Section 3: Etching

Jaeger Chapter 2
Reader
Etch Process - Figures of Merit

- Etch rate
- Etch rate uniformity
- Selectivity
- Anisotropy
Bias and anisotropy

Bias \( B \equiv d_f - d_m \)

Complete Isotropic Etching
Vertical Etching = Lateral Etching Rate
\( B = 2 \times h_f \)

Complete Anisotropic Etching
Lateral Etching rate = 0
\( B = 0 \)
Degree of Anisotropy

\[ A_f \equiv 1 - \frac{r_{\text{lat}}}{r_{\text{ver}}} \]

\[ 0 \leq A_f \leq 1 \]

isotropic \quad \leftrightarrow \quad \text{anisotropic}

\( r_{\text{lat}} \): lateral etch rate
\( r_{\text{ver}} \): vertical etch rate
\( A_f \): degree of isotropy
**Etching Selectivity** $S$

$$S_{AB} = \frac{r_A(\text{vertical etching velocity of material } A)}{r_B(\text{vertical etching velocity of material } B)}$$

**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

SiO₂ / Si etched by HF solution

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

SiO₂ / Si etched by RIE (e.g. CF₄ plasma)

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

(a) Film thickness variation across wafer

\[ h_{f(\text{max})} = h_f \cdot (1+\delta) \]

Nominal thickness \( h_f \)

Thickness variation factor \( \delta \)

- The variation factor \( \delta \) is dictated by the deposition method, deposition equipment, and manufacturing practice.

(b) Film etching rate variation

\[ r_{f(\text{min})} = r_f (1-\phi_f) \]

variation factor

Worst-case etching time required to etch the film

\[ \frac{h_{f(\text{max})}}{r_{f(\text{min})}} = \frac{h_f}{r_f} \cdot \frac{(1+\delta)}{(1-\phi_f)} \]
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
- Etch rate is governed by temperature, concentration, chemicals, etc.
- Wet etch processes can be highly selective
- Acids are commonly used for etching:
  \[ \text{HNO}_3 \leftrightarrow \text{H}^+ + \text{NO}_3^- \]
  \[ \text{HF} \leftrightarrow \text{H}^+ + \text{F}^- \]
  \( \text{H}^+ \) is a strong oxidizing agent
  \( \Rightarrow \) high reactivity of acids
Wet Etch Processes

(1) Silicon Dioxide

To etch SiO₂ film on Si, use

HF + H₂O

\[
\text{SiO}_2 + 6\text{HF} \rightarrow \text{H}_2 + \text{SiF}_6 + 2\text{H}_2\text{O}
\]

Note: HF is usually buffered with NH₄F to maintain [H⁺] at a constant level (for constant etch rate). This HF buffer is called Buffered Oxide Etch (BOE)

\[
\text{NH}_4\text{F} \rightarrow \text{NH}_3 + \text{HF}
\]
Wet Etch Processes (cont.)

(2) Silicon Nitride

To etch Si$_3$N$_4$ film on SiO$_2$, use

H$_3$PO$_4$

*(phosphoric acid)*

(180°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 SiO₂, use

\[ \text{H}_3\text{PO}_4 + \text{CH}_3\text{COOH} + \text{HNO}_3 + \text{H}_2\text{O} \]

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

_(~30°C)_

\[ 6\text{H}^+ + 2\text{Al} \rightarrow 3\text{H}_2 + 2\text{Al}^{3+} \]

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

(i) Isotropic etching

Use HF + HNO₃ + H₂O

3Si + 4HNO₃ \rightarrow 3SiO₂ + 4NO + 2H₂O

3SiO₂ + 18HF \rightarrow 3H₂SiF₆ + 6H₂O

(ii) Anisotropic etching (e.g. KOH, EDP) for single crystalline Si
Drawbacks of Wet Etching

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

=> Wet etching used for noncritical feature sizes
Reactive Ion Etching (RIE)

Plasma generates (1) Ions
(2) Activated neutrals

Enhance chemical reaction
Remote Plasma Reactors

Plasma Sources

(1) Transformer Coupled Plasma (TCP)

(2) Electron Cyclotron Resonance (ECR)

Pressure

$pump_{1 \text{mTorr}} \rightarrow 10 \text{mTorr}$

bias~ $\leq 1 \text{kV}$

e.g. quartz coils

wafers

-($bias$)
RIE Etching Sequence

1. Diffusion of reactant
2. Absorption
3. Chemical reaction
4. Desorption
5. Diffusion of by product

Gas flow

Substrate
Volatility of Etching Product

* Higher vapor pressure $\Rightarrow$ higher volatility

\[ e.g. \quad Si + 4F^* \rightarrow SiF_4 \uparrow \quad (\text{high vapor pressure}) \]

\[ e.g. \quad Cu + Cl \rightarrow CuCl (\text{low vapor pressure}) \]

Example

Difficult to RIE Al-Cu alloy with high Cu content
Examples

For etching Si

Use $CF_4$ gas

$CF_4 + e \Leftrightarrow CF_3^+ + F^* + 2e$

$Si + 4F^* \rightarrow SiF_4 \uparrow$

$F^*$ are Fluorine radicals (highly reactive, but neutral)

Aluminum

$CCl_4 + e \Leftrightarrow CCl_3^+ + Cl^* + 2e$

$Al + 3Cl^* \rightarrow AlCl_3 \uparrow$

Photoresist

$C_xH_yO_z + O_2 \rightarrow CO_x$ $HO_x$
How to Control Anisotropy?

1) ionic bombardment to damage expose surface.
2) sidewall coating by inhibitor prevents sidewall etching.
How to Control Selectivity?

E.g. $SiO_2$ etching in $CF_4 + H_2$ plasma

$S = \frac{Rate \ SiO_2}{Rate \ Si}$

Reason:

$F^\ast + H \rightarrow HF \ \therefore F^\ast \ content \ \downarrow$

$\therefore SiF_4 \downarrow$
Example: Si etching in CF4+O2 mixture

Reason:

(1) \( O + CF_x \rightarrow COF_x + F^* \)

\( F^* \) increases Si etching rate

(2) \( Si + O_2 \rightarrow SiO_2 \cdot \cdot \cdot rate \downarrow \)
Example: RIE of Aluminum Lines

* It is a three-step sequence:
  1) Remove native oxide with BCl$_3$
  2) Etch Al with Cl-based plasma
  3) Protect fresh Al surface with thin oxidation

1) Remove native oxide with BCl$_3$
2) Cl$_2$-based RIE
3) Form oxide again (gently)