ASTRON: A Toroidal Plasma Source and its Applications

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Outline

• I. Background on remote plasma processes
• II. ASTRON plasma devices
• III. Applications
  – CVD chamber clean
  – Photoresist removal
  – Plasma abatement
Some Background on Plasma Sources

• In semiconductor processing, plasmas are used to create activated species to enable or accelerate chemical and physical reactions.

• For ion driven processes, plasma is generated in process chamber and exposed to substrate.

• For processes driven by neutral reactive gases, plasma is generated outside process chamber. Activated gas is flowed to the process chamber to eliminate charged particles.
Conventional Plasma Processing Chambers

Ion Bombardment + Reactive Neutrals
• Chemical reactions of neutral species have certain advantages
  – avoids damage from charging or sputtering
  – higher selectivity than plasma processes

• Highly reactive species can be produced and transported
  – F, O, H, N, O₃

• The use of a separate generator of reactive species allows their production to be optimized, outside of the process chamber
Examples of Reactive Gas Generators Manufactured by MKS

• Ozone
  – dielectric barrier discharge
  – used in SiO₂ deposition, wafer cleaning and wet bench
• Microwave
  – microwave discharge in dielectric tubes
  – stripping, wafer cleaning, annealing, chamber clean
• ASTRON
  – RF toroidal plasma
ASTRON (™) LOW-FIELD TOROIDAL PLASMA SOURCE

• Delivers high flows of reactive gases:
  - atomic F, O, N, H

• Uses a plasma to activate gases
  - \( n_e = 10^{13} \text{ cm}^{-3} \)
  - \( T_e = 2-3 \text{ eV} \)

• Three functions in a single package
  - Control
  - Power generation
  - Plasma generation
• Current in primary coil induces a current in the plasma (secondary) in opposite direction (Faraday’s induction law)
• Ferrite core confines the electromagnetic field to improve magnetic coupling
• DC break required to couple electromagnetic fields through conductor
ASTRON Principles Of Operation (Cont’d)

• The primary of the transformer is powered by an on-board 400 kHz switching RF power supply.

• The electric fields within the plasma are kept low so that sputtering of walls is avoided. Electric fields range from 4-8 v/cm.

• Energy efficiency from wall power to plasma is 85-90%.

• The aluminum plasma channel is water-cooled and allows very high power density.
# ASTRON Product Line

<table>
<thead>
<tr>
<th></th>
<th>Primary Applications</th>
<th>Flow Capabilities</th>
<th>Power Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASTRON 2L</strong></td>
<td>CVD chamber clean</td>
<td>2 slm NF3 @10 Torr</td>
<td>5 kW</td>
</tr>
<tr>
<td><strong>ASTRONi</strong></td>
<td>CVD chamber clean</td>
<td>2.5-3 slm NF3 @10 Torr</td>
<td>6.5-7 kW</td>
</tr>
<tr>
<td><strong>ASTRONe</strong></td>
<td>CVD chamber clean</td>
<td>4-8 slm NF3 @10 Torr</td>
<td>8-10 kW</td>
</tr>
<tr>
<td><strong>Abatement ASTRON</strong></td>
<td>PFC removal</td>
<td>0.1-1 slm CF4</td>
<td>5-10 kW</td>
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</tbody>
</table>
Typical Setup of Remote Plasma Device

1-5 slm gas flow
1-10 Torr pressure

0.5-5 Torr pressure

Typical transport time for reactive species 1-10 millisec
Key issues in remote plasma applications

• **Activation** - activating or dissociating gases in a plasma
  – appropriate wall materials in the plasma source
  – enough power to do the job

• **Transport** - distributing reactant to process chamber
  – The reactant species are relatively unstable (lifetimes of msec’s). Short residence time is key.
  – Great attention must be paid to materials of construction.

• **Reaction** - typically driven by thermal mechanisms.
  – Reaction rates follow an exponential dependence on substrate temperature
  – Reaction rate are proportional to the partial pressure of reactive gases
Application: CVD Chamber Clean

• CVD chambers need to be cleaned periodically to prevent chamber deposits from flaking and generating particles.

• Clean time is a significant part of tool time, sometimes longer than deposition time.

• Due to use of aggressive chemistry, in situ clean causes significant damage to chamber internal surfaces.

• Remote plasma clean is preferred because
  – reduced damage to chamber internals
  – higher clean rates
  – higher uniformity
  – separates optimization processes for deposition and clean
CVD Chamber Clean Techniques

In-Situ RF

NF\textsubscript{3}
C\textsubscript{2}F\textsubscript{6}/O\textsubscript{2}
CF\textsubscript{4}/O\textsubscript{2}
cleaning gases

plasma

substrate

rf coil (powered)

Atomic Fluorine

ASTRON

NF\textsubscript{3}/Ar cleaning gas

substrate

rf coil (off)
Materials etched at our labs with F

$\text{SiO}_2$
$\text{Si}_3\text{N}_4$
Si
W
WN
TiN
SiC
Ta
Ru
Production Of Atomic Fluorine

- NF₃, CF₄, C₂F₆, C₃F₈ are common sources of atomic fluorine
  - When fluorocarbon is used, oxygen is added to form CO, CO₂ and F

- Production efficiency of atomic fluorine can be measured by FTIR or by comparing SiO₂ etch rate with the calculated maximum etch rate for given source gas flow rate and pressure.


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<th>Reaction Probability:</th>
<th>[ P = 1.12 \times 10^{-2} \times e^{-\frac{1892}{T(k)}} ]</th>
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</thead>
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<tr>
<td>Etch Rate (μm/min):</td>
<td>[ R = 6.14 \times 10^{-17} \times N_F \text{ (cm}^{-3}) \times T^{1/2(k)} \times e^{-\frac{1892}{T(k)}} ]</td>
</tr>
</tbody>
</table>
Production Efficiency Of Atomic Fluorine Is Near Unity

- Atomic fluorine production efficiency is nearly independent of flow rates of argon and pressure.
SiO$_2$ etch rate vs. chamber pressure

- There is an optimal pressure that corresponds to peak etch rate
  - At low pressures atomic fluorine is lost due to vacuum pump
  - At high pressures atomic fluorine is lost during transport due to recombination

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150 sccm NF$_3$ / 750 sccm Ar
T=150 C
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Transport of Atomic Fluorine vs. Flow Tube
Materials and Temperature

- Transport efficiency of atomic fluorine is measured from SiO₂ etch rate with and without transport tubes

![Graph showing transport of F vs. flow](image)

- Over 90% of F can be transported through a 1-m long tube
- Higher temperature improves transport efficiency

![Graph showing transport of F vs. temperature](image)
Etching W with Atomic Fluorine

Unlike the case for SiO$_2$, the published rate constants for W-etching show that there can be contributions from both F and F$_2$


For F: \[ \text{rate} = 2.92 \times 10^{-14} \sqrt{\text{Tg}(k)} \times n(\text{F}) \times \exp\left(-\frac{3900}{\text{T}(k)}\right) \text{ (um/min)} \]

For F$_2$: \[ \text{rate} = 6.6 \times 10^{-15} \sqrt{\text{Tg}(k)} \times n(\text{F2}) \times \exp\left(-\frac{6432}{\text{T}(k)}\right) \text{ (um/min)} \]

Note that the etching for F$_2$ has a much higher activation energy than for F
Etching W With Atomic and Molecular Fluorine

- F etch dominates at low pressure
- F₂ etch becomes significant at high temperature and pressure
ETCHING Si₃N₄ WITH ATOMIC FLUORINE

- Data taken in ASTeX test chamber with ASTRON;
- 0.3 slm NF₃ / 1.5 slm Ar
Application: Photoresist Etching

- Photoresist is used to create patterns on wafers
- Once patterns are created, photoresist must be removed and the surface be cleaned.
- Atomic gases are preferred due to reduction of damage and higher selectivity
- Typical process uses atomic oxygen
  - Dopant gases are added to improve process
    - add $\text{N}_2$ to increase dissociation
    - add $\text{CF}_4$, $\text{H}_2\text{O}$ etc. to increase rates and enhance chemistry
- Typical etch rate a few $\mu\text{m}$ per minute at temperature of 200-250 $\text{C}$. 
Generation of Atomic Oxygen

- Production of atomic oxygen is monitored by photoresist etch
- Higher flow rate of argon increases delivery of atomic oxygen

Effect of Oxygen Flow on Etch Rate
\( \text{Ar}=10 \text{ slm}; \text{N}_2=0.1\times\text{O}_2; \text{Pump Speed Fixed} \)

![Graph showing the effect of oxygen flow on etch rate.]

Etch Rate (\(\mu\text{m/min}\))

\(\text{O}_2\) Flow (slm)

T = 30°C
Photoresist Removal Data from a Strip Chamber

Fixed Pumping Speed

![Graph showing photoresist strip rate vs. Ar flow with fixed pumping speed at 2 Torr.]

Fixed Pressure: 2 Torr

![Graph showing photoresist strip rate vs. Ar flow with fixed pressure at 2 Torr.]

800 sccm O₂ / 70 sccm N₂
Argon flow rate as shown
Application: PFC Abatement

- PFCs are used in semiconductor manufacturing for plasma etch and CVD chamber clean
  - SiO\textsubscript{2} Etch: CHF\textsubscript{3}, CF\textsubscript{4}, C\textsubscript{2}F\textsubscript{6}
  - Chamber Clean: CF\textsubscript{4}, C\textsubscript{2}F\textsubscript{6}, C\textsubscript{3}F\textsubscript{8}, NF\textsubscript{3}

- PFCs are greenhouse gases with long-term impact on global climate
  - Strong absorbers of infrared radiation (1000x higher than CO\textsubscript{2})
  - Long atmosphere life results in accumulation in atmosphere
Plasma Abatement of PFCs

• Concept - Chemically destruct undesirable species in a plasma reactor
  – Add reactive gases, such as $O_2$, $H_2$ and $H_2O$, to the chamber exhaust so that the plasma converts the PFCs to harmless or manageable ones.

  e.g.  
  $PFC + O_2 \xrightarrow{\text{Plasma}} CO_2 + F_2$

  – Oxygen is needed to reduce free carbon to $CO_2$. Chemical balance dictates the ratio of $O_2$ to C to be 1 or greater.
ABATEMENT OF CF₄

- Destruction efficiency of > 98% at CF₄ flow of 250 sccm obtained with ASTRON.