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GENERATING OF LOW ENERGY INTENSIVE ION STREAMS IN CONDITIONS OF LOW PRESSURE

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In the work the method of forming of low energy ion streams near the sample surface with separating the generation area of plasma and the acceleration area of ion is offered. It allows to lower pressure in acceleration area essentially (0.01 Pa and below). The separating of the areas takes place at the expense of vacuum resistance in a plasma generating device. The dependence of plasma parameters on exterior parameters of the device is determined and the way of the further decreasing of working pressure in the modification area up to 10^{-3} – 10^{-4} Pa are shown.

INTRODUCTION

In resent years the range of ion source application in various fields of science and industry has been extended. In this connection the active research work in making and perfecting of ion sources with different parameters is being carried out.

Ion sources of low energies (with energy up to 1000 eV) are of great interest. It is linked, from the one hand, with wide implementation of new materials in industry, which handling owing to radiative damages does not allow use of high-energy ion beams. On the other hand, the energy of reacting particles at a level of tens electron-volt is necessary for synthesis of new materials with unique properties in conditions of plasma-chemical conversion.

One of the simplest ways of making intensive low energy ion beams is the method of ion stream forming from plasma immediately at a modified surface. In this case ion stream is formed at the expense of a potential difference between plasma and negatively charged surface [1].

Main problem at use of this method is making dense plasma in working volume. As a rule, for this purpose the plasma generators based on some type of gas discharge are used. For steady-state combustion of the discharge it is necessary to support increased working pressure in the modification region, that is an essential limitation of this method.

So, for the extraction of intensive ion streams (with the ion current density about tens mA/cm^2) it is necessary to create the dense plasma (with the concentration 10^{12}–10^{13} particles/cm^3) in the plasma generator. In this connection the working gas pressure in the device is necessary to support at a level 10^{-3} Torr. Such pressure for many problems is intolerably high. The decreasing of working gas pressure leads first, to astable burning of the discharge and second, to reducing of plasma concentration, and consequently to reducing of ion current density.

In this paper for decreasing working pressure in the modification region with keeping of ion stream intensity on a surface the method is offered, in which the zone of plasma production and zone of ion stream formation are separated in plasma production volume through the vacuum resistance. On the basis of theoretical and experimental results the efficiency of application of this method for forming low energy ion streams is shown.

PRINCIPLE OF THE DEVICE OPERATION

The principle scheme of the device operation is submitted in Figure. The working gas ionization is carried out in a metal discharge tube of the extended configuration and the diameter of 40 mm through a primary electron beam. The primary electron beam is formed by an electron gun with hot cathode, which is located in a discharge tube end face. The gun anode is a discharge tube wall, which is under an earth potential. For decreasing losses of electrons on the discharge tube walls the plasma column is contained by a longitudinal magnetic field with intensity maximum in the middle of discharge tube. A primary electron beam forming takes place in a double electrical layer at the hot cathode surface.

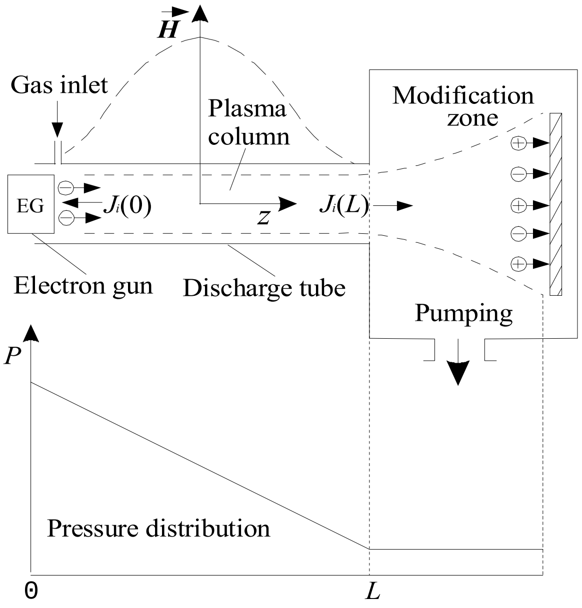

Figure. The principle scheme of the device operation

The working gas is inleted into the electron gun area. The gas pumping is yielded through a vacuum chamber. At the expense of vacuum resistance of a discharge tube interior cavity there is a pressure difference between an electron gun and vacuum chamber. The discharge tube length was chosen such, that at known pump speed of the used high-vacuum device to ensure a pressure drop between an electron gun field and modification area in 15 times. Such difference is explained by that the working range of pressures for the discharge with hot cathode is at a level 10^{-3} Torr, and necessary in our case pressure is 10^{-4} Torr and lower in a modification zone.

In the assumption of a molecular mode of gas flow the estimation of anode cavity vacuum resistance was yielded with the help of expression for gas conductance of the round section short tube [2]

$$U = 38{,}1 d^3 \sqrt{T_a / M_a} \Big/ \left(1{,}33 d + l\right), \qquad (1)$$

where U is gas conductance of the tube [m^3/s], d is the tube internal diameter [m], l is the tube length [m], T_a is the gas temperature [°K], M_a is the gas molecular weight [atomic mass unit].

To pressure drop $p = p_{\mathrm{g}} - p_{\mathrm{m}}$ between the electron gun zone p_{g} and the modification area p_{m} corresponds the gas stream $Q = U\,(p_{\mathrm{g}} - p_{\mathrm{m}})$. For pump speed of the high-vacuum device S and pressure p_{m} the stream Q is determined by expression $Q = S{\cdot}p_{\mathrm{m}}$. Using relations (1), we gain

$$l = 38{,}1 \frac{d^3}{S} \left(\frac{p_{\mathrm{g}}}{p_{\mathrm{m}}} - 1 \right) \sqrt{\frac{T_a}{M_a}} - \frac{4}{3} d \,. \qquad (2)$$

In our case for an argon at a pressure drop $p_g/p_m = 15$ and the vacuum chamber pump speed $S = 380$ L/s the anode tube length value is $l = 19$ cm.

In a longitudinal nonhomogeneous magnetic field at presence of a great concentration gradient plasma runs out into the vacuum chamber working volume in reduced pressure area. The carried out measurings have shown, that on an exit from a discharge tube ion current density was 15–20 mA/cm^2 at the discharge current of 2–3 A and the discharge voltage 30–400 V.

DEVICE WORK EFFICIENCY

The efficiency of ion use in this type plasma generator is viewed in magnetoplasmadynamics approach for one-dimensional case. Thus it was taken into account, that the ion generation in volume happens both at the expense of beam primary electrons, and at the expense of plasma electrons. It was supposed that the ion drifting from a disruptive gap happens only through end faces of the system along a magnetic field. The electron drifting in a radial direction can be neglected, as the magnetic field hold electrons well in a transverse direction, and those, in turn, by bulk charge retain ions from a transverse displacement. For viewing simplicity the magnetic field inhomogeneity in an anode tube disruptive gap was not taken into account.

From the account of the entered assumptions the continuity equation for a stationary case looks like

$$\operatorname{div}\left(n_i \vec{v}_i\right) = \gamma_{ib} n_{be} + \gamma_{ip} n_{pe}\,, \qquad (3)$$

where n_i is the ion density in a sectional space point; $\vec{v}_i$ is the ion velocity; γ_{ib} is the frequency of neutral gas ionization by beam electrons; n_{be} is the beam electron density; γ_{ip} is the frequency of neutral gas ionization by plasma electrons; n_{pe} is the plasma electron density.

As $\gamma_{ib} = v_{be}/\lambda_{be}$ and $\lambda_{be} = 1/\ n_0(z)\cdot \overline{\sigma}_i$, where v_{be} is the beam electron velocity; λ_{be} is the ionization free length; $n_0(z)$ neutral gas atom concentration; $\overline{\sigma}_i$ is the medial section of neutral atom ionization by beam electrons, so

$$\gamma_i\ n_{be} = n_0(z)\,\overline{\sigma}_i\ v_{be}\ n_{be}\,.$$

Considering, that the plasma is quasi-neutral, i.e. $n_{pe} \approx n_i$ from (3) it follows

$$\operatorname{div}\left(n_i \vec{v}_i\right) = n_0(z)\,\overline{\sigma}_i\ v_{be}\ n_{be} + \gamma_{ip} n_i(z)\cdot \qquad (4)$$

In view of that $v_{be}\ n_{be} = J_e/e$, where J_e is the current density of primary electrons from a hot cathode, e is the electron charge, and J_{be} from a Langmuir relation for a double layer is defined as

$$J_{be} = \beta\, J_{pi}(0) \sqrt{M_i / m_e}\ , \qquad (5)$$

where J_{pi} is the ion current density through a double layer; M_i is the ion mass; m_e is the electron mass; β is the coefficient taking into account free and not free modes of discharge burning ($0 < \beta < 1$) [3], and as in the assumption, that the ion drifting across a magnetic field is missed, the equation (4) becomes

$$\frac{d}{d\,z}\left(n_i v_{iz}\right) = n_0(z)\,\beta\,\overline{\sigma}_i \sqrt{M_i / m_e}\ J_i(0)/e + \gamma_{ip} n_i\,. \qquad (6)$$

After integration on z from 0 up to L, where L is the discharge tube length

$$n_i v_{iz}\Big|_0^L = \beta\,\overline{\sigma}_i \frac{J_i(0)}{e} \sqrt{\frac{M_i}{m_e}} \int_0^L n_0(z)\,dz + \int_0^L \gamma_{ip} n_i\,dz\,, \qquad (7)$$

$$\gamma_{ip} = \int_{v_{ie}}^{\infty} n_i(z)\, n_0(z)\, \sigma_i(v)\, v_{ep} f_{ep}(v)\,dv = $$

$$= n_i(z)\, n_0(z) \int_{v_{ie}}^{\infty} \sigma_i(v)\, v_{ep} f_{ep}(v)\,dv \,.$$

Taking into account, that $n_i v_{iz} = \dfrac{J_i}{e}$ and $\int_0^L n_0(z)\,dz = \overline{n}_0\ L$, where J_i is common ion stream (on the cathode and in a vacuum chamber) and at a linear relation of neutral atom concentration on the discharge tube length $\overline{n}_0 = \left(n_0(L) + n_0(0)\right)/2$ ($\overline{n}_0$ is the average on length neutral atom concentration), equation (7) becomes

$$\frac{1}{e}\left(J_i(L)+J_i(0)\right)=\beta\,\bar{\sigma}_i\,\frac{1}{e}J_i(0)\sqrt{\frac{M_i}{m_e}}\,L\,\bar{n}_0+\int\limits_{v_{ie}}^{\infty}\sigma_i(v)v_{ep}f_{ep}(v)dv\cdot\int\limits_0^L n_i{}^2 n_0\,dz\,,$$

where J_i (L) is the ion stream on the discharge tube exit, J_i (0) is the ion stream at the cathode. Or,

$$\frac{J_i(L)}{J_i(0)}=\beta\,\bar{\sigma}_i\sqrt{\frac{M_i}{m_e}}\,L\,\bar{n}_0-1+\int\limits_{v_{ie}}^{\infty}\sigma_i(v)v_{ep}f_{ep}(v)dv\cdot\int\limits_0^L\frac{e\,n_i{}^2 n_0}{J_i(0)}dz$$

As well as $n_0(L)=p(L)/kT_a$, $n_0(0)=p(0)/kT_a$ and $\bar{n}_0=\left(n_0(L)+n_0(0)\right)/2$ we receive $\bar{n}_0=\frac{p(L)}{kT_a}\left(1+\frac{S}{2U}\right)$.

Then the last equation becomes

$$\frac{J_i(L)}{J_i(0)}=\beta\,\bar{\sigma}_i\sqrt{\frac{M_i}{m_e}}\,L\,\frac{p(L)}{kT_a}\left(1+\frac{S}{2U}\right)-1+\int\limits_{v_{ie}}^{\infty}\sigma_i(v)v_{ep}f_{ep}(v)dv\cdot\int\limits_0^L\frac{e\,n_i{}^2 n_0}{J_i(0)}dz\,.$$

As the last term of the expression is always more then 0, the account of ionization at the expense of plasma electrons increases a relation J_i (L) $/J_i$ (0). Without the account of the contribution of plasma electrons into ionization the simplified estimate of the bottom of ion use efficiency looks like

$$\frac{J_i(L)}{J_i(0)}=\beta\,\bar{\sigma}_i\,L\sqrt{\frac{M_i}{m_e}}\,\frac{p(L)}{kT_a}\left(1+\frac{S}{2U}\right)-1\,. \qquad (8)$$

RESULTS AND DISCUSSION

The expression (8) displays the relation of an ion stream on the exit from the plasma generator to an ion stream on the gun cathode necessary for the discharge maintenance (forming of a double layer at the cathode). It is well visible, that $J_i(L)$ directly proportional depends on sorts of working gas, the discharge tube length, and the pressure on the exit from the plasma generator and the vacuum chamber pump speed.

Knowing $J_i(0)$, it is possible to estimate quantitatively the ion current density $J_i(L)$. At a thermionic current equal 2 A and cathode diameter of 18 mm the ion current density on the cathode for a free mode of the discharge combustion ($\beta = 1$) in argon medium from (7) in our case makes ~3 mA/cm^2. Then from (9) for the discharge tube length $L = 19$ cm, pressure in the chamber $p(L) = 2\cdot10^{-4}$ Torr and the pump speed $S = 0{,}38$ m^3/s ion current density on the exit $J_i(L)$ makes 550 mA/cm^2.

The overflow of a theoretical estimation above experimental values is stipulated by that the ion streams of great intensity are obtained experimentally to not free mode of discharge combustion, when the Langmuir relation is not executed ($\beta << 1$). At use of a discharge free mode the theoretical estimations almost coincide with the experimental ones, but the ion stream intensity on the exit in this case made less than 1 mA/cm^2.

Thus, in the work the simple method of forming of intensive ion beams in conditions of low pressure in a modification zone (10^{-4} Torr and below) is offered. At increasing of pump speed or discharge tube length it is possible to decrease pressure essentially (up to 10^{-6} Torr and below). In our experiments, at increasing of pump speed for a short time (up to 15 s) at the expense of thermal evaporation of metal in the vacuum chamber, ion current density on the exit was steadily supported at a level of 20 mA/cm^2 at pressure $2\cdot10^{-6}$ Torr.

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