Etch Process - Figures of Merit

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

Bias:
\[ B \equiv d_f - d_m \]

(1) For complete isotropic etching, same lateral and vertical etching rate:
\[ B = 2 \times h_f \]

(2) For complete isotropic etching:
Lateral etching rate = 0
\[ B = 0 \]

Degree of Anisotropy

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

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

\[ 0 \leq A_f \leq 1 \]

isotropic    anisotropic
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

SiO$_2$

Si

SiO$_2$/Si etched by HF solution

$S_{\text{SiO}_2, \text{Si}}$ Selectivity is very large ($\sim$ infinity)

SiO$_2$/Si etched by RIE (e.g. CF$_4$ plasma)

$S_{\text{SiO}_2, \text{Si}}$ Selectivity is finite ($\sim 10$)
Uniformity

(a) Film thickness variation across wafer

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

Nominal thickness

Thickens variation factor

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

(b) Film etching rate variation

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

Worst-case etching time required to etch the film

\[ \frac{h_{f_{\text{max}}}}{r_{f_{\text{min}}}} = \frac{h_f}{r_f} \left(1 + \delta \right) \]

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

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:
  \[ \text{HNO}_3 \leftrightarrow H^+ + \text{NO}_3^- \]
  \[ \text{HF} \leftrightarrow H^+ + F^- \]
  H\(^+\) is a strong oxidizing agent
  \(\Rightarrow\) high reactivity of acids

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Wet Etch Process for SiO\(_2\)

To etch SiO\(_2\) film on Si, use HF + H\(_2\)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 NH\(_4\)F 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 Process for Si$_3$N$_4$

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

Wet Etch Process for Aluminum

- To etch Al film on Si or SiO$_2$, use
  - H$_3$PO$_4$ + CH$_3$COOH + HNO$_3$ + H$_2$O @ 30°C
    (phosphoric acid), (acetic acid), (nitric acid)

- 6H$^+$ + 2Al $\rightarrow$ 3H$_2$ + 2Al$^{3+}$
  - Al$^{3+}$ is water-soluble
Wet Etch Process for Silicon

- Isotropic etching
  - Use HF + HNO₃ + H₂O
  - 3 Si + 4 HNO₃ → 3 SiO₂ + 4 NO + 2 H₂O
  - SiO₂ + 6 HF → H₂SiF₆ + 2H₂O
- Anisotropic etching
  - KOH for single crystalline Si

Drawbacks of Wet Etching

- Lack of anisotropy
- Poor process control
- Poor uniformity
- 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 1mTorr to 10mTorr bias < 1kV
RIE Etching Sequence

1. diffusion of reactant
2. adsorption
3. chemical reaction
4. gas flow
5. diffusion of by product desorption

Substrate

Volutility of Etching Product

* Higher vapor pressure $\rightarrow$ higher volatility

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

Example

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

For etching Si  
\[CF_4 + e \leftrightarrow CF_3^+ + F^* + 2e\]
\[Si + 4F^* \rightarrow SiF_4\]

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

Aluminum
\[CCl_4 + e \leftrightarrow CCl_3^+ + Cl^- + 2e\]
\[Al + 3Cl^- \rightarrow AlCl_3\]

Photoresist
\[C_{x}H_{y}O_z + O_2 \rightarrow CO_x + HO_z\]

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

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

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

$\therefore SiF_4 \downarrow$

Example:  

Si etching in CF4+O2 mixture

Reason:

1) $O + CF_x \rightarrow COF_x + F^*$  
   $F^*$ increases Si etching rate

2) $Si + O_2 \rightarrow SiO_2$
   $SiF_4 + O_2 \rightarrow SiO_2 + 4F^* \downarrow$  

Poly-Si

Oxide
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

Cl$_2$-based RIE

1) BCl$_3$

Form oxide again (gently)

native Al$_2$O$_3$