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Ion angle distribution at the target surface in pure gas direct current glow discharge

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1. Introduction

Knowledge of the energy and angle distributions of ions bombarding the target (cathode) surface is of a great importance for simulation of the process of solid state etching in DC glow discharge. The energy distribution function of ions in the cathode sheath (CS) of discharge was calculated in a number of articles both analytically and numerically. Simulation of the ion angle distribution function (ADF) was usually fulfilled numerically on the basis of the Monte Carlo method [1-4]. In Ref. 5 an approximate analytical expression for the ion ADF was obtained in case the mean ion path length λ in the fill gas exceeds the CS width d_c, which is valid at quite low gas pressures only. In [6,7] a single scattering model of monoenergetic ion beam motion in a gas filled electric field free volume was used for estimations of the ion angle distribution. Because the ion energy spectrum in the discharge CS is rather wide and scattered ions are accelerated by the electric field, obtained results have a very limited range of applicability.

In this work, the ion ADF in the glow discharge CS in a pure gas is calculated in case the cross section of ion-atomic resonant charge exchange exceeds that of isotropic elastic scattering.

2. Theory

Under ion motion in its parent gas, the main types of ion-atomic interactions are resonant charge exchange (anisotropic elastic scattering) and isotropic elastic scattering [8]. In the process of charge exchange, the fast ion disappears and a new ion with zero velocity is produced. Energy of such ion until the next collision is determined by its acceleration in the CS electric field and direction of motion is perpendicular to the cathode surface. During isotropic elastic scattering the ion loses a part of its energy and changes direction of motion, deflecting from the cathode normal. Therefore, it is convenient to divide the ion velocity distribution function (VDF) into two parts as follows:

$$F(\vec{r},\vec{v}) = F_0(\vec{r},\vec{v}) + F_1(\vec{r},\vec{v}) \ , \qquad (1)$$

where $F_0(\vec{r},\vec{v})$ is the VDF of ions which undergo no isotropic elastic scattering after the last charge exchange and $F_1(\vec{r},\vec{v})$ is the VDF of ions which undergo at least one isotropic elastic scattering after the last charge exchange.

Let the z-axis be perpendicular to the cathode surface, $z=0$ and $z=d_c$ be coordinates of the CS boundary and the cathode surface. Then the function $F_0(\vec{r},\vec{v})$ has the form

$$F_0(\vec{r},\vec{v}) = f_0(z,v_z)\delta(v_x)\delta(v_y), \qquad (2)$$

where $f_0(z,v_z)$ is the ion longitudinal velocity distribution function.

The VDF parts $F_0(\vec{r},\vec{v})$ and $F_1(\vec{r},\vec{v})$ fulfill equations following from the ion kinetic equation for the ion VDF $F(\vec{r},\vec{v})$. Substitution of expression (2) in the first of them and its integration with respect to v_x and v_y give an equation for $f_0(z,v_z)$. Under $\lambda_0 << d_c$ the electric field strength varies slightly at the ion path length, therefore in the vicinity of the cathode it can be considered as a constant value equal to $E_c = 2U_c/d_c$, where U_c is the cathode voltage drop. Then solution of the equation for $f_0(z,v_z)$ is [9]

$$f_0(z,\varepsilon_z) = \frac{1}{eE_c\lambda_c}\exp\left(\frac{z_0 - z}{\lambda_0}\right), \qquad (3)$$

where $\varepsilon_z = Mv_z^2/2$ and M are the ion energy and mass respectively, $\lambda_0 = \left(1/\lambda_c + 1/\lambda_e\right)^{-1}$, λ_c and λ_e are the ion path lengths with respect to charge exchange and isotropic elastic scattering processes respectively, $z_0 = z - \varepsilon_z/eE_c$ is coordinate of the last charge exchange of an ion which has energy ε_z in point z.

For many gases the ion charge exchange cross section exceeds that of isotropic elastic scattering [4,8,10], which results in condition $\lambda_c < \lambda_e$, and just a small fraction of ions undergoes more than one elastic scattering between two charge exchanges. Therefore, the corresponding term in the equation for $F_1(\vec{r},\vec{v})$ can be omitted. Using the hard sphere model of isotropic elastic scattering, in which the path length λ_e is independent on ion energy [11], it can be written as follows

$$\frac{\partial F_1}{\partial z} + eE\frac{\partial F_1}{\partial \varepsilon_z} = \frac{1}{2\pi\lambda_e\varepsilon_z} f_0\left[z, \varepsilon_z\left(1+\frac{\varepsilon_r}{\varepsilon_z}\right)^2\right] - \frac{1}{\lambda_c}\sqrt{1+\frac{\varepsilon_r}{\varepsilon_z}}\ F_1 \qquad (4)$$

with boundary condition $F_1(0,\varepsilon_r,\varepsilon_z)=0$, where ε_z and ε_r are the energies of ion longitudinal and lateral motions respectively.

Solution of Eq.4 is defined by expression

$$F_1(z,\varepsilon_r,\varepsilon_z)=\frac{1}{2\pi\lambda_c\lambda_e(eE_c)^2}\int_0^1 \exp\left\{-\frac{\varepsilon_z}{eE_c\lambda_c}\left[\left(1+\frac{\lambda_c}{\lambda_e}\right)\left(1+\frac{\varepsilon_r}{\varepsilon_z t}\right)^2 t+\int_t^1\sqrt{1+\frac{\varepsilon_r}{\varepsilon_z t'}}\;dt'\right]\right\}. \quad (5)$$

The flow density of isotropically scattered ions at the cathode surface is

$$dj_1(d_c,\theta,\varepsilon_z)=2\pi F_1(d_c,\varepsilon_r,\varepsilon_z)\varepsilon_z d\varepsilon_z\frac{tg\theta}{\cos^2\theta}d\theta\,, \quad (6)$$

where θ is the angle between the ion velocity direction and the surface normal.

Substitution of expression (5) in (6) and integration with respect to ε_z and t taking into account the condition $d_c >> \lambda_c$ results in expression

$$\frac{dj_1}{d\theta}=\frac{\lambda_c}{\lambda_e}\frac{\sin\theta\;\;\cos^2\theta}{\beta(\theta)}\left[\frac{\cos^2\theta}{\alpha}-2\cos\theta+\frac{\beta(\theta)-\cos^2\theta+2}{\sqrt{\beta(\theta)}}\ln\frac{\sqrt{\beta(\theta)}+\cos\theta}{\sqrt{\beta(\theta)}-\cos\theta}\right], \quad (7)$$

which describes the angle distribution of ions isotropically scattered after the last charge exchange, where $\alpha=1+\lambda_c/\lambda_e$, $\beta(\theta)=4\alpha\, tg^2\theta\cos\theta+\cos^2\theta$.

Ions falling on the cathode without isotropic scattering after the last charge exchange are moving along the z-axis. Therefore, the total angle distribution of the ion flow bombarding the cathode surface is

$$\frac{dj}{d\theta}=\frac{1}{\alpha}\delta(\theta)+\frac{dj_1}{d\theta}\,. \quad (8)$$

Calculations show that in a wide range of parameter α values it satisfies condition $\int_0^{\pi/2}(dj/d\theta)d\theta=1$ with a good accuracy.

The ion ADF (7) at the cathode surface under $\lambda_c/\lambda_e=0.71$ is presented in Fig.1. Its form corresponds to the results of numerical simulation [1,4]. The energy–weighted average ion impact angle which is defined by following expression

$$\overline{\theta}_e=\frac{\int\int\theta\;\;\cos^{-2}\theta\;\;\varepsilon_z\;\;dj_1(d_c,\theta,\varepsilon_z)}{\int\int\cos^{-2}\theta\;\;\varepsilon_z\;\;dj_1(d_c,\theta,\varepsilon_z)+\int\varepsilon_z f_0(d_c,\varepsilon_z)d\varepsilon_z} \quad (9)$$

equals to 8 degrees in this case, which is in a good agreement with its value (9 degrees) calculated numerically in Ref.12.

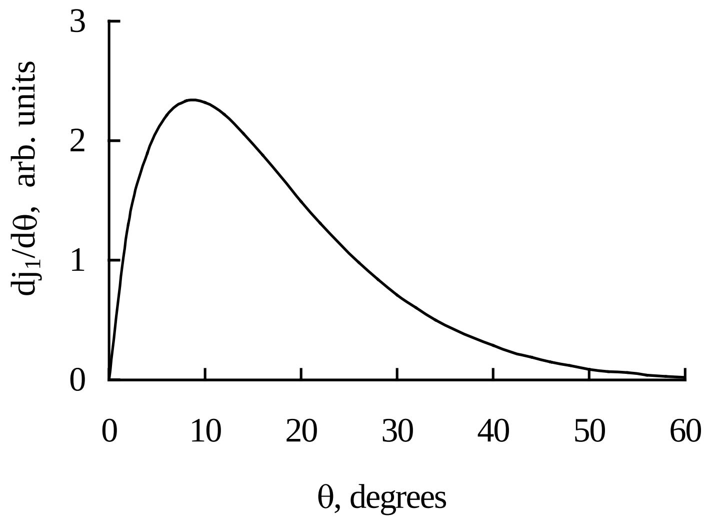

Fig.1. Angle distribution function of ions bombarding the cathode surface under $\lambda_c / \lambda_e = 0.71$.

3. Conclusion

An analytical model of ion motion in the glow discharge CS, taking into account ion-atomic resonant charge exchange and isotropic elastic scattering in case the cross section of the first processes exceeds that of the second one, is developed. An expression for the ion ADF has been obtained which can be used for estimations of ion angle distribution at the cathode surface of glow discharge in a pure gas. Calculated energy–weighted average ion impact angle is in good agreement with its numerically found value.

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