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ON THE SECONDARY ELECTRON EMISSION IN DC MAGNETRON DISCHARGE

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The presence of a curved magnetic field in the vicinity of a surface can drastically influence the secondary electron emission induced by ion impact. This phenomenon was studied for the metallic cathode of a DC planar magnetron discharge. The spatial dependence of the secondary electron emission coefficient is obtained from the boundary conditions imposed for particle fluxes in two-dimensional fluid model. The effect of the gas pressure, magnetic field strength magnitude and orientation upon the coefficient of the secondary emission is discussed. The contribution of the electron reflection on the surface is also investigated.

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1. Introduction

Secondary electron emission by ion impact is an essential phenomenon for both breakdown and self-sustaining condition of the gas discharges [1]. Hence, any change of the coefficient of the secondary electron emission affects the stationary regime of the discharge. The presence of a magnetic field close to the cathode surface, as in magnetron discharges, may strongly influence the secondary emission process [2]. This will be further reflected on the commodities of the magnetron, mainly used as sputtering/deposition source [3], modifying thus the deposition rate, the physical proprieties of the deposited films, the efficiency of the method, etc.

In the case of a planar magnetron, the ions are accelerated into the cathode fall and they knock the cathode (also known as target) extracting from the surface secondary electrons and atoms. Due to the magnetic field, secondary electrons follow helicoidal trajectories, allowing some of them to return to the surface despite of the strong repulsive electric field. Once back, these electrons can be either reflected or captured. All reflected electrons are re-injected into the discharge while the others stay on the target. Hence, not all of the secondary electrons are important for the discharge. To point out this idea, in the reference [2] an effective coefficient of secondary electron emission was introduced.

In our work, secondary electron emission problem was studied through a 2D (r,z) fluid model developed and used to describe a DC circular planar magnetron discharge [4,5]. The effective coefficient of the secondary emission was yielded from the fluid boundary conditions imposed at the cathode. It was investigated its dependence on the gas pressure, on the magnetic field strength and on the electron reflection probability on the surface.

2. Theoretical aspects

The magnetron plasma is studied with a bi-component fluid model. The first three moments of Boltzmann equation are solved for electrons while only the first two of the corresponding

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equations are considered for the positive ions, Ar^+. Plasma potential is given by Poisson equation. Appropriate boundary conditions are imposed for fluxes and for the electric potential [4]. The interest of this paper being the secondary electron emission, we will further present only some theoretical consideration for electrons.

For the case of a magnetized discharge, the momentum transfer equation for electrons is written as

$$m_e n_e \left[\frac{\partial \overrightarrow{\mathrm{v}_e}}{\partial t} + \left(\overrightarrow{\mathrm{v}_e} \cdot \nabla \right) \overrightarrow{\mathrm{v}_e} \right] = -e n_e \left(\vec{E} + \overrightarrow{\mathrm{v}_e} \times \vec{B} \right) - \nabla \overline{\overline{P_e}} - m_e n_e f_{me} \overrightarrow{\mathrm{v}_e} \left(1 + \frac{f_{iz}}{f_{me}} \right), \tag{1}$$

where n_e is the electron density, m_e – the electron mass, $\overrightarrow{\mathrm{v}_e}$ – the velocity of the fluid particle, f_{iz} – the ionisation frequency by electron-neutral impact, f_{me} – the total momentum transfer frequency for electron – neutral collision, $\vec{E}$ – the electric field intensity, $\vec{B}$ – the magnetic field strength, $\overline{\overline{P_e}}$ – the pressure tensor, t – the time. Equation (1) can be reduced under some simplifying assumptions as following: *i*) the inertial term can be neglected due to the small mass of the electron, *ii*) the ionisation frequency, f_{iz}, can be neglected with respect to the momentum transfer frequency for electrons, f_{me}, *iii*) scalar pressure for electrons, $P_e = n_e k T_e$. Consequently, the electron flux, $\overrightarrow{\Gamma_e} = n_e \overrightarrow{\mathrm{v}_e}$, can be expressed as

$$\overrightarrow{\Gamma_e} = \overrightarrow{\Gamma_e^0} + \overrightarrow{\Gamma_e^1}, \tag{2}$$

where $\overrightarrow{\Gamma_e^0}$ is the classical drift-diffusion flux and $\overrightarrow{\Gamma_e^1}$ is the contribution of the magnetic field. These terms detail as:

$$\overrightarrow{\Gamma_e^0} = -\mu_e n_e \vec{E} - \nabla (D_e n_e) \tag{3}$$

$$\overrightarrow{\Gamma_e^1} = -\overrightarrow{\Gamma_e} \times \overrightarrow{\Omega_e} / f_{me}, \tag{4}$$

with $\mu_e = e / m_e f_{me}$ the electron mobility, $D_e = kT_e / m_e f_{me}$ the electron diffusion coefficient, $\overrightarrow{\Omega_e} = e\vec{B} / m_e$ the angular cyclotron velocity and e the elementary charge. Due to the axial symmetry, a cylindrical coordinate system is used. The electric and magnetic fields present only radial and axial components and the plasma is supposed to be axially symmetric. Thus, the classical drift-diffusion flux has only two components, Γ_{er}^0 and Γ_{ez}^0, while $\overrightarrow{\Gamma_e^1}$ has three, since the electric drift $\vec{E} \times \vec{B}$ induces the angular one. From the combination of the equations (2) and (4), $\overrightarrow{\Gamma_e^1}$ can be expressed as:

$$\begin{pmatrix} \Gamma_{er}^1 \\ \Gamma_{e\varphi}^1 \\ \Gamma_{ez}^1 \end{pmatrix} = \frac{1}{f_{me}^2 + \Omega_e^2} \begin{pmatrix} -\Omega_{ez}^2 & \Omega_{er}\Omega_{ez} \\ f_{me}\Omega_{ez} & -f_{me}\Omega_{er} \\ \Omega_{er}\Omega_{ez} & -\Omega_{er}^2 \end{pmatrix} \begin{pmatrix} \Gamma_{er}^0 \\ \Gamma_{ez}^0 \end{pmatrix}. \tag{5}$$

Solving fluid equations requires some boundary conditions. For the charged particles these conditions are imposed for the fluxes. All the fluxes parallel to any electrode in the discharge are zero. In the absence of a magnetic field, the normal electron flux to the cathode is given only by the secondary electrons issued by ion impact on the surface

$$\Gamma_e^{\perp} = -\gamma_i \Gamma_i^{\perp}, \tag{6}$$

with γ_i the coefficient of the secondary electron emission and $\Gamma_i^{\perp}$ the normal ion flux incident to the cathode. If a magnetic field is present, the cathode boundary condition changes, according to relation (2), in

$$\Gamma_e^{\perp} = \Gamma_e^{0\perp} + \Gamma_e^{1\perp}, \tag{7}$$

where $\Gamma_e^{0\perp}$ is given by (6), while $\Gamma_e^{1\perp}$ can be calculated from (5), resulting thus

$$\Gamma_e^{\perp} = -\gamma_i \Gamma_i^{\perp}\left(1 - \frac{\Omega_{e\|}^2}{f_{me}^2 + \Omega_e^2}\right) \equiv -\gamma_{net}\Gamma_i^{\perp}. \quad (8)$$

The two directions, parallel and perpendicular, are defined with respect to the cathode surface. The influence of the magnetic field on the ion flux is neglected because the ion cyclotron giro-radius, which is the order of several cm, is much larger than the thickness of the cathode fall, limited at a few mm. In the equation (8) was introduced a new coefficient, γ_{net},

$$\gamma_{net} = \gamma_i\left(1 - \frac{\Omega_{e\|}^2}{f_{me}^2 + \Omega_e^2}\right). \quad (9)$$

While γ_i is a measure of all secondary electrons emitted by ion bombardment of the cathode, γ_{net} is an effective coefficient corresponding only to those secondary electrons which remain in the discharge, excluding the electrons recaptured by the cathode. This net coefficient is the one which really counts for both the breakdown and self-sustain mechanism of the discharge. The relation (9) reveals the dependence of γ_{net} on some discharge parameters. The total momentum transfer frequency for electron – neutral collision f_{me} depends on the gas nature and pressure, while angular cyclotron velocity vector $\overrightarrow{\Omega_e}$ contains the dependence on the magnetic field strength. The difference between the net coefficient, γ_{net}, and the ion induced one, γ_i, can be expected to vanish with the increase of the pressure due to electron-neutral collisions and also if the magnetic field lines become perpendicular to the surface.

Due to its helicoidal trajectory around the magnetic field lines, a secondary electron leaving the target can return to the surface in the regions where the magnetic field lines are not perpendicular to the cathode. Then, it can be reflected or captured by the surface. It is noteworthy mentioning that the possible reflection of the electrons to the cathode is not included in relation (9). Thus, all the electrons returning to the cathode are considered recaptured. In the expression (9) they are represented by the negative fraction in the parenthesis. As shown in the previous works [2,6,7], the reflection coefficient of the electrons, R, is not negligible. In our case, if a non-zero reflection coefficient is considered, it must be applied only to the returned electrons. In this case, the net flux of electrons, $\Gamma_e^{\perp}$, injected into the discharge increases and the effective coefficient γ_{net} becomes

$$\gamma_{net} = \gamma_i\left[1 - \frac{\Omega_{e\|}^2}{f_{me}^2 + \Omega_e^2}(1 - R)\right]. \quad (10)$$

3. Results

Due to the cylindrical symmetry of the DC planar magnetron considered, a 2D (r,z) treatment is sufficient. Numerical calculations were performed in Argon. The linear dimensions of the discharge are $R_{max} = Z_{max} = 26.95$ mm. The cathode is a metallic disc ($r_{cath} = 16.5$ mm) and the magnetic field map in front of it was obtained according to [8] (Fig. 1). The length of the plotted vectors is scaled by ln$B$. At the cathode surface, at $r \approx 9.5$ mm, the magnetic field strength is about 750 Gauss and it axially decreases to several Gauss in about 12 mm. For $p = 20$ mTorr, $T_{Ar} = 350$ K and $V_{cath} = -550$ V, plasma torus of the negative glow is also figured, the darkest zone corresponding to the highest density.

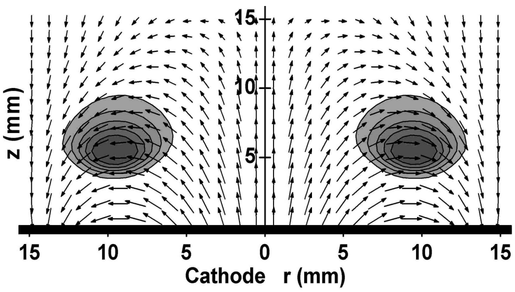

Fig. 1. Magnetic field map in front of the cathode (axial cross section).

Further, the results concerning the spatial variation of γ_{net} and the manner it is influenced by the gas pressure, magnetic field strength and the reflection coefficient of the electrons on the cathode surface are presented. In Fig. 2, the net coefficient of the secondary electron emission γ_{net}/γ_i and the electron flux at the cathode $\Gamma_e^{\perp}$ are plotted for different reflection coefficients, R = 0, 0.25, 0.5, keeping constant the incident ion flux, $\Gamma_i^{\perp}$. Both fluxes are normalised to the peak value.

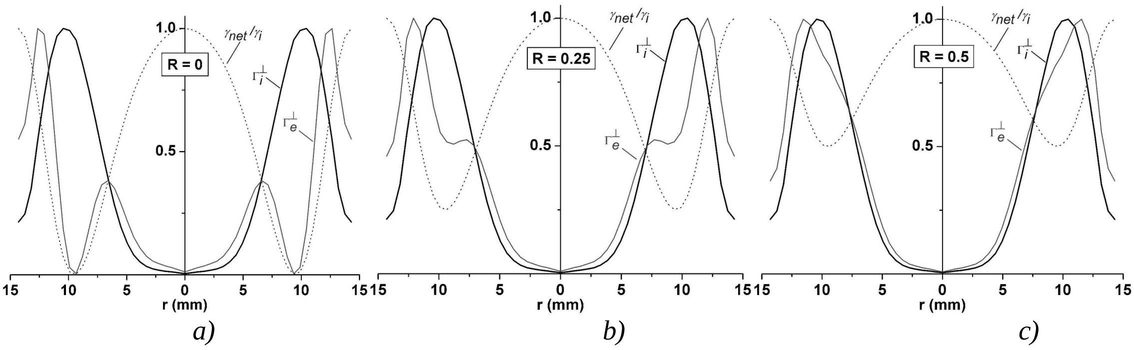

Fig. 2. Radial dependence of the ratio γ_{net}/γ_i, normalised ion ($\Gamma_i^{\perp}$) and electron ($\Gamma_e^{\perp}$) fluxes at the cathode: a) R = 0; b) R = 0.25; c) R = 0.5.

As shown in Fig. 1, the magnetic field strength varies radially both in magnitude and direction. According to equation (9), it induces a spatial dependence for γ_{net} (see Fig. 2a). This fact has an immediate influence on the flux of the secondary electrons. Since they are not affected by the magnetic field, the ions are directly accelerated to the cathode, with their maximum flux corresponding to the maximum of plasma density, at a radial position about 9.5 mm. In contrast, the maximum flux of the secondary electrons does not correspond to the region where the ion flux is optimal. It can be observed that the most part of the electrons is not injected into the discharge in the region of the maximum ion flux, where the magnetic field lines are parallel to the cathode, but on the both sides of it, where the magnetic field lines are close to the normal to the cathode (Fig. 2a). In the area where the magnetic field is parallel to the surface many secondary electrons return to the cathode and their contribution to the discharge is controlled by the reflection probability (Fig. 2b,c). This probability is considered around 50% by some authors [7]. Our calculation is made below this value. Obviously, the reflection coefficient, R, states the minimum of the ratio γ_{net}/γ_i. Increasing R, the secondary electron flux shapely approaches to the ion flux, which is an expected result. Fig. 3 presents the influence of the magnetic field strength on the γ_{net}. For a constant gas pressure of 20 mtorr, a reflection coefficient R = 0.5 and for the same field map as in Fig. 1, only the magnitude of the magnetic field was modified. B_0 is the magnetic field matrix having the values described above.

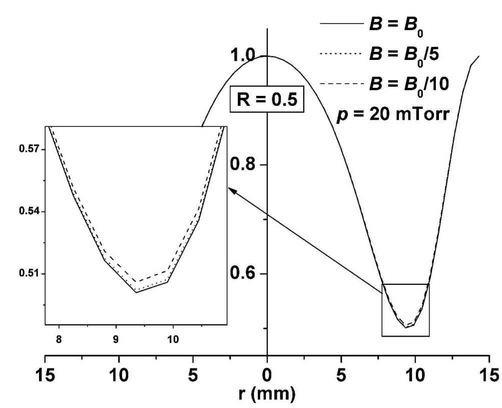

Fig. 3. Radial dependence of the ratio γ_{net}/γ_i at several magnetic field strength.

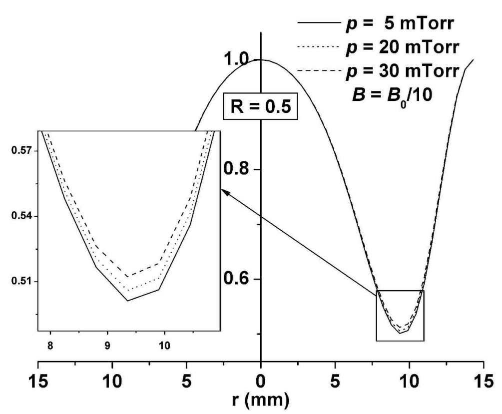

Fig. 4. Radial dependence of the ratio γ_{net}/γ_i at several gas pressures.

For the discussed conditions, the ratio f_{me}/Ω_e is much smaller than 1, inducing a small difference between the three curves. In this case, the variation of B or p does not affect more than 1% of the net coefficient γ_{net}. Keeping constant the magnetic field matrix B_0 and changing the gas pressure in the range of 5-30 mTorr no change was noticed for γ_{net}. Anyway, to illustrate that the pressure can also modify the secondary electron emission coefficient, the radial dependence of γ_{net} is plotted in Fig. 4 for a reduced magnetic field (B_0/10) and the gas pressure varying between 5 and 30 mTorr.

4. Conclusions

This paper presents some aspects about the process of the secondary electron emission at the cathode of a magnetron discharge. Due to the presence of an inhomogeneous magnetic field to the surface, not all the secondary electrons are involved in the discharge balance. Their active fraction is given by a net coefficient of the secondary emission, γ_{net}. This coefficient depends on the gas pressure, on the magnetic field strength and on the reflection probability of the electrons on the cathode surface. The first two dependences result from the imposed boundary conditions for the fluxes of the charged particles in a bi-dimensional time-dependent fluid model. It is remarkable that, in our work, the effective coefficient results directly from the model, without other external parameters except electrons reflection on the electrodes. The effect of the pressure and of the magnetic field with respect to each other is significant only if the total momentum transfer frequency for electron – neutral collision f_{me} and the electron cyclotron giro-frequency Ω_e have the same order of magnitude. The inhomogeneity of the magnetic field determines the spatial variation of the net secondary emission coefficient, with a minimum value in the region where the magnetic field lines are parallel to the cathode, corresponding to the maximal plasma density. The minimum value of γ_{net} is controlled by the reflection probability of the electrons on the surface.

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