Fundamentals of Plasma Physics III

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Group Plasma Technology
3.1. Gas discharge plasmas

*electric breakdown in gases*
*Townsend mechanism*
*micro discharges / streamers*
*Paschen’s law*

3.2. Stationary gas discharges

*Townsend discharge*
*glow discharge*
*structures of a glow discharge*
*hollow cathode effect, magnetron effect*
*arc discharge*

3.3. Plasma surface interaction

*stationary plasma boundary sheath*
*Child-Langmuir law*
*Bohm criterion*
3.1. Gas Discharge Plasmas

**mechanical compression**
- gas is heated by shock waves (*ballistic compression*)

**electromagnetic compression**
- gas heating for short duration by high-current pulse discharges to very high temperatures
- special form of electromagnetic compression at *Pinch effect* where a rapidly increasing magnetic field compresses the plasma

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**plasma generation by electric fields**

- plasmas are mostly generated by *electrical discharges*
- in principle, a gas becomes ionized by an electric field (ignition) and a self-sustaining mechanism stabilizes the plasma at a certain current
- time regime (frequency) of the field, gas pressure and electrode material are of great importance

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**plasma generation by waves / radiation**

- for ionization of a gas also *waves* or *particle beams* can be used
- e.g. microwave radiation, electron beams, laser, radioactive radiation
3.1. Gas Discharge Plasmas

- plasma generation (energy supply)
  - heating/compression
    - electric field
      - glow discharge
        - positive column
        - low-pressure lamps
        - cathode sputtering
        - hollow cathode
      - arc discharge
        - high-pressure lamps
        - plasma welding
      - corona discharge
      - dielectric barrier discharge (DBE)
        - plasma display panel (PDP)
      - capacitively coupled plasma (CCP)
  - particle beam/external source
    - electron beam plasma
    - plasma jet
    - magnetohydrodynamic generator (MHD)
  - electromagnetic field
    - inductively coupled plasma (ICP)
      - plasma torch
    - magnetron discharge
    - plasma focus
  - electromagnetic waves
    - microwave plasma
      - electron cyclotron resonance (ECR)
    - surface wave plasma
    - helicon wave plasma
3.1. Gas Discharge Plasmas

low pressure dc glow discharge in neon (positive column)

low pressure rf discharge in argon

atmospheric pressure discharge
3.1. Gas Discharge Plasmas

plasma application: for example for illumination
3.1. Gas Discharge Plasmas

energy conversion: field, plasma, surface
3.1. Gas Discharge Plasmas

Particle interaction: charge carriers in plasma

Non-thermal plasmas

Electrons gain energy from electric field $\sim e\lambda_e|E|$

Thermalization of field energy through elastic collisions: hot electrons $T_e \uparrow$

Inelastic collisions

Optical emission

Reactive species

New ions and electrons

Electrons and their collisions carry and distribute the energy from the matchbox to process gas (neutrals, ions) to the substrate.
3.1. Gas Discharge Plasmas

energy conversion: field, plasma, surface

power loss (heat)

power

power loss (heat)

plasma

different reactive species

electron density $n_e$
electron collision rate $\nu$
voltage $U$
free mean path $\lambda_+$

etch rate
selectivity
homogeneity

plasma application:
for example semiconductor etching
3.1. Gas Discharge Plasmas

Collision processes in non-isothermal plasmas

- Electron-electron interaction
- Heavy particle reactions

Electron collisions with heavy particles

- Elastic collision: $e^- + A \rightarrow e^- + A$
- Excitation: $e^- + A \rightarrow e^- + A^*$
- Deexcitation: $e^- + A^* \rightarrow e^- + A$

Heavy particle reactions

- Ionization: $e^- + A \rightarrow 2e^- + A^+$
- $e^- + A^+ \rightarrow 2e^- + A^{++}$
- $e^- + A_2 \rightarrow 2e^- + A + A^+$

- Attachment: $e^- + A + B \rightarrow A^- + B$
- $e^- + A_2 \rightarrow A^- + A^-$

- Dissociation: $e^- + AB \rightarrow e^- + A + B$
- $e^- + AB \rightarrow e^- + A^+ + B^-$

- Recombination: $e^- + A^+ \rightarrow A + hv$
- $e^- + A_2^+ \rightarrow A + A$

No change of particle number

Change of particle number

Collision processes: generation of charge carriers
3.1. Gas Discharge Plasmas

collision processes: generation of charge carriers

\[ A + B^\pm \rightarrow A^+ + B^\pm + e^- \]
\[ A + h\nu \rightarrow A^+ + e^- \]
\[ A + B^* \rightarrow A^+ + B + e^- \]
\[ e_{\text{fast}}^- + A \rightarrow A^+ + e_{\text{slow}}^- + e_{\text{slow}}^- \]
3.1. Gas Discharge Plasmas

collision processes: generation of charge carriers

donnant at high energy

• Direct electron impact ionization

\[ M + e^- \xrightarrow{K_i} M^+ + 2e^- \]

• Ionization from excited levels

\[ M^* + e^- \xrightarrow{K_i^*} M^+ + 2e^- \]

• Penning Ionization

\[ Ar^* + M \xrightarrow{K_p} M^+ + Ar + e^- \]

channels of ionization (\(\rightarrow \alpha\))
3.1. Gas Discharge Plasmas

collision processes: generation of charge carriers
3.1. Gas Discharge Plasmas

collision processes: generation of charge carriers

![Graph showing energy levels](image)

- Ionization
- Excitation
- Elastic

Ar

- Ionization via impact ionization
- Ionization via excited states and Penning effect

Excitation energy

Ionization energy
energy and momentum conservation

collision of an electron \((m_e, \vec{v}_e)\) and an atom \((m_a, \vec{v}_a)\)

\((m_a >> m_e, \nu_a << \nu_e)\)

typical total cross section \(Q \left( u = \frac{m_e v_e^2}{2} \right) : \)

- **elastic collision**

\[
\begin{align*}
  m_e \vec{v}_e + m_a \vec{v}_a &= m_e \vec{v}_e' + m_a \vec{v}_a' \\
  \frac{m_e v_e^2}{2} + \frac{m_a v_a^2}{2} &= \frac{m_e v_e'^2}{2} + \frac{m_a v_a'^2}{2}
\end{align*}
\]

- **exciting collision**

\[
\begin{align*}
  m_e \vec{v}_e + m_a \vec{v}_a &= m_e \vec{v}_e' + m_a \vec{v}_a' \\
  \frac{m_e v_e^2}{2} + \frac{m_a v_a^2}{2} &= \frac{m_e v_e'^2}{2} + \frac{m_a v_a'^2}{2} + u_a^{ex}
\end{align*}
\]

- **ionizing collision**

\[
\begin{align*}
  m_e \vec{v}_e + m_a \vec{v}_a &= m_e (\vec{v}_e' + \vec{v}_e'') + m_a \vec{v}_a' \\
  \frac{m_e v_e^2}{2} + \frac{m_a v_a^2}{2} &= \frac{m_e (v_e'^2 + v_e''^2)}{2} + \frac{m_a v_a'^2}{2} + u_a^{io}
\end{align*}
\]
3.1. Gas Discharge Plasmas

collision processes: generation of charge carriers
3.1. Gas Discharge Plasmas

collision processes: losses of charge carriers

\[ A + e^- \rightarrow A^- + h\nu \] radiative attachment

\[ AB^* + e^- \rightarrow A^- + B \] dissociative attachment

\[ e^- + A^+ + e^- \rightarrow A + e^-_{\text{faster}} \] 3 body recombination

\[ e^- + AB \rightarrow AB^- \] associative attachment

\[ AB^- + C^+ \rightarrow AB + C \] ion-ion recombination

Volume loss rate depends on concentrations

Surface loss rate depends on fluxes

neutralisation
3.1. Gas Discharge Plasmas

multiplication of charge carriers

\[ \nu_d = \mu_e E = \frac{e_0 \tau}{m_e} E \]

\[ dN = N \frac{dx}{\lambda_i} \]

\[ N = N_0 \exp \left( \frac{x}{\lambda_i} \right) \]

or

\[ N = N_0 \exp (\alpha x) \]
3.1. Gas Discharge Plasmas

Townsend’s coefficient

*Drift energy activates the ionisation process*

\[
\alpha = \frac{\lambda_i}{\lambda} = \text{const. } \lambda^{-1} \exp(-V_i/E\lambda)
\]

\[
\alpha = Ap \exp(-Bp/E)
\]

\[\text{cf: } R = R_0 \exp(-\varepsilon_a/kT)\]
3.1. Gas Discharge Plasmas

Streamers

Pieter van Musschenbroek (1692-1761)
Leiden jar's
3.1. Gas Discharge Plasmas

streamers

Funkenentladung
Elektrischer Durchschlag
in Luft: $E \sim 30 \text{ kV/cm}$
3.1. Gas Discharge Plasmas

micro discharges: DBD

presence of at least one dielectric in the discharge space
Microdischarges of short duration

- thin cylindrical weakly ionized plasma columns, $\Phi \approx 200 \, \mu$m
- electron densities: $10^{14} \ldots 10^{15} \, \text{cm}^{-3}$
- duration: 1 .. 10 ns
- non-equilibrium plasmas ($T_e >> T_{gas}$) ⇒ well suited for initiation of plasma-chemical reactions
3.1. Gas Discharge Plasmas

electric breakdown

\[ \gamma N_0 \exp[(\alpha d) - 1] = N_0 \]

\[ \alpha d = \ln(1 + \gamma^{-1}) \]
3.1. Gas Discharge Plasmas

multiplication of charge carriers

ignition of discharge
3.1. Gas Discharge Plasmas

Paschen's law

\[
\alpha = Ap \cdot \exp\left(-\frac{Bp}{E}\right) \quad \alpha d = \ln(1 + \gamma^{-1})
\]

\[
Apd \cdot \exp\left(-\frac{Bp}{E}\right) = \ln(1 + \gamma^{-1}) \quad \frac{V_b}{d} \text{ (planar geometry)}
\]

\[
V_b = \frac{Bpd}{\ln(Apd) - \ln\ln(1 + \gamma^{-1})}
\]
3.1. Gas Discharge Plasmas

Paschen’s law

breakdown voltage depends on pressure, distance and gas
3.1. Gas Discharge Plasmas

Paschen’s law

Johann W. Hittorf (1824-1914)
3.2. Stationary Gas Discharges
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Townsend discharge
3.2. Stationary Gas Discharges
3.2. Stationary Gas Discharges

glow discharge

A schematic drawing of the visible regions of the normal glow discharge.
3.2. Stationary Gas Discharges

glow discharge

Negative glow - self sustaining (high $E$)

Positive column - self sustaining (low $E$)

$J = ne \mu E$
Axial variation of the characteristics of the normal glow discharge.
3.2. Stationary Gas Discharges

- cylindric cathode,
- ring shaped anode
  (at positive potential)
- merging of glow edge
- „ideal plasma“: only negative glow
- oscillation of electrons $\rightarrow$ increase of ionization and dissociation
- hollow cathode effect
3.2. Stationary Gas Discharges

micro hollow cathode discharge

500 \mu m
3.2. Stationary Gas Discharges

glow discharge

Various forms of the dc glow discharge.
3.2. Stationary Gas Discharges

magnetron discharge

principle of dc cathode sputtering, diode system
a gas flow
b pump
c cathode
d target
e anode
f deposited layer
g cathode fall
h positive column
i screening, shield

diode system (E)

magnetron system (E X B)

influence of magnetic field
3.2. Stationary Gas Discharges

rf discharge

- Capacitive discharges are used in etching and deposition
- Radiofrequency domain is such that electrons follow the rf field while ions follow time-averaged field
- Ionization degree is small ($<0.001$)
- Gas pressure is low (a few Pa); collisionless heating is often dominant
3.2. Stationary Gas Discharges

rf discharge: CCP, ICP

- medium to low pressure
- volume production
- surface loss
3.2. Stationary Gas Discharges

rf discharge: CCP, ICP

CCP-mode: 
- "piston"-principle

ICP-mode: 
- transformer-principle
3.2. Stationary Gas Discharges

rf discharge: CCP

PPR

symmetric, asymmetric

plasma jet
3.2. Stationary Gas Discharges

- plasma excitation by an electric field generated by the transformer principle
- changing magnetic field of the conductor induces an electric field in which the electrons are accelerated
- high plasma density

rf discharge: ICP

300 mm ETCH TOOL:
ELECTRIC FIELD, POWER, ION DENSITIES

- $\text{Ar/Cl}_2/\text{BCl}_3 = 1/1/1$, 10 mTorr, 600 W ICP, 100 V bias, 150 sccm

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OPTICAL AND DISCHARGE PHYSICS
3.2. Stationary Gas Discharges

arc discharge
3.2. Stationary Gas Discharges

arc discharge

plasma welding and cutting
3.2. Stationary Gas Discharges

plasma sources at different gas and charge carrier densities

Coulomb-dominated plasmas

non-ideal plasmas

thermal plasmas

stationary gas discharges

non-maxwellian electron energy distribution

ideal weakly ionized, non-isothermal plasmas

"reactive" neutral-dominated plasmas
3.3. Plasma Surface Interaction
role of charge carriers in plasma:

- occurrence of electrical conductivity
- screening of electric fields
- occurrence of oscillations and waves, and corresponding instabilities
- interaction with magnetic fields
- formation of characteristic boundary sheaths due to contact with walls

characteristic dimensions / time constants:

**Debye length** $\lambda_D$ is the shielding length for the long range Coulomb interaction. It is the distance over which thermal motion causes significant deviations from quasi-neutrality.

The **plasma frequency** $\omega_p$ is critical for the propagation of electromagnetic waves in plasmas (supply of energy).
3.3. Plasma Surface Interaction

plasma in contact with floating wall:

plasma boundary sheath

floating potential \( V_{fl} \)

\( \mu_e \gg \mu_i \)

\( \Rightarrow \) wall charges up until ion flux equals electron flux


\[
\begin{align*}
    j_f &= \frac{n_i e v_i}{4} = j_e = \frac{n_e e v_e}{4} \\
    n_e &= n_i \exp\left(-e(V_{pl} - V_{fl})/k T_e\right) \\
    \text{sheath potential:} &\quad V_{bias} = V_{fl} - V_{pl} - \frac{k T_e}{2} \ln\left(m_i/m_e\right) \\
    \text{or for additional } V_s, \text{ then:} &\quad V_{bias} = V_s - V_{pl}
\end{align*}
\]
3.3. Plasma Surface Interaction

potential and charge carrier density for a typical glow discharge
3.3. Plasma Surface Interaction

Collisionless power dissipation in the sheath
3.3. Plasma Surface Interaction
3.3. Plasma Surface Interaction

plasma boundary sheath

\[ \frac{\Delta \rho}{\Delta V} = \frac{+ve \text{ change in space charge}}{-ve \text{ change in potential}} \]
3.3. Plasma Surface Interaction

plasma boundary sheath

\[ \frac{m_e}{2} \cdot v^2 = e \cdot U \]
3.3. Plasma Surface Interaction

plasma boundary sheath

\[ n_e = n_0 \exp\left(\frac{e\phi}{kT_e}\right) \quad \text{Boltzmann} \]

\[ n_i = \frac{n_0 v_i}{\sqrt{v_i^2 - 2e\phi/M}} \quad \text{Free-fall} \]
3.3. Plasma Surface Interaction

plasma boundary sheath

\[
\frac{d^2 \phi}{dx^2} \approx -\frac{n_i e}{\varepsilon_0}
\]
3.3. Plasma Surface Interaction

plasma boundary sheath: Child-Langmuir

\[ \frac{d^2 \phi}{dx^2} \approx -\frac{n_i e}{\varepsilon_0} \]

\[ \frac{e \phi}{kT_e} = \frac{1}{2} \left( \frac{3}{\sqrt{2}} \frac{x}{\lambda_D} \right)^{4/3} \]
3.3. Plasma Surface Interaction

plasma boundary sheath : Child-Langmuir

Negative voltage pulse applied:

• **electrons are repelled**
  → ion matrix sheath

• **ions are attracted**
  → expanding sheath

• energetic ions arrive at substrate

• stationary sheath position may be reached if

\[
\omega_{pl,e}^{-1} = \left( \varepsilon_0 \frac{m_e}{e^2 n_e} \right)^{1/2}
\]

\[
\omega_{pl,i}^{-1} = \left( \varepsilon_0 \frac{m_i}{e^2 n_i} \right)^{1/2}
\]

ion current in plasma = space-charge limited current
(Child current for given voltage and actual sheath thickness)
3.3. Plasma Surface Interaction

plasma boundary sheath : Child-Langmuir

• The transition zone between bulk plasma and a surface, the SHEATH, is fundamental in plasma-surface interaction, plasma-assisted deposition of films, and ion extraction in ion sources.

• Child Law (1911):

\[
\dot{j}_i = \frac{4}{9} \left( \frac{2eQ}{m_i} \right)^{1/2} \frac{\varepsilon_0 |\phi_{wall}|^{3/2}}{d^2}
\]

• Can be interpreted as
  – limited current density, \( j \), for given distance, \( d \), or
  – adjusting sheath thickness for given current density and voltage.
plasma boundary sheath: Child-Langmuir

\[
\frac{d^2 V}{dx^2} = -\frac{dE}{dx} = \frac{e_0}{\varepsilon_0} (n_e - n_i) \quad \text{with} \quad n_e = \frac{j_e}{e_0 v_e} = \frac{j_e}{-e_0 b_e E} \quad \text{and} \quad n_i = \frac{j_i}{e_0 v_i} = \frac{j_i}{e_0 \sqrt{2e_0 V/m_i}}
\]

\[
\frac{d^2 V}{dx^2} = -\frac{e_0}{\varepsilon_0} \left( \frac{j_e}{e_0 b_e E} + \frac{j_i}{\varepsilon_0 \sqrt{2e_0 V/m_i}} \right) = -\frac{dE}{dx} \quad c_1 = \frac{j_e}{b_e \varepsilon_0} \quad c_2 = \frac{j_i \sqrt{m_i}}{\varepsilon_0 \sqrt{2e_0}}
\]

\[
\frac{dE}{dx} = \frac{c_1}{E} + \frac{c_2}{\sqrt{V}} \quad \Rightarrow \quad \frac{1}{2} \frac{d}{dx}\left[ \left( \frac{dV}{dx} \right)^2 \right] = c_1 + 2c_2 \frac{d}{dx}\left( \frac{V^2}{2} \right) = \frac{1}{2} d\left[ \left( \frac{dV}{dx} \right)^2 \right] = c_1 dx + 2c_2 d\left( \frac{V^2}{2} \right)
\]

integration limits?

\[
\int_{E(d_c)}^{E(x)} d\left[ \left( \frac{dV}{dx} \right)^2 \right] = 2c_1 \int_{d_c}^{x} dx + 4c_2 \int_{V(d_c)}^{V(x)} d\left( \frac{V^2}{2} \right)
\]

\[
E(x)^2 - E(d_c)^2 = 2c_1 (x - d_c) + 4c_2 \left( V(x) \frac{V}{2} - V(d_c) \frac{V}{2} \right)
\]

\[
\left( \frac{dV}{dx} \right)^2 \approx 0
\]
plasma boundary sheath : Child-Langmuir

\[ \Rightarrow \frac{dV}{dx} = \left( 2c_1(x - d_c) + 4c_2 \left( V(x)^{\frac{1}{2}} \right) + E(d_c)^2 \right)^{\frac{1}{2}} \]

if sheath determined by positive space charges, then : \( j_i \gg \sqrt{\frac{m_e}{m_i}} j_e \Rightarrow c_1 \ll c_2 \Rightarrow c_1 \approx 0 \)

\[ \frac{dV}{dx} \approx \left( 4c_2 \left( V(x)^{\frac{1}{2}} \right) + E(d_c)^2 \right)^{\frac{1}{2}} \]

\[ dV = \left( 4c_2 \left( V(x)^{\frac{1}{2}} \right) + E(d_c)^2 \right)^{\frac{1}{2}} dx \]

\[ \uparrow \]

\[ V(d_c)^{\frac{1}{2}} \approx 0 \]

\[ \frac{dV}{dx} \approx 2\sqrt{c_2} V(x)^{\frac{1}{4}} \]

\[ \int_{0}^{V_c} \frac{dV}{V(x)^{\frac{1}{4}}} = 2\sqrt{c_2} \int_{d_c}^{0} dx \]

\[ \frac{4}{3} V_c^4 = -2\sqrt{c_2} d_c \Rightarrow d_c^2 = \frac{4}{9} \frac{1}{c_2} V_c^3 \]

\[ d_c^2 = \frac{4}{9} V_c^3 \frac{\varepsilon_0 \sqrt{2\varepsilon_0}}{j_i \sqrt{m_i}} \]

\[ (p \leq 10 \text{ Pa}) \leftrightarrow d_c \geq \lambda_{mpf} \]

\[ \frac{d_c^2}{9} = \frac{4}{9} \frac{V_c^3}{j_i} \sqrt{\frac{2\varepsilon_0^2 e_0}{m_i}} \]

\[ j = \frac{4\varepsilon_0}{9} \left( \frac{2e_0}{m_i} \right)^{\frac{1}{2}} \frac{V_c^3}{d_c^2} \]

\[ d_c \sim d_{sh} \]
plasma boundary sheath: Child-Langmuir

\[ V_0 = V_c \]

\[ S = d_c \]

A schematic of the potential, electric field, and electron number density profiles across a Child law sheath.

Thickness of the plasma sheath \( d_s \) versus electron temperature \( T_e \) for different electron densities. This is valid only for lower pressures when the ion mean free path is longer than the thickness of the plasma sheath. On the right axes the mean free path \( \lambda \) of Ar atoms for selected pressures is shown.
3.3. Plasma Surface Interaction

plasma boundary sheath
3.3. Plasma Surface Interaction

plasma boundary sheath

trench-to-sheath size is crucial for conformal treatment
3.3. Plasma Surface Interaction

plasma boundary sheath : magnetron

not to scale
3.3. Plasma Surface Interaction

plasma boundary sheath

depends on discharge power and pressure

Argon, 0.005mbar, 10W
Argon, 50W

30W
0.005mbar
0.01mbar

50W
3.3. Plasma Surface Interaction

Argon
p: 1.0 E-1 mbar --> 3.0 E-2 mbar
P = 2 W

10Pa

3Pa
Time-averaged potential

Impedance depends on:
- Voltage, $V_{\text{rf}}$
- Electron density, $n_e$
- Sheath size, $s_m$

To find a self-consistent solution:
- Child law
- Particle balance
- Power balance

$$Z_{\text{sheath}} = \frac{1}{j c_s \omega}$$

$$Z_{\text{plasma}} = R_p + j L_p \omega$$
3.3. Plasma Surface Interaction

plasma boundary sheath: Bohm

\[
\frac{\partial \rho}{\partial \phi} = \frac{n_0 v_i (-2e/M)}{(v_i^2 - 2e\phi/M)^{3/2}} + \frac{e}{kT_e} n_e < 0
\]

\[\Rightarrow v_i^2 > \frac{kT_e}{M}\]

\[c_s = \sqrt{\frac{kT_e}{M}}\]

Bohm speed
plasma boundary sheath : Bohm

\[ x = 0 \ldots x = d_{sh} = (S) \quad \text{no ionization in the sheath} \]

--- sheath ---

continuity equation of ions: \[ n_i(x)v_i(x) = n_i(0), v_i(0) \]

conservation of energy: \[ \frac{1}{2}m_i v_i^2(0) = \frac{1}{2}kT_i + e_0V_{pl} \quad x = 0 \quad kT_i << e_0V_{pl} \Rightarrow v_i(0) = \sqrt{\frac{2e_0V_{pl}}{m_i}} \]

\[ v_i(x) \text{ between } 0 \text{ and } d_{sh}: \]
\[ v_i(x) = \sqrt{\frac{2e_0(V_{pl} - V(x))}{m_i}} \]
\[ n_i(x) = n_i(0) \sqrt{\frac{2e_0V_{pl}}{m_i}} \]

Boltzmann: \[ n_e(x) = n_e(0)e^{\frac{e_0V(x)}{kT_e}} \]

Poisson-equation: \[ \frac{d^2V}{dx^2} = -\frac{e_0}{\varepsilon_0} [n_i(x) - n_e(x)] \Rightarrow \frac{d^2V}{dx^2} = -\frac{e_0n_e(0)}{\varepsilon_0} \left[ \frac{V_{pl}}{V_{pl} - V(x)} \right]^{\frac{1}{2}} e^{\frac{e_0V(x)}{kT_e}} \]
plasma boundary sheath: Bohm

\[ E^2(x) = \frac{2e_0 n_e(0)}{\varepsilon_0} \left[ 2V \left( 1 - \frac{V(x)}{V_{pl}} \right)^{1/2} - 1 \right] + \frac{kT_e}{e_0} \left[ \frac{e_0 V(x)}{kT_e} - 1 \right] \]

with \((1 - x)^{1/2} \approx 1 - \frac{1}{2} x - \frac{1}{8} x^2\) and \(e^x \approx 1 + x + \frac{x^2}{2}\)

for \(V(x) << V_{pl}\) and \(e_0 V(x) << kT_e\)

\[ E^2(x) \approx \frac{2e_0 n_e(0)}{\varepsilon_0} \left[ 2V_{pl} \left( 1 - \frac{1}{2} \frac{V(x)}{V_{pl}} - \frac{1}{8} \frac{V^2(x)}{V_{pl}^2} - 1 \right) + \frac{kT_e}{e_0} \left( 1 + \frac{e_0 V(x)}{kT_e} + \frac{e_0^2 V^2(x)}{2k^2 T_e^2} - 1 \right) \right] \]

\[ E^2(x) \approx \frac{e_0 n_e(0)}{\varepsilon_0} \left[ -V(x) - \frac{1}{4} \frac{V^2(x)}{V_{pl}} + V(x) + \frac{e_0 V^2(x)}{2kT_e} \right] \]

\[ E^2(x) \approx \frac{e_0 n_e(0) V^2(x)}{\varepsilon_0} \left[ \frac{e_0}{kT_e} - \frac{1}{2V_{pl}} \right] \]

in order to have a real solution, it must

\[ \frac{e_0}{hT_e} \geq \frac{1}{2V_{pl}} \Rightarrow \frac{e_0 V_{pl}}{kT_e} \geq \frac{1}{2} \]

Bohm criterion
3.3. Plasma Surface Interaction

**plasma boundary sheath**

**IEDF**

- Ar, $p = 5\text{Pa}$, $V_{rf} = 520\text{V}_{pp}$
3.3. Plasma Surface Interaction

plasma boundary sheath

IEDF: dependence on power→intensity

IEDF: dependence on pressure→intensity, mean energy
3.3. Plasma Surface Interaction

chemistry in bulk plasma provides etch species
physics provides ions and e⁻

physics in space charge sheaths

etch species
activation energy
ionic current
ion energy and current

etch rate
selectivity
homogeneity

desorption of etch products
physical sputtering
chemical etching

plasma boundary sheath: etching
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