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Plasma Decay at Low Pressure

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ABSTRACT

The article gives a detailed description of the process of plasma decay in a weak electric field for a diode gap with a glowing cathode at low pressure. The analysis of the process is carried out under conditions when the neutralization of charged plasma particles is carried out on the diode electrodes during ambipolar diffusion. A mathematical description of the process of plasma decay is considered taking into account the displacement of its boundary — the ion layer relative to the anode; a joint solution of the ambipolar diffusion equation for unsteady mode and the law of 3/2 degree law for the ion layer near the anode is presented, taking it as a gas-filled gap. An equation is also obtained for the time of the plasma boundary moving from the anode to the cathode, and the relationship between the plasma boundary moving time and the total plasma decay time from the main discharge characteristics is shown. A new method was found for determining the plasma decay constant by constructing the dependence of the time of the plasma boundary moving from the anode to the cathode. The relationships were experimentally verified and a fairly high consistency was obtained between the theoretical and experimental values of the plasma decay time constant.

Key words: diode, plasma, decay, field, pressure, low.

1.INTRODUCTION

The process of plasma decay determines many phenomena in gas-discharge devices. This phenomenon determines the mechanism of interruption of the discharge in gas-discharge photon counters [1] and the recovery time of the arrester in resonant arresters of antenna switches [2]. The presence of the phenomenon of post-discharge conductivity during plasma decay reduces their frequency properties in thyratrons [3] and leads to a loss of control properties in controlled thyratrons (tasitrons) [4]. The phenomenon of post-discharge conductivity has to be considered in protective dischargers, since these processes [5] determine the value of the voltage of the extinction of the discharge.

The study of plasma decay in an external electric field is of theoretical and practical interest. The main works are summarized in educational and specialized literature [6; 3; 7]. It can be noted that more attention was paid to plasma decay in the instruments under the influence of reverse voltage, and the kinetics of plasma decay with a moving boundary is still poorly understood. From the point of view of increasing the frequency characteristics of a number of gas-discharge devices, their study would be promising, and it is also necessary for a deeper understanding of the gas discharge as a whole.

The decay of plasma in gas-discharge devices occurs mainly with reverse voltage at the anode. At voltages up to 1-2 kV at the anode, the density of the reverse current to the anode is determined by the concentration of ions that enter the ionic shell at the anode due to their random (thermal) motion from the residual plasma. With a reverse voltage of more than 1-2 kV, the reverse current will consist of two components. The first is static, which is determined by ions entering the shell as a result of thermal motion from plasma layers adjacent to the shell; the second is dynamic, which is determined by ions remaining in the increasing layers of the shell due to the escape of electrons from them under the action of reverse voltage [8].

At the initial moment of plasma decay in a weak electric field, when the concentration of charged particles in the decaying plasma is high, the dynamic component of the current density is less than static. As the plasma decays and the particle concentration decreases, the contribution of the dynamic component in the reverse current increases and may become predominant at the final stage of plasma decay. Therefore, the rate of plasma decay at different stages can vary significantly.

This article discusses the kinetics of plasma decay in a weak electric field at low pressure. In a low-pressure plasma, the volume recommendation of charged particles can be neglected in comparison with the losses due to their departure to the electrodes of the device. Therefore, it is assumed that the neutralization of charged plasma particles is carried out on the electrodes of the device, and the main process in this case is ambipolar diffusion.

2.THEORETICAL BASIS

The discharge gap is a flat diode with a heated cathode. A schematic distribution of the potential φ in the gap at a negative voltage at the anode is shown in Figure 1. It is known that there is a minimum potential near the heated cathode. Since the length of the minimum of the potential is much smaller than the size of the discharge gap, the length of the region of the minimum of the potential is neglected. The current length of the residual plasma is denoted by $b(t)$, the total length of the discharge gap is d. Taking into account that the reverse voltage significantly exceeds the value of the potential minimum, its value is also not shown in the potential distribution diagram in a decaying plasma.

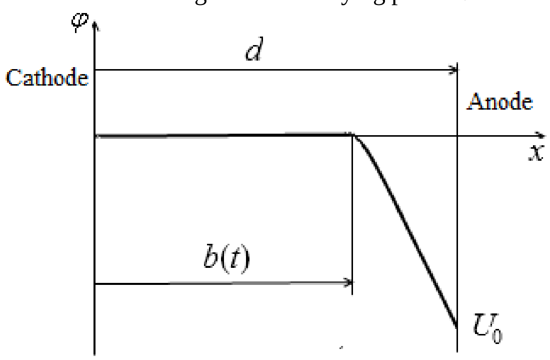

Figure 1: Potential distribution in a decaying plasma.

We analyze plasma decay for the following conditions:

1) the length of the discharge gap is small, so that the temperature of the filling gas is equal to the temperature of the cathode;

2) neglect the contribution of the volumetric recommendation to the neutralization of charged particles;

3) the temperature of electrons and ions in the plasma is the same and remains constant.

To determine the change in the concentration $n(x,t)$ of charged particles in a plasma decaying in an electric field, it is necessary to solve the diffusion equation for an arbitrarily moving plasma boundary. At a moving plasma boundary, the particle concentration can be equated to zero as a first approximation. Assuming that the depth of the minimum of the potential is sufficiently large, it is possible to assume that the ion flux to the cathode is zero as the second boundary condition.

Based on this, the boundary conditions of the problem have the form

$$n = 0 \text{ for } x = b(t); \quad \frac{\partial n}{\partial x} = 0 \text{ at } x = 0.$$

When considering the kinetics of the distribution of charged particles in the post-discharge period, we will take the residual plasma to be completely homogeneous throughout the entire interval $b(t)$. Plasma decay proceeds, as indicated above, due to ambipolar diffusion followed by recombination at the electrodes of the device. The equation of ambipolar diffusion under unsteady mode has the form [7]

$$\frac{\partial n}{\partial t} = D_a \frac{\partial^2 n}{\partial^2 x}, \quad (1)$$

where D_a is the ambipolar diffusion coefficient.

To solve equation (1), methods of mathematical physics are used [9]. In the approximation of the first term of the expansion of $n(x,t)$ in a series in the fundamental functions of this problem, one can find

$$n(x,t) = n_0 z^{-1/2} \cos\frac{\pi x}{2zd} \exp\left(-\int_0^t \frac{\partial t}{z^2 \tau}\right). \quad (2)$$

Here: $z = \frac{b(t)}{d}$ is relative current coordinate;

$\tau = \frac{4d^2}{\pi D_a}$ is plasma decay time constant.

The value n_0 is the initial value of the amplitude of the first term in the expansion of $n(x,0)$ in a series with respect to the cosines of the fundamental function adopted in solving this problem.

For a complete description of plasma decay, it is necessary to find the dependence of the dimensionless coordinate z on time t. The initial equation for the analysis of processes in the anode region of a decaying plasma is the Poisson equation [10]. For the planar case, which is an ionic layer near the anode, the Poisson equation is written in the form $\frac{\partial^2 U}{\partial^2 x} = 4\pi\rho_i$, where ρ_i is the ion charge density. Expressing the charge density in terms of current density I and the velocity of ions in the layer, we obtain

$$\frac{\partial^2 U}{\partial^2 x} = 4\pi \frac{I}{V_i}, \quad (3)$$

where V_i is directional ion velocity.

To determine the speed V_i we accept:

– an ion in a collision with a neutral molecule in the layer transfers charge to the molecule without energy transfer;

– a new ion begins to move at zero speed;

– the rate of thermal motion of ions is neglected.

From the expression $\frac{MV^2_i}{2} = e\lambda E$, where e is the electron charge, λ is the mean free path of the ion, E is the electric field strength in the layer, M is the mass of the ion, for the directed ion velocity we obtain

$$V_i = \frac{1}{2}\sqrt{\frac{2eE}{MpQ}} \text{ or}$$

$$V_i = \frac{1}{2}\sqrt{\frac{2eU}{MpQa}}. \quad (4)$$

Here: p is the gas pressure in the gap;

Q is the total cross section of the collision of ions with gas molecules, reduced to the unit pressure.

Substituting in (3) the value of V_i from (4) and taking into account that $a = d(1-z)$, we obtain for the ion current density on the anode

$$I=\frac{1}{\sqrt{pQ}}\sqrt{\frac{2e}{M}}.\frac{U^{\frac{3}{2}}}{d^{\frac{5}{2}}}\frac{1}{(1-z)^{\frac{5}{2}}} \text{ or } I=\frac{I_0}{(1-z)^{\frac{5}{2}}} \quad (5)$$

where $I_0=\frac{1}{\sqrt{pQ}}\sqrt{\frac{2e}{M}}.\frac{U^{\frac{3}{2}}}{d^{\frac{5}{2}}}$ is the current that will flow through the diode at a cathode-anode distance of d.

Equation (5) expresses the law of degree 3/2 of the gas-filled gap when the directional speed is proportional $\sqrt{E/p}$.

On the other hand, the current density in the cross section $x=b$ can be found through the diffusion flux of ions from the plasma [7]

$$I=-eD_a\frac{dn}{dx}. \quad (6)$$

Using expression (2) from equation (6) we obtain for the current density

$$I=\frac{eD_a n_0\pi}{2dz^{\frac{3}{2}}}e^{-\int_0^t\frac{dt}{\tau z^2}}. \quad (7)$$

Equating the right-hand sides of equations (5) and (7), we obtain an expression for the relationship between z and t, i.e. plasma boundary position with time

$$\frac{2cz^{\frac{3}{2}}}{(1-z)^{\frac{5}{2}}}=e^{-\int_0^t\frac{dt}{\tau_0 z^2}}, \quad (8)$$

where $c=\frac{dI_0}{\pi en_0D_a}$.

Differentiating expression (8) with respect to time t, we obtain

$$\frac{(3cz^{\frac{1}{2}}(1-z)^{\frac{5}{2}}+2c\frac{5}{2}(1-z)^{\frac{3}{2}}z^{\frac{3}{2}})dz}{(1-z)^{\frac{5}{2}}}=\frac{dt}{\tau z^2}e^{-\int_0^t\frac{dt}{\tau\cdot z^2}}.$$

Replacing the resulting expression $e^{-\int_0^t\frac{dt}{\tau_0 z^2}}$ with its expression from (8), we find

$$-\frac{dt}{\tau}=(\frac{3}{2}z+\frac{5}{2}\frac{z^2}{1-z})dz. \quad (9)$$

We represent the second term in parenthesis in the form

$$\frac{5}{2}\frac{z^2}{1-z}=\frac{5}{2}\frac{z^2-1+1}{1-z}=\frac{5}{2}\left[\frac{1}{1-z}-(1+z)\right].$$

Using the resulting expression from equation (9) we find

$$-\frac{dt}{\tau}=(\frac{5}{2}\frac{z}{1-z}-\frac{5}{2}-z)dz. \quad (10)$$

Let z_1 denote the position of the plasma boundary at the initial instant of its decay. Then, as a result of integration of expression (10) for time, we find the following equation

$$t=\tau\frac{5}{2}(\ln\frac{z}{1-z_1}-z_1-\frac{z_1^2}{5})-\frac{5}{2}\tau(\ln\frac{z}{1-z}-z-\frac{z^2}{5}). \quad (11)$$

When, in the course of plasma decay, its boundary reaches the cathode, the value of z becomes zero. This will correspond to the total plasma decay time in the discharge gap. Based on this, it follows that the total decay time will be

$$t_n=\tau\frac{5}{2}(\ln\frac{z}{1-z_1}-z_1-\frac{z_1^2}{5}). \quad (12)$$

Finally, the equation for moving the plasma boundary during decay can be written as follows

$$t=t_n-\frac{5}{2}(\ln\frac{z}{1-z}-z-\frac{z^2}{5}). \quad (13)$$

To determine the values of t_n, depending on the plasma parameters, we find the value of z_1. From relation (8) for $t = 0$ and $z = z_1$ we find

$$\frac{cz_1^{\frac{3}{2}}}{(1-z_1)^{\frac{5}{2}}}=1.$$

With a weak electric field (subject matter), to a first approximation, we take $z_1 = 1$. Then, after the logarithm, the equality takes the form

$$\ln\frac{1}{c}=\ln(\frac{1}{1-z})^{\frac{5}{2}}.$$

Substituting the obtained expression into formula (12) and revealing the value of c as $\frac{2dI_0}{\pi en_0D_a}$, we obtain the final equation for determining the time t_n

$$t_n=\tau\frac{5}{2}(\ln\frac{\pi enD_a}{dI_0}-z_1-\frac{z_1^2}{5}). \quad (14)$$

As can be seen from the expressions obtained, the time t and t_n in a first approximation should depend on the pressure of the filling gas, and increase with increasing discharge current, ion mass and with a decrease in the reverse voltage at the anode. Using expressions (12) and (14), we can determine the time constant τ, which is the main characteristic of plasma decay. One of the ways to calculate it is to construct the dependence of t_n on $\ln(1/U^{3/2})$. In this case $\tau=\frac{2}{3}\frac{\Delta t_n}{\Delta U}$. Another way to determine the constant τ is to build the dependence of t on $f(z)$, the tangent of which is $\tau=\frac{\Delta t}{\Delta f(z)}$, where $f(z)=\frac{5}{2}(\ln\frac{z}{1-z}-z-\frac{z^2}{5})$.

3.METHODOLOGY

For experimental studies of plasma decay, the method of oscillography of the current on a moving probe introduced into the plasma was used [11]. The position of the plasma boundary in the course of its decay was determined at the instant of current interruption to the probe, when the plasma boundary passed through the cross section of the discharge gap where the probe was placed.

The experimental model was a flat diode with a heated cathode. The anode in the device was made movable, which made it possible to study plasma decay at various distances between the cathode and anode. The studies were carried out in hydrogen in the pressure range from 0.16 to 0.6 mm Hg.

The determination of the plasma boundary position at different instants of time was carried out using a movable cylindrical probe with a working part of 4 mm and a diameter of 0.08 mm. The probe was moved in the central part of the gap between the cathode and the anode. A voltage was set at the anode of the device from a negative power source, the value of which did not exceed 1 kV. To excite a discharge in the gap, a rectangular voltage pulse was applied to the anode, the amplitude of which exceeded the negative voltage at the anode and was sufficient to maintain a stationary pulse discharge. The value of the discharge current in the gap was set by the value of the positive voltage at the anode.

With the pulsed nature of the discharge current, a circuit with a storage capacitance was used to power the probe (Figure 2).

This scheme avoids the influence of the internal resistance of the probe power source on the measurement results. To ensure measurements of small probe currents by an oscilloscope, the resistance R_u was chosen equal to 1000 Ohms. The value of the capacitance C of 0.5 μF is determined taking into account the fact that during the pulse of the discharge, it should not be significantly discharged. The resistance $R_з$ is 10 kΩ, which eliminates the influence on the mode of the measuring circuit. The pulse repetition period was 1 ms, the probe potential was 5 V.

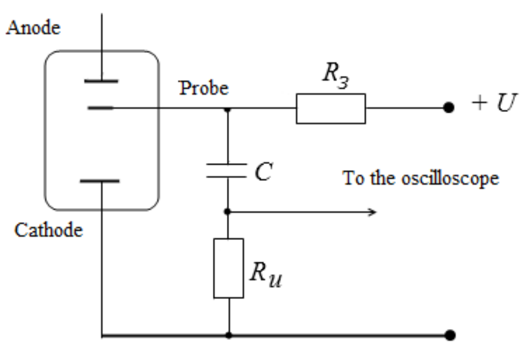

Figure 2: Diagram of probe measurements with storage capacity

4.RESULTS

Figure 3 shows the dependences of the total plasma decay time on the logarithm of the voltage at the anode at a filling gas pressure of 0.36 mm Hg. When constructing the graph for the convenience of the image, a transition was made from the natural logarithm to decimal. The form of the dependences is completely consistent with equation (14).

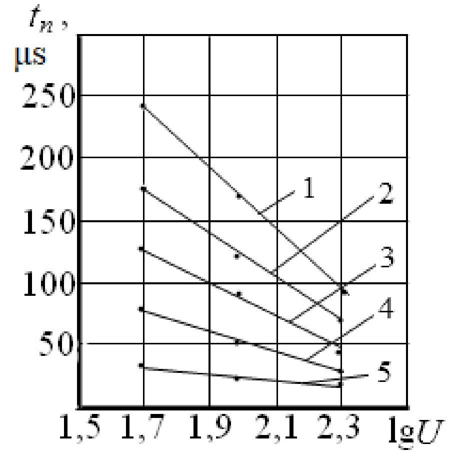

Figure 3: Dependence of the total plasma decay time on lg*U* at a discharge current of 1 A: *d* = 16 mm; *d* = 14 mm; *d* = 12 mm; *d* = 10; *d* = 8 mm

Dependencies are linear. From the obtained dependences, plasma decay time constants were found. The calculation results of the experimental values $\tau_э$ are presented in table 1.

Table 1: Experimental and theoretical values of the plasma decay constant at different distances between the cathode and anode

d, mm	8	10	12	14	16
$\tau_э$, μs	11,2	20	31,8	40	54
τ_m, μs	13	20,4	30,2	41	52,7

Theoretical values of τ_m were determined using the expression $\tau = \frac{4d^2}{\pi^2 D_a}$. To calculate the ambipolar diffusion coefficient, the formula $D_a = 2\frac{kT}{e}\mu_i$ was used, where μ_i is the ion mobility. At an electron temperature equal to the cathode temperature, we have $\frac{kT}{e} = 0{,}086$ V. Using the value $\mu_i = 9{,}1\cdot10^3$ cm$^2\cdot$c$^{-1}\cdot$B^{-1}, for the constant we can find $\tau_m = 256d^2p$ (table 1).

The results of studies of the kinetics of plasma decay for currents 1 and 5 A at a pressure of 0.6 mm Hg are presented as graphical dependencies in Figure 4.

Figure 5 shows the dependences $t = f(z)$. Dependencies are plotted from the values of curves 1 and 2, presented in Figure 4.

From the slope of the linear parts of the characteristics (Figure 5), the experimental values of the constant $\tau_э$ equal to 127 and 122 μs, respectively, were determined. The theoretical value of the constant is τ_m = 131 μs.

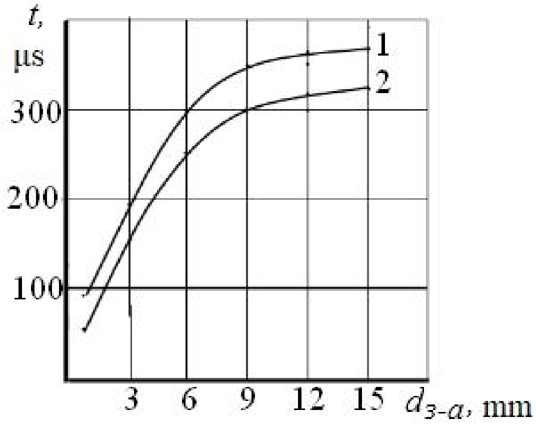

Figure 4: Dependence of the plasma decay time between the cathode and the anode at a pressure of 0.2 mm Hg, with a reverse voltage U = 100 V for various values of the discharge current: 1 – *I* = 5 A ; 2 – *I*= 1 A

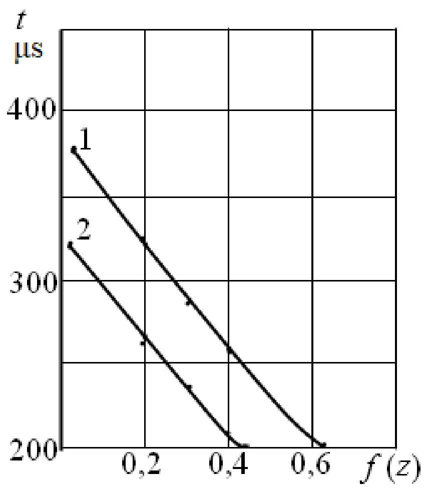

Figure 5: Graph of the time *f* (*z*) for currents: 1 – *I* = 5 A ; 2 – *I*= 1 A

5.DISCUSSION

According to table 1, the experimental and theoretical values of the decay constant at different distances between the cathode and the anode differ by less than 13%, which shows good agreement between the results, i.e., the methods of the theoretical approach to calculating the constant τ and the experiment are consistent.

The graphs in Figures 4 and 5 serve for the experimental determination of the decay constant for various values of the discharge current. As can be seen from the graphs with *f* (*z*) values less than 0.4, which corresponds to the location of the probe at a distance of 5 mm from the anode, the dependences are linear.

For large values of the location of the probe relative to the anode, the character of the dependences becomes nonlinear, which is due to an increase in the velocity of the plasma boundary due to a decrease in the concentration of charged particles during its decay. We can assume that the dynamic component of the ion current density on the anode begins to influence the decay nature. In this case, the experimental and theoretical values of the desired value in the linear part of the graphs are also consistent with each other.

If we consider table 1 from the point of view of the influence of the distance between the cathode and the anode on the decay constant, then the experimental characteristics do not give a proportional dependence on the value of d^2: $\tau = \frac{4d^2}{\pi D_a}$. This is due to the fact that under the logarithm function the distance *d* is in the denominator (formula 14).

It was also found that the time of moving the plasma boundary from the anode to the cathode under these conditions is hundreds of microseconds.

6.CONCLUSION

In this work, the kinetics of plasma decay under the prevalence of ambipolar diffusion in weak electric fields was theoretically studied.

An analysis of the given experimental results confirmed the analytical dependences obtained by entering the consideration of the proposed theory. The obtained expressions describing the process of plasma decay allow us to use them to determine the decay time constant under various conditions of the discharge.

The obtained new results in the field of plasma decay supplement the theory of gas discharge physics.

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