Equilibrium gas pressure in various operating modes of ion-plasma accelerators

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Abstract. The results of measurements gas equilibrium pressure and elemental composition for various operating modes of two-stage ion-plasma accelerators using a discharge in a transverse strongly inhomogeneous magnetic field are presented. It is established that the gas pressure in the chamber is most strongly changed at small ion currents to the collector. The main process of gas separation is the desorption from the surface of the electrodes under the action of low-energy ions. In steady state, with an accelerating voltage more than 1 kV, the gas pressure changes slightly. The main process is spraying.

1. Introduction

Ion-plasma accelerators without differential pumping systems and separation by ion masses are used in many technological processes. These devices are installed in the immediate vicinity of the surface to be treated. The method of carrying out the process should ensure the implementation of a continuous technological cycle for the formation coatings. The cycle includes cleaning, etching, activation of substrates, the formation of sub-layers and ion implantation on substrates of complex geometry. Vacuum conditions in such process must be highly-pure and stationary. The most effective cleaning of the surfaces of samples and electrodes from adsorbed gas and contamination is carried out by a flow of strongly nonequilibrium plasma. The ion energy in the stream should not exceed the sputtering threshold ~30 eV. The temperature and electron concentration should be sufficiently large and provide a high probability of dissociation of polluting molecules [1, 2]. The binding energy molecules of the adsorbed gas with the surface varies from 1 eV for the lowest monolayer to 0.01 eV for the upper monolayer. This layer can be desorbed already under the action of a random molecular flow from the volume of the vacuum chamber ~\(NV/4\). The desorbed gas creates a flux of ~0.1 A/cm\(^2\). When a pure working gas is injected into the chamber volume at a pressure of ~0.01 Pa, the polluting layers on the surface of the sample are completely replaced by the working gas molecules. This is realized at an ion current density of 0.1 A/cm\(^2\) in less than 1 s. The surface of the sample is etched by spraying the crystal lattice. The energy of the ion flux (as a rule, ions of inert gases are used) should be above the threshold. But it should not exceed 1 keV so that defects of the crystal lattice do not arise. The etching process takes considerably longer time and requires a high uniformity of the ion flux along the sample surface. For deposition of a thin film coating, a stream of neutral molecules or ions with energy below the sputtering threshold of the crystal lattice of the substance is introduced into the plasma composition, which must be introduced into the film. By exciting their own electronic and molecular levels of the molecules and crystal lattices of the target deposited on the surface, the plasma activates...
the coating process. For the implantation of semiconductor materials, the ion energy should not exceed 1 keV, while for doping the surface of instruments with the purpose of their hardening, ions in the stream must have an energy of more than 30 keV. The energy dispersion should not exceed 10% at an ion current density of up to 10 mA/cm². Two-stage ion-plasma accelerators based on a discharge in a transverse strongly inhomogeneous magnetic field have been developed in All-Russian Electrotechnical Institute [3, 4]. They are able to work in all the modes considered. Accelerators are easily reconfigured in a wide range of parameters and create flows of various configurations - annular, ribbon, radially converging and divergent. This allows the processing of extended parts of arbitrary curvature for one entry into the vacuum chamber.

2. Experimental results and their discussion
The parameters of ion sources using cathodes from various materials are measured. Figure 1 shows the current-voltage characteristics of the discharge in argon at the same pressure of 0.03 Pa in the chamber. The use of various cathode materials shows that the burning voltage of a high-current discharge with a graphite cathode is much larger than when using a molybdenum cathode. The discharge characteristics are significantly affected by cathode sputtering. Surfaces of electrodes in a stationary discharge are quickly cleaned of adsorbed gas. Therefore, the composition of the ion flux will mainly include the ions of the gas of the cathode material being pumped into the ion source and ionized atoms. The ion flux to the cathode surface is determined by the coefficient of ion-electron emission $\gamma$ and the discharge current density: $J_i = J_p(1 + \gamma)^{-1}$. The flux of atoms atomized from the surface of the cathode is determined by the sputtering coefficients for various types of ions.

![Figure 1. Current-voltage characteristics of a high-current discharge.](image)

Let us consider how the discharge characteristics change when the effect of sputtering on the elemental composition of the ion beam is taken into account. The change in the concentration of sputtered $N_p$ atoms and $N_e$ gas in the discharge gap is described by the equations:

$$\frac{dN_p}{dt} = -\nu_p^0 N_p N_e;$$

$$\frac{dN_e}{dt} = -\nu_p^0 N_p N_e - \frac{v_e}{v_p} \frac{V_p}{S} d \frac{S}{V_p} - \nu_p N_e \chi_p \left(1 - \frac{v_p d}{v_p} S \right) \frac{V_p}{V_p} + K_p \nu_p^0 N_p N_e \frac{dS}{V_p} + K_p \nu_p^0 N_p N_e \frac{dS}{V_p},$$

where $\nu_p^0$, $\nu_e^0$ are the frequencies of ionization of sputtered atoms and gas per particle; $v_p$ is the frequency of elastic collisions of atoms; $\chi_p$ is the probability of adsorption of sputtered atoms; $S$ is the surface area of the discharge through which the gas flows; $S_p$ is the cathode area; $V_p$ is the discharge volume; $K_p$ and $K_e$ are the cathodes sputtering coefficients under the action of gas ions and ions formed in the discharge gap as a result of the ionization of sputtered atoms at an average ion energy.
Stationary conditions are realized when the concentration gradient of the atomized substance is small and the cathode can be neglected by gas ions.

Assuming \( v_p = v_{p0}N_p \), the average concentration of sputtered atoms in the discharge gap can be estimated from the formula

\[
N_p = \frac{K_p \frac{d_k}{d} - 1 - \chi_p \frac{v_p}{v_{p0}N_d} d_p v_{p0} N_p}{\chi_p + \frac{S_b}{S_p} \frac{v_p}{4v_p}}.
\]

It follows that discharge in crossed electric and magnetic fields with a preferential cathode sputtering process can be considered stationary if the following condition is satisfied:

\[
K_p > \frac{d}{d_k} \left( 1 + \chi_p \frac{v_p}{v_{p0}N_d} \right)
\]

Using the known expressions for the sputtering coefficient \( K_p \approx K_0(eU_p/E_b)^{1/2} \) and the width of the active zone of the discharge \( d_k \approx (2U_{pm}^3/eB^2v_0)^{1/2} \) from this ratio, it is possible to estimate the value of the minimum voltage necessary for burning the discharge in the atomized substance

\[
U_{p_{min}} \approx \left( \frac{v_p E_b}{2v_p m} \right)^{1/2} \frac{Bd}{K_0} \left( 1 + \chi_p \frac{v_p}{v_{p0}N_d} \right),
\]

where \( N_e = e_B B^2 v_0 / m v_0 \). The parameters \( K_0, E_b \) and \( \chi_p \) depending on the cathode material. This explains the experimentally observed strong dependence of the magnitude of the burning voltage of the discharge on the cathode material.

For the realization of various technological processes, the pressure and composition of the gas in the process chamber under various operating conditions of the ion accelerator are of great importance. Figure 2 shows the dependence of the gas pressure on the current density of the ion beam at different discharge current values in argon at a flow rate of \( \sim 0.5 \) A. At each point of the graph, the gas pressure and the parameters of the ion accelerator are steady. Measurements of the pressure in the chamber were carried out using a PMI-27 ionization manometer, and the elemental composition of the neutral gas and ion beam was monitored by a magnetic mass spectrometer.

The pressure changes most strongly at low values of the accelerating voltage at the second stage of the accelerator. If no voltage is applied to the second stage of the accelerator between the cathode and the collector, the ion current to the collector is small, and the cathode takes a negative floating potential. The main fraction of ions passing through the gap in the cathode from the high-current discharge is returned to the cathode. The average energy of the ions that fly to the collector in the retarding field becomes below the spraying threshold. The main process of gas evolution is desorption from the surface of the cathode and the collector. With the ion flow formed, the pressure remains sufficiently low and depends little on the ion current density. In this mode, the mass spectrometer records a significant fraction of \( \sim 30 \% \) of the atomized cathode atoms made of molybdenum.

Another important characteristic of the ion source is the dependence of the ion current density on the collector on the magnitude of the accelerator cathode potential relative to the collector. These characteristics are presented in figure 3 and for a complete understanding of the physical processes in the accelerator should be compared with the graph in figure 2.

It is seen that under negative voltages the ions accelerated in the anode layer of the high-current discharge of the first stage of the accelerator decelerate. Acceleration of ions in the second stage is most effective at voltages greater than 1 keV. In the region of the \( J_i(U_i) \) dependence plateau, the efficiency of the second stage of the accelerator is rearranged, by changing the position of the emitter.
3. Conclusion
Thus, it is established that the gas pressure in the chamber of the ion-plasma accelerator is most strongly changed at small ion currents to the collector. The main process of gas separation is desorption from the surface of the electrodes under the action of low-energy ions. In steady state, with an accelerating voltage of more than 1 kV, the gas pressure varies little, and the main process is spraying.

References
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