Sustaining of a Glow Discharge with Electrostatic Confinement of Electrons for Plasma Emitter Production in Small-Sized Beam Sources of Fast Neutral Molecules

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Abstract − Two approaches are presented for sustaining of a glow discharge with electrostatic trap volume V=0.001−0.01 m³ in the pressure range 0.03−0.3 Pa. The discharge produces plasma emitters for broad beam sources of fast atoms and molecules intended to etch dielectric and conductive substrates with particles accelerated to 0,5−1,5 keV energy and to bombard the substrate surface with 50−200 eV neutral particles during deposition of evaporated or sputtered material. Fast molecules are produced in charge exchange collisions of ions accelerated by potential difference between the plasma emitter and a secondary plasma outside the beam source both plasmas being separated from each other with a single negatively biased emissive grid. The first approach is based on an increase of the electron emission from the cathode due to bombardment of its surface by electrons penetrating into the source through the grid from the secondary plasma. The second approach is based on the pressure overfall between the electrostatic trap and an outer hollow anode, which prevents the anode plasma decay of a double layer located inside the trap.

1. Introduction

Structure, density, hardness, internal stress and other important properties of thin films deposited by means of material vaporization in vacuum are influenced by ions bombarding the film during deposition. In the case of a dielectric film deposition or deposition on a dielectric substrate it is not possible to accelerate the ions from a plasma filling the chamber by means of a negative bias potential, in this case for a beam-assisted deposition broad-beam sources are indispensable.

Between them broad-beam sources of fast neutral molecules (FNM) [1] or of fast atoms are remarkable for a beam cross-section up to ~10000 cm² and an equivalent current up to 10 A at any beam energy ranging from ~10 eV to ~10 keV. In contrast to other sources of accelerated particles the sizes and beam cross-section of the FNM sources may be easily enlarged up to any needed values. Only production of small-sized sources with volume ~1 liter and beam cross-section ~100 cm² is difficult and requires additional means to sustain the discharge.

To solve the problem of small-sized FNM beam sources it is reasonable first to investigate a big-sized source and interdependence of its plasma emitter and of the secondary plasma in the working chamber.

2. Characteristics of the FNM sources in the middle pressure range of the electrostatic trap effect

A working gas pressure ~0.1 Pa is optimum for FNM sources because at this pressure value the charge exchange length amounts to 5−20 cm depending on the mass and energy of accelerated ions and in the most coating systems it is comparable with the usual distance from emissive grids of beam sources to the substrates. As the FNM sources are based on the glow discharge with electrostatic confinement of electrons [2] they should depend on whether the pressure 0.1 Pa is in the middle or in the lower pressure range of the electrostatic trap effect (ETE) [3]. Minimum value of the border p_o^* between two pressure ranges may be calculated using the following formula

$$p_o^*(\text{Pa})=\lambda_N^*(U_c)/[(W/eU_c)(M/2m)^{1/2}(4V/S)], \quad (1)$$

where V and S are the trap volume and surface (a sum of its hollow cathode and emissive grid surfaces), M is the mass of ions, m and e are the mass and charge of electrons, W is the mean energy lost per electron-ion pair created by electrons [4] emitted at the cathode and U_c is the cathode fall in the middle pressure range.

The Fig. 1 presents functions $\lambda_N^*(U_c)$ calculated for temperature 293 K and p=1 Pa of argon (W=26 eV), nitrogen (W=37 eV), neon (W=37 eV) and helium (W=46 eV, all the W values taken from [5]), using the formula

$$\lambda_H(p,U) = \frac{1}{n_O(p)(eU - W)} \int\limits_{W}^{eU} \frac{d\varepsilon}{\sigma(\varepsilon)}, \quad (2)$$

where $U=U_c$, $\sigma(\varepsilon)$ is dependence on electron energy of the ionization cross-section [2] and the molecule density n_o=2,5·10¹⁴ cm⁻³ at p=1 Pa.

The fig. 2 presents schematic diagram of a source with rectangular beam cross-section 17×90 cm², the

trap volume $V=2\cdot10^4$ cm³ and surface $S=2,8\mathrm{x}10^3$ cm². For $U_c=520$ V in argon the electron pass $\lambda_N^*=16$ cm (Fig. 1) and the formula (1) gives $p_0^*=0.058$ Pa. It means that the pressure $p=0.1$ Pa belongs to the middle pressure range of the ETE where U_c does not depend on p and has a minimum value [2].
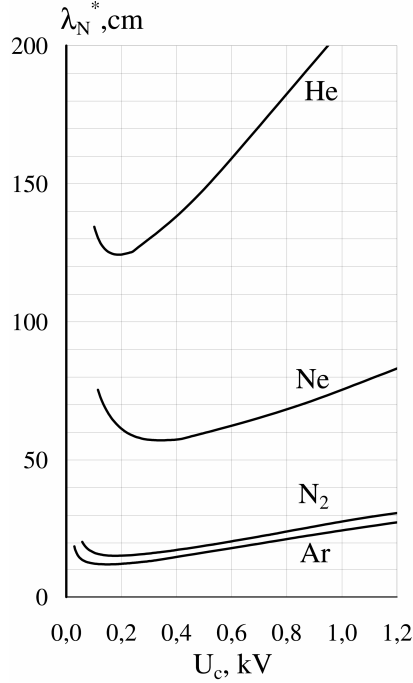

Fig. 1. Dependence on the cathode fall U_c of the mean pass between ionizing collisions λ_N^* of electrons emitted by the cathode at the gas pressure 1 Pa
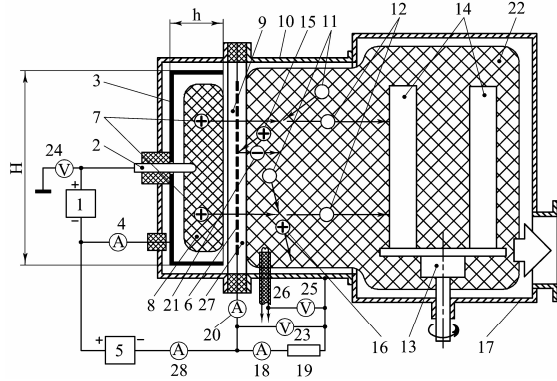

Fig. 2. Schematic diagram of a FNM beam source. 1 and 5 − power supplies; 2 − anode; 3 − hollow cathode; 4,18,20 and 28 − ammeters; 6 − emissive grid; 7 − ions to be accelerated; 8 − plasma emitter; 9 and 27 − space charge sheaths; 10 − charge exchange chamber; 11 − slow molecules; 12 − fast molecules; 13 − rotating table; 14 − substrates; 15 and 16 − slow ions; 17 − working chamber; 19 − resistor; 21 − secondary electron; 22 − secondary plasma; 23, 24 and 25 − voltmeters; 26 − thermo-emissive probe

At $p\geq0.1$ Pa it is possible to vary the resistance R of the resistor 19 from zero to infinity thus regulating in

a wide range the energy of fast neutral molecules 12, which corresponds to potential difference between a plasma emitter 8 and secondary plasma 22. The secondary plasma 22 is a result of compensation by secondary electrons 21 from the emissive grid 6 and from the chambers 10 and 17 walls of a positive space charge of ions 7, 15 and 16 as well as a result of gas ionization inside the chambers. Detailed investigation showed that electron current in the circuit of a positive additional electrode immersed in the plasma 22 is comparable with the current of ions 7 injected into the chambers 10 and 17 through the grid 6. The slow ions 15 and 16 are the result of charge exchange collisions of slow gas molecules 11 and ions 7, which are first accelerated in the sheath 9 between the emitter 8 and the grid 6 and then decelerated in the sheath 27 between the grid 6 and the secondary plasma 22.

The Fig. 3 presents dependence of the beam source characteristics on the resistance R of the resistor 19. It shows that at $R>1$ kΩ the cathode fall U_c as well as the secondary plasma 22 potential φ and the sum of currents in the grid 6 and the resistor 19 circuits keep their values constant. In this region a variation of the grid potential, for instance by means of changing the resistance R, allows the beam energy regulation from ~ 10 eV up to ~ 10 keV at a constant beam current 1 A. But a decrease of the resistance R from 1 kΩ down to 0.1 k at almost constant current in the grid circuit leads to an increase of the current in the resistor circuit from 0.18 A up to 0.38 A, to a potential rise of the secondary plasma from 5 V up to 85 V and to the cathode fall decrease from 520 V down to 360 V.
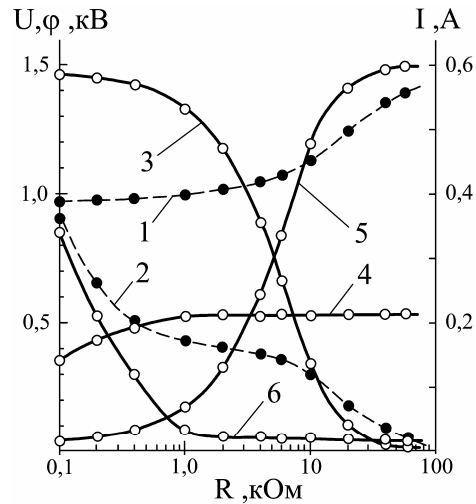

Fig. 3. Dependence of the currents in the grid (1) and the resistor (2) circuits as well as of the plasma emitter potential (3), of the cathode fall U_c (4), of the potential difference between the chambers and the grid (5) as well as of the secondary plasma potential φ (×10) on the resistance R at argon pressure 0.2 Pa, current in the cathode circuit 1 A and voltage 1.5 keV between the anode and the grid

The above changes of the source characteristics are the result of the grid retarding potential decrease and of the hollow cathode 3 bombardment by electrons from the secondary plasma 22.

3. Glow discharge sustaining in a small-sized beam source by means of its cathode bombardment with electrons from the secondary plasma

The above dependence of the plasma emitter on the secondary plasma may be used to sustain the glow discharge with electrostatic trap in the lower pressure region of the ETE. To prove it, an additional power supply has been connected to the grid in order to vary the grid potential φ independently of other parameters. Fig. 4 presents investigation results of a rectangular 35×8 cm² cross-section beam source with the trap volume V=1680 cm³ and surface S=1076 cm². The formula (1) gives for the U_c=520 V in argon p_o^*=0.27 Pa. It means that the optimum charge exchange pressure p=0.1 Pa belongs to the lower pressure ETE range. For this reason a substantial rise of the cathode fall U is needed to keep the current value constant when the gas pressure is decreasing.
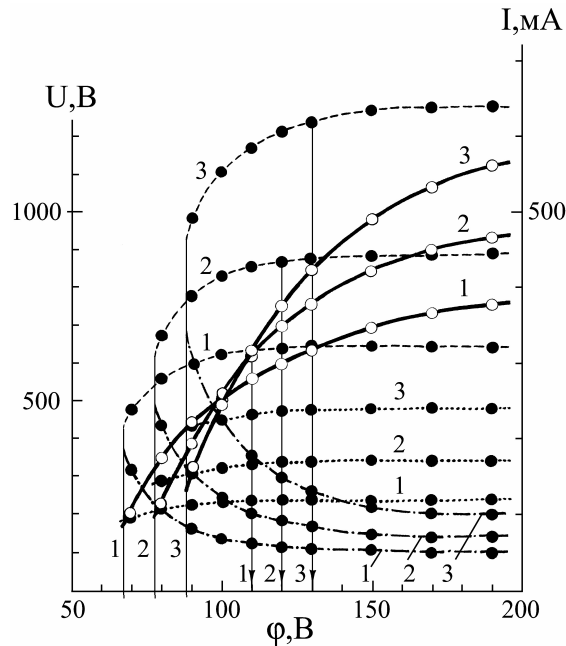

Fig. 4. Dependence on the grid retarding potential φ of the discharge cathode fall U (full curves), cathode current (hatch curves), grid current (dotted curves) and of the current in the resistor circuit at the anode current 0.5 (1), 0.7 (2) and 1 A (3), anode-to-chamber voltage 2 kV and argon pressure 0.2 Pa

The results show that at a discharge current 1 A an increase of the electron emission from the cathode surface due to its bombardment with electrons from the secondary plasma may lead to the cathode fall decrease from about 1000 V down to about 100 V. At the pressure 0.1−0.3 Pa the electron bombardment al-lows a beam production of fast atoms or molecules with an equivalent current up to 1 A if their energy exceeds 1 keV. But the bombardment cannot be used for production of a beam with an energy 50−200 eV because at the emitter-to-grid potential fall lower than 500 V the energy of electrons bombarding the cathode and the electron-electron emission coefficient both go down to zero.

Another approach is used for sustaining of the discharge in small-sized sources of low energy atoms or molecules. In this case the gas flows into the beam source trap through a small orifice in its wall from a hollow anode and near the orifice inside the trap there is a ball of plasma penetrating from the hollow anode and separated from the plasma emitter with a double layer. Usually at pressures lower than 0.5−1 Pa the anode plasma of the double layer decays and the discharge extinguishes. An indispensable sustaining condition of such a discharge is therefore a gas pressure inside the hollow anode exceeding 0.5−1 Pa.

Fig. 5 presents schematic diagram of a beam source with a trap composed of a cylindrical 12-cm-diam and 8-cm-long hollow cathode 1, a flat emissive grid 2 and a disc 3 with a 0.8-mm-diam central orifice through which the gas flows into the trap from a hollow anode 4. The gas discharge power supply 6 is connected to the anode 4 and to the hollow cathode 1. The DC power supply 7 allows potential φ variation of the trap from −1 kV up to +1 kV relative to the grounded vacuum chamber.
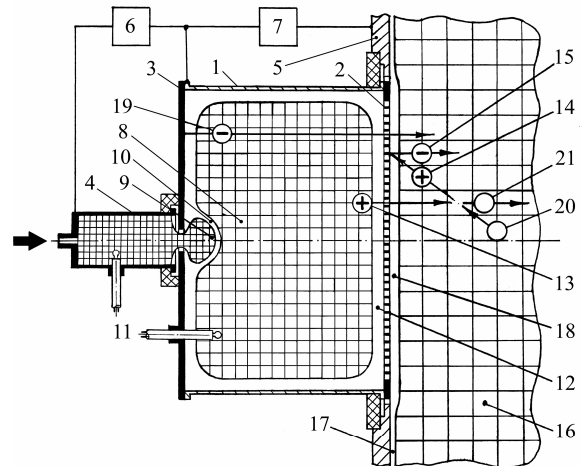

Fig. 5. Scheme of an experimental beam source of low-energy fast neutral molecules

Experimental investigation results presented at the Fig.6 prove that at the argon pressure about 0.1 Pa inside the 0.9-liter volume of the trap a high enough speed of the gas flow through the 0.5-cm² orifice maintains a pressure overfall needed to fulfill the above condition of preventing the anode plasma 9 of the double layer 10 from decay and sustains the gas discharge and the plasma emitter 8.
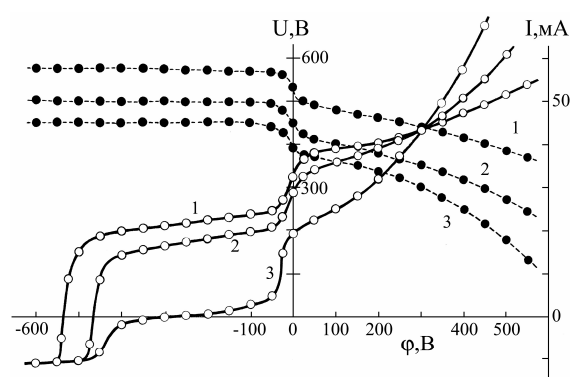
Fig. 6. Dependence of the anode-to-cathode voltage U and of the current I in the vacuum chamber circuit on the bias potential φ of the source trap

The source at the Fig. 5 produces a 100-cm^2 cross-section beam of argon atoms with equivalent current up to 0.3 A their energy being adjustable from about zero up to 600 eV. Sources of the same type with larger emissive grid area produce beams of low energy particles with an equivalent current 1−2 A.

6. Conclusions

The investigation results revealed an interdependence of the glow discharge with electrostatic confinement of electrons, which produces plasma emitters of broad beam sources of fast neutral molecules, on the one hand, and of a non-self-sustained glow discharge with electrostatic confinement in the working chamber, which fulfills the role of its electrostatic trap, on the other hand.

The interdependence is based on the electrons run-away from the secondary plasma inside the working chamber through the beam source emissive grid into its plasma emitter and is observed when the retarding potential of the grid is low enough to let the electrons into the beam source. Due to the run-away of electrons the secondary plasma potential rises up to ~100 V and it results in such gas ionization in the chamber which makes available electron current into the beam source exceeding the beam current.

The electron bombardment of the source cathode allows production of small-sized sources of fast atoms and molecules with energy exceeding 1 keV for the substrates pre-treatment before the coating deposition.

The gas pressure overfall from a hollow anode to the source electrostatic trap allows production of small-sized sources of 50−200 eV molecules for the substrates bombardment during the coating deposition.

The two above approaches allowed development of small-sized universal beam sources which are able to produce broad electron beams for pre-heating of massive substrates, broad beams of fast argon atoms for pre-activating their surfaces and finally to produce a combined flow of metal atoms accompanied by 50−200 eV molecules, for instance, a flow of titanium atoms accompanied by nitrogen molecules during TiN deposition.

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