NEW VISION OF THE PHYSICS OF GAS MAGNETRON-TYPE DISCHARGES

O.A. GONCHAROV, A.M. DOBROVOL'SKYI, A.M. EVSYUKOV, I.M. PROTSENKO, I.V. LITOVKO[1]

Institute of Physics, Nat. Acad. of Sci. of Ukraine
(46, Nauky Prosp., Kyiv 03680, Ukraine)

[1]Institute of Nuclear Research, Nat. Acad. of Sci. of Ukraine
(47, Nauky Prosp., Kyiv 03680, Ukraine; e-mail: gonchar@iop.kiev.ua)

UDC 533.9

We present the results of complex theoretical and experimental investigations of cylindrical gas discharges in the configuration of crossed electric and magnetic fields inherent to axially symmetric plasma lenses. An original cylindrical sputtering device constructed based on the principles of plasmaoptics is proposed and tested. A new systematic vision of plasmadynamics of gas magnetron-type discharges is formulated. The proposed approach predicts the presence of three quasiautonomous regions in a discharge, where the current transfer is realized by different particles.

1. Introduction

The idea of plasmaoptics based upon the principle of magnetic isolation of electrons and the equipotentialization of force lines of a magnetic field is used in many plasmadynamic systems [1–3]. In the 1970s, it was discovered that the inversed scheme of an anode-layer accelerator is easily transformed into a self-sustained gas discharge of the magnetron type that can be used for the effective sputtering of a cathode-target. In turn, this resulted in the appearance of power planar technological sputtering systems. Plane magnetron sputtering systems of various configurations find their deserved niche in the up-to-date plasma technologies, by providing a high quality and a uniformity of deposited functional coatings and by representing an effective plasmachemical reactor for the synthesis of binary compounds of chemically active metals. At the same time, one actively investigates cylindrical systems of the magnetron type (both direct-action and reversed) due to their doubtless technological advantages in the processing of cylindrical samples of a complicated form, the high efficiency of a utilization of a target material and a steam flow, as well as due to the possibility to construct adequate theoretical models. [4–6].

The experimental investigations of plasmadynamic characteristics of electrostatic plasma lenses [7] discovered that, under certain conditions, there exists a possibility of the ignition of a self-sustained stable gas discharge in them. This fact allowed one to consider the configuration of a plasma lens as a suitable prototype for the creation of a new generation of plasmadynamic devices. In particular, a successive account of the plasmaoptical principles, as well as certain modifications of the configuration of fixing electrodes, gave a possibility to propose and to realize experimentally a cylindrical magnetron-sputtering system with magnetoelectronic virtual anode [7, 8]. Plasmaoptical systems are extremely complicated for an integral successive description of physical processes that determine the mechanisms of their action. Modern theoretical concepts are based upon kinetic, hydrodynamic, and hybrid models that describe separate quasiautonomous regions of such systems in a fairly adequate way [2, 3]. For example, in dielectric-wall plasma accelerators, one distinguishes several quasiautonomous regions [2], among them a near-anode area and the regions of ionization and acceleration of a working substance spaced along the channel of the plasma accelerator. According to the recent experimental investigations [3], the region of the dominant potential drop (acceleration region) is mainly

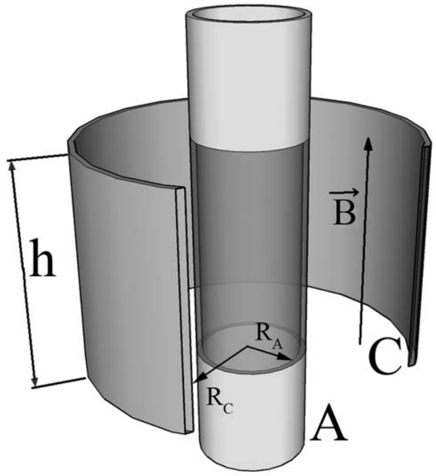

Fig. 1. Simplified diagram of gas-filled diode gap. Cathode (C) with the height h and hollow anodes (A) are spaced by the cathode height

concentrated at the cutoff of the acceleration channel near the cathode.

In what follows, we propose a closed hydrodynamic model of such a system and compare our conclusions with experiment.

2. Plasmadynamic Model of Discharge

Following the general plasmadynamic approaches used for the analysis of similar systems, we consider a one-dimensional gas-filled diode gap with magnetized electron background and free nonmagnetized ions. The simplified diagram of such a gap is presented in Fig. 1. The internal surface of the cylindrical cathode can serve as a target for the sputtering by accelerated ions. A virtual cylindrical surface is emerged along the forming spaced anode electrodes; it acquires a potential close to the anode one by virtue of the equipotentiality condition. Let us adhere to some characteristic parameters: a pressure of the plasma-forming gas (argon) is (2–6)$\times 10^{-3}$ Torr, magnetic field strength H=500–800 Oe, discharge voltage U_d=400–600 V, discharge current density j_d=20-30 mA/cm^2, and characteristic size of the diode gap L=1–3 cm.

In the considered pressure range, gas magnetron-type discharges are high-current. That's why it is natural to assume the presence of three basic quasiautonomous zones in this diode gap by analogy with plasma accelerators with extensive acceleration area. In this case, the discharge voltage drop can be presented in the form $U_d = U_{Cpl} + E_{pl}\Delta r + U_{plA}$, where U_{Cpl} is the cathode voltage drop, E_{pl} is the electric field of the plasma cylinder, Δr denotes its thickness, and U_{plA} is the anode potential drop.

The first zone is the region of cathode potential drop U_{Cpl}, where the main acceleration (additional acceleration) and the formation of an ion flow directed to the cathode-target take place. The discharge current in this region is transferred by ions with the density j_{iC} and secondary emission electrons from the cathode $j_e^f = \gamma j_{iC}$. Since $\gamma \leq 0.1$ in our case, we can assume that the ion current at the cathode $j_{iC} = j_d/(1+\gamma)$ is approximately equal to the discharge current. In the zero-order approximation, the ion current density in the cathode layer can be estimated according to the Langmuir formula $j_d \approx j_{iC} = (1/9\pi)\sqrt{2e/M}U_{Cpl}^{3/2}/d_{Cpl}^2$, where e is the electron charge, M is the mass of the argon ion, and d_{Cpl} is the size of the cathode area. It is worth noting that this formula is valid in the case where the electric field E=0 at the plasma interface. Then the ion current density at the interface is determined by the Bohm formula $j_{iC} = 0.4en_i\sqrt{2kT_e/M}$, where n_i denotes the ion density, and T_e is the electron temperature. It is the case of the optimal current transfer, where the plasma concentration can be determined from the discharge current to within the temperature of plasma electrons.

Assuming $U_{Cpl} \approx U_d$ in the zero-order approximation and taking the characteristic values of j_d and H, we can ascertain that, at the indicated characteristic parameters, the dimension of the cathode layer $d_{Cpl} < \rho_e$, where ρ_e is the electron Larmor radius calculated from the potential drop in the layer. This indicates that the secondary ion-electron emission electrons in the layer are nonmagnetized and easily penetrate to the second region, being accelerated by the voltage U_{Cpl}.

The second zone is the zone of a positive column with the characteristic size Δr, where the ionization of charged particles takes place in its bulk. It is the region of a low-temperature plasma, where both fast and appearing slow electrons are magnetized, whereas ions move freely under the action of the finite field E_{pl} toward the cathode. Here, the current is transferred by both ions and electrons. Therefore, $j_d = j_{ipl} + j_{epl}$. In this region, the following one-dimensional equations of two-liquid magnetic hydrodynamics hold true:

$$\frac{d^2\varphi}{dx^2} = -4\pi e(n_i - n_e^s - n_e^f), \quad (1)$$

$$\nabla \cdot \overrightarrow{j_{e,ipl}} = \gamma j_{iC} n_a \sigma_{ei}(v_e^f), \quad (2)$$

$$j_{epl} = \mu_\perp e n_e^s \left(E_{pl} - \frac{\nabla(n_e^s k T_e)}{e n_e^s} \right). \quad (3)$$

Here, $\Delta x = x_{Cpl} - x_{Apl}$ stands for the plasma layer thickness, $\mu_\perp = e\nu_e/m_e\omega_{eH}^2$ is the mobility, $\omega_{eH} = eH/m_e c$ is the cyclotron frequency, ν_e denotes the frequency of elastic collisions with atoms and ions, and $\omega_{eH}/\nu_e \gg 1$.

Equations (2) describe the origination of electrons and ions in the plasma column only due to the impact ionization of a neutral gas by fast secondary-emission electrons. These electrons do not essentially contribute to the current transfer and, at the same time, represent the principal ionizing factor making a certain contribution to the total space charge. Having lost the ionization ability, these electrons reach the anode, insignificantly participating in the total current transfer. The flow of created slow electrons across the magnetic field toward the anode is caused by both the mobility $\mu_\perp$ in the electric field E_{pl} and the diffusion. The emission of electrons along H is not taken into account, though it can take place in real finite systems.

The third zone is a narrow near-anode area of the order of the Larmor electron radius, where the magnetic isolation is violated, and the discharge current is transferred by electrons. If the anode area S_A is so small that $I_d > j_e S_A$, then the anode potential is higher than that of the plasma $U_{plA} > 0$, and the anode current of electrons obeys the Langmuir law. Otherwise, $I_d < j_e S_A$, $U_{plA} < 0$, and the anode electron current is limited by the Boltzmann law $\sim \exp(-eU_{plA}/kT_e)$.

Both the first and second cases are not optimal, because a part of the discharge voltage in the first case is spent on the acceleration of electrons; while, in the second case, a part of ions created in the discharge has a possibility to move to the anode.

The system of equations (1)–(3) is rather complicated and requires numerical calculations. Let us make a certain assumption. As the weakly dissipative systems with magnetic isolation of electrons are characterized with superthermal volume electric fields, the diffusion term in Eq.(4) can be neglected. Considering that $E_{pl} \gg \nabla p_e/en_e^s$, relation (3) yields $n_e^s = j_{epl}/e\mu_\perp E_{pl}$. The concentration of slow electrons and ions can be determined from the expressions $n_e^s = \dfrac{\gamma j_{iC}\Delta x}{e\lambda_{ei}\mu_\perp E_{pl}}$ and $n_i = \dfrac{\gamma j_{iC} n_a \sigma_i (v_e^f)\Delta x}{e v_S(\langle\Delta\varphi\rangle)}$, respectively, where v_s is the mean velocity of ions in the E-field of the plasma column. In order to estimate the concentration of fast electrons, we take into account that the fast electrons enter the plasma column with the energy of the order of eU_d, lose the energy ε_i in each ionization act, and leave the layer with the energy of about 30–40 eV. Their mean lifetime $\tau = L_{\text{eff}}/\langle v_e^f\rangle$, where $\langle v_e^f\rangle$ is the mean velocity of electrons leaving the system; L_{eff} is the effective free path that can be obtained from the condition of self-sustained discharge $\gamma n_a \sigma_{ei} L_{\text{eff}} \approx 1$. Thus, we obtain $L_{\text{eff}} = (\gamma n_a \sigma_i)^{-1} \gg \Delta x$. The concentration of fast electrons can be qualitatively estimated from the expression $\gamma j_{iC} S_C \approx n_e^f V/\tau$, where $V = \pi(R_C^2 - R_A^2)h$ is the volume, and $S_C = 2\pi R_C h$ is the surface area of the cathode. In this case, one can derive

$$n_e^f = \frac{2R_C}{R_C^2 - R_A^2}\frac{j_{iC}}{e n_a \sigma_{ei}\langle v_e^f\rangle} = \Re \frac{j_{iC}\lambda_{ei}}{e\langle v_e^f\rangle},$$

where $\lambda_{ei} = 1/n_a\sigma_{ei}$ is the free path of electrons in electron impact ionization acts, while $\Re = \dfrac{2R_C}{R_C^2 - R_A^2}$ is the geometric multiplication factor. Supposing that the quasineutrality condition $n_i = n_e^f + n_e^s$ holds true in the plasma column and making reasonable assumptions for the corresponding physical parameters, one can obtain an estimate for E_{pl} that testifies that the self-sustained existence of a discharge requires the potential drop in the plasma column be about 25–30% of the discharge voltage.

3. Experimental Model of Cylindrical Magnetron-Type Gas Discharge and Results

We proposed and realized an experimental model of a plasmaoptical cylindrical gas-discharge system of the magnetron type. The diagram of the experimental set-up is shown in Fig. 2. The working gas (argon) was supplied directly to a vacuum chamber. The experiments were performed in the pressure range 10^{-3}–1 Pa. We obtained the integral current-voltage characteristics (CVCs) of the discharge in the optimal mode of operation and measured the distribution of the floating potential in the diode gap in the central cross-section. For this purpose, a modified Langmuir probe was used.

The experiments demonstrated that, depending on the pressure of the plasma-forming gas in the system, there exist two modes of operation of the cylindrical magnetron-type gas discharge with radically different plasmadynamic characteristics. The first type of the discharge is low-current and high-voltage (the current is of the order of 10 mA, the discharge voltage is of about 1 kV), while the second one is high-current (in our experiments, the current reached 2.5 A, the voltage was approximately 400 V). The transition from the

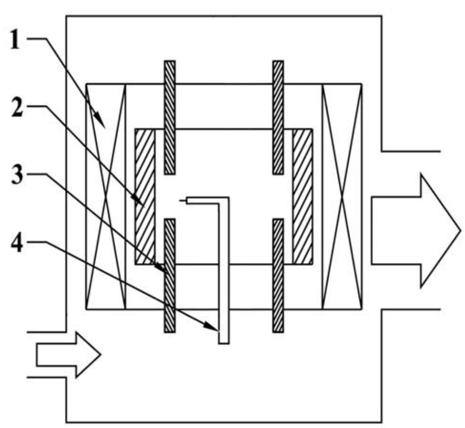

Fig. 2. Scheme of the experimental set-up: *1* – magnetic system, *2* – cathode, *3* – anode system, *4* – Langmuir probe

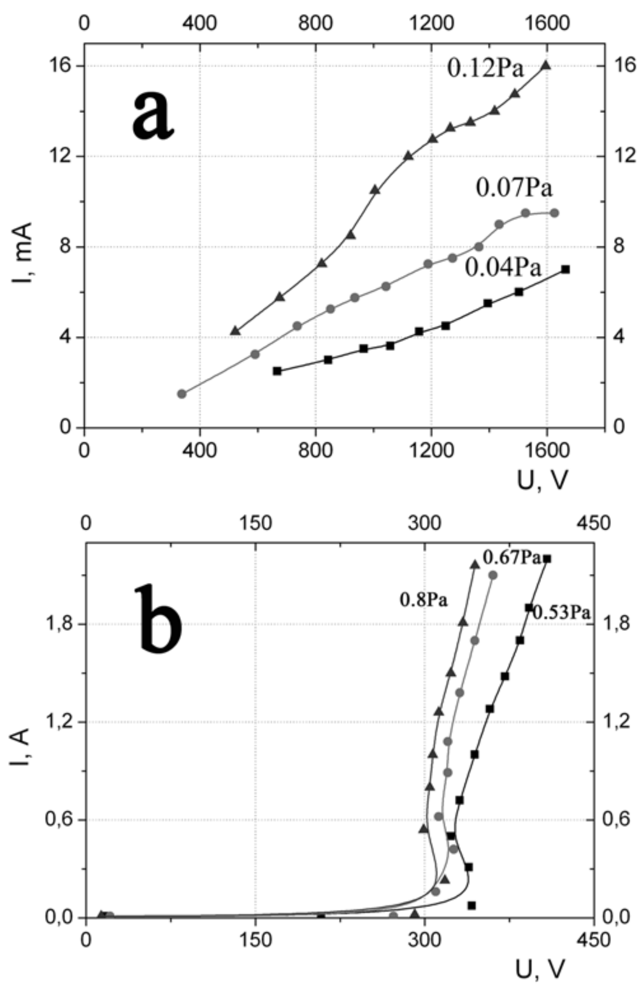

Fig. 3. CVCs of low-current (*a*) and high-current (*b*) discharge

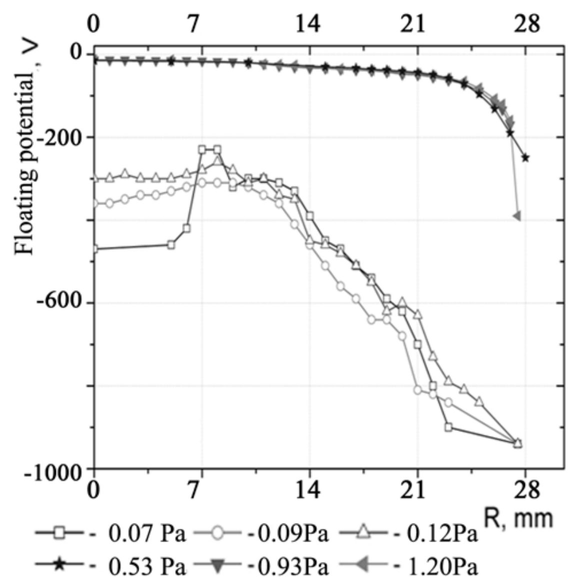

Fig. 4. Radius-variation of floating potential for both types of discharge

low-current mode to the high-current one occurs spasmodically and depends on many factors such as the electrode purity, discharge power, pressure and sort of a gas, arrangement of anode units, *etc.* Each type of the discharge has characteristic external signs [8]. Figure 3 represents the CVCs of the low-current discharge at small pressures (*a*), and the high-current one at large pressures (*b*). One can see that, in the weak ionization mode (low-current mode), an increase of the discharge power is spent on the growth of ionization, and the current rises with increase in the voltage. The behavior of the CVC in the high-current mode is rather interesting. Here, one observes an obvious tendency to the formation of an *S*-type CVC. The physics of magnetron discharges is complicated by the necessity to consider the cathode spraying which results in the appearance of atoms of a cathode material in the discharge gap. Under certain conditions, these atoms can be ionized and get back to the cathode in the form of ions, thus intensifying the ionization process. As a result, the CVC is distorted and acquires the *S*-form investigated for the first time in [9]. Figure 4 shows the results of measurements of the floating potential inside the diode gap both in the low-current and high-current modes. Here, one can clearly see a cathode drop region with an abrupt potential drop and a positive column zone with a slight variation of the potential. The anode region is practically unnoticeable. We may assume that the current-collector surface of the anode has optimal dimensions under these conditions. It is also worth noting that, in the low-current mode, the potential distribution is typical of cylindrically symmetric reverse ion magnetrons with an anode layer studied in detail in the middle of the last century [1]. In addition, the proposed plasmaoptical model of cylindrical sputtering systems of the magnetron type is characterized by a very high (up to 100%) potential by the expenses of a target material.

4. Conclusions

The presented plasmaoptical model of cylindrical magnetron-type gas discharge satisfactory agrees with the experimental results. The model is based upon the assumption about the presence of three quasiautonomous regions in the diode gap of the discharge essentially differing in the pattern of current transfer.

It is worth noting that the model does not take the influence of sputtered atoms of a cathode material into account. Surely, this influence can be substantial under certain conditions, which is qualitatively testified by the experimental data. An important problem is the clarification of physical processes restricting the form of the discharge. Based on the performed consideration, the increase of the discharge current density at the cathode is, first of all, caused by a decrease of the size of the cathode layer d_{Cpl}. The thickness of the layer in the experiment was of the order of 10^{-2} cm. The electric field at the cathode surface approximated 4×10^4 V/cm at a voltage of 400 V. It is usually believed that the field emission that will stimulate the disruption of the discharge and its transition to the arc mode becomes noticeable at fields of about 10^5 V/cm. Naturally, this value can be larger or smaller depending on the cathode material, state of the surface, etc. Nevertheless, one can state that, for such magnetron-type discharges, the limiting discharge current densities lie in the range 30–50 mA/cm^2. This fact is confirmed by numerous experimental data of many investigations.

In the presented plasmaoptical model of gas-filled diode gap, the magnetic field is practically uniform inside the anode-cathode gap. That's why both a low-current discharge, where the discharge voltage falls mainly across the anode layer, and a high-current one with the principal voltage drop across the layer pressed to the cathode can be realized in such a system. In contrast, the magnetic field in plane sputtering systems is maximal near the cathode and abruptly decreases toward the anode which appears in the region, where the magnetic field is practically absent. The only form of discharge that can exist in such a strongly nonuniform system of crossed E and H fields is the high-current discharge with a cathode layer, which is indeed observed in practice. We can assume with confidence that, in spite of the strong nonuniformity of the configuration space, these discharges will also consist of three characteristic quasiautonomous regions.

The work was performed within the framework of Project 93/08-N.

1. S.D. Grishin, V.S. Erofeev, and A.V. Zharinov, in *Plasma Accelerators*, edited by L.A. Artsimovich (Mashinostroenie, Moscow, 1973) (in Russian).
2. A.I. Morozov, *Introduction to Plasmadynamics* (Fizmatlit, Moscow, 2006) (in Russian).
3. *Encyclopedia of Low-Temperature Plasma*, edited by V.E. Fortov (Nauka, Moscow, 2000) (in Russian).
4. P.V. Kashtanov, B.M. Smirnov, and R. Hippler, Usp. Fiz. Nauk **177**, 5 (2007).
5. Yu.B. Golubovskii, I.A. Porokhova, V.P. Sushkov, M. Holik, and P. Kudrna, in *Proc. of the XXVIIth Int. Conf. on Phenomena in Ionized Gases, Eindhoven, 2005*, edited by G.M.W. Kroesen (IOP, Eindhoven, 2005).
6. D.A. Glocker, M.M. Romach, and V.W. Lindberg, Surf. Coat. Technol. **146-147**, 457 (2001).
7. A.A. Goncharov and I.G. Brown, IEEE Trans. Plasma Sci. **35**, 4 (2007).
8. A.M. Dobrovol's'kii, A.N. Evsyukov, A.A. Goncharov, and I.M. Protsenko, PAST. Ser. Plasma Physics **13**, 1 (2007).
9. V.V. Vladimirov, M.D. Gabovich, I.M. Protsenko, V.Ya. Poryts'kyi, and L.N. Tkachenko, Zh. Tekhn. Fiz. **11**, 4 (1981).

Translated from Ukrainian by H.G. Kalyuzhna

НОВИЙ ПОГЛЯД НА ФІЗИКУ ГАЗОВИХ РОЗРЯДІВ МАГНЕТРОННОГО ТИПУ

О.А. Гончаров, А.М. Добровольсъкий, А.М. Євсюков, І.М. Проценко, І.В. Літовко

Р е з ю м е

Представлено результати комплексного теоретичного та експериментального дослідження циліндричних газових розрядів у конфігурації схрещених електричних та магнітних полів, притаманних аксіально-симетричній плазмовій лінзі. Запропоновано та випробувано оригінальний циліндричний розпилюючий пристрій, побудований на принципах плазмооптики. Сформульовано нове системне бачення плазмодинаміки газових розрядів магнетронного типу. Запропонований підхід передбачає наявність трьох квазіавтономних областей у розряді, в яких струмоперенос здійснюється різними частинками.