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INFLUENCE OF THE MAGNETIC FIELD OF THE CURRENT PASSING THROUGH THE ANODE ON A GLOW DISCHARGE IN A COAXIAL SYSTEM

M.S. Melnichenko, S.B. Sydorenko, A.I. Kuzmichev, S.O. Maikut

Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine

E-mail: serg@sydorenko.org.ua

To study the influence of the magnetic field on the normal low-pressure glow discharge, an electrode coaxial system with a meshy tubular cathode and an internal anode was used. A current was passed through the anode to obtain the azimuthal magnetic field crossed with electric field. Oscillography of the signals from the electric probe and photodiode, together with video recording, made it possible to establish the movement of the discharge luminous region along the electrodes. When AC current with a frequency of 50 Hz was passed through the anode, the discharge movement was oscillatory – from one end of the system to another.

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INTRODUCTION

Plasma treatment of the metal surface is widely used in industry, a striking example is the technology of ion nitriding for surface hardening or dielectric coating [1]. Traditionally, this technology uses a glow low current density (< 1 mA/cm^2) discharge in nitrogen. Nitrogen ions, generated in the discharge, bombard the surface (it serves as a cathode) and penetrate into the subsurface layer with the formation of nitrides with needed properties.

In many cases, it is required to carry out ion treatment of the inner surface of long tubes with small diameter and ensure the treatment uniformity. The use of the glow discharge with a long hollow tubular cathode and an anode outside the tube does not provide uniformity due to poor penetration of the electric field into the tube. Therefore, it is advisable to use a coaxial internal anode that maintains the discharge along the entire length of the tube; however, even in such a system, treatment inhomogeneity is possible for various reasons. To minimize the inhomogeneity of ion treatment, mechanical or magnetic scanning of the ion-generating discharge over the surface is usually applied [3]. In the case of a coaxial system of electrodes, the scanning effect may be created by the azimuthal magnetic field generated by the current passing through the anode. Indeed, this field, together with the electric field within the discharge, generates the Lorentz force, which causes the charged particles in the discharge plasma to drift along the axis of the coaxial system. Particle drift phenomenon in crossed fields is observed in various gas-discharge magnetron systems [3]. In the work [4], the influence of the magnetic field of the internal thermionic cathode on the current in a vacuum coaxial diode was studied and the effect of self-cutoff of the electron current to the anode was revealed at a high heating current of the thermionic cathode and, accordingly, when there was a strong azimutal magnetic field. However, the behavior of a low-current glow discharge in the magnetic field of the internal anode when current is passed through it by a separate source has not been considered in the literature. The purpose of this work is to study the influence of the anode magnetic field on a normal glow discharge and its moving when a current is passed through the anode by an additional source.

1. EXPERIMENTAL SETUP

A coaxial electrode system 33 cm long was used. It consisted of a cylindrical cathode 23 mm in diameter, made of meshy foil with small holes for visual observation of the discharge, and an internal copper rod anode 5 mm in diameter. The electrode system was placed in a vacuum chamber filled with air at pressure of 20…100 Pa corresponding to the minimum of the Paschen curve. Outside the cathode, near its upper end, there was a photodiode (for registrating the light radiation of the discharge plasma) and a flat probe (for collecting ions that emerged from the cathode cavity through the cathode mesh; the probe had a negative potential of 70 V relative to the cathode). The electrical circuit for connecting the electrodes, photodiode and probe to power sources and measuring instruments is shown in Fig. 1. An alternating current (AC) with frequency of 50 Hz was passed through the anode rod with a step-down transformer. To measure the AC current a current transformer TA and an ammeter PA2 were used. The AC current generated the azimuthal magnetic field of variable polarity. In order to register and then visualize the movement of the luminous region of the glow discharge (i.e., the area of its existence) along the interelectrode gap, a video recording of the discharge was carried out in normal and slow modes.

To obtain additional information about the effect of the azimuthal magnetic field on the glow discharge, there were made calculations of the distribution of magnetic induction and density of charged particles flows in the interelectrode gap using the COMSOL code.

2. RESULTS AND DISCUSSION

Fig. 2 shows calculated values of the induction of the azimuthal magnetic field in the interelectrode gap (right branch of the curve) and inside the anode (left branch of the curve).

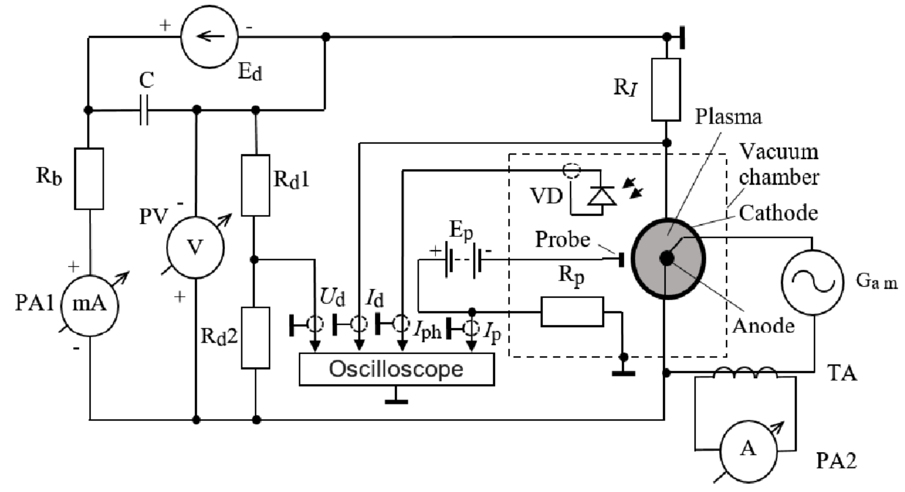

Fig. 1. The electrical circuit of the experimental set-up. E_d – glow discharge power source, E_p – battery for the probe voltage supply, Ga m – AC current source for the anode, I_d – glow discharge current, I_p – probe current, I_{ph} – photodiode signal, PA1 – ammeter for measuring the discharge current, PA2 – ammeter for measuring the current generating the azimuthal magnetic field, PV – voltmeter for measuring discharge voltage, R_b – ballast resistor, R_I – shunt for measuring the discharge current I, R_d1/R_d2 –voltage divider, R_p – shunt for measuring the probe current, TA – current transformer, U_d – glow discharge voltage, VD – photodiode

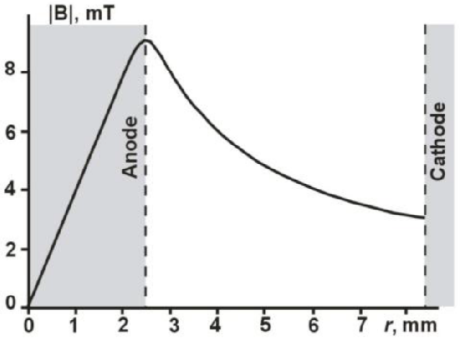

Fig. 2. Change in the induction of the azimuthal magnetic field around the anode along the radius r. The current through anode is 120 A

With a current passing through the anode of tens of amperes, the magnetic induction is several millitesla. With such an induction, the influence of the magnetic field on the ions is minimal.

Based on the results of modeling a glow discharge at voltage of 300 V and pressure of 133 Pa, Fig. 3 shows the distributions of discharge current along the coaxial system at different values of direct current through the anode, generating azimutal magnetic field ($I_{\mathrm{M.F}}$). The left curve shows that at $I_{\mathrm{M.F.}} = 0$ the normal glow discharge mode is established in the middle part of the coaxial system as a localized discharge zone.

The middle and right curves in Fig. 3 show that when an azimuthal magnetic field is created in a coaxial system at a current of $I_{\mathrm{M.F.}} = 37$ A, the localized character of the glow discharge in the normal mode is retained, but the discharge zone shifts in one direction or another from the center of the system, depending on the direction of the current through the anode. Herein, the smaller the current through the anode, the smaller the shift of the discharge zone from the middle of the system.

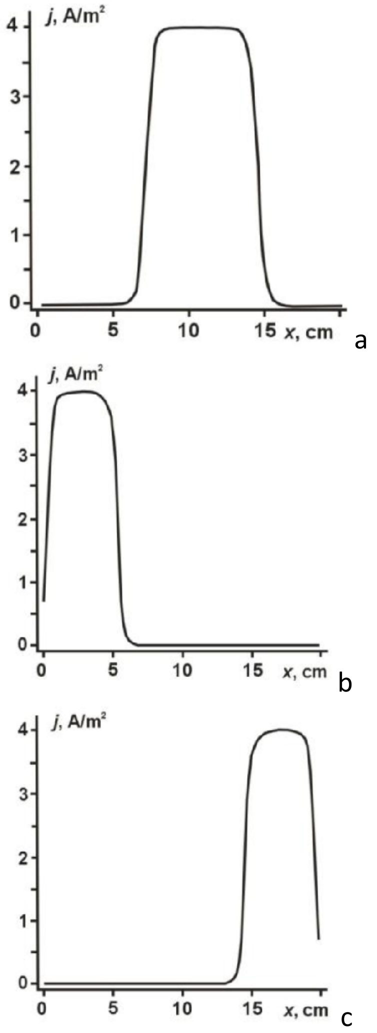

Fig. 3. Distributions of normal glow discharge current density along the coaxial system at different values of current ($I_{M.F.}$) through the anode, generating azimutal magnetic field : $I_{M.F.} = 0$ (a), $I_{M.F.} = -37$ A(b), $I_{M.F.} = +37$ A (c)

Typical photographic results of visual and oscillographic observations of the influence of the azimuthal magnetic field on the normal glow discharge are shown in Figs. 4, 5. The lower oscillograms of a two-beam oscilloscope in Fig. 4 show the change in time of the signals of the photodiode VD (see Fig. 1) located opposite the upper part of the interelectrode gap. The sinusoidal curves on oscillograms in Fig. 4 are synchronized with the voltage of the source of AC current passed through the anode, and when the current is applied, they characterize the change in time of the alternating magnetic field, due to which the signal of the photodiode VD is time-bound to the value of the magnetic induction in the interelectrode gap.

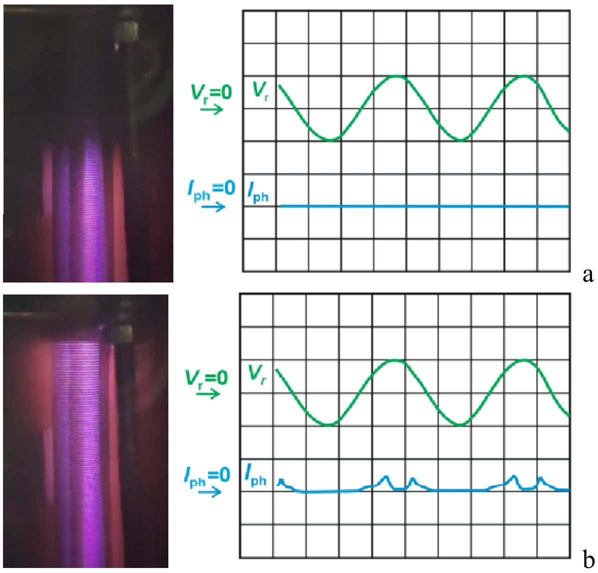

Fig. 4. Photos of glow discharge in the coaxial system with meshy cathode at 45 Pa and power of 2.6 W, and oscillograms: the down waves are the photodiode signals (I_{ph}); the upper sinusoidal waves (V_r) are the reference 50 Hz voltage synchronized with the AC current through the anode and the changes in the magnetic field. $I_{M.F.}$: a – 0, b – 120 A. The reference V_r voltage waves sets the time scale for the photodiode waves and gives binding of photodiode waves to time changes in the azimutal magnetic field. The signal scales are 5 V/div for V_r and 5 mV/div for I_{ph}; the time scale is 5 ms/div

Fig. 4,a shows the photo of the discharge glow in the absence of a magnetic field ($I_{M.F.} = 0$), which demonstrates the localization of the discharge zone typical for the normal glow discharge (in our electrode system, the initial localization of the discharge occurred at the lower end of the system). The photodiode VD located opposite the upper part of the interelectrode gap, respectively, did not register the discharge glow.

Fig. 4,b shows the photo of the discharge glow in the presence of the azimuthal magnetic field ($I_{M.F.} = +120$ A), the induction of which varied sinusoidally in accordance with the upper reference oscillogram (V_r). The photo sums up the glow over the entire period of the magnetic field change, and it can be seen that the discharge was maintained in all sections of the interelectrode gap. Due to the inertia of human vision, it is not possible to visually register the movement of the discharge zone, however, high-speed video recording with slow-motion viewing of frames shows that during the positive half-wave of AC current through the anode and, accordingly, magnetic induction, the discharge zone rises up to the upper end of the electrode system. Thus, the oscillogram of the photodiode signal and the video recording are consistent with each other.

Oscillograms on the screen of the two-beam oscilloscope in Fig. 5 show, at different values of the AC current $I_{M.F.}$ through the anode, the change in time of the synchronized signals of the photodiode VD (the upper oscillograms) and the electric probe (the lower oscillograms) both located opposite the upper part of the interelectrode gap. It can be seen that both signals unambiguously indicate shifting the localization of the discharge zone of the normal glow discharge to the upper part of the interelectrode gap during the positive half-wave of the azimuthal magnetic field and subsequent return of the discharge zone to the lower part of the interelectrode gap.

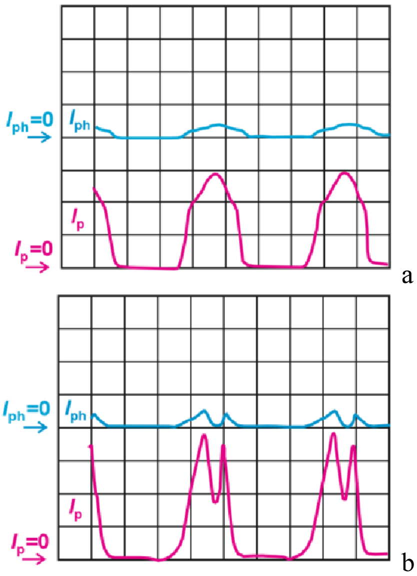

Fig. 5. Oscillograms of the probe ion current (I_p, the lower waveforms) and signal from the photodiode (I_{ph}, the top waves), at 45 Pa and power of 2.6 W. $I_{M.F.}$: a – 90 A, b – 120 A. The signal scale is 5 mV/div; time scale is 5 ms/div

Thus, the experiments confirm the simulation results presented in Fig. 2. The direction of shift of the localization of the normal glow discharge in the azimuthal magnetic field corresponds to the direction of drift of charged particles in crossed fields [**EB**] (**E** is the electric field strength, **B** is the magnetic induction).

It is important to note that the azimuthal magnetic field not only shifts the discharge zone along the interelectrode gap, but also compresses it, *i.e.* how to focus it. We draw this conclusion on the basis that, at a higher AC current through the anode, the width of the signal pulses of the photodiode and electric probe decreases; compare Fig. 5,a for $I_{M.F} = 90$ A and Fig. 5,b for $I_{M.F.} = 120$ A.

The measurements revealed a feature of the signals of the photodiode (I_{ph}) and the electric probe (I_p) in the presence of an increased azimuthal magnetic field in the interelectrode gap (at $I_{M.F.} \sim 120$ A and more), namely: the appearance of a dip in the oscillograms of these signals at time points near the maximum of the positive half-wave of the AC current through the anode; again compare Fig. 5,a for $I_{M.F} = 90$ A and Fig. 5,b for $I_{M.F} = 120$ A.

The appearance of the dip in the oscillograms of the photodiode and electric probe signal waves can be associated with the effect of suppression of the glow discharge by the increasing azimuthal magnetic field, the induction vector of which is orthogonal to the direction of the exit of secondary γ-emission electrons from the cathode, and to the discharge current density vector in the gap. The first can reduce the emission of γ-electrons due to their return to the cathode; the second can create the effect of magnetic isolation of the anode, similar to the cutoff effect in magnetrons. The increased losses of charged particles on the upper-end surface of the used electrode system, to which the discharge zone is pressed by the increasing azimuthal magnetic field, may also have an effect.

The appearance of a dip in the oscillograms can be explained not only by the discharge suppression effects. The second reason may be that the strong magnetic field, as its induction approaches its maximum value, shifts the discharge zone above the location of the photodiode and electric probe, with a corresponding decrease in their signals. When the magnetic field decreases, the discharge zone descends, and at first these signals increase when the discharge zone passes by the photodiode and probe, and then drop to zero when the discharge zone returns to the lower end of the electrode system.

CONCLUSIONS

The study of the influence on the normal low-pressure glow discharge (20...100 Pa) in the coaxial electrode system of the azimuthal magnetic field of the anode, through which a current is passed with a value sufficient to generate magnetic induction of several millitesla, has revealed the effect of magnetic shifting of the discharge zone along the interelectrode gap with the system length of tens of centimeters. The direction of the magnetic shifting/scanning of the discharge zone or the so-called magnetic “blowing” was determined by the direction of drift of charged particles in crossed fields [**EB**]. When the alternating current was passed through the anode, the effect of magnetic scanning in the forward and reverse direction was achieved. This effect can be used in the technology of ion-plasma treatment of the inner surface of long tubes with small diameter. It is advisable to further study the influence of the azimuthal magnetic field of the anode on the anormal glow discharge in the coaxial system of electrodes in order to determine the possibility of implementing magnetic scanning at increased discharge current densities.

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ВПЛИВ МАГНІТНОГО ПОЛЯ СТРУМУ, ЩО ПРОХОДИТЬ ЧЕРЕЗ АНОД, НА ТЛІЮЧИЙ РОЗРЯД У КОАКСІАЛЬНІЙ СИСТЕМІ

М.С. Мельниченко, С.Б. Сидоренко, А.І. Кузьмичєв, С.О. Майкут

Для дослідження впливу магнітного поля на нормальний тліючий розряд низького тиску використовували коаксіальну систему електродів із сітчастим трубчастим катодом і внутрішнім анодом, через який пропускали струм для отримання азимутального магнітного поля, схрещеного з електричним. Осцилографування сигналів з електричного зонда і фотодіода спільно з відеозйомкою дозволило встановити рух області розрядної зони, що світиться, вздовж електродів. При пропусканні змінного струму частотою 50 Гц через анод рух розряду був коливальним – від одного торця системи до іншого.