PLASMA-OPTICAL MODEL FOR MAGNETRON TYPE CYLINDRICAL GAS DISCHARGE

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Introduction

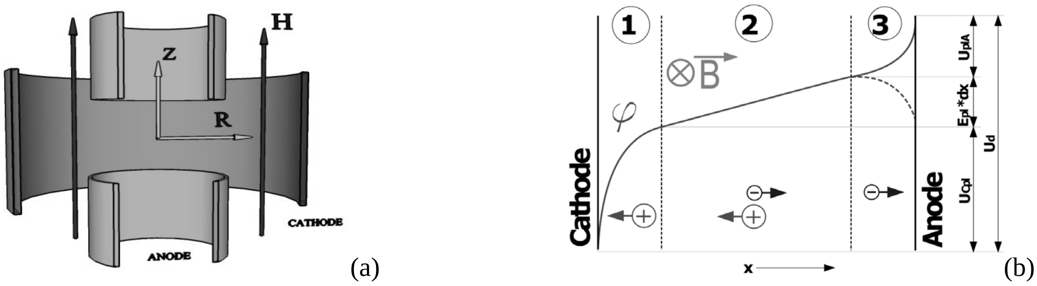
The plasma-optical concept firstly described in [1] based on application principles of magnetic insulation electrons and equipotentialization magnetic field lines for the manipulating of extra thermal electric fields introduced into the plasma medium. As follows from these principles variation of the magnetic field line configuration and the distribution of electric potential enables the formation and control of high current ion beams while maintaining their quasi-neutrality. This makes the application of such devices attractive for the formation and manipulation of high current heavy ion beams. The electrostatic plasma lens provides a unique tool for these things. This kind of cylindrical plasma lens is a well-explored device for manipulating and focusing high current, large area, moderate energy, heavy ion beams, where the concern of beam space charge compensation is critical [2, 3]. In those investigations was noted an increasing in the focused ion beam current density for specific low magnetic field strengths. A narrow range of low magnetic field strength was found for which the focusing properties of the lens improved significantly that opened possibility to elaborate a plasma lens based on the use of permanent magnets. The simple design, robust construction, the need for only a single power supply, and the high efficiency are all attractive advantages of a lens using permanent magnets rather than current-driven coils.

We have developed several cylindrical permanent magnet plasma devices based on this method for ion treatment and material synthesis. They can be operated as stand-alone tool for ion treatment of substrates, or as part of integrated processing system together with cylindrical sputtering system**.** The plasma-optical model for magnetron type cylindrical gas discharge has been developed [4]. The model based on assumption about existing of three basic quasi-autonomous regions in the diode-space, as it is the case for plasma accelerators with an extensive acceleration zone. The results of theoretical consideration plasma dynamical discharge characteristics and experiments are present here.

A model of cylindrical gas discharge and simulations results

A general plasmodynamical approach for the analysis of this kind of system is based on a one dimensional, gas-filled diode gap with magnetized electrons and free unmagnetized ions. The principal scheme of the cylindrical diode setup is shown in Figure 1a. The inner space of the cylindrical cathode with radius R_C and height h it serves as target, sputtered by accelerated ions. There are two cylindrical hollow anodes with radius $R_A<R_C$, it separated by a distance h. The magnetic field is parallel to the walls of the electrodes. The envelope of the disjoined anode electrodes are forming a virtual cylindrical surface, the potential approximately equals the anode potential according to condition of equipotentialization. The samples can place on the system axe.

Typical operating parameters are: working gas is Ar, pressure is 2-6·10^{-3} Torr, the magnetic field is 0,05-0,08 T, discharge voltage U_d= 400-600 V, discharge current density j_d=20-30 mA/cm^2, R_C=2-3 cm, R_A=1-2 cm. A magnetron- type gas discharges in such pressure range are high-currents, thus one can assume the existing of three basic quasi-autonomous regions in the diode-gap, as it is the case for plasma accelerators with an extensive acceleration zone (see Fig.1b). In our previous paper we described such kind plasma-optical model [4,5].



(a) (b)

Fig. 1. The principal scheme (a) and three basic quasi-autonomous regions (b) in the diode gap

The first zone (1 on Fig. 1b) is the cathode potential drop region where the main acceleration and ion stream formation occurs. In this region, discharge carrying current is provided by ions. The second zone (2 on Fig.1b) is the positive column zone. Inside this zone, ionization and generation of charge particles takes place. The third zone (3 on Fig.1b) is a narrow region attached to anode that has a size close to the Larmour radius of the electron. The magnetic isolation is eliminated and the electrons are carrying the discharge current here.

Let us stop now on looking zone 2. It is a low temperature zone, where the entering high-velocity electrons as well as the generated low-velocity electrons are magnetized. The ions are free to move to the cathode under the influence of a finite plasma electric field E_{pl}. In this region, the one-dimensional equations of two-fluid magneto-hydrodynamics are applicable:

$$\frac{d^2\varphi}{dx^2} = 4\pi e(n_e + n_{efast} - n_i) \qquad (1)$$

$$en_i = \frac{\gamma j_{ik} n_a \sigma_i}{\sqrt{2\frac{e}{M}}} \int_x^{x_0} \frac{dx'}{\sqrt{\varphi(x') - \varphi(x)}} \qquad (2)$$

$$j_{epl} = \mu_\perp en_e \left(E_{pl} - \frac{\nabla(n_e kT_e)}{en_e} \right) \quad (3) \quad \text{and} \quad \nabla \cdot j_{epl} = \gamma j_{ik} n_a \sigma_i(v_e), \quad \nabla \cdot j_{ipl} = \gamma j_{ik} n_a \sigma_i(v_i) \quad (4)$$

here $\mu_\perp = \frac{e\nu_e}{m\omega_{he}^2}$ is the electron mobility and ν_e is the frequency of elastic collisions with neutrals and ions. Equation (4) describes the generation of electrons and ions in the plasma column due to impact ionization of neutral gas by fast secondary electrons only. These electrons do not contribute much to the discharge current, but they are the main ionization factor. The stream of generated slow electrons across the magnetic field to the anode is determined by the mobility $\mu\perp$ along the electric field E_{pl} and diffusion.

The analysis and simplest solutions (1-4) was made in [5]. For the typical parameters given above we investigate these equations numerically with the appropriate boundary conditions in cylindrical coordinates, using an iterative method for getting self-consistent solutions. The simulation results are shown in Fig. 2.

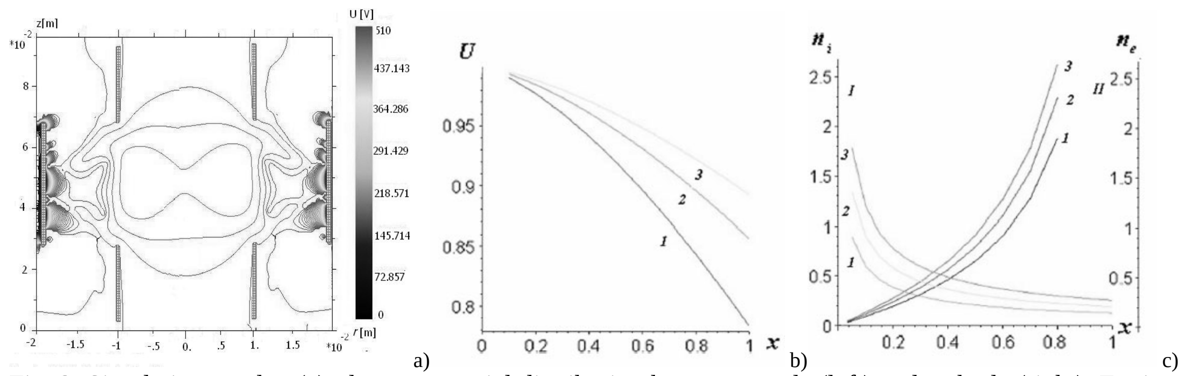
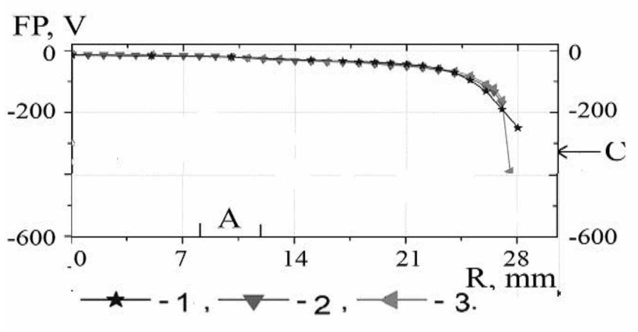
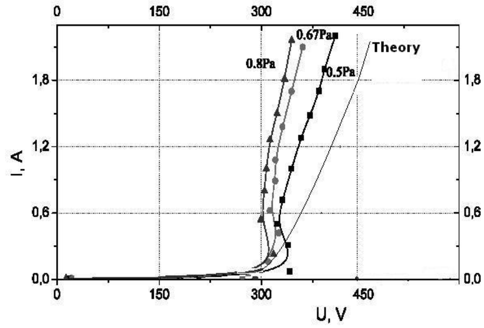


Fig. 2. Simulation results: (a)-plasma potential distribution between anode (left) and cathode (right). Equipotential lines are shown; (b) distribution of plasma layer potential ; (c)- distribution of ion (I) and electron (II) density for different discharge potentials(V):1 – 300, 2 – 450, 3 – 600 (H = 600 Oe, j_d = 30 mA/cm^2)

Ones can see that the potential drop in the plasma layer can reach 30-50V and it occurs in a narrow cathode layer as it can be seen in Fig. 2a, b). From Fig. 2a is shown that split anode leads to formation of a virtual anode with potential equal to the anode potential that could serve as confirmation of the equipotentialization principle [1]. The distribution of ion and electron density along plasma layer for different discharge potential is shown is shown in Fig. 2c. The describing numerical plasmooptical model of the cylindrical magnetron type gas discharge is in satisfying consent with experimental results (see Fig.3).



a)



b)

Fig.3. Distribution of a) floating potential along radius for different pressure (Torr) in high-current mode: 1-4x10^{-3}, 2-7x10^{-3}, 3-9x10^{-3}; b) current-voltage characteristics for high-current mode.

Conclusion

A plasma-optical model for magnetron type cylindrical gas discharges has been developed. The model is in satisfactory consents with experimental results. Importantly, note that the influence of atoms sputtered from the cathode was not taken into account in the model. Obviously, for certain conditions this influence can be substantial, as confirmed by the experimental results. An important question is the nature of the physical mechanisms determining the form of the discharge. One might conclude from the present results that growth of the discharge current density at the cathode is related primarily to the decrease of the near-cathode layer thickness d_{Cpl}. The layer thickness is about 10^{-2} cm for our experimental conditions. The electrical field at the cathode surface is approximately $4 \cdot 10^4$ V/cm for a voltage of 400 V. Field emission stimulation of arc discharges becomes noticeable for fields of 10^5 V/cm, varying more or less depending on the cathode material, its surface state, and so on. Nevertheless we may conclude that for such magnetron type discharges the limiting discharge current density lies in the range 30-50 mA/cm^2. This is confirmed by numerical calculations also.

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