LOW TEMPERATURE PLASMA PHYSICS

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Outline

- Operation of capacitively coupled radio-frequency discharges ✔
- Particle-in-Cell / Monte Carlo Collisions (PIC/MCC) simulation method ✔
- Electron power absorption in electropositive and electronegative discharges ✔
- Regions of the RF plasma
- Impedance matching
- Methods of controlling the ion flux and energy
Capacitively coupled radio-frequency discharges

The physical (model) system

- Mobile electrons follow field variation → ionization
- Ions “feel” the time-averaged electric field
- **Sheath + bulk** structure develops
- Symmetric / asymmetric configurations
- α and γ modes of operation
- Mathematical description:
  - fluid
  - hybrid
  - Particle-in-Cell
- Applications in plasma processing

Ion & electron density distributions
in an electropositive discharge (e.g. noble gases)

Ion space charge

Capacitive coupling

RF (~1...100 MHz) generator

Electron cloud

Capacitive coupling

C

[recap.]
Particle-in-Cell simulation with Monte Carlo collisions (PIC/MCC)

- **Collisional plasma**
  - MC: Check for collisions, add/remove particles
  - Assign charges to grid points
  - Calculate electric field at grid points (Poisson eq.)
  - Weight field to particle positions (calculate forces)
  - Advance particles (equation of motion) new velocities and positions
  - Check for boundaries: remove/add particles

- **Bounded plasma**

[recap.]
Electron power absorption modes

**ALPHA mode**
($\alpha$: ionisation coefficient)
Maximum ionisation near the edge of the expanding sheath

**GAMMA mode**
($\gamma$: electron emission coefficient)
Maximum ionisation within the sheaths, in electron avalanches starting from the electrodes

**DRIFT-AMBIPOLAR mode**
Ionisation within the bulk plasma and at the edge of the collapsing sheath

$\phi(t) = \phi_0 \cos(2\pi ft)$
Spatial regions of RF plasmas

1) The sheath

Argon,
\[ f = 13.56 \text{ MHz}, \ L = 2.5 \text{ cm}, \ \ p = 10 \text{ Pa}, \ \phi_0 = 300 \text{ V} \]

\[ E(s) = 0 \]
\[ \phi(s) = 0 \]

Determination of the sheath length:

\[
\int_0^s n_e(x)\,dx = \int_s^{L/2} [n_i(x) - n_e(x)]\,dx
\]

\[ \phi(t) = \phi_0 \cos(2\pi ft) \]

[Brinkmann R P 2007 J. Appl. Phys. 102, 093303]
Spatial regions of RF plasmas

1) The sheath

The length of the sheath: \( s \)

The electric field within the sheath:

\[
E(x) = -\frac{e}{\varepsilon_0} \int_x^s n_i(x')dx'
\]

The potential of the electrode:

\[
\phi_p(x = 0) = \phi(x = s) - \int_0^s E(x)dx = \int_0^s E(x)dx = -\frac{e}{\varepsilon_0} \int_0^s \int_x^s n_i(x')dx'dx
\]

Total charge within the sheath:

\[
Q = As\bar{n}_i e
\]

\[
\phi_p(t) = -\frac{1}{2e\varepsilon_0} \left( \frac{Q}{A} \right)^2 \frac{I_s}{\bar{n}}
\]

NONLINEAR CAPACITOR

- \( \xi = x/s \) normalised space coordinate
- \( \bar{n}_i = \frac{1}{s} \int_0^s n_i(x)dx \) mean ion density
- \( P(\xi) = n_i(\xi)/\bar{n}_i \) normalised density profile
Spatial regions of RF plasmas

1) The sheath

\[ \phi(t) = \phi_0 \cos(2\pi ft) \]

Sheath length

\[ \phi_p(t) = -\frac{1}{2\varepsilon_0} \left( \frac{Q}{A} \right)^2 \frac{I_s}{n_i} \]

Voltage drop over the sheath

Total net charge in the plasma

Argon,

\[ f = 13.56 \text{ MHz}, \ L = 2.5 \text{ cm}, \]

\[ p = 10 \text{ Pa}, \ \phi_0 = 300 \text{ V} \]
Spatial regions of RF plasmas

2) The quasi-neutral region

The current is conducted by the electrons

Momentum balance

Homogeneous plasma → density and electron temperature are spatially constant (approximation)

\[ m_e n_e \frac{du_e}{dt} = -n_e e E - m_e n_e \nu_m u \]

Current:

\[ I = -e n_e u_e A \rightarrow u_e = -\frac{I}{en_e A} \]

\[ E = \frac{1}{en_e} \left[ m_e n_e \frac{du}{dt} + m_e n_e \nu_m u \right] = \frac{m_e}{e} \left[ \frac{1}{en_e A} \frac{dI}{dt} + \nu_m \frac{1}{en_e A} I \right] = \frac{m_e}{e^2 n_e A} \left[ \frac{dI}{dt} + \nu_m I \right] \]

The impedance consists of a resistive and an inductive part

\[ \phi_b = \frac{m_e L_b}{e^2 n_e A} \left[ \frac{dI}{dt} + \nu_m I \right] \]

\[ R = \frac{m_e L_b \nu_m}{e^2 n_e A} \]

\[ L = \frac{m_e L_b}{e^2 n_e A} \]
Spatial regions of RF plasmas

2) The quasi-neutral region

$$\phi_b = \frac{m_e L_b}{e^2 n_e A} \left[ \frac{dI}{dt} + \nu_m I \right]$$

The impedance consists of a resistive and an inductive part

$$R = \frac{m_e L_b \nu_m}{e^2 n_e A} \quad L = \frac{m_e L_b}{e^2 n_e A}$$

Originates from the collisions that hinder the motion of the electrons: proportional to the collision frequency and the inverse of the density

originates from the inertia (final mass of the electrons)

Argon,

$$f = 13.56 \text{ MHz}, \quad L = 2.5 \text{ cm},$$

$$p = 100 \text{ Pa}, \quad \phi_0 = 150 \text{ V}$$

The current lags behind the voltage: indication of an inductive part of the impedance
The impedance of the RF plasma

\[ Z_d = R_d + iX_d \]

Argon,
\[ f = 13.56 \text{ MHz}, \quad L = 2.5 \text{ cm}, \quad p = 100 \text{ Pa}, \quad \phi_0 = 150 \text{ V} \]

\[ Z_d = (10 - i71) \Omega \]

development
Impedance matching

\[ \tilde{\phi}_d = \phi_s \frac{Z_d}{R_s + Z_d} \]
\[ \tilde{I}_d = \frac{\tilde{\phi}_d}{Z_d} = \frac{\phi_s}{R_s + Z_d} = \frac{\phi_s}{R_s + R_d + iX_d} \]

The definition of complex power for alternating current (AC) circuits:

\[ S = \tilde{\phi}_{d,\text{eff}}\tilde{I}_{d,\text{eff}} \]

The power absorbed by the load (i.e. the plasma) is the real part:

\[ P = \frac{1}{2} \text{Re}[\tilde{\phi}_d\tilde{I}_d^*] = \frac{1}{2} \phi_s^2 \frac{R_d}{(R_s + R_d)^2 + X_d^2} \]

Conditions for maximum delivered power:

\[ \frac{\partial P}{\partial R_d} = 0 \quad \rightarrow \quad R_d = R_s \]
\[ \frac{\partial P}{\partial X_d} = 0 \quad \rightarrow \quad X_d = 0 \quad \text{usually do not hold} \]

Consequences: (1) little part of the power is absorbed in the plasma and (2) major part of the power is reflected to the generator (can cause damage)
Impedance matching

The aim is that the generator “sees” an impedance

The matching circuit should have no losses (good quality, reactive elements only!)

\[ Z = R_s \]
Impedance matching

Two equations for the real and imaginary parts:

\[
\begin{align*}
\omega L + X_d &= \omega R_d R_s C \\
R_d &= [1 - \omega^2 L C - \omega X_d C] R_s
\end{align*}
\]

\[
C = \frac{1}{\omega \sqrt{\frac{R_s - R_d}{R_s^2 R_d}}}
\]

\[
L = \frac{1}{\omega} \left[ \sqrt{R_d (R_s - R_d) - X_d} \right]
\]

Example: Argon, \( f = 13.56 \text{ MHz} \), \( L = 2.5 \text{ cm} \), \( p = 100 \text{ Pa} \), \( \phi_0 = 150 \text{ V} \)

\( A = 750 \text{ cm}^2 \quad Z_d = (10 - i71)\Omega \quad C = 469 \text{ pF} \) and \( L = 1.07 \mu\text{H} \)

depends on the operating conditions!!
Development of DC self-bias voltage

\[ \phi_s(t) = \phi_c(t) + \phi_p(t) + \phi_b(t) + \phi_g(t) \]

The AC voltage drop on the blocking capacitor is negligible, however a DC component may build up that compensates for the DC self-bias of the discharge.

\[ \phi_c = -\eta \]

e.g. asymmetric electrode configuration

The DC self-bias voltage ensures that the same number of electrons and ions reach a given electrode during one RF cycle (= no DC current)

\[ Z_d = R_d + iX_d \]
Discharge symmetry and the DC self-bias voltage

\[ \phi_p(t) + \phi_g(t) \]

\[ 0 + \hat{\phi}_g \]

\[ \hat{\phi}_p + 0 \]

Positive extremum

\[ \phi_{s,\text{max}} + \eta = \hat{\phi}_g \]

\[ \hat{\phi}_g > 0 \quad Q = Q_{\text{max},g} \]

Negative extremum

\[ \hat{\phi}_p < 0 \quad Q = Q_{\text{max},p} \]

\[ \phi_{s,\text{min}} + \eta = \hat{\phi}_p \]

We neglect the voltage drop over the quasineutral bulk region

\[ \epsilon = \left| \frac{\hat{\phi}_g}{\hat{\phi}_p} \right| \]

\[ \epsilon = \left( \frac{A_p}{A_g} \right)^2 \frac{\overline{n}_{i,p}}{\overline{n}_{i,g}} \left( \frac{Q_{\text{max},g}}{Q_{\text{max},p}} \right)^2 \frac{I_{sg}}{I_{sp}} \]

Symmetry parameter

DC self-bias voltage

\[ \eta = -\frac{\phi_{s,\text{max}} + \epsilon \phi_{s,\text{min}}}{1 + \epsilon} \]

Geometrical or electrical asymmetry
Ion properties at the surfaces: flux and energy

Most of the applications: etching, deposition

At typical RF frequencies the ions “feel” only the time-average of the electric field

Ion energy distribution is defined by:

- voltage drop over the sheath region
- ratio of the ion transit time and the RF period
- number of collisions within the sheath (ratio of mean free path and sheath length)

\[ V(t) = V_0 \sin(2\pi ft) \]
PIC/MCC results: Ion energy distribution at the electrodes

Argon, $L = 2.5$ cm, $\gamma = 0.1$, $\phi_1 = 300$ V (150 V*)
**PIC/MCC results: Ion energy distribution at the electrodes**

- Ar discharge
- $f = 13.56$ MHz
- $p = 50$ mTorr
- $V = 350$ V

**Flux-energy distribution**

- Periodic acceleration in the sheath
- Effect of charge exchange collisions: the “new” ion starts with thermal energy, starts to accelerate when field appears next time
- Ions “wait” together for the next accelerating period — synchronisation of the ions’ motion (peaks)
Limitations of single-frequency CCRF discharges

Single frequency discharge:
Argon @ 10 Pa
$f = 13.56\, \text{MHz}$, $L = 2.5\, \text{cm}$

The RF voltage influences both the ion flux and mean ion energy

Independent control??

Dual frequency excitation

$$V(t) = V_{HF} \sin(2\pi f_{HF} t) + V_{LF} \sin(2\pi f_{LF} t)$$

Heating & ion flux

Ion energy

Other solutions:
- Hybrid discharges
  - inductive + capacitive
  - helicon + capacitive
  - DC + RF
- Customised waveforms
• Ar discharge
• $p = 25\ \text{mTorr}$
• $L = 2\ \text{cm}$
• $V_{HF} = 60\ \text{V}$
• $f_{HF} = 100\ \text{MHz}$

**Effect of LF voltage at $f_{LF} = 1\ \text{MHz}$**

$\gamma = 0$

Functional separation works best at low pressures and at $f_{HF} \gg f_{LF}$
Control of ion properties in dual-frequency discharges

Argon
$V_{HF} = 200 \text{ V}$
$p = 6.6 \text{ Pa}$
$L = 2.5 \text{ cm}$
$T = 400 \text{ K}$

$\Gamma_i \quad [10^{14} \text{ cm}^{-2} \text{s}^{-1}]$

$\overline{\varepsilon_i}$

$V_{LF} \quad [\text{ V}]$

$\gamma = 0.25$
$\gamma = 0.225$
$\gamma = 0.2$
$\gamma = 0.15$
$\gamma = 0.1$
$\gamma = 0$

$\Gamma_{i \gamma}$

$\overline{\varepsilon_{i \gamma}}$

$f_{HF} = 27.118 \text{ MHz}$, $f_{LF} = 1.937 \text{ MHz}$ ($= f_{HF} / 14$)

- At low $\gamma$ ion flux decreases with increasing LF voltage
- At medium $\gamma$ nearly steady ion flux
- At high $\gamma$ the ion flux increases with increasing LF voltage

Limitation of the independent control of ion flux and energy

Control of ion properties in dual-frequency discharges

Ionisation source function

$V_{LF} = 0$ V

$V_{LF} = 500$ V

Argon
$V_{HF} = 200$ V
$p = 6.6$ Pa
$L = 2.5$ cm
$T = 400$ K

$\gamma = 0$

$\gamma = 0.225$

J. Schulze, Z. Donko, D. Luggenhölscher and U. Czarnetzki, PSST 18, 034011 (2009)
The Electrical Asymmetry Effect

\[ \epsilon = \left| \frac{\hat{\phi}_g}{\hat{\phi}_p} \right| = \left( \frac{A_p}{A_g} \right) \frac{n_{i,p}}{n_{i,g}} \left( \frac{Q_{\max,g}}{Q_{\max,p}} \right)^2 \frac{I_{sg}}{I_{sp}} \]

\[ \phi_{s,\text{max}} + \eta = \hat{\phi}_g \]
\[ \phi_{s,\text{min}} + \eta = \hat{\phi}_p \]

Symmetric waveform: \( \phi_{s,\text{max}} = -\phi_{s,\text{min}} \)

Asymmetric waveform: \( \phi_{s,\text{max}} \neq -\phi_{s,\text{min}} \) even with geometric symmetry: \( \eta \neq 0 \)

Example: \( \phi_s(t) = \phi_0[\cos(\omega t + \theta) + \cos(2\omega t)] \)

\[ A_{sp} = A_{sg} \]

The Electrical Asymmetry Effect

\[ \phi_s(t) = \phi_0[\cos(\omega t + \theta) + \cos(2\omega t)] \]

\[ \eta = -\frac{\phi_{s,\text{max}} + \epsilon \phi_{s,\text{min}}}{1 + \epsilon} \]

DC bias

Ion energy distributions

Ion flux

Mean ion energy

Grounded electrode / Phase = 0 deg.

Powered electrode / Phase = 0 deg.
Main points

- Operation of capacitively coupled radio-frequency discharges
- Particle-in-Cell / Monte Carlo Collisions (PIC/MCC) simulation method
- Electron power absorption in electropositive and electronegative discharges
- Regions of the RF plasma
- Impedance matching
- Methods of controlling the ion flux and energy