Optical and kinetic characteristics of a pulsed discharge in argon with aluminum vapor at atmospheric pressure

V S Kurbanismailov¹, S A Maiorov²,³, G B Ragimkhanov¹ and Z R Khalikova²

¹ Dagestan State University, 43 Gadzhiev Str., Makhachkala, 367003, Russia
² A.M. Prokhorov General Physics Institute RAS, 38 Vavilov Str., Moscow, 119991, Russia
³ Joint Institute for High Temperatures RAS, 13 Bld. 2 Izhorskaya Str., Moscow, 125412, Russia

E-mail: gb-r@mail.ru

Abstract. Experimental studies of the space-time dynamics of the formation and spectra of optical radiation of a pulsed discharge in argon in external electric and magnetic fields were performed. It was shown that during the formation of a pulsed discharge in argon in the process of diffuse luminescence propagation, cathode spots form on the cathode on it, as evidenced by the presence of lines of electrode material vapor in the plasma emission spectrum. Monte Carlo methods are used to study the kinetic characteristics of the drift of aluminum ions in argon.

1. Introduction

Despite the large number of publications devoted to the study of the properties of low-temperature pulsed plasma, there are many questions related to the physics of pulsed breakdown and the mechanisms of the initial stages of formation that remain not fully studied [1–8]. Modern technologies often use plasma processes in which there are vapors of metals in the core. They fall into the gas discharge zone or due to the spraying of the structural elements of the gas discharge chamber.

The presence of lines of emission of atoms and ions of the material of the substance of the electrodes in the spectrum of the gas-discharge plasma, serves as direct evidence of the sputtering of the material of the substance of the electrodes. Metal pairs significantly change the electron energy distribution function and [9] and, accordingly, the entire discharge kinetics. On the other hand, the ion distribution function (IDF) over velocities is of interest in cases involving the study of plasma-chemical reactions involving ions, the determination of the mobility of ions in a plasma object, the heating of the neutral component of the plasma, and several others. The features of ion drift have been theoretically studied in many papers; these results are presented in [10–14].

This paper presents the results of experimental studies of the spatial-temporal dynamics of formation and the optical emission spectra of the near-electrode plasma of a pulsed discharge in argon at atmospheric pressure, as well as the calculation of the kinetic characteristics of metal ions (Al) in argon.
2. Research methods

2.1. Experimental set-up and methods of investigation

In this paper, studies were conducted both in pulsed electric and in pulsed electric and magnetic fields. For this, two discharge chambers were made: one to study various stages of pulsed discharges without a magnetic field, and the other to study the development of a spark channel in magnetic fields.

In the absence of a magnetic field, the distance between the aluminum electrodes was 1 cm, and the diameter of the electrodes was 4 cm. Two types of electrodes were used for research in a magnetic field – hemispherical with a radius of curvature of $R \sim 30$ cm and flat electrodes. The diameter of the hemispherical aluminum electrodes was $2r = 4$ mm.

A voltage pulse with a leading edge duration of $\sim 10$ ns with an amplitude in the range from a static breakdown value to 20 kV was applied to the interelectrode gap. The investigated interval was irradiated by a spark discharge through the grid anode or by placing a UV source in the same gas – at a distance of 5–7 cm from the axis of the main gap. Thus, pre-ionization with an initial electron concentration of $\sim 10^7$ cm$^{-3}$ was created in the gas.

A discharge in a pulsed longitudinal magnetic field was carried out in a region with a characteristic size of 10 mm with a strength of pulsed magnetic fields up to 250 kG and a duration of more than 100 $\mu$s. The experimental setup scheme and research methods are given in [7]. The magnetic field was created by the discharge of a capacitor battery through a solenoid, in which the gap was placed.

The concentration of charged particles was measured at low currents by the current density, and at high currents by the Stark contour of spectral lines. The plasma temperature was measured by the relative intensity of the spectral lines and was estimated from the plasma conductivity. Recording the spatial and temporal development of luminescence using an electron-optical converter (FER-2) and an electro-optical shutter (EOZ), recording the emission spectra in the visible and near ultraviolet regions with spatial and temporal resolution.

2.2. Statement of the problem and the method of modeling the drift of metal ions in argon

To simulate ion-atomic collisions when an ion moves in a uniform electric field, the equations of motion of ions were integrated according to the second-order Runge-Kutta scheme. At each time step, the collision of an ion with an atom was played out. Let us list the main stages of the developed algorithm for ion-atomic collision modeling [10]:

- in the system of the center of mass of the colliding particles, in accordance with the probability of a collision, the velocities and the impact parameter of the collision are randomly selected;
- when moving in the center of mass of the particles with the polarization interaction potential, the following are determined: the distance of the closest approach $r_{min}$, the relative velocity of the particles at the point of closest approach $v_{12}(r_{min})$, the scattering angle $\chi$;
- if the distances of the closest approach are $r_{min} < d_{gas}$ (the diameter of an atom), then the velocities of the ion and the atom deviate by an angle of $\chi$; otherwise, i.e. if $r_{min} < d_{gas}$, then the velocities of the ion and the atom are recalculated in accordance with the law of collision of elastic spheres, the distance of the minimum approach is assumed $r_{min} = d_{gas}$, the relative velocity of the particles at the point of closest approach $v_{12}(r_{min})$ is determined;
- speeds are recalculated in the laboratory system, statistics is accumulated on various collision characteristics.

The developed algorithm reproduces the well-known solution of the Boltzmann kinetic equation for the drift of charged solid spheres, the mobility in the weak field limit, as well as the well-known theoretical results on the collision kinetics of elastic spheres [10].
3. Results and discussion

3.1. The results of the experimental researches and their investigation

In a volume discharge in argon, the spark channel is initiated by processes at the cathode. After applying a voltage pulse exceeding $U_{st}$ to the pre-ionized discharge gap ($U_{st}$ is the average breakdown voltage), after 250 ns a weak glow of a wide diameter ($2r = 0.5$ cm) propagates to the cathode with a speed of $\sim 10^7$ cm s$^{-1}$ (figure 1). The intensity of the glow along the radius of the pillar is not the same, the central part glows more intensely. The discharge is tied to the center of the electrodes, where the field strength is maximum (spherical electrodes with a radius of curvature of $R \approx 30$ cm). When the ionization front approaches the cathode, the luminescence intensity of the column increases sharply (see figure 1) and as the front approaches the cathode, a filamentary glow appears ($2r = 0.2$ mm), which closes the discharge. The diameter of the diffuse channel at this stage was 4 mm.

![Figure 1. Photographs of luminescence in the gap ($p = 1$ atm, $d = 1$ cm, $E/p = 10.53$ V (cm·Torr)$^{-1}$).](image)

After 20–25 ns, after the gap overlaps with the ionization front, a bright cathode spot appears and the discharge takes the form of a cone with a top at the cathode (see figure 1(3)). The cathode spot brightness is significantly higher than the column brightness (see figure 1(4)) and the cathode region acquires brightly defined boundaries ($2r = 0.2–0.3$ mm), and the diameter of the glow column narrows ($2–3$ mm from the anode). The formation of a cathode spot coincides with the onset of a sharp increase in current and a voltage drop across the discharge gap.

The study of the space-time dynamics of a pulsed discharge formation in atmospheric pressure argon in centimeter inter electrode gaps (with an initial electron concentration in the interval $n_0 \sim 10^7$ cm$^{-3}$ and insignificant over voltages $W \sim (10–100\%)$ show that during the formation of a discharge, the first recorded luminescence occurs on anode, which propagates to the cathode at a velocity of $\sim 2-5 \times 10^7$ cm s$^{-1}$. As the emission front moves toward the cathode, the electron concentration in it increases and reaches values of $\sim 10^{13}$–$10^{14}$ cm$^{-3}$.

We have carried out investigations of the emission spectra from the near-cathode plasma of the discharge in atmospheric pressure argon. It has been established that with the formation of a cathode spot, the spectrum of the near-cathode plasma is characterized by intense lines of the cathode material Al II 396.1 nm, 394.4 nm, 280.1 nm, 281.6 nm with high excitation potentials and an intense continuum in the 260–360 nm range. The lines of aluminum ions are recorded simultaneously with the onset of a sharp current increase and reach a maximum value in 20–30 ns. After 30 ns from the onset of sharp current growth, the Stark half-width of the 480.6 nm argon line is 0.5–0.6 nm, and the line 422.8 nm $\sim 0.5$ nm. These half-widths correspond to an electron density of $\sim 10^{19}$ cm$^{-3}$, and after 20 ns the concentration decreases to a value of $2 \times 10^{18}$ cm$^{-3}$.

The effect of a longitudinal magnetic field on the emission spectra of a cathode plasma of the discharge is investigated. It is established that with an increase in the strength of the magnetic field the maximum radiation energy shifted to the short-wave region of the spectrum: at $H = 0$, $\lambda_{max} = 420$ nm, at $H = 140$ kOe $\sim 400$ nm, at $H = 200$ kOe $\sim 380$ nm. Thus, in the magnetic field the intensity of continuous radiation increases, the brightness of the ion lines in the ultraviolet region also increases: Ar II 280.6 nm, Ar IV 280.9 nm and lines of the electrode material Al – 280.1 nm, 281.6 nm.

At the stage of slow channel expansion, i.e. from the moment $t = 500$ ns, the intensity of continuous radiation decreases, the intensity of ionic lines also decreases, while the brightness of the
lines of neutral argon is 394.89 nm, 392.9 nm and aluminum lines Al I – 302.9 nm, 308.2 nm; Al II – 281.6 nm, 280.1 nm increases. In the longitudinal magnetic field, from the moment $t = 700$ ns, the emission of Ar I lines 394.89 nm strongly increases; Ar II 280.6 nm; Ar IV 280.9 nm and aluminum 281.6 nm; 280.1 nm; 309.27 nm and 308.216 nm, while the intensity of the lines in the visible range of the spectrum decreases with increasing magnetic field strength.

3.2. The results of the numerical experiment and their consideration

Consider the drift characteristics of aluminum ions in argon. Figure 2 presents the results of calculating the velocity distribution function of aluminum ions in argon along (figure 2a) and across (figure 2b) the field in argon for field strength values of 10 and 100 Td and gas temperatures of 300 and 600 K.

![Figure 2](image)

**Figure 2.** The results of the calculation of the distribution function of aluminum ions (in relative units) in velocity along the field direction (a) and across the field direction (b) in argon at various electric field strengths.

As can be seen, the dispersion of the distribution function both along and across the field is the higher, the larger the field $E/N$ and the lower the gas temperature. It should be noted that even with a sufficiently high reduced electric field strength, the formation of a highly supersonic ion flow does not occur, at which the speed of directional motion (drift) considerably exceeds the speed of their thermal chaotic motion. The reason for this is that as the field strength increases, along with an increase in the drift velocity, the dispersion of the distribution function increases, i.e. values of longitudinal and transverse ion temperatures increase.

From an analysis of the ion distribution functions over velocities, it follows that there are significant differences in the distribution of the magnitude of the velocity and of the projections of the velocities from the corresponding Maxwellian distributions. Moreover, there is a difference not only in the tails of the distribution functions, but also in the central part. Accordingly, the ion velocity distribution function when they drift in a gas in a strong field cannot be described by a Gaussian curve.

The following important fact should also be noted. Since there is a large difference between the longitudinal and transverse ion temperatures $T_\| \text{ and } T_\perp$, the diffusion coefficients vary greatly along and across the field.

One of the most interesting effects observed during ion drift in a gas is diffusion anisotropy, i.e. the difference in diffusion coefficients in the directions along and across the electric field. The degree of anisotropy can be estimated by the ratio of the coefficients of the longitudinal and transverse diffusion $D_\| / D_\perp$. The corresponding dependences of the degree of anisotropy on the electric field intensity are shown in figure 3 at different temperatures of atoms: 100, 300, 500 and 600 K. The maximum of anisotropy with a decrease in temperature will be mixed in the direction of lower fields, which is
difficult to explain. It can be associated with the fact that at low temperatures of atoms in weak fields
the fraction of collision with backscattering tends to zero.

4. Conclusion
Thus, it was shown in the paper that the formation of a pulsed discharge in argon occurs in the mode
of sputtering of the material of the electrode material. Metal vapor, having a much lower ionization
potential than argon, can change the kinetics of the discharge due to a change in the ionic composition.
The drift of metal ions in argon also has a number of important features that lead to a significant
change in the characteristics of the discharge. All this indicates the complexity of the processes in the
discharge and stimulates further studies of the properties of the discharge.

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