Dry Etching and Reactive Ion Etching (RIE)

MEMS 5611
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Contents refer slides from UC Berkeley, Georgia Tech., KU, etc. (see reference)
Contents

• Etching and its terminologies
• Wet etching
• Dry etching
  – Plasma systems
  – Sputtering (Ion milling)
  – Reactive ion etching
• Lab introduction
Etching or Lift-off?

- Two principal means of removing material.
- Etching: top to bottom methodology.
  - Chemical reaction (Most metals, Si products, organics)
- Lift-off: bottom up methodology.
  - Gold, Platinum, etc.
**Classic Procedures**

**Etching**
- Si wafer
- Deposition
- Al
- Spin-coating
- Photoresist
- Photolithography
- Etching

**Lift-off**
- Si wafer
- Spin-coating
- Photoresist
- Photolithography
- Deposition
- Al
- Lift-off
Etching Techniques

• Chemical etching in liquid (wet etching) or in gaseous form (dry etching) is used to remove any barrier materials protected by hardened PR (or mask).

• Depending on the sources used for etching

  - **Wet**
    - Immersion
    - Spray
  - **Dry**
    - Plasma etch
      - 13.56 MHz
    - RIE (reactive ion etch)
      - 2.54 GHz
    - Sputter Etch
Terminologies in Etching Process

- Etch Rate
- Selectivity
- Anisotropy
- Uniformity
Etch Rate & Selectivity

• Etch Rate: How fast the material is removed in the etch process

\[
\text{Etch Rate} = \frac{\text{Thickness before etch} - \text{Thickness after etch}}{\text{Etch time}}
\]

• Selectivity: Ratio of the etch rates between the different materials (PR and the target material, hard mask material and the target material)

\[
\text{Selectivity} = \frac{\text{Etch Rate of Material 1}}{\text{Etch Rate of Material 2}}
\]
Anisotropy & Uniformity

• Anisotropy: degree of anisotropy, $A_f$

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

$0 \leq A_f \leq 1$

• Uniformity: Measuring the thickness at certain points before and after the etch process.

$$Uniformity = \frac{\text{Maximum etch rate} - \text{Minimum etch rate}}{\text{Maximum etch rate} + \text{Minimum etch rate}}$$
Wet Etching

• Placing wafer in solution that attacks the film, not the mask.
Problem of Wet Etching

Isotropic Phenomenon
(Wet Etching)

Anisotropic Phenomenon
(Dry Etching)
Dry Etching

• Gaseous form can obtain highly anisotropic etching profiles, mainly avoid the undercutting problem of wet etching.

• Common used dry etching techniques:
  – Plasma systems
  – Ion milling
  – Reactive ion etching
Plasma Systems

- Use RF excitation to ionize a variety of source gases in vacuum system.
- The plasma contains fluorescent or chlorine ions to etch Si, SiO2, SiN4, organics and metals.
- RF power operates at 13.56MHz, why?
  - FCC assigned frequency for industrial and scientific purposes
What is Plasma Processing?

• Plasma is one of the four fundamental states of matter. The matter in plasma contains ions, free radicals and byproducts.

• The free radicals and byproducts decrease the activation energy in a chemical reaction, resulting in material removal.
Sputtering (Ion Milling)

- Use energetic noble gas ions such as Argon (Ar\(^+\)) to bombard the wafer surface.
- Etching occurs by *physically knocking atoms off* the surface.
- Highly anisotropic etching.
- Poor selectivity.
Reactive Ion Etching (RIE)

- Combines the plasma and sputter (ion milling) etching processes.
- Plasma systems are used to ionize reactive gases, the ions are accelerated to bombard the surface.
- Etching occurs through:
  - 1. Chemical reaction.
  - 2. Physical momentum transfer from the etching species.
Reactive Ion Etching (Continue)

Plasma state generates:
(1) Ions.
(2) Activated neutrals.

RIE chamber: strong electromagnetic field makes gas transfer into plasma state
Two Power Sources: ICP & RF

- Inductively coupled plasma (ICP): A 2.54 GHz plasma source producing electromagnetic induction.
  - Generate high density of ions.
- RF: A 13.56 MHz RF powered magnetic field to create directional electric fields to achieve more anisotropic etch profiles
Features and plasma sources for dry etching

**Physically Sputtering** (and Ion Beam Milling)
- Physical momentum transfer
- Anisotropic etch profile
- Low etch rate
- Poor selectivity
- Radiation damage possible

**RIE (Reactive ion etch)**
- Physical (ion) and chemical
- Anisotropic, controllable etch profile
- More selective than sputtering

**Plasma Etching**
- Chemical, thus faster by 10-1000X
- Isotropic etch profile
- High etch rate
- Good selectivity
- Less prone to radiation damage

**Table 2.3 Etching Pressure Ranges**

<table>
<thead>
<tr>
<th>Etching Mode</th>
<th>Pressure (Torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Milling</td>
<td>$10^{-4}$–$10^{-3}$</td>
</tr>
<tr>
<td>Reactive Ion Etching/Ion Milling</td>
<td>$10^{-3}$–$10^{-1}$</td>
</tr>
<tr>
<td>Plasma Etching</td>
<td>$10^{-1}$–$5$</td>
</tr>
</tbody>
</table>

**Table 2.4 Plasma-Etching Sources**

<table>
<thead>
<tr>
<th>Material</th>
<th>Source Gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic materials</td>
<td>$O_2$, $SF_6$, $CF_4$</td>
</tr>
<tr>
<td>Polysilicon</td>
<td>$CCl_4$, $CF_4$, $NF_3$, $SF_6$</td>
</tr>
<tr>
<td>Silicon Dioxide</td>
<td>$CF_4$, $C_2F_6$, $C_3F_8$, $CHF_3$</td>
</tr>
<tr>
<td>Silicon Nitride</td>
<td>$CF_4$, $C_2F_6$, $CHF_3$, $SF_6$</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$CCl_4$, $Cl_2$, $BCl_3$</td>
</tr>
<tr>
<td>Titanium</td>
<td>$C_2ClF_4$, $CF_4$</td>
</tr>
<tr>
<td>Tungsten</td>
<td>$Cl_2$</td>
</tr>
</tbody>
</table>
Dry Etching Processes

**Dielectric Etch (SiO$_2$, SiN$_4$)**
- requires F-based plasma chemistry.
- \( \text{plasma} \)
  - \( \text{CF}_4 \rightarrow \text{CF}_3 + \text{F} \) (radicals)
  - \( \text{plasma} \)
  - \( \text{F} + \text{SiO}_2 \rightarrow \text{SiF}_4 + \text{O} \)
  - \( \text{plasma} \)
  - \( \text{F} + \text{Si}_3\text{N}_4 \rightarrow \text{SiF}_4 + \text{N} \)

**Polysilicon Etch**
- \( \text{plasma} \)
  - \( \text{Cl}_2 \rightarrow \text{Cl} + \text{Cl} \) (radicals)
  - \( \text{plasma} \)
  - \( \text{Cl} + \text{Poly Si} \rightarrow \text{SiCl}_4 \)

**Metal Etch (Al, TiN, Ti)**
- \( \text{plasma} \)
  - \( \text{Cl}_2 \rightarrow \text{Cl} + \text{Cl} \)
  - \( \text{plasma} \)
  - \( \text{Cl} + \text{Al} \rightarrow \text{AlCl}_3 \)
  - Reaction of Al with F $\rightarrow$ nonvolatile AlF$_3$
  - \( \text{plasma} \)
  - \( \text{Cl} + \text{TiN} \rightarrow \text{TiCl}_4 + \text{N} \)
  - \( \text{plasma} \)
  - \( \text{Cl} + \text{Ti} \rightarrow \text{TiCl}_4 \)

**Single-Crystal Silicon Etch**
- \( \text{Cl}_-, \text{Br}-\text{based chemistries have high etch rate and high selectivity of Si over SiO}_2. \)
  - \( \text{plasma} \)
  - \( \text{HBr} \rightarrow \text{H} + \text{Br} \)
  - \( \text{plasma} \)
  - \( \text{Br} + \text{Si} \rightarrow \text{SiBr}_3 \)
# Comparison of Wet & Dry Etching

<table>
<thead>
<tr>
<th>Feature size</th>
<th>Wet Etch</th>
<th>Dry Etch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 3 μm</td>
<td>Small</td>
</tr>
<tr>
<td>(&gt; 10nm)</td>
<td></td>
<td>(&gt; 10nm)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Etch Profile</th>
<th>Wet Etch</th>
<th>Dry Etch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Isotropic</td>
<td>Anisotropic</td>
</tr>
<tr>
<td></td>
<td><img src="image1" alt="PR Film Substrate" /></td>
<td><img src="image2" alt="PR Film Substrate" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Etchant</th>
<th>Chemical</th>
<th>Reactive gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etch rate</td>
<td>High</td>
<td>Acceptable, controllable</td>
</tr>
<tr>
<td>Selectivty</td>
<td>High</td>
<td>Acceptable, controllable</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Throughput</td>
<td>High (batch)</td>
<td>Acceptable, controllable</td>
</tr>
</tbody>
</table>
LAB: Oxford Plasmalab 100

- Temperature: -150 °C to +400 °C
- Gases: Cl₂, SiCl₄, BCl₃, SF₆, Ar, O₂, H₂ and N₂
- ICP and RF Power: Up to 300W
## LAB: Al Etching Recipe

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (mTorr)</td>
<td>200</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>RIE (W)</td>
<td>0</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>ICP (W)</td>
<td>0</td>
<td>300</td>
<td>150</td>
</tr>
<tr>
<td>Time (sec)</td>
<td>30</td>
<td>15</td>
<td>240</td>
</tr>
<tr>
<td>Gas 1 (scmm)</td>
<td>Ar: 50</td>
<td>BCL3: 30</td>
<td>BCL3: 30</td>
</tr>
<tr>
<td>Gas 2 (scmm)</td>
<td></td>
<td>CL2: 15</td>
<td>CL2: 8</td>
</tr>
<tr>
<td>Temperature (Celsius)</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Comment</td>
<td>Purge the chamber</td>
<td>Al2O3 etching</td>
<td>Al etching</td>
</tr>
</tbody>
</table>

**Diagram:**
- **Silicon Wafer**
  - **Native SiO2**
  - **Al**
  - **Al2O3**
  - **~500nm**
  - **~200nm**
  - **several nm**

**Steps:**
- **Step 2**: S1805
- **Step 3**: Native SiO2
- **Step 4**: several nm

**Comments:**
- Purge the chamber
- Al2O3 etching
- Al etching
- Purge the chamber

**Notes:**
- 200mTorr for initial pressure
- 10min RIE step
- 450mW ICP power
- 850mW RIE power
- 15s RIE time
- 0.015 sccm Cl2
- 50s ICP purge time
- Air flush after ICP
- Chamber evacuation
- Unloaded wafer for Al2O3 etch
S1805 Residual Removal

• Some S1805 left on the sample surface...
• Removal
  – Lift-off: Use Remover-PG to soak the substrate.
  – Further Etching: O2 to remove organics.
    (potentially further oxidizes the Al)
Wire-grid Polarizer (100nm)

Al

SiO2

Parallel

Perpendicular
Review

• Etching and its terminologies
• Wet & Dry etching
  – Plasma systems
  – Ion milling
  – Reactive ion etching
• Lab
Reference

Questions??