Dry Etching
Semiconductor Technology

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1 Preliminaries
   - Etching
   - Some Definitions
   - Requirements for Etching
   - Wet Etching vs Dry Etching

2 Dry Etching
   - Types
     - Non-plasma based etching
     - Plasma based etching

3 Advanced Topics
   - Chemistry of Etching
   - Misc Effects
   - Latest Technologies
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Etching
What & Why?

- Removal of deposited thin film or the substrate itself according to the mask.
  - \( Si \) (Doped, Undoped): Gates
  - \( SiO_2 \): Spacers, Dielectric
  - \( Ti / TiN, Al, Cu \): Metal interconnects
  - \( W, WSi_x, TiW \): Contact filling
  - Photo-resist (PR): Strip, Trim
Etching
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  - $Si$ (Doped, Undoped): Gates
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Figure: Etched wells
Fabrication Process

Various steps

- Deposition
- Doping
- Photolithography (defining the pattern)
- Etching
Wet etching, where the material is dissolved when immersed in a chemical solution
- Relatively more isotropic
- Can be anisotropic for crystalline substrates

Dry etching, where the material is sputtered or dissolved using reactive ions or a vapor phase etchant
- Better control over isotropy
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Etch Rate

- Rate of Removal of material
- Lateral Etch Ratio ($R_l$)
  - Horizontal Etch Rate ($R_h$)
  - Vertical Etch Rate ($R_v$)

$$R_l = \frac{\text{Horizontal Etch Rate} (R_h)}{\text{Vertical Etch Rate} (R_v)}$$
Isotropy
Isotropic vs Anisotropic Etching

- Isotropic Etching: Etching rate is the same in both horizontal and vertical direction
- Anisotropic Etching: Etching rate is different in horizontal and vertical direction, generally horizontal rate is zero
- Degree of Anisotropy

\[ A = 1 - R_I = 1 - \frac{R_h}{R_v} \]
Under Cut and Over Etching

(\( R_l = 1 \), pattern dimension is poorly defined)

"Under Cut"

Over-Etch
- results in more vertical profile but larger bias

(\( R_l = 0.5 \), pattern dimension is better defined)

Worse in thick film
- Poor CD control in thick film using wet etch
Selectivity

\[
Selectivity, \quad S = \frac{Etch \ Rate \ of \ a}{Etch \ Rate \ of \ b}
\]

- Depending upon application:
  - Selectivity to different materials is required: Different masks and different material to be etched
  - Different Selectivity constant is required (1 < S < 1000)
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Characteristics of a useful Etching Process

- Economical
  - Suitably rapid etch rate
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- Selectivity
  - The etch must selectively remove material (e.g. attack of the mask material and the underlying layers must be minimal)
Characteristics of a useful Etching Process

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- **Anisotropy**
  - To have sharp and correctly defined structures (e.g., square shaped trenches, gates) and to keep CD (critical Dimension) control.
Characteristics of a useful Etching Process

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- **Process control**
  - Uniformity
  - Reproducibility
  - Critical Dimension Control
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## Differences between Dry and Wet Etching

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<thead>
<tr>
<th></th>
<th>Wet</th>
<th>Dry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Method</strong></td>
<td>Chemical Solutions</td>
<td>Ion Bombardment or Chemical Reactive</td>
</tr>
<tr>
<td><strong>Environment and Equipment</strong></td>
<td>Atmosphere, Bath</td>
<td>Vacuum Chamber</td>
</tr>
<tr>
<td><strong>Directionality</strong></td>
<td>Isotropic (Except for etching crystalline material)</td>
<td>Anisotropic</td>
</tr>
</tbody>
</table>
Comparison between Dry and Wet Etching

Advantages of Wet Etching
- Low cost, easy to implement
- High Etching rate
- Good selectivity for most materials
Comparison between Dry and Wet Etching

- Advantages of Wet Etching
  - Low cost, easy to implement
  - High Etching rate
  - Good selectivity for most materials

- Advantages of Dry Etching
  - Isotropic or anisotropic etch profiles
  - High resolution and cleanliness
  - Eliminates handling of dangerous acids and solvents, though some gases are quite toxic
  - Better process control
  - Ease of automation
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Types of Dry Etching

- Non-plasma based
  - Uses spontaneous reaction of appropriate reactive gas mixture

- Plasma based
  - Uses Radio Frequency (RF) power to drive the etching
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Non-plasma based etching

- Isotopic etching
- Typically fluorine-containing gases (fluorides or interhalogens) that readily etch Si
- Highly selective to masking layers
- No need for plasma processing equipment
- Highly controllable via temperature and partial pressure of reactants
Example of Non-plasma based 
Xenon Difluoride (XeF₂) Etching

- Isotropic etching of Si
- Highly selective for Al, SiO₂, Si₃N₄, PR

\[ 2\text{XeF}_2 + \text{Si} \rightarrow 2\text{Xe} + \text{SiF}_4 \]

- Typical etch rates of 1 to 3 \( \mu m/min \)
- Exothermic reaction
- XeF₂ reacts with water (or vapor) to form HF, which is highly reactive with SiO₂
Example of Non-plasma based Interhalogen ($BrF_3 \& ClF_3$) Etching

- Interhalogens $BrF_3$ and $ClF_3$ used for etching Si
- Nearly isotropic profile
- Gases react with $Si$ to form $SiF_4$
- Masks: $SiO_2$, $Si_3N_4$, $PR$, $Al$, $Cu$, $Au$ and $Ni$
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Problems with non-plasma based etching: 
Isotropic
- Unable to achieve pattern size smaller than film thickness

Main purpose of plasma is to achieve anisotropic etching

Types of plasma based etching
- Physical Sputtering
  - Physical Bombardment
- Plasma Etching
  - Plasma assisted chemical reaction
- Reactive Ion Etching (RIE)
  - Chemical Reaction + Ion Bombardment
**Etch Mechanism**

- Generation of etching species
- Diffusion to surfaces
- Adsorption
- Reaction
- Desorption (gaseous by-products!)
- Diffusion to bulk gases
Plasma

- Plasma
  - Partially ionized gas consisting of equal +ve (ions) and -ve charge (electrons) and some neutral molecules
  - An ion-electron pair is continuously created by ionization and destroyed by recombination

- Plasma discharge is characterized by
  - A central glow or bulk region (semi-neutral region)
  - Dark/Sheath regions near electrodes (nearly all potential drop)
Plasma Formation

- Chamber is evacuated
- Chamber is filled with gas(es)
- RF energy is applied to a pair of electrodes
- When electric field of sufficient magnitude is applied, the gas breaks down and is ionized
Physical Sputtering

- Based on physical bombardment with ions or atoms
- Plasma is used to energize a chemically inert projectile so that it moves at high velocity when it strikes the substrate
- Momentum is transferred during the collision
- Substrate atoms are dislodged if projectile energy exceeds bonding energy
- Highly anisotropic
- Etch rates for most materials are comparable (i.e. low selectivity)
- Argon (Ar/Ar\(^+\)) is the most commonly used ion source
- May result in redeposition
Plasma Etching
Or chemical etching

- Purely chemical etching
- Plasma is used to produce chemically reactive species (atoms, radicals, and ions) from inert molecular gas
- A typical reaction:

\[
\begin{align*}
CF_4 & \rightarrow F, CF, CF_2, CF_3, etc. \\
Si(S) + 4F & \rightarrow SiF_4(g)
\end{align*}
\]

- Etch product should be volatile species
- Similarly \(BCl_3\) used for Al, since \(AlCl_3\) is gaseous
- Highly selective
- Isotropic in nature
Reactive Ion Etching (RIE)
Best of both worlds

- Chemical Etching is accompanied by ionic bombardment
- Reactive ions (e.g. $CF_3^+$, $CCl_3^+$) produced in discharge are accelerated onto the wafer surface at high energies
- Suitably selective
- High anisotropy
- Higher etching rate than would be predicted from simply adding
  - Bombardment opens areas for reactions
## Comparison of types of Dry Etching

<table>
<thead>
<tr>
<th>Types</th>
<th>Geometry</th>
<th>Selectivity</th>
<th>Excitation Energy</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma</td>
<td>Isotropic</td>
<td>High</td>
<td>10s-100s W</td>
<td>Medium (&gt;100 mtorr)</td>
</tr>
<tr>
<td>Reactive Ion</td>
<td>Directional</td>
<td>Fair</td>
<td>100s W</td>
<td>Low (10-100 mtorr)</td>
</tr>
<tr>
<td>Sputtering</td>
<td>Directional</td>
<td>Low</td>
<td>100s-1000s W</td>
<td>Low (10 mtorr)</td>
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# Dry Etch Chemistry

Examples of Chemicals used

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<thead>
<tr>
<th>Materials</th>
<th>Etch Gases</th>
<th>Etch Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Si$, $SiO_2$, $Si_3N_4$</td>
<td>$CF_4$, $SF_6$, $NF_3$</td>
<td>$SiF_4$</td>
</tr>
<tr>
<td>$Si$</td>
<td>$Cl_2$, $CCl_2F_2$</td>
<td>$SiCl_2$, $SiCl_4$</td>
</tr>
<tr>
<td>$Al$</td>
<td>$BCl_3$, $CCl_4$, $SiCl_4$, $Cl_2$</td>
<td>$AlCl_3$, $Al_2Cl_6$</td>
</tr>
<tr>
<td>Organics</td>
<td>$O_2$, $O_2 + CF_4$</td>
<td>$CO$, $CO_2$, $H_2O$, $HF$</td>
</tr>
<tr>
<td>Other:(W, Ta, Mo)</td>
<td>$CF_4$</td>
<td>$WF_6$,...</td>
</tr>
</tbody>
</table>
Even with Plasma the etch rate is slow: Insufficient $F$ concentration

Adding $O_2$ helps

$$O + CF_3 \rightarrow COF_2 + F$$
$$O + COF_2 \rightarrow CO_2 + 2F$$

Etch rate maximizes around 12% of $O_2$.

Higher $O_2$ concentrations $\Rightarrow$ Lower $F$ concentration.

Etch rate higher for Si.
Effects of $H_2/CF_4$ Ratio
Effect on Etch rate and $Si/SiO_2$ Selectivity

- Adding $H_2$ drastically lowers $Si$ etch rate
  - Lowers $F$ concentration
    \[ H^+ + F + e^- \rightarrow HF \]
  - Nearly 0 at 40% $H_2$
- However, etch rate of $SiO_2$ remains nearly constant
- Allows etch selectivity to be increased tremendously
Increase the Degree of Anisotropy
Formation of sidewall Passivating Films

- **Polymerization**: Formation of nonvolatile fluorocarbons
- Deposit can be removed by physical collisions with incident ions
- Fluorocarbon films deposit on all surfaces, but the ion velocity is nearly vertical. Hence, there is little bombardment on sidewalls, and film accumulates
- Adding hydrogen encourages the formation of fluorocarbon since hydrogen scavenge fluorine, creating carbon-rich plasma
  - Same effect observed when $C_2F_6$ used instead of $CF_4$
Controlling Polymerization using $F/C$ Ratio

Effect of $H_2$ and $O_2$

- Higher $F/C$ ratio leads to more etching
- Lower $F/C$ ratio leads to more polymerization
- Adding $H_2$ consumes $F$
- Adding $O_2$ consumes $C$
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Sidewall Trenching effect

- Ions deflected towards sidewall due to electron accumulation
- Thus no Trenching observed if PR is conducting
- Less trenching observed on broad trenches due to increase in polymerization
Etch Stop

- Etch rate decreases with depth
- Formation of Polymer
- Aspect ratio dependent
Damage in RIE

- Typical flux of $10^{15}$ ions/cm$^2$ delivered at energies of 300 to 700 eV.
- After typical etch in a carbon containing RIE, the top 30 Å is heavily damaged.
- Hydrogen containing ambient also have $Si - H$ defects observed as deep as 300 Å.
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To increase etch rates, it is often necessary to work at high powers.

High power in turn leads to significant substrate damage.

In Magnetron Ion Etching (MIE), carefully positioned magnets surrounding RF chamber causes electrons to travel in spiral paths.

Increase in path length, thus increase in probability of them striking a gas molecule.

Electron Cyclotron Resonance (ECR) similar to MIE, except that Microwave used.
References I

- **Prof Tianhong Cui**
  Mechanical Engineering, University of Minnesota.
  Lecture for ME8243

- **Dr Paul May**
  School of Chemistry, University of Bristol
  Lectures on Plasma Processing of Semiconductor Materials

- **Eddy Kunnen**
  Microelectronics Training Center, IMEC
  Silicon Processing Course
References II

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