Properties of Magnetron Discharge with Hollow Cathode as Generator of Plasma Emitting Charged Particle Ampere Beams

A.P. Semenov, I.A. Semenova

Physical Problems Department at the Presidium of Buryat Scientific Center SB RAS, St. 8, Sakhyanova, 670047 Ulan-Ude, Russia, Ph.: 8(3012)433324, Fax: 8(3012)433238, E-mail: semenov@pres.bsc.buryatia.ru

Abstract – The properties of the magnetron discharge cold hollow and not cooled rod cathodes are considered. Availability of electrode structure of the magnetron discharge with hollow cathode as generator of emitting plasma is shown. At discharge current of 2 A and accelerating voltage 10 kV emission ion current is of 0,1–0,15 A, emission electron current 1 A. The price of extracted ion 1–2 W/mA, that is in 2–5 times lower, than in typical ion sources, and power efficiency 15 mA/W, that in 5–6 times overtops electron emitters on the basis of reflective discharge with hollow cathode, are determined.

1. Introduction

In the gas discharges with cold cathode the degree of generated in the discharge ion participation in emission can be characterized by extracted ion price, expressed by the relation of the emitter power to emission ion current $C_i \sim I_p U_p / I_i$ (I_p – discharge current, U_p – discharge voltage, I_i – ion beam current). The degree of electron participation in emission is characterized by power efficiency $W_e \sim I_e / I_p U_p$ (I_e – electron beam current). In the reflective low pressure discharge with cold hollow cathode [1], voltage of which burning is $U_p \sim$ 400–450 V, C_i is rather high ~10 W/mA, W_e – low ~2,5 mA/W. The reason of extracted ion price increase and low power efficiency is the high voltage of discharge burning. The rather high voltage of discharge burning facilitate rather fast destruction of emission channel walls and undesirable heating of cathodes. In the applied plasma ion and electron sources [2–7] the essential part of energy is removed by the appropriate cooling system. Except for high voltage of reflective discharge with hollow cathode burning the redistribution of charges density in plasma is characteristic as a result of change of radial movement conditions of charges between the output aperture of the cavity and reflective cathode [2], the steepness of plasma density dependence on discharge current at $I_p > 0{,}6$ A is reduced. Some properties of the magnetron discharge ensuring the most effective mode of stationary discharge burning with high emission parameters of plasma are examined below and the experimentally established features of the thermal defeat in the discharge of the rod cathode face part are shown.

2. Technique of Experiment, Results and Discussion

In Fig. 1 the electrode structure of magnetron discharge with hollow cathode is schematically submitted [8], in which cathode electrode is heated in the discharge up to temperatures, sufficient for thermoionic emission.

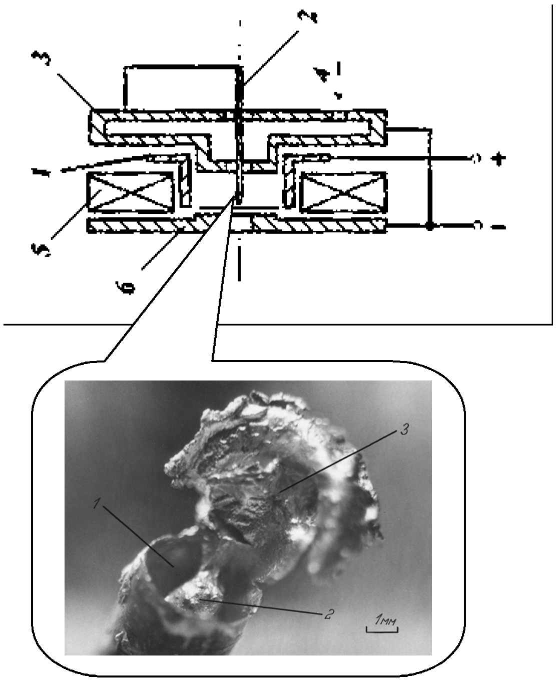

Fig. 1. Electrode structure of discharge device and photo of erosion (thermal defeat) trace of face part of the rod cathode from a brass: the *1* – anode, *2* – rod cathode, *3* – hollow cathode, *4* – gas feeding, *5* – constant magnet, *6* – reflective cathode

The circuit of electrodes consists of cylindrical copper anode 1 with diameter 18 and length 12 mm. The anode coaxial covers the moving rod cathode *2* with diameter d = 1,5–4 mm. The rod cathode is located on the axis of cathode box cavity *3* coaxial to the output aperture of the cavity and forms backlash with the aperture in the reflective cathode *6*. The induction of axial magnetic field of 0,1 T is created in the anode cylinder by the ring magnet *5*. Through the aperture in the reflective cathode 6 pumping of working gas is carried out. It also can serve as the emission channel at use of the discharge device as the plasma generator of plasma ion or electron source, or ejector nozzle removing flow of atomic hydrogen. The direct measurement of the rod cathode temperature was carried out by thermo-electrical tungsten-rhenium transformer. Plasma forming gas (air) accumulates through the aperture *4* on periphery of the cavity. The speed of flooding is of 0,8–1,2 mPa·m^3/s. For measurement of plasma parameters into the aperture of the cathode 6 was entered cylindrical tungsten probe with diameter 0,05 mm, working length of 1 mm was limited by alundum covering of non-working part of the probe. For high-voltage extraction of the charged particles from discharge cathode plasma the acceleratingelectrode was used [6], located coaxial to the cathode *6*.

The properties of magnetron discharge with hollow cathode (Fig. 1) are substantially defined by thermoemission properties of the rod cathode [9], heated by the power egested in the discharge [10–12]. For measurement of the rod cathode temperature $T_к$ on face section of the rod thermocouple junction from tungsten and rhenium was formed, on the basis of thermocouple junction the thermo-electrical tungsten-rhenium transformer graduation BP-5/20 is formed. Tungsten-rhenium thermocouple junction was heated up to $T_к$ and did not break structure and mode of discharge burning. Thermo-emf was measured by oscillograph C8-11. The display was estimated subject to radiation of plasma. Temperature $T_к$ was measured after fast discharge quenching. If to accept speed of cathode temperature reduction of ~10^6 K/s [13], during decomposition of plasma ~10^{-5} s, measured temperature will be below required on ~10 K. In Fig. 2 the oscillogram of thermo-emf after gas-discharge quenching is given (time of discharge switching-off of $5\cdot10^{-6}$ s).

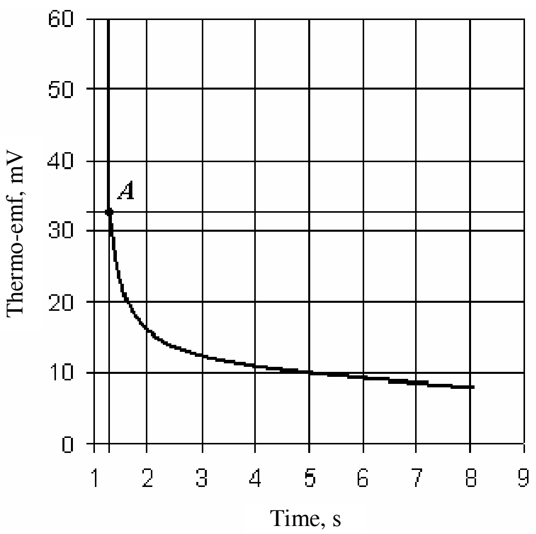

Fig. 2. Oscillogram of thermo-emf after gas-discharge quenching: I_p = 0,66 A, rod cathode from tungsten with diameter d = 1,5 mm

The plasma decomposition is characterized by abrupt drop of thermo-emf up to true $T_к$ (point A), as at discharge burning plasma considerably overstates the thermo-electrical tungsten- rhenium transformer indications. On oscillogram the site is lower than point A haracterizes change of the rod cathode temperature from the maximum magnitude up to some determined through some seconds after plasma decomposition.

Thermo-emf in point A corresponds to the cathode temperature ~$2{,}6\cdot10^3$ K and coincides with temperature measured pyrometer [14].

In Fig. 3 the oscillogram of anode current is submitted (amplitude of initiation pulse voltage 10^3 V). The discharge development up to the establishing of equilibrium burning passes through intermediate stages (Fig. 4). The time of discharge development τ_f depends on initiation pulse voltage amplitude $U_з$. With increase $U_з$ from 0,7 up to 1,2 kV τ_f was reduced from 0,35 up to 0,15 s. At restart of a voltage pulse $U_з$ in time less than 0,1 s after gas-discharge quenching the intermediate stages of burning did not note.

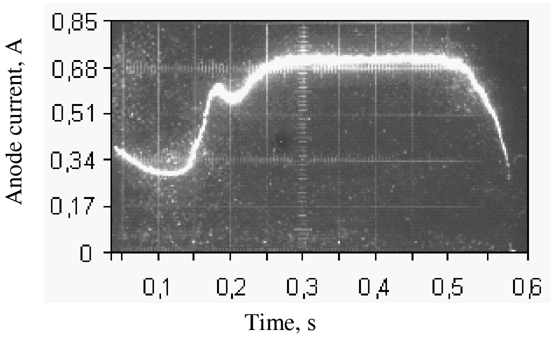

Fig. 3. Oscillogram of anode current: τ_f = 0,225 s, I_p = 0,715 A

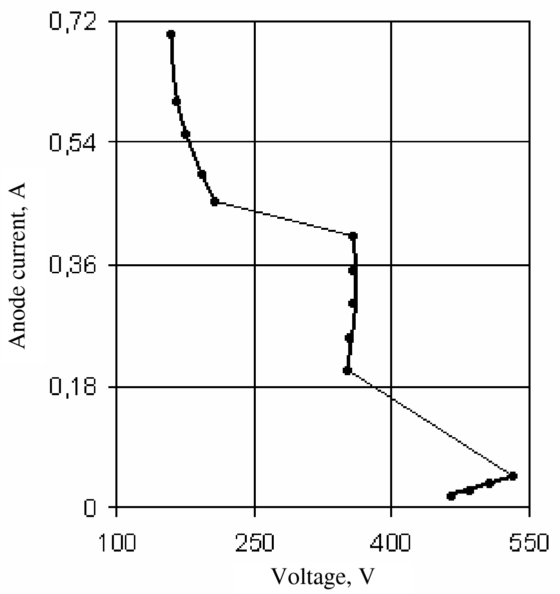

Fig. 4. Voltage-current characteristic of the discharge: d = 1,5 mm

At $U_з$ < 0,7 kV was initiated and burned low current magnetron discharge. The occurrence of falling voltage-current characteristic (Fig. 4) is caused by change of the emission mechanism of the rod cathode, when there is essential the contribution of thermoionic emission in ionization processes in the cathode area of the discharge. Temperature of the rod reaches 2500–2700 K and provides thermoemission current density of 0,3–1,6 A/cm^2. To this testify voltage-current characteristic with cathode rods from various materials [9], as experiments have shown [9] the lowest burning voltage corresponds to the rod cathode from LaB_6, characterized by high thermoemission properties. Oscillogram of discharge current I_p (Fig. 2) shows the transition of discharge to the mode of equilibrium burning through 0,225 s from the moment of initiation pulse voltage feed. The delay in the discharge development is caused by cathode rod initial heating. In Fig. 5 (*2*) the dependence of axial density of plasma on discharge current is given which was evaluate by saturation ion current on the probe placed in the aperture of the cathode 6, in conditions of electron emission from the tungsten rod which has been heated up to white heat by plasma ions, accelerated in the cathode drop.

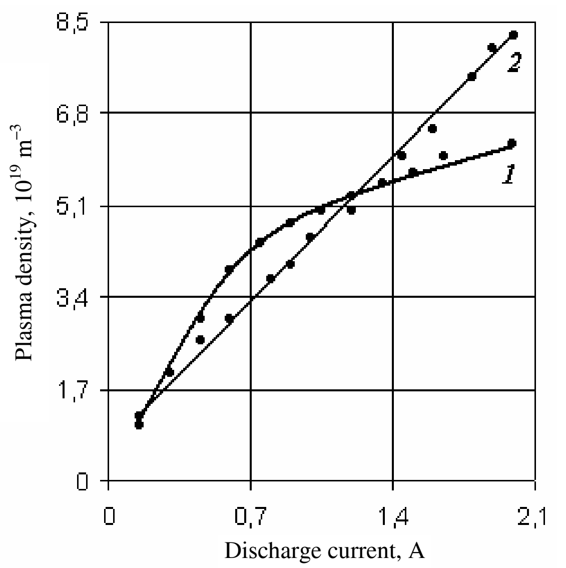

Fig. 5. Dependence of plasma density on discharge current: *1* – reflective discharge with hollow cathode [2], *2* – magnetron discharge with hollow cathode

Dependence (*1*) plasma density in the axial aperture of the cathode 6 on the reflective discharge current is shown [2]. The effect of charges density restriction is not appeared in electrode structure of the magnetron discharge with hollow cathode, in which the absorption of discharge energy by not cooled rod electrode can heat it up to temperatures, sufficient for electronic emission. Last circumstance allows to lower essentially the burning discharge voltage, to receive linear growing dependence of plasma concentration on discharge current at the large currents >0,6 A and to create conditions of smooth transition of the abnormal glow discharge in arc and to ensure diffusion (without cathode spot) mode of arc discharge burning. In the considered conditions the appreciable contribution to ionization thermoelectrons bring in. Than above temperature of the rod and is wider emission surface, the lower is the discharge burning voltage. The effective influence of these two factors is shown at certain distance between the open end face of the rod and reflective cathode, at which U_p is the lowest. It is experimentally established (Fig. 6), that in process of the rod deepening in the discharge gap, the dependence of burning voltage carries not monotonous character.

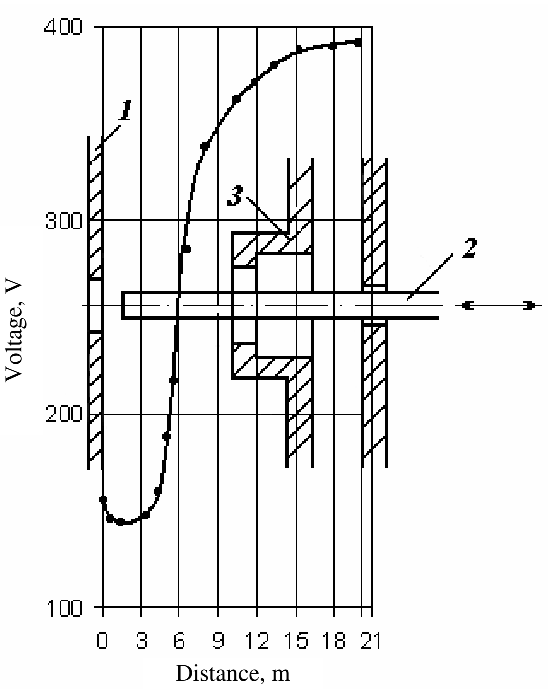

Fig. 6. Dependence of burning voltage on distance between the end face of the rod cathode and reflective cathode: *1* – reflective cathode, *2* – rod cathode, *3* – hollow cathode (d = 1,5 mm, I_p = 0,5 A)

In measurements the rod with the help of the microscrew moved along the axis of the discharge chamber at continuous discharge burning. At initial position face rod section was combined with the basis plane of the cavity. On embedding of the rod on the cavity length ~9 mm, the burning voltage was reduced from 390 up to 375 V (discharge current 0,5 A). On length of the cavity aperture ~2 mm the reduction of U_p up to 360 V was observed. At the rod position in the space between the cavity aperture and reflective cathode on distance up to 8,5 mm from the aperture the voltage sharply fell from 360 up to 145 V. The current in a circuit appreciably increases. At face rod section approach to the reflective cathode the character of voltage dependence changed from falling to growing, thus the growth of rod current was slowed down. The point of the minimum defines the sizes of the optimum backlash d_{opt} between face rod section and reflective cathode wall. The extent of the backlash at which U_p is minimal is of ~1,5 mm at $d_{opt} \sim \lambda_o$, where λ_o – free path.

It is established, that for rather short time < 10^{-1} s from the moment of discharge switching in the mode of equilibrium burning with hollow cathode the different destruction of face rod section of cylindrical rods Ø 4 mm from stainless steel, aluminium and brass were observed. So the end face of the rod from stainless steel fuses and takes the form of sphere, at the same time the face part of the rod from aluminium was softened and as a pear-shaped drop of liquid metal was extended and having touched the cold surface of the reflective cathode, solidified.

The most complex character of destruction is found out in the rod from a brass. As is obvious from Fig. 1 and 7 liquid metals 3 is displaced through the end face of the rod and having touched a cold surface of the reflective cathode is cooled. Thus on the replacement place of liquid metal the crater with 1 depth 4 mm was formed. As a result of explosive emission of liquid metal, inside the crater the cone 2 was formed. The analysis of thee longitudinal section of the rod cathode face part (Fig. 7) shows, that at displacement of the fused metal from rod volume, it surface cylindrical layer remained cold and has not fused, though the melt border was from the surface on depth of 0,1 mm (0,1 mm thickness of the kept walls limiting the crater). The explosive displacement of metal through the rod end face with formation of the crater (Fig. 1 and 7), apparently, is connected to resonant processes in the backlash: face section of the rod cathode – reflective cathode representing concentrated capacity of the toroidal resonator.

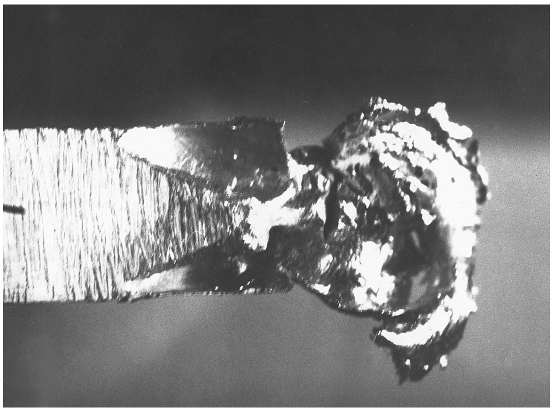

Fig. 7. Photo of the longitudinal shear of the rod cathode damaged face part (Fig. 1)

Consideration of the toroidal resonator as concentrated capacity (formed by the end face of the rod cathode) and concentrated inductance (formed by cavity of the anode cylinder) [15] and the estimation of resonant frequency has given value ~1 GHz, coincident with frequency of plasma fluctuations. However findings out of a physical nature of the phenomenon need statement of additional experiments deserving separate discussion. On an output of the aperture in the reflective cathode 6 at the discharge current of 2 A and accelerating voltage 10 kV the emission ion current is 0,1–0,15 A, emission electron current 1 A.

3. Conclusion

Thus, electrode circuit of the magnetron discharge with hollow cathode, characteristic, conditions of formation and parameters of cathode plasma, which for the first time were considered in works [11, 10, 16–18] allows to solve more rationally the task of high current ion beams generation with the low price of the extracted ion ~1 W/mA and electron beams with high power efficiency ~15 mA/W. So, the unambiguity of dependence of plasma density on discharge current (Fig. 5 (2)) and revealed falling voltage-current characteristic of the discharge is caused by rather low voltage of discharge burning and define effective extraction of ions and electrons on a direction of an axis of the rod cathode.

The carried out consideration of some features of the magnetron discharge with hollow cathode gives only qualitative representation about its consumer properties. The observable reduction of burning voltage is connected with thermoemission of rod cathode. Similarly the falling of discharge voltage burning is influenced by change of extent of the backlash between the end face of the rod cathode and reflective cathode.

Nevertheless designated properties of the discharge allow to use of magnetron for formation of tungsten pins, effective generation of atomic hydrogen by high-temperature activation of molecular hydrogen, that is especially important at deposition of diamond-like carbon films and processing of semiconductors surfaces [19], formations of refractory metals coverings on tubular cavities [20], reception of high density plasma. Effective ion and electron sources with the not cooled rod cathode are developed on the basis of the magnetron discharge with hollow cathode [8].

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