Study of a Micro Hollow Cathode Discharge at medium argon gas pressure

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I-V characteristic

Aubert et al., PSST 16 (2007) 23–32
Example of a 2D simulation

L. PITCHFORD, K. MAKASHEVA (LAPLACE, Toulouse)
Geometry of the system

- CATHODE REGION
- POSITIVE COLUMN
- ANODE REGION
- Molybdenum
- Alumina

Dimensions:
- 150 µm
- 250 µm
- 400 µm
Geometry of the system
Geometry of the system

CATHODE REGION

POSITIVE COLUMN

ANODE REGION

Sheath
Geometry of the system
Geometry of the system
Setup for spectral measurements

- Cathode
- Anode
- $f' = 30\, \text{mm}$
- Filter
- Monochromator
  - $f' = 2\, \text{m}$
  - 1200 g/mm
  - Spatial resolution = 2 µm
- CCD
- Reflection gating
- Mirrors

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Pressure influence

- Two origins for the light emission:
  - in the centre
  - near the edges

- Leads:
  - centre $\rightarrow$ recombination
  - Edge $\rightarrow$ excitation by high energy electron emitted from the cathode
Study of the cathodic region

![Diagram showing the cathode region, positive column, and anode region with dimensions and materials labeled.](image-url)
Calculation of the sheath thickness (d)

- One-dimensional cylindrical geometry:

\[ \Gamma_i(R - d) = \xi \Gamma_i(R) \]
\[ \Gamma_i(R) \]
\[ \Gamma_e(R - d) \]
\[ \Gamma_e(R) \]

Cathode

Sheath

\[ \vec{\nabla} \Gamma_e = \alpha(r) \Gamma_e \]
Calculation of the sheath thickness (d)

\[ \Gamma_i(R - d) = \xi \Gamma_i(R) \]

P (Torr)

Distance from the cathode (µm)

\( T=470K \)

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Calculation of the sheath thickness ($d$)

Distance from the cathode (µm)

Ar line maximum

Ar$^+$ line maximum

T=470K
Calculation of the sheath thickness (d)

- decrease of the sheath size with the increase of $\xi$
- maxima of both emission lines located after the sheath edge whatever the value of $\xi$
- same trends for the evolution of d that of the maxima of the emission line
- the sheath edge coincide with the maxima of the ionic line

T=470K
1D stationary model of the cathodic region
1D stationary model of the cathodic region
Model description

• 3 species: $e^-$, $Ar^+$, $Ar_2^+$

• 3 reactions:

\[ Ar + e^- \rightarrow Ar^+ + 2e^- \quad (K_{iz}) \]
\[ 2Ar + Ar^+ \rightarrow Ar_2^+ + Ar \quad (K_1) \]
\[ Ar_2^+ + e^- \rightarrow Ar^* + Ar \quad (K_{rec}) \]

• Numerical tool: MATLAB
Governing equations

• Set of equations:
  – Quasi-neutrality: \( n_e = n_{Ar^+} + n_{Ar_2^+} \)
  – Continuity equation: \( \frac{d\Gamma_i}{dr} = P - L - \frac{\Gamma_i}{r} \)
  – Momentum conservation (drift-diffusion): \( \vec{\Gamma}_i = n_i \mu_i \vec{E} - D_i \nabla n_i \)

\( \rightarrow \) no energy equation: we need to give us a \( n_e \)

• Boundary conditions
  – Integration until the entrance of the sheath (to respect the electroneutrality)
  – Shooting method: ions speed value at the sheath edge \( \rightarrow T_e(r) \)
Ionization rate shape

Emission intensity of Ar\(^+\) line \(\alpha \nu_{iz}\)

100 Torr

\(\nu_{iz}\) (10\(^6\) s\(^{-1}\))

Radial position (mm)

Radial position (mm)

Intensity (arb. u.)

Ar\(^+\) line
Ionization rate shape

Emission intensity of Ar$^+$ line $\alpha \nu_{iz}$

Radial position (mm)

30 Torr
50 Torr
100 Torr
150 Torr
200 Torr

$\nu_{iz} \left(10^6 \text{s}^{-1}\right)$
Electron temperature

\[ T_e (eV) = \frac{E_{i0}}{\log(\frac{v_{i0}}{v_{iz}})} \]

\[ E_{i0} = 17.44 \text{ eV} \quad \text{and} \quad v_{i0} = K_{iz0} \times n_g = 5.10^{-14} \times 3.2 \times 10^{19} \times 1000 \times P(\text{Torr}) \]
Conclusions of the cathodic region

- Sheath structure
- Radial profile of densities: $n_e(r)$ has to be confirmed experimentally
- Lack on a theoretical point of view:
  - Non linear model $\Rightarrow$ need of $n_e \Rightarrow$ power balance

Power balance complicated in the cathodic region but not in the positive column $\Rightarrow$ easier study of this region

- Sheath negligible
- Electric field uniform $\Rightarrow$ power balance possible
- Instationary model
Study of the positive column

CATHODE REGION

alumina

 POSITIVE COLUMN

ANODE REGION
1D stationary model of the positive column
Model description

• same species: \( e^-, Ar^+, Ar_{2}^+ \)

• same reactions:

\[
\begin{align*}
Ar + e^- & \rightarrow Ar^+ + 2e^- \\
2Ar + Ar^+ & \rightarrow Ar_{2}^+ + Ar \\
Ar_{2}^+ + e^- & \rightarrow Ar^* + Ar
\end{align*}
\]

• same equations:
  – Quasi-neutrality
  – Continuity equation
  – Momentum conservation
  – Ionization rate constant: \( v_{iz}=cte \)
Species density

$n_0$ given

Radial position (mm)
Electron temperature

![Graph showing electron temperature vs. pressure (Torr)]
0D non-stationnary model of the positive column

CATHODE REGION

POSITIVE COLUMN

ANODE REGION

sheath
0D non-stationary model of the positive column
0D non-stationnary model of the positive column
Governing equations

**PARTICLE CONSERVATION**

**Fluid equation**

\[
\frac{\partial n_e}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r n_e \right) = \nu_{iz} n_e
\]

Integration over the space coordinates (between 0 and R)

**Balance equation**

\[
\frac{dn_0}{dt} = \nu_{iz} n_0 - h_R u_B n_0
\]

with

\[
h_R = \frac{\chi_{01} J_1(\chi_{01})}{Ru_B} D_a
\]

Same equations for the ionic species
Edge-to-centre density ratio $h_r$

![Graph showing edge-to-centre density ratio $h_r$ as a function of pressure (Torr). Curves for $h_r(Ar^+)$ and $h_r(Ar_2^+)$ are depicted, with data points indicating a non-stationary model.]
Governing equations

- Energy balance:
  \[
  \frac{d\left(\frac{3}{2}n_e e T_e\right)}{dt} = P_{abs} - P_{loss}
  \]

- System of 3 temporal equations with \(n_e\), \(n_\text{Ar}_2^+\) and \(T_e\):
  \[
  \begin{align*}
  \frac{dn_e}{dt} &= v_{iz} n_e - K_{rec} n_e n_\text{Ar}_2^+ - \frac{A}{V} \chi_{01} \Gamma_e \\
  \frac{dn_\text{Ar}_2^+}{dt} &= K_1 n_\text{Ar}^+ n_\text{Ar}_2^+ - K_{rec} n_e n_\text{Ar}_2^+ - \frac{A}{V} \chi_{01} \Gamma_\text{Ar}_2^+ \\
  \frac{dT_e}{dt} &= \frac{2}{3} \left( P_{abs} - P_{loss} \right) - \frac{T_e}{n_e} \frac{dn_e}{dt}
  \end{align*}
  \]

- Electric field: \(E = f(I, n_e)\)
Temporal evolution of the densities

\[ n_e/n_0 \]

\[ t (\mu s) \]

I=1mA

Post-discharge: I=0

200 Torr

150 Torr

100 Torr

50 Torr

30 Torr
Densities temporal evolution

- $n_{e}$
  - 200 Torr
  - 150 Torr
  - 100 Torr
  - 50 Torr
  - 30 Torr
- $n_{Ar^+}$
  - 50 Torr
  - 100 Torr
  - 150 Torr
  - 200 Torr
  - 30 Torr
- $n_{Ar_2^+}$
  - 200 Torr
  - 150 Torr
  - 100 Torr
  - 50 Torr
  - 30 Torr
Electron temperature and reduced field temporal evolution
Summary

- Cathodic region:
  - Experimental results
    - Ar$^+$ emission: direct excitation by energetic beam electrons
    - Ar emission: direct excitation + recombination argon/e$^-$
  - Theoretical results
    - Ionizing-sheath model → sheath structure
    - 1D transport model → density and flux profiles
      BUT $n_e =$ input parameter (complexity of the power balance)

- Positive column
  - Stationary model: density and flux profiles, $T_e(P)$ and $h_r(P)$
  - Non-stationary model: power balance easy → $n_e =$ output parameter → temporal evolution of the different parameters ($n$, $T_e$, $E/N$, …)

Next step

- Experiment: same experimental measurements temporally resolved during the self-pulsing regime
- Theory: - input parameter of the 0D model = experimental discharge current
  - power balance in the cathodic region
  - introduction of the metastables
Comparison between the two models

Good agreement between the two models
Comparison between the two models

Good agreement between the two models

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