Very High Frequency Capacitively Coupled Plasmas of Electronegative Gases

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Introduction

- Stringent processing requirements have led to the development of very high frequency (VHF) capacitively coupled plasma (CCP) etchers in recent years.
- Large electrode sizes and high frequencies dictate that electromagnetic effects can play a major role in determining plasma spatial profile.
- Electromagnetic effects in CCPs have previously been investigated using analytical models by Lieberman\(^1\) and Chabert\(^2\).
- In this paper, we describe a 2-dimensional computational plasma model that self-consistently considers electromagnetic effects in the operation of VHF CCPs.
- The model is used to understand discharge behavior in electropositive (Ar) and electronegative (Ar/SF\(_6\), Ar/CF\(_4\)) plasmas operating at 180 MHz.
- It is found that plasma spatial profile is influenced by both electrostatic and electromagnetic effects, where electromagnetic effects pull the plasma towards the chamber center while electrostatic effects are more dominant at the electrode edge.

The computational model consists of the following equations:

- Continuity equation (charged species):
  \[
  \frac{\partial n_i}{\partial t} - \nabla \cdot \left( D_i \nabla n_i - \frac{q_i}{q_i} \mu_i n_i \vec{E} \right) = S_i
  \]

- Continuity equation (neutral species):
  \[
  \frac{\partial n_i}{\partial t} - \nabla \cdot D_i \nabla n_i = S_i
  \]

- Electron energy conservation equation:
  \[
  \frac{3e}{2} \frac{\partial n_e T_e}{\partial t} = P_e - n_e \sum_i n_i k_i - \nabla \cdot \left( \frac{15}{4} e T_e \vec{I}_e - \lambda_e \nabla T_e \right)
  \]

- Maxwell equations:
  \[
  \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \nabla \cdot \vec{E} = \rho
  \]
  \[
  \nabla \times \vec{B} = \mu_o \vec{J} + \mu_o \varepsilon \frac{\partial \vec{E}}{\partial t} \quad \nabla \cdot \vec{B} = 0
  \]
The following potential formulation is used to solve the Maxwell equations:

\[
\begin{align*}
\vec{B} &= \nabla \times \vec{A} \\
\vec{E} &= -\nabla \phi - \frac{\partial \vec{A}}{\partial t} \\
\nabla \cdot \vec{A} &= 0
\end{align*}
\]

Maxwell equations are then transformed into:

\[
\begin{align*}
\nabla \cdot (\varepsilon \nabla \phi) &= -\rho \\
\nabla^2 \vec{A} - \varepsilon \mu_o \frac{\partial^2 \vec{A}}{\partial t^2} - \sigma \mu_o \frac{\partial \vec{A}}{\partial t} &= -\mu_o \vec{J} + \varepsilon \mu_o \frac{\partial \nabla \phi}{\partial t} + \mu_o \sigma \nabla \phi
\end{align*}
\]  

(1)  

(2)

The coupled set of Eq. (1) and continuity equations for charged species are solved implicitly in time.

Equation (2) is solved in frequency domain using self-consistently computed currents and potential. The model is capable of addressing \( n \) harmonics although only first harmonic is considered in this paper.
Electrostatic electric field

\[ \vec{E} = -\nabla \phi - \frac{\partial \vec{A}}{\partial t} \]

Electromagnetic electric field

Electron total power deposition:

\[ P_e = \int_V \vec{J}_e \cdot \vec{E} \, dV \]

**Electromagnetic** power deposition:

\[ P_e(EM) = \int_V \sigma \omega^2 |\vec{A}|^2 \, dV \]

**Electrostatic** power deposition:

\[ P_e(ES) = P_e - P_e(EM) \]
At 100 W, peak in electron density occurs at the chamber center.

Time-averaged electrical potential ($\phi^{(0)}$) is small.

- RF current flowing through the plasma generates a standing wave in the inter-electrode gap.

- $n_e$ (Max = 2.65 x 10^{16} m^{-3})$

- $\phi^{(0)}$ (Max = 35.7 V, Min = -4.76 V)

- $|J_z^{(1)}|$ (Max = 121.77 A/m^2)

- $|A_z^{(1)}|$ (Max = 3.23 x 10^{-7} V·s/m)

- 100 mT, 100 W, Ar, 180 MHz
Plasma Dynamics at VHF - 2

- With a large plasma density, sheaths are thin and electrons gain substantial energy in the sheath/pre-sheath region (electrostatic power deposition).
- Electrons are also heated in the center of the chamber by the electromagnetic standing wave (electromagnetic power deposition).
- Plasma profile is strongly influenced by electromagnetic power deposition, which occurs over the bulk of the plasma region.

\[ |\phi^{(1)}| \text{ (Max = 67.19 V)} \]

\[ |\omega A_z^{(1)}| \text{ (Max = 365.13 V/m)} \]

\[ P_{e(ES)} \text{ (Max = } 1.27 \times 10^5 \text{ W/m}^{-3} \)\]

\[ P_{e(EM)} \text{ (Max = } 1.36 \times 10^4 \text{ W/m}^{-3} \)\]

- 100 mT, 100 W, Ar, 180 MHz
Experimental and computational results show that peak in plasma density moves towards electrode edge as RF power is increased.

- **[e] (Max = 1.05×10^{16} \text{ m}^{-3})**
- **[e] (Max = 2.65×10^{16} \text{ m}^{-3})**
- **[e] (Max = 5.78×10^{16} \text{ m}^{-3})**
- **[e] (Max = 8.21×10^{16} \text{ m}^{-3})**
- **[e] (Max = 15.26×10^{16} \text{ m}^{-3})**

**Langmuir Probe Meas.**

- **100 mT, 1.25”, 162 MHz**
- **100 mT, Ar, 180 MHz**

- **50 W**
- **100 W**
- **200 W**
- **400 W**
- **600 W**
- **800 W**
- **1000 W**
- **1500 W**

**Ion Sat. Current (a.u.)**

**Radius (cm)**
Effect of RF Power on Ar Plasma Characteristics - 2

100 W

$|J_r^{(1)}| \text{ (Max} = 52.9 \text{ A/m}^2)$

$|A_r^{(1)}| \text{ (Max} = 7.24 \times 10^{-8} \text{ V} \cdot \text{s/m})$

$|A_z^{(1)}| \text{ (Max} = 3.23 \times 10^{-7} \text{ V} \cdot \text{s/m})$

$P_e(\text{EM}) \text{ (Max} = 1.36 \times 10^4 \text{ W/m}^3)$

800 W

$|J_r^{(1)}| \text{ (Max} = 843.95 \text{ A/m}^2)$

$|A_r^{(1)}| \text{ (Max} = 2.50 \times 10^{-7} \text{ V} \cdot \text{s/m})$

$|A_z^{(1)}| \text{ (Max} = 1.94 \times 10^{-7} \text{ V} \cdot \text{s/m})$

$P_e(\text{EM}) \text{ (Max} = 2.22 \times 10^4 \text{ W/m}^3)$

*100 mT, Ar, 180 MHz*
Effect of SF₆ Addition to Ar - 1

- Electron density decreases considerably as SF₆ is added to an Ar plasma.
- Electron density peak moves towards the electrode edge with SF₆ addition.

![Graph showing electron density changes with SF₆ addition](image)

- [e] (Max = 2.08 × 10¹⁴ m⁻³)
- [e] (Max = 3.08 × 10¹⁴ m⁻³)
- [e] (Max = 5.97 × 10¹⁴ m⁻³)
- [e] (Max = 2.65 × 10¹⁶ m⁻³)

500 W, 50 mT, Ar/SF₆, 3.76", 160 MHz

- 0% SF₆
- 5% SF₆
- 10% SF₆
- 15% SF₆
- 20% SF₆
- 30% SF₆

100 mT, 100 W, Ar/SF₆, 180 MHz
Effect of SF₆ Addition to Ar - 2

- SF₆ is highly electronegative and negative ion density is orders of magnitude larger than electron density with > 10% SF₆.
- Major negative ions are SF₆⁻ and SF₅⁻. Ar⁺ is the dominant positive ion.

100% Ar
- [e] (Max = 2.65×10¹⁶ m⁻³)
- [Ar⁺] (Max = 2.65×10¹⁶ m⁻³)

70% Ar, 30% SF₆
- [e] (Max = 2.08×10¹⁴ m⁻³)
- [Ar⁺] (Max = 1.22×10¹⁶ m⁻³)
- [SF₆⁻] (Max = 7.56×10¹⁵ m⁻³)

• 100 mT, 100 W, Ar/SF₆, 180 MHz
Effect of SF₆ Addition to Ar - 3

- As $n_e$ decreases with SF₆ addition, larger RF potential is needed to deliver the same power in the plasma, making electrostatic effects more important.
- Simultaneously, current through the plasma decreases making electromagnetic effects weaker.

100% Ar

- $|\phi^{(1)}| \text{ (Max} = 67.19 \text{ V)}$
- $P_e(ES) \text{ (Max} = 1.27 \times 10^5 \text{ W/m}^3)$
- $P_e(EM) \text{ (Max} = 1.36 \times 10^4 \text{ W/m}^3)$

70% Ar, 30% SF₆

- $|\phi^{(1)}| \text{ (Max} = 89.14 \text{ V)}$
- $P_e(ES) \text{ (Max} = 3.54 \times 10^4 \text{ W/m}^3)$
- $P_e(EM) \text{ (Max} = 1.06 \times 10^2 \text{ W/m}^3)$

*100 mT, 100 W, Ar/SF₆, 180 MHz*
CF₄ is mildly electronegative with F⁻ being the major negative ion.

As CF₄ is added to an Ar discharge, electron density decreases and plasma density profile becomes more uniform.

Even with 99% CF₄, the model does not predict shift of electron density peak to electrode edge.

- 0% CF₄: [e] (Max = 2.65×10¹⁶ m⁻³)
- 25% CF₄: [e] (Max = 4.82×10¹⁵ m⁻³)
- 50% CF₄: [e] (Max = 1.93×10¹⁵ m⁻³)
- 75% CF₄: [e] (Max = 9.35×10¹⁴ m⁻³)
- 99% CF₄: [e] (Max = 5.51×10¹⁴ m⁻³)

• 100 mT, 100 W, Ar/CF₄, 180 MHz
Conclusions

- A self-consistent 2-dimensional plasma model that includes the full set of Maxwell equations is used to understand the behavior of VHF capacitively coupled plasmas.
- Plasma spatial profile is influenced by both electrostatic and electromagnetic effects, where electromagnetic effects pull the plasma towards the chamber center while electrostatic effects are more dominant at the electrode edge.
- Current through the discharge creates a standing electromagnetic wave in the chamber, which pulls the plasma towards the center at low RF powers.
- As RF power is increased, $E_r$ related “inductive” effects become important and plasma density peak moves towards the electrode edge.
- In electronegative discharges, electromagnetic effects become less important with increasing plasma electronegativity and peak in plasma density moves towards electrode edge.