transport to surface

2 Selective and controlled reaction of etchant with the film to be etched

3 Transport of by-products away from surface

Wet Etching (cont.)

- Wet etch processes are generally isotropic
- Wet etch processes can be highly selective
- Acids are commonly used for etching:

$HNO_3 \Leftrightarrow H^+ + NO_3^-$

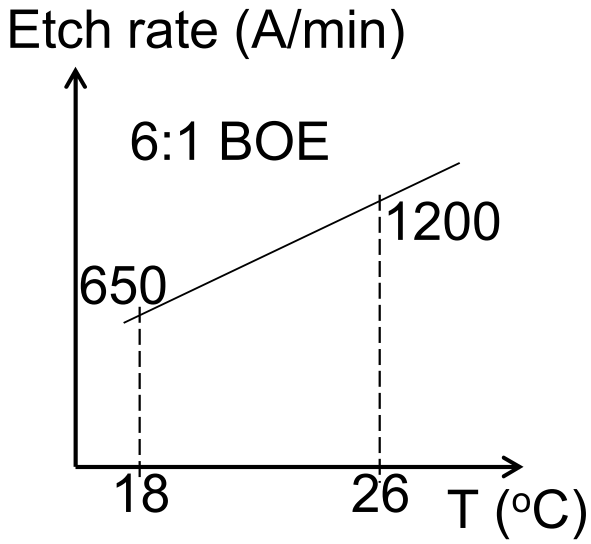
$HF \Leftrightarrow H^+ + F^-$

H^+ is a strong oxidizing agent

=> high reactivity of acids

Wet Etch Processes

(1) Silicon Dioxide



To etch SiO_2 film on Si, use

$HF + H_2O$

$$SiO_2 + 6HF \rightarrow H_2 + SiF_6 + 2H_2O$$

<u>Note</u>: HF is usually buffered with NH_4F to maintain $[H^+]$ at a constant level (for constant etch rate)

$$NH_4F \rightarrow NH_3 + HF$$

Wet Etch Processes (cont.)

(2) Silicon Nitride

To etch Si_3N_4 film on SiO_2, use

H_3PO_4

(phosphoric acid)

(180^{o}C: ~100 A/min etch rate)

Typical selectivities:

- 10:1 for nitride over oxide
- 30:1 for nitride over Si

Wet Etch Processes (cont.)

(3) Aluminum

To etch Al film on Si or SiO_2, use

$H_3PO_4 + CH_3COOH + HNO_3 + H_2O$

(phosphoric acid) (acetic acid) (nitric acid)

(~30°C)

$$6H^+ + 2Al \rightarrow 3H_2 + 2Al^{3+}$$

(Al^{3+} is water-soluble)

Wet Etch Processes (cont.)

(4) Silicon

(i) Isotropic etching

Use $HF + HNO_3 + H_2O$

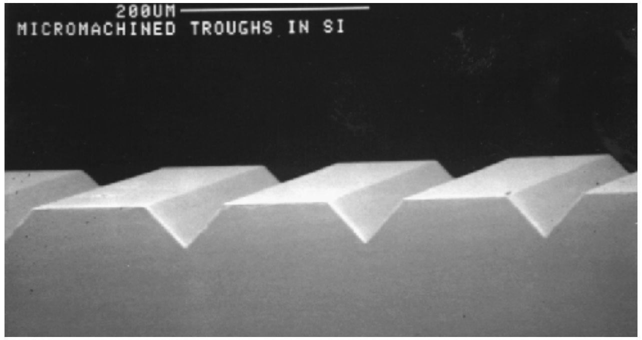
$$3Si + 4HNO_3 \rightarrow 3SiO_2 + 4NO + 2H_2O$$

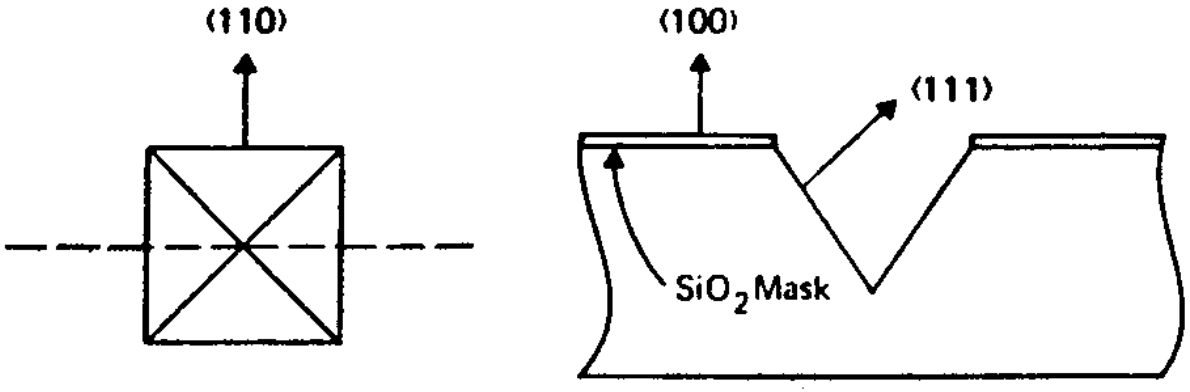
$$3SiO_2 + 18HF \rightarrow 3H_2SiF_6 + 6H_2O$$

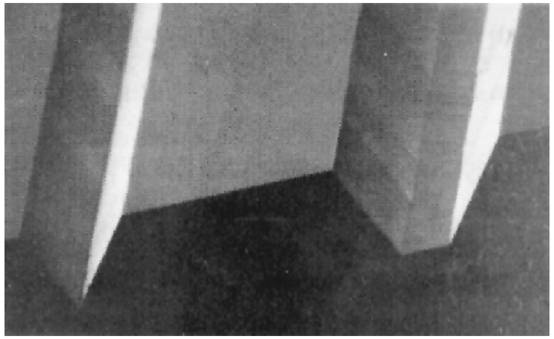
(ii) **Anisotropic etching (e.g. KOH, EDP)**

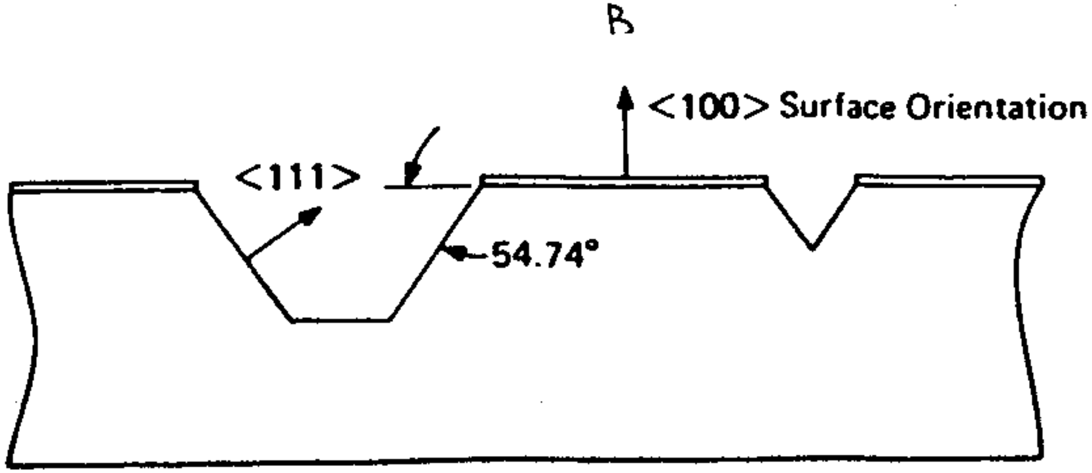
Effect of Slow {111} Etching with KOH or EDP

Mask opening aligned in <110> direction => {111} sidewalls





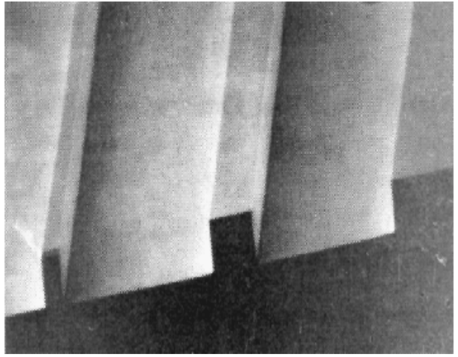


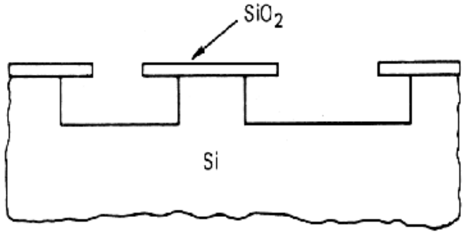


[110]-Oriented Silicon

{111} planes oriented perpendicular to the (110) surface

=> possible to etch pits with vertical sidewalls!



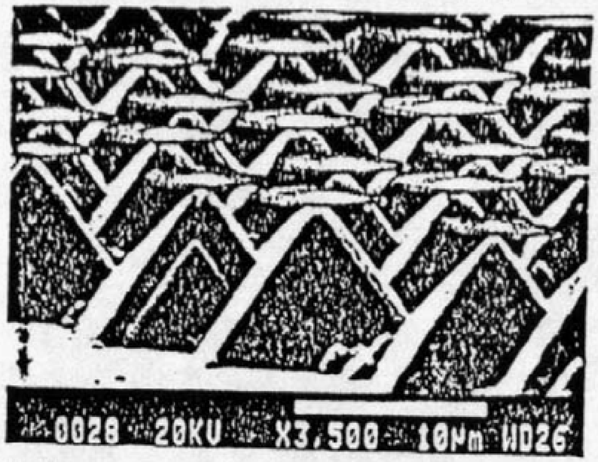


Bottom of pits are

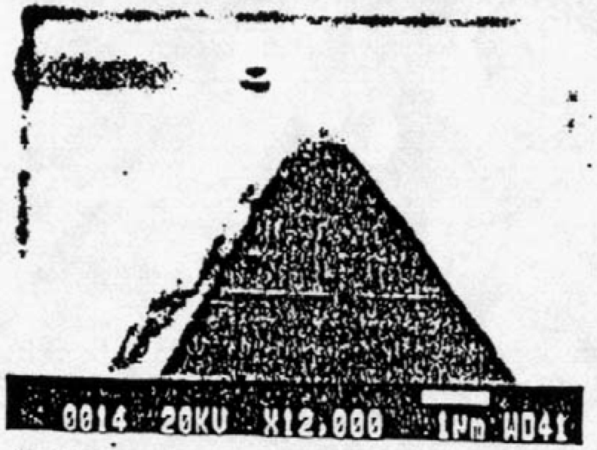
- flat ({110} plane) if KOH is used
  {100} etches slower than {110}
- V-shaped ({100} planes) if EDP is used
  {110} etches slower than {100}

(3) Field-Emission Tips

Tungsten Field Emitter

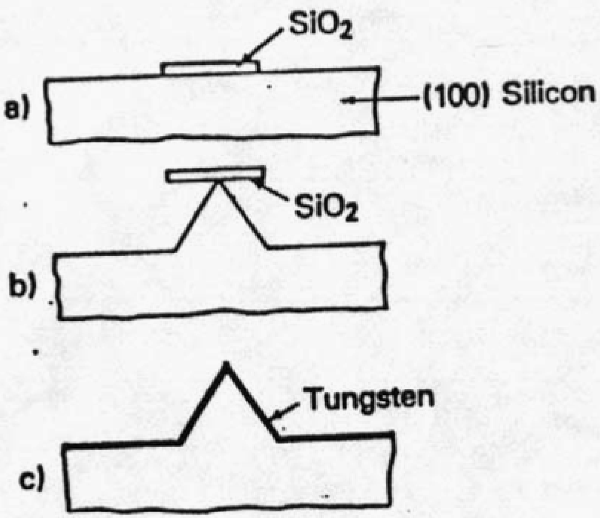


Before tungsten conversion



After tungsten conversion

Protruding From the Silicon Pyramid



EPW Etchant

- 660 ml ethylenediamine
- 140 gr pyrocatechol
- 330 ml water

110°C, 15 min.

Drawbacks of Wet Etching

- Lack of anisotropy
- Poor process control
- Excessive particulate contamination

=> Wet etching used for **noncritical** feature sizes