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
$B = 0$

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**Degree of Anisotropy**

$r_{\text{lat}}$: lateral etch rate
$r_{\text{ver}}$: vertical etch rate
$A_f$: degree of isotropy

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

$$0 \leq A_f \leq 1$$

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**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.

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**Selectivity Example**

<table>
<thead>
<tr>
<th></th>
<th>SiO₂</th>
<th>Si</th>
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SiO₂/Si etched by HF solution

\[ S_{\text{SiO}_2, \text{Si}} \text{ Selectivity is very large ( ~ infinity)} \]

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

\[ S_{\text{SiO}_2, \text{Si}} \text{ Selectivity is finite ( ~ 10 )} \]
**Uniformity**

(a) Film thickness variation across wafer

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

Nominal thickness

Thickness variation factor

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

(b) Film etching rate variation

\[ r_{f_{\text{min}}} = r_f \left(1 - \phi_f\right) \]

variation factor

*Worst-case etching time required to etch the film*

\[ \frac{h_{f_{\text{max}}}}{r_{f_{\text{min}}}} = \frac{h_f}{r_f} \cdot \frac{1 + \delta}{1 - \phi_f} \]

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**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:
  \[
  \begin{align*}
  \text{HNO}_3 & \rightleftharpoons \text{H}^+ + \text{NO}_3^- \\
  \text{HF} & \rightleftharpoons \text{H}^+ + \text{F}^-
  \end{align*}
  \]

  \(\text{H}^+\) is a strong oxidizing agent
  
  \(\Rightarrow\) high reactivity of acids

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**Wet Etch Processes**

1. Silicon Dioxide

To etch SiO\(_2\) film on Si, use

\[
\text{HF} + \text{H}_2\text{O}
\]

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

Note: HF is usually buffered with \(\text{NH}_4\text{F}\) to maintain \([\text{H}^+]\) at a constant level (for constant etch rate). This HF buffer is called Buffered Oxide Etch (BOE)

\[
\text{NH}_4\text{F} \rightarrow \text{NH}_3 + \text{HF}
\]
(2) Silicon Nitride

To etch Si₃N₄ film on SiO₂, use

H₃PO₄

*(phosphoric acid)*

*(180°C: ~100 A/min etch rate)*

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

(3) Aluminum

To etch Al film on Si or SiO₂, use

H₃PO₄ + CH₃COOH + HNO₃ + H₂O

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

*(~30°C)*

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

*(Al³⁺ is water-soluble)*
Wet Etch Processes (cont.)

(4) Silicon

(i) Isotropic etching

Use HF + HNO₃ + H₂O

\[ 3\text{Si} + 4\text{HNO}_3 \rightarrow 3\text{SiO}_2 + 4\text{NO} + 2\text{H}_2\text{O} \]

\[ 3\text{SiO}_2 + 18\text{HF} \rightarrow 3\text{H}_2\text{SiF}_6 + 6\text{H}_2\text{O} \]

(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)

- e.g. quartz coils
- wafers
- Pressure $pump 1\text{mTorr} \rightarrow 10\text{mTorr}$
- bias $\sim \leq 1\text{kV}$
**RIE Etching Sequence**

1. Diffusion of reactant
2. Diffusion of by product desorption
3. Chemical reaction
4. Gaseous by products
5. Gas flow

**Substrate**

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**Volutility of Etching Product**

* Higher vapor pressure $\Rightarrow$ higher volatility

- $e.g.$ $Si + 4F^* \rightarrow SiF_4 \uparrow$ (high vapor pressure)
- $e.g.$ $Cu + Cl \rightarrow CuCl (low vapor pressure)$

**Example**

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

For etching Si

\[ CF_4 + e \leftrightarrow CF_3^+ + F^* + 2e \]

\[ Si + 4F^* \rightarrow SiF_4 \uparrow \]

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

**Aluminum**

\[ CCl_4 + e \leftrightarrow CCl_3^+ + Cl^- + 2e \]

\[ Al + 3Cl^- \rightarrow AlCl_3 \uparrow \]

**Photoresist**

\[ C_xH_yO_z + O_2 \rightarrow CO_x \]

\[ HO_x \]

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**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. \( \text{SiO}_2 \) etching in \( \text{CF}_4 + \text{H}_2 \) plasma

\[
S = \frac{\text{Rate SiO}_2}{\text{Rate Si}}
\]

Reason:

\[
F^* + H \rightarrow HF \quad \therefore \quad \text{F}^* \text{ content} \downarrow
\]

\[
\therefore \quad \text{SiF}_4 \downarrow
\]

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**Example: Si etching in CF4+O2 mixture**

Reason:

1. \( O + \text{CF}_x \rightarrow \text{COF}_x + F^* \)
   
   \( F^* \) increases \( \text{Si etching rate} \)

2. \( \text{Si} + \text{O}_2 \rightarrow \text{SiO}_2 \quad \therefore \text{rate} \downarrow \)

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Example: RIE of Aluminum Lines

* It is a three-step sequence:
1) Remove native oxide with BCl₃
2) Etch Al with Cl-based plasma
3) Protect fresh Al surface with thin oxidation

1. Remove native oxide with BCl₃
2. Cl₂-based RIE
3. Form oxide again (gently)