Physics of Very High Frequency (VHF) Capacitively Coupled Plasma Discharges

Shahid Rauf, Kallol Bera, Steve Shannon, and Ken Collins

Applied Materials, Inc., Sunnyvale, CA

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Agenda

- Introduction
- Computational Model
- Plasma Dynamics at Very High Frequency
- Influence of Chamber Design
- Influence of Plasma Chemistry
- Conclusions
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 Ar 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):
  \[
  \frac{\partial n_i}{\partial t} - \nabla \cdot \left( D_i \nabla n_i - \frac{q_i}{|q_i|} \mu_i n_i E \right) = S_i
  \]

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

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

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

\[ \vec{B} = \nabla \times \vec{A} \quad \vec{E} = -\nabla \phi - \frac{\partial \vec{A}}{\partial t} \quad \nabla \cdot \vec{A} = 0 \]

Maxwell equations are then transformed into:

\[ \nabla \cdot (\varepsilon \nabla \phi) = -\rho \quad (1) \]

\[ \nabla^2 \vec{A} - \varepsilon \mu_o \frac{\partial^2 \vec{A}}{\partial t^2} - \sigma \mu_o \frac{\partial \vec{A}}{\partial t} = -\mu_o \vec{J} + \varepsilon \mu_o \frac{\partial \nabla \phi}{\partial t} + \mu_o \sigma \nabla \phi \quad (2) \]

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 and 3 harmonics are considered in this paper.
Electrostatic electric field

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

Electromagnetic electric field

**Electron total power deposition:**

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

**Electromagnetic power deposition:**

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

**Electrostatic power deposition:**

\[ P_e(ES) = P_e - P_e(EM) \]
Plasma Dynamics at VHF - 1

- 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 = $2.65 \times 10^{16}$ 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 = $3.23 \times 10^{-7}$ V·s/m)

- 100 mT, 100 W, Ar, 180 MHz
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.

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

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

$P_e(ES) \text{ (Max = } 1.27 \times 10^5 \text{ W/m}^3\text{)}$

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

• 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.

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

Radiation Probe Meas. — 100 mT, 1.25”, 162 MHz

- 50 W
- 100 W
- 200 W
- 400 W
- 1000 W

- 100 mT, Ar, 180 MHz
Effect of RF Power on Ar Plasma Characteristics - 2

100 W

- $|J_r^{(1)}|$ (Max = 52.9 A/m²)
- $|A_r^{(1)}|$ (Max = $7.24 \times 10^{-8}$ V·s/m)
- $|A_z^{(1)}|$ (Max = $3.23 \times 10^{-7}$ V·s/m)
- $P_e(EM)$ (Max = $1.36 \times 10^4$ W/m³)

800 W

- $|J_r^{(1)}|$ (Max = 843.95 A/m²)
- $|A_r^{(1)}|$ (Max = $2.50 \times 10^{-7}$ V·s/m)
- $|A_z^{(1)}|$ (Max = $1.94 \times 10^{-7}$ V·s/m)
- $P_e(EM)$ (Max = $2.22 \times 10^4$ W/m³)

• 100 mT, Ar, 180 MHz
Effect of Inter-Electrode Gap - 1

- Plasma is more uniform at smaller inter-electrode gap.
- Plasma density increases in the center of the chamber as the gap is increased. This is due to larger loss at smaller gaps with an effectively larger area/volume ratio.

\[ [e] \text{ (Max = } 1.91 \times 10^{16} \text{ m}^{-3}) \]

\[ [e] \text{ (Max = } 2.65 \times 10^{16} \text{ m}^{-3}) \]

\[ [e] \text{ (Max = } 2.49 \times 10^{16} \text{ m}^{-3}) \]

• 100 mT, Ar, 100 W, 180 MHz
Effect of Inter-Electrode Gap - 2

- Plasma is more uniform at smaller gaps because electrostatic effects are stronger, plasma produced at the electrode edge has less opportunity to diffuse to chamber center, and electromagnetic power deposition is over a smaller volume.

1.0"

- $|A_z^{(1)}| \text{ (Max = } 4.49 \times 10^{-7} \text{ V·s/m)}$
- $P_e(ES) \text{ (Max = } 1.43 \times 10^5 \text{ W/m}^3)$
- $P_e(EM) \text{ (Max = } 2.01 \times 10^4 \text{ W/m}^3)$

2.0"

- $|A_z^{(1)}| \text{ (Max = } 2.92 \times 10^{-7} \text{ V·s/m)}$
- $P_e(ES) \text{ (Max = } 1.13 \times 10^5 \text{ W/m}^3)$
- $P_e(EM) \text{ (Max = } 1.01 \times 10^4 \text{ W/m}^3)$

*100 mT, Ar, 100 W, 180 MHz*
Effect of Lower Electrode Radius - 1

- Plasma is quite uniform over the lower electrode if the lower electrode radius is 10 cm.
- Electromagnetic effects move the plasma to chamber center as electrode size is increased.
- Plasma is more intense with a smaller lower electrode for a given input power as the power is deposited over a smaller volume.

\[ e \text{ (Max } = 2.10 \times 10^{16} \text{ m}^{-3}) \]

\[ e \text{ (Max } = 2.65 \times 10^{16} \text{ m}^{-3}) \]

\[ e \text{ (Max } = 4.56 \times 10^{16} \text{ m}^{-3}) \]

\[ 100 \text{ mT, Ar, 100 W, 180 MHz} \]
Electrostatic effects are relatively more important with a smaller lower electrode.

- **10 cm**
  - $|A_z^{(1)}|$ (Max = $2.35 \times 10^{-7}$ V·s/m)
  - $P_e(ES)$ (Max = $2.10 \times 10^5$ W/m$^{-3}$)
  - $P_e(EM)$ (Max = $1.10 \times 10^4$ W/m$^{-3}$)

- **22.5 cm**
  - $|A_z^{(1)}|$ (Max = $3.36 \times 10^{-7}$ V·s/m)
  - $P_e(ES)$ (Max = $1.06 \times 10^5$ W/m$^{-3}$)
  - $P_e(EM)$ (Max = $1.18 \times 10^4$ W/m$^{-3}$)

- $100 \text{ mT}, \text{ Ar}, 100 \text{ W}, 180 \text{ MHz}$
Effect of SF$_6$ Addition to Ar - 1

- Electron density decreases considerably as SF$_6$ is added to an Ar plasma.
- Electron density peak moves towards the electrode edge with SF$_6$ addition.

![Graph showing electron density changes with SF$_6$ addition](image)

- 0% SF$_6$, [e] (Max = 2.65x10$^{16}$ m$^{-3}$)
- 5% SF$_6$, [e] (Max = 5.97x10$^{14}$ m$^{-3}$)
- 10% SF$_6$, [e] (Max = 3.08x10$^{14}$ m$^{-3}$)
- 15% SF$_6$, [e] (Max = 2.08x10$^{14}$ m$^{-3}$)
- 20% SF$_6$, [e] (Max = 2.08x10$^{14}$ m$^{-3}$)
- 30% SF$_6$, [e] (Max = 2.08x10$^{14}$ m$^{-3}$)

- 500 W, 50 mT, Ar/SF$_6$, 3.76", 160 MHz
- 100 mT, 100 W, Ar/SF$_6$, 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 = \(2.65 \times 10^{16} \text{ m}^{-3}\))
- \([\text{Ar}^+]\) (Max = \(2.65 \times 10^{16} \text{ m}^{-3}\))

**70% Ar, 30% SF₆**

- \([e]\) (Max = \(2.08 \times 10^{14} \text{ m}^{-3}\))
- \([\text{Ar}^+]\) (Max = \(1.22 \times 10^{16} \text{ m}^{-3}\))
- \([\text{SF}_6^-]\) (Max = \(7.56 \times 10^{15} \text{ m}^{-3}\))

- 100 mT, 100 W, Ar/SF₆, 180 MHz
Effect of SF$_6$ Addition to Ar - 3

- As $n_e$ decreases with SF$_6$ 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

|$\phi^{(1)}$| (Max = 67.19 V)

$P_e$(ES) (Max = $1.27 \times 10^5$ W/m$^{-3}$)

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

70% Ar, 30% SF$_6$

|$\phi^{(1)}$| (Max = 89.14 V)

$P_e$(ES) (Max = $3.54 \times 10^4$ W/m$^{-3}$)

$P_e$(EM) (Max = $1.06 \times 10^2$ W/m$^{-3}$)

*100 mT, 100 W, Ar/SF$_6$, 180 MHz*
Effect of Upper Electrode Radius – 100 W - 1

- As long as the upper electrode is larger than the lower electrode, upper electrode size has little impact on the plasma distribution under conditions where electromagnetic standing wave effects are dominant.

\[ e \text{ (Max } = 2.65 \times 10^{16} \text{ m}^{-3}\text{)} \]

- 17.8 cm

\[ e \text{ (Max } = 2.52 \times 10^{16} \text{ m}^{-3}\text{)} \]

- 20.1 cm

\[ e \text{ (Max } = 2.52 \times 10^{16} \text{ m}^{-3}\text{)} \]

- 22.4 cm

- 100 mT, Ar, 100 W, 180 MHz
Upper electrode size has little impact on power deposition or electromagnetic fields.

- For an upper electrode radius of 17.8 cm:
  - $|A_z^{(1)}|$ (Max = $3.23 \times 10^{-7}$ V·s/m)
  - $P_e(ES)$ (Max = $1.27 \times 10^5$ W/m$^3$)
  - $P_e(EM)$ (Max = $1.36 \times 10^4$ W/m$^3$)

- For an upper electrode radius of 22.4 cm:
  - $|A_z^{(1)}|$ (Max = $3.21 \times 10^{-7}$ V·s/m)
  - $P_e(ES)$ (Max = $1.29 \times 10^5$ W/m$^3$)
  - $P_e(EM)$ (Max = $1.27 \times 10^4$ W/m$^3$)

100 mT, Ar, 100 W, 180 MHz
At large RF powers where electron density is large and electromagnetic effects become weaker, upper electrode size has little impact on plasma distribution near the chamber center.

Plasma at the lower electrode edge starts getting perturbed when upper electrode size becomes comparable to lower electrode size.

\[ [e] \text{ (Max} = 1.53 \times 10^{17} \text{ m}^{-3} \text{)} \]

\[ [e] \text{ (Max} = 1.28 \times 10^{17} \text{ m}^{-3} \text{)} \]

\[ [e] \text{ (Max} = 1.24 \times 10^{17} \text{ m}^{-3} \text{)} \]

\(100 \text{ mT, Ar, 800 W, 180 MHz}\)
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, “inductive” effects become important and plasma density peak moves towards the electrode edge.
- The relative importance of electrostatic effects can be increased by decreasing inter-electrode gap.