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МОДЕЛИРОВАНИЕ ТЛЕЮЩЕГО РАЗРЯДА В ПОЛОМ КАТОДЕ

Нгуен Бао Хынг
(г. Томск, Национальный исследовательский Томский политехнический университет)

THE MODELLING OF GLOW DISCHARGE IN A HOLLOW CATHODE

Nguyen Bao Hung
(Tomsk, National Research Tomsk Polytechnic University)

This article discusses the modeling of low-temperature glow discharge generated plasma with a large area hollow cathode, both in a self-sustained mode and additional electron injection mode. The results of theoretical and numerical investigations of the discharge characteristics agree with experiments.

Introduction

Application of vacuum plasma technology for efficient ion cleaning and surface modification of large objects is based on obtaining low-temperature plasma generated by a glow discharge [1]. In this case, electron emission is a result of cathode bombardment by the ions formed in the discharge plasma [2–3]. If the electron energy relaxation length ($\Lambda = N\lambda$) is larger than the effective width $a = 4V/S_c$, then electrostatic trap effect appears. The discharge differs from the usual glow discharge, and the ionization rate by fast electrons is much higher than the ionization rate by plasma electrons [3]; λ – electron ionization range, N – the average number of unbound electrons produced on the way of a fast electron, V and S_c – volume and surface area of a hollow cathode.

The modeling of a low-pressure gas discharge in a hollow cathode

We consider a gas discharge inside a cylindrical cathode cavity with length D and diameter D. Anode (in the form of two tubes with a total area S_a) is located in the cathode sidewall (figure 1).

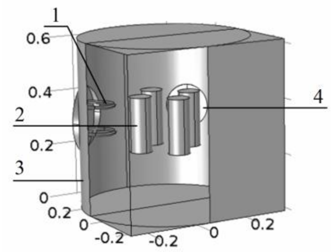

Figure 1 Model of a hollow cathode;
1 – anode; 2 – samples; 3 – cathode; 4 – hole for additional discharge

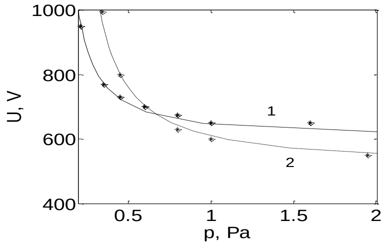

Figure 2. Dependence of burning intensity on gas pressure: 1 – nitrogen, 2 – argon,
* – experiment [1], lines – calculation

The discharge in a hollow cathode is described by the system of equations showing the balance between energy and charged particles, as well as the current continuity. In general, by defining the ion current to the cathode in non self-sustained discharge mode as $I_i = (1 - \alpha)e\nu_I n_f V$, we can get the relation between the dimensionless voltage $u = e\,U_c/W$ and gas pressure p:

$$p = p_0 \frac{u^{3/2}}{(1-\alpha)[(\gamma+(1+\delta)(1-\eta)]u-1}, \qquad (1),$$

where $p_0 = kT_eS_a(2W/m)^{1/2}/(8V\sigma_i\text{v})$; $\eta = (S_al_i/4V)(M/m)^{1/2}\exp(-eU_a/kT_e)V$; n_f – concentration of fast electrons; α – fraction of the ions not taking part in the cathode processes; $\delta = I_p/I_i$; I_p – additional discharge current; $\text{v}_i = n_g\sigma_i\text{v}$ – ionization frequency; e – electron charge; U_a – negative anode potential drop, $U_c = U_p - U_a \approx U_p$ – cathode potential drop; W – ionization energy of atoms; $\gamma(U_c)$ – ion-electron emission coefficient; S_a – anode area; v_e and n_e – velocity and density of plasma electrons; M and m – mass of the ion and electron; $V = (V_c - V_a)(1 - h/2D)$ – cathode cavity volume, h – anode height; v and v_i – velocity of fast electrons and ions, $l_i = T_i\text{v}_i$, T_i – exiting time of ions to cathode.

Figure 2 shows the dependence of burning intensity on gas pressure (argon and nitrogen) in a self-sustained burning mode on the basis of (1), when $S_a = 500$ cm^2, $V_c = 2\text{x}10^5$ cm^3.

Plasma density distribution in the hollow cathode is investigated numerically using a hydrodynamic model describing the electronic density of charged particles (n_e) and their average energy (n_ε) as functions of time and space [4]. Equations of electron transfer (e) and energy density (ε) have the form:

$$\frac{\partial n_{e,\varepsilon}}{\partial t} + \nabla\cdot\mathbf{\Gamma}_{e,\varepsilon} + \boldsymbol{E}\cdot\mathbf{\Gamma}_{e,\varepsilon} = R_{e,\varepsilon},\ \mathbf{\Gamma}_{e,\varepsilon} = -\left(\mu_{e},_{\varepsilon}\cdot\boldsymbol{E}\right)n_{e,\varepsilon} - \boldsymbol{D}_{e,\varepsilon}\cdot\nabla n_{e,\varepsilon}\,,$$

where $\mathbf{\Gamma}_{e,\varepsilon}$ – electron and energy fluxes, $\mu_{e,\varepsilon}$ – mobility, $\boldsymbol{E}$ – electric field, $\boldsymbol{D}_{e,\varepsilon}$ – diffusion coefficients, $R_{e,\varepsilon}$ – ionization rate and energy loss/acquisition due to inelastic collisions. Transport coefficients $\mu_{e,\varepsilon}$ *and* $\boldsymbol{D}_{e,\varepsilon}$ are calculated in BOLSIG + program. In this work, the self-sustained discharge and discharge with additional electron injection are simulated.

Figure 3 shows the calculated dependence of plasma density distribution and electron temperature on gas pressure in self-sustained burning mode, when: total current $I_c = 30$ A and $S_a = 200$ cm^2. Figure 4 shows the calculated radial plasma density distribution in a hollow cathode with and without processed parts.

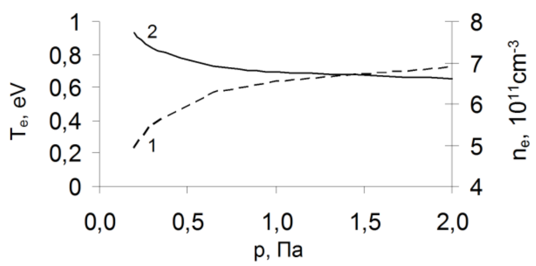

Figure 3. Dependence of plasma concentration distribution (1) and electron temperature (2) in self-sustained burning mode on gas pressure

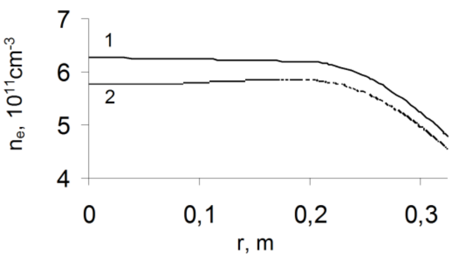

Figure 4. Calculated radial distribution of plasma concentration in a hollow cathode with (1) and without processed parts (2)

Conclusion

This work simulated the generation of low-temperature glow discharge plasma with a large area hollow cathode, both in a self-sustained mode and additional electron injection mode. The relation describing the dependence of the burning intensity on gas pressure was obtained.

Numerical experiments were carried out by using a hydrodynamic model. It is shown that the high homogeneity of plasma is reached with concentration up to 10^{12}cm^{-3} and plasma temperature reaches 1eV. The effect of processed parts placed inside hollow cathode on the plasma concentration distribution and electron temperature was investigated. It is shown that the independent adjustment of the discharge current and discharge burning intensity is impossible due to the extra discharge current. The results of theoretical and numerical investigations of the discharge characteristics agree with experiments [1].

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