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Plasma sources based on a low-pressure arc discharge

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Abstract

This article presents two types of a hollow-cathode plasma source based on an arc discharge where the electrons emitted either by a hot filament or by a surface-discharge-based trigger system initiate a gas arc discharge. The sources produce gas plasmas of densities 10^{10}–10^{12} cm^{-3} in large volumes of up to 0.5 m^3 at a discharge current of 100–200 A and at a pressure of 10^{-1}–10^{-2} Pa. Consideration is given to some peculiarities of the operation of the plasma sources with various working gases (Ar, N_2, O_2). The erosion rate of the cold hollow cathode in the designed plasma sources is shown to be 10 times lower than that found in an ordinary one. The sources are employed for plasma-assisted surface modification of solids.

Keywords: Arc discharge; Gas plasma; Hollow cathode; Plasma source

1. INTRODUCTION

The gas-discharge plasma finds wide application in surface modification of solids: nitriding of steels and alloys (Schanin *et al.*, 2001; Sanchette *et al.*, 1997), ion implantation (Conrad *et al.*, 1987), deposition of thin films, formation of nanocrystalline and amorphous compounds, ion-plasma deposition of hardening, and protective coatings (Borisov *et al.*, 1998*a*). On the one hand, the choice of a discharge is dictated by the parameters of plasma which provide the required surface modification during the interaction of the plasma with a solid and, on the other hand, by the demand for high energy efficiency of the technological process.

The low operating voltage, the high discharge current, and the wide range of pressures at which an arc discharge shows stable initiation and operation have stimulated the development and studies of different arc-based devices, among which are plasma emitters (Oks & Schanin, 1999) and plasma generators (Borisov *et al.*, 1994). Arc sputterers, which are widely employed for coating deposition, cannot be used directly in plasma-assisted processes due to a great number of atoms and macrodroplets of the sputtered cathode material present in the plasma flow.

Hot-cathode arc discharges make it possible to produce pure gas-discharge plasma. However, their lifetime at high discharge currents is limited, ranging from more than several tens of hours in an atmosphere of inert gases (Ar, N_2) to no more than several tens of minutes in an atmosphere of reactive gases (O_2, CH_4, etc.) due to oxidation of the tungsten cathode and its bombardment by the ions arriving from the discharge gap. Cold-hollow-cathode discharge systems (Gavrilov *et al.*, 1988), where a cathode spot is initiated at the internal surface of the hollow cathode at microsecond pulse durations, possess a longer lifetime. With a definite design of the hollow cathode (Vintizenko *et al.*, 2001), macrodroplets and atoms of the cathode material are essentially prevented from entering the anode region of the discharge.

2. PLASMA GENERATOR WITH A HOT HOLLOW CATHODE

The design of a plasma generator with a cylindrical hollow cathode is shown in Figure 1. Cylindrical hollow stainless steel cathode **4** of internal diameter 90 mm and length 280 mm is mounted on water-cooled flange **2**. Hot cathode *5* made of a tungsten wire of diameter 1.8 mm is located on two water-cooled copper current leads **1** inside the cavity. A longitudinal magnetic field of induction $2.5 \cdot 10^{-2}$ T, which stabilizes the discharge, is induced by solenoid **6**. The cathode unit is fixed to water-cooled case **8** through insulating gasket **3**. The case **8** of the plasma generator is at the anode potential and is connected to the vacuum chamber of dimensions 600 × 600 × 600 mm. In this discharge system, the vacuum chamber plays the role of a hollow anode. The plasma generator is powered from a filament-circuit transformer which provides a current of up to 180 A at a voltage

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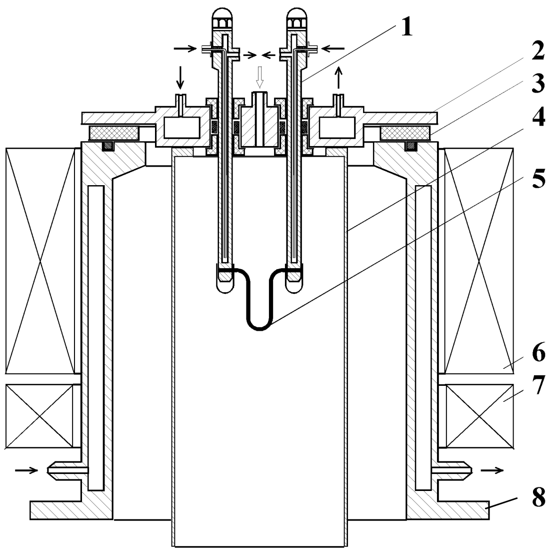

Fig. 1. Plasma generator with a cylindrical hollow cathode: **1**: water-cooled current leads; **2**: water-cooled flange; **3**: insulator; **4**: hollow cathode; **5**: hot filament; **6**: solenoid; **7**: focusing coil; **8**: housing.

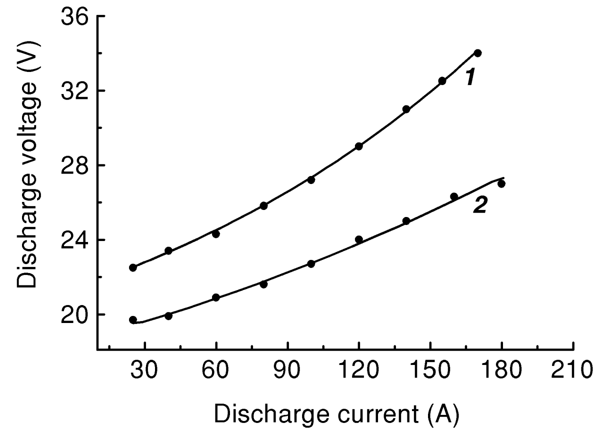

Fig. 2. Current-voltage characteristics of the discharge at two pressures: **1** $p = 0.3$ Pa: **2**: $p = 0.5$ Pa.

of 12 V and from a three-phase rectifier which allows gradual current tuning in the range from 10 to 180 A at an open-circuit voltage of 70 V. The two-channel automatic gas leak-in system ensures gas leak-in.

The path of the electrons emitted by the hot cathode increases in the magnetic field and therefore these electrons efficiently ionize the working gas and generate gas-discharge plasma in the hollow cathode. The unmagnetized ions accelerated in the region of near-cathode potential fall knock secondary electrons out of the walls of the hollow cathode. The processes of ionization in the cavity are intensified, and the conditions are thus established for the initiation and operation of a high-current gas discharge at low discharge pressures and voltages. By varying the filament current and, consequently, the electron emission from the cathode, it is possible to control the discharge current and to initiate a non-self-sustained arc discharge without a cathode spot. The main characteristics of the discharge have been obtained under the following experimental conditions: the hot cathode was connected to the cavity and the working gas was argon.

Figure 2 shows the current-voltage characteristic of the discharge at a filament current $I_f = 135$ A and at two pressures. Figure 3a depicts the discharge operating voltage V_d and the discharge current I_d versus the filament current I_f at a pressure $p = 3 \cdot 10^{-1}$ Pa. The pressure dependences of the discharge operating voltage and discharge current presented in Figure 3b are similar in character, that is, as the pressure is increased in the range from $7 \cdot 10^{-2}$ to $9 \cdot 10^{-1}$ Pa, the discharge current increases, while the discharge operating voltage decreases.

Further increasing the length of the hollow cathode causes a rapid increase in the pressure of stable initiation of the discharge, because it is difficult for the cavity to take the anode potential, whereas decreasing the length of the hollow cathode provides a decrease in discharge current.

In non-self-sustained arcing, the hollow cathode plays an important role. Table 1 shows how the length of the hollow cathode affects the characteristics of the discharge at a constant cavity diameter $D = 9$ cm. In this table, L is the length of the hollow cathode, I_d is the discharge current, V_d is the operating voltage, and p_{in} is the pressure at which a non-self-sustained arc discharge is initiated. As shown in Borisov *et al.* (1998*b*), the optimum ratio between the length and the diameter of the hollow cathode, L/D, is 3–4.

At discharge currents $I_d = 90$–150 A, operating voltages $V_d = 60$–70 V, pressures $p = 0.1$ Pa, the generator produces nitrogen and argon plasmas of density 10^{10} cm^{-3} and spatial distribution homogeneity no worse than $\pm 20\%$ from the average value. The plasma has a positive potential of the order of $+10$ V with respect to the anode. The electron temperature is $T_e = 4$ eV. Probe measurements have revealed that there also exists a group of fast electrons with temperature $T_e = 10$ eV in the plasma. With a negative bias applied to the probe, the saturation ion current is 5 mA/cm^2.

3. PLASMA SOURCE WITH A COLD HOLLOW CATHODE

The design of a plasma source with a cold hollow cathode is shown schematically in Figure 4. The cylindrical hollow cathode **1** of diameter 110 mm and length 200 mm is made of stainless steel or copper and is immersed in the axial magnetic field induced by short magnetic coil **3**. The hollow cathode is completely cooled with water. The cathode spot at the internal surface of the hollow cathode is initiated by a surface discharge in initiating system (trigger) **2**. At one end of the cathode facing the hollow anode (the vacuum chamber) there is arc arrester **4** in the form of a cup with a hole diameter smaller than the hollow cathode diameter by a factor of three. The arc arrester is at the floating potential

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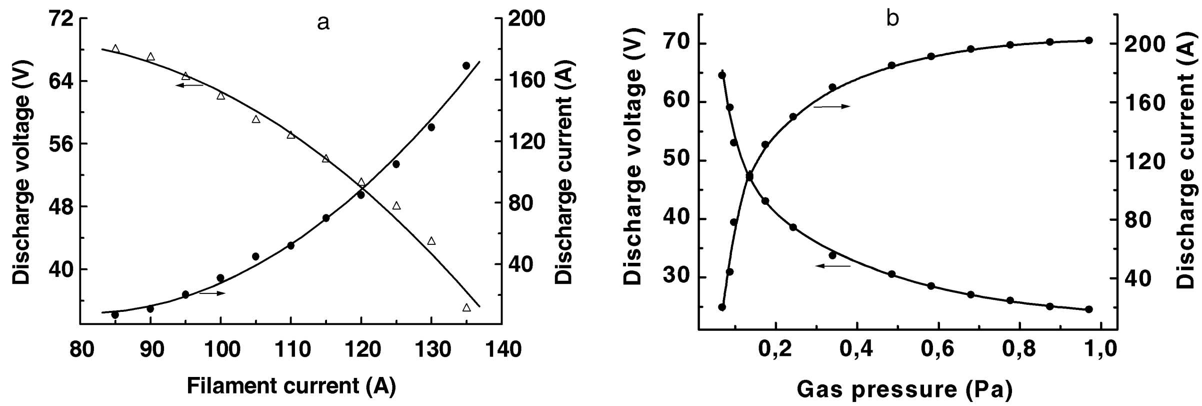

Fig. 3. Discharge operating voltage and discharge current versus the filament current (a) and pressure (b).

and precludes the evolution of the arc over the surface of insulator **6** through which the hollow cathode is connected to the vacuum chamber **7**. The vacuum chamber in this discharge system plays the role of a hollow anode. The arc arrester precludes direct penetration of neutral particles and macrodroplets of the cathode material into the hollow anode, since the diameter of the central hole is much smaller than that of the hollow cathode. The working gas (Ar, N_2, O_2) is supplied directly to the hollow cathode through controllable gas leak-in **6**. In experiments, the gas flow was controlled in the range from 30 to 100 Sccm (Standard cubic centimeter per minute) (Mean cubic centimeter per minute at atmospheric pressure), depending on the operating mode of the source, on the type of the working gas, and on the cathode material. In so doing, in the mode of stable operation of the discharge the pressure in the vacuum chamber varied in the range $5 \cdot 10^{-2}$–1.2 Pa.

With a pulsed voltage of the order $U_i = 5$ kV applied to the trigger and dc voltage $U_d = 50$ V applied to the discharge gap, a cathode spot is initiated at the internal surface, thus producing the primary plasma in the hollow cathode. Through this plasma the cavity takes the anode potential and an arc is initiated in the gap. The cathode spot in the cross magnetic and electric fields follows a circular orbit over the internal surface of the hollow cathode in the maximum magnetic field. The speed of rotation increases with increasing magnetic field and discharge current. So, increasing the discharge current from 30 A to 150 A causes an increase in the speed of rotation from 1.5 m/s to 7 m/s and as the magnetic field is varied in the range $B = 0.002$–0.012 T at a constant discharge current of 100 A, the speed of rotation increases six times.

With constant pressure and magnetic field, the arc operating voltage depends almost not at all on the discharge current in a wide range, that is, the current-voltage characteristics (Fig. 5) for all gases used in the experiments are linear in character. As can be seen in Figure 5, the lowest arc operating pressure occurs where argon is used as the working gas. An appreciable effect of the cathode material on the operating voltage of the arc discharge is also observed. In the case where the stainless steel cathode is replaced by a copper one, the operating voltage for all gases used decreases by 20–30%.

In the range of the average discharge currents, which are governed by the power supply, the variation in the pressure and in the magnetic field affect in various ways the operation of the discharge, depending on the type of working gas. With a constant magnetic field and with an increase in pressure by an order (0.1–1 Pa), the discharge current for Ar

Table 1. *The dependence of plasma parameters on hollow cathode length*

L, cm	I_d, A	V_d, V	p_{in}, Pa
0	15	74	$1 \cdot 10^{-2}$
28.5	40	60	$7 \cdot 10^{-2}$
31.0	42	59.5	$9 \cdot 10^{-2}$
34.0	47	59	$16 \cdot 10^{-2}$

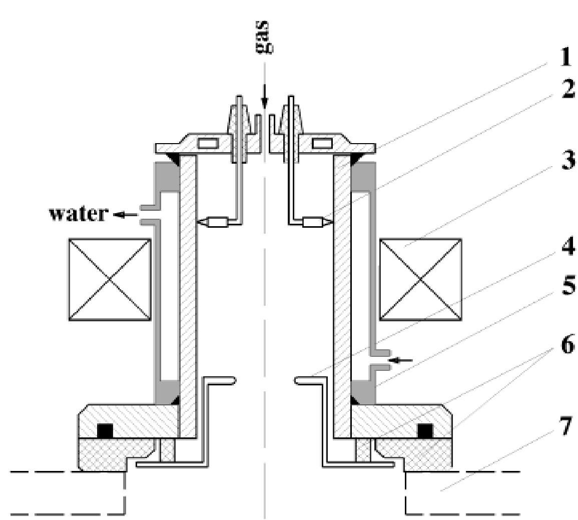

Fig. 4. Plasma generator with cold hollow cathode.

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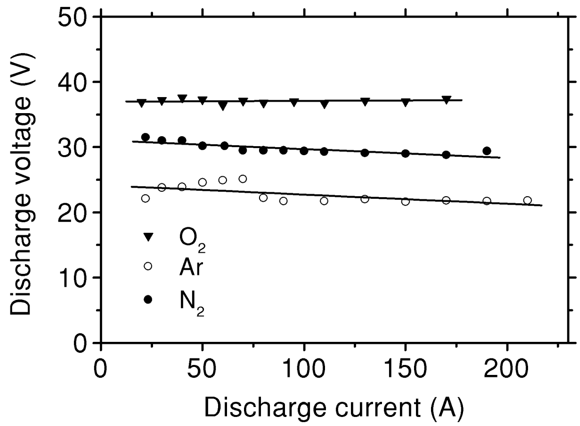

Fig. 5. Current-voltage characteristics of the discharge at pressure $p =$ 0.8 Pa, magnetic field $B = 2.5$ mT.

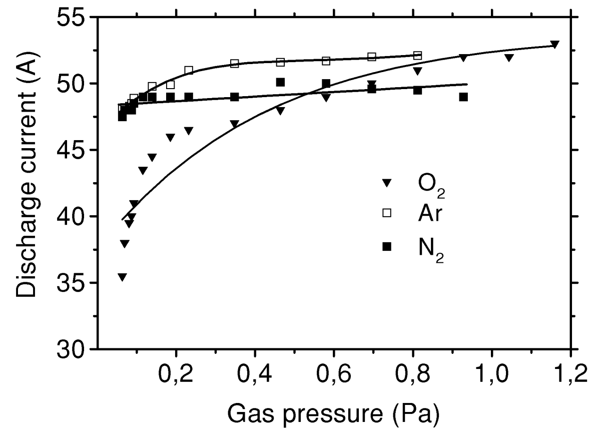

Fig. 6. The dependence of discharge current on gas pressure.

increases by 10%, for O_2 by 40%, being nearly the same for N_2 (Fig. 6).

It can be seen from Figure 7 that in similar conditions, the operating voltage decreases from 50 to 20 V (Ar) and from 52 to 34 V (O_2), remaining invariant for N_2. Varying the magnetic field from 1 to 14 mT causes a nearly linear increase in operating voltage and the same decrease in discharge current, no matter what type the working gas is (Figs. 8 and 9).

Such a character of the dependences of the parameters of the cold-hollow-cathode arc discharge can be explained as follows. In the cross electric and magnetic fields, the electrons emitted by the cathode spot and accelerated in the region of the cathode potential fall are acted upon by the forces working to return them to the cathode. The electrons which undergo no inelastic collisions (electron cutoff) mainly return back to the cathode. As the magnetic field is increased, the path of such electrons decreases and the number of electrons which do not participate in ionization processes increases. Elementary calculations show that with maximum pressures of 0.1 Pa and discharge voltages of 20–50 V, the free path of the electrons is comparable with the path of an electron, when moving in the cross fields. This leads to a decrease in discharge current and an increase in operating voltage. The voltage is increased to increase the cathode potential fall and the relative ionization (Francis, 1964):

$$S_e = ap(V - V_i),$$

where $a = 2.6 \cdot 10^3$ is a constant, p is the gas pressure, V_i is the ionization potential, and V is the electron energy

In plasma-assisted processes, it is desirable to obtain pure gas-discharge plasma free of atoms and macrodroplets of the cathode material. In this discharge system, fast atoms and ions emitted by the cathode spot settle on that side of the hollow cathode which is opposite to the cathode spot, thus decreasing the erosion rate of the cathode and increasing the lifetime of the plasma source. Tests of the sources have shown that during the operation at an Ar pressure $p = 3 \cdot 10^{-2}$ Pa and at a discharge current of 70 A for 120 min, the erosion rate of the stainless steel hollow cathode is $(15–20) \cdot 10^{-5}$ g/C, which is an order of magnitude lower than the erosion rate achieved elsewhere (Lafferty, 1982).

By moving the magnetic coil along the cathode, it is possible to change the place where the cathode spot operates and to use efficiently the entire internal surface of the hollow cathode of the source, when operated for a long period of time. The electrons knocked by ions intensify the ionization processes in the hollow cathode and ensure operation of the discharge at low voltages and gas pressures.

In this design, there is, however, some probability of particles of the cathode material entering the chamber: macrodroplets due to repeated collisions, atoms due to scattering at gas molecules, and ions due to recharging and pulse loss. Figure 10 shows a photo (dark-field image) of the glass surface located 30 cm from the hollow cathode after the time the plasma source with a copper cathode has been operated in the atmosphere of oxygen at a discharge current

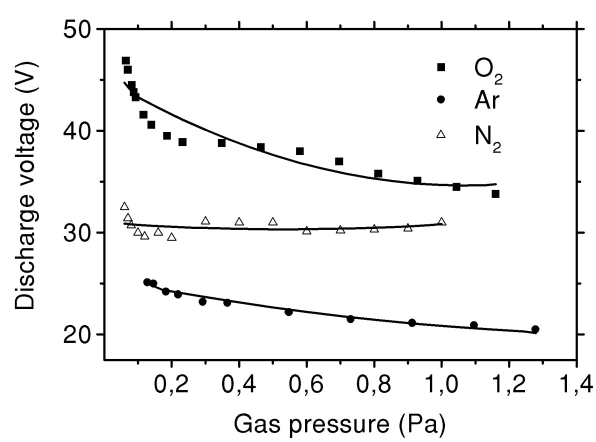

Fig. 7. Discharge operating voltage versus gas pressure.

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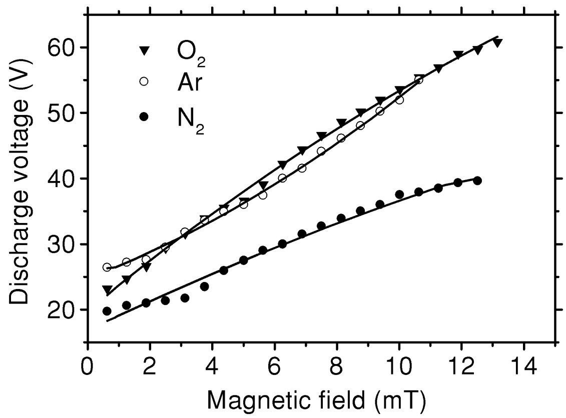

Fig. 8. The dependence of discharge operating voltage on magnetic field.

of 70 A for 30 min. Despite the fact that the cup transparency remains the same, there are macrodroplets of size 0.5–3 μm. The average number of macrodroplets determined by measurements at three different points of the specimen surface is 40 macrodroplets per square millimeter.

The parameters of the generated plasma were measured in the vacuum chamber (hollow anode) with Langmuir probes. At a discharge current of 100 A and at an argon pressure of 0.5 Pa, the plasma density is $n_e = 10^{11}$ cm^{-3} and the electron temperature is $T_e = 4.5$ eV. The plasma potential with respect to the anode is positive ($\Delta\varphi \approx 6V$) and the measurements show that this potential increases monotonously in going from the hollow cathode to the center of the hollow anode with a gradient of 0.2 V/cm. The plasma density in the hollow cathode is thus an order of magnitude higher than that in the hollow anode.

4. CONCLUSION

The use of hollow-cathode arc discharges makes it possible to decrease substantially the discharge operating voltage at low pressures and at high discharge currents and to retard notably the penetration of particles of the cathode material into the hollow anode of the plasma source and, in some cases, to preclude the process completely. In a source with a hollow cathode, the initiation of a cathode spot at the internal surface of the hollow cathode greatly decreases the erosion rate of the cathode and increases the lifetime of the plasma source owing to deposition of macrodroplets and atoms on the side of the hollow cathode which is opposite to the cathode spot.

In plasma-assisted processes the application of a cathode material similar to the material of the treated specimen allows one to eliminate the influence of the cathode material on the properties of the modified layer. The low arc operating voltage and its constant value at widely varying discharge currents ensures a high energy efficiency of the plasma-assisted process.

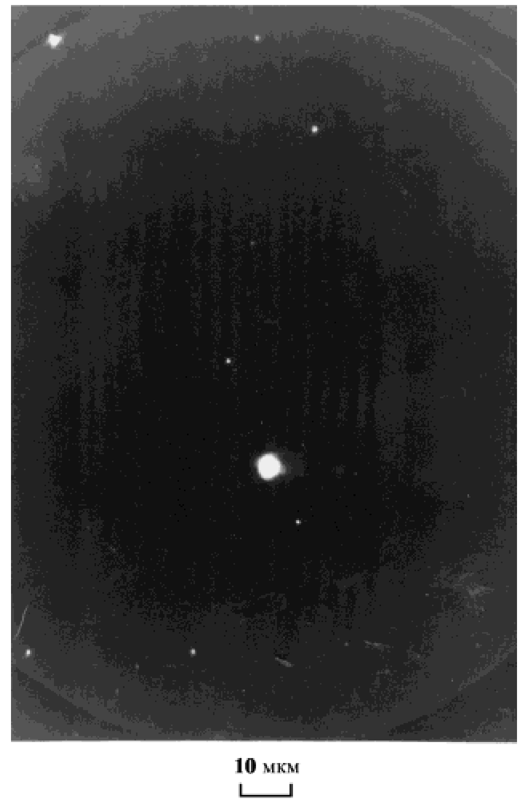

Fig. 10. The number of macrodroplets on surface of glass.

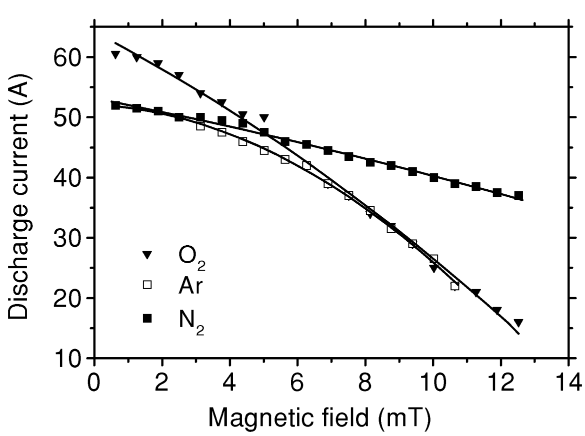

Fig. 9. Discharge current versus magnetic field.

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