MODELING OF COLLISIONAL, LOW TEMPERATURE PLASMAS: FUNDAMENTALS AND APPLICATIONS

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AGENDA

• Role of collisional plasmas in high technology manufacturing.
• Role of modeling in development and analysis of plasma tools.
• Historical perspective of model development.
• Examples of the use of modeling in equipment design.
• Concluding remarks.
COLLISIONAL, LOW TEMPERATURE PLASMAS

- The plasmas of interest are low temperature (1-10 eV), partially ionized ([e]/N = 10^{-6}-10^{-2}) where electron collisions with neutrals (usually) dominate over collisions with ions (or other electrons).
These systems are the plasmas of everyday technology, "eV physics"

Electrons act as a mechanism to transfer power from the "wall plug" to the internal modes of atoms and molecules to "make a product".

As a consequence, it is often difficult to separate the study of low temperature, partially ionized plasmas from the technology for which they are used.
The microelectronics industry is tasked with economically producing devices of increasing complexity (PIII >10^7 transistors) and shrinking size (0.13 µm).

Ref: IBM Microelectronics

These innovations are enabled by low temperature, collisional plasmas.
• Plasmas play a dual role in microelectronics fabrication.

• First, electron impact on otherwise unreactive gases produces neutral radicals and ions. That is, electrons are a power transfer medium.

\[
e + CF_4 \rightarrow CF_3^+ + F + 2e \\
\rightarrow CF_2 + 2F + e
\]

• These active species drift or diffuse to the wafer where they remove or deposit materials.
Second, ion acceleration in sheaths delivers directed activation energy to surfaces which enables fine features to be fabricated having extreme and reproducible tolerances.

- Ion Assisted Etching
- Neutral Dominated Etching

0.25 µm Feature (C. Cui, AMAT)
The typical low pressure (<10s - 100s mTorr) plasma processing reactor is powered by inductive and capacitive coupling, and may have auxiliary static magnetic fields.
• The general properties of an Ar/Cl\(_2\) inductively coupled plasma tool will be examined.

• The inductively coupled electromagnetic fields have a skin depth of 3-4 cm.

• Absorption of the fields produces power deposition in the plasma.

• Electric Field (max = 6.3 V/cm)

• Ar/Cl\(_2\) = 80/20
• 20 mTorr
• 1000 W ICP
• 250 V bias, 2 MHz (260 W)
Ar/Cl\textsubscript{2} ICP TOOL: POWER AND ELECTRON TEMPERATURE

- Power deposition from the inductive fields results in electron heating.
- At 2 MHz, power from the capacitive fields produces ion acceleration with little electron heating.

Power Deposition (max = 0.91 W/cm\textsuperscript{3})

Electron Temperature (max = 5 eV)

- Ar/Cl\textsubscript{2} = 80/20, 20 mTorr, 1000 W ICP, 250 V, 2 MHz bias (260 W)

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• Electron impact ionization by the bulk electrons heated by the inductively coupled fields dominates.

• Ionization by sheath accelerated beam electrons is less important due to their long mean-free-paths at the low operating pressure.

**Beam ionization (max = 1.3 x 10^{14} /cm^3-s)**

**Bulk ionization (max = 5.4 x 10^{15} /cm^3-s)**

• Ar/Cl$_2$ = 80/20, 20 mTorr, 1000 W ICP, 250 V, 2 MHz bias (260 W)
• The diffusion of plasma from the remote sources produces a fairly uniform positive ion density in the vicinity of the substrate.

• In general, better uniformity is obtained with a bias than without.

• $\text{Ar/Cl}_2 = 80/20$, 20 mTorr, 1000 W ICP, 250 V, 2 MHz bias (260 W)
- The small current collection area of the substrate produces a large negative dc bias.

- The large sheath potential results in electron current being collected during a small fraction of the rf cycle.

- The non-linearity of the sheaths at different surfaces also contributes to the non-sinusoidal current.

- \( \text{Ar/Cl}_2 = 80/20, 20 \text{ mTorr, } 1000 \text{ W ICP, 250 V, 2 MHz bias (260 W)} \)
• The acceleration of ions through the time varying sheaths produces directed fluxes to the substrates. The mixture of isotropic neutral radicals and anisotropic ions produces high aspect ratio etch profiles.

Example:

- SiO\textsubscript{2} etching in an ICP fluorocarbon plasma with rf substrate bias.
PHYSICS TO BE ADDRESSED

- GAS INJECTORS (fluid dynamics)
- BULK PLASMA (plasma hydrodynamics, kinetics, chemistry, electrostatics, electromagnetics)
- SOLENOID (magnetostatics)
- COILS (electromagnetics)
- DOME (surface chemistry, sputter physics)
- rf BIASED SUBSTRATE
- E-FIELD (sheath physics)
- POWER SUPPLY (circuitry)
- PROFILE EVOLUTION (surface chemistry, sputter physics, electrostatics)
- POLYMER (surface chemistry, sputter physics)
- Secondary emission (beam physics)
- M+ e

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The development of models for plasma processing has significantly progressed for almost 2 decades leveraging contributions from a wide range of disciplines.
The coupling of atomic and molecular physics (i.e., atomic structure) to macroscopic properties (i.e., transport coefficients) is through moments of the electron energy distribution (EED) with collision cross sections.

\[ k = \int_{0}^{\infty} f(\varepsilon) \left( \frac{2\varepsilon}{m_e} \right)^{1/2} \sigma(\varepsilon) \, d\varepsilon \]

\[ f(\varepsilon) = \text{Electron energy distribution} \]
\[ \sigma(\varepsilon) = \text{Electron collision cross section} \]

The EED is obtained through solution of the collisional Boltzmann's equation.

\[ \frac{\partial f(\vec{v})}{\partial t} = -\vec{v} \cdot \nabla_x f(\vec{v}) - \vec{a} \cdot \nabla_v f(\vec{v}) + \left( \frac{\partial f}{\partial t} \right)_c \]

where the collision operator accounts for elastic, inelastic and superelastic collisions.

The difficulty of solving BE with inelastic collisions stifled progress in modeling of complex plasma chemistries.
In highly collisional plasmas with weak electric fields, the electron velocity distribution is essentially isotropic. As the field strengthens, $f(\vec{v})$ becomes only moderately anisotropic in the direction of the field. 

These conditions enabled the transformation of $f(\vec{v})$ to $f(|\vec{v}|)$ or $f(\vec{e})$ by using a spherical harmonic expansion about the angle between $\vec{v}$ and $\vec{E}$ (Allis, 1956; Shkarofsky, et al, 1966).

$$f(\vec{v}, \vec{r}) = \sum_{i} f_{i}(v, \vec{r})P_{i}(\theta) = f_{o}(v, \vec{r}) + f_{1}(v, \vec{r})\cos(\theta) + ...$$

$f_{o}$ = Isotropic component

$f_{1}$ = Anisotropic component
With the advent of high speed computers, this formulation was numerically implemented with increasing sophistication to address science and technological issues.

<table>
<thead>
<tr>
<th>Name(s)</th>
<th>Description</th>
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<tbody>
<tr>
<td>W. L. Nighan</td>
<td>EEDs in molecular gases for electric discharge lasers</td>
</tr>
<tr>
<td>(PRA, 2, 1989 (1970)</td>
<td></td>
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<tr>
<td>S. D. Rockwood</td>
<td>Electron-electron collisions</td>
</tr>
<tr>
<td>(PRA 8, 2348 (1973))</td>
<td></td>
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<tr>
<td>L. Pitchford and A. Phelps</td>
<td>Higher order expansions to address higher degrees of anisotropy; density</td>
</tr>
<tr>
<td>(PRA 1980-1990)</td>
<td>gradient expansions</td>
</tr>
<tr>
<td>C. M. Ferreira; M. Capitelli</td>
<td>Coupling of EED with excitation of internal modes of molecules</td>
</tr>
<tr>
<td>and C. Gorse</td>
<td></td>
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<tr>
<td>(1985-1995)</td>
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<tr>
<td>W. L. Morgan</td>
<td>ELENDIF (first publically available collisional Boltzmann solver)</td>
</tr>
<tr>
<td>(CPC 58, 127 (1990))</td>
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A flurry of activity in the 1980s resulted in a fundamental understanding of the dynamics of EEDs in collisional plasmas, which produced a core knowledge for present modeling activities.
Rockwood’s work stands out for “standardizing” numerical solutions of Boltzmann’s equation including inelastic and electron-electron collisions.

The method borrows from Allis, and Canavan and Proctor in the use of fluxes of electrons along the energy axis in phase space.

\[
\frac{\partial n}{\partial t} = -\frac{\partial J_s}{\partial \varepsilon} - \frac{\partial J_{el}^s}{\partial \varepsilon} + \sum_{s,j} N_s^0 \left( R_{sj}(\varepsilon + \varepsilon_{sj}^*) n(\varepsilon + \varepsilon_{sj}^*) + R_{sj}(\varepsilon - \varepsilon_{sj}^*) n(\varepsilon - \varepsilon_{sj}^*) \right) \frac{N_s^j}{N_s^0} \\
+ R_s^i(\varepsilon + \varepsilon_{si}^*) n(\varepsilon + \varepsilon_{si}^*) + \delta(\varepsilon) \int_{\varepsilon_{si}^*}^{\infty} R_s^i(\varepsilon) n(\varepsilon) \, d\varepsilon - [P_{sj}(\varepsilon) + R_{sj}^i(\varepsilon) + R_s^i(\varepsilon)] n(\varepsilon)
\]

Rockwood demonstrated the method by “backing out” electron impact cross sections from swarm data for Hg, values still in use today.

PRA 8, 2348 (1973)
The availability of "Commodity" numerical solutions of Boltzmann's equation enabled fundamental properties of electron interactions with molecules to be accurately incorporated into plasma equipment models.

Example: Electron swarm properties in $N_2$: The low energy vibrational cross sections produce a "cut-off" EED whose tail rises only at high $E/N$. 

![Graph showing electron energy distribution and vibrational cross sections.](image)
The fundamental understanding of electron swarms afforded by mastery of Boltzmann's equation enabled integrated plasma models to evolve.

Integrated models are time and spatially dependent accountings of electron, ion and neutral transport while including consequences of "chemistry" and "boundaries".

The first integrated models were for capacitively coupled rf discharges in which sheath motion produces electron heating.

**End Results:**

- Potentials
- EEDs
- Heating and excitation rates
- Energy resolved ion fluxes to substrate
Given the baseline fundamental understanding of electron transport afforded by mastery of Boltzmann's equation, 2 methodologies evolved for integrated plasma models:

- Kinetic models are time and spatially dependent solutions of Boltzmann's equation which produce electron and ion velocity distributions, either directly or statistically.

- Fluid models solve moments of Boltzmann's equation.
• Although computationally intensive, integrating Boltzmann's equation for $f(\vec{v}, \vec{r}, t)$ provides the most detail and is least dependent on apriori assumptions.

• Direct integrations typically involved use of "propagators" or Greens functions to transport electron and ion pseudoparticles through the $(\vec{v}, \vec{r})$ phase space.

T. J. Sommerer, et. al., PRA 43, 4452 (1991)
RF DISCHARGE IN He: STOCHASTIC HEATING

- Solving BE using a Greens function or "propagator" method, Sommerer et al (PRA 43, 4452 (1991)) demonstrates stochastic heating.

- He, 13.56 MHz, 0.1 Torr, 500 V
Early fluid modeling of rf discharges were 1-d simulations using simple gases and “local” electron momentum and energy transport.

Large strides were made in our understanding of both discharge dynamics and numerical methods.

He/electronegative gas, 1 MHz, 1 Torr

• Increasing sophistication in numerical methods and availability of computing power allowed higher dimensionality and more complete physics in fluid modeling.

• Fully hydrodynamic 2-d models demonstrated “edge effects” in rf discharges which still dominate design considerations of etch tools.

\[
\frac{\partial n_e}{\partial t} = -\nabla \cdot (u_e n_e) + u n_e
\]

\[
\frac{\partial (m n_e u_e)}{\partial t} = -\nabla \cdot (m n_e u_e u_e) - n_e q E - \nabla P_e - \frac{m n_e u_e}{\tau_m}
\]

\[
\frac{\partial n_e w}{\partial t} = -\nabla \cdot (n_e w u_e) - n_e q u_e E - \nabla \cdot (u_e P_e) - \frac{n_e w}{\tau_w}.
\]

• He, 13.56 MHz, 1 Torr

• F. F. Young and C-H. Wu, Trans. Plasma Sci. 21, 312 (1992)
HYBRID MODELING OF rf DISCHARGES

- As chemistries became more complex, the need for kinetically derived transport coefficients and rate constants increased.
- Since fluid methods have significant computational advantages over purely kinetic formulations, hybrid models evolved to meet these needs.

- In hybrid models, different numerical techniques are iteratively combined to address different physics or different time/spatial scales.
- Kinetic methods are used for non-local energy transport to derive transport coefficients.
- Fluid methods provide densities and electric fields.
• Hybrid techniques enabled complex gas chemistries to be addressed and, with including additional modules, modeling of electromagnetically excited systems, such as inductively coupled plasmas (ICPs).

- He/CCl₄=9/1, 0.25 Torr, 600 V
- Sommerer et al, JVST B 10, 2179 (1992)

- Ar, 10 mTorr, 150 W
- Ventzek et al. JVST B 12, 3118 (1994)
ELECTROMAGNETICS

- The wave equation is typically solved in the frequency domain:

\[
- \nabla \left( \frac{1}{\mu} \nabla \cdot \bar{E} \right) + \nabla \cdot \left( \frac{1}{\mu} \nabla \bar{E} \right) = \frac{\partial^2 (\varepsilon \bar{E})}{\partial t^2} + \frac{\partial (\sigma \bar{E} + \bar{J})}{\partial t} \quad \sigma = \sum_j \frac{q^2 n_j}{m_j v_j (1 - \frac{i \omega}{v_j})}
\]

\[
\bar{E}(\bar{r}, t) = \bar{E}'(\bar{r}) \exp(-i(\omega t + \varphi(\bar{r})))
\]

- With static applied magnetic fields, conductivities are tensor quantities:

\[
\bar{\sigma} = \sigma_o \frac{m v_m}{q \alpha} \frac{1}{(\alpha^2 + |\vec{B}|^2)} \begin{pmatrix}
\alpha^2 + B_r^2 & \alpha B_z + B_r B_\theta & -\alpha B_\theta + B_r B_z \\
-\alpha B_z + B_r B_\theta & \alpha^2 + B_\theta^2 & \alpha B_r + B_\theta B_z \\
-\alpha B_\theta + B_r B_z & -\alpha B_r + B_\theta B_z & \alpha^2 + B_z^2 \\
\end{pmatrix}
\]

\[
\bar{j} = \bar{\sigma} \cdot \bar{E} \quad \alpha = \frac{(i \omega + v_m)}{q / m} \quad \sigma_o = \frac{q^2 n_e}{m v_m}
\]

- Circuit models are used to provide antenna currents.
ELECTRON ENERGY TRANSPORT

• Under conditions where collisional heating and diffusive transport dominate, electron transport coefficients and electron impact source functions are obtained by solving the electron energy equation.

\[
\frac{\partial}{\partial t}\left( \frac{3}{2} n_e k T_e \right) = S(T_e) - L(T_e) - \nabla \cdot \left( \frac{5}{2} \Phi k T_e - \kappa (T_e) \nabla T_e \right) + S_{EB}
\]

where

- \(S(T_e)\) = Power deposition
- \(L(T_e)\) = Electron power loss due to collisions
- \(\Phi\) = Electron flux
- \(\kappa(T_e)\) = Electron thermal conductivity
- \(S_{EB}\) = Electron source from beam electrons

• Transport coefficients are obtained as a function of average energy \((\epsilon = (2/3) T_e)\) from solution of Boltzmann' Equation for the electron energy distribution.
ELECTRON ENERGY TRANSPORT

- When electron energy deposition is non-collisional and/or transport is non-diffusional, Monte Carlo techniques are used.
  - Secondary electron emission and acceleration through sheaths.
  - Wave heating and trapping.
  - Long mean-free-path transport.
- Conduction currents are kinetically derived from the MCS for use in solving the wave equation.

\[
J_e(r) = J_0(r) \exp(i\phi_V(r)) \hat{\theta} = -q n_e(r) v_\theta (r) \exp(i\phi_V(r)) \hat{\theta}.
\]
Multi-fluid techniques are used where continuity, momentum and energy equations are solved for each species, with coupling terms for exchange of momentum and energy.

\[ \frac{\partial N_i}{\partial t} = -\nabla \cdot (N_i \vec{v}_i) + S_i \]

\[ \frac{\partial (N_i \vec{v}_i)}{\partial t} = \frac{1}{m_i} \nabla (kN_i T_i) - \nabla \cdot (N_i \vec{v}_i \vec{v}_i) + q_i N_i \left( \vec{E} + \vec{v}_i \times \vec{B} \right) - \nabla \cdot \vec{\mu}_i \]

\[ - \sum_j \frac{m_j}{m_i + m_j} N_i N_j \left( \vec{v}_i - \vec{v}_j \right) \nu_{ij} \]

\[ \frac{\partial (N_i \varepsilon_i)}{\partial t} + \nabla \cdot Q_i + P_i \nabla \cdot U_i + \nabla \cdot (N_i U_i \varepsilon_i) = \frac{N_i q_i^2 \varepsilon_i}{m_i (v_i^2 + \omega^2)} E^2 \]

\[ + \frac{N_i q_i^2}{m_i v_i} E_s^2 + \sum_j \frac{m_{ij}}{m_i + m_j} N_i N_j R_{ij} k B (T_j - T_i) \pm \sum_j 3N_i N_j R_{ij} k B T_j \]

Slip boundary conditions are used for neutral transport for momentum and energy to address momentum and temperature jump conditions.
Given the hierarchy of time scales and large number of species, fully implicit solutions of all transport equations are typically not done.

Due to the extremely short dielectric relaxation times ($< 10^{-12}$ s), Poisson's equation must be implicitly solved.

A typical method uses a prediction of densities for the time at which the fields will be used. Surface charges are included here.

$$\nabla \cdot \varepsilon \nabla \Phi(t + \Delta t) = - \left( \rho_s + \sum_i q_i N_i - \Delta t \cdot \sum_i \left( q_i \nabla \cdot \vec{\phi}_i \right) \right)$$

When sheaths are not resolved by the mesh, semi-analytic models are used to obtain sheath potentials, which are inserted as potential "jump-conditions" at surfaces.
CIRCUIT MODELS

- Circuit models for the reactor and driving electronics provide voltage harmonics (amplitude and phase) on metal surfaces for solution of Poisson's equation.

- Sheath models are typically employed to account for non-linearities in the plasma response to harmonic excitation.
The MCFP model predicts time and spatially dependent etch profiles using neutral and ion fluxes from the PCMCS.

Any chemical mechanism may be implemented in the MCFP using a "plasma chemistry" input hierarchy.

e.g., $\text{Cl}^+ + \text{SiCl}_2(\text{s}) \rightarrow \text{SiCl}_2(\text{g})$

All pertinent processes can be included: thermal etch, ion assisted etch, sputter, redeposition, passivation.

Energy dependent etch processes may be implemented using parametric forms.

The MCFP may utilize ALL flux statistics from the PCMCS:
- Ion energy and angular distributions
- Neutral energy and angular distributions
- Position dependent fluxes

MONTE CARLO FEATURE PROFILE MODEL (MCFP)
EXAMPLES OF PLASMA EQUIPMENT MODELING FOR TOOL DESIGN

IONIZED METAL PHYSICAL VAPOR DEPOSITION

MAGNETICALLY ENHANCED INDUCTIVELY COUPLED PLASMAS
Ionized Metal PVD (IMPVD) is being developed to fill deep vias and trenches for interconnect, and for deposition of seed layers and diffusion barriers. In IMPVD, a second plasma source is used to ionize a large fraction of the sputtered metal atoms prior to reaching the substrate.

**Typical Conditions:**
- 10’s mTorr Ar buffer
- 100s V bias on target
- 100s W - kW ICP
- 10s V substrate bias
In Physical Vapor Deposition (PVD), the majority of the metal flux to the substrate is neutral, having a broad angular distribution. This leads to nonconformal deposition and creation of voids.

In IMPVD, the addition of anisotropic metal ions to the flux produces conformal deposition by anisotropic filling and sputtering of overhangs.
- PVD/IMPVD reactor with Cu Target
- 3.5-20 mTorr Ar (constant pressure), 150 sccm
- Annular magnetic field (200 G below target)
- Target: -200 V dc (2.4 kW)
- Substate: 40 V, 10 MHz, 350 W
- Coils: 2 MHz, 1250 W with Faraday shield

- Physics included:
  - Gas heating by sputtered target atoms
  - Ion energy dependent sputter yield
  - Neutral and ion momentum and energy
  - Bulk electron energy equation
  - Monte Carlo secondary electrons
  - Cross field Lorentz forces

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AFOSR9912
MAGNETRON SPUTTER TOOL: Ar/Cu

- Secondary electron emission from the target, and electron heating in the sheath, produces a torroidal electron source.

- Peak ion densities are mid-$10^{12}$ cm$^{-3}$.

- Ar, 3.5 mTorr
- -200 V Target, 200 G
FLUXES IN THE Ar/Cu PVD TOOL

- Ion sputtering of the target produces a neutral Cu flux into the plasma.

- The low gas pressure and long mean free path of Cu atoms results in the flux to the substrate being “direct” neutrals.

- Ar, 3.5 mTorr
- -200 V Target, 200 G
The added inductively coupled electric field from the rf coils heats electrons in the bulk plasma producing a peak in temperature away from the target.

- Ar, 20 mTorr
- -200 V Target, 200 G
- 1.25 kW ICP, 2 MHz
The combination of the magnetron fields and heating from the rf coils produces a more extended electron source and electron density. The ion density is 75% argon.

- Ar, 20 mTorr
- -200 V Target, 200 G
- 1.25 kW ICP, 2 MHz
IMPVD TOOL: ION FLUX AND SPUTTER SOURCE

- The magnetron focuses the ion flux to the target, producing a sputter source of Cu atoms.

- Due to the high gas pressure, the Cu atoms are thermalized in the vicinity of the target.

- Ar, 20 mTorr
- -200 V Target, 200 G
- 1.25 kW ICP, 2 MHz
IMPVD TOOL: Cu DENSITIES

- Due to the longer residence time of Cu in the chamber and the higher electron temperature produced by the rf heating, the Cu inventory is largely converted to ions and metastables [Cu(2D)].

- Ar, 20 mTorr
- -200 V Target, 200 G
- 1.25 kW ICP, 2 MHz
• The flux of Cu to the substrate is 85-90% ionized.

• The neutral flux is largely metastable Cu(2D).

• Ar, 20 mTorr
• -200 V Target, 200 G
• 1.25 kW ICP, 2 MHz
With increasing ICP power deposition, a larger proportion of the Cu metal flux striking the substrate is ionized.

The end result is conformal trench filling and elimination of the void.

ICP Power = 0.3 kW  
Cu\(^+\) : Cu Neutrals = 1.4:1  
0.6 kW  
2.5:1  
1.0 kW  
3.0:1

Ar 30 mTorr, 300 W Magnetron, -30 V bias
WAVE PROPAGATION IN MAGNETICALLY ENHANCED ICPs

- It is often desirable to produce plasmas in the "volume" of large reactors. This is difficult to accomplish using ICPs due to their finite skin depth.
- With a solenoidal magnetic field, electromagnetic waves can be made to propagate into the volume of the plasma.

- In magnetically enhanced ICP excitation occurs through electromagnetic and electrostatic modes.
- Helicon
- Trivelpiece-Gould

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The HPEM was applied to analysis of a commercial MEICP etching tool.
At low B-fields, the electromagnetic propagation is mainly inwardly radial producing standing wave patterns.

As the B-field increases, propagation shifts to the axial direction with increasing wavelength.

- Ar, 10 mTorr, 1kW, 50 sccm
As the magnetic fields increase, axial propagation dominates depositing power in the downstream region.

- Ar, 10 mTorr, 1kW, 50 sccm
As the static magnetic field increases, the ion saturation current peaks further downstream.

For constant power deposition, the peak downstream plasma density decreases due to the larger volume of the lower chamber.

- Ar, 2.3 mTorr, 1kW (Trikon Technologies, Inc.)
- Ar, 10 mTorr, 1kW, 50 sccm
WAVELENGTH IN CYLINDRICAL GEOMETRY

- Using the dispersion relation for a helicon wave, the wavelength for an $m = 0$ mode can be obtained. From the simulation, the wavelength resembles an $m = 0$ in a cylindrical geometry.

\[
\lambda_z = \frac{3.83 B_0}{R e \mu_o n_e f} \quad \text{for } k_\perp >> k_z
\]

\[
\lambda_z = \sqrt{\frac{2 \pi B_0}{e \mu_o n_e f}} \quad \text{for } k_z >> k_\perp
\]

Theoretical Wavelength

Computed Wavelength

\[
\lambda_z (\text{cm}) = \frac{7.6 \times 10^6}{R_{cm}} (\frac{B_0 (\text{Gauss})}{n_e (\text{cm}^{-3})})^{0.6}
\]
Azimuthal and axial components of the electric field will be shown for: Ar, 1 kW, 10 mTorr, B = 20-300 G
• With increasing B-field, the downstream electric field is increasingly dominated by axial and radial components.

• The end result is a large acceleration gradient in a direction of high mobility for conditions where the mean-free-path of electrons is large.

- 300 G, 1 kW, 10 mTorr

![Amplitude/Phase](image1)

\[ E(\theta) \ [0.15 - 15 \text{ V/cm}] \]

![Amplitude/Phase](image2)

\[ E(z) \ [0.05 - 5 \text{ V/cm}] \]
The long mean free path of electrons of 10s eV (while lower energy electrons are collisional) and the presence of axial electric fields downstream results in collisionless heating and some Landau damping.

The effect is more pronounced at lower pressures where mean-free-paths are longer.

- Ar, 1 kW, 50 sccm, 300 G
The tail end of the EED continues to “lift” with increasing distance downstream from the coils indicating some amount of electron trapping.

The axial component of the electromagnetic field is responsible for most of the power deposition.

- Ar, 1 kW, 300 G, 2mTorr
CONCLUDING REMARKS

- Plasma equipment modeling has developed to the point that quantitative design of tools can be performed and the design cycle can be shortened.

- Process design based on modeling is in a more qualitative state, though progress is being made.

- Significant improvements are required in our databases of fundamental parameters (e.g., cross sections) so that more complex plasma chemistries can be addressed.