CAPACITIVE DISCHARGES DRIVEN BY COMBINED DC/RF SOURCES

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MOTIVATIONS FOR ADDING DC SOURCE

- “Tune” discharge particle and energy balance
  \( \Rightarrow T_e \downarrow, n_e \uparrow \), radial uniformity)
- “Tune” secondary electron bombardment of substrate
  (etch selectivities, charging damage)

OUTLINE

- Structure of DC/RF sheaths — theory
- Equal area diode discharges — theory and 1D PIC simulations
- Asymmetric diode discharges — theory and 1D PIC simulations
- Secondary electrons — timescales and energy deposition
- Triode discharges — theory and 2D PIC simulations
STRUCTURE OF A DC/RF SHEATH

- DC voltage \( \bar{V} = \bar{V}_0 + \bar{V}_1 \)
- RF voltage \( \tilde{V} = \tilde{V}_0 + \tilde{V}_1 \)

- New result for Child law for collisionless ions:

\[
\tilde{J}_i = \frac{4}{9} \varepsilon_0 \left( \frac{2e}{M} \right)^{1/2} \frac{1}{s^2} \left( \bar{V}^{1/2} - \frac{1}{3} \bar{V}_1^{1/2} \right) \left( \bar{V}^{1/2} + \frac{2}{3} \bar{V}_1^{1/2} \right)^2
\]

- New result for Child law for collisional ion sheath also obtained

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EQUAL AREA DIODE DISCHARGE

- Comparison of theory with 1D particle-in-cell (PIC) simulations

(Symbols: PIC with argon pressure in mTorr; lines: theory; $\beta \propto \lambda_D/\lambda_i = \text{collisionality};
\gamma_i = \text{secondary emission coefficient})

- Excellent agreement of PIC with collisional Child law

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**DENSITY AND VOLTAGE AT CONSTANT \( P_{\text{rf}} \)**

(60 mTorr, 6 cm gap, 4 MHz, 0.017 W/cm\(^2\), \( V_{\text{dc}} = 350 \text{ V} \))

![Graph showing density and voltage profiles](image)

<table>
<thead>
<tr>
<th>( \gamma_i )</th>
<th>( V_{\text{rf}} ) (V)</th>
<th>( \overline{V}_b ) (V)</th>
<th>( \epsilon_{\text{eff}} ) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rf only</td>
<td>0</td>
<td>1064</td>
<td>436</td>
</tr>
<tr>
<td>Dc+rf</td>
<td>0</td>
<td>1277</td>
<td>398</td>
</tr>
<tr>
<td>Rf only</td>
<td>0.2</td>
<td>805</td>
<td>330</td>
</tr>
<tr>
<td>Dc+rf</td>
<td>0.2</td>
<td>980</td>
<td>283</td>
</tr>
</tbody>
</table>

(\( \overline{V}_b \) = plasma potential; \( \epsilon_{\text{eff}} \) = collisional energy loss/electron-ion pair)

- Plasma potential \( \overline{V}_b \) and sheath width \( s_b \) independent of \( V_{\text{dc}} \)
- Secondary electrons increase discharge efficiency
- \( V_{\text{dc}} \) reduces bulk plasma thickness
**ASYMMETRIC DIODE RESULTS**

- Excellent agreement between 1D (cylindrical) PIC and collisional CL theory

- Introduce rf voltage asymmetry ratio $\alpha_{ab} = \frac{\tilde{V}_{a1}}{\tilde{V}_{b}}$

![Diagram showing DC/RF sheath and RF sheath with notation $V_{dc}$, $V_{rf}$, $V_{a0}$, $V_{a1}$, $V_{a2}$, $V_{b}$, $s_a$, $s_a0$, $s_a1$, $s_b$, and $\alpha_{ab}$ values.](image)

- Numbers near each symbol: mTorr ($\alpha_{ab}$)

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SECONDARY ELECTRON LOSS PROCESSES

• Surface losses to substrate and walls:
  — Transit time across gap \( \tau_{fr} = d/v_h \) at low pressures
  — Diffusion time \( \tau_{diff} = d^2/2D_h \) at higher pressures \( (D_h = \lambda_h \bar{v}_h/3) \)
  — Trapping time \( \tau_{trap} = \delta/f \) (favorable configuration of rf voltages can trap secondaries for a fraction \( \delta \) of the rf period \( 1/f \))

\[
\tau_{lh} = \left( \tau_{fr}^2 + \tau_{diff}^2 + \tau_{trap}^2 \right)^{1/2} = \nu_{lh}^{-1}
\]

• Volume losses: secondary electrons lose energy and join the thermal population

\[
\tau_{izh}^* = \frac{\mathcal{E}_h}{\nu_{izh} \mathcal{E}_{ch}}
\]

(\( \mathcal{E}_h, \nu_{izh} \) are secondary energy and ionization frequency; \( \mathcal{E}_{ch} \approx 20 \text{ V} \) is secondary collisional energy loss/e-i pair created)

• Total loss frequency is \( \nu_h = \nu_{lh} + \nu_{izh}^* \)

  If \( \nu_{izh}^* \gg \nu_{lh} \), secondary electrons efficiently produce e-i pairs
  If \( \nu_{lh} \gg \nu_{izh}^* \), secondary electrons efficiently bombard the substrate
Most interesting regions are where trapped and untrapped electrons behave differently.
TRIODE DC/RF DISCHARGE

- Substrate can have a dielectric layer which cannot draw dc current

A triode configuration is necessary

- A global model incorporating the collisional dc/rf sheath is used to determine the voltages, currents, and sheath widths
• Collisional theory results for triode

- Example (red solid line):
  DC electrode area = ground electrode area = $\frac{1}{2} \times$ RF electrode area
  For $V_{dc} \to 0$, equal area diode and $\tilde{V}_b/V_{rf} = 0.5$
  For $V_{dc} \to \infty$, asymmetric diode and $\tilde{V}_b/V_{rf} = 0.86$. 

\[
\begin{align*}
\tilde{V}_b/V_{rf} & \approx 0.86 \\
V_{dc}/V_{rf} & \approx 0.5 \\
\end{align*}
\]
2D PIC SIMULATION BASE CASE

- $p = 30$ mTorr, $P_{\text{rf}} = 2.2$ W, $\gamma_i = 0.2$ at all surfaces
- Secondaries in “trapped deposition, untrapped diffusion” regime
UNIFORMITY IS MODIFIED BY $V_{dc}$

Plasma density ($m^{-3}$)

- Thinner bulk plasma near midplane ($y = 0.06$ m) for DC/RF case

$\Rightarrow$ center-low plasma density profile

Secondary density ($m^{-3}$)

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• Secondary electrons are ballistic and have high energies for DC/RF case
• Effects of $V_{dc}$ on profile:
  Thinner bulk plasma $\Rightarrow$ center-low profile
  Increased secondary ionization $\Rightarrow$ center-high profile
CONCLUSIONS

• Collisionless and collisional DC/RF Child laws determined
• DC voltage can control the discharge asymmetry
• DC voltage increases secondary electron ionization
• DC voltage reduces bulk plasma thickness
• DC voltage promotes the formation of ballistic electrons
• DC voltage modifies the plasma density profile

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