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TRANSITION MODE OF MAGNETRON DISCHARGE WITH ANODE SHEATH

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The characteristics of the combined Magnetron Ion-Plasma System (MIPS) in the transition mode, which is optimal for the synthesis of nanostructured coatings on heat-sensitive materials, are presented. The system consists of a magnetron sputtering system and a Hall-type ion source with a common magnetic system and two power supply units. It was found that the presence of a positive magnetically insulated anode leads to a 2-3 times decrease in the gas pressure threshold of the magnetron discharge extinction as a result of the appearance of a transient mode. In this regime, a significant dependence of the anode potential of the ion source on the gas pressure and the magnetic field is observed.

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INTRODUCTION

Modern ion-plasma technologies for deposition of complex nanostructured coatings require the formation of combined flows of atoms and radicals, ions and electrons with independent control of energy, current density, and mass composition, in a wide range of values of these parameters [1-3]. For example, the application of hard plastic films with high internal stresses requires a large additional non-equilibrium energy per condensed atom (100…1000 eV/at.). At the same time, according to the Thornton-Anders structural zone diagram [4], the formation of coatings with low internal stress and defect density requires low energies (1…10 eV) of bombarding ions with a controlled current density in the range 0.1…10) mA/cm^2.

These technologies require research and development of new improved ion-plasma systems. Papers [5-7] presented the Magnetron-Ion-Source Sputtering System (MISSS) with two modifications of the Hall-type ion source (IS): the high-energy ion-beam system MIBS (average ion energy 300…500 eV) and the low-energy ion-plasma system MIPS (average ion energy 10…100 eV). The main discharge characteristics of these systems were investigated, the parameters of charged particle flows were measured, and the ability to deposit both solid films of α-phase alumina and plastic coatings of amorphous Al_2O_3 on polypropylene at a temperature below 100 degrees was demonstrated [5].

From the point of view of the physics of discharges in crossed electric and magnetic fields, it was established that the formation of a near-anode sheath in the IS with a low potential drop (10…300 V) is realized due to injection of primary electrons from the magnetron plasma. Thanks to this, it is possible to achieve a high ion current density (up to 20 mA/cm^2) with low ion energy. It is possible to control the ion energy by changing the magnitude of the magnetic field and the pressure of the filling gas. In [8], the operation of MIPS with one power supply unit in two modes was investigated: 1) with a grounded magnetron (GM mode); 2) with a magnetron under a floating potential (FM mode), and a theoretical model of the plasma mode was proposed. The experimental studies were carried out at a filling gas pressure of more than 2 mTorr.

In this work, further, more detailed, experimental studies of the mechanism of the formation of the near-anode sheath in the plasma and transition modes of MIPS operation with one and two independent power sources at a working gas pressure of less than 2 mTorr were carried out.

1. EXPERIMENTAL SETUP

The scheme of MIPS, vacuum chamber with technological and diagnostic equipment and power supply system is presented in Fig. 1. A detailed description of the MIPS design and associated equipment is given in [5, 6].

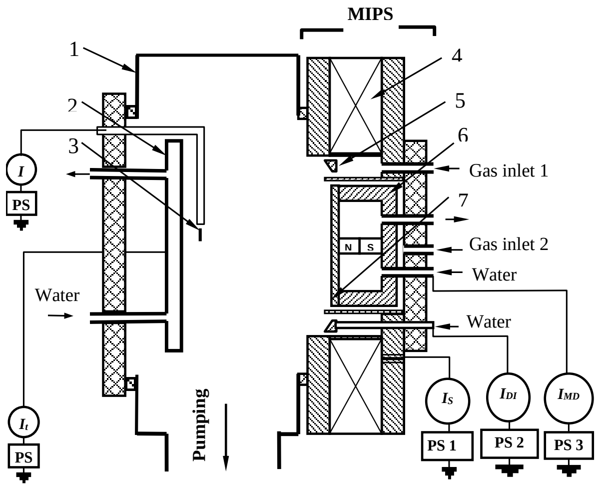

Fig. 1. Scheme of MIPS:
1 – vacuum chamber; 2 – sample table; 3 – probe; 4 – solenoid; 5 – anode; 6 – magnetron; 7 – target

In the experiments, two independent power supply units were used: PS2 for the ion source (IS) and PS3 for the magnetron discharge (MD). The power supply parameters are as follows: PS2 voltage U_{IS} = 0…3 kV, current I_{IS} = 0…600 mA; PS3 voltage U_{MD} = 1…1000 V, current I_{MD} = 0…1 A. The PS3 unit can be set for current or voltage stabilization, while the PS2 has a "falling" loading characteristic. Probe 3 was used for measurements of plasma potential U_p. The magnetic field strength H near the anode of the IS was determined by the current of the magnetic coil power source PS1, and the magnetic field topology was revealed by the numerical calculations using the COMSOL Multiphysics 5.6 program.

2. EXPERIMENTAL RESULTS

The main purpose of the conducted experiments was to investigate the effect of gas pressure p and magnetic field strength H on the discharge characteristics of the system during autonomous or joint operation of MD and IS. Special attention was paid to the transition mode of the ion source operation between the plasma and the accelerating modes.

First, consider the dependence of the MIPS parameters on the gas pressure. Fig. 2 shows the dependence of the discharge voltage U and current I of the ion source, the floating potential of the probe U_p on the Argon pressure during autonomous operation of the IS (power is supplied only from PS2) for two variants of discharge stabilization: at constant current (I = 200 mA, $p > 1.2$ mTorr) or voltage ($U = 2$ kV, $p < 0.4$ mTorr) (red lines) or at constant power (blue lines).

One can see that the source operation is possible in different modes. The boundaries of these modes are tentatively shown in Fig. 2 by dotted lines, and brief characteristics of them are the following:

1. At $p > 1.2…1.6$ mTorr, the plasma mode of IS operation is realized, which may be called low-voltage or high-current regime. The main feature of this mode is the zener-like character of the current-voltage dependence: $U \approx 400$ V in a wide current range $I = 100…600$ mA, the width of which is determined by the power of the power source. As can be seen from the above graphs, the discharge voltage and current in the plasma mode are weakly dependent on the pressure of the filling gas.

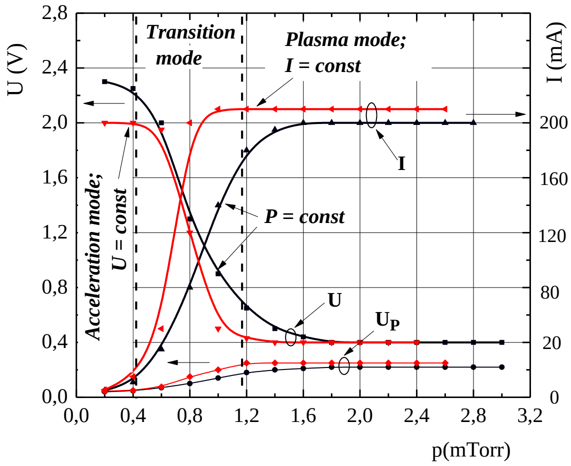

Fig. 2. Discharge voltage U and current I of the ion source, the floating potential of the probe U_p vs. Argon pressure during autonomous operation of the IS. Solenoid current IS = 1.5 A

2. At $p < 0.4…0.6$ mTorr, the discharge goes into the acceleration (high-voltage, low-current) mode, in which the discharge current depends linearly on the gas pressure at constant voltage, the current-voltage characteristic of the discharge has a monotonically increasing, practically linear character. This mode of the IS operation was studied in detail in [9].

3. In the range ($0.4 < p < 1.6$) mTorr, a transient mode of operation is realized in the system, which, in terms of its characteristics, is significantly different from the plasma and accelerator modes. It is the transition mode of operation of MIPS that is the subject of further, more detailed, research.

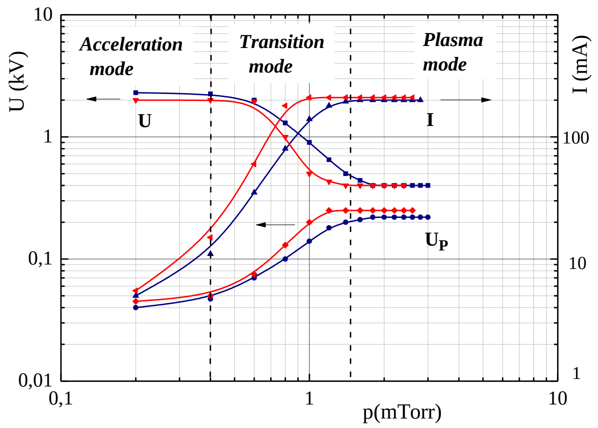

Fig. 3. Discharge voltage U and current I of the ion source, the floating potential of the probe U_p vs. Argon pressure on a logarithmic scale during autonomous operation of the IS. Solenoid current IS = 1.5 A

Fig. 3 presents graphs similar to those shown in Fig. 2, but on a logarithmic scale. These graphs demonstrate the different modes of operation of the system more clearly.

When powering the system from two independent sources PS2 and PS3 (see Fig. 1), we will separately present the voltages of the ion source U_{IS} and the magnetron discharge U_{MD}, as well as their currents I_{IS} and I_{MD}. Fig. 4 shows the dependences of U_{IS}, U_{MD} and floating potential of the probe U_p on Argon pressure. The MD and IS discharge currents were maintained at a constant value of $I_{IS} = I_{MD} = 300$ mA in the plasma mode.

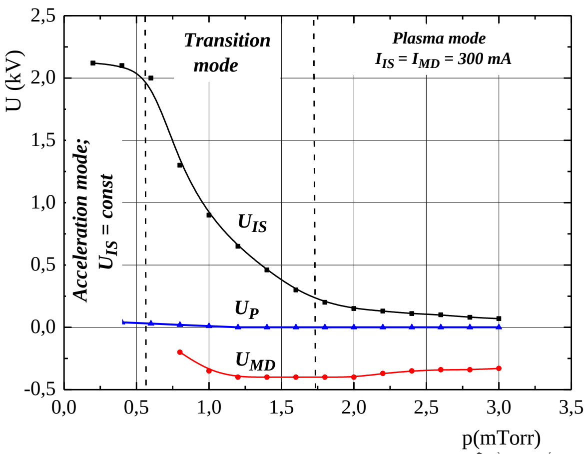

Fig. 4. Dependencies of the ion source voltage U_{IS}, the magnetron voltage U_{MD} and the floating potential of the probe U_P on the Argon pressure when feeding IS and MD from independent blocks PS2 and PS3. IS = 1.5 A

When comparing the graphs shown in Figs. 2, 4, please note that with the simultaneous use of independent power sources for IS and MD, the floating potential of the probe relative to the chamber (which is approximately equal to the plasma potential) is $U_p = 0$, in contrast to $U_p = 200$ V at the autonomous IS operation (see Fig. 2). But at lower gas pressure $p < 1.0$ mTorr, this value gradually decreases to $U_p \approx 30$ V. Also, at $p < 1.0$ mTorr, the magnetron discharge gradually fades. Thus, in the acceleration mode, the MIPS parameters are determined mostly by the operation of the ion source.

It was found in further studies that the limits of the MIPS operating modes and the IS voltage in the transition mode depend significantly on the magnetic field strength. This is demonstrated by the plots shown in Fig. 5.

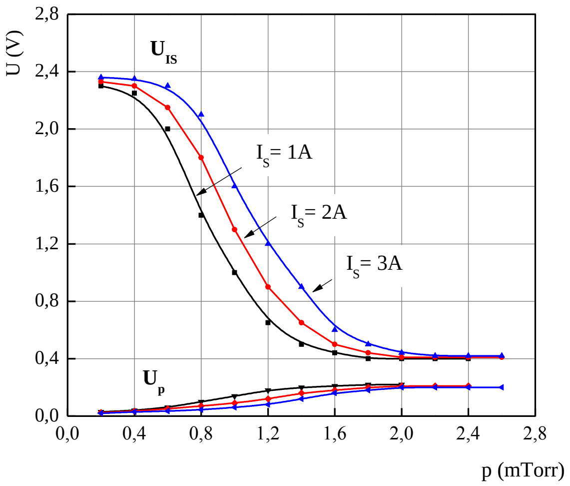

Fig. 5. Dependencies of the voltage on the IS anode U_{IS} and the probe floating potential U_P for different values of the magnetic field strength (determined by the solenoid current I_S)

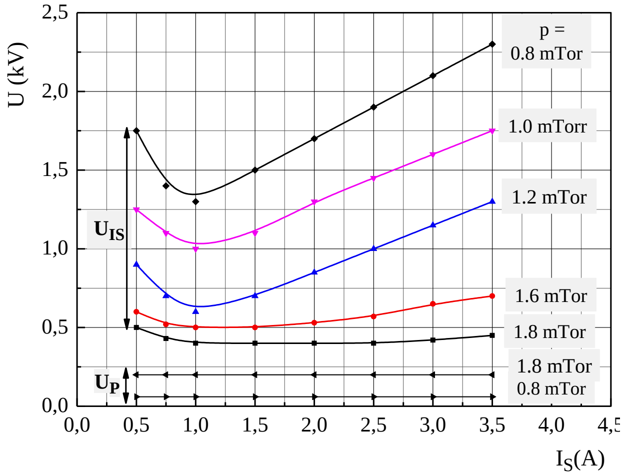

Fig. 6. Dependencies of the ion source voltage U_{IS} and the floating potential of the probe U_P on the solenoid current for different gas pressures during autonomous operation of the IS. I_{IS} = 300 mA

As can be seen from the figure, just in the transition mode in the range of operating pressure $0.4 < p < 1.6$ mTorr the significant dependence of U_{IS} and U_P on the magnetic field strength is observed. The dependencies of U_{IS} and U_P on the magnetic field strength ($H \sim I_S$) during IS autonomous operation are presented in Fig. 6. Analogous dependencies at the simultaneous operation of IS and MD are presented in Fig. 7.

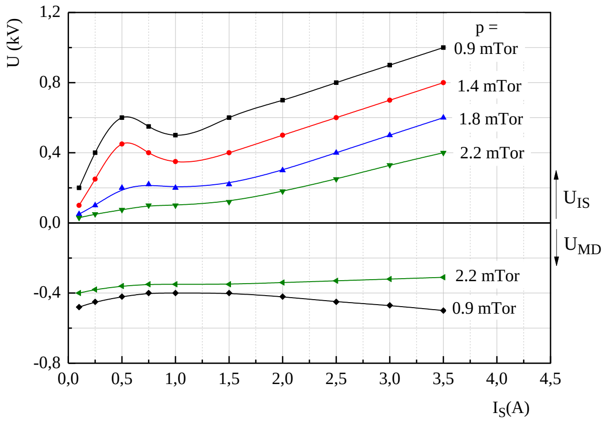

Fig. 7. Dependencies of the ion source voltage U_{IS} and the magnetron discharge voltage U_{MD} on the solenoid current for different gas pressures during joint operation of the IS and MD. $I_{IS} = I_{MD}$ = 300 mA. $U_p = 0$

Now let's reveal the relationship between ignition/extinction curves and discharge modes in MIPS. A general picture of the existence of different modes of MIPS operation depending on the gas pressure, the magnetic field strength, and the method of powering the electrodes can be represented by the diagram shown in Fig. 8. As can be seen from the above graphs, the presence of a magnetically isolated anode in the system significantly, almost by three times, reduces the extinction pressure threshold of the magnetron discharge (MD only mode) as a result of the appearance of the transition mode (MD + IS).

The most important from the point of view of coating deposition by magnetron discharge with additional ion bombardment are the current-voltage characteristics of MIPS in the transition mode, which are presented in Fig. 9.

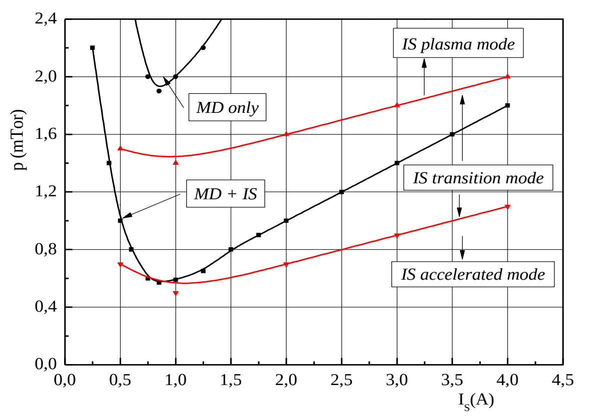

Fig. 8. Diagram of MIPS operating modes depending on the gas pressure and magnetic field strength (H ~ IS)

The curves in the Fig. 9 demonstrate the dependence of U_{IS} on I_{IS} at a constant current of the magnetron discharge I_{MD} = 400 mA for different solenoid currents. The figure also demonstrates the influence of the discharge in the IS on the magnetron discharge voltage U_{MD} and the plasma potential U_p.

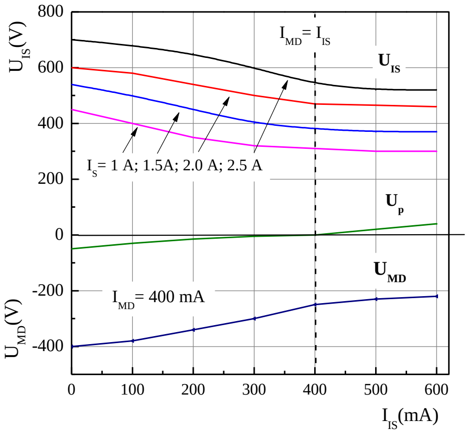

Fig. 9. Current-voltage characteristics of the combined magnetron ion-plasma discharge at different values of the magnetic field strength in the transition mode. Argon pressure p = 1.2 mTorr

The presented graphs demonstrate the possibility of independent control of the voltage and current of the IS in a wide range changing the magnetic field but without significant influence on the MD. Previous studies [6] showed that the ion current to the sample table is 10…40% of the IS discharge current, and the maximum ion energy is determined by the IS voltage U_{IS}. Also, the dependence of the probe floating potential U_p on the IS discharge current demonstrates full charge compensation of the particle flow to the sample table (U_p = 0) at $I_{IS} = I_{MD}$.

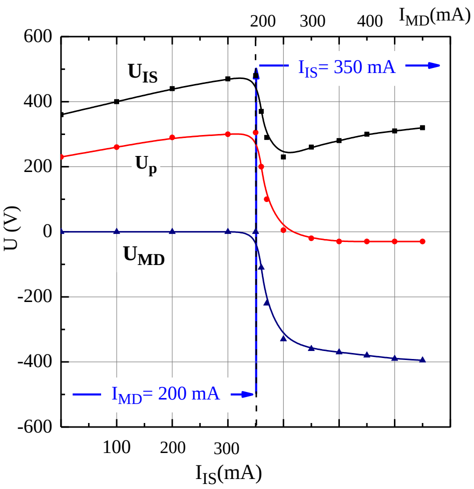

Fig. 10. Dependencies of IS parameters when turning on the magnetron discharge. p = 1.2 mTorr, I_S = 1.5 A

Fig. 10 shows the influence of the magnetron discharge on IS operation in the autonomous mode. The measurements were carried out as follows. Initially, the voltage from PS2 was applied to the IS anode and the discharge current increased to I_{IS} = 350 mA. At the same time, the ion current on the magnetron target was I_{MD} = 200 mA. Next, a negative voltage was applied to the magnetron target from the PS3 power supply and the magnetron discharge current was increased to the value of I_{MD} = 600 mA at a constant IS current I_{IS} = 350 mA. As can be seen from Fig. 10, the ignition of an independent magnetron discharge leads to a significant decrease in the IS voltage and a decrease in the floating potential of the probe to a negative value of $U_p \approx$ -30 V.

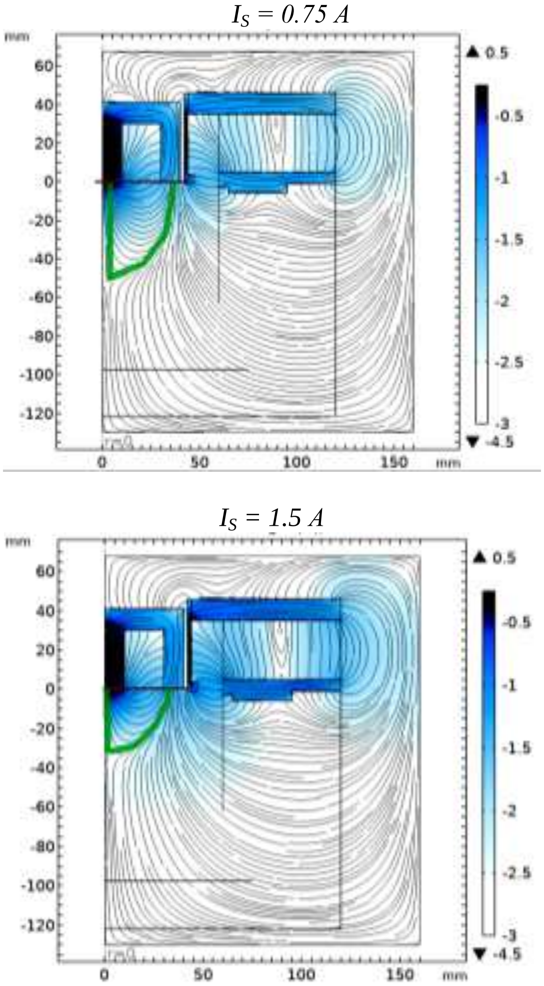

Fig. 11. MFL topology in MIPS at different solenoid currents. The last arc terminated at the magnetron target on both ends is shown by the green line

3. DISCUSSION

To determine the physical mechanism of the combined discharge in MIPS, consider the diagram of operation modes depending on gas pressure and solenoid current shown in Fig. 8. It was experimentally and theoretically shown in [10] that for a magnetron discharge, the similarity parameter for gas the pressure *p* and the geometric dimensions is the product *pd*, where $d = V/S_i$ is the characteristic size of the ionization trap for electrons, *V* is the volume where ionization is carried out, S_i is the surface area of ion escape. In an independent MD, almost all the ions from the volume exit to the magnetron target, and the value *d* is determined by the maximum height of the arcs of the magnetic field lines (MFL) terminated on the magnetron target, which retain the primary γ-electrons. The minimum value $(pd)_{min} \approx 3$ mTorr·cm was experimentally determined in [10], below which independent MD does not exist. Theoretically, from the conservation equation of charged particles, it was proven that the reason for this is the increase in the electron temperature T_e with a decrease in *pd* and the limitation of the ionization rate by electrons as a result of the T_e increase. This dependence will be shown further in Fig. 13.

To improve the MIPS design shown in Fig. 1, additional calculations of the MFL topology were carried out for different values of the solenoid current I_S using the "COMSOL Multiphysics 5.6" program. Typical calculation results are presented in Fig. 11. According to the results of these calculations, the maximum height of MFL arcs d_{max} at different solenoid currents was determined, the dependence of which on I_S is presented in Fig. 12. It should be noted that a significant dependence of the d_{max} value on the location of the magnetron body relative to the solenoid along the longitudinal axis Z was found, which is shown in Fig. 12 (Z = 5 mm corresponds to the MIPS scheme presented in Fig. 1).

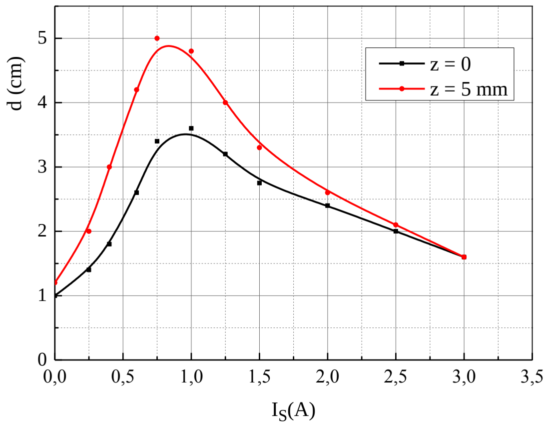

Fig. 12. Dependence of the maximum height of the MFL arcs terminated at the magnetron target d_{max} on the solenoid current I_S for different locations of the magnetron along the Z axis relative to the solenoid (see Figs. 1, 11)

According to Fig. 12, from the diagram in Fig. 8, it was determined $(pd)_{min1}$ = 7…9 mTorr·cm for the magnetron discharge transformation to the transition mode and $(pd)_{min2}$ = 2.5…3 mTorr·cm for the acceleration mode appearance. These values are marked in Fig. 13.

As shown in Fig. 13, in the independent MD mode, when all the grounded surfaces are included in the anode, the electron temperature $T_e < 4$ eV. At the same time, the presence of a positive anode, which is isolated from the plasma by a magnetic field, allows the realization of a transition regime with electron temperature in the plasma in the range of 4 eV < T_e < 10 eV. In this regime, there is a significant dependence of the near-anode potential drop on the gas pressure and magnetic field strength, which is demonstrated by the experimental data shown in Figs. 2-7. At the same time, the voltage-stabilized character of the current-voltage characteristics is preserved (see Fig. 9), which makes it possible to obtain significant flows of high-energy ions that are generated in the anode sheath.

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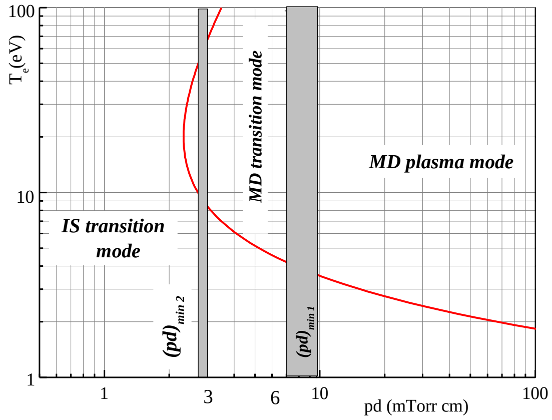

Fig. 13. Dependence of the equilibrium electron temperature T_e on the similarity parameter pd. (Solution in Arrhenius approximation of electron ionization rate)

In the previous research [8], a theoretical model of the anode sheath formation in the transition mode of MIPS operation was presented, which explains the linear dependence of anode voltage on the magnetic field strength (U ~ H) and the inverse dependence (U ~ 1 / p) on the gas pressure, which is observed in experiments.

CONCLUSIONS

In the present research, the characteristics of the combined Magnetron-Ion-Plasma System (MIPS) in transition mode were studied. The system includes a magnetron sputtering system and a Hall-type ion source with a common magnetic system and separate power supplies.

A comparative analysis of the results of experimental studies of two modes of MIPS operation was carried out: i) a mode with one power supply of the ion source and a grounded magnetron, ii) a mode with two independent power supplies for IS and MD. The common feature of these modes is the existence and interaction of two regions with intense ionization, namely, the magnetron plasma and the anode sheath. These regions interact due to the injection of primary electrons from the plasma into the anode sheath and to the current of ions from the anode sheath to the cathode.

However, there is a fundamental difference between these regimes. In the case of one power source feeding the IS, the applied voltage is divided self-consistently between anode and cathode sheaths keeping the system in an energy optimum, which is characterized by the maximum current and the minimum discharge voltage. This explains the Zener-like shape of the current-voltage characteristics. In addition, the estimated value of the plasma potential $U_p \approx 0.5U_{IS}$ is in reasonable agreement with the experiment. The current of primary electrons from the plasma to the anode sheath (as well as the ion current to the plasma) is determined by the anode potential regardless of the magnetic field.

In this mode, the entire grounded surface is the cathode of the discharge, on which the ions escape, including the table for samples, the chamber and the magnetron target, the plane of which does not change when the magnetic field changes. Thus, the value $d = V/S_i$ weakly depends on H, which explains the difference in the boundaries of the regimes for MD and IS in Fig. 8.

In the second mode, with two independent power supplies for IS and MD, the plasma potential relative to the table and the chamber is $U_p \leq 0$ at $I_{IS} \leq I_{MD}$, which weakens the influence of ions from the IS on the value of the plasma potential and breaks the connection between the cathode and anode potential drops. Thus, IS and MD operate relatively independently.

At the same time, it was found that the presence of a positive magnetically insulated anode leads to a decrease in the MD extinction pressure threshold by 2-3 times as a result of the appearance of the transition regime. Just in this mode, a significant dependence of the anode potential on the gas pressure and the magnetic field is observed.

In general, the question of building a general numerical-analytical model of a gas discharge in magnetic field allowing not only a qualitative but also a quantitative comparison of theory and experiment, remains relevant.

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ПЕРЕХІДНИЙ РЕЖИМ МАГНЕТРОННОГО РОЗРЯДУ З АНОДНИМ ШАРОМ

О. Зиков, С. Дудін, С. Яковін, В. Сидоренко

Представлено характеристики комбінованої магнетронної іонно-плазмової системи (МІПС) у перехідному режимі, який є оптимальним для синтезу наноструктурних покриттів на термочутливі матеріали. Система складається з магнетронної розпилювальної системи та джерела іонів холлівського типу зі спільною магнітною системою та двома блоками електроживлення. Встановлено, що наявність позитивного магнітоізольованого анода призводить до зниження в 2-3 рази порога згасання магнетронного розряду за тиском робочого газу внаслідок появи перехідного режиму. У цьому режимі спостерігається суттєва залежність анодного потенціалу джерела іонів від тиску робочого газу і магнітного поля.