Low-pressure glow discharge modeling in transverse supersonic gas flow

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Abstract. Article presents a model for the realization of a glow discharge at low pressures due to the organization of supersonic gas flow in a limited region of discharge chamber. A model of flow regime of a supersonic flow in a vacuum chamber is described. Results of experiments on realization of a glow discharge at low pressures due to the organization of a transverse supersonic gas flow are shown.

1. Relevance
Field of glow discharge application for plasma processing of details surfaces continuously expanding. Ion-plasma sputtering of material or modification of surfaces is increasingly used in optic industry, electronics and other fields. One of new area is additive technologies.

In ion-plasma technological process is necessary to organize smooth achievement of the particles to processing surface. To achieve this condition free path length $\lambda$ of particles should be several times larger than the distance $L$ from the area of movement beginning to processing surface.

One of conditions for glow discharge existence is presence of all near-electrode zones. Number of electron collisions with neutral particles determines length of each zone. With pressure, decreasing length of cathode zones is increasing and certainly, there comes a time that the electrode gap is not enough space for all near-electrode zones. Therefore, at very low pressures, discharge cannot exist. To find the critical pressure, at which it is still possible glow discharge, we assume condition of cold discharge. We assume that inter-electrode distance of 10 cm and number of collisions 10, so mean of free path $\lambda$ is 1 cm. Critical pressure for glow discharge existing

$$P_c = \frac{1}{n \cdot \lambda^2}$$

Thus, existence of glow discharge at pressures below 10-2 Torr hampered. Therefore, there is an insoluble problem: on one side discharge existence pressure above 10-2 Torr is necessary and from another glow discharge application in technological processes of coating deposition required pressure below 10-2 Torr.

One solution to this problem is magnetron sputtering application [1, 2, 3]. Magnetic field may increase the probability of collision of electrons with neutral atoms to order more times at low pressures by the joint action of electric and magnetic fields on moving charges. All this gave opportunity to magnetron discharge application at a pressure of about 10-3 Torr. That led to a widespread of magnetron systems in installations for ion-plasma treatment.

In works [4-7] is proposed a fundamentally new solution to problem. Namely, they proposed the creation of zones of different concentrations of neutral particles in electrode gap. For example, in
cathode area to create a high vacuum with a minimum concentration of neutral particles, in anode area to provide a relatively high concentration of neutral particles. Electrons in region with high concentration of neutral particles can experience dozens of collisions with neutral particles, while the processing of the material will take place at the maximum possible low pressures. For this condition, it is necessary to create a stream with particles of the working gas in the interelectrode space and at the same time to maintain the vacuum in the discharge chamber below 10-2 Torr. To achieve such a separation of zones in the electrode gap may allow the supersonic gas flow. The density of pumped gas through the working area should provide more than a dozen collisions of electrons with neutral particles, which will allow maintaining the glow discharge, keeping chamber pressure below 10-2 Torr.

To maintain different particle concentrations in chamber device shown (Fig.1), providing the organization with a continuous supersonic flow and its pumping from the vacuum chamber using a supersonic nozzle and mixing chamber. In mixing chamber, flow restore and removed after by vacuum pump. At certain conditions device can operate as a jet pump that will not only keep the initial chamber pressure, but also lowering it.

![Fig.1 Vacuum chamber with organization of different particle concentration.](image)

RV- rotary vacuum pump, EV-valve, VB- valves box, PK- prev vacuum chamber, DOV - diffusion vacuum pump, ML - oil trap, VL - nitrogen trap, R – vacuum chamber, T1, T2 - thermocouple vacuum gauges, P - high vacuum gauge.

The aim of the work is to create a model of supersonic flow and carry out experimental studies on the implementation of a glow discharge at pressures of 0.03 Torr.

Nozzle and mixing chamber consists of a diffuser and confusor parts and passage of critical cross-section flow velocity reaches critical speed, with the further expansion of flow occurs the growth rate. In calculation of nozzle, main dependencies deduced from analysis of equations of flow continuity and the first two laws of thermodynamics [7].
Calculating mixing chamber geometric parameters and operating gas flow regimes in supply system, field of continuous flow and pumping [8] allowed carrying out modeling and pilot studies of implementing low-pressure glow discharge in transverse supersonic flow.

2. Simulation

Based on the obtained model [8], geometric dimensions of confuser-mixing chamber elements were calculated. Pressure parameters were as follows: before nozzle $P_1 = 1 \text{ atm}$, in vacuum chamber $P_2 = 0.03 \text{ Torr}$, after mixing chamber in vacuum pumping system $P_3 = 0.2 \text{ Torr}$, gas air. Simulation results (Fig. 2) indicate the possibility of creating a continuous flow in a vacuum to produce zones with different particle concentrations.

![Fig. 2. Distribution of gas particles velocity in a vacuum chamber with supersonic pumping of the working gas: a) axisymmetric model; b) velocity distribution along vacuum chamber axis of symmetry.](image)

When supersonic flow is organized in a vacuum chamber, pressure remains unchanged (Fig 3), flow is continuous [9-10]. Gas flow is restored after passing mixing chamber.

![Fig. 3 Pressure distribution in a vacuum chamber with supersonic pumping of working gas](image)
Simulation of glow discharge were carried out using following form (Fig. 4a). Between cathode and anode potential difference is 1250V. In interelectrode gap an area of high particle concentration is organized through the organization of continuous flow described above.

![Simulation of glow discharge](image1)

Fig. 4 Result of simulation: a) surface electron density pattern; b) electric potential in interelectrode gap.

3. Experimental studies

Experimental studies were conducted to determine accuracy of modeling.

Gas consumption defined through characteristic of the used vacuum pump 2NVR-5DM with ultimate total pressure $P_n=5\times10^{-3}$ Torr, pumping speed $G = 5.5$ l/s. By use coefficient 0.9 at 1 Torr pressure get $G = 4.1$ l/s.

As a result of experimental studies (Fig. 5a), a volt-ampere characteristic of discharge was obtained (Fig. 5b)

![Experimental studies](image2)

Fig. 5 Result of experimental studies: a) glow discharge pressure 0.03 Torr; b) volt-ampere characteristic of the discharge.
4. Conclusion
As a result of simulation and experimental studies, parameters of supersonic flow in vacuum chamber and characteristics of the glow discharge with transverse supersonic pumping of working gas flow were determined. The steady-state pressures in the gas flow, behind the confuser and in the cathode region are determined. The specific values of the parameters for this case were as follows:

Supersonic flow velocity was from 250 to 550 m/s in the gap between the nozzle and the mixing chamber. Pressure in vacuum chamber remained uniform and amounted to 0.03 Torr.

Distribution of the potential of glow discharge indicates a high voltage along the discharge of 550-650 V, a high concentration of electrons is observed in the near-cathode zone and region of high particle concentration. Results of the experiments confirm implementation of discharge at a pressure of 0.03 Torr and model accuracy in the region of 8%.

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