Etching
Overview

Capabilities

<table>
<thead>
<tr>
<th>Tool Name</th>
<th>Type</th>
<th>Materials</th>
<th>Restricted Materials</th>
<th>Available Gases</th>
<th>Max RF Power</th>
<th>Wafer Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>AJA ICP Argon Ion Mill Etcher</td>
<td>ICP Ion Mill</td>
<td>?</td>
<td>Au</td>
<td>Ar</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Branson Asher</td>
<td>Barrel Asher</td>
<td>Si, Oxides, Nitriles, Polymers, Organics</td>
<td>O₂, Ar</td>
<td>?</td>
<td>4 inch (100 mm) SEMI Specification</td>
<td></td>
</tr>
<tr>
<td>March Jupiter II Etcher</td>
<td>CCP RIE</td>
<td>Si, Oxides, Nitriles, Polymers, Organics</td>
<td>O₂, Ar, SF₆</td>
<td>600 Watts</td>
<td>6 inch (150 mm) SEMI Specification</td>
<td></td>
</tr>
<tr>
<td>Panasonic E620 ICP RIE Etcher</td>
<td>ICP RIE</td>
<td>Si, Oxides, III-IV’s, Ti, Al, SiC</td>
<td>Au, Ag, Pt, Cu, O₂, Ar, SF₆, CHF₃, CF₄, Cl₂, N₂, O₂, BCl₃</td>
<td>1250 ICP / 600 Platen</td>
<td>6 inch (150 mm) JEIDA Specification</td>
<td></td>
</tr>
<tr>
<td>Plasma-Therm Apex SLR</td>
<td>ICP RIE</td>
<td>Si, Oxides, III-IV’s, Ti, Al, SiC</td>
<td>Au, Ag, Pt, Cu, Ar, CHF₃, CF₄, SF₆, Cl₂, N₂, O₂, BCl₃, H₂, C₄F₈</td>
<td>2000 ICP / 600 Platen</td>
<td>6 inch (150 mm) SEMI Specification</td>
<td></td>
</tr>
<tr>
<td>STS AOE</td>
<td>ICP RIE</td>
<td>Silicon, Silicon Nitride, Silicon Oxide, Silicon Carbide / Photo resist, Ni, Cr, and Al</td>
<td>Au, Ag, Pt, Cu, O₂, Ar, SF₆,C₄F₈</td>
<td>3000 ICP / 1200 Platen</td>
<td>4 inch (100 mm) SEMI Specification</td>
<td></td>
</tr>
<tr>
<td>STS ASE</td>
<td>ICP RIE</td>
<td>Si (Bosch Process)</td>
<td>Au, Ag, Pt, Cu, O₂, Ar, SF₆,C₄F₈</td>
<td>3000 ICP / ? Platen</td>
<td>6 inch (150 mm) SEMI Specification</td>
<td></td>
</tr>
<tr>
<td>Wet Etching</td>
<td>Wet Etching</td>
<td>?</td>
<td>?</td>
<td>NA</td>
<td>NA</td>
<td>?</td>
</tr>
<tr>
<td>Xactix E1 Xenon Difluoride (XeF₂) Etcher</td>
<td>Vapor Phase Etch</td>
<td>Si</td>
<td>?</td>
<td>XeF₂</td>
<td>NA</td>
<td>4 inch (100 mm) SEMI Specification</td>
</tr>
</tbody>
</table>

Terminology

**Wet Etching** - Substrates are immersed in a reactive solution (etchant). The layer to be etched is removed by chemical reaction or by dissolution. The reaction products must be soluble and are carried away by the etchant solution. Generally, wet etching is isotropic.

**Dry Etching** - Substrates are immersed in a reactive gas (plasma). The layer to be etched is removed by chemical reactions and/or physical means (ion bombardment). The reaction products must be volatile and are carried away in the gas stream.

- **Plasma Etching** - Typically high pressure, no ion bombardment. (Substrate is placed on a grounded electrode)
- **Reactive Ion Etching** - Typically lower pressures, ion bombardment. (Substrate is placed on a powered electrode)

**Anisotropic Etch** - Etch rate is not equal in all directions.

**Isotropic Etch** - Etch rate is equal in all directions.

**Etching** - The process by which material is removed from a surface.
**Mask** - Used to protect regions of the wafer surface. Examples include photoresist, Ni, Cr, or oxide layer.

**Selectivity** - The ratio of etch rate of film to etch rate of substrate or mask.

**Aspect Ratio** - Ratio of depth to width of an etched feature.

**Plasma** - Partially ionized gas containing an equal number of positive and negative charges, as well as some other number of none ionized gas particles.

**Glow Discharge** - Globally neutral, but contains regions of net positive and negative charge. (Many thin film processes utilize glow discharges, but “plasma” and “glow discharge” are often used interchangeably)

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**Plasma Fundamentals**

The fourth state of matter, an ionized gas into which sufficient energy is provided to free electrons from atoms or molecules and to allow neutral molecules, radicals, ions and electrons to coexist. Below is a high level overview of plasma fundamental physics. For a more details look at plasma, see the paper "A Short Introduction to Plasma Physics".

<table>
<thead>
<tr>
<th>Typical Plasma Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neutral Molecules</strong></td>
</tr>
<tr>
<td>• 10 E sub 16 sup 3 per cm sup 3</td>
</tr>
<tr>
<td>• Do not contribute to the etching process.</td>
</tr>
<tr>
<td><strong>Radicals</strong></td>
</tr>
<tr>
<td>• 10 E sub 14 sup 3 per cm sup 3</td>
</tr>
<tr>
<td>• Uncharged atoms with unsatisfied chemical bonds that react with the surface to produce volatile products that are pumped away.</td>
</tr>
<tr>
<td>• Form more easily and their lifetime is much longer, resulting in a million times more radicals than ions or electrons.</td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
</tr>
<tr>
<td>• 10 E sub 8 sup 3 per cm sup 3</td>
</tr>
<tr>
<td>• Electrons are low mass (9.1 x10 sub -31 kg) and are rapidly accelerated toward the positively charged anode, on the way they collide into other gas molecules creating new species.</td>
</tr>
<tr>
<td><strong>Positive and Negative Ions</strong></td>
</tr>
<tr>
<td>• 10 E sub 8 sup 3 per cm sup 3</td>
</tr>
<tr>
<td>• Fast moving, heavy molecules that affect the process through energetic (physical) bombardment of the surface.</td>
</tr>
<tr>
<td>• Positive ions are much heavier than electrons (Argon mass 6.6 x10 sub -26 kg), and are accelerated toward the negatively charged cathode.</td>
</tr>
<tr>
<td>• Negative ions are short lived and therefore rare in plasma.</td>
</tr>
</tbody>
</table>

**Collision Processes and the Production of Active Species**
Electron Excitation

- This accounts for the glow. When electrons collide with atoms or molecules, they excite or energize electrons to higher energy levels. When these electrons fall back to lower levels, they emit energy usually in the form of photons of visible light.
- \( \text{Ar} + \text{e}^- \rightarrow \text{Ar} + \text{e}^- + \text{photon} \)

**Simple Ionization**

- An electron is completely removed from a gas molecule or atom, to make a positive ion. (Negative ions are rare in plasma)
- \( \text{Ar} + \text{e}^- \rightarrow \text{Ar}^+ + 2\text{e}^- \) (Electron collision with an Argon atom resulting in one positive Ar ion and 2 electrons)
- \( \text{O}_2 + \text{e}^- \rightarrow \text{O}_2^+ + 2\text{e}^- \) (Electron collision with an Oxygen molecule resulting in one positive Oxygen ion and 2 electrons)

**Dissociative Ionization**

- \( \text{CF}_4 + \text{e}^- \rightarrow \text{CF}_3^+ + \text{F} + 2\text{e}^- \) (Electron collision with a CF\(_4\) molecule resulting in one CF\(_3\) positive ion, one F radical, and two electrons)
Dissociative Ionization with Attachment

- $\text{CF}_4 + e^- \rightarrow \text{CF}_3^+ + F^- + e^- $ (Electron collision with a CF$_4$ molecule resulting in one CF$_3$ positive ion, one negative F ion, and one electron)

Molecular Dissociation, Radical Formation

- Electron collisions break up molecules into fragments which as a result have unsatisfied chemical bonding and are chemically reactive. These are called radicals. Radicals have no net charge and therefore are not accelerated by the field or are not attracted by charged particles.
- $\text{CF}_4 + e^- \rightarrow \text{CF}_3 + F + e^- $ (Electron collision with CF$_4$ molecule resulting in on CF$_3$ radical, one F radical, and one electron)
- $\text{O}_2 + e^- \rightarrow 2\text{O} + e^- $ (Electron collision with an Oxygen molecule resulting in two oxygen radicals and an electron)
- $\text{CF}_3\text{Cl} + e^- \rightarrow \text{CF}_3 + \text{Cl} + e^- $ (Electron collision with CF$_3$Cl molecule resulting in one CF$_3$ radical, one Cl radical, and one electron)

Plasma Loss Mechanisms

In a stable plasma, unstable particles are continuously generated and lost. The concentration of ions, radicals, and electrons increase until their loss rate is equal to their generation rate and steady state is reached.

Recombination of Ions and Electrons

- Positively charged ions and negatively charged electrons attract each other, combine, and become neutral atoms and molecules.
Recombination of Radicals

- Radicals join together creating stable chemical bonds. ($2O \rightarrow O_2$)

**Recombination of Radicals**

Chemical Reaction

- Radicals combine with surface creating volatile byproducts that are pumped away. (example: $4F + Si \rightarrow SiF_4$)

**Chemical Reaction**

Drift and Diffusion

- Electrons are lost and ions are converted to neutral particles through contact with conductive surfaces. (i.e. chamber walls and electrodes)

**Drift / Diffusion**

How is Plasma Made
DC Glow Discharge

- With sufficient voltage, the gas rapidly becomes filled with positive and negative particles throughout its volume, i.e., it becomes ionized.
- Portions of the glow discharge may be charged negatively or positively, but overall must always remain neutral.
- Insulating materials will not sustain a plasma. Ion current will charge the insulator positively and extinguish the plasma. For this reason, this method of plasma creation is not used in dry etching equipment.

![DC Glow Discharge Diagram]

RF Plasma

- AC voltage overcomes the problem of charge which accumulates on an insulator in the DC system.
- The positive charge which accumulates due to ion bombardment during one half of the AC cycle can be neutralized by electron bombardment during the next half cycle.
- At frequencies > 100kHz electrons respond and ions do not, ensuring the half period will be shorter than the charge up time of the insulator.
- Although there are a number of differences in the practical operation of AC plasma, the principles of DC glow discharges can be applied to AC. One simply considers the AC as a rapidly reversing DC plasma.

![RF Plasma Diagram]

Dry Etch Fundamentals

Dry Etch Material Removal Mechanisms

<table>
<thead>
<tr>
<th>Reactive Etching</th>
<th>Reactive Etching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotropically</td>
<td>( \text{Si} + 4\text{F} \rightarrow \text{SiF}_4 \text{ (gas)} )</td>
</tr>
</tbody>
</table>
**Ion Etching**
- Anisotropic process
- Low selectivity
- Low etch rate

**Reactive Ion Etching**
- Anisotropic process
- Variable selectivity
- High etch rate (on the order of 5x faster than either reactive etching or ion etching alone)
## Dry Etching Equipment Configurations

### Capacitive RIE Etch Chamber
- Low density plasma
  - $n_e \approx 10^9$ electrons/cm$^3$
- Ionization efficiency $10^{-7}$
- RF Power Source (Typ. 13.56 MHz)

### Inductive RIE Etch Chamber
- High density plasma
  - $n_e \approx 10^{13}$ electrons/cm$^3$
- Ionization efficiency $10^{-3}$
- RF Power Source (Typ. 13.56 MHz)

## Directionality of Etching
### Degree of Anisotropy (A)

$$ A = \frac{Z - X}{Z} $$

#### Vertical Etch
- $X = 0$
- $A = 1$

#### Anisotropic Etch
- $X < Z$
- $0 < A < 1$

#### Isotropic Etch
- $X = Z$
- $A = 0$

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**References**

- [Introduction to Plasma Etching_Lecture_102417_Day2_sntzd.pdf](#)
- [BookDry etch for semiconductors _Nooiri.pdf](#)
- [Purdue Etchers - 1.xlsx](#)

**Materials**

**Aluminum Oxide**
From a quick search, seems to be typically etched in high density plasmas with a chlorine based chemistry - JCW

The ETCH Mechanism for Al2O3 in Fluorine and Chlorine Based RF Dry Etch Plasmas

Temperature dependence on dry etching of Al2O3 thin films in BC13/CI2/Ar plasma

Dry Etching of Al2O3 Thin Films in O2/BC13/Ar Inductively Coupled Plasma

"Aluminum Oxide", Oxford Instruments